NEUTRONIC AND FUEL CYCLE ANALYSIS FOR THE ANNULAR PEBBLE-BED ADVANCED HIGH TEMPERATURE REACTOR

2009 NE 170 Senior Design Project

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EXECUTIVE SUMMARY

The Pebble Bed Advanced High Temperature Reactor (PB-AHTR) is a liquid fluoride salt cooled, pebble-fuel high temperature reactor. This senior design report presents the results of the Neutronics and Fuel Cycle (NFC) design group's project to perform preliminary neutronic and depletion analysis for a thorium seed/blanket annular core design for the PB-AHTR, and to develop a method for sorting seed and blanket pebbles as they are removed from the reactor. The NFC group collaborated with a Reactor Safety and Mechanical Design group that constructed a scaled, 15° sector experiment to demonstrate the pebble radial zoning. The core design developed by the NFC and RSMD groups uses radial pebble blankets to provide fast-neutron shielding of the solid graphite structures, while the fuel region has alternating layers of seed and blanket pebbles to increase the core's conversion ratio. The pebbles are recirculated through the core, and the thorium blanket pebbles are held in decay storage to increase the production of U-233 and minimize parasitic neutron capture on Pa-233.

Initial depletion analysis was performed using a simplified analytical model to investigate the effects of pebble recirculation rate and decay storage length on conversion ratio, as well as to gauge the maximum obtainable fissile content in blanket pebbles. As expected, conversion ratio increases with increasing decay time, and decreases with increasing irradiation time. Using this analytical model, a blanket pebble cycling scheme of 10 days spent of irradiation followed by 10 days spent in decay storage was chosen. A numerical model was then constructed using MOCUP to couple MCNP5 for neutronics with ORIGEN2 for burnup. The core is simplified as an infinite cylinder, and the pebble circulation is simulated by a static core cycled through 10 days of irradiation followed by 10 days of decay. To approximate an equilibrium core, blanket pebbles in six different regions were enriched in U-233 to simulate different levels of burnup. This core was then run for 11 cycles, or 220 days, in order to build up fission products. The results of this simulation show that the reactor

can stay critical while achieving a conversion ratio greater than one, indicating that this reactor could run sustainably on a pure thorium fuel cycle. In addition, the initial fissile material required to start up this reactor is around 0.6 kg per MW_e, substantially less than the nominal 4.0 kg/MW_e required to start up a light water reactor.

A set of scoping calculations was performed on the infinite cylinder model to test the sensitivities to various parameters in the reactor design. For simplicity the level of burnup was held constant for all seed pebbles during the scoping calculations and in the full-core 3D model. The baseline parameters used for the scoping calculations resulted in the following important reactor characteristics: keff of 1.02, total shutdown rod worth of 0.052, and void reactivity of –0.047. Additionally, the inner and outer graphite reflector lifetimes are computed to be 7.62 and 63.5 years, respectively. The scoping calculations involved varying a few key parameters, including the mass of U-233 loaded into each driver pebble, the radius of the center control channel, and the outer radius of the blanket pebble region. The results of these calculations indicate that an increase in the overall mass of U-233 will increase k_{eff} while decreasing the conversion ratio. The same behavior is observed when the control channel radius is increased or the outer blanket radius is decreased, thus increasing the ratio of U-233 to Th-232 in the reactor. The results additionally demonstrate that the shutdown rods effectively decouple the control channel system (inside the rods) from the rest of the reactor system (outside the rods).

A more realistic full-core 3D MCNP model was developed to obtain information about the reactor that the infinite cylinder approximation could not provide. This analysis yielded the axial leakage, parameterization of core regions, and solid graphite reflector lifetime. The axial leakage calculations showed the excess reactivity needed to compensate for the approximations of the infinite cylinder model. A raw percent estimate of this excess reactivity was done by a simple simulation in MCNP in which all regions of the three dimensional model were kept constant and the height of the main cylindrical region of the core was increased to approach the infinite cylinder approximation. This calculation yielded a percent difference of 1.15 %. A more accurate assessment was done by finding the actual percent leakage out of both axial regions of the core. This yielded a value of 1.67%. The next step was to see whether the height of the necking regions affected the percent leakage in the core. We found out that the leakage was inversely proportional to the height of the necking region, and that the leakage at the desired core dimensions was sufficiently low. When analyzing the flux in the inlet and outlet chutes, we found that the best place to position the graphite partitions for the radial zoning of pebbles was 270 cm from the necking region.

Finally, an analysis of the feasibility of sorting and categorizing pebbles upon extraction from the core was performed. Blanket and seed pebbles are fabricated to have slightly different weights to facilitate initial sorting. Simulations then showed that the concentration of Pa-233 can be measured with a germanium detector to optimize blanket pebble decay storage time, while total burnup can be assessed by measuring Cs-137.

1.0 INTRODUCTION

Advanced High Temperature Reactors (AHTR's) are Generation IV reactors that use high-temperature coated particle fuels, along with a liquid fluoride salt coolant, to achieve high-temperature operation at high power density and low pressure. The 2008 NE 170 senior design class developed a detailed plant design for a 410-MWe Pebble Bed AHTR, shown in Fig. 1-1. The 2009 NE 170 senior design class has studied a new annular core design for the PB-AHTR. This design, shown schematically in Fig. 1-1, uses a solid graphite central reflector similar to the PBMR, with a radial and axially zoned pebble bed. As with other PB-AHTR designs, the pebbles float and are injected at the bottom of the core and removed from defueling chutes located above the top of the core. Our Neutronics and Fuel Cycle design group studied how this new core design can be used to implement a closed thorium based fuel cycle.

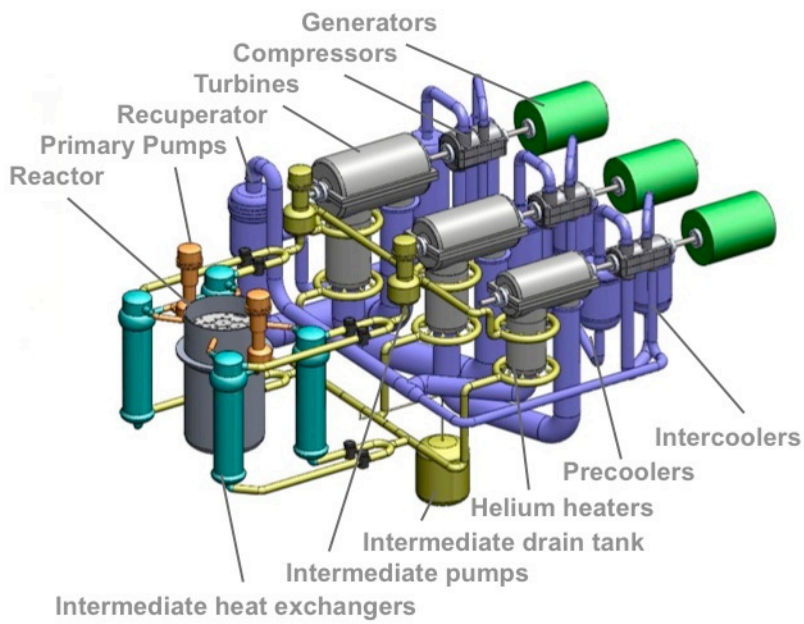


Fig. 1-1 900 MWth, 410 MWe PB-AHTR power plant design [1-1].

2.0 ANNULAR PB-AHTR

2.1 – Annular PB-AHTR Core Design Description

In this annular core design, the pebble blanket is divided into 3 to 8 radial zones. The inner and outer zones are occupied by graphite, thorium or thorium-uranium blanket pebbles. The inner driver fuel zones are occupied by alternating axial layers of seed and blanket pebbles.

The blanket pebbles serve two roles.

First, the radial blanket pebbles zones provide neutron shielding to reduce fast neutron dose (neutrons with energy greater than 100 keV) to the inner and outer graphite reflectors, sufficiently to allow a long time interval to replacement, with life-of-plant being the design goal. The degree to which the radial reflectors can be shielded is also impacted by the need for the inner reflector to house shutdown rod channels, and the outer reflector to potentially house control rod channels. Because the major effect of the thorium blankets is to moderate high-energy neutrons and absorb epithermal neutrons, the effectiveness of the shutdown and control rod channels, where thermal neutron absorbing poisons are inserted, will depend primarily upon how the inner radial blanket effects the reflection of thermal neutrons. Detailed neutronics simulation is needed to assess this affect.

Second, the radial and axial breeding blankets improve the neutron economy, by breeding U-233 from Th-232. A typical 900 MWth annular PB-AHTR may have 2.2 million pebbles. The typical recirculation time for a pebble in a PB-AHTR will be 5 to 30 days, corresponding to pebble defueling and injection rates ranging from 5.1 to 0.85 Hz. This can be compared to the 27.0-day half-life of protactinium-233, formed by neutron capture in Th-232. By storing blanket pebbles outside the core for a sufficient period of time to allow the optimal decay of Pa-233 to U-233, these blanket pebbles can become an effective source of fissile material within the PB-AHTR fuel cycle. Currently, the molten salt reactor (MSR) can achieve the best thermal-spectrum neutron economy of any known reactor design. Table 2-1 compares the MSR and the PB-AHTR with a radially and axially zoned core design.

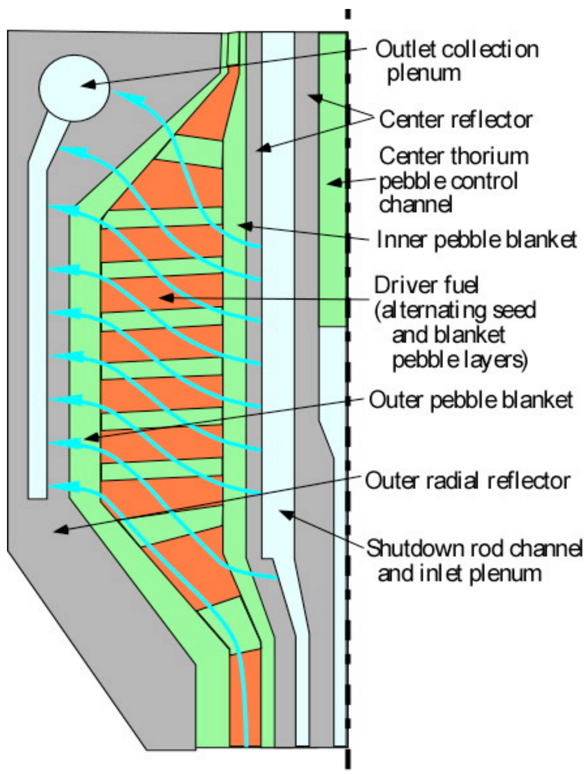


Fig. 2-1 Schematic diagram showing a radially and axially zoned pebble bed core with inner and outer radial blankets, center thorium pebble control channel, and coolant flow distribution.

Table 2-1 Comparison of neutron-economy features of the PB-AHTR with a radially and axially or azimuthally zoned core, with the molten salt reactor (liquid fluoride thorium reactor).

	MSR/LFTR	PB-AHTR
Online refueling	Yes	Yes(1)
Xe-135 removal	Yes	No
Pa-233 removal/decay	Yes(2)	Yes(3)
Thorium breeding blanket around core	Difficult	Yes
Radial zoning of core and blanket	No	Yes
Axial alternating seed and blanket layers	No	Yes

(1) A small amount of excess reactivity is required to manage xenon transients. If this reactivity control is provided by removable Th-232 elements (as shown in Fig. 1-1), no conversion ratio penalty occurs.

(2) Pa-233 management depends upon salt reprocessing rate to recover Pa-237

(3) Pa-233 management depends upon blanket pebble recirculation time and external storage time.

2.2 – Annular PB-AHTR Closed Thorium Cycle

With its potential capability to support blankets, the annular PB-AHTR is a candidate to operate with a closed thorium fuel cycle. Fig. 2-2 illustrates, schematically, a thorium based PB-AHTR fuel cycle that would also provide the capacity to start up new PB-AHTR reactors, and to provide transmutation services to destroy transuranic waste materials recovered from LWR spent fuel.

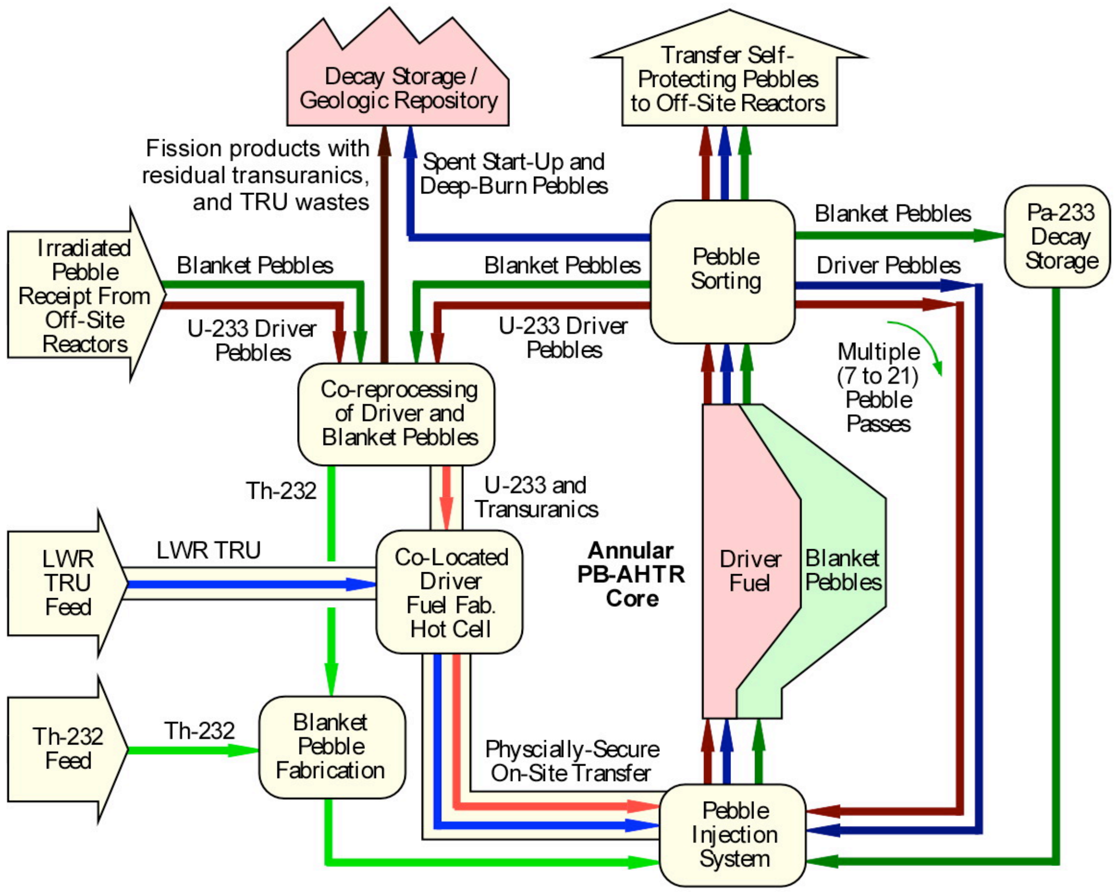


Fig. 2-2 Annular PB-AHTR thorium fuel cycle schematic.

As shown in Fig. 4, the annular PB-AHTR closed thorium cycle requires technology for co-reprocessing of fuel and blanket pebbles, and for remote (hot cell) fabrication of new driver pebbles. Remote fabrication is required due to gamma radiation from U-232 in the driver fuel, which is present in substantial concentrations (no Pa-233 chemical separation occurs in this reactor design). These TRISO fuel reprocessing and fabrication technologies are now being developed under the DOE Deep Burn Fuel program. The thorium will also contain Th-228 with a 1.9-year half-life. Some decay storage may be justified for the thorium to allow direct-contact handling for the refabrication of new blanket pebbles.

As with the mixture of plutonium and minor actinides that is recycled in the integral fast reactor (IFR), in the closed fuel cycle for the annular PB-AHTR the U-233, other uranium isotopes, Np-237, and higher actinides that are recovered by reprocessing would be weapons usable. Therefore, as with the IFR all transfers of fresh driver pebbles occur under remote handling conditions in hot cells or in shielded transfer casks in underground transfer tunnels, providing substantial passive barriers to theft. Driver pebbles destined for use in off-site reactors receive 1 to 3 passes through an on-site reactor before transport, so that all pebbles transported in a PB-AHTR thorium fuel cycle are self-protecting. Both spent and fresh pebbles are transported in the same heavily shielded transport casks. The capability to partially irradiate fresh pebbles is a physical security benefit provided by the on-line refueling capability of the PB-AHTR.

The Spring 2009 UCB NE-170 senior design class will be studying thorium fuel cycle options for the annular PB-AHTR, to determine the core and blanket design parameters that can optimize the conversion ratio under an equilibrium thorium cycle. If this conversion ratio can be shown to be greater than unity, then a wide variety of flexible fuel cycles become possible.

2.3 – Simplified Annular PB-AHTR Neutronics Model For a Closed Thorium

The annular PB-AHTR's capability to manage a wider variety of potential fuel cycles will depend upon how optimally it can operate with thorium as a fertile material. A key performance parameter to assess the flexibility of PB-AHTR fuel cycles is the maximum conversion ratio (CR) for the annular PB-AHTR operated under an equilibrium thorium fuel cycle. This section discusses issues associated with maximizing the PB-AHTR equilibrium thorium-cycle CR, as well as other major performance parameters.

The NE-170 senior design class will be studying the limits on the maximum PB-AHTR CR. The following material outlines how this can be done.

The simplified model for parametric studies for CR will use a cylindrically symmetric, simplified 3-D representation of the core, which will treat neutron leakage from the top and bottom using an assumed neutron leakage fraction. The pebbles in the core will be modeled using a stacked hexagonal lattice, filling the annular blanket and driver fuel regions shown below. Pebbles lying at boundaries will be cut off at the boundary. An initial set of dimensions is shown in the Fig. 2-3, but these dimensions will be varied and optimized. Fig. 2-3 also illustrates one of several potential geometries for azimuthal zoning of seed and blanket pebbles. The configuration shown allows for uniform heating of coolant flowing radially outward through the blanket. The average power density in the driver fuel region should be 30 MW/m^3 (corrected for fission energy also generated by subcritical multiplication in the fertile blanket).

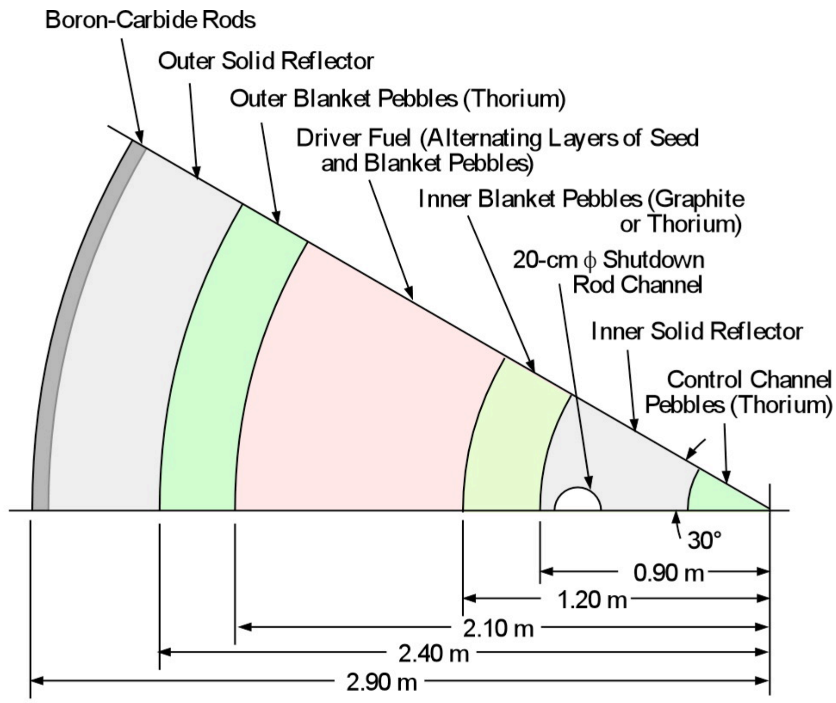


Fig. 2-3 Annular PB-AHTR neutronics model for a 30°C segment.

In addition to having fertile thorium pebbles in the blanket, it is also likely desirable to have axial zoning with blanket pebble layers alternating with the seed pebble layers in the driver region. These blanket pebbles will be easily separated from the seed pebbles, so that they can have decay storage (like the radial blanket pebbles).

In addition, at the center of the inner radial reflector it may be valuable to have a separate channel that can be filled, and emptied, with a mixture of uranium seed and thorium blanket pebbles. Absorption of neutrons by the blanket pebbles provides a method to reduce reactivity, and removing or adding them to this channel may thus allow reactivity control for slowly-evolving reactivity transients, including those associated with xenon buildup following power reduction. By using blanket pebbles to control reactivity, the parasitic neutron absorption by control rods (e.g., boron) can be reduced further and the reactor conversion ratio increased.

The two-dimensional model also allows the reactivity worth of the 6 or 12 shutdown rods to be modeled, by placing boron in the shutdown channel region and determining the change in keff. The model can also evaluate the reactivity worth of adding, or removing, thorium blanket pebbles from a central channel in the inner reflector.

In all cases the driver pebble carbon to heavy metal ratio (C/HM) must be adjusted to provide a slightly under-moderated system with negative coolant temperature feedback.

There are several parameters that need to be varied to identify the maximum conversion ratio:

(1) Ratio of carbon-to-heavy-metal (C/HM) for seed pebble heavy metal in the driver fuel region. This ratio must be adjusted to obtain a negative coolant temperature coefficient. To obtain the correct seed-pebble HM inventory, it will be necessary to vary the particle kernel diameter (nominally 300 micron), particle packing fraction, and diameter of the pebbles' inner graphite kernel. The density of the inner graphite kernel is adjusted to give an average pebble density of 1.72 g/cc. The minimum density for the center kernel graphite is 0.5 g/cc.

(2) Mass of thorium in each blanket pebble. To obtain different thorium loading, the particle kernel diameter (nominally 600 micron), particle packing fraction, and diameter of the pebble's inner graphite kernel, as with seed pebbles.

(3) Mixing ratio of blanket and seed pebbles in the driver fuel region. Reasonable values to explore include 0/100, 5/100, 10/100, 20/100, and 40/100. Adding blanket pebbles into the driver fuel region will require increasing the heavy metal loading in the seed pebbles to maintain the correct C/HM ratio for negative coolant temperature feedback.

(4) Mixing ratio of blanket and inert graphite pebbles in the inner blanket region.

(5) Pebble residence time in core (7 to 30 days) and blanket pebble storage time outside the core (2 to 5 times the pebble residence time). Blanket pebbles in the driver fuel region will receive a higher total fluence and will have a larger Pa-233 inventory upon discharge than blanket pebbles in the blanket regions. There may be benefits to swapping blanket pebbles between these regions, so that after a driver region pebble undergoes decay storage it then goes to the lower-flux region of the blanket, where less of the residual Pa-233 is destroyed.

(6) Radial and axial dimensions of the blanket and driver fuel regions. Various combinations may be considered.

There are several performance metrics for comparing the different parametric variations:

(1) Conversion ratio (CR): The rates at which seed and blanket pebbles are discharged is determined by the total inventories of each, and the time required for them to reach full discharge burn up. Each discharged seed and blanket pebble must be replaced by a new pebble. The discharged blanket and seed pebbles are co-reprocessed, and the separated uranium (U-232, U-233, U-234, U-235, and U-236) is refabricated back into new seed pebbles. To obtain the design C/HM ratio for the core either make-up U-233 is added to each pebble (CR<1), or some of the discharged uranium is placed in storage (CR>1). Thorium is separated and stored for decay prior to refabrication into new blanket pebbles. Np-237 and other transuranics are not recycled (for this case of determining the maximum CR). In an actual annular PB-AHTR, these transuranics could be fabricated into separate deep-burn pebbles for transmutation.

(2) Seed and blanket pebble lifetime: The amount of time required for a seed or blanket pebble to reach full discharge burn-up is an important parameter that affects how rapidly fuel qualification testing can occur. This is particularly important for seed pebbles. The

design goal for the start-up core is to have pebbles reach full discharge burn up in under one year.

(3) Neutron dose to solid reflectors: Neutron dose rate (> 100 keV) to the inner and outer solid graphite reflectors is a major parameter affecting their life expectancy. In particular, it is desirable for the outer reflector to have a long life expectancy (60 to 100 years) if possible.

(4) Shutdown rod reactivity worth: The annular PB-AHTR will have 6 to 12 shutdown rod channels. Reactivity worth for these rods is an important performance parameter that will affect the design of the inner blanket pebble region (potentially requiring that the pebbles be inert graphite). The requirement for sufficient shutdown rod reactivity worth may also affect the capability to shield the inner solid reflector sufficiently to provide very long life.

(5) Reprocessing rate for seed and blanket pebbles: It is desired to minimize the rate and volume of pebbles being reprocessed, to reduce reprocessing costs and to minimize the quantity of irradiated pebble graphite that must be recycled or discarded. Obviously the rate of reprocessing can be reduced by increasing the burn up level for seed and blanket pebbles. This comes with a penalty on the achievable conversion ratio. For blanket pebbles, high burn up levels may also require very long pebble residence times, which affects the difficulty of blanket pebble irradiation testing and which may prolong the start-up phase for PB-AHTR power plants.

(6) Peak particle power (mW/particle): Current design limit is 300 mW/particle. This must be achieved while meeting particle packing density limits (maximum of 40%). This may also provide the basis to change the core average power density (current baseline is 30 MW/m^3)

For the purpose of identifying the maximum conversion ratio, the first performance metric is most important. But the other 6 performance metrics are also important, and thus they should be quantified during the initial parametric study to determine how the major design parameters affect these performance metrics.

3.0 FULL THREE-DIMENSIONAL CORE ANALYSIS

3.1 – MCNP Model

MCNP5 is the program used to simulate the conditions in the thorium based PB-ATHR. A full-core 3-D model was constructed to obtain axial leakage in the core and provide a reasonable set of assumptions for a simplified model. This simplified model was then used for more time-intensive calculations.

The modeled pebbles consist of three layers, as shown in Fig. 3-1. The inner layer is a sphere of low-density graphite. The second layer, the fuel region, is generated by a repeating cubical lattice of TRISO particles surrounded by a graphite matrix. The outer layer is a high-density graphite shell. Initial dimensions for seed and blanket pebbles were different, and were taken from reference [3-1]. The specifications used for this model are shown in Table 3-1.

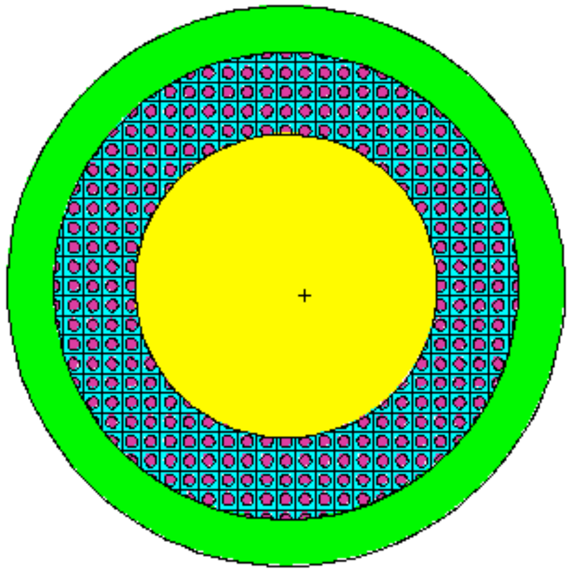


Fig. 3-1 MCNP5 geometry for a blanket pebble. The green, yellow and blue regions are graphite of various densities. The red circles are thorium oxide TRISO particles.

Table 3-1 Thorium PB-AHTR fuel properties, for average driver region power density of 30 MW/m^3.

	Seed	Blanket
Pebble diameter (mm)	30.0	30.0
Pebble shell thickness (mm)	2.5	2.5
Pebble center kernel diameter (mm)	3.62	8.14
Pebble center kernel density (g/cm^3)	0.5	0.25
HM load (g/pebble)	0.44	6.0
Th atom fraction	0 %	98.0 - 100.0%
^{233}U atom fraction	100 %	2.0 - 0.0 %
Average pebble density (g/cm^3)	1.77	1.99
TRISO particles packing factor	4.95%	44.7%
TRISO particles per pebble	691	5.27×10^3
Particle kernel diameter (mm)	500	634
Particle buffer layer thickness (mm)	150	64
Particle inner PyC layer (mm)	35	26
Particle SiC layer (mm)	35	31

Particle outer PyC layer (mm)	40	55
Average pebble power (W)	706	706
Average kernel power (mW)	1021	134

These pebbles were then placed into the reactor using a repeating lattice of hexagonal prisms consisting of one pebble with the rest of the volume filled with coolant, which in this case is flibe, a eutectic mixture of LiF and BeF_2. An equilibrium concentration (4.2 ppm) of ^{6}Li in the flibe was taken from reference [3-2]. The pitch of the hexagonal cell was made slightly larger than the diameter of the pebble to simulate an imperfect close-pack configuration, with a packing fraction of 0.60. Using these lattices, the core was filled to model the effects of axial and radial zoning.

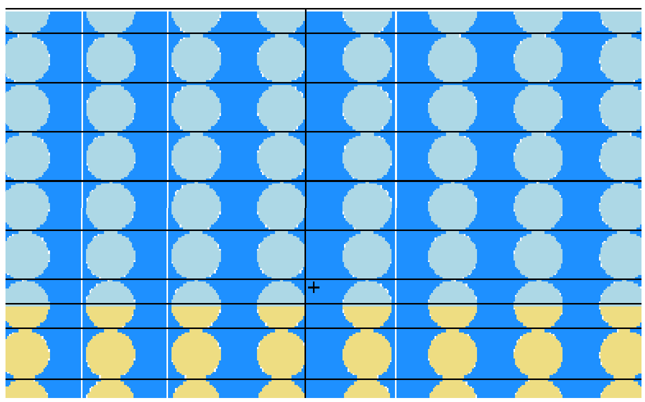
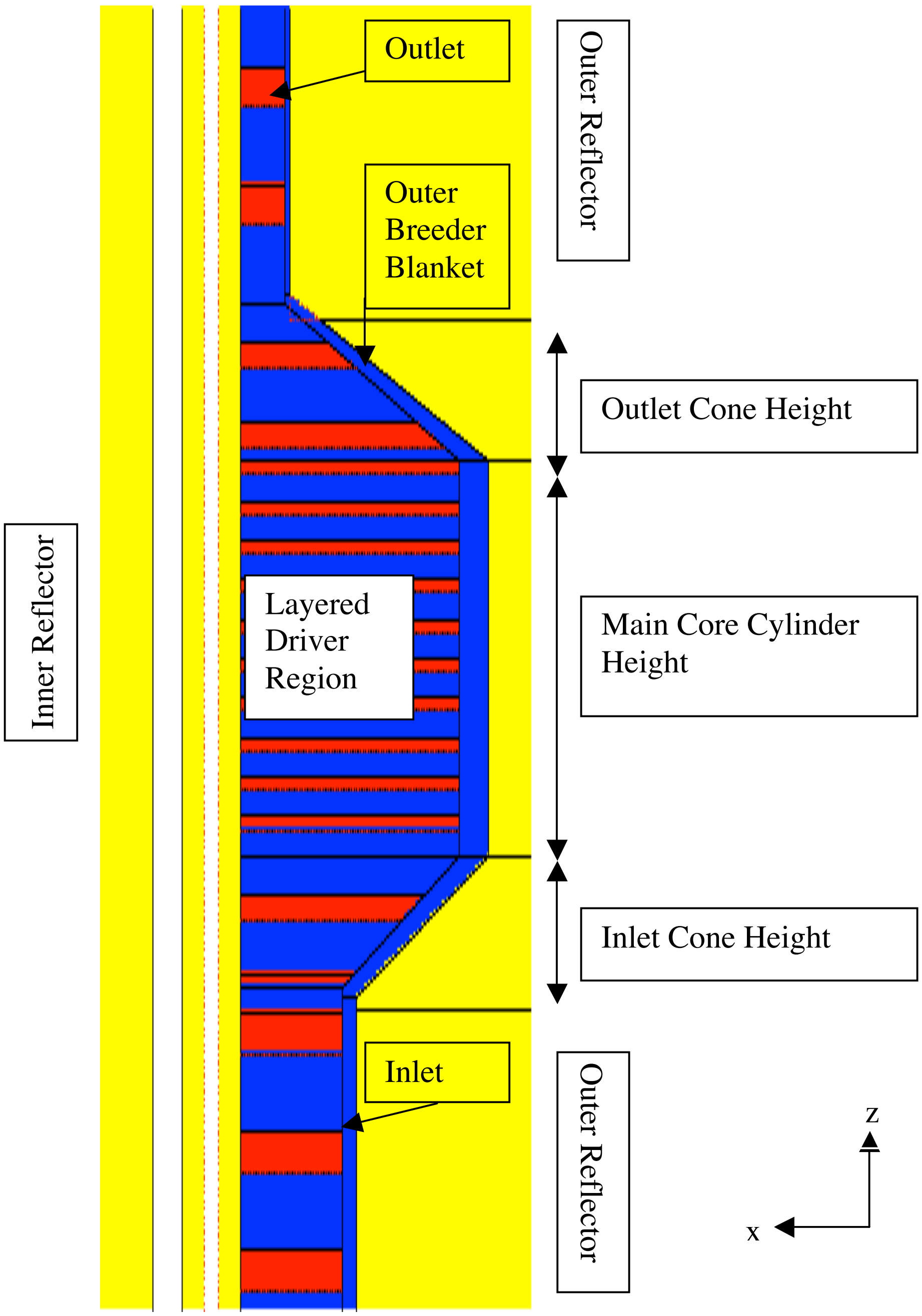


Fig. 3-2 MCNP5 geometry for pebbles in the reactor. The light blue pebbles are ^{232}Th pebbles, the yellow ones are ^{233}U pebbles. The dark blue region is FLiBe.

The three-dimensional model was used to assess four essential aspects of the pebble bed core: Axial Leakage, Flux in the inlet region, k_∞ in the outlet and inlet regions, and the life expectancy of the inner and outer reflector. Furthermore the three dimensional model was used to confirm the results for k_{eff} derived from the 2 dimensional model.

The baseline design is as follows:

The Baseline design uses two radial regions or blankets. One of the blankets consists of the 3 to 1 driver to fertile pebble ratio stacked axially. The second blanket is composed of fertile pebbles only. The core also has three distinct axial regions the inlet region, main cylinder, and the outlet region. The inlet and outlet regions are composed by the inlet and outlet chutes, which are used to pipe pebbles in and out of the core, and the inlet and outlet cones which serve as transitions to and from the main cylinder. Figure 3-3 shows a cross sectional view of the full core.



Region	Parameter
Inner Graphite Reflector	Radius= 115 cm
Driver Region	Radius= 210 cm
Breeder Blanket	Radius= 240 cm
Outer Graphite Reflector	Radius= 289 cm
Outer Boron shield	Radius= 290 cm
Outlet Cone	Height= 250 cm
Inlet Cone	Height= 200 cm
Main Core	Height= 300 cm
Inlet Chute	Radius= ½*Blanket Region
Outlet Chute	Radius= 1/5* Blanket Region

Fig. 3-3 Right: X-Z two dimensional cross section of the full core. Notice the thickening of the layers around the inlet and outlet. This is done to simulate the conservation of volume as the layer travels through the core. Left: Table containing all dimensions relevant to the construction of the MCNP model. (All simulations use these dimensions unless stated otherwise.).

3.2 – Infinite Height Approximation

The first series of simulations were done by varying the height of the central main cylinder and looking at its effects on k_{eff}. The results of these simulations should agree with the infinite cylinder solution assumed by the simple 2-D model. As figure 3-4 shows, k_{eff} approaches an upper limit which corresponds to the solution of the Infinite cylinder geometry. This upper limit is 1.04613 ± 0.00413 in agreement with the results of 2-D model.

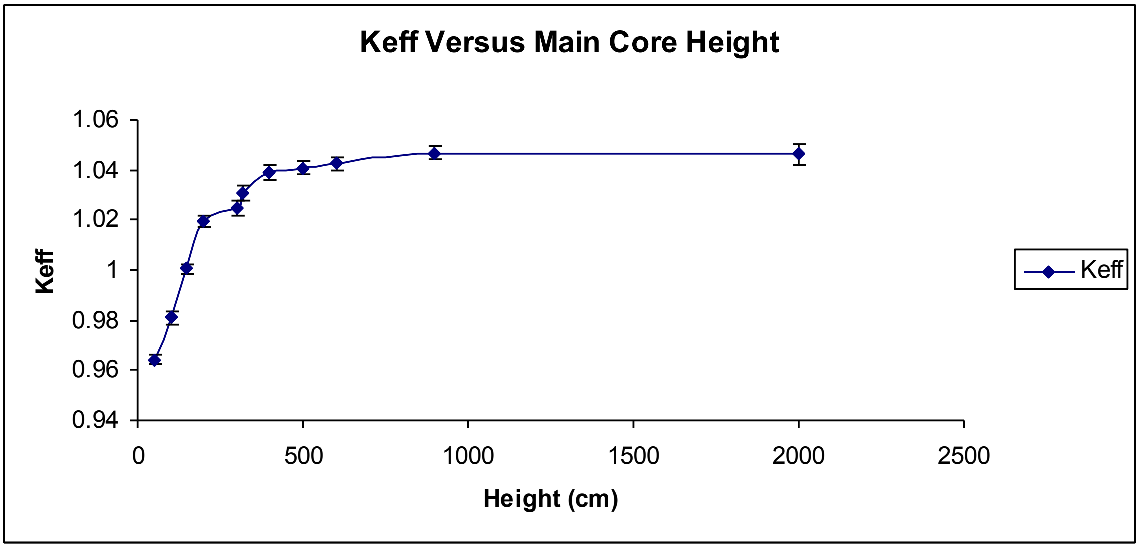


Fig. 3-4 Graph of $\mathbf{k_{eff}}$ versus main core height. As it can be seen $\mathbf{k_{eff}}$ is approaching an upper limit which is equivalent to the infinite cylinder solution.

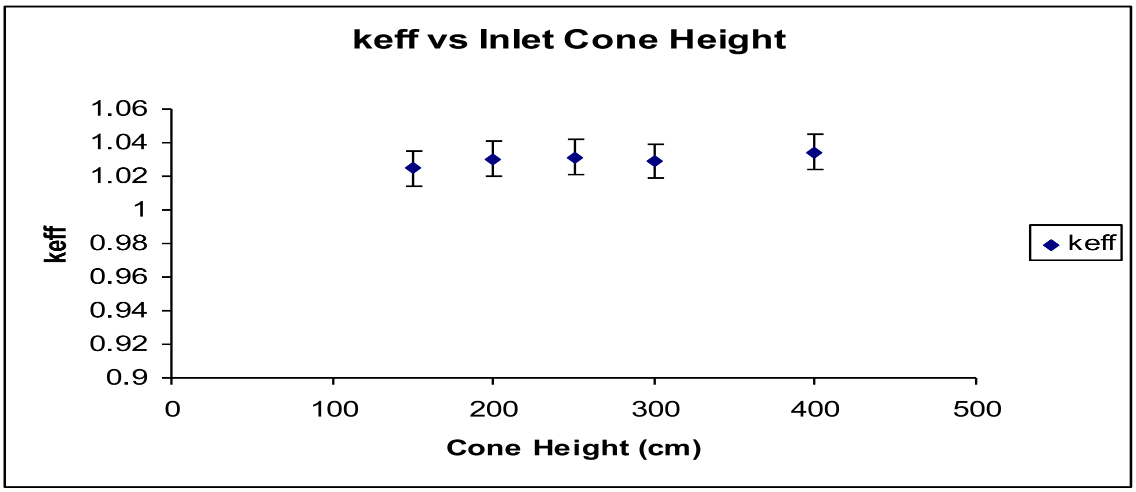
We expect to have a startup k_{eff} of 1.01 in order to overcome the initial Xenon buildup in the core. This value of k_{eff} is achieved at main core heights of 150cm to 200 centimeters as it can be seen in Figure 3-4. The problem with having such low main core height is that granular flow will not be well behaved unless the inlet and outlet cone heights are increased significantly. Thus it is more convenient and cost effective to have a slightly larger main cylinder to reduce the heights of the cones and keep the total height of the core compact. Furthermore it is apparent from the two dimensional model that the conversion ration is better when the layered pattern is kept at a 1 to 3 pebble stacking. This stacking pattern is only achieved in the main core since in the inlet and outlet regions the layers expand to conserve volume. Our plan calls for an optimal main cylinder height of 320 centimeters. The k_{eff} at this height is 1.03096 ± 0.00312. Thus we can see that the difference between the real value and asymptotic limit of the infinite cylinder is:

$$\mathbf{\Delta = 0.01517}$$

This is the fraction that the 2D model has to compensate by in order to accurately depict the conditions of the real core geometry.

3.3 – Cone Height

The next step was to see the effect that varying the cone height would have on $k_{eff.}$ Interestingly Figures 3-5 shows that k_{eff} will not be changed as cone height increases. This is due in part to the fact that by increasing the cone height the leakage is reduced but the neutron absorption rate is increased. This was confirmed by a simulation which kept track of the reactions that the neutrons entering the outer thorium blanket underwent. Of all the neutrons entering the blanket 8.5% were absorbed 0.004% caused fission and 91.4% escaped the blanket. From the neutrons that escaped the blanket 62.2% were reflected back into the driver region and 37.8% went into the outer graphite.The absorption that happens in the blanket is a possible hint at the fact that the conversion ratio may be higher than predicted by the 2-D model.



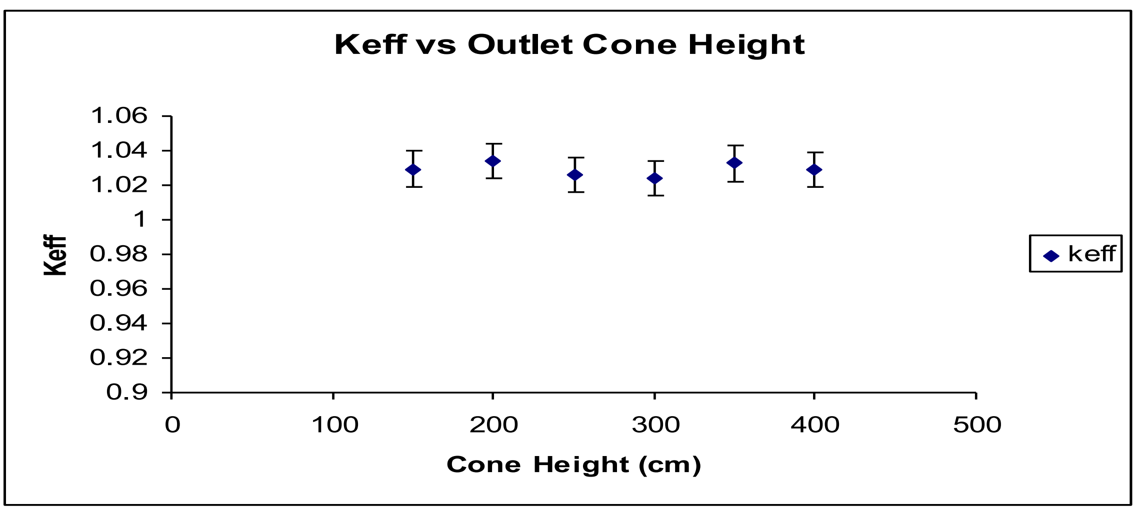


Fig. 3-5 Top) Height of inlet cone is varied while the height of the outlet cone is held at 100 cm. Bottom) Height of outlet cone is varied while the height of the inlet cone is held at 100 cm.

3.4 – Axial Leakage:

The reason why the results from the three dimensional model differ from the infinite cylinder is because of axial leakage. Axial leakage is the number of neutrons escaping out of the assembly through the conical surfaces and the inlet and outlet chutes. The axial leakage was calculated as a function of height of the inlet and outlet cones. This is important because we want to minimize the leakage while keeping the height of the inlet and outlet cones at a reasonable value. Keeping the height of the core at a minimal is important since this reduces the size of the housing structure thus reducing the costs of construction. Figure 3-6 shows a schematic of the axial leakage.

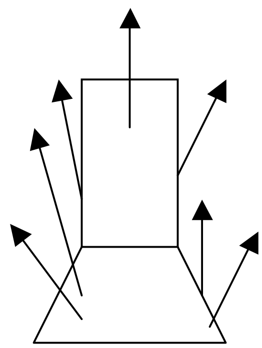


Fig. 3-6 The arrows represent neutrons leaking out of the core through the outlet region.

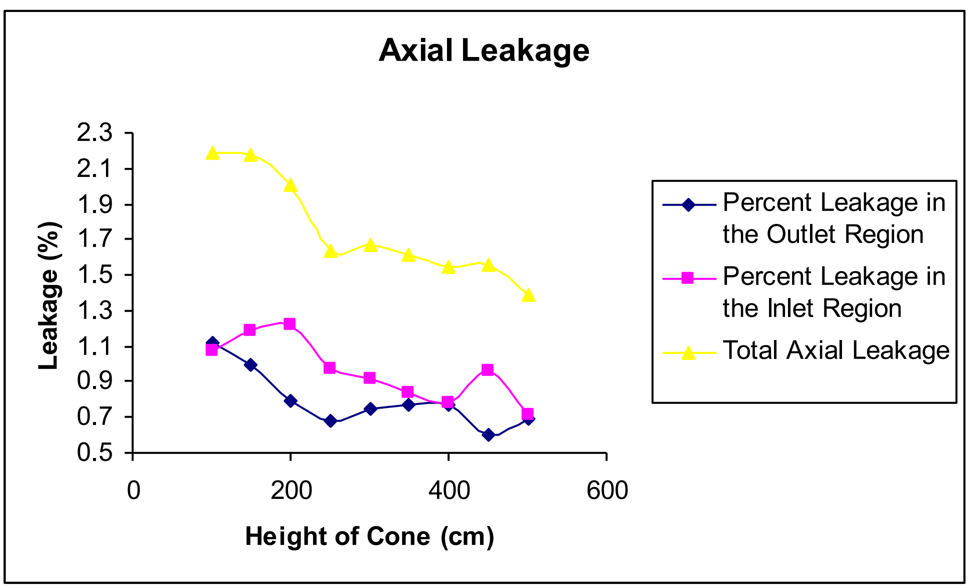


Fig. 3-7 **Percent of neutrons leaking out of the core and from the outlet and inlet regions.**

As it can be seen in figure 3-7 the total leakage decreases with increasing cone height. This is because as we increase the cone height we increase the amount of material that the neutron has to cross before it can escape. The increase in material that the neutron has to cross increases the probability of an interaction to occur. Thus the neutron is more likely to scatter back into the assembly or get absorbed. This reduces leakage significantly. Another important thing about this trend is that we are free to choose heights that aid the flow of pebbles in order to achieve both axial and radial layering. If the cone height is too small the pebbles will spread out faster and in a more turbulent manner which can lead to a great deal of random mixing. A higher cone has a smaller opening angle which allows for a more gentle transition for the pebbles which will allow for a more ordered expansion of the assembly into the desired distribution thus enabling us to zone pebbles in both the axial and radial directions. Besides zoning the pebbles one needs to keep in mind that another important goal is to minimize the total height of the core. From figure 3-7 one can see that the curve for total axial leakage shows a fast decrease from height of 50 cm to 250 cm and then it decreases fairly slowly afterwards. Thus a good candidate for cone height is 250 cm. The reason for this is because at 250 cm we can achieve a good granular flow and a small enough leakage while still keeping the overall height of the core low. The total axial leakage at the desirable height is 3.18% which is slightly bigger than expected but still acceptable. From the mechanical perspective a physical experiment is in progress to see how the cone parameters will affect granular flow.

3.5 – Safety Factor

Next we calculated k_∞ at the inlet and outlet regions to assess whether criticality was occurring at these regions. This is important since calculating the k_∞ gives us an idea of how the pebbles behave as they enter and exit the core and the severity of neutron damage to the solid graphite reflectors and other structures. Furthermore it will allow us to see if it will safe to store the pebbles in vessels of similar dimensions to that of the outlet chute. To estimate the criticality we must first note that if k_∞ is lower than one then that region is definitely sub critical. This is because $k=k_\infty (1-N_L)$ where N_L is the fraction of neutrons leaking out of the region in question, thus $k< k_\infty$. The way in which k_∞ will be calculated is as follows:

$$\mathbf{k_\infty \square \eta(N_f)/ (N_a)}$$

η is the average number of neutrons produced per fission, (N_f) is the number of neutrons causing fission, and (N_a) is the total number of neutrons absorbed ((n,f), (n,γ), (n,α), (n,β), (n,p) and so on). Note that (N_a) is the total absorption rate, which is Neutrons absorbed plus neutrons causing fission.

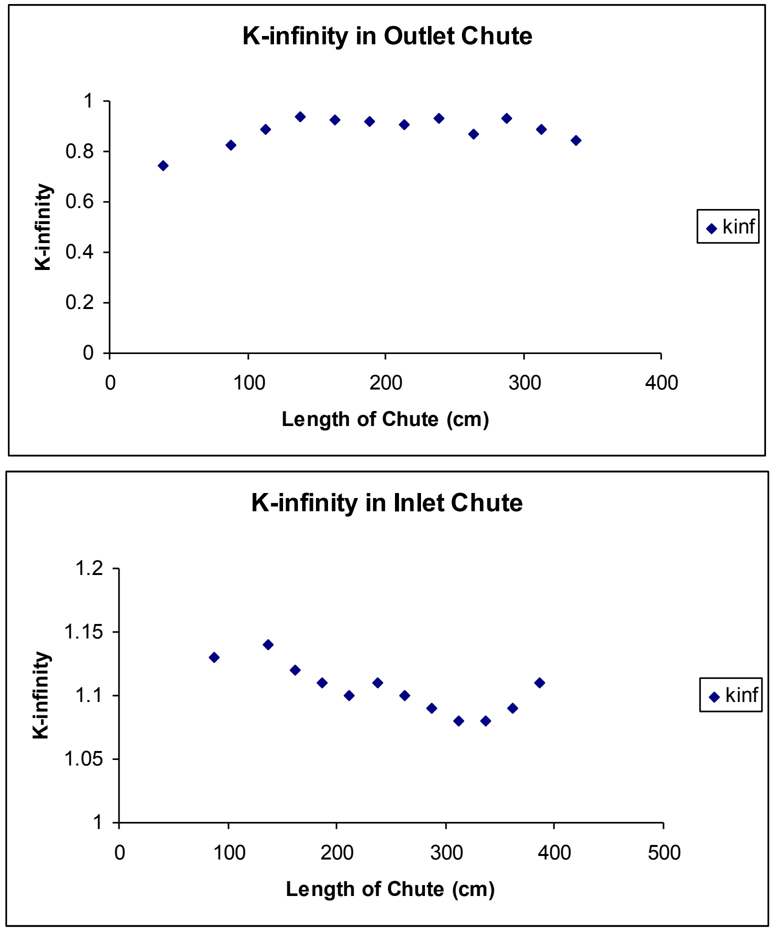


Fig. 3-8 Plot of k_∞ in the Inlet and outlet chutes

From Figure 3-8 one can see that the outlet chute is sub-critical at all lengths. The inlet on the other hand stays more or less constant at 1.1. Thus one can conclude that the outlet can be made short without many problems. But the situation with the inlet is different, since k_∞ is above one in this region we cannot conclude anything about the safety in this region thus a different measure must be taken to ensure that the partitions used for radial zoning are safe from fast neutron damage.

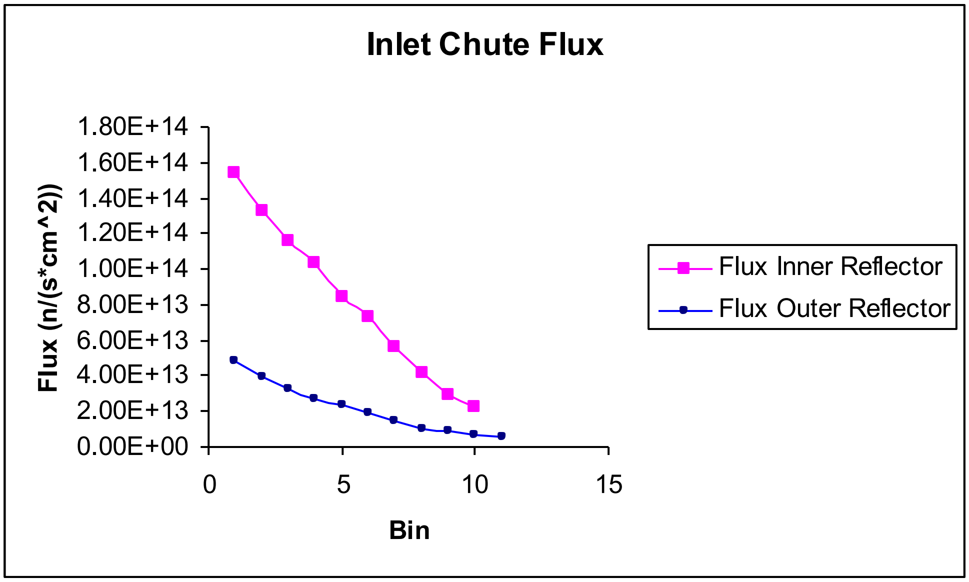


Fig. 3-9 Flux to the inner and outer reflector as a function of distance from the conical region.

The X-axis in Figure 3-9 shows bins. Each bin is a section of the inlet chute of about 30 cm in height. Bin one is the closest to the conical region and the 11th bin is the furthest from the conical region. Figure 3-10 shows the set up of the bins.

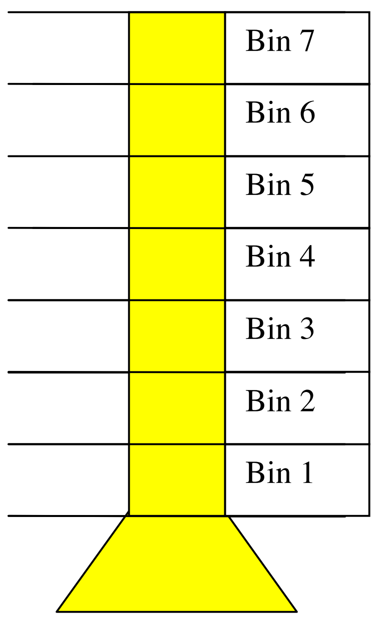


Fig. 3-10 Schematic for flux calculations in the inlet chute shown only up to 7 bins but the total is 11.

As Figure 3-9 shows, the flux is inversely proportional to chute length. The bin furthest from the conical region has a flux of 2.29×10^{13} n/s*cm^2 which is two orders of magnitude smaller than the flux at the cone. This means that a good point in which to place the radial zone separators should be at about bin 9 or ten which corresponds to a distance of 2.7 meters from the conical region.

3.6 Life Expectancy of Inner and Outer Reflectors

Measurements of fast neutron flux (energies above 0.1 MeV) were taken in the graphite inner and outer reflectors. These values for the flux were then used to estimate the lifetime of the inner and outer reflectors in the following manner. The maximum allowed neutron fluence to graphite is 3.0×10^{22} n/cm^2**.** A higher fluence will result in excessive swelling of the structure due to void formation and clustering.

Life time in seconds= ($3x10^{22}$ n/cm^2)/(Flux calculated in n/s*cm^2)

Then this value is divided by 365*24*3600 to give us the lifetime in years. Figure 3-11 shows the life expectancy of the inner and outer graphite reflectors as a function of core height.

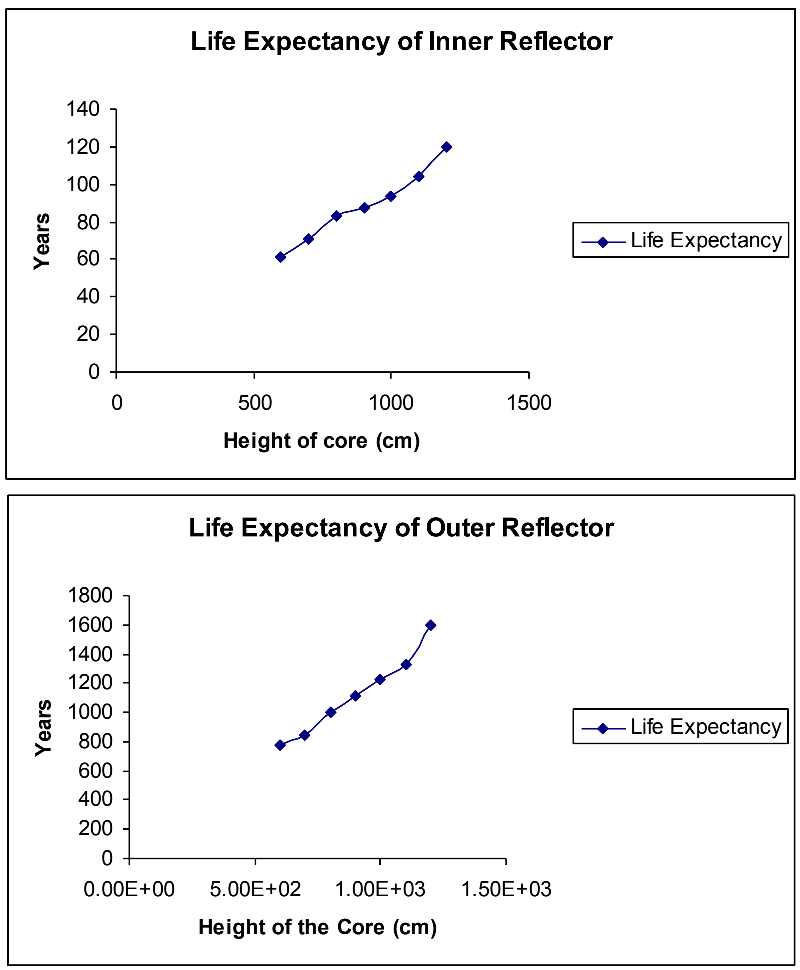


Fig. 3-11 Reflector life expectancy.

One can deduce from these graphs that as the height of the core increases the lifetime is prolonged. The outer reflector has a longer lifetime because of both its large volume and the shielding provided by the outer breeder blanket. Thus the outer reflector has no constraints on height. The inner reflector has a good life expectancy at around a height of 700 centimeters and higher. However this lifetime is the averaged lifetime of the structure. If one considers that the main cylindrical region is exposed to a higher flux than the other core regions one would see that the lifetime of the central region will be shorter than one at a lower flux. Thus although the rest of the structure will last for 65 years the central region of the core will swell due to void saturation. Thus it would be considerable to replace the inner reflector when this occurs to prevent obstruction of the pebble flow. The estimated lifetime of the high flux region is 5 years.

3.7 – Reactor Kinetics and Control

The 2 dimensional model predicted that it was difficult to achieve a significant amount of control when an inner blanket of carbon pebbles was present. That is why the baseline design only has 2 blankets present, the driver and the outer thorium blanket. The 3 dimensional model was used to do a simple calculation to asses the reactivity change due to rod insertion in both a two blanket and three blanket assembly. For both the 2 and 3 blanket designs the center control channel has a radius of 30 centimeters and the 12 shutdown channels are 10 centimeters in radius and are located at a distance of 75 centimeters from the center of the core. The only difference between the two designs is the radius of the inner reflector. In the three blanket design the inner reflector has a radius of 90 centimeters and from 90 to 115 centimeters it contains a carbon pebble blanket. The 2 blanket design has an inner reflector radius of 115 centimeters and no carbon pebble blanket. The three blanket design is shown with the center rod partially inserted in Figure 3-12.

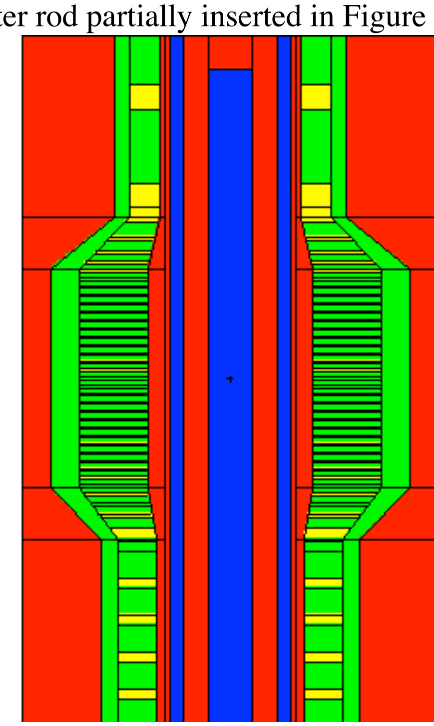


Fig. 3-12 Three blanket design

The first simulations were done to see the rod worth of the center channel loaded with fertile pebbles (pure thorium pebbles) and fissile pebbles (pure Uranium-233). Figures 3-13 and 3-14 show the results respectively.

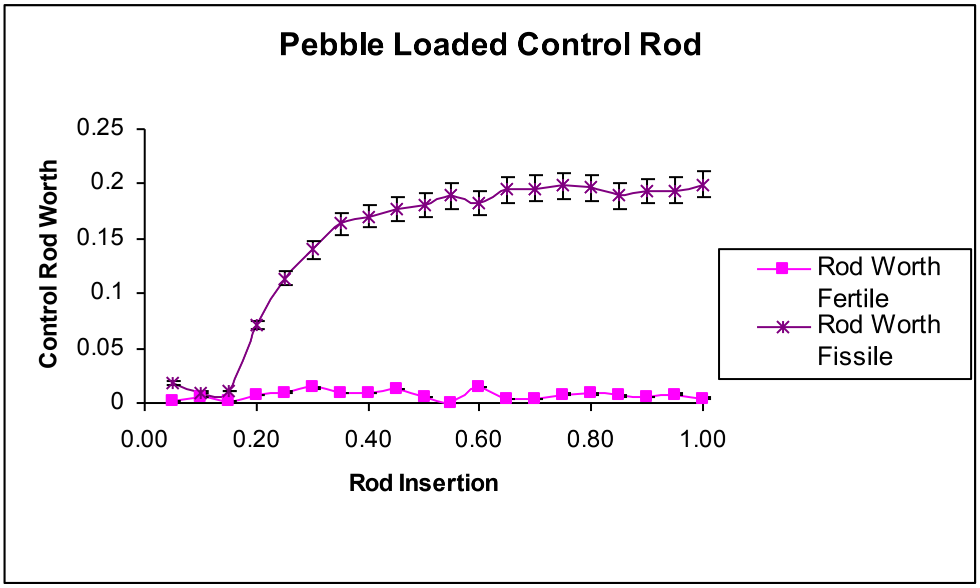


Fig. 3-13 Results for the baseline core design with two blankets

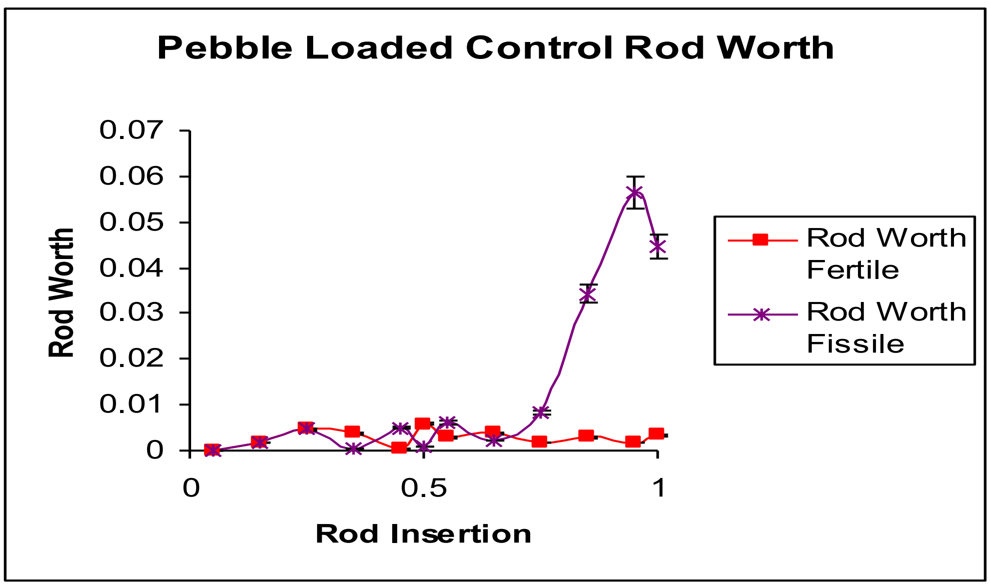


Fig. 3-14 Rod worth results for the three blanket original design.

The Rod worth for pure Thorium loading is poor for both the 2 and 3 blanket designs. The use of fertile material is necessary. From figures 3-13 and 3-14 we can see that the three blanket design has a poor rod worth, it only achieves a five percent change at an insertion fraction of 0.95 while the 2 blanket design achieves the same at an insertion of 0.2.

The second part of this analysis was aimed at the 12 shutdown rods. The rod design is a cruciform neutral buoyancy passive insertion system. The rods are made of boron carbide infused in a graphite matrix to achieve the desired density. Figure 3-15 shows the rod layout.

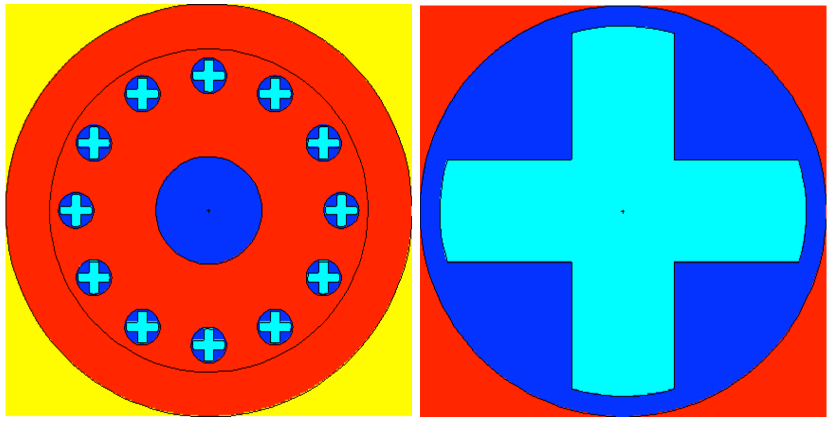


Fig. 3-14 Left) inner reflector with the inserted cruciform rods. Right) Close up of the cruciform rod.

The rod worth at full insertion of all twelve rods is 7.23% for the 2 blanket design and at 10.3% for the three blanket design. The immediate deductions are that the shutdown systems work better for the three blanket design. Another advantage of having an inner blanket is that it increases the life expectancy of the inner reflector at the high flux region from 5 years to 9.3 years. The inner blanket also provides added moderation and reflection of neutrons which leads to an increase in k_{eff} from 1.04 to 1.3 at the same core dimensions as the 2 blanket design. Thus with the inner blanket criticality can be achieved with a smaller concentration of fissile material thus reducing the inventory cost. The problem with having an inner blanket is that the central control rod worth is very poor and almost non-existent. Although the shutdown rods perform better in the 3 blanket design the ability to control the criticality is very important thus the three blanket design is not optimal.

3.8 – Conclusions and further inquiry:

From the data acquired and analyzed it can be concluded that the optimal parameters for the core are as follows:

Main core height = 300 cm
Inlet cone height = 200 cm
Outlet cone height = 250 cm
Inlet chute length = 270 cm
Outlet chute length = 100 cm
Total core height = 808 cm
Average Inner life expectancy = 81.68 years
Minimum life Expectancy= 5 years
Outer life expectancy = 1046.3 years
$K_{eff} = 1.03747 \pm 0.00212$

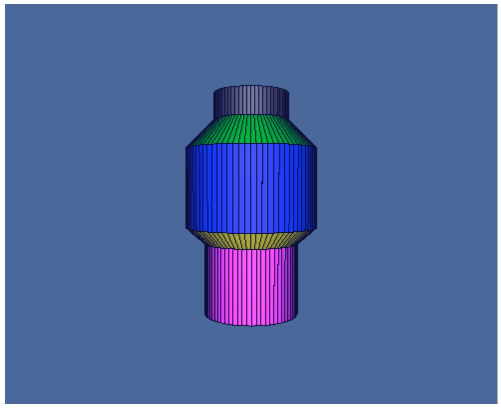


Fig. 3-15 Rendition of the final core design.

The use of an inner blanket is very desirable but it is necessary to look at the effects of loading thorium pebbles into the inner blanket to improve the criticality. Furthermore the void coefficient can be acquired from a series of simulations to see if it can help the criticality in the assembly. But the most important thing will be to do a safety risk analysis of the 12 rods at different combinations of insertions to simulate the failure of the passive rod insertion system.

4.0 FUEL DEPLETION ANALYSIS WITH SIMPLIFIED GEOMETRY

4.1 – Simplified Analytical Solution

In order to develop a feel for the sensitivities of depletion in this system to different parameters, a simplified analytical solution was generated. The three main simplifications in the solution are:

(1) Only three nuclides, ^{232}Th ^{233}Pa and ^{233}U are tracked. The 23-minute half-life of ^{233}Th is ignored and radiative capture on ^{232}Th is assumed to lead immediately to ^{233}Pa. Radioactive decay of ^{232}Th and ^{233}U are also neglected.

(2) Constant, time-averaged uniform flux is assumed in driver and blanket regions during irradiation, although the flux is not necessarily assumed to be the same in both regions.

(3) One-group reaction cross sections are used, ignoring all neutron-induced reactions besides (n,γ) and (n,f).

With these simplifications, we can develop three linear first-order coupled differential equations for the inventories of ^{232}Th (N_{02}), ^{233}Pa (N_{13}) and ^{233}U (N_{23}):

$$\frac{dN_{02}}{dt} = -\phi\sigma_{02}^{Tot} N_{02} \tag{4.1}$$

$$\frac{dN_{13}}{dt} = -\left(\lambda_{13} + \phi\sigma_{13}^{T}\right)N_{13} + \phi\sigma_{02}^{abs}N_{02} \tag{4.2}$$

$$\frac{dN_{23}}{dt} = -\phi\sigma_{23}^{Tot}N_{23} + \lambda N_{13} \tag{4.3}$$

where t is the irradiation time, ø is the one-group neutron flux, λ_{13}=λ is the decay constant for ^{233}Pa, and σ is the microscopic cross section for capture or absorption.

These equations have the solutions, after introducing some simplifying notation, of

$$N_{02}(t) = N_{02}^{0}e^{-\Lambda_{02}t_i} \tag{4.4}$$

$$N_{13}(t) = N_{13}^{0}e^{-\Lambda_{13}t_i} + \frac{\Lambda_{02}N_{02}^{0}}{\Lambda_{13} - \Lambda_{02}}\left(e^{-\Lambda_{02}t_i} - e^{-\Lambda_{13}t_i}\right) \tag{4.5}$$

$$\begin{aligned} N_{23}(t) = N_{23}^{0}e^{-\Lambda_{23}t_i} &+ \frac{\lambda N_{13}^{0}}{\Lambda_{23} - \Lambda_{13}}\left(e^{-\Lambda_{13}t_i} - e^{-\Lambda_{23}t_i}\right) \\ &+ \frac{\lambda\Lambda_{02}N_{02}^{0}}{\Lambda_{13} - \Lambda_{02}}\left(\frac{e^{-\Lambda_{02}t_i} - e^{-\Lambda_{23}t_i}}{\Lambda_{23} - \Lambda_{02}} - \frac{e^{-\Lambda_{13}t_i} - e^{-\Lambda_{23}t_i}}{\Lambda_{23} - \Lambda_{13}}\right) \end{aligned} \tag{4.6}$$

where

$$\Lambda_{02} = \phi\sigma_{02}^{Tot} \tag{4.7}$$

$$\Lambda_{13} = \lambda_{13} + \phi\sigma_{13}^{T} \tag{4.8}$$

$$\Lambda_{23} = \phi\sigma_{23}^{Tot} \tag{4.9}$$

A solution may also be generated for pebbles in decay storage, by setting the flux to zero.

$$N_{02}(t_d) = N_{02}^{0} \tag{4.10}$$

$$N_{13}(t_d) = N_{13}^{0}e^{-\lambda t_d} \tag{4.11}$$

$$N_{23}(t_d) = N_{23}^{0} + N_{13}^{0}\left(1 - e^{-\lambda t_d}\right) \tag{4.12}$$

where t_d is the decay time.

Finally, a solution for the instantaneous conversion ratio may be obtained, in order to evaluate how long a pebble should spend in the system before either being disposed of or reprocessed. Ignoring the contribution of other fissile nuclides in the system, we can define the conversion ratio as the ratio of ^{233}U bred to ^{233}U destroyed in one cycle:

$$CR = \frac{N_{bred}}{N_{destroyed}} = \frac{\int_0^{T_{irrad}} \lambda N_{13}(t)dt + \int_{T_{irrad}}^{T_{irrad}+T_{decay}} \lambda N_{13}(t)dt}{\int_0^{T_{irrad}} \Lambda_{23} N_{23} dt}. \tag{1.13}$$

which has the solution:

$$N_{bred} = N_{13}^0 \left[\lambda \frac{1 - e^{-\Lambda_{13} T_{irrad}}}{\Lambda_{13}} + e^{-\Lambda_{13} T_{irrad}} \left(1 - e^{-\lambda T_{decay}}\right) \right]$$

$$+ \frac{\Lambda_{02} N_{02}^0}{\Lambda_{13} - \Lambda_{02}} \left[\lambda \left(\frac{1 - e^{-\Lambda_{02} T_{irrad}}}{\Lambda_{02}} - \frac{1 - e^{-\Lambda_{13} T_{irrad}}}{\Lambda_{13}} \right) + \left(e^{-\Lambda_{02} T_{irrad}} - e^{-\Lambda_{13} T_{irrad}} \right) \left(1 - e^{-\lambda T_{decay}} \right) \right] \tag{1.14}$$

$$N_{destroyed} = N_{23}^0 \left(1 - e^{-\Lambda_{23} T_{irrad}}\right) + \frac{\lambda \Lambda_{23} N_{13}^0}{\Lambda_{23} - \Lambda_{13}} \left(\frac{1 - e^{-\Lambda_{13} T_{irrad}}}{\Lambda_{13}} - \frac{1 - e^{-\Lambda_{23} T_{irrad}}}{\Lambda_{23}} \right) \tag{1.15}$$

$$+ \frac{\lambda \Lambda_{23} \Lambda_{02} N_{02}^0}{(\Lambda_{13} - \Lambda_{02})} \left[\frac{1}{(\Lambda_{23} - \Lambda_{02})} \left(\frac{1 - e^{-\Lambda_{02} T_{irrad}}}{\Lambda_{02}} - \frac{1 - e^{-\Lambda_{23} T_{irrad}}}{\Lambda_{23}} \right) - \frac{1}{(\Lambda_{23} - \Lambda_{13})} \left(\frac{1 - e^{-\Lambda_{13} T_{irrad}}}{\Lambda_{13}} - \frac{1 - e^{-\Lambda_{23} T_{irrad}}}{\Lambda_{23}} \right) \right].$$

Note that this does not take into account the fact that the reactor must maintain $k_{eff} > 1$ at each irradiation step. This inconsistency is overcome by using MCNP5 to find a configuration that is critical, and finding the ^{233}U destruction rate for that step. This destruction rate is then taken to be a constant for the reactor operating at the given power density. In this manner, the conversion ratio for one pebble can be defined as the rate of ^{233}U production in one blanket pebble divided by the ^{233}U consumption per blanket pebble required to keep the reactor critical.

Starting with the composition of a fresh blanket pebble and a fresh driver pebble, in the 3:1 ratio used for this exploration, and choosing values for the cross sections and neutron flux based on the MCNP5 simulation with $k_{eff} > 1$, the following plots are obtained.

Fig. 4-1 shows the mass of ^{232}Th in a blanket pebble as a function of irradiation time. This plot gives a sense of the timescale for burnup in the blanket pebbles.

Fig. 4-2 shows the mass of ^{233}U in a seed pebble as a function of irradiation time, which gives a sense of the lifetime of a seed pebble in the reactor. Seed pebbles would most likely have to be replaced with fresh pebbles when the rate of ^{233}U consumption (indicated by the slope of the curve) is significantly different from the initial value, in order to maintain criticality.

Fig. 4-3 and 4-4 show the mass of ^{233}U in a blanket pebble over time, for various configurations of irradiation time and decay storage. Clearly, in terms of breeding ^{233}U, the ideal would be to have infinitely short irradiation time followed by infinitely long decay storage. However, the length of decay storage depends on the storage capacity of the plant. From Fig. 4-3 it is clear that increasing the length of decay storage produces diminishing returns, so the optimal ratio of irradiation time to decay time is likely to be around 1:2. The length of irradiation time is limited by the speed at which pebbles can be removed from the reactor and sorted. For this study, a10-day irradiation period is assumed to be achievable.

Fig. 4-5 shows the conversion ratio as defined above for various ratios of ^{232}Th mass to ^{233}U mass in the fresh pebbles. As expected, higher thorium to uranium ratios are favorable. The mass of thorium that can be fit into one pebble is limited to less than 6g per pebble in order to allow the pebble to float. This indicates that in order to sustain a conversion ratio greater than one, the seed pebbles should contain an average of no more than ~350mg of ^{233}U. In practice seed pebbles would be fabricated with more ^{233}U than this, but with the depletion of seed pebbles the average concentration would be approximately this value.

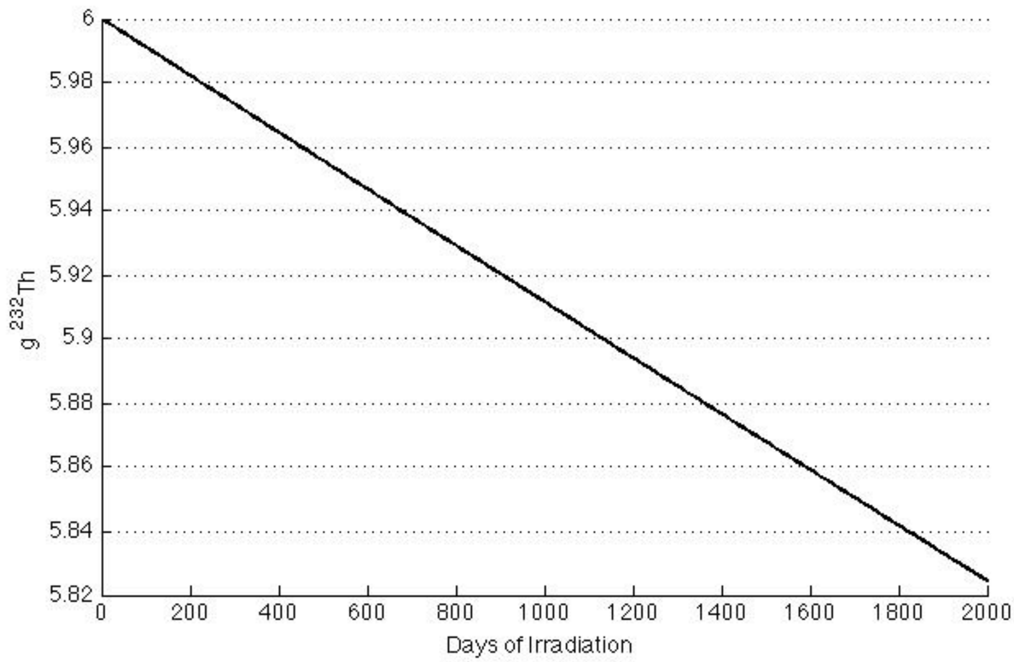


Fig. 4-1 Mass of 232Th in one blanket pebble, as a function of time spent in the reactor.

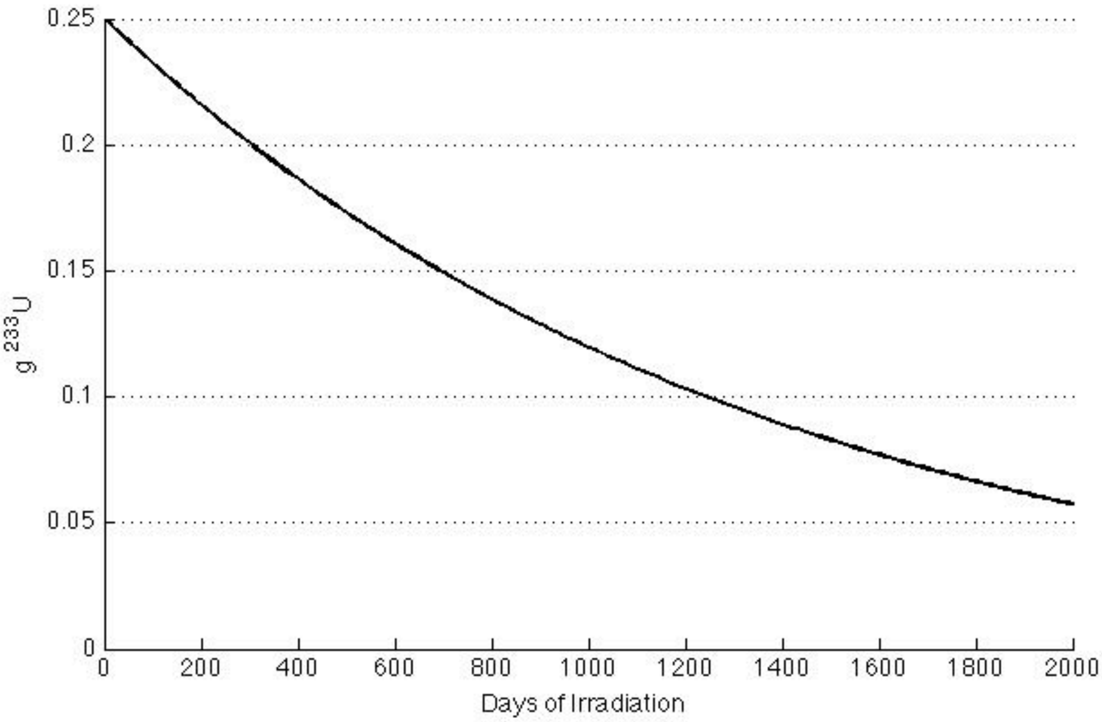


Fig. 4-2 Mass of ^{233}U in one seed pebble, as a function of time in the reactor

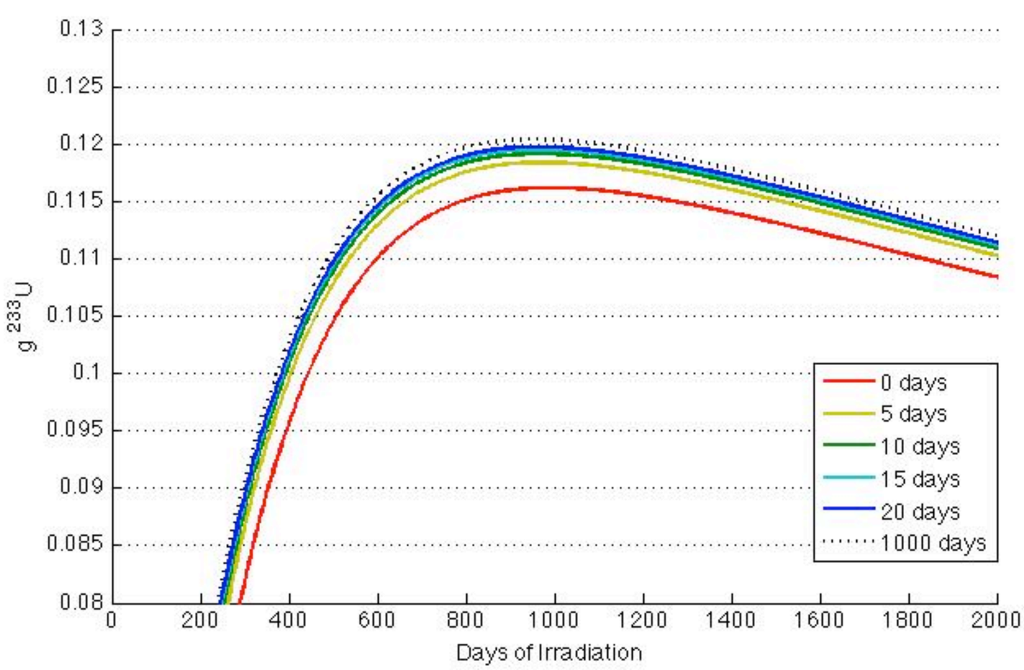


Fig. 4-3 Mass of 233U in one blanket pebble, originally containing 6g ^{232}Th, subjected to cycles of 5 days of irradiation time followed by various lengths of decay storage.

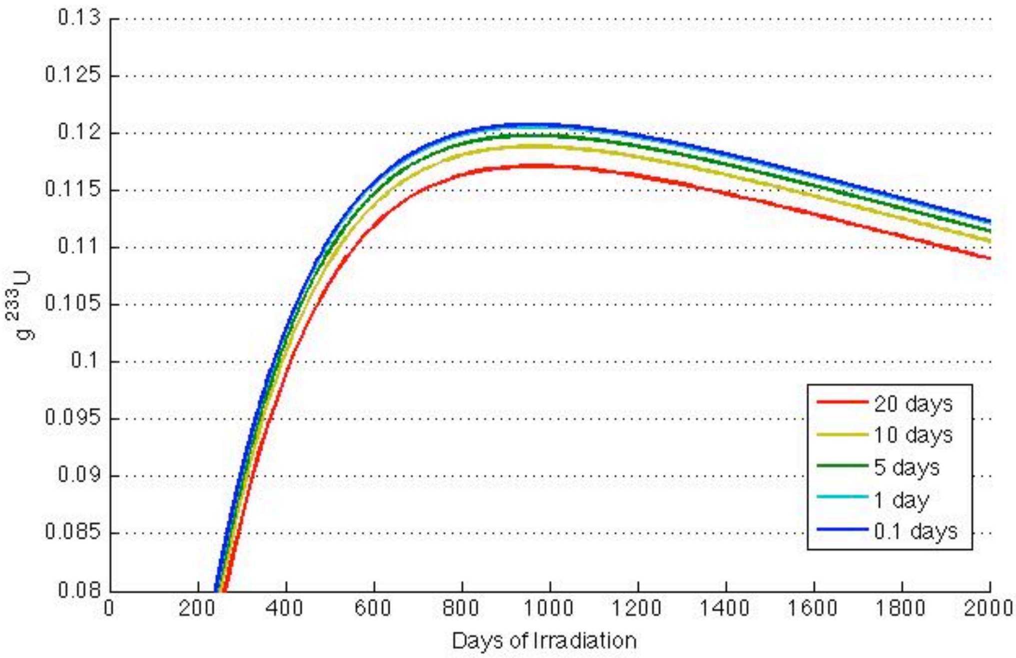


Fig. 4-3 Total 233U in one blanket pebble initially containing 6g 232Th, with a decay-irradiation time ratio of 4:1 and various lengths of irradiation time per cycle.

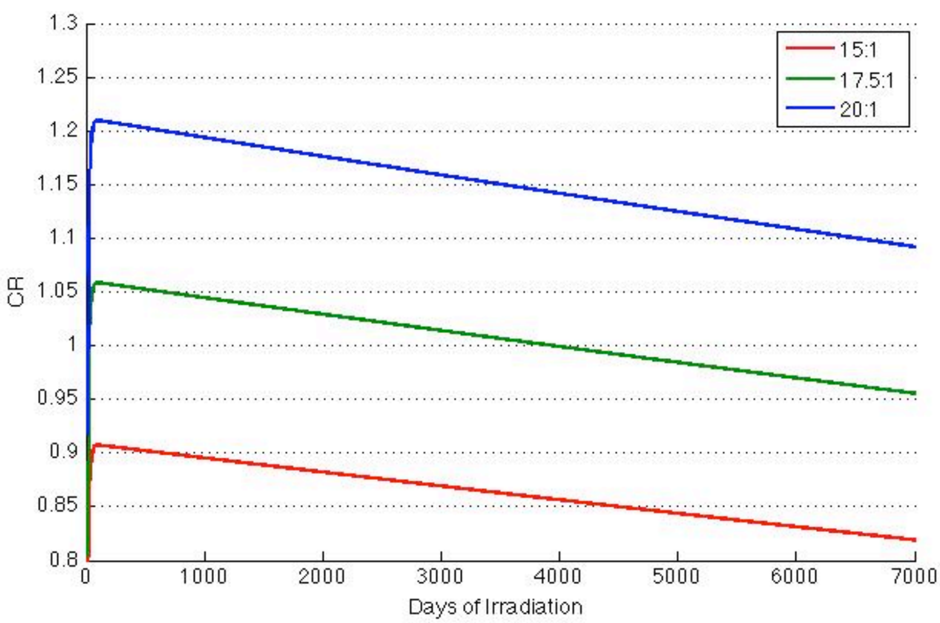


Fig. 4-4 Conversion ratio for various ratios of initial mass of ^{232}Th in one blanket pebble to initial mass of ^{233}U in one seed pebble. Note that 1000 days of irradiation corresponds to about 1.5% burnup in a blanket pebble.

5.2 – Numerical Model

Once these depletion sensitivities have been explored using the analytical model, a more realistic model should be applied to ensure that the reactor will stay critical while breeding ^{233}U. This model is constructed by using MOCUP to interface between MCNP5 for neutronics and ORIGEN2 for depletion. To speed up the multiple iterations required, the reactor is simplified and modeled as an infinite cylinder. The axial leakage that is neglected by this simplification is overcome by requiring a $k_{eff} > 1.02$.

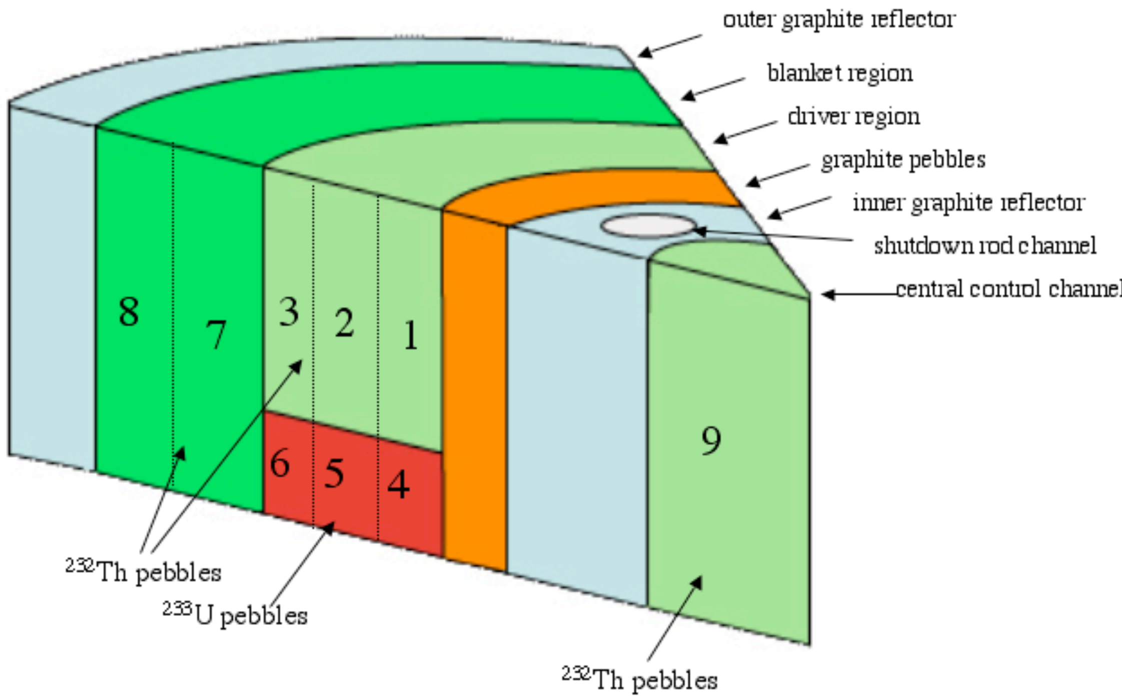


Fig. 4-6 Core-level MCNP5 geometry, indicating 9 zones for depletion. Note that while diagram presents a 30° wedge in order to show the axial layering, the actual model is a 360° axial slice in the shape of a hockey puck. Also note that this figure is not to scale.

In one potential pebble circulation scheme, fresh blanket pebbles would be injected into the outer blanket and as they achieve higher burnup they would be promoted inwards until, at maximum ^{233}U content, they would be injected into the center channel before being reprocessed. As a first-order approximation to this configuration, a fraction of the ^{232}Th in the blanket pebbles was replaced by ^{233}U in each of the zones, as shown in Table 2. Depletion in each zone is tracked to confirm that a net gain of 233U is achieved while maintaining criticality with $k_{eff} > 1.02$. For this study, a 10-day irradiation period is followed by 10 days of decay storage. To simplify the calculations, the pebbles are held static in their locations, and the power is cycled on and off to simulate the irradiation and decay storage periods.

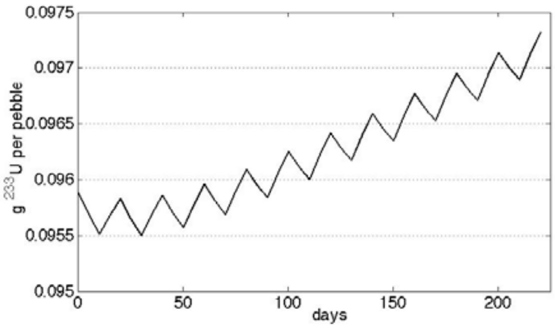
Table 4-1 Artificial enrichment of blanket pebbles to simulate steady-state operation.

Zone	^{233}U enrichment
1	1.6%
2	1.2%
3	0.8%
7	0.4%
8	0.01%
9	1.8%

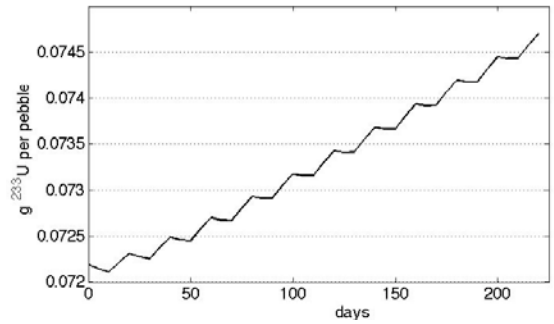
The results of the MOCUP calculation suggest that the reactor can indeed stay critical while breeding more ^{233}U than it consumes. As shown in Fig. 4-7, every blanket region is breeding except for the central control channel, which was apparently enriched slightly beyond it's equilibrium ^{233}U content. Fig. 4-8 shows the total ^{233}U inventory in the region increasing, indicating that more ^{233}U is being created than consumed. Fig. 4-9 shows a plot of k_{eff} averaged over each irradiation period. While k_{eff} stays above 1.03 for the entire time, sufficient to assure criticality for an actual 3-D core, there is a downward trend. This is not unexpected, because the seed pebbles are being depleted and fission products are building up, partially compensated by the total overall increase in U-233 inventory due to breeding. During actual operation, the seed pebbles would be continuously replenished with fresh seed pebbles to maintain criticality and this would not be a problem.

Over the 22-day period of irradiation, the ^{233}U inventory in the core increases by 4.4%. This corresponds to a ^{233}U doubling time of 9.7 years, if pebbles were instantly recycled and new fuel inserted at the end of this irradiation time. The actual fuel cycle for a PB-AHTR may be once through (e.g., a Radkowski-type seed/blanket cycle) or a closed cycle. In either case, the capability to obtain a significant fraction of fission energy from blanket pebbles and to replace most or all of the fissile material consumed with new ^{233}U should increase the flexibility and reduce the cost of fuel.

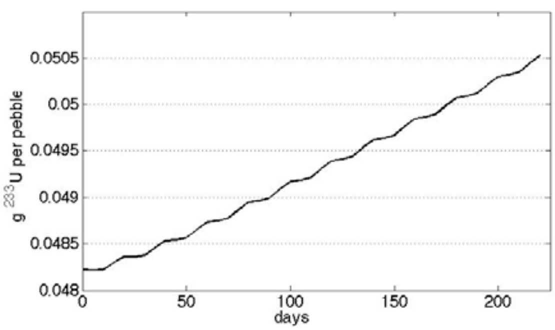
With that in mind, the initial fissile loading for this model is 5.73 kg in the blanket pebbles, and 6.10 kg in the seed pebbles. Since there is an equal number of blanket pebbles in decay storage and in the reactor, an additional 5.73 kg is needed, giving a total of 17.56 kg. The height of the model is 24.06 cm, while the height of the main cylinder of the actual reactor would be 320 cm. Thus, the fissile requirement for the full cylinder would be 233.5 kg. The reactor is designed to run at 900 MW_{th}, or 410MW_e, so this gives a loading of .569 kg per MW_e. This compares favorably with other reactor designs (Fig. 4-10).



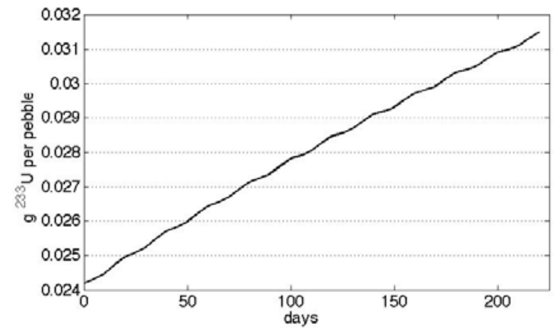
zone 1



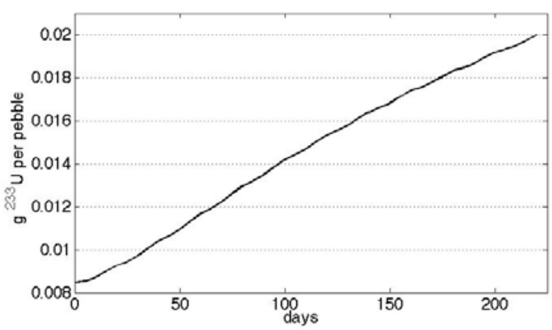
zone 2



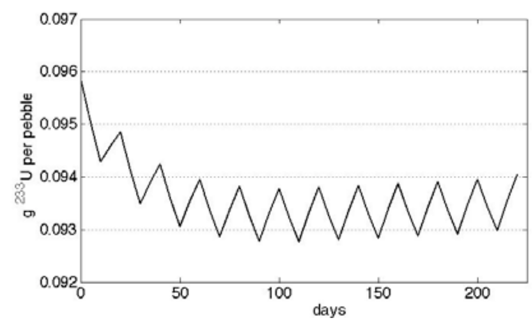
zone 3



zone 7



zone 8



zone 9

Fig. 4-7 ^{233}U mass per pebble over 11 cycles in 6 different blanket pebble regions.

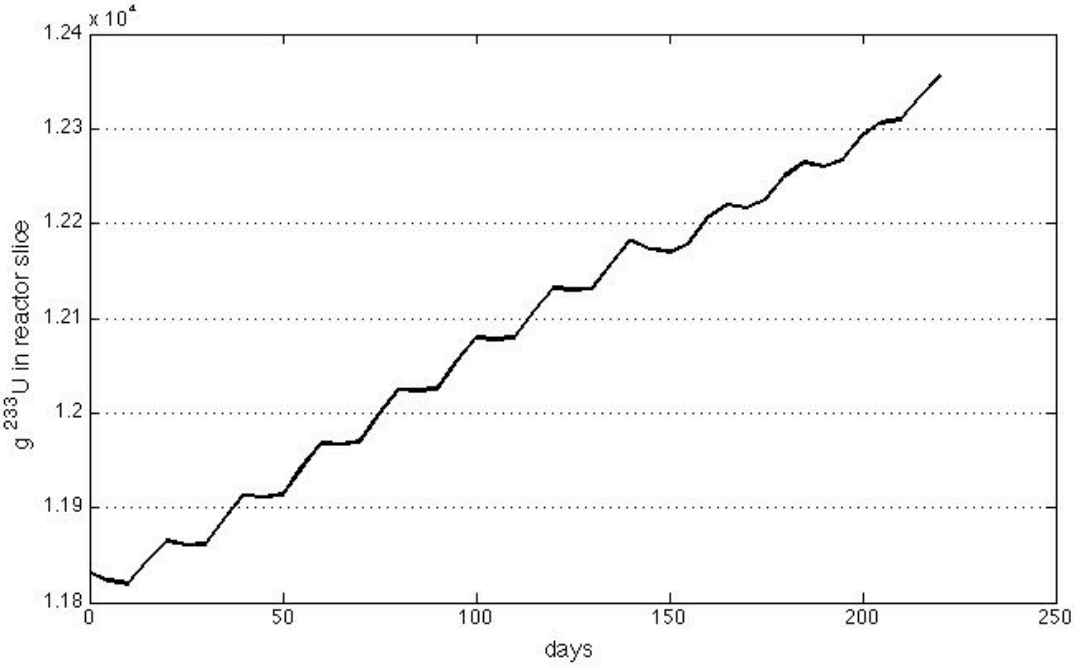


Fig. 4-8 Total ^{233}U in the entire simulated reactor slice, including seed pebbles.

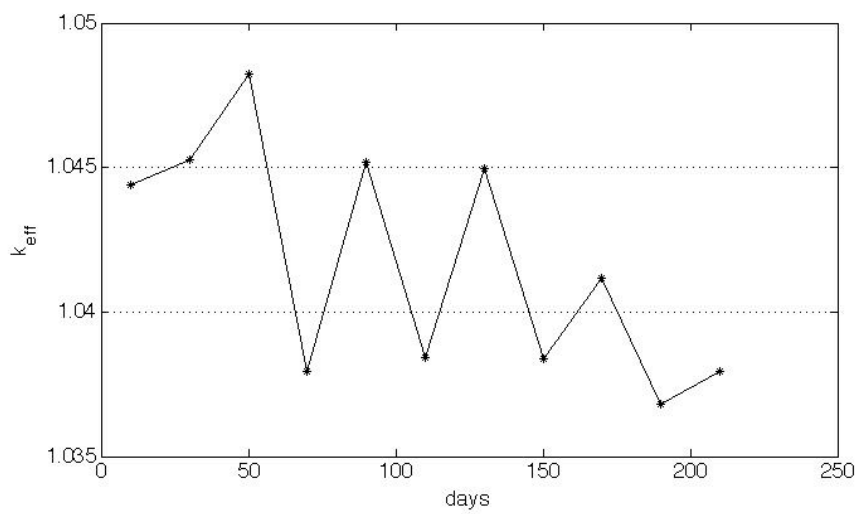


Fig. 4-9 Average k_{eff} per cycle.

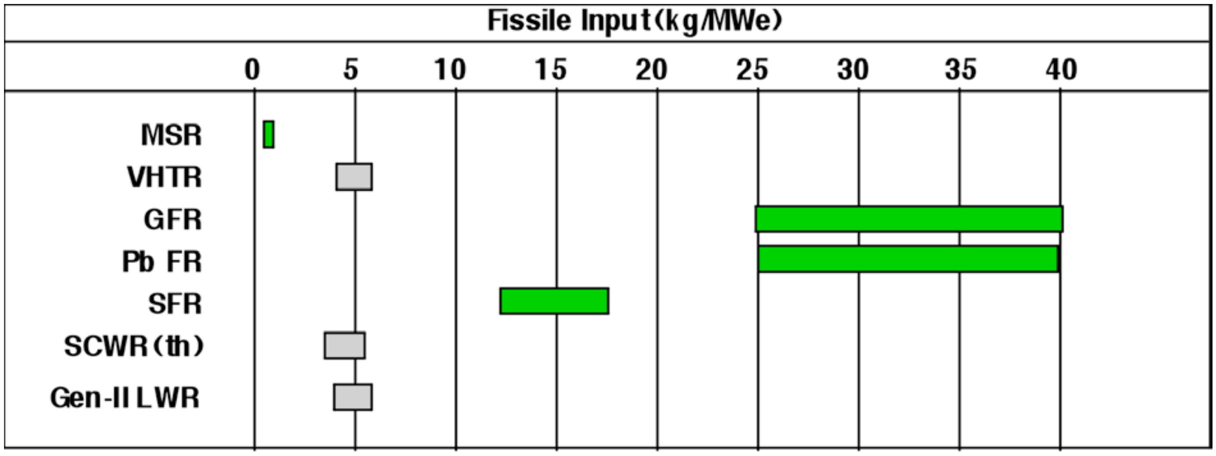


Fig. 4-10 Fissile Input required for various reactor types.

5.0 ANALYSIS OF PERFORMANCE METRIC THROUGH VARIATIONS IN DESIGN PARAMETERS

The MCNP5 program was used to perform variation on the design parameters in the thorium based PB-ATHR in order to analyze the affect on various performance metrics.

5.1 – Description of Variations

The annular-core PB-AHTR design is quite different from other reactors studied before, and so this project performed a wide range of scoping calculations using a simplified model of the reactor to substantially decrease the computing time required for each simulation, while still achieving a reasonably low uncertainity associated with the results. To do this the scoping calculations used a two-dimensional slice through the center of the core to model the reactor and test the effects of varying parameters within the model. Reflective boundary conditions are used for the top, bottom, and side walls of this sector to mimic a cylindrically infinite reactor core. An example input deck used by the program MCNP5 can be found in Appendix A. This 2-D model was also used for depletion and conversion ratio calculations.

Because the annular PB-AHTR core enables radial and axial zoning, a major goal of this project was to study the potential performance of thorium-based fuel cycles. The simplest problem to check potential thorium performance involves starting the reactor up with a core composed of pure thorium and U-233. This is what was done in the Light Water Reactor Breeder program at Shippingport [5-1], which confirmed that LWRs do have the capability to breed on a pure thorium cycle. Thus all of the neutronics modeling performed here uses pebbles containing thorium and/or uranium.

For thorium blanket pebbles, six grams of a mixture of 99 atom perent Th-232 and 1 atom percent U-233 is assuned to be loaded into each pebble. The U-233 is included in the blanket pebbles to account for breeding that will occur in the lifetime of those pebbles while in the reactor, and to properly assess the solid graphite reflector fast-neutron dose that may occur due to subcritical neutron multiplication in the blanket pebbles. The baseline seed pebble design contains 0.273 grams of U-233, and the quantity of U-233 is adjusted to obtain the desired value of keff. Both the driver region and the center control channel consist of alternating axial layers of 12 rows of blanket pebbles and 4 rows of seed pebbles. Twelve cruciform shutdown rods composed of boron carbide and graphite are located in the inner reflector.

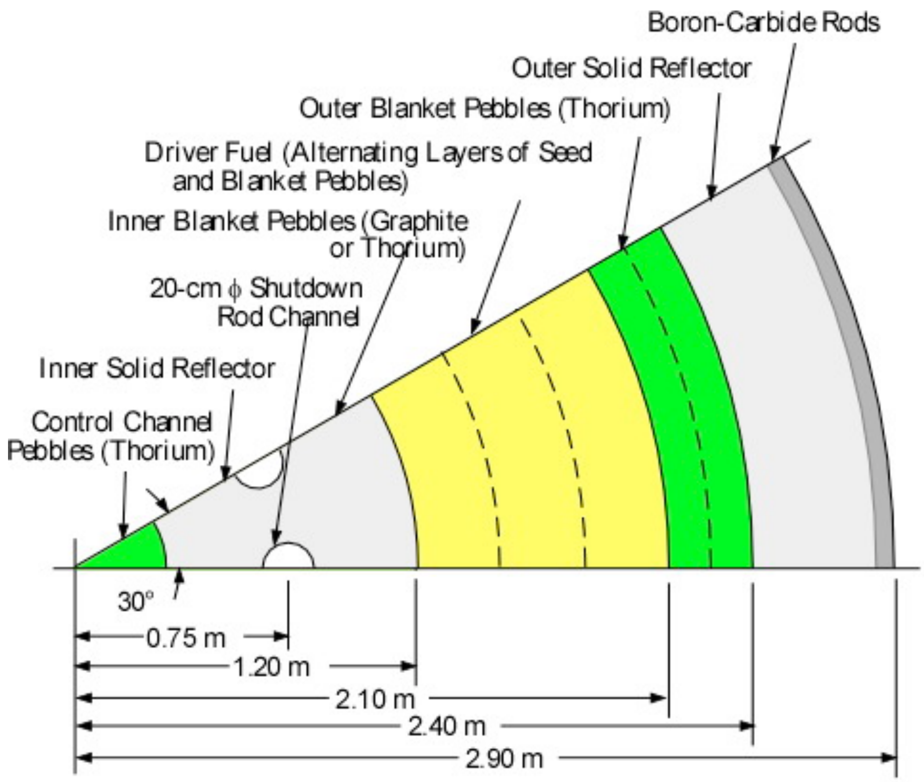


Fig. 5-1 A top-down image of the annular regions in the reactor core using a 1/12 sector of the core.

5.2 – Results of Analysis

The characterisitcs of the baseline reactor model (before any variation studies) are shown in Table 5-1.

Table 5-1 Characteristics of the the thorium based PB-ATHR generated using the 2D MCNP5 model.

Characteristic	Value	Associated Uncertainity (±σ)
Keff	1.01961	0.00196
Initial Converstion Ratio	1.12310	0.00906
Total Shutdown Rod Worth(1)	0.05243	0.0028995
Void Reactivity(2)	–0.04665	0.0027422
Inner Graphite Reflector Lifetime	7.62 years	0.244 years
Outer Graphite Reflector Lifetime	63.5 years	2.22 years

(1) The total shutdown rod worth is the change in keff when inserting all 12 shutdown rods into the inner graphite reflector ($\Delta keff = keff_{[Rods\_Out]} - keff_{[Rods\_In]}$).

(2) The void reactivity is the change in keff when the entire reactor is voided of all flibe coolant ($\Delta keff = keff_{[Reactor\_Void\_of\_All\_Flibe]} - keff_{[Reactor\_with\_Flibe]}$).

The mass of U-233 used in each seed pebble was varied by changing the radius of the fuel kernel in the uranium Triso particle, to determine how strongly U-233 loading in the seed pebbles effect the reactivity (keff) and conversion ratio in the reactor. As is shown in Fig. 5-2, the reactivity increases and the conversion ratio decreases as more uranium is loaded into the seed pebbles.

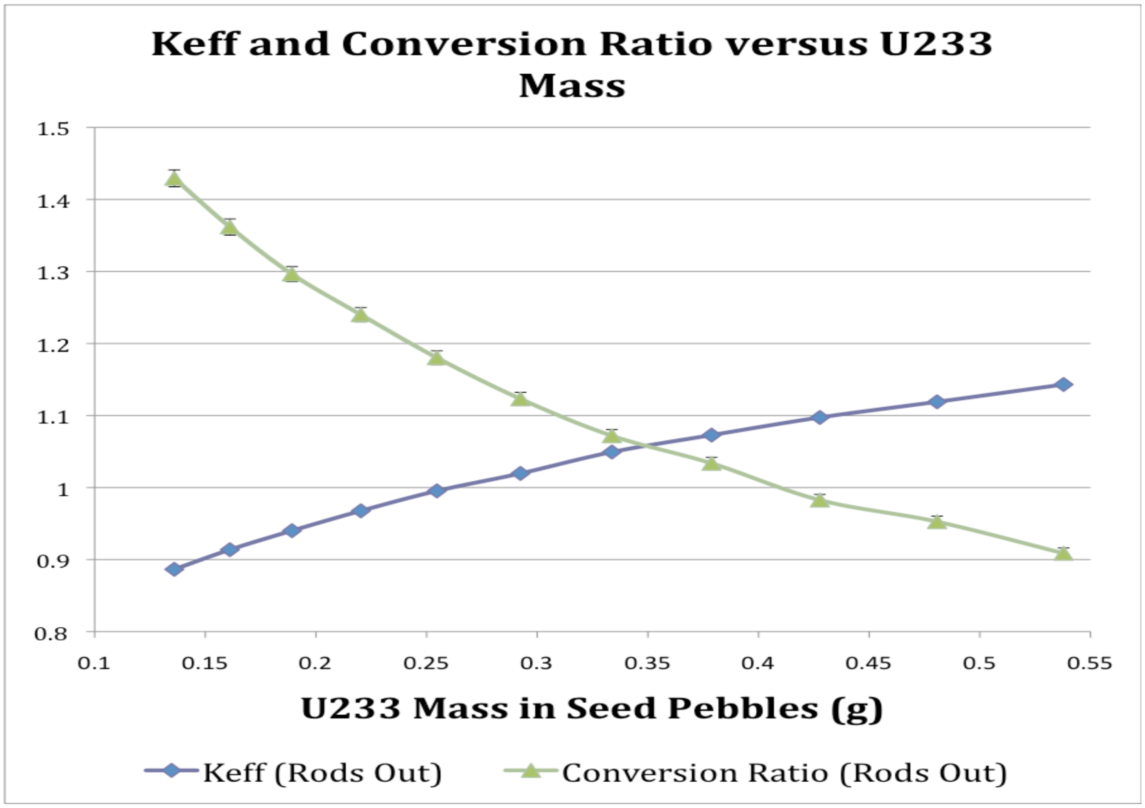


Fig. 5-2 Keff and conversion ratio for the baseline 2-D core design, as a function of the mass of U-233 loaded into each seed pebble. Shutdown rods are removed.

The lifetime of components in the thorium based PB-ATHR is an additional concern requiring a shielding analysis for the reactor design. A maximum fluence of $3*10^{22}$ neutrons/cm^2 for neutrons with energy greater than 100 keV [5-2] is used to compute the lifetime of the graphite reflectors. Using the parameters listed in Appendix A for the reactor model, the lifetimes for the center and outer solid graphite reflectors were computed to be about 7.62 years and 63.5 years, respectively. These component lifetimes are acceptable, however the lifetime of the outer reflector is sensitive to the assumed amount of U-233 in the blanket pebbles and the resulting subcritical neutron multiplication. It is desirable to ensure that the outer radial reflector never needs to be replaced during the reactor lifetime, which may be 80 to 100 years, so it will be important to minimize the U-233 content in the blanket pebbles injected into the outer radial blanket region.

The U-233 mass loaded into seed pebbles used only in the control channel was varied to observe the effect of adding and removing U-233 from the control channel as a means of tuning certain characteristics of the core. Fig. 5-3, 5-4, and 5-5 show the effects of these variations on the reactivity, conversion ratio, and graphite reflector lifetimes. The graphite lifetime is calculate using the neutron flux passing through the inner radius of each reflector, since each reflector annulus surrounds a region containing seed pebbles. For the inner reflector, this region is the control channel; for the outer reflector, it is the driver region.

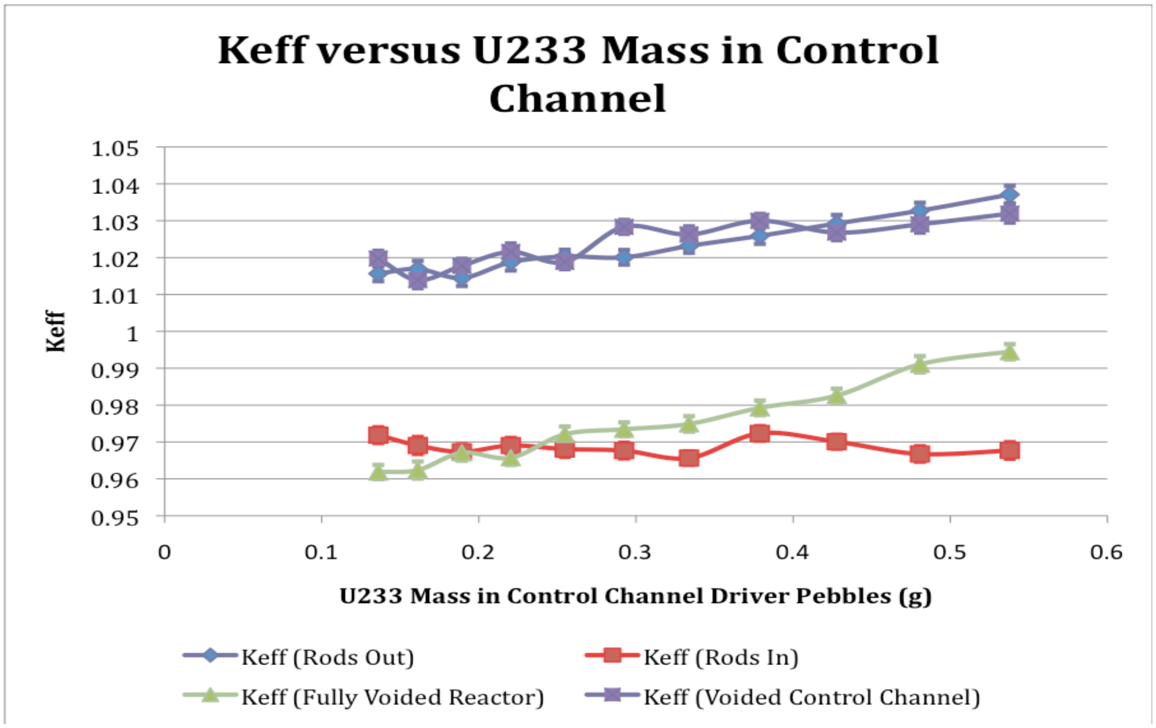


Fig. 5-3 Keff for the baseline 2-D core design, as a function of the mass of U-233 loaded into each seed pebble in the control channel (seed pebbles in driver region are not changed).

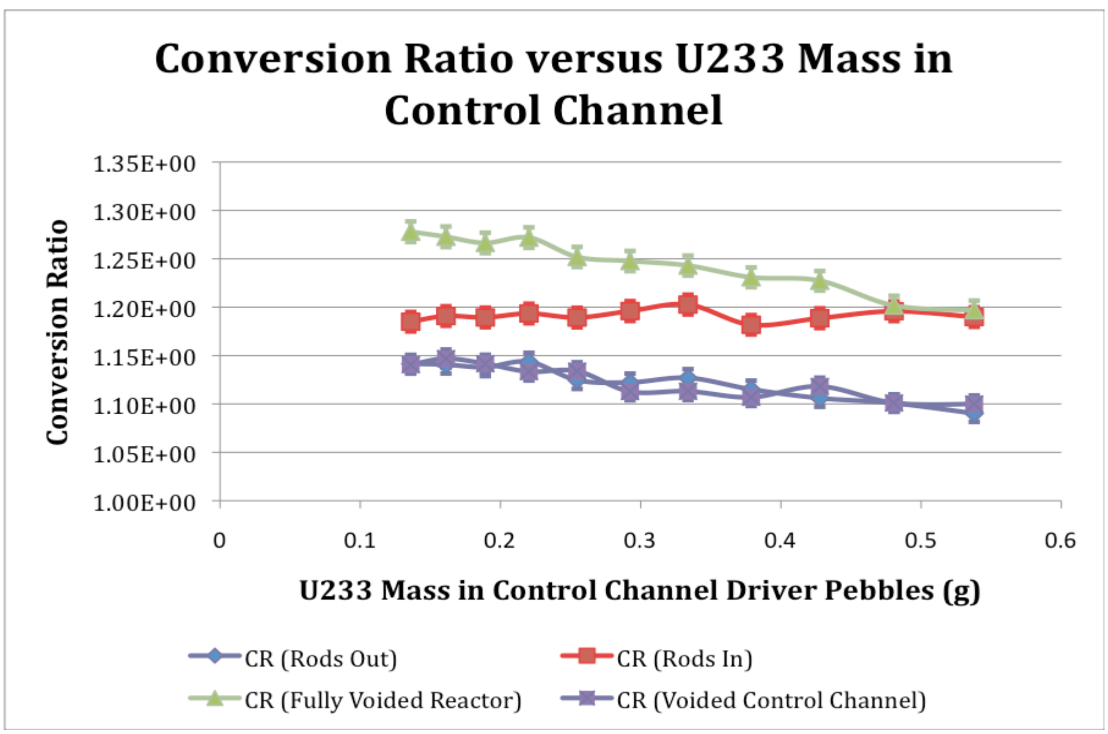


Fig. 5-4 Initial Conversion Ratio (CR) for the baseline 2-D core design, as a function of the mass of U-233 loaded into each seed pebble in the control channel (seed pebbles in driver region are not changed).

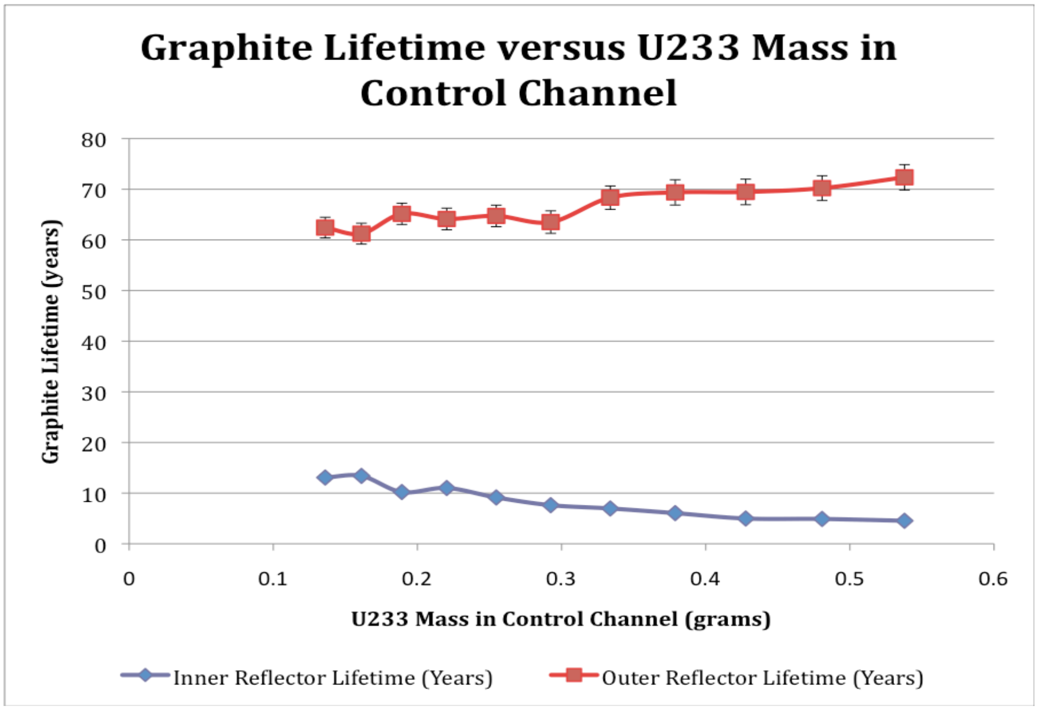


Fig. 5-5 Graphite Reflector Lifetime for the baseline 2-D core design, as a function of the mass of U-233 loaded into each seed pebble in the control channel (seed pebbles in driver region are not changed).

Several observations may be made about the results displayed in the figures above. As should be expected, keff increases while the conversion ratio decreases as the loading of U-233 in the control channel is increased. Additionally, the lifetime of the inner reflector decreases as the U-233 loading increases, due to increased neutron flux from the added U-233. Interestingly, the lifetime of the outer reflector appears to increase as more U-233 is loaded into the control channel, which might occur because higher loading in the control channel focuses the power peaking and neutron flux more towards the center of the core.

When all the shutdown rods are inserted into the reactor core, keff and the conversion ratio do not seem to change significantly as the U-233 loading in the control channel is varied. This demonstrates that the shutdown rods do function as expected by mostly decoupling the control channel system from the rest of the reactor core. Also, Fig. 5-2 and 5-3 show that voiding only the control channel of flibe does not have a significant effect on the characteristics of the reactor.

The volumes of several regions were varied by adjusting specific radii within the reactor; this was done to observe their effects on keff and the conversion ratio. The outer control channel radius was varied, resulting in a change in the volumes of the control channel and the inner reflector. Also, the outer blanket region radius was varied, changing the volumes of the blanket region and outer reflector. Fig. 5-6 through 5-9 below display the results of these variations:

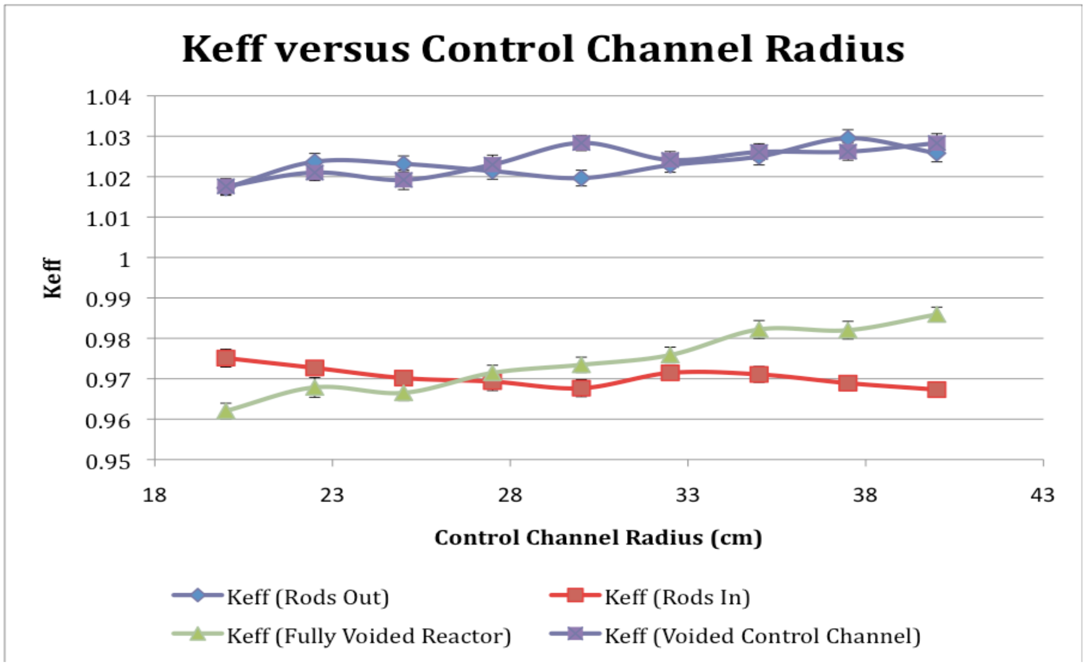


Fig. 5-6 Keff for the baseline 2-D core design, as a function of the control channel outer radius.

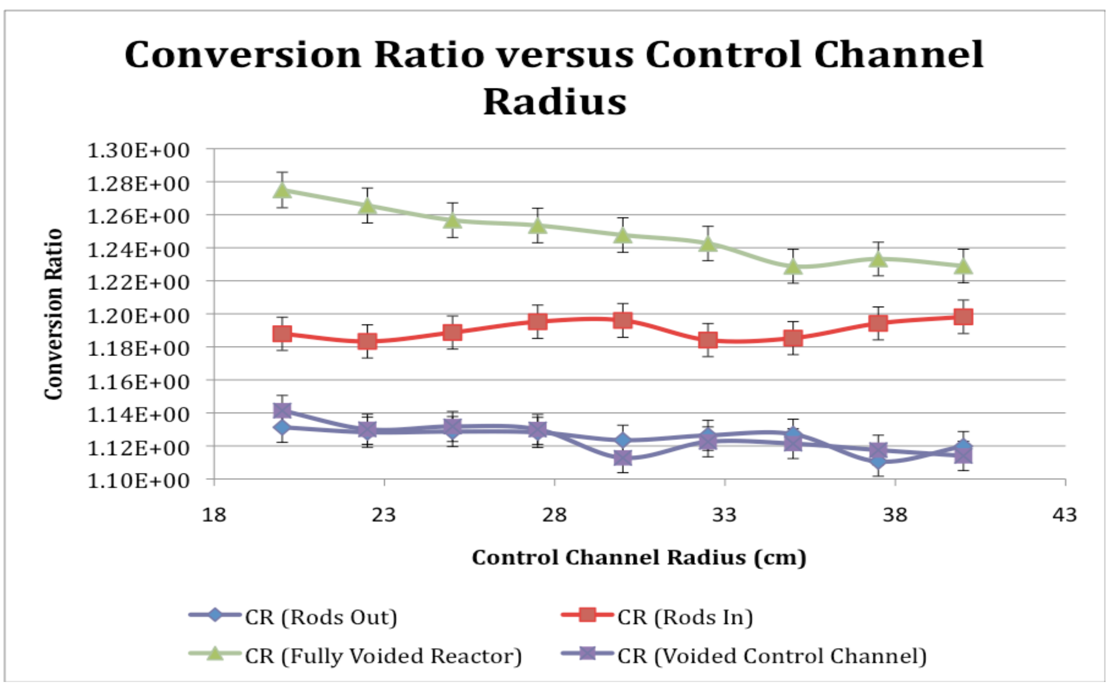


Fig. 5-7 Conversion Ratio for the baseline 2-D core design, as a function of the control channel outer radius.

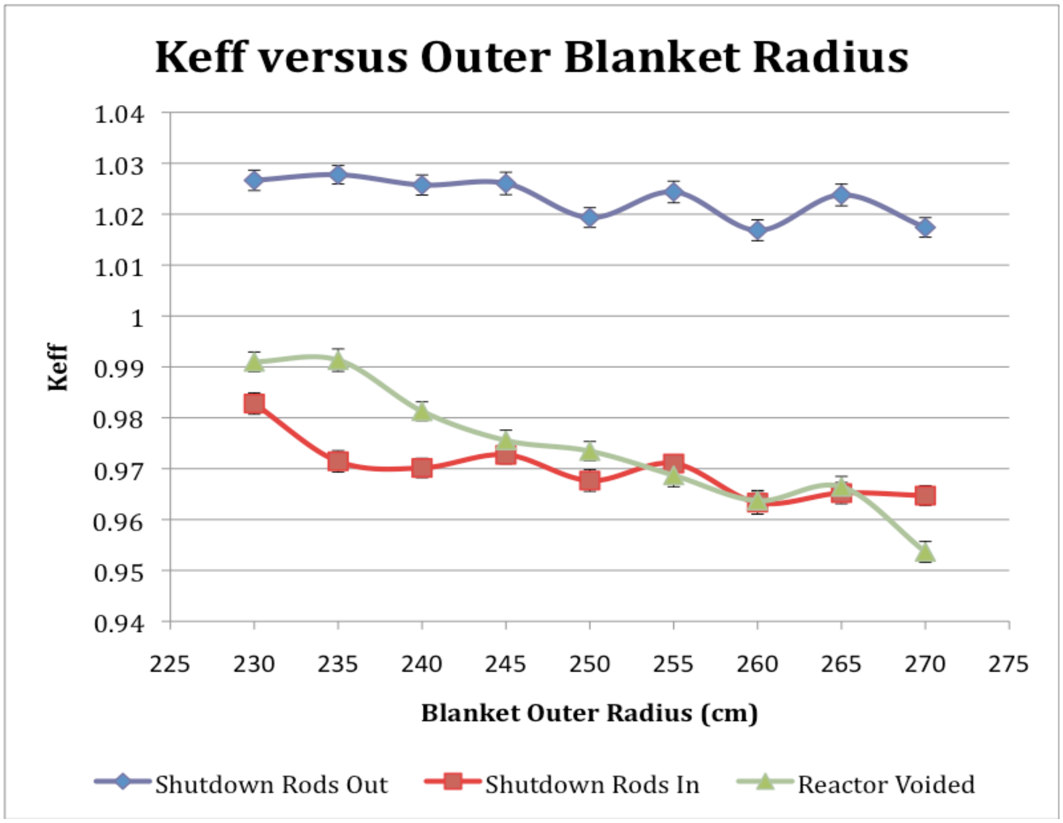


Fig. 5-8 Keff for the baseline 2-D core design, as a function of the outer radius of the blanket region.

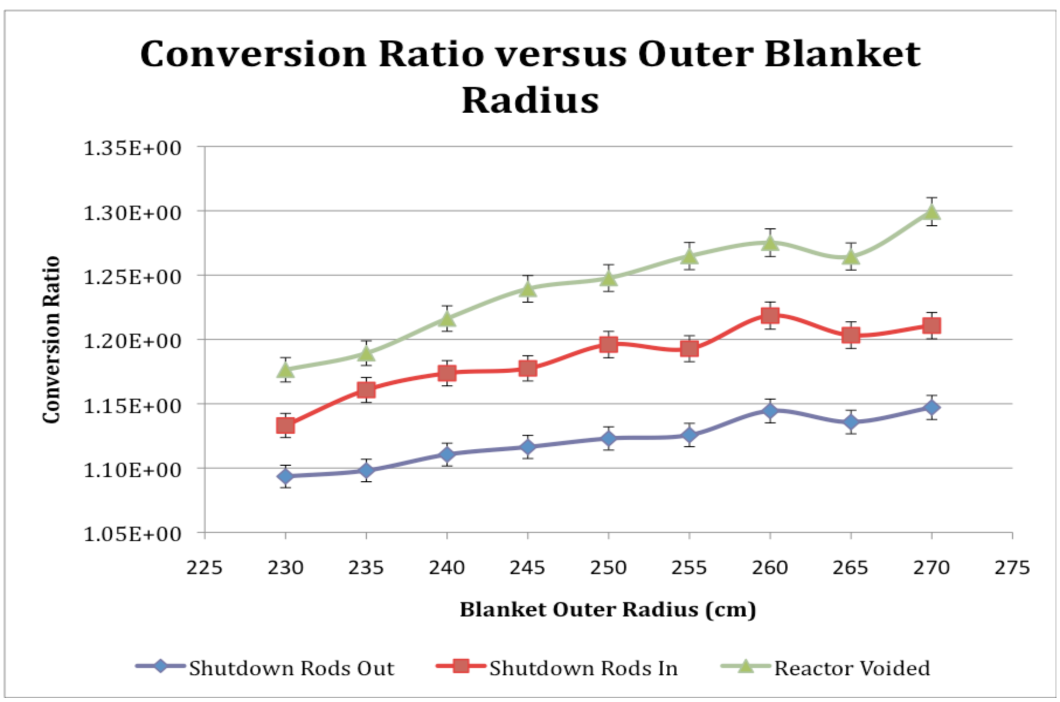


Fig. 5-9 Conversion Ratio for the baseline 2-D core design, as a function of the outer radius of the blanket region.

Increasing the control channel radius does generally increase keff and decrease the conversion ratio, since more seed and blanket pebbles are added to the reactor when the control channel volume is increased. However, the changes in these values are not consistent nor significant (keff changes by less than 0.02 when the radius is increased from 20 cm to 40 cm), indicating that adjusting the radius of the control channel will not have a notable impact on keff and the conversion ratio. When the outer radius of the blanket region is increased, keff decreases while the conversion ratio increases. This is exactly what should be expected, since increasing this radius increases the amount of thorium in the blanket pebble region, which should result in more breeding, thus driving the conversion ratio up and decreasing keff.

6.0 PEBBLE INTERROGATION AND SORTING

[INSERT JACK'S SECTION HERE]

7.0 APPENDICES

7.1 – Appendix A: Example MCNP5 Input Deck Used For 2D Thorium Based PB-AHTR Model

```
Thorium Based PB-AHTR - With Flibe (Not Void)
c Replacer program (Version 1.0) used to generate this File
c Values in Primary ("Title") Sets used in this File:
c     Title VectorSet Used Triso Kernel Radius: (0.031704,0.0222,0.0222)
c
c   Other Replacements Used:        VectorSet Layer: Indicator = !layer, Values = [(-
1.50382,16.54202,22.557299999999998) ; ]
c        SingleValue PebbleBox: Indicator = !pebbleBox, Value = 1.50382
c        VectorSet Radials: Indicator = !radial, Values =
[(30.0,114.99,115.0,210.0,250.0,289.0,290.0) ; ]
c        VectorSet SurfaceAreas: Indicator = !surfaceArea, Values =
[(4535.410438847999,17384.228212104383,17385.740015584,31747.873071935996,37795.0869903
9999,43691.1205609024,43842.300908863996) ;
(4535.410438847999,17384.228212104383,17385.740015584,31747.873071935996,37795.08699039
999,43691.1205609024,43842.300908863996) ;
(4535.410438847999,17384.228212104383,17385.740015584,31747.873071935996,37795.08699039
999,43691.1205609024,43842.300908863996) ;
(4535.410438847999,17384.228212104383,17385.740015584,31747.873071935996,37795.08699039
999,43691.1205609024,43842.300908863996) ;
(4535.410438847999,17384.228212104383,17385.740015584,31747.873071935996,37795.08699039
999,43691.1205609024,43842.300908863996) ;
(4535.410438847999,17384.228212104383,17385.740015584,31747.873071935996,37795.08699039
999,43691.1205609024,43842.300908863996) ;
(4535.410438847999,17384.228212104383,17385.740015584,31747.873071935996,37795.08699039
999,43691.1205609024,43842.300908863996) ;
(4535.410438847999,17384.228212104383,17385.740015584,31747.873071935996,37795.08699039
999,43691.1205609024,43842.300908863996) ;
(4535.410438847999,17384.228212104383,17385.740015584,31747.873071935996,37795.08699039
999,43691.1205609024,43842.300908863996) ;
(4535.410438847999,17384.228212104383,17385.740015584,31747.873071935996,37795.08699039
999,43691.1205609024,43842.300908863996) ;
```

```
(4535.410438847999,17384.228212104383,17385.740015584,31747.873071935996,37795.08699039
999,43691.1205609024,43842.300908863996) ; ]
c        VectorSet NumLayers: Indicator = null, Values = [(12.0,4.0) ; ]
c        VectorSet Shutdown: Indicator = !shutdown, Values = [(99.0,99.0) ; ]
c        SingleValue UrTrisoHalfBox: Indicator = !urHalfBox, Value = 0.1130152
c        EntireLine Kcode: Indicator = !kcode, Line = "kcode   1E3 1 30 130"
c
c TRISO (DF PF = 2.5%, TF PF = 40%) - Axially Infinite Model
c *note only the volumes of depletion cells (11 21 31 41) are correct no other cells
flux are calculated
c Flibe composition has been corrected!
c -------------------------------------------------------------------------------
c                                    Cells
c -------------------------------------------------------------------------------
c UNIT CELL OF THORIUM FERTILE TRISO PARTICLE (Th232)
10  0         -11 12 -13 14 -15 16 fill=104 lat=1 u=101 imp:n=1
11  10  6.638157e-02    -1    imp:n=1 u=104 tmp=8.38434e-08
17  6 -1.7910597  1 imp:n=1 u=104 tmp=8.16892e-08 $ homogenized
c                                                          layers outside kernel
c UNIT CELL OF URANIUM DRIVER TRISO PARTICLE (U233 in Driver Region)
40  0         -21 22 -23 24 -25 26 fill=114 lat=1 u=111 imp:n=1
41  40  7.158645e-02   -6    imp:n=1 u=114 tmp=8.38434e-08
47  7 -1.7419371  6 imp:n=1 u=114 tmp=8.16892e-08 $ homogenized
c                                                          layers outside kernel
c UNIT CELL OF THORIUM FERTILE PEBBLE (Th232)
100  0  -102 103 -104 105 -106 107 -108 109 lat=2 imp:n=1 fill=94 u=91
101  3  -0.25 -99      imp:n=1 tmp=8.38434e-08 u=94  $ PebbleCore
102  0        -101 99  imp:n=1 u=94 fill=101         $ Fissile Matl
103  3  -1.74 -100 101 imp:n=1 tmp=8.16892e-08 u=94  $ Pebble Shell
104  5  -1.96      100 imp:n=1 tmp=7.95349e-08 u=94  $ Flibe
c UNNIT CELL OF URANIUM DRIVER PEBBLE (U233 in Driver Region)
115  0  -102 103 -104 105 -106 107 -108 109 lat=2 imp:n=1 fill=84 u=81
116  3  -0.5  -98      imp:n=1 tmp=8.38434e-08 u=84  $ Pebble Core
117  0        -101 98  imp:n=1 u=84 fill=111         $ Fissile Matl
118  3  -1.74 -100 101 imp:n=1 tmp=8.16892e-08 u=84  $ PebbleShell
119  5  -1.96      100 imp:n=1 tmp=7.95349e-08 u=84  $ Flibe
c UNIT CELL OF URANIUM DRIVER TRISO PARTICLE (U233 in Control Channel Region)
340  0         -21 22 -23 24 -25 26 fill=214 lat=1 u=211 imp:n=1
341  40  7.158645e-02   -96    imp:n=1 u=214 tmp=8.38434e-08
347  7 -1.7419371  96 imp:n=1 u=214 tmp=8.16892e-08  $ homogenized
c                                                          layers outside kernel
c UNIT CELL OF URANIUM DRIVER PEBBLE (U233 in Control Channel Region)
315  0  -102 103 -104 105 -106 107 -108 109 lat=2 imp:n=1 fill=284 u=281
316  3  -0.5  -98      imp:n=1 tmp=8.38434e-08 u=284  $ Pebble Core
317  0        -101 98  imp:n=1 u=284 fill=211         $ Fissile Matl
318  3  -1.74 -100 101 imp:n=1 tmp=8.16892e-08 u=284  $ PebbleShell
319  5  -1.96      100 imp:n=1 tmp=7.95349e-08 u=284  $ Flibe
c UNIT CELL OF SHUTDOWN ROD CRUCIBLE
200  92 -2.5 (51 -52 54 -57):(55 -56 50 -53) u=5    imp:n=1      $ Boron Crucible
201  5 -1.96 (-50:53:(56 (-51:57:52)):(-55 (-51:-54:52))) imp:n=1 u=5 $ Flibe
202  0       58 -59 60 -61              imp:n=1 lat=1 fill=5 u=6
203  0       62 -63 64 -65              imp:n=1 lat=1 fill=5 u=7
c
c CORE LEVEL GEOMETRY  ( "o" indicates a zone with pebbles)
c      *|-------------------------------------------------------------------|*
c       |      |      |910/916|   |         |   903   |         |         |   |
c       |933   |      |911/917|   |         |ooooooooo|         |         |   |
```

```
c       |ooooo |901   |912/918|901|   902   |---------|   905   |   907   |909|
c       |------|      |913/919|   |         |         |         |         |   |
c       |934   |      |914/920|   |         |   904   |         |         |   |
c       |ooooo |      |915/921|   |         |ooooooooo|oooooooo |         |   |
c      *|------------------------------------------------------------------|*
c
399  5 -1.96     -908 -920 922 imp:n=1 tmp=7.52264e-08     u=99       $ Pure Flibe
c
933  0       -915     -920 921         imp:n=1  fill=281               $ Inner control
channel (filled with Driver/Ur Pebbles)
934  0       -915     -921 922         imp:n=1  fill=91                $ Inner control
channel (filled with Blanket/Th Pebbles)
c
901  3 -1.74 -900 915 909 910 911 912 913 914 930 931 932 933 934 935
        -920 922  imp:n=1 tmp=7.52264e-08                         $ Inner Solid
Reflector
902  9 -1.96 -901 900 -920 922         imp:n=1                         $ Inner Blanket
Pebbles (Thorium Zone 2)
903  0       -904 901 -920 921         imp:n=1  fill=81                $ Driver
Pebbles  (Uraniun Zone 1)
904  0       -904 901 -921 922         imp:n=1  fill=91                $ Fertile
Pebbles Middle Zone (Thorium Zone 3)
905  0       -906 904 -920 922         imp:n=1  fill=91                $ Outer Blanket
Pebbles (Thorium Zone 1)
c 903  2 -1.0  -904 901 -920 921         imp:n=1           $ Homogenized pebbles - use
for plotting (FOR PLOTTING ONLY)
c 904  1 -1.0  -904 901 -921 922         imp:n=1           $ Homogenized pebbles -don't
use these for runs (FOR PLOTTING ONLY)
c 905  1 -1.0  -906 904 -920 922         imp:n=1           $ Homogenized pebbles (FOR
PLOTTING ONLY)
907  3 -1.74 -907 906 -920 922         imp:n=1         tmp=7.52264e-08 $ Outer Solid
Reflector
909  8 -1.74 -908 907 -920 922         imp:n=1         tmp=7.52264e-08 $ Outer Boron
Sheild
c
910  0       -909     -920 922         imp:n=1   fill=9.9000E1    $ Shutdown Rods
911  0       -910     -920 922         imp:n=1   fill=9.9000E1    $ ...
912  0       -911     -920 922         imp:n=1   fill=9.9000E1    $ ...
913  0       -912     -920 922         imp:n=1   fill=9.9000E1    $ ...
914  0       -913     -920 922         imp:n=1   fill=9.9000E1    $ ...
915  0       -914     -920 922         imp:n=1   fill=9.9000E1    $ Shutdown Rods
916  0       -930     -920 922         imp:n=1   fill=9.9000E1    $ ...
917  0       -931     -920 922         imp:n=1   fill=9.9000E1    $ ...
918  0       -932     -920 922         imp:n=1   fill=9.9000E1    $ ...
919  0       -933     -920 922         imp:n=1   fill=9.9000E1    $ ...
920  0       -934     -920 922         imp:n=1   fill=9.9000E1    $ ...
921  0       -935     -920 922         imp:n=1   fill=9.9000E1    $ ...
c
999  0   908:920:-922                   imp:n=0                         $ Outside
World

c ------------------------------------------------------------------------------
c                                    Surfaces
c ------------------------------------------------------------------------------
c DIMENSIONS of Th232 TRISO KERNALS
1    so   3.1704E-2  $ radius of Th232
c DIMENSIONS OF U233 TRISO KERNALS
```

```
6    so   2.2200E-2  $ radius of (U233 Kernal in Driver Region)
96   so   2.2200E-2  $ radius of (U233 Kernal in Control Channel) Region)
7    so   0.030  $ radius of Buffer Layer
8    so   0.0335 $ radius of Inner PyC
9    so   0.0370 $ radius of ZrC
10   so   0.0410 $ radius of Outer Layer
c DIMENSIONS OF UNIT CELL Th232 TRISO PF = 40%
11   px   .05196048
12   px  -.05196048
13   py   .05196048
14   py  -.05196048
15   pz   .05196048
16   pz  -.05196048
c DIMENSIONS OF UNIT CELL U233 TRISO PF = 20%
21   px   1.1301E-1
22   px  -1.1301E-1
23   py   1.1301E-1
24   py  -1.1301E-1
25   pz   1.1301E-1
26   pz  -1.1301E-1
c DIMENSIONS OF PEBBLE
98   so   0.362492 $ radius of Pebble Core (Driver)
99   so   0.814448 $ radius of Pebble Core (Fertile)
100  so   1.5    $ radius of Pebble
101  so   1.25   $ Inner radius of Pebble
102  px   1.5038E0
103  px  -1.5038E0
104  p    1.  1.732050808  0.   3.00764
105  p    1.  1.732050808  0.  -3.00764
106  p   -1.  1.732050808  0.   3.00764
107  p   -1.  1.732050808  0.  -3.00764
108  pz   1.5038E0
109  pz  -1.5038E0
c 110  rhp 0 0 -1.50382 0 0 -3.00765 1.50382 0 0
c SHUTDOWN ROD CRUCIBLE SURFACES
50 px -9
51 px -2.5
52 px 2.5
53 px 9
54 py -9
55 py -2.5
56 py 2.5
57 py 9
58 px -18.75
59 px 18.75
60 py -32.475
61 py 32.475
62 px -32.475
63 px 32.475
64 py -18.75
65 py 18.75
c CORE LEVEL SURFACES
915  cz  3.0000E1       $ Radius of control channel
900  cz  1.1499E2       $ Radius of inner reflector
901  cz  1.1500E2       $ Carbon Pebbles and Flibe
904  cz  2.1000E2       $ outer radius of driver region
906  cz  2.5000E2       $ Outer radius of outer thorium blanket
```

```
907  cz  2.8900E2       $ Outer radius of outer reflector
908  cz  2.9000E2       $ Outer radius of Boron Shield
909  c/z 75 0 9.9         $ Shutdown Rod channel 0deg
910  c/z 37.5  64.95 9.9  $ Shutdown Rod channel 60deg
911  c/z -37.5 64.95 9.9  $ Shutdown Rod channel 120deg
912  c/z -75 0 9.9        $ Shutdown Rod channel 180deg
913  c/z -37.5 -64.95 9.9 $ Shutdown Rod channel 240deg
914  c/z 37.5 -64.95 9.9  $ Shutdown Rod channel 300deg
930  c/z 0 75 9.9         $ SRC 90deg
931  c/z 64.95 37.5 9.9   $ SRC 150deg
932  c/z 64.95 -37.5 9.9  $ SRC 210deg
933  c/z 0 -75 9.9        $ SRC 270deg
934  c/z -64.95 -37.5 9.9 $ SRC 330deg
935  c/z -64.95 37.5 9.9  $ SRC 30deg
*920 pz  2.2557E1       $ Upper Reflective Boundary layer in vertical direction
 921 pz  1.6542E1       $ Interface Between Fertile and Driver Pebbles
*922 pz  -1.5039E0     $ Lower Reflective Boundary layer in vertical

c ------------------------------------------------------------------------
c                                  Data
c ------------------------------------------------------------------------
m10     6000.16c 1.000000e-24
        8016.16c 4.425260e-02
       90232.78c 2.190504e-02
c
m20     6000.16c 1.000000e-24
        8016.16c 4.425260e-02
       90232.78c 2.190504e-02
c
m30     6000.16c 1.000000e-24
        8016.16c 4.425260e-02
       90232.78c 2.212923e-02
c
m40     6000.16c 1.000000e-24
        8016.16c 4.772160e-02
       92233.78c 2.386080e-02c
m50     6000.16c 1.000000e-24
        8016.16c 3.971789e-02
       92233.78c 2.386080e-02
c
m60     6000.16c 1.000000e-24
        8016.16c 3.971789e-02
       92233.78c 2.386080e-02
c
m1   90232 1. 8016 2      $ Throium Oxide
m2   92233 1. 8016 2      $ Uranium Oxide
m3   6000.78c  1              $ Graphite
mt3    grph.65t
m4   6000.11c  .5 40091 .5    $ Zirconium Carbide
m5   4009.78c 1.1918e-02 $ Flibe at equilibrium composition
     3007.78c 2.3826e-02
     9019.60c 4.7674e-02
     3006.78c 9.9260e-08
m6    6000.11c 9.64345e-01    $ homogenized TRISO Layers (Thorium)
     14000.11c 3.56548e-02
mt6    grph.65t
m7    6000.11c 9.97377e-01    $ homogenized TRISO Layers (Uranium)
```

```
     14000.11c 2.62264e-03
mt7    grph.65t
m8    6000.78c 1.             $ Boron Shield Material (TBD)
mt8    grph.65t
m9   6000.78c 0.087    $ homogeneous mixture of graphite and flibe
     4009.78c 0.007919
     3007.78c 0.015838
     9019.60c 0.031677
     3006.78c 1.17e-06
m90  3006.78c 1.0         $ Li-6
m91  4009.78c 1.0         $ Be-9
m92  5010 2 5011 8 6000.11c .25  $ B4C Shutdown Rod Material
c ****************************************************************************
c                                  Source ETC
c ****************************************************************************
c Neutron Fluence Tallies
f12:n    915 900 901 904 906 907 908
sd12     4.5354E3  1.7384E4  1.7385E4
         3.1747E4  3.7795E4  4.3691E4  4.3842E4
e12       1E-6   0.1    20
c Conversion Ratio Tallies
f14:n (11)
fm14  (-1 10 (102) (-6))
sd14     1
f24:n (41 341)
fm24  (-1 40 -6)
sd24   1
ksrc -190 5 0
kcode   1E3 1 30 130
prdmp 130 130 130
c
c
```

8.0 REFERENCES

[1-1] D. Caron, A. Cheng , T. Dhanania, C. Eastridge, K. Evans, T. Fei, M. Foxe, D. Johnson, E. Keldrauk, Z. Kline, A. Mai, J. Mintz, D. Ogata, E. Park, K. Pham, B. Reinhart, J. Rodriguez, M. Solom, T. Visnjic, C. Wootton, C. Zhao, C. Xu, "A Modular Pebble-Bed Advanced High Temperature Reactor," NE-170 Senior Design Project, UC Berkeley Thermal Hydraulics Laboratory, Report UCBTH-08-001, May 16, 2008.

[3-1] Talamo, Alberto: "Studies on the Feasibility of the LWRs Waste-Thorium In-Core Fuel Cycle in the gas Turbine-Modular Helium Reactor" Journal of Nuclear Science and Technology, Vol. 43, No. 11, p. 1379-1394 (2006)

[3-2] Fratoni, Massimiliano: "Development and applications of methodologies for the neutronic design of the Pebble Bed Advanced High Temperature Reactor (PB-AHTR)"

[5-1] See "Water Cooled Breeder Program Summary Report", Paper #WAPD-TM-1600 from Bettis Atomic Power Laboratory

[5-2] Dose Limit for Graphite taken from http://thoriumenergy.blogspot.com/2006/07/wash-

1097-appendix-e-two-fluid-msbr.html.