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INDIVIDUAL PEBBLE TEMPERATURE PEAKING FACTOR DUE TO LOCAL PEBBLE ARRANGEMENT IN A PBMR CORE

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Scientists at the German AVR pebble bed nuclear reactor discovered that some of the core pebbles reached a temperature 200 K higher than was previously predicted by reactor physics calculations. The goal of this research paper is to determine whether there is a reactor physics explanation for this unexpected temperature peak. If it were reactor physics driven, there could be implications for the need for core physics monitoring which is not now being considered for pebble bed reactors. Through exhaustive Monte Carlo modeling of a PBMR-400 pebble environment, no simple pebble arrangements were found to account for the 200K temperature difference. Simple thermal hydraulics analyses were performed which do show that significant coolant blockage would be needed to account for such an increase in temperature. The identified worst case scenarios are presented and discussed in detail. The conclusion of this work is that the stochastic nature of the pebble bed is not the cause of excessive temperatures observed but rather coolant blockage is the likely cause.

1. INTRODUCTION

The PBMR is a high temperature gas cooled reactor whose main design feature is the fact that the uranium oxide fuel is contained in silicon carbide coated microspheres in graphite matrix surrounded by a protective layer of graphite. The graphite acts as a moderator for the helium cooled reactor. The pebble is shown on Figure 1. Each pebble is 6 cm in diameter containing from 10,000 to 15,000 pebbles. These 6 cm graphite spheres are continuously circulated through the 11 meters core vessel which allows for online refuelling.

The high temperature pebble bed reactor has been operated for many years in Germany at the Arbeitsgemeinschaft Versuchsreaktor (AVR) 1967 – 1988. Most recently Tsinghua University has build and operated a small 10 MWth pebble bed reactor in China. To support the safety of the plants numerous studies have been conducted in Germany, China and South Africa for the PBMR. Additionally, General Atomics has done extensive research on helium cooled reactors based on their gas reactor program and plants using the same microsphere fuel technology but prismatic fuel design. One of the most notable safety analysis studies was done by General Atomics and submitted to the NRC in a Preliminary Safety Information Document (PSID) for their early prismatic designs. (Shenoy, 2010) It showed that under all postulated accident scenarios the PBMR design would not experience fuel melt down and most, if not all, of fission products would be contained within the individual silicon carbide coated fuel micropheres. Consequently a traditional reactor containment building is not required because the reactor is inherently safe. This analysis showed that the peak fuel temperature would not exceed 1600 C based on their operating conditions. Similar calculations have been performed for the PBMR by the South Africans for their high temperature gas reactor.

Some researchers argue that, due to the lack of in-core instrumentation and the stochastic flow of the pebbles through the core, theoretical analysis cannot give an accurate enough representation of the reactor physics in the core to guarantee the desired level of safety. Rainer Moormann supports the idea of the necessity to enclose future PBMR reactors in containment buildings based on experimental data. (Moormann, 2009) He reports that by inserting wires with different melting points (melt wires) into the pebbles to be sent through a PBMR core research scientists at the German AVR reactor found that 1/3 of the pebbles fed into the radial outer zone of the AVR core experienced temperatures 200 Kelvin (K) higher than previously predicted through reactor physics calculations. This implies that safety analysis previously

conducted based on reactor physics models of a PBMR core could be as much as 200 K off. In this case during a full loss of coolant accident (LOCA) scenario fuel temperatures could exceed the 1600 C design limit for silicon carbide causing some of the microspheres to fail releasing fission products to the coolant should this hypothetical accident occur. This experimental data is certainly cause for concern for the PBMR design because it suggests that there is some possible geometric arrangement of fuel pebbles inside the core that would lead to unpredictably high fuel temperatures and therefore need either for incore monitoring of the flux (which would be very difficult given the use of pebbles) or the need for a containment building making the plant more costly.

As most of the PBMR modeling to this date has been conducted by smearing the material properties of the pebbles into a homogeneous material for different core regions, this project will focus on finding a possible geometric arrangement of pebbles that would lead to a high temperature peak by modeling the individual pebbles and their local environment.

The objective of this project is to provide a hypothesis, verifiable through computational methods, of what possible arrangement of pebbles could have occurred to have resulted in the 200 K temperature peak in the German AVR. It is speculated that two different effects could have possibly contributed to the triggering of the melt wire:

1) In the reactor physics hypothesis, there might be a possible geometric arrangement of pebbles of various burn-up that would result in a high peaking factor in a certain pebble causing it to heat up more than previously predicted.
2) In the thermo-fluids hypothesis, it is proposed that the pebble was jammed is such an awkward geometric configuration within the reactor core that it was simply not getting enough heat removal.

The objective of this specific paper is to address the reactor physics side of the problem. It is proposed that through modeling many different geometric arrangements of pebbles it may be possible to see if reactor physics considerations could be the cause of the unexpected high temperatures observed in Germany.

A detailed model, down to the TRISO particles, of a PBMR pebble will be build in a Monte Carlo transport code. A body-centered-cubic (BCC) lattice of 559 such pebbles will be simulated to be immersed in an average pebble bed core environment. Next, different geometric

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arrangements of pebbles will be tested to determine in which scenario the highest temperature peak in a single pebble relative to the average pebble will be recorded. Within the different geometric arrangements of pebbles will be included models with fresh pebbles and pebbles of varying in burn-up and also different arrangements of fuelled and graphite pebbles at various pebble packing fractions. An investigation will also be made into a scenario where the 559 pebble array is in contact with a core graphite reflector and corresponding flux conditions. From all of the mentioned combinations of models, a worst case scenario, one that gives the highest temperature peak, will be selected as the most likely configuration to have occurred in the German AVR.

In what follows, Section 2 will begin with an extensive description of the model of the pebble, then go on to describe the modeling codes and methods used, and conclude with the procedure used to obtain an accurate approximation of the isotopic concentration inside of pebbles of different burn-up. Section 3 will present the peaking factors found for pebbles in different geometric configurations, both in the middle of the core and near a core reflector. Section 4 will give a simple assessment of the possible temperature implications of flow blockages. Finally, Section 5 will give the concluding remarks of this project and answer the hypothesis posed above. This last section will also give suggestions for further research in this topic.

2. MODELING METHODS AND PROCEDURES

2.1 Pebble Description

The PBMR pebble parameters for this work are based on the pebble bed benchmarking activity established by the Nuclear Energy Agency in a study of the PBMR-400 Coupled Neutronics/Thermal Hydraulics. (Reitsma, F., 2005) The pebble was accurately reproduced in the model, including the 15 000 TRISO particles, preserving the double heterogeneity of PBMR pebbles. The only approximation that was made modeling the pebble was that the TRISO particles inside the graphite matrix were arranged in a simple cubic lattice with a packing fraction of 0.093 instead of being distributed stochastically. See Figure 1. The impact of this approximation is discussed in Brown. (Brown, 2004) The uranium loading is 9 grams per fuel-pebble with the U-235 enrichment at 9.6 percent by weight. The maximum fuel pebble burn-up

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is 90,000 Megawatt days per metric ton Uranium (MWd/MTHM). The core contains approximately 452 000 pebbles with a packing fraction of 0.61.

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FIGURE 1: Author: Vladimir Sobes

2.2 Modeling Codes

Monte Carlo N-Particle transport code (MCNP5) was chosen as the code to be used for the modeling of the pebbles since it is able to accurately represent the double heterogeneous nature of the pebbles and provides solutions based on continuous energy cross-sections. MCNP is a general-purpose neutron transport code that is designed to do criticality and surface source calculations. (Booth, 2005)

In order to create the appropriate isotopic compositions for pebbles of different burn-ups, MCNP-ORIGEN DEpletion Program (MCODE) was used to link the depletion calculation power of ORIGEN with the geometric modeling capabilities of MCNP5. MCODE is a linkage program developed at MIT, which combines the continuous-energy simulation power of MCNP and the one-group depletion code, ORIGEN2.2, (Xu, 2006) to perform burn-up calculations for nuclear fission reactor systems. In terms of the depletion calculations, it is important to note that MCODE will not propagate uncertainties in isotopic calculations; however sensitivity studies were performed in order to minimize the impact of statistical uncertainties on the isotopic composition.

2.3 Accurate Representation of a Depleted Pebble

In order to determine an accurate representation of the isotopic composition of a depleted pebble, the steps described in this section needed to be taken.

2.3.1 Initial Material Approximation

First a full MCODE depletion (0 – 90,000 MWd/MTHM) on a simple unit cell in a BCC arrangement with reflective boundary conditions was run. The reflective boundary conditions expanded the unit cell to an infinite lattice. All of the pebbles in the unit cell were depleted with a constant power of 885 Watts (W) per pebble as an eigenvalue calculation. This depletion provided a rough approximation of the material specification inside the pebbles at different

depletion points. Using an MCNP model of a cylindrical reactor core filled with homogenous pebbles arranged in a BCC lattice, it was determined that leakage would account for approximately a 4% neutron loss, i.e. that an eigenvalue of ~ 1.04 in an infinite array approximately corresponds to an eigenvalue of 1 in the reactor vessel. It was found that the equilibrium point (k_∞=1.04) occurred at 45,000 MWd/MTHM or 50% of our depletion interval.

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2.3.2 Flux Approximation

In order to adequately represent the average environment that a pebble will see during its life in the core, an average of the core neutron flux that will impact a pebble had to be modeled. This spectrum can than be used at the boundaries of a sub-domain to reflect the impact of an equilibrium core. The first approximation to the equilibrium neutron flux spectrum was obtained by running an eigenvalue calculation on a unit cell with reflective boundary conditions. All the pebbles were at the estimated equilibrium (45,000 MWd/MTHM burn-up) material obtained from the first MCODE depletion. The energy spectrum of the neutrons impacting on the outside of the central pebble (an arbitrarily chosen surface) was recorded. Further, a larger lattice model was built, but this time the reflective boundary conditions were replaced with source boundary conditions representative of the recorded neutron spectrum. The new model contained the central pebble and the nearest 558 neighbours in a BCC lattice. One way to think of the different regions of this model is to consider it as the central pebble surrounded by 6 layers of pebbles. Each concentric layer is a collection of pebbles located on the surface of an imaginary cube of increasing size. See Figure 2.

FIGURE 2 Author: Vladimir Sobes

The next step was to simulate the average of the environment that a single pebble would see throughout its lifetime in the core – neighbouring pebbles of an average burn-up and an average core neutron flux. Effectively, a model which simulates 559 pebbles immersed in an equilibrium reactor core without the core geometric effects was created.

This model was run with the ~~initial~~ first approximation of the boundary conditions obtained from the earlier eigenvalue calculation. Here, once again, the neutron flux was tallied to provide a representation of the flux spectrum seen inside the pebble bed core. The initial idea

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was to iteratively arrive at an accurate equilibrium flux spectrum by placing the newly tallied spectrum on the central pebble as the source spectrum for the next run; this way, after some iterations, converging on a true spectrum. However, running such an iteration proved to be unnecessary as no significant change in the spectrum was observed through the first few iterations performed. This model was then used to perform a full 90,000 MWd/MTHM depletion of a fresh pebble surrounded by pebbles of equilibrium burn-up.

2.3.3 Pebble Depletion

Finally, an extended depletion (0% - 111%, 0 – 100 WMd/ktU) was carried out on a single pebble at constant power. This pebble was surrounded by 3 layers (90 nearest neighbours in a BCC lattice) of 45,000 MWd/MTHM burned pebbles, modeled with TRISO particles then 3 layers of homogeneous (to save computational speed) fuel ~~buffer~~ pebbles, also at 45,000 MWd/MTHM burn-up, and an average reactor source at the boundary of the model to simulate the environment of the core outside of the 559 pebbles. The central pebble was depleted in this manner and its material composition at different burn-ups was compared to the material composition of the pebbles depleted in the initial infinite lattice calculation. It was found that the major isotope amounts were almost identical, hence, justifying the use of the equilibrium material obtained from the infinite lattice run for the source depletion calculation.

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At this point, the material composition of a pebble at different burn-ups was available and different geometric configurations were ready to be tested for their effects on the temperature of a single pebble. MCNP5 was used to calculate power peaking factors, which are related to a temperature peak through a simple thermodynamics model.

3. THE SEARCH FOR POWER PEAKING FACTORS

3.1 Middle of the Core

The goal was to identify a pebble configuration where the power in one pebble, the central pebble, peaked in comparison to the reference/equilibrium configuration: a 50% depleted pebble surrounded by 50% depleted pebbles (an average representation of the pebbles in a pebble bed core).

The variables that were considered in different combinations were as follows:

Central pebble depletion: 0%, 25%, 50%, 75%, 90%, 100% (of 90,000 MWd/MTHM burn-up)

Surrounding 90 pebbles: 0%, 25%, 50%, 75%, 100% (of 90,000 MWd/MTHM burn-up) graphite

The most notable peaking factors are summarized in the Table 1 and explained below. The results of all of the runs completed for the middle of the core are provided in Table 2.

TABLE 1

TABLE 2

As can be seen from Table 2, the 25% depleted pebble appears to be the main culprit in pebble power peaking. It cannot be said for certain that 25% depletion yields the maximum peaking factor due to the balance between plutonium-239 build up and uranium-235 depletion as only 0, 25, 50, 75, 90, 100 percent depleted pebbles were used in the calculations. Therefore, the worst case scenario pebble burn up can be something in between the models simulated and could possibly yield even higher peaking factors.

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In a BCC lattice there is a possibility of having a packing fraction as high as 0.68 compared to the 0.61 modeled here. An increase in packing fraction could lead to even higher power peak. The worst case scenario model above, a 25% depleted pebble surrounded with 3 layers of graphite pebbles, which lead to a 27% power peaking factor was rerun with a 0.68 packing fraction to test the dependence of the power peaking factor.

It was found the with a 0.68 packing fraction a 25% depleted pebble surrounded by 3 layers of carbon pebbles resulted in a power peaking factor of 1.43 relative to the reference case of uniformly 50% depleted pebbles.

3.2 Near a Core Reflector

The graphite reflector model utilized the core graphite reflector to moderate the neutron flux in the model and achieved a higher power level in a given pebble. To create this scenario, the 559 pebble model had the pebbles on one side of the central pebble removed and a large

block of graphite material built in their place. In the model with the reflector there are only 5 source surfaces bounding the pebbles; the sixth surface of the cube is the graphite reflector as shown in Figure 3.

FIGURE 3 Author: Vladimir Sobes

Effectively what has been simulated here is a large collection of pebbles in a BCC configuration next to a flat graphite reflector (the curvature of the reflector was dismissed as insignificant) with an average core flux impinging on them from the outside.

Table 3 gives the results of the runs conducted with the reflector model. Instead of the peaking factor being calculated relative to the 559 pebble model filled completely with pebbles of average burn-up, here the peaking factor is relative to a model where pebbles of average burn-up are placed next to a reflector.

TABLE 3

~~The most interesting pattern that emerges from the first five lines of this table is that the relationship between the burn-up of the central pebble and the power peaking factor is almost identical to the relationship that is seen when the graphite reflector is not present. This correlation between the burn-up of the central pebble and the peaking factor can be seen for models without a reflector in the full record of simulations in Table 2 under the reference number (#) 1. Do note; that the reference case for Table 3 is 3.64 times larger in power than the reference case for Table 2.~~

Once again the worst case scenario from all of the reflector cases simulated was rerun with a higher, 0.68, pebble packing fraction. An individual pebble power peaking factor of 1.27 was found for a 25% depleted pebble with a core graphite reflector on one side and three layers of graphite pebbles packed with 68% volume efficiency on the other side.

4. THERMODYNAMICS ANALYSIS – POWER PEAKS TO TEMPERATURE PEAKS

4.1 Heat Diffusion – No Flow Restriction

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This section discusses how the power peaking factors found as a result of the MCNP modeling can be related to temperature peaks inside the pebbles through simple thermodynamic analysis of the pebble.

The reactor physics analysis has so far shown that a 25% depleted pebble (22,500 MWd/MTHM) surrounded by 90 graphite pebbles in the middle of the core will produce 27% more power than the average pebble. And a 25% depleted pebble wedged in between a core graphite reflector and several layers of graphite pebbles will produce 15% more power than an average pebble next to a core graphite reflector. The probability of such scenarios occurring is very small because the PBMR 400 MW usually only operates with graphite pebbles at start up when all of the fuel is fresh. The graphite pebbles are slowly removed as the core average burn-up approaches the equilibrium 45,000 MWd/MTHM. However, in the worst case scenario situation such configurations could occur.

A simple thermodynamic calculation on a homogeneous pebble model gives an analytic solution for the temperature profile inside the pebble if the following assumptions are made:

A homogeneous model of the pebble is used assuming two regions – an inner sphere of radius 2.5 cm producing (885 W x local power peaking factor) and an outer spherical shell from 2.5 cm to 3 cm made of graphite. The inner region is assumed to have a homogeneous material with the thermal conductivity of graphite (this is justified by the fact that 0.9775 (atom fraction) of all of the material is graphite).

Next, the thermal diffusion equation, Equation 1, is solved for the inner sphere in spherical coordinates.

$$\frac{1}{r^2}\frac{\partial}{\partial r}\left(k r^2 \frac{\partial T}{\partial r}\right) + \frac{1}{r^2 \sin^2\theta}\frac{\partial}{\partial \phi}\left(k \frac{\partial T}{\partial \phi}\right) + \frac{1}{r^2 \sin\theta}\frac{\partial}{\partial \theta}\left(k \sin\theta \frac{\partial T}{\partial \theta}\right) + \frac{\partial q}{\partial t} = \rho c_p \frac{\partial T}{\partial t} \quad (1)$$

(Incropera, 1990)

Where T is the temperature, t is the time, q is the heat produced, r is the radius, ϕ is the azimuthal angle, θ is the polar angle, k is the thermal conductivity, ρ is the density, and c_p is the specific heat capacity at constant pressure.

Thermal equilibrium (steady state) and uniform power production per unit volume are assumed. Temperature is taken to have only a radial dependence. The only boundary

conditions that are needed are a finite temperature at the center of the sphere and ~~some defined temperature, T_0, at the outside of the sphere, radius 2.5 cm.~~a the temperature of the Helium coolant, which is assumed to be 1000 K with all thermodynamic properties calculated at that temperature.

A thermal resistor model accounting for thermal conduction through the graphite spherical shell, and convection and radiation from the pebble to the helium coolant is solved simultaneously with the heat diffusion equation applied to the fuel portion of the pebble. The helium has a mass flow rate of 192.7 kg/s. (Reitsma, 2005)

The solution of the thermal diffusion equation, Equation 2, gives the maximum temperature in any pebble as a function of the power peaking factor, GP.

$$T(GP) = \frac{\partial q}{\partial t} GP\left(\frac{R_i^2}{6 k_g V} + R_{tot}\right) + T_{He} \quad (2)$$

Where T is the temperature, t is the time, q is the heat produced, GP is the geometric (local) power peaking factor, R_i is the inner radius of the graphite shell of the pebble, k_g is the thermal conductivity of graphite, V is the volume of the fuel portion of the pebble, R_{tot} is the total thermal resistance between the helium flow and the fuel part of the pebble, and T_{He} is the helium temperature.

It is now possible to calculate the temperature peak inside a pebble in any of the models of this project versus an average pebble inside the PBMR core. Table 4 gives the results for the maximum temperature peak in a single pebble relative to the average pebble.

TABLE 4

However, what has not yet been considered here is the fact that the PBMR core experiences large radial and axial power peaking factors (global) predicted by transport theory. These factors multiply to as high as a 3.7 power peaking factor in some regions of the core. Because the temperature peak in a given pebble is linearly proportional to the power in that pebble, to achieve the worst case scenario the temperature peaks above need to be multiplied by the highest power peak in the appropriate region of the core. Based on the work done by Everson (Everson, 2009) on the radial and axial core peaking factors of the PBMR-400 MW reactor using Very Superior Old Programs (VSOP) simulations it can be concluded that in the

center of the core a peaking factor of 3.0 is calculated and 3.7 near the reflector. This would result in a temperature peaks reported in Table 5:

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TABLE 5

4.2 Thermo-fluids Analysis and Coolant Flow Blockage

Here, a brief discussion is given of the other hypothesized explanation for the temperature peaks found by Rainer Moormann – a thermo-fluid problem where the pebble of interest is not getting enough cooling due to a geometric configuration of pebbles that restrict helium flow.

From the simplified thermodynamics treatment of the pebble in Section 4.1 it can be shown that the temperature peak inside the pebble is linearly dependent on the total thermal resistance between the inner sphere and the external helium flow. (Incropera, 1990) See Equation 2. The total thermal resistance is in turn a complicated function of the mass flow rate of the coolant. Therefore, it is possible to solve how much coolant flow blockage is needed to achieve a temperature peak of 200 K. Figuring out a possible geometric configuration of pebbles that could lead to such a local coolant flow blockage becomes a problem that this paper will not address.

Three questions were investigated using the thermodynamics approximation of Section 4.1:

1) How much coolant flow restriction is needed for an average pebble to increase in temperature by 200 K relative to the average pebble?

2) How much coolant flow restriction is needed for a pebble in the worst possible geometric configuration (local power peak of 1.27 and a global power peak of 3.0) to increase in temperature by 200 K relative to an average pebble in a high global peak configuration (local power peak 1 and a global power peak of 3.0).

3) How much coolant flow restriction is needed for a pebble in the worst possible geometric configuration next to the core graphite reflector (local power peak of 1.15 and a global power peak of 3.7) to increase in temperature by 200 K relative to an average pebble in a high global peak configuration next to a core graphite reflector (local power peak 1 and a global power peak of 3.7).

The results are presented in Table 6:

TABLE 6

The simple thermodynamics model of this section assumes that during an increased pebble packing fraction in a high power peaking area of the core the overall coolant mass flow rate through the core is still 192.7 kg/s. Therefore, with a reduced cross sectional area for the coolant to flow through, the helium coolant, in this model, moves faster by the hot pebbles providing better heat transfer. As a consequence of this, the results appear as if more coolant flow blockage is needed for the higher pebble packing fractions. However, in an actual PBMR core the helium flow rate through a region of increased pebble packing should be less than the core average because the helium is more like to flow to less densely packed regions. With the helium flow rate already obscured by the high pebble packing fraction in a region of high power peaking the percent of coolant flow rate restricting needed to achieve a 200 K temperature peak will be significantly less than predicted by the thermodynamics analysis above.

In conclusion, there needs to be significant coolant flow rate reduction for an average pebble to heat up by an extra 200 K. However, a combination of at most 54% coolant flow reduction and a worst case scenario (from a reactor physics analysis stand point) pebble arrangement could lead to the 200 K temperature peak inside a pebble.

5. CONCLUDING REMARKS

A possible geometric arrangement of pebbles that would explain, solely through reactor physics, the 200 K temperature peak inside a pebble describe by Rainer Moormann was not found. A maximum temperature peak of 129.5 K in a single pebble was reported in the worst case scenario analyzed. This temperature peak is predicted to occur if a 22,500 MWd/MTHM burn-up pebble is surrounded by 90 graphite pebbles in a region of the core with a 3.0 power peaking factor and a local pebble packing fraction of 0.68. Very simple thermo-fluids analysis gave further insight to the size of the temperature peaking factors. It was shown that almost complete coolant flow blockage is needed for an average pebble to heat up an extra 200 K. However, the combination of the worst case scenario (from the reactor physics viewpoint)

combined with 54% coolant flow blockage could lead to a temperature 200 K greater than was previously predicted by reactor physics calculations.

Further consideration for this project would be modeling more depletion points around the 22,500 MWd/MTHM burn-up point to find truly the highest power peaking point achievable due to local geometry. Additionally, a computational fluid dynamics model could provide further insight on flow blockage analysis.

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TABLES

TABLE 1: Selected Power Peaking Factors – Middle of the Core

#	Power Peaking Factor (Uncertainty)	Central Pebble (% depleted)	Layer 1 (percent depleted)	Layer 2 (percent depleted)	Layer 3 (percent depleted)	Pebble Packing Fraction
0	*1.00 Reference*	*50*	*50*	*50*	*50*	*0.61*
1	**1.04** (.12%)	25	50	50	50	0.61
2	**1.11** (.12%)	25	0	0	0	0.61
3	**1.27** (.12%)	25	Graphite	Graphite	Graphite	0.61
4	**1.43** (.12%)	25	Graphite	Graphite	Graphite	0.68

0. Reference case
1. Largest obtainable peaking factor at the average pebble packing fraction by only varying the depletion of the central pebble.
2. Largest obtainable peaking factor at the average pebble packing fraction without graphite pebbles and/or graphite reflector.
3. Largest obtainable peaking factor at the average pebble packing fraction without resorting to a graphite reflector.

TABLE 2: Power Peaking Factors – Middle of the Core

#	Power Peaking Factor (Uncertainty)	Central Pebble (% depleted)	Layer 1 (percent depleted)	Layer 2 (percent depleted)	Layer 3 (percent depleted)	Pebble Packing Fraction
0	*1.00 Reference*	*50*	*50*	*50*	*50*	*0.61*
1	0.90 (.12%)	0	50	50	50	0.61
1	**1.04 (.12%)**	**25**	**50**	**50**	**50**	**0.61**
1	1.00 (.12%)	50	50	50	50	0.61
1	0.93 (.12%)	75	50	50	50	0.61
1	0.88 (.12%)	90	50	50	50	0.61

2	1.06 (.12%)	50	0	0	0	0.61
2	1.01 (.12%)	50	25	25	25	0.61
2	1.00 (.12%)	50	75	75	75	0.61
2	1.00 (.12%)	50	100	100	100	0.61
2	0.95 (.12%)	0	0	0	0	0.61
2	**1.11 (.12%)**	**25**	**0**	**0**	**0**	**0.61**
2	0.98 (.12%)	75	0	0	0	0.61
2	0.90 (.12%)	100	0	0	0	0.61
3	1.09 (.12%)	0	Graphite	Graphite	Graphite	0.61
3	**1.27 (.12%)**	**25**	**Graphite**	**Graphite**	**Graphite**	**0.61**
3	1.22 (.12%)	50	Graphite	Graphite	Graphite	0.61
3	1.13 (.12%)	75	Graphite	Graphite	Graphite	0.61
3	1.08 (.12%)	90	Graphite	Graphite	Graphite	0.61
4	**1.43 (.12%)**	**25**	**Graphite**	**Graphite**	**Graphite**	**0.68**

TABLE 3: Power Peaking Factor – Near a Core Graphite Reflector

Power Peaking Factor (Uncertainty)	Central Pebble (% depleted)	Layer 1 (percent depleted)	Layer 2 (percent depleted)	Layer 3 (percent depleted)	Pebble Packing Fraction
1.00 Reference	*50*	*50*	*50*	*50*	*0.61*
0.87 (.09%)	0	50	50	50	0.61
1.03 (.09%)	25	50	50	50	0.61
0.93 (.09%)	75	50	50	50	0.61
0.89 (.09%)	90	50	50	50	0.61
1.07 (.09%)	25	0	0	0	0.61
1.15 (.09%)	**25**	**Graphite**	**Graphite**	**Graphite**	**0.61**
1.27 (.09%)	**25**	**Graphite**	**Graphite**	**Graphite**	**0.68**

TABLE 4: Individual Pebble Temperature Peaks due to Local Power Peaking

Worst Case Scenario			Average				
Local Power Peaking Factor	Pebble Packing Fraction	Maximum Pebble Temperature	Local Power Peaking Factor	Pebble Packing Fraction	Maximum Pebble Temperature	Near a core graphite Reflector?	Temperature Difference
1.27	0.61	**1162.8 K**	1.00	0.61	1128.2 K	No	**34.6 K**
1.15	0.61	**1147.4 K**	1.00	0.61	1128.2 K	Yes	**19.2 K**
1.43	0.68	**1171.4 K**	1.00	0.61	1128.2 K	No	**43.2 K**
1.27	0.68	**1152.2 K**	1.00	0.61	1128.2 K	Yes	**24.0 K**

TABLE 5: Individual Pebble Temperature Peaks due to Local and Global Power Peaking

Worst Case Scenario			Average				
Local Power Peaking Factor	Pebble Packing Fraction	Maximum Pebble Temperature	Local Power Peaking Factor	Pebble Packing Fraction	Maximum Pebble Temperature	Global Power Peaking Factor	Temperature Difference
1.27	0.61	**1488.5 K**	1.00	0.61	1384.6 K	3.0	**103.9 K**
1.15	0.61	**1545.6 K**	1.00	0.61	1474.4 K	3.7	**71.2 K**
1.43	0.68	**1514.1 K**	1.00	0.61	1384.6 K	3.0	**129.5 K**
1.270	0.68	**1563.1 K**	1.00	0.61	1474.4 K	3.7	**88.7 K**

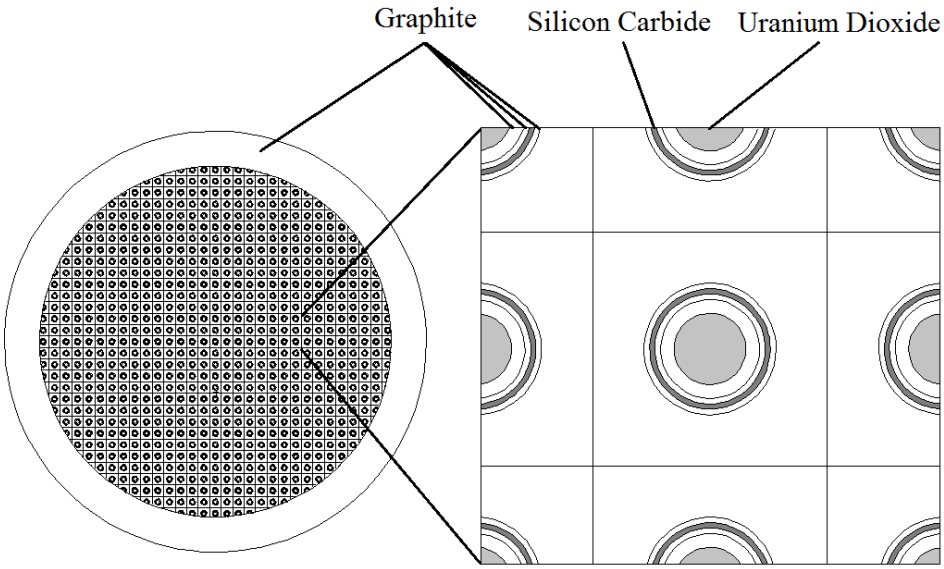
TABLE 6: Amount of Coolant Mass Flow Rate Restriction Needed to Achieve a 200 K Temperature Peak in an Individual Pebble

Worst Case Scenario			Average				
Local Power Peaking Factor	Pebble Packing Fraction	Mass Flow Rate Needed	Local Power Peaking Factor	Pebble Packing Fraction	Normal Mass Flow Rate	Global Power Peaking Factor	Percent Mass Flow Rate Restriction
1.00	0.61	**9.5 kg/s**	1.00	0.61	192.7 kg/s	1.0	**95%**

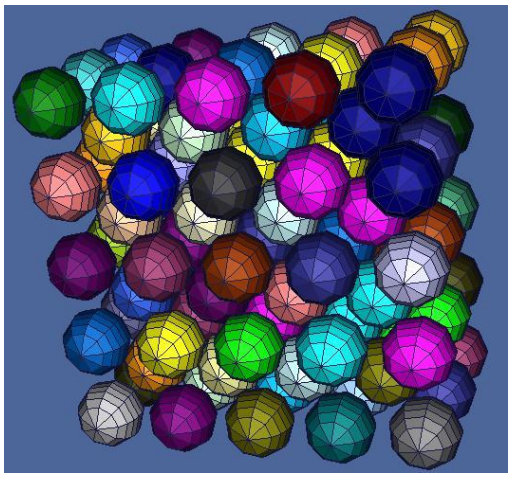
1.27	0.61	**86.0 kg/s**	1.00	0.61	192.7 kg/s	3.0	**55%**
1.15	0.61	**75.1 kg/s**	1.00	0.61	192.7 kg/s	3.7	**61%**
1.00	0.68	**5.7 kg/s**	1.00	0.61	192.7 kg/s	1.0	**97%**
1.43	0.68	**89.1 kg/s**	1.00	0.61	192.7 kg/s	3.0	**54%**
1.270	0.68	**69.1 kg/s**	1.00	0.61	192.7 kg/s	3.7	**64 %**

FIGURES

Author: Vladimir Sobes Figure: 1



Author: Vladimir Sobes Figure: 2



Author: Vladimir Sobes Figure 3

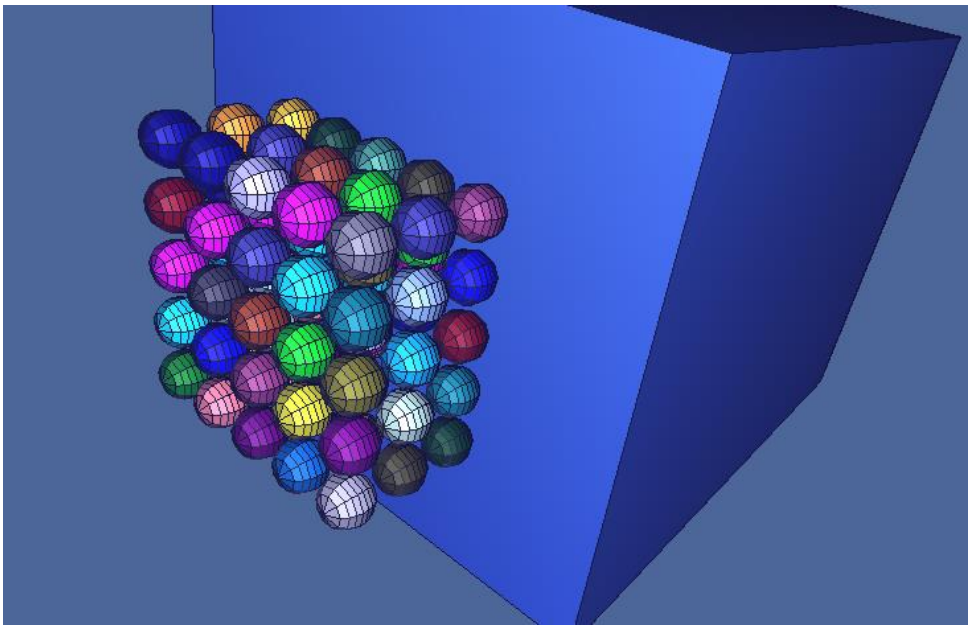


FIGURE DESCRIPTIONS

Figure 1: A cross section cut of the MCNP model of a pebble. Enlarged is the graphite matrix region showing the TRISO particles modeled in a simple cubic lattice.

Figure 2: A 3-D representation of the four inner most layers of the 559 pebble model. The view shown is a cross section through the middle of the model showing the whole central pebble. Also note, although the pebbles are depicted in different colors, the material compositions of the pebbles are identical. The helium surrounding the pebbles and the neutron source surfaces located outside of the model are not shown.

Figure 3: A 3-D representation of the four inner most layers of a typical model with the graphite reflector. Please note that the outside layers of pebbles are not shown as well as the helium surrounding the pebbles and the neutron source surfaces. The picture also shows a cross sectional cut through the core graphite reflector.