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A. M. Ougouag
J. Ortensi
H. Hiruta

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ANALYSIS OF AN EARTHQUAKE-INITIATED-TRANSIENT IN A PBR

A. M. Ougouag, J. Ortensi, H. Hiruta
Idaho National Laboratory
MS-3870, PO Box 1625, Idaho Falls, ID 83415-3870
Abderrafi.Ougouag@inl.gov; Javier.Ortensi@inl.gov;
Hikaru.Hiruta@inl.gov

ABSTRACT

The safe shutdown earthquake event is one of the design basis accidents for the pebble bed reactor. Heretofore, analysis methods have been based on a postulated change in the bulk or average packing density during an earthquake. These past studies have essentially focused on the changes to the steady state conditions of the core before and after the compaction, followed with the performance of safety analysis calculations with the more densely packed core. Therefore, no time dependent simulation of the core slumping during an earthquake event has been performed in the past. This work presents a new method for analyzing a transient initiated by the earthquake-induced local mechanical changes. The new method captures the dynamic geometric compaction of the pebble bed core. The neutronic and thermal-hydraulic grids are dynamically re-meshed to simulate the re-arrangement of the pebbles in the reactor during the earthquake. Preliminary results are shown for the PBMR-400 assuming it is subjected to the Idaho National Laboratory's design basis earthquake. The CYNOD-THERMIX-KONVEK coupled code system shows that the PBMR-400 can safely withstand the reactivity insertions induced by the slumping of the core and the resulting relative withdrawals of the control rods. This characteristic stems from the large negative Doppler feedback of the fuel.

Key Words: PBMR, earthquake, transient, packing fraction, CYNOD.

1. INTRODUCTION

The safe shutdown earthquake event has been identified as a Design Basis Accident (DBA) in the licensing basis event selection for the Pebble Bed Modular Reactor (PBMR), which was submitted in 2006 for U.S. Design Certification [1]. A similar event was also identified as a DBA for the HTR-10 certification in China [2]. To meet licensing requirements this DBA needs to be studied and the safety behavior of the reactor understood in order to provide the technical basis for the appropriate operating response.

The slumping of the pebble bed caused by the re-distribution of the pebbles during the shaking of the vessel effectively constitutes fuel densification and thus results in reactivity insertion. Furthermore, if the reactor operates with partially inserted control rods, the relative control rod withdrawal caused by the reduction in core height constitutes a secondary reactivity insertion mechanism that must also be quantified and accounted for in the resulting transient. For the HTR-10 design, the operating safety earthquake is defined as the packing of the core with one reflector rod withdrawing uncontrolled with a speed of 1 cm s^{-1} and assuming failure of the control system. The calculated changes in pebble bed packing fraction are from 0.61 to 0.615 in 4 minutes and the reactivity inserted by the pebble packing is roughly 40 cents. For the PBMR-400 analysis [3] the "Safe Shutdown Earthquake" (SSE) uses geometrically un-compacted and compacted models. In addition, two earthquake durations are used in the analysis, 5 and 15 seconds, respectively, with a nominal global packing fraction of 0.61. Their corresponding compacted models have used the predicted pebble bed packing fractions of 0.62 and 0.64, where the latter can be recognized as the commonly reached limit packing level from shaking until a maximally random jammed packed state arises [4]. In these simulations, the core height decreases by 17.7 cm and 51.6 cm and the densification-induced reactivity insertions for the two earthquake events are 60 cents and 180 cents, respectively.

2. PEBBLE BED REACTOR EARTHQUAKE ANALYSIS METHOD

During the starting of operations of a PBR reactor with a recirculation scheme, the core experiences two physically distinct time dependent phenomena. The first is the approach to an asymptotically packed core, which is determined by the geometric compaction of the pebbles as they are re–circulated. The approach to an asymptotic burnup distribution in the core is the second phenomenon, which occurs at a later time and is a consequence of the recirculation of pebbles in the presence of a neutron flux. During an earthquake, the reactor core evolves toward denser packing levels as the shaking rearranges the pebbles, thus departing from the asymptotic packing. In models, this compaction can be directly translated into a shifting of the calculation mesh that captures the average behavior of the pebbles and their corresponding physical effects. Since it is expected that the neutronic phenomena, including temperature feedback, dominate the transient behavior, the new method is primarily concerned with modeling neutronic parameters. The foundation of the method relies on the assumption that local, relative small, changes in packing fractions do not significantly affect, or change, the neutron spectrum in the calculation cell. This assumption allows the modification of the diffusion parameters with a simple cell volume weighting scheme within the neutron dynamics code without recourse to running a spectrum code.

2.1. Volume Weighting Method for Diffusion Parameters

The homogeneous macroscopic cross-section for a given interaction in a calculation cell k is described by Eq. 1. In the model of an earthquake event, the pebble bed reactor (PBR) fuel cannot be considered static, because the effective fuel densification normally affects both of the parameters in this equation. Therefore, the diffusion parameters (macroscopic cross sections and diffusion coefficients) from any library that describes the asymptotically packed core would be invalidated and would require modification or re-calculation.

$$\Sigma_k^{\text{hom}} = \sum_{i=1}^{M} N_i \sigma_i \tag{1}$$

where,

N_i = Number density of the i$^{\text{th}}$ isotope
σ_i = microscopic cross-section of the i$^{\text{th}}$ isotope

The rigorous approach would be to re-compute the number densities, microscopic cross sections, and the diffusion parameters during the transient, but these are very computationally intensive tasks. However, an approximate method is possible if the compaction of the pebble bed is modeled as a re-arrangement of the neutronic calculation mesh. The cross sections assigned to each newly re-meshed cell need to be appropriately modified to ensure mass conservation.

Since HTR cores are influenced by a low moderating power and a high moderating ratio, they have large neutron thermal diffusion lengths and therefore, we expect that small, local changes in packing fraction do not significantly alter the neutron spectrum within the calculational cell. Therefore, we anticipate that the transient is dominated by the global change in density and not by the small local variations. This assumption makes the microscopic cross section nearly constant. Re-writing Eq. 1 in terms that reflect explicitly the percentages of the constituent isotopes of cell k yields:

$$\Sigma_k^{\text{hom}} = \frac{M_k N_A}{V_k} \sum_{i=1}^{M} \frac{w_i}{100 M_i} \sigma_i \tag{2}$$

In the above equation

M_k = average mass in the kth calculation cell
V_k = volume of the kth calculation cell
N_A = Avogadro's number
w_i = weight percent of the ith isotope
M_i = atomic mass of the ith isotope

The parameters in Eq. 2 indicate that if the cross sections are constant and if the average mass (and composition) of the isotopic mixture is maintained within the calculational cell one can simply express the diffusion parameters after the earthquake in terms of their values prior to the earthquake. This is done using the ratio of the cell volumes before and after the earthquake according to the following approximations:

$$\Sigma_{k,new}^{\text{hom}} \approx \Sigma_{k,old}^{\text{hom}} \frac{V_{k,old}}{V_{k,new}} \tag{3}$$

and,

$$D_{k,new}^{\text{hom}} \approx D_{k,old}^{\text{hom}} \frac{V_{new}}{V_{k,old}} \tag{4}$$

Therefore, the essence of this new method is the determination of the new cell volumes as the earthquake progresses and changes the geometry of the core.

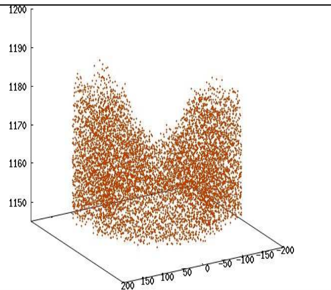
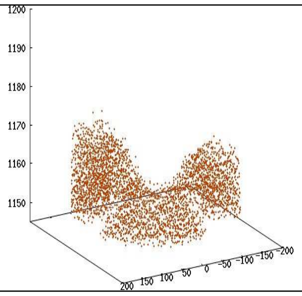
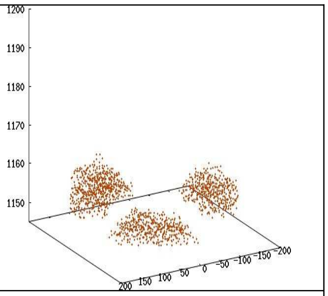
2.2 Determination of the Packing Fractions and Dynamic Re-meshing Data

The discrete element method code PEBBLES [5] is used to calculate the position of pebbles over the course of an earthquake. The forces used in the simulation include the weight of the pebble, a normal elastic contact force between pairs of touching neighboring pebbles, static friction, and velocity-related tangential and normal damping forces. The linear and angular velocities of the pebbles are calculated from the accelerations and torques caused by these external forces. A set of pebble maps, which specify the location of each pebble's center point, are obtained from the earthquake simulation [6, 7]. Table I shows how the slumping of the core reduces the core height during the postulated Idaho National Laboratory's (INL) design basis earthquake.

The PEBBLES simulation, which for this analysis starts with a randomly packed core, lasts 40 seconds and calculates a decrease in the core height of roughly 24 cm during the earthquake with a global packing fraction change of 1.7%.

These numbers agree well with the first analysis in Reference 3, which uses a global packing fraction change from 0.61 to 0.62 and calculates a core height drop of 17.7 cm. The difference in magnitude of the core height drop has to do with the fact that PEBBLE models explicitly the cones that form on the upper portion of the pebble bed as illustrated in Table I.

Table I. Top view of the PBMR-400 core during the earthquake simulation

			
Time [sec]	0.0	5.3	33.7
Pack. Fraction	0.6122	0.6145	0.6224
Core Height [cm]	1184.38	1171.31	1160.98

The code SHAKE is a data reduction program used to calculate the local and global packing fractions, as well as the core height distribution in R-Z geometry. Starting from a PEBBLES position map [7], the volume of each pebble is geometrically partitioned and each portion is assigned to the appropriate calculational cell. Figure 1 shows the calculated global packing fraction and core height as a function of time, as produced by SHAKE from input provided by the PEBBLES code.

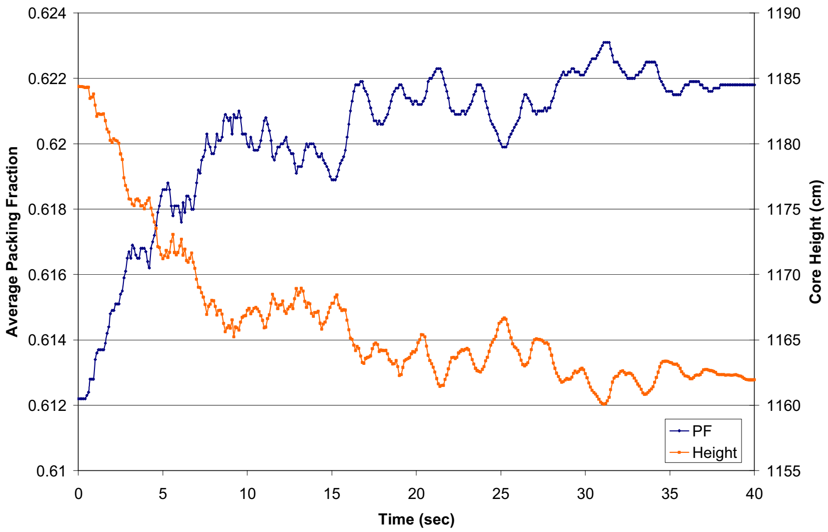


Figure 1. Variation of the packing fraction and core height during the PBMR-400 earthquake simulation (based on runs from Reference 7)

The SHAKE program also includes a module that performs the re-meshing of the core to obtain the new cell dimensions based on the pebble position maps provided by PEBBLES. The use of a nodal code in cylindrical (R-Z) geometry for the neutronic calculation restricts the re-meshing method to the use plane-averaged displacements in order to reposition the mesh lines as the average packing fraction changes near the plane. A set of radial and axial bands (δr, δz) are placed around the mesh for the determination of the radial and axial components of the material displacement vectors, as shown in Figure 2. Only pebbles that have their center point within the volume between the band and the mesh-line are used in the re-meshing calculation, since they determine the movement of the material between these mesh-lines. The axial and radial components of each plane are averaged and a new mesh line position is determined for all of the available time-dependent pebble position maps.

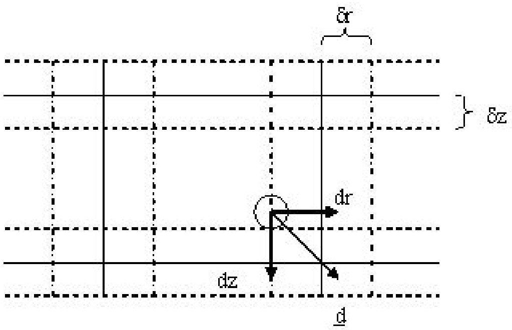


Figure 2. Re-meshing bands used to calculate the displacement vectors.

The calculations for the PBMR-400 design were performed on 26 axial cells of approximately 50 cm in horizontal depth and 5 radial cells of 17 cm radial extent. The location of the optimal bands changes during the calculation as the core density changes. A sensitivity analysis was performed that provided the optimal location of the bands for the first time steps, for which the rate of densification is highest. The re-meshing results are found to be quite sensitive to the location of the bands in the upper portion of the core where there is significant movement of the pebbles and low densification. Therefore, all pebbles are used in the re-meshing calculation of the two top nodes. The model used in the neutronic and thermal-hydraulic simulation has a flattened top and bottom regions since they contain the re-fueling cones and de-fueling chutes, respectively. This simplification is justified, since these regions are of relatively low importance in the neutronic calculation.

2.4. Modeling Parameters and Testing of the Method

The PBMR-400 model used is devised per the prescription of the OECD-PBMR-400 Benchmark Problem [8]. The model is built in cylindrical (R-Z) geometry with control rods represented as a homogeneous grey blanket. The transient starts from full power steady state conditions and the diffusion parameters are based on the 5-dimensional PBMR-400 benchmark library. This particular library does not accurately represent the randomly packed core needed for the earthquake analysis, since the benchmark library was developed assuming a global packing fraction of 0.61. In order to overcome this limitation, we approximate the initial cross sections for the randomly packed core using the ratio of the local packing fraction to the benchmark global packing fraction. The inverse of the packing fraction ratio is used for the determination of the initial diffusion coefficient. The same correction is employed throughout the calculation.

In order ascertain the level of fidelity (and accuracy) of the new volume weighting approximate method, a set of CYNOD static core eigenvalue calculations were performed at various times with both the ordinary approach of preparing diffusion data with a spectrum code (the “spectral” approach) and the volume weighting approximate approach. These calculations were performed at cold and hot temperatures without feedback. For the “spectral” data a set of diffusion parameters were generated with the code COMBINE-7.0 [9]. These lattice physics runs used the number densities provided in the PBMR-400 benchmark. For each time step, the initial set of number densities was modified to reflect the local packing fractions in the calculation cell. The modification was performed according to:

$$N_{i,m}^{n} = N_{i,m}^{PBMR} \frac{pf_m^n}{pf^0} + \delta N_{i,m}^{n}, \tag{5}$$

where,

$N_{i,m}^{n}$ = Number density of the i^{th} isotope in the k^{th} cell at time n

$N_{i,m}^{PBMR}$ = Number density of the i^{th} isotope in k^{th} cell from the PBMR benchmark

pf^0 = reference packing fraction from the PBMR benchmark (0.61)

pf_m^n = packing fraction in the k^{th} cell at time n

$\delta N_{i,m}^{n}$ = correction factor

Since the packing fraction ratio does not strictly conserve mass, a correction factor was added to ensure mass conservation. The average mass correction was less than 1%. For the volume-weighting scheme the diffusion parameters developed for the steady state configuration were modified per Equations 3 and 4.

2.5 Incorporation into the Coupled Neutronic-Thermal-Hydraulic Solver

The neutron kinetics code CYNOD [10] was modified to adjust dynamically the fuel zone geometry (areas and volumes) and the diffusion parameters at every time step for which re-meshing data were available. The diffusion parameters were modified according to Equations 3 and 4. The coupling between the neutronic and thermal-hydraulic components of the code uses an iterative scheme. The iterations between the neutronics and thermal-hydraulics are carried out until convergence is achieved for each time step. In order, to capture the relative withdrawal of the control rod, the CYNOD control rod model was modified to allow the control rod to remain static as the axial mesh-lines change position. Control rod-cusping is limited in CYNOD via re-homogenization of the diffusion theory parameters by mixing rodded and un-rodded zones using the Analytic Nodal Method (ANM) with Green's functions.

The re-meshing of control volumes was also captured in the thermal-hydraulics calculation, but local porosity factors were not used because of limitations in the number of material cards that could be specified. Instead, a global porosity factor for the pebble bed was used in the thermal-hydraulic model. Although a limitation, this approximation should not have a dominant effect on the analysis.

3. NUMERICAL RESULTS

3.1 Re-meshing Results

The axial re-meshing results from the SHAKE runs are depicted in Figure 3 for a selected number of time steps. Although the (local) changes to individual calculational cell dimensions are small, their cumulative effect amounts to a decrease in the core height of over 24 cm. As expected there is little movement in the bottom of the pebble bed, whereas the mid an upper portions experience significant movement.

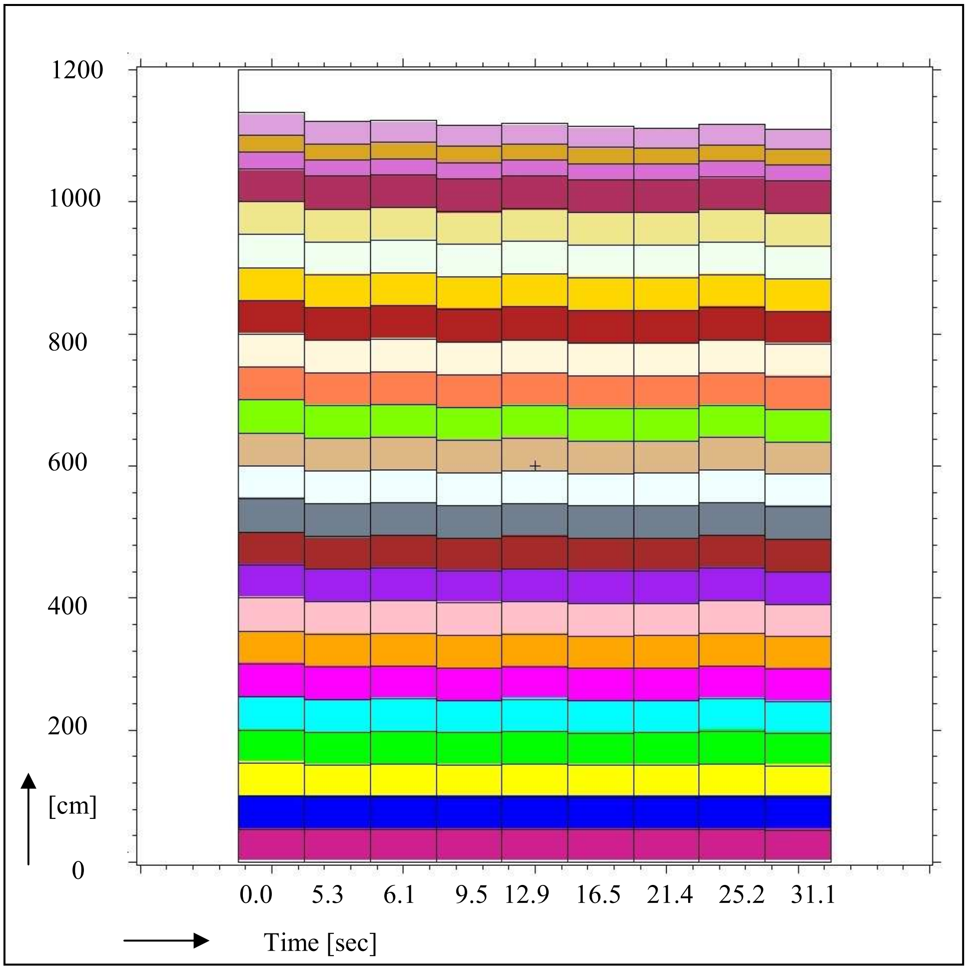


Figure 3. Variation of the axial mesh at various points in time

3.2 Testing of the Volume Weighting Method

Figures 4 and 5, for cold and hot un-rodded operating conditions, respectively, show that the results from the "spectral" and "approximate" methods are in good agreement for steady state calculations. The "spectral" results use re-computed cross sections based on the actual local packing fraction information, whereas the "approximate" results are based on using scaled diffusion theory data, per Equations 3 and 4.

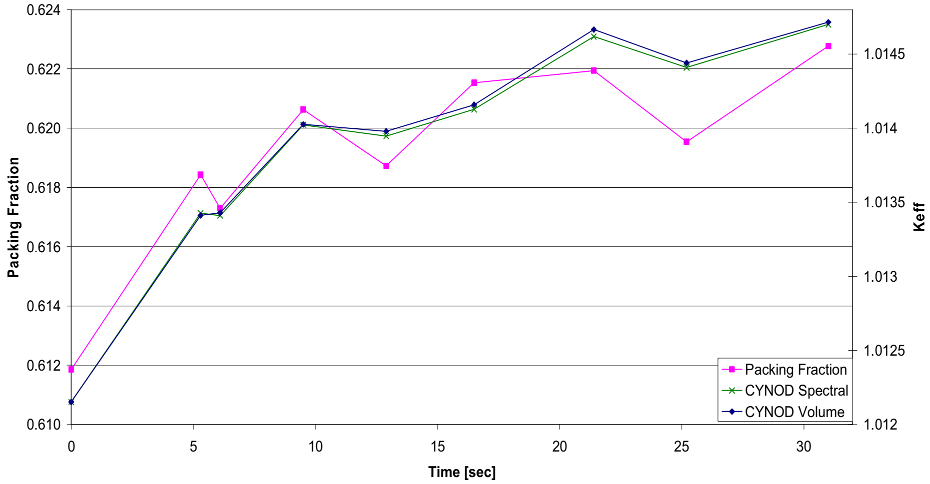


Figure 4. Comparison of the volume weighted and spectral calculations with cold operating conditions (T_{fuel} and T_{mod} 300K)

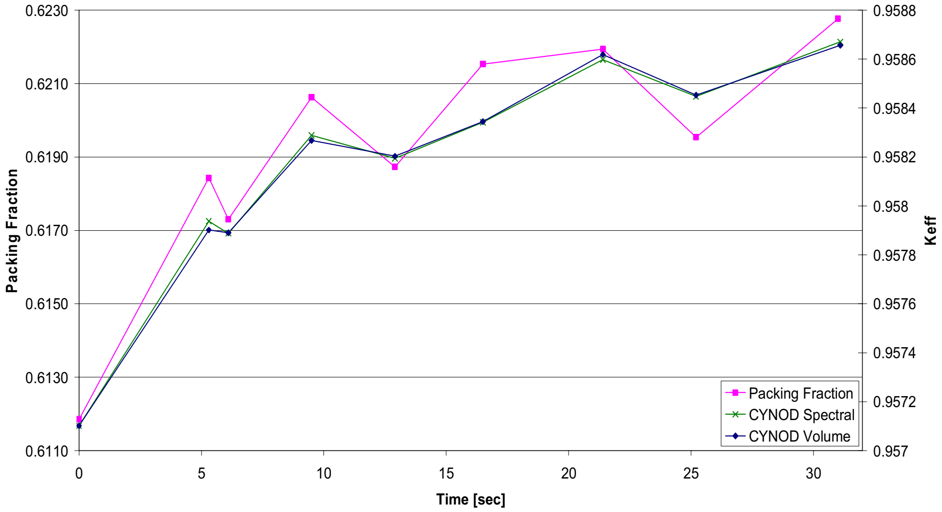


Figure 5. Comparison of the volume weighted and spectral calculations with hot operating conditions (T_{fuel} 1400 K, T_{mod} 1100 K)

The final reactivity insertions due to the densification of the core without feedback are approximately 37 and 27 cents, for the cold and hot cases, respectively. The reactivity value reported in Reference 3 was 60 cents, but it includes the reactivity insertions due to the withdrawal of the control rods. The volume-weighting scheme tends to underestimate the eigenvalue slightly; nevertheless, the difference in the two methods is less than one cent of reactivity worth. Consequently, the volume weighting scheme should yield acceptable results within the packing fraction domain studied for this transient.

3.3 Earthquake Coupled Neutronic-TH Simulation

Figure 6 shows the relative core power during the earthquake transient with thermal feedback. Two power profiles are included: one with and one without the control rods. During the first second of simulation small increases in the packing fraction produce enough negative Doppler feedback to start shutting down the reactor until the first significant increase in the global packing overcomes the negative feedback and produces a small power escalation. This first turnaround point is magnified with the control rod model since it also includes the additional insertion from the relative rod withdrawal. The magnitude of the reactivity insertions due to the control rods increases their relative position with respect to the core.

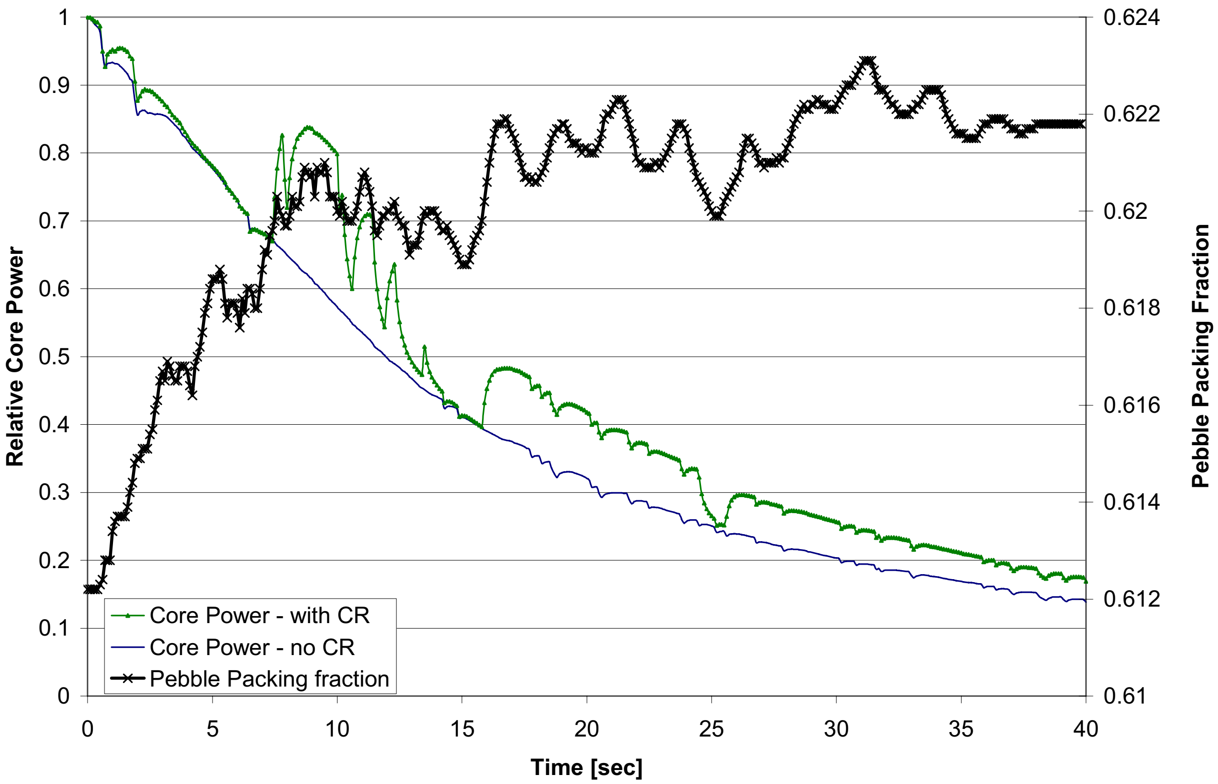


Figure 6. Core power profile during the earthquake transient for rodded and un-rodded conditions in the PBMR-400

A few other power increases are visible throughout the transient. These events demonstrate the fine balance between the negative reactivity insertions due to Doppler feedback and the positive reactivity insertions due to densification and the relative control rod withdrawal during the event.

There are still unexplained portions of the power profile near 40 seconds where the power is fluctuating when the packing fraction seems to have stabilized. These oscillations could be the result of a number of effects including temperature feedback, coolant flow feedback, etc.

In addition, the treatment of the control rods still seems to exhibit cusping behavior 10 seconds into the transient. At the end of the 40 sec transient the controlled model is at a higher core power than the non-controlled model, as expected, since more reactivity is inserted due to the relative control rod withdrawal. Figure 7 shows how both the average fuel and moderator temperatures approach the same asymptotic value expected for a slow transient. The average fuel temperature and power fluctuations are in good agreement and represent well the strong negative fuel temperature feedback of this reactor.

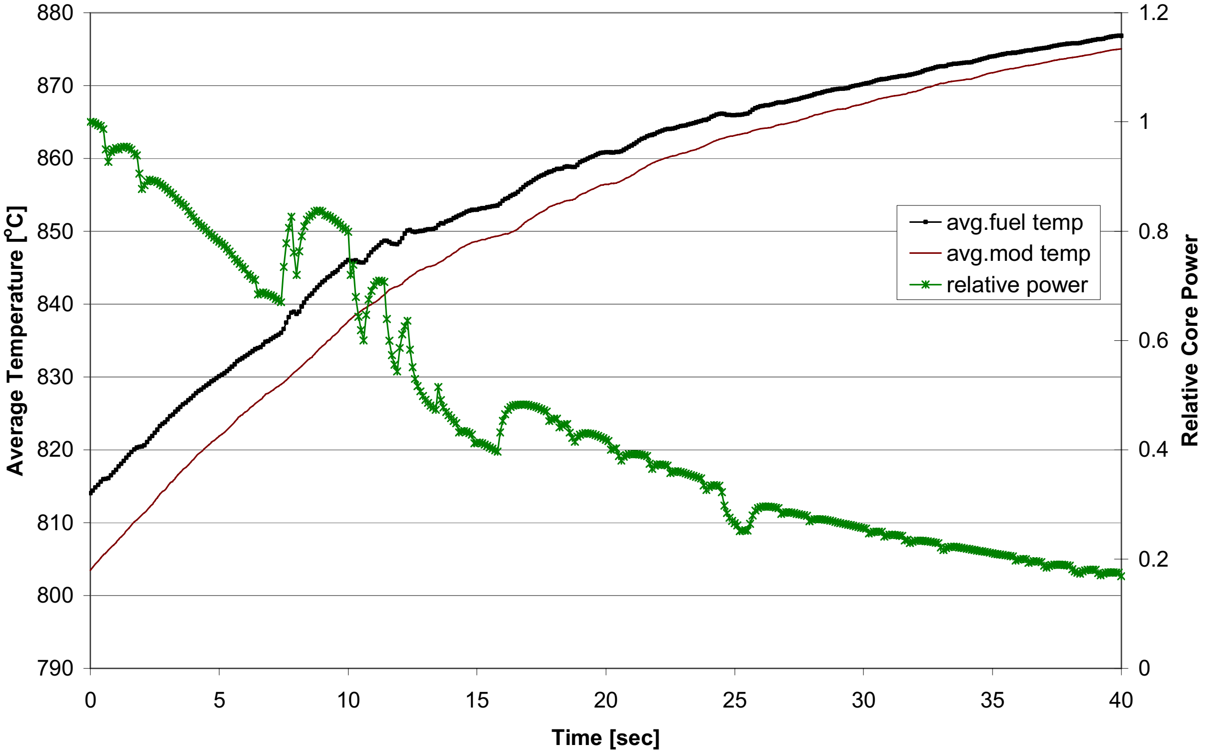


Figure 7. Fuel and moderator temperatures during the earthquake transient in the PBMR-400

4. CONCLUSIONS

A method has been presented that dynamically analyzes the safe shutdown earthquake event for a pebble bed reactor. The method is based on a simple volume-weighting scheme that is possible because of the neutronic characteristics of HTGR's. The large thermal diffusion lengths in these cores allow simplifications and the avoidance of a massive computational effort for the re-calculation of the diffusion theory parameters during core densification. The implementation of the method is also straightforward and only requires small modifications to an existing nodal code. The new method relies on the availability of pebble mechanics data to determine the re-meshing of the computational grid. In this work the PBMR-400 design was analyzed. It was shown that the strong Doppler feedback of the design safely shuts down the reactor. The small power fluctuations that occur during the power down suggest a delayed-super-critical condition. Some of the unexplained power oscillations could be a consequence from a number of phenomena including temperature and coolant flow feedback. The use of time dependent modeling of the thermal hydraulic effects with local porosity changes is recommended for future work. This would have to include detailed CFD calculations that could capture how these local changes to the porous media model affect the closure models.

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