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PEBBED ANALYSIS OF HOT SPOTS IN PEBBLE-BED REACTORS

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ABSTRACT

The Idaho National Laboratory's PEBBED code and simple probability considerations are used to estimate the likelihood and consequences of the accumulation of highly reactive pebbles in the region of peak power in a pebble-bed reactor. The PEBBED code is briefly described, and the logic of the probability calculations is presented in detail. The results of the calculations appear to show that hot-spot formation produces only moderate increases in peak accident temperatures, and no increases at all in normal operating temperatures.

KEYWORDS: Pebble-bed reactors, hot spots, PEBBED

1. INTRODUCTION

In pebble-bed reactors, pebbles are dropped in at the top, and a mound develops below each drop point. The pebbles roll off the mounds until they reach stable positions, and then they move downward in an essentially axial direction. However, some radial wandering is expected, and the stable position on the top from which any pebble begins its downward course is somewhat randomly determined. These stochastic processes generate concern about the possibility that "hot spots" may develop, where clusters of highly reactive pebbles may form in regions of high thermal neutron flux, so that excessive heat generation might occur locally.

This paper reports studies with the Idaho National Laboratory (INL) pebble-bed reactor (PBR) physics and fuel management code PEBBED[1] on the consequences of the formation of such clusters, and it presents estimates of the probability that clusters of different sizes will occupy locations of peak fission power. From these calculations, it is argued that the formation of hot spots has only a minor influence on the course of loss-of-coolant accidents, and no influence at all on normal operations.

2. THE PEBBED CODE, MODEL, AND RESULTS

As explained in Reference [1], for a PBR with a flowing core, PEBBED obtains simultaneous solutions in steady state of the neutron diffusion equation and the nuclide concentration equations directly, without tracking the evolution of the steady state in time. PEBBED has been under development at the INL since 1999, and it has grown in sophistication throughout this time. A paper in this conference[2] presents validation studies of an *r-z* cylindrical version of PEBBED, in which the diffusion equation is solved by finite-difference or analytical nodal techniques.

PEBBED also solves the three-dimensional diffusion equation in using a finite difference technique and a nodal solution in cylindrical geometry is being implemented. However, the three-dimensional nodal version of PEBBED is not yet operational, and since the hot-spot analysis requires a three-dimensional treatment, we applied the r-θ-z version of PEBBED in which the diffusion equation is solved by finite differences.

PEBBED offers two thermal analysis options for the calculation of temperatures in steady state and also in loss-of-coolant accidents. One is a simple one-dimensional (radial) conduction module, and the other is the THERMIX-KONVEK code, which has been grafted into PEBBED.

PEBBED can model arbitrary pebble circulation schemes, with several different pebble types (e.g., fuel pebbles and dummy pebbles). It can also be run by a genetic algorithm for design optimization, although that option was not needed for this study.

PEBBED was applied to a PBR design that was developed during the "point design study" of the "Next Generation Nuclear Plant" (NGNP), a prototype high-temperature gas-cooled reactor proposed for construction at the INL[3]. This NGNP core is annular, with inner and outer radii of 40 cm and 175 cm, respectively, and a height of 940 cm. It produces 300 MW of thermal power. On average, each pebble makes 11 passes through the core before it is discarded for excessive burnup.

The simple one-dimensional thermal analysis option was used to calculate temperatures. The peak fuel temperature in steady-state operation is 1151 °C, and the peak fuel temperature in a depressurized loss-of-flow cooldown accident (DLOFC) is 1580 °C.

In a zone of varied extent at the radial and axial location of peak power, the steady-state composition was replaced by a composition representing pure fresh fuel. In reality, such an arrangement is impossible, because pebbles on their first pass through the core will sustain some burnup before they reach the axial location of the peak. However, this representation is conservative and approximately represents a hot spot. Because the thermal conductivity of the pebbles is high, the fuel temperature in a pebble in normal operation is determined by the coolant temperature at the pebble surface. Therefore, the peak fuel temperature in all cases in normal operation is unchanged from the unperturbed value of 1151 °C. Table 1 shows the peak fuel temperatures in a DLOFC accident for hot spots of various volumes. The effective volume of one pebble (packed at a packing fraction of 61%) is 185.4 cm^3, which leads to the nearest integral numbers of pebbles shown next to the hot-spot volumes in the table.

A clump of two fresh pebbles was analyzed in an approximate fashion by replacing the mixed and depleted composition in a small sector of the PEBBED model with a composition corresponding to fresh pebble nuclide densities. This is an unexpectedly small clump; however, even very large clumps of fresh fuel (e.g., 46 pebbles) are seen not to raise the peak DLOFC temperature very far above the limit. Studies indicate that significant fission product release occurs only after the silicon carbide layer exceeds a temperature of 2000 °C.[4]

Table 1. PEBBED Results for DLOFC Peak Temperatures

CASE	Peak Power (W/cm^3)	Peak DLOFC temp (°C)	Volume of clump (cm^3)	Number of pebbles in clump
Nominal	7.38	1580	NA	NA
1	10.0	1613	350	2
2	10.1	1617	700	4
3	10.1	1636	3389	18
4	10.1	1637	4519	24
5	10.1	1638	5649	30
6	10.1	1641	8473	46

3. PROBABILITY OF HOT-SPOT FORMATION

In this section, an estimate is given of the probability that a clump of pebbles would occupy the region of peak power during a DLOCF accident. Only three clump sizes are considered: two, four, and 18 pebbles. A two-pebble clump is a baseline, at which the peak DLOFC temperature only slightly exceeds the limit, so that no adverse consequences would occur. The four-clump pebble produces a small excess temperature (17 °C), but its probability of occurring at the peak-power location is small. The probability of occurrence of an 18-pebble clump, which still produces a modest temperature excess, is so small that it is pointless to consider even larger clumps, which would be even more improbable.

If N is the number of pebbles in the core, the number of ways in which clumps of n pebbles may be formed is given by [5]

$$C_N^n = \frac{N!}{n!(N-n)!} \qquad (1)$$

A similar expression may be written for clumps of n fresh pebbles, of which there are N_o in the reactor (in the chosen NGNP design, $N_o/N=1/11$). Then the probability that any arbitrarily chosen clump of n pebbles is all fresh is

$$P_{fresh}^{n} = \frac{\dfrac{N_o!}{n!(N_o-n)!}}{\dfrac{N!}{n!(N-n)!}} = \frac{N_o!}{(N_o-n)!}\frac{(N-n)!}{N!} \tag{2}$$

For small values of n and large values of N_o and N, Eq. 2 is readily evaluated as

$$P_{fresh}^{n} = \frac{N_o(N_o-1)...(N_o-n+1)}{N(N-1)...(N-n+1)} \approx \left(\frac{N_o}{N}\right)^n \tag{3}$$

The probability that any particular clump of pebbles will occur in the hottest region of the core is simply the fraction of the core occupied by that hottest region. It is seen in detailed thermal calculations of annular PBR cores that the power is near the peak in a zone occupying about 10% of the core height and 20% of the annular thickness at a location in the core near the interface between the core and the inner reflector.[6] For a core of inner and outer radii a and b, with a hot region extending from the inner reflector surface to a radius R and occupying a fraction c of the height, the fraction of the core occupied by the hot region is

$$P_v = \left(\frac{b-a}{b+a}\rho^2 + \frac{2a}{b+a}\rho\right)c\,, \tag{4}$$

where ρ is the fraction of the annular thickness; i.e.,

$$\rho = \frac{R-a}{b-a} \tag{5}$$

The number of clumps of n fresh pebbles that will be found in the hot region, on average, may be found as

$$N_f^{hz} = \frac{\#\ of\ fresh\ clumps\ in\ hot\ zone}{\#\ of\ clumps\ in\ hot\ zone}\frac{\#\ of\ clumps\ in\ hot\ zone}{\#\ of\ clumps\ in\ core}\#\ of\ clumps\ in\ core \tag{6}$$

The ratio of the number of fresh clumps in the hot zone to the total number of clumps in the hot zone is the same as the ratio of the fresh and total clumps in the whole core, i.e., P_{fresh}^{n}. The ratio of the number of clumps in the hot zone to the number of clumps in the core is the volume ratio given in Eq. 4. The number of clumps in the core is equal to N/n, the number of pebbles in the core divided by the number of pebbles in a clump. Therefore,

$$N_f^{hz} = P_{fresh}^{n} P_v N / n \tag{6}$$

This quantity is given in Table 2 for the three values of n being considered. For the NGNP model used in this study, the active core volume is 87.5 m^3, which implies that there are about

470,000 pebbles in the core. The average pebble makes 11 passes through the core, so that (N_o/N)=1/11. The core dimensions are given in Section 2, while R=0.2 and c=0.1.

Table 2. Number of n-Fresh-Pebble Clumps in Hot Zone of 300 MWt NGNP PBR

n	P^n_{fresh}	P_v	N/n	N^{hz}_f
2	8.26E-3	9.95E-3	235,000	19
4	6.83E-5	9.95E-3	117,500	7.98E-2
18	1.799E-19	9.95E-3	26,111	4.67E-17

4. CONCLUSIONS

In Table 2, it is seen that clumps of two fresh pebbles are likely to be always present in the hot region of the core, but the peak fuel temperature in a DLOFC event only slightly exceeds the established limiting value of 1600 °C in a two-pebble clump. The number of four-pebble all-fresh clumps in the hot zone is less than 0.1; this number can be interpreted to mean that a four-pebble all-fresh clump is likely to appear in the hot zone less than 10% of the time. A large agglomeration, such as an 18-pebble all-fresh clump, is extremely unlikely; yet even if it did occur, the peak fuel temperature in a DLOFC event would be only moderately above the limiting value.

Furthermore, the agglomerations of all-fresh pebbles, even if they involve at least as many as 46 pebbles, do not cause discernible increases in peak fuel temperature in normal operating conditions.

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