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**Monte Carlo Calculations
of Control-Rod Worth of a
Medium-Size Pebble-Bed Reactor**

J. S. Tang
B. A. Worley

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Engineering Physics Division

MONTE CARLO CALCULATIONS OF CONTROL-ROD WORTH
OF A MEDIUM-SIZE PEBBLE-BED REACTORJ. S. Tang*
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ABSTRACT

Three-dimensional full-core control-rod worth calculations by the Monte Carlo method are performed for a 1640 MWth pebble-bed reactor. The worths of all control rods at several insertions are investigated. The reactivity provided by the control rods in the 1-meter void above the core is about 3% and a 20% negative reactivity can be obtained by axially inserting all control rods 3/4 into the reactor core.

The multigroup KENO Monte Carlo code with a six-group neutron cross-section library was used in the calculations.

I. INTRODUCTION

The Pebble-Bed High-Temperature Gas-Cooled Reactor has been undergoing development in the Federal Republic of Germany for over a decade.¹ The fuel elements of the reactor are small pebbles having a diameter of 6 cm. The inner zone of the fuel elements contains a mixture of coated fuel particles and graphite and is surrounded by an outer shell of graphite cladding. During operation, the pebbles are continuously fed at the top and discharged at the bottom of the reactor. The pebbles are randomly distributed in the core and cooled by a downward flow of helium gas. The cylindrical core is surrounded by graphite reflectors with a void between the top reflector and the fuel. Reactivity control and shutdown capability are provided by control rods which penetrate through the top reflector into the upper void and the fuel pebbles.

The purpose of this study is to calculate the control-rod worth of a pebble-bed reactor using the Monte Carlo method and the Monte Carlo Perturbation Source Method.² The calculations were performed using the KENO-IV Monte Carlo code³ with a six-group neutron cross-section library.

II. CALCULATIONAL MODEL

The reference reactor used in this study is the 1640 MW_{th}, continuously fueled pebble-bed reactor proposed in Germany. Pertinent reactor design data is presented in Table 1.

For reactivity calculations, the reactor was assumed to be operating at equilibrium. The fuel pebbles and the space between pebbles were homogenized, and the fuel distribution was treated using 18 axial fuel zones to describe the axial variation in fuel burnup. The reactor was first modeled in two-dimensional R-Z geometry as shown in Fig. 1. A diffusion theory calculation was performed to obtain the equilibrium state using the VENTURE code system.⁴ The upper void and the top reflector, with a 1/v absorber to represent the control rods, were homogenized in the VENTURE calculation because diffusion theory cannot properly treat the large void region above the core. A transport calculation was also performed for this model using the DOT-IV discrete ordinates code⁵ for the purposes of cross-section data checking and comparing of diffusion and transport theory results. Once compatibility of data was assured, the upper void, the top reflector with a smeared 1/v absorber, and a central rod were represented explicitly in a discrete ordinates calculation using R-Z geometry. This central rod problem was chosen as a benchmark against which a three-dimensional representation using Monte Carlo could be compared on an exactly equivalent basis. Results of the diffusion and transport theory calculations are shown in Table 2 along with results of the three-dimensional Monte Carlo calculation.

A three-dimensional model of the reactor with all 85 control rods represented explicitly (corresponding to 1 rod/1.57 m²) was set up for the KENO calculations. The top view of this geometry is shown in Fig. 2. Because of the limitation of the KENO geometry in describing the control rod pattern, the side surfaces of the core and side reflector were approximated by a saw-tooth pattern where the cross-sectioned areas of the core and reflector were preserved. The control rods are cylindrical tubes having B₄C absorber imbedded in iron walls. For convenience of modeling, the bottoms of the rods were left open. Details of the control rod dimensions are shown in Table 1. Results of the total control rod worth as a function of rod insertion are presented in Table 3. The control rod worths in the upper void region, calculated by the direct method and the perturbation source method, are shown in Table 4. It should be noted that a perturbation source calculation consists of a direct k_{eff} calculation of the "unperturbed state" and a Δk_{eff} calculation due to the perturbation. Hence the first part of the perturbation source calculation is exactly equivalent to a direct calculation of the "unperturbed state". Between the two perturbation source calculations in Table 4, case II should be an improvement over case I because in case II more importance regions were implemented and more adjoint particles were allowed for Δk_{eff} estimation.

Table 1. Data of the Reference Pebble-Bed Reactor

Reactor Core

Power (MW _{th})	1640
Power density (w/cm ³)	5.511
Active core height (m)	5.50
Active core radius (m)	4.15
Volume fraction of pebbles	0.61

Reflectors

	<u>Top</u>	<u>Bottom</u>	<u>Radial</u>
Thickness (m)	1.0	1.0	1.0
Graphite density (gr/cm ³)	1.40	1.40	1.60
Upper void (m)	1.0	-	-

Pebble Design

Diameter (cm)	6.0
Graphite shell thickness (cm)	0.5
Graphite density (gr/cm ³)	1.70

Coated Particle Design

Kernel material	U/ThO ₂
Kernel diameter (μm)	400
Kernel density (gr/cm ³)	9.50
Uranium enrichment (%)	0.93
Graphite coatings, thickness (μm)	85/30/80
Graphite coating density (gr/cm ³)	1.0/1.6/1.85

Control Rod Model

Inner region (Helium) outer radius (cm)	3.5
Inner iron outer radius (cm)	4.5
B ₄ C absorber outer radius (cm)	5.5
Outer iron radius (cm)	6.5

Fig. 1 Two-dimensional R-Z model of the pebble-bed reactor

Table 2. Calculated Results of R-Z Model

	VENTURE	DOT-IV			KENO	
		A	B	C	Direct	Perturbation
Top reflector, absorber, and void representation	smeared	smeared	explicit ^a	explicit ^a	explicit ^a	explicit ^a
Central control rod insertion	no	no	bottom of top reflector	bottom of core	bottom of top reflector	bottom of core
k_{eff}	0.9911	0.9867	0.9790	0.9736	0.9780 (± 0.0018)	0.0041 ^b (± 0.0037)
CPU (IBM 3033 min.)	2.0	58.0	71.7	70.5		85.8

^a Except for the central rod all other rods are represented by a smeared 1/v absorber in the top reflector.

^b This is the k_{eff} between the two central rod insertions.

^c One standard deviation.

Fig. 2 Top view of the three-dimensional pebble-bed reactor model

Table 3. Reactivity Worth of All 85 Control Rods in a 1640
MW_{th} Pebble-Bed Reactor

Case identification	Rod position, cm (0.0 = top of bed)	k_{eff}	Number of histories	CPU minutes (IBM 3033)
A	+200.0 (out of top reflector)	1.01598 $\pm 0.00139^b$	150,000	103.8
B	+100.0 (out of void, in top reflector)	0.99506 ± 0.00189	90,000	57.8
C	0.0 (top of bed)	0.96175 ± 0.00176	90,000	111.9 ^a
D	-93.5 (into 3 fuel zones)	0.91734 ± 0.00157	90,000	57.0
E	-187.0 (into 6 fuel zones)	0.88680 ± 0.00116	150,000	104.5
F	-405.2 (into 13 fuel zones)	0.80388 ± 0.00127	150,000	105.9

^a This is a perturbation source calculation for control rod movement out of upper void.

^b One standard deviation.

Table 4. Reactivity Worth of All Control Rods in the Upper Void Region

Calculational Method	Δk_{eff} due to rods withdrawn out of the upper void	Number of histories	CPU minutes (IBM 3033)
Direct calculation	0.0331 ± 0.00258^a	180,000	169.7
Perturbation source calculation			
I	0.02555 ± 0.00121	90,000	111.9
II	0.02740 ± 0.00135	90,000	142.5

^a Obtained by subtracting k_{eff} of case C from that of case B in Table 3.

For the three cases where the control rods penetrated into the core, the heights of the affected fuel zones were increased to maintain constant volumes of the fuel zones. The starting source distribution for all the Monte Carlo calculations in Tables 2, 3, and 4 was derived from the fission density of the DOT calculation which had the central control rod and the smeared $1/v$ absorber in the top reflector. This distribution provided an averaged source distribution as a function of the fuel zone and assumed a uniform distribution within each fuel zone. Presented in Table 5 is the normalized starting source distribution employed in the Monte Carlo calculations. Note that this distribution peaks around the top few fuel zones and drops off rapidly toward the bottom of the core. This is due to the higher enrichment of the fresh fuel which is being fed continuously into the top of the reactor.

The six-group neutron cross-section data were generated from a 123-group library using the XSDRNPM module of the AMPX code system.⁶ The resonance self-shielding calculation of the fine group library was performed using the NITAWL module in AMPX. More detailed descriptions of the cross-section treatment can be found in Ref. 7. Table 6 presents the energy boundaries of the six-group cross-section library used in this study.

Table 5. Normalized Starting Source Distribution for Monte Carlo Calculations

Fuel Zone	Probability Density
1	0.1417
2	0.2180
3	0.1962
4	0.1526
5	0.1090
6	0.0676
7	0.0436
8	0.0273
9	0.0164
10	0.0109
11	0.0065
12	0.0039
13	0.0025
14	0.0015
15	0.0010
16	0.0006
17	0.0004
18	0.0002

Table 6. Energy Group Structure of the Six-Group Neutron Library

Energy Group	Upper Energy Boundary (eV)
1	1.492+7*
2	1.832+5
3	5.829+2
4	7.889+1
5	1.068+1
6	1.855+0
	5.000-3

* Read as 1.492×10^7 .

III. DISCUSSION OF RESULTS

The results of this study are summarized in Tables 2, 3, and 4. For the R-Z reactor model in Table 2, a general agreement in k_{eff} was obtained between the diffusion and S_n transport calculations for the case where the top reflector, control rods, and upper void were homogenized. Excellent agreement was obtained between the S_n transport and direct Monte Carlo calculations of central rod insertion into the top reflector. The Monte Carlo perturbation source calculation predicted the central rod worth of 0.0041 with a very large uncertainty. This Δk_{eff} is 24% lower than that calculated by S_n transport theory.

The results in Table 3 have demonstrated that accurate three-dimensional full-core control rod worth calculations by the Monte Carlo method are not only possible but also practical. It was found that the number of histories required to obtain meaningful results was quite large for this large, thermal reactor. Furthermore, from Cases A, E, and F in Table 3 it is evident that the starting source distribution played a very important role in determining the number of histories required to achieve convergence of the fundamental mode in k_{eff} calculations. The results in Tables 3 and 4 indicate that the reactivity worth of the control rods in the upper void is about 3% and as much as 20% worth can be obtained by control-rod insertion of 3/4 into the reactor core. Finally the Δk_{eff} 's calculated by the Monte Carlo perturbation source method are significantly lower than that by the direct method.

IV. CONCLUSIONS

Three-dimensional full-core control-rod worth calculations by the Monte Carlo method have been performed. For the medium-size (1640 MW_{th}) pebble-bed reactor, the control rods are worth about 3% in reactivity in the upper void and worth as much as 20% at 3/4 full-core insertion. Lastly, the applicability of Monte Carlo method to full-core three-dimensional models is shown to be practical, but the use of the Monte Carlo perturbation source method to this problem is not recommended.

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