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**Idaho National Laboratory  
Idaho Falls, Idaho 83415**

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# Evaluation of Control Rod Designs for a Potential Configuration of the Versatile Test Reactor

Abdalla Abou-Jaoude,\* Gilles J. Youinou\*

\*Idaho National Laboratory, 2525 Fremont Ave., Idaho Falls, ID 83402, [abdalla.aboujaoude@inl.gov](mailto:abdalla.aboujaoude@inl.gov)

## INTRODUCTION

Different Versatile Test Reactor (VTR) configurations are being explored as a means to provide fast neutron irradiation capabilities. One possible core configuration is outlined Fig. 1. The VTR would be designed to rely on two control systems, one for mitigating excess reactivity (control rods, CR) and another for emergency shutdown (safety rods, SR). The most limiting design criteria is to ensure sufficient reactivity worth margin with the most active control assembly stuck (N-1). This corresponds to 4,245 pcm for the CR and 1,245 pcm for the SR respectively.

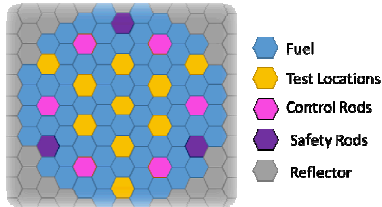


Fig. 1. VTR preliminary core layout highlighting control and safety rod locations.

Boron carbide ( $B_4C$ ) was selected as the absorber material, as is typical in fast reactors. Usually, 7 [1] to 61 [2] pins tend to be hexagonally arranged with varying  $^{10}B$  enrichments and maximum burnup levels. [3,4] While it may be advantageous to maximize  $B_4C$  volume, this can bring other drawbacks. The main purpose of the analysis is to identify optimal volume fractions balancing the different criteria. TABLE I highlights the range of layouts considered; two of which are illustrated in Fig. 2.

TABLE I. The different control rod numbers per assemblies.

Case	CR61	CR37	CR19	CR7
Rod rings	5	4	3	2
$B_4C$ diameter (cm)	0.87	1.19	1.78	3.12
$B_4C$ vol. fraction	26.04%	29.72%	34.21%	38.61%
$B_4C$ (SA)/V	4.63	3.38	2.27	1.31

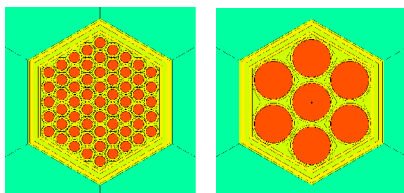


Fig. 2. Control rod layouts CR61 (left) and CR7 (right).

## ANALYSIS AND SIMULATIONS

### Control Rod Reactivity Worth

The first step in the analysis is to compare the control rod worth of different CR configurations. A starting  $^{10}B$  enrichment of 48% (based on [4]) was selected. MCNP6 was used for the analysis, [5] with results shown in TABLE II. All cases meet the N-1 requirement, with CR61 the closest to the limit. Iterations were conducted to identify the axial position corresponding to around 2,500 pcm worth. The results in each case only varied by a few cm. Similar evaluations were conducted for the SR, with SR61 closest to the N-1 limit and the all-inserted criteria ( $>1,965$  pcm).

TABLE II. Control and Safety rod with 48%  $^{10}B$ . Average reactivity standard deviation is approximately 23 pcm.

Case	CR61	CR37	CR19	CR7
All 6 inserted (pcm)	7117	7730	8403	8948
Worth/kg- $B_4C$ (pcm/kg)	181	172	163	154
N-1 reactivity (pcm)	5769	6243	6748	7200
2,500 pcm insertion (cm)	33.6	31.4	30.1	28.8
N-1 partial insertion (pcm)	1970	1984	2027	2064
	SR61	SR37	SR19	SR7
All 3 inserted (pcm)	2401	2590	2722	2957
Worth/kg- $B_4C$ (pcm/kg)	181	172	163	154
N-1 reactivity (pcm)	1528	1671	1794	1892

A  $^{10}B$  enrichment search was conducted to identify the most ideal composition of each CR design. A target of 8,000 pcm was set to provide sufficient margins. CR7 was found to require 20 percentage points less enrichment than CR61. End-of-life (EOL) reactivity worth was also evaluated in all three cases. This was done by assuming that a total of  $1.5 \times 10^{22}$  cap/cc occurred in the form of  $^{10}B(n,\alpha)^7Li$  reactions. The resulting difference with beginning-of-life (BOL) illustrates how the cases with larger volume fractions see the steepest drop in reactivity worth.

TABLE III. Control Rod boron enrichment search to reach a target of  $\sim 8,000$  pcm, and reactivity loss at EOL.

Case	CR61	CR37	CR19	CR7
$^{10}B$ enrichment	60.5%	51.4%	44.7%	39.1%
EOL pcm reduction	-1050	-1308	-1510	-1782

## Control Rod Heat Generation

Another limitation to control rod design is internal heating, notably due to  $(n,\alpha)$  reactions. Heat production exponentially increases inside the core as shown in Fig. 3. Gamma heating was found to be non-negligible in Fig. 4, contributing up to 7% of the total. Non- $(n,\alpha)$  neutron reactions are even more significant, contributing up to 20%. This includes neutron scattering and  $^{11}\text{B}$ -reactions. The analysis was repeated for each case (see TABLE IV).

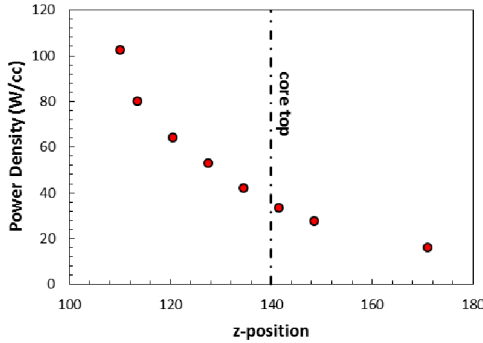


Fig. 3. Axial evolution of power generation inside CR7 with 39% enrichment and inserted 30 cm into the core.

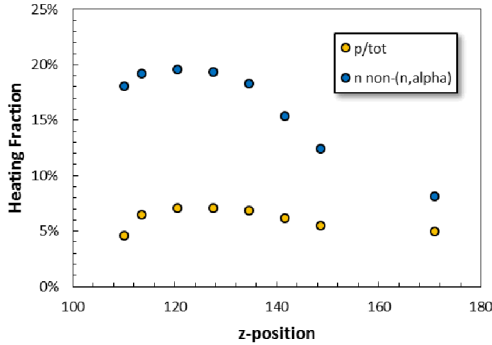


Fig. 4. CR7 heat generation from non- $(n,\alpha)$  reactions.

Because of the optimized enrichment, heat generation does not vary greatly between each design. Small increases with  $\text{B}_4\text{C}$  volume fraction can be mostly attributed to non- $(n,\alpha)$  sources of heating (e.g.  $^{11}\text{B}$  reactions). Flux depression is more pronounced with increasing number of pins due to self-shielding effects.

TABLE IV. Heat generation metrics for 30 cm insertion.

Case	CR61	CR37	CR19	CR7
Boron enrichment	60.5%	51.4%	44.7%	39.1%
CR worth (pcm)	2391	2396	2476	2442
Peak heat gen. (W/cc)	96.71	97.99	100.48	102.47
Peak $(n,\alpha)$ ( $10^{14}$ cap/cc)	2.10	2.09	2.10	2.11
Gamma heating frac.	3.1%	3.6%	4.1%	4.6%
Flux ( $10^{15}$ n/cm <sup>2</sup> -s)	1.31	1.50	1.72	1.93

The centerline temperature inside the pins was estimated using Equation 1. Heat generation was fixed at 115 W/cc accounting for 15% overpower conditions.

$$T_{\text{B}_4\text{C}} = T_{\text{Na}} + q' \left[ \frac{1}{2\pi R_{\text{co}} h} + \frac{1}{2\pi k_{\text{cl}}} + \delta + \frac{1}{4\pi k_{\text{B}_4\text{C}}} \right] \quad (1)$$

The thermal conductivity of the clad ( $k_{\text{cl}}$ ) and boron carbide ( $k_{\text{B}_4\text{C}}$ ) was taken to be 0.26 and 0.04 W/cm-K respectively. The gap thermal resistance ( $\delta$ ) was ignored for the purpose of this study. A heat transfer coefficient ( $h$ ) of 5 W/cm<sup>2</sup>-K was assumed. The resulting temperature values are reported in TABLE V. Ample margins to  $\text{B}_4\text{C}$  melting were reached in all cases ( $T_{\text{melt}} = 2763^\circ\text{C}$ ). CR7 had the smallest margin (at only  $401^\circ\text{C}$ ), and represented a  $1273^\circ\text{C}$  temperature jump relative to the next nearest case (CR19).

TABLE V. Estimates of peak boron carbide temperatures.

Case	CR61	CR37	CR19	CR7
Heat gen. (W/cc)	115	115	115	115
Linear power (W/cm)	72	135	304	930
$T_{\text{Na}}$ ( $^\circ\text{C}$ )	450	450	450	450
$T_{\text{clad-in}}$ ( $^\circ\text{C}$ )	466	472	484	512
$T_{\text{boron-center}}$ ( $^\circ\text{C}$ )	609	741	1089	2362

## CONCLUSION

Different control rod layouts were investigated for a conceptual configuration of the Versatile Test Reactor (VTR). Reducing the number of rods per assembly increases the  $\text{B}_4\text{C}$  volume fraction, thus increasing reactivity worth. Doing so also reduces the melting margin inside the pellets and the reactivity loss at EOL. As a result, the two most extreme cases, CR61 and CR7, were deemed less favorable. Overall, CR19 was found to have sufficient safety margins with the second best reactivity worth. The design only required a 44%  $^{10}\text{B}$  enrichment to reach the conservative margins put forward. The arrangement is recommended for both the control and safety rods of the VTR.

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