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APAE-Memo-15

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COMPARISON OF BORON AND HAFNIUM IN APPR CONTROL RODS

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APRIL 26, 1956

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COMPARISON OF BORON AND HAFNIUM IN APPR CONTROL RODS

INTRODUCTION:

There is a possibility of dimensional instability in the B-10-iron APPR-1 control rods due to helium production. This effect will be evaluated following the irradiation of B-10-iron samples in the MTR. It has been proposed that hafnium be considered as an alternate control rod material, should the present rods appear unsatisfactory.

This report is a comparison of the B-10-iron rod, with a hafnium rod. Initial blackness will be considered, and burnup through the 15 megawatt year core life. The basis for the analysis is the relative blackness of rods using the two materials. Variations other than blackness are best evaluated experimentally.

METHOD:

The difference between boron and hafnium as neutron absorbing materials is primarily due to the variation of their absorption cross section with neutron energy. B-10 has a $\frac{1}{v}$ cross section, and is most effective for thermal neutrons. H_f has a small thermal cross section relative to B-10, but a large resonance cross section. In order to illustrate this difference, the analysis is performed using 2 energy groups of neutrons. The thermal group is assumed to have a Maxwellian distribution, at 450° F. The resonance group is assumed to be a $\frac{1}{E}$ spectrum down to .4 ev. ⁽¹⁾ The relative magnitudes of the two groups $\frac{\phi_{th}}{\phi_R}$ was determined from APPR critical experiment measurements.

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Transmission through the absorbing walls of either control rod is calculated using the expression:⁽²⁾

$$R(\alpha_i) = \frac{I(t)}{I_0} = \frac{1}{1+\alpha_i} \left[\alpha_i e^{-\alpha_i} + (2-\alpha_i) \int_0^1 e^{-\frac{\alpha_i}{x}} x dx \right]$$

Where: $R(\alpha_i)$ = Probability that neutrons of energy i pass through absorber plate, of thickness t . (See Figure I).

$I(t)$ = no. of neutrons passing through a unit area of absorber plate, of thickness, t

I_0 = no. of incident neutrons per unit area of absorber

$$\alpha_i = N \sigma_a^i t = \Sigma_a^i t$$

N = number of absorber atoms per unit volume of absorber material, $\frac{at}{cc}$

σ_a^i = absorption cross section of absorber material for neutrons in the i energy group, $\frac{cm^2}{atm}$

t = thickness of absorber material, cm

To account for the hollow construction of the rods, the effectiveness of each material was determined by calculating probability that a neutron pass through the rod wall twice. Fast neutrons which pass through into the center were assumed to be 100% thermalized in the water there. The results of the analysis are negligibly affected by the validity of this assumption.

The blackness⁻¹ of a rod then can be defined as the fractional transmission of incident neutrons. The rod may be considered black if less than 1% of neutrons incident pass through the rod (Blackness⁻¹ $< 10^{-2}$).

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$$\text{Blackness}^{-1} = (\text{Probability that thermal neutrons pass through Rod}) \frac{\phi_{th}}{\phi_{Total}} + (\text{Probability that resonance neutrons pass through Rod}) \frac{\phi_R}{\phi_{Total}}$$

$$\text{Blackness}^{-1} = [R(\alpha_{th}) \cdot R_{\alpha_{th}}] \frac{\phi_{th}}{\phi_{Total}} + [R(\alpha_R) \cdot R_{\alpha_{th}}] \frac{\phi_R}{\phi_{Total}}$$

From critical experiment data;

$$\frac{\phi_{th}}{\phi_{Total}} = .8, \quad \frac{\phi_R}{\phi_{Total}} = .2$$

(3)

SPECIFICATIONS:

Boron Rods - (APPR-1 design)

Boron Content - 14.1 gms B-10/plate

Absorber Area/plate - 20.75 in x 2.24 in = 46.5 in² = 300 cm²

Absorber thickness, t, = 0.090 in = .2286 cm

$$N \text{ B-10, no. absorber atoms/cc} = \frac{14.1 \times 6.02 \times 10^{24}}{10 \frac{\text{gm}}{\text{gm mole}}} \frac{\text{atm}}{\text{gm mole}} = 1.24 \times 10^{22} \frac{\text{at}}{\text{cc}} \\ (300) \times (.2286) \text{cc}$$

$$\sigma_a^{th}, \text{ B-10, } (4) \text{ @ } 450^\circ \text{ F } \frac{4010 \times 10^{-24} \times .7616}{1.128} = 2707 \times 10^{-24} \frac{\text{cm}^2}{\text{atm}}$$

$$\sigma_a^R \text{ B-10 } (4) = \int_{.4\text{eV}}^{\infty} \sigma_a(E) \frac{dE}{E} = 2000 \times 10^{-24} \frac{\text{cm}^2}{\text{atm}}$$

$$\alpha_{th} \text{ B-10} = \left(1.24 \times 10^{22} \frac{\text{at}}{\text{cc}} \right) \left(2707 \times 10^{-24} \frac{\text{cm}^2}{\text{atm}} \right) (.2286 \text{ cm}) = 7.6$$

$$\alpha_R \text{ B-10} = \left(1.24 \times 10^{22} \frac{\text{at}}{\text{cc}} \right) \left(2000 \times 10^{-24} \frac{\text{cm}^2}{\text{atm}} \right) (.2286) = 5.6$$

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Hafnium Rods:

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Assumptions: Square rods, 2.618 in. on a side;

Solid hafnium walls

Vary hafnium thickness from .150 in. to .400 in.

Density of hafnium = 12.1 $\frac{\text{gm}}{\text{cc}}$

$$N - \text{Hafnium} = \left(\frac{12.1 \text{ gm}}{\text{cc}} \right) \left(\frac{.602 \times 10^{24} \text{ at}}{\text{gm mole}} \right) = 4.09 \times 10^{22} \text{ at/cc}$$

$$\left(\frac{178 \text{ gm}}{\text{gm mole}} \right)$$

$$\sigma_{a, \text{Hf}}^{th} (4) @ 450^\circ \text{ F} = \frac{105 \times 10^{-24} \times .7616}{1.128} = 70.9 \frac{\text{cm}^2}{\text{atm}}$$

$$\sigma_{a, \text{Hf}}^R (1) \int_{.4\text{ev}}^{\infty} \frac{\sigma_a(E) dE}{E} = 1400 \times 10^{-24} \frac{\text{cm}^2}{\text{atm}}$$

Table: α_i of Hf - vs - Hf thickness, t

<u>t, in</u>	<u>t, cm</u>	<u>α^{th}</u>	<u>α^R</u>
.150	.381	1.1	21.8
.200	.508	1.47	29.1
.300	.762	2.21	43.6
.400	1.02	2.96	58.4

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Calculations indicate that the APFR-1 will have about 4% excess reactivity, average for 15 mw yr at 450° F. To control this excess, the 5 rods must be inserted as a gang 8 inches into the core. Several calculations indicate that the average absorber atom burnup in these 5 rods will be about $2 \times 10^{16} \frac{\text{atms}}{\text{sec}}$. For the purpose of this report a burnup rate of $4 \times 10^{16} \frac{\text{atms}}{\text{sec}}$ is assumed, to better represent the burnup in the rod tips.

This burnup rate results in a 33% average atom burnup of B-10 atoms in the lower 8 inches of the design APFR rods in 15 mw yrs. The reduction in total cross section at the end of life is determined by reducing the B-10 concentrations by this amount.

Since the total number of hafnium atoms is much greater than that of B-10, the atom percent burnup is smaller. The absorptivity at the end of life was calculated by computing the relative burnup of the 6 hafnium isotopes, and finding an average cross section using the new isotopic concentration. The resonance cross section of hafnium was assumed to be due to Hf-177, and its value at the end of 15 mw yrs. was calculated relative to the burnup of this isotope.

The results of all calculations are presented in figures II and III.

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CONCLUSION:

The analysis here performed shows that it is possible to use control rods of solid Hafnium plate as a substitute for the present APPR-1 rods, B-10 in iron, clad with stainless plate. The wall thickness of a hafnium rod will have to be .3-.4 in. Increasing the wall thickness will result in a smaller water volume at the rod center. Reduction of this moderating center will not decrease the effectiveness of hafnium rods. It is essential that an experimental evaluation of hafnium rods be made in the APPR-1 core before a final decision is made to use them. Factors not readily considered in a simple analytical evaluation may effect the reactivity worth of the rod.

Burnup of hafnium results in only a small change of the rod's initial blackness. Since neutron absorption in the majority of the hafnium isotopes are (n,γ) reactions there is no appreciable heat generation in the rod.

By using hafnium as the absorbing material in an APPR type rod, one loses the advantage of a moderating center. Also large thicknesses of hafnium are required for thermal blackness. A pure thermal neutron absorber material would make the most use of the moderating center design.

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1. Donald J. Hughes, Pile Neutron Physics (Addison-Wesley Publishing Co., 1953)
2. F. Neill, Test of APPR Type Control Rod in the MTR - to be published.
3. Reactor Analysis on APPR - to be published.
4. Hughes & Harvey, Neutron Cross Sections, BNL-325 - 1955.

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Figure I: $R(\alpha) - \text{vs} - \alpha$

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Figure II: Initial Hafnium Blackness-us- Hafnium Thickness

$$\frac{I(t)}{I_0} = \left[R(\alpha_{th}) \cdot R(\alpha_{th}) \right] \frac{\Phi_{th}}{\Phi_{total}} + \left[R(\alpha_R) \cdot R(\alpha_{th}) \right] \frac{\Phi_R}{\Phi_{total}}$$

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Figure III: Blackness⁻¹ vs. Core Life

MODEL

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for Hf and B-10 Rods

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