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FTR CONTROL ROD CALCULATIONS

R. A. HARRIS AND L. L. MAAS

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FTR CONTROL ROD CALCULATIONS

R. A. Harris and L. L. Maas

ABSTRACT

The worths of representative in-core and reflector poison rods in an 800 liter, zoned, oxide fueled FTR core are shown. The variations of these worths with both rod composition and rod location are described. The accuracy of the values obtained are adequate for preliminary design purposes since the methods employed compare reasonably well with experiments.

I. INTRODUCTION

As presently envisioned, the FTR will be controlled with poison rods located both in the core and in the reflector. The total control requirements for the FTR are now estimated to be about 12% Δk . Shim requirements are 4% Δk , test compensation requires about 2% Δk , and 6% Δk is provided for safety shutdown. The purpose of this report is to present, in a preliminary form, some of the information required to determine the location, composition, and number of control rods for the FTR reference design.

To carry out this objective, the worths of several representative control rods and rod patterns were determined. The variation in these worths with changes in both rod composition and rod location were calculated; the perturbations in the neutron flux caused by the poison rods were also obtained.

The calculational methods employed utilized several simplifying assumptions. Similar methods have been used by R. A. Bennett and S. L. Engstrom⁽¹⁾ in the analysis of some recent control rod experiments in ZPR-III with good results. Hence, the methods employed in this investigation are considered adequate for this purpose.

II. FTR MODEL

The reactor model chosen for these calculations was an 800 liter, mixed oxide fueled core containing 91 core locations. Each reactor tube has a volume of (800/91) liters. The dimensions and arrangement of the reactor are shown in Figure 1.

The reactor core was subdivided into two equal volume zones. The fuel density in each zone was adjusted so that the total power in each zone was equal. The composition of each of the reactor regions is shown in Table I.

For one-dimensional calculations, an equivalent bare core height of 117.8 cm was used. This value was obtained by comparing one-dimensional (cylindrical) calculations with two-dimensional (R-Z) calculations.

III. REFLECTOR ROD CALCULATIONS
AND RESULTSEffect of Rod Number and Pattern

The worths of reflector rods (fully inserted) were determined from two-dimensional transport theory⁽²⁾ calculations in R- θ geometry using the S2 approximation. There are 36 possible rod locations in the reflector ring

FIGURE 1. FTR Model

adjacent to the core. Each location in the control rod row was represented by a sector of a cylindrical shell. The arrangements of the poison rods in the cases considered are shown in Figure 2. These patterns were chosen so that the rods were separated as much as possible to reduce interactions, except in the 18 rod bunched case where the interaction effects were specifically examined.

To conserve computer running time, a five energy group set of cross sections was obtained from the 26 energy group set⁽³⁾ currently employed at Pacific Northwest Laboratory for FTR design calculations. The 26 group parameters were collapsed in the FCC⁽⁴⁾ code over neutron spectra characteristic of each reactor region. The spectra for the control rod, reflector, and follower were obtained from one-dimensional transport theory⁽⁵⁾ calculations. Fundamental mode fluxes were used for the two core zones. The worth of a full ring of rods on the core periphery calculated with the five energy group set differed less than 1.7% from the

TABLE I. Reactor Composition

Material	Material Composition of Each Region, vol%					
	Core Zone 1	Core Zone 2	Control Rod	Rod Follower	Radial Reflector	Axial Reflector
PuO ₂	5.15	7.15				
U ²⁸⁰ O ₂	19.85	17.85				
Na	45.00	45.00	30.00	40.00	20.00	70.00
304 SS	25.00	25.00	20.00	60.00		30.00
B ₄ C			50.00			
Inconel					80.00	
Void	5.00	5.00

FIGURE 2. Control Rod Patterns for FTR ($R-\theta$ calculations)

worth calculated using all 26 groups. Therefore, no significant loss in accuracy was incurred by using the few group set.

The worth of several patterns of control rods on the core periphery using the five energy group set of

cross sections in $R-\theta$ calculations are shown in Figure 3. Also shown in the figure are the worths obtained from one-dimensional cylindrical calculations in which the rod material was distributed uniformly throughout the rod row.

FIGURE 3. Reflector Control Rod Worths

The variation in the total flux with azimuthal angle in the center of the rod row is shown in Figures 4A and 4B. The radial total flux distributions are shown in Figure 5. Since the R-θ calculations have no axial detail, the fluxes shown are axially averaged over a bare core height of 117.8 cm.

Effect of Rod Composition

The worths of control rods containing 30 vol% B₄C (20 vol% SS, 50 vol% Na) and 50 vol% Ta (20 vol% SS, 30 vol% Na) were also determined. These worths are compared with the base rod case (50 vol% B₄C) in Table II.

TABLE II. Worth of Complete Ring of Rods (36) on Core Periphery

	Rod Composition		
	50 vol% B ₄ C	30 vol% B ₄ C	50 vol% Ta
Δk	0.086	0.076	0.062

The variation in the worth of the reflector rods with changes in the ¹⁰B content of the B₄C for the 12 rod case is shown in Figure 6.

Effect of Rod Axial Position

Two-dimensional calculations in R-Z geometry were made to estimate the worth of partially inserted reflector

FIGURE 4A. Total Flux Versus Azimuthal Angles in Center of Rod Row

FIGURE 4B. Total Flux Versus Azimuthal Angles in Center of Rod Row

FIGURE 5. Total Flux Versus Radius
(R - θ calculations)

FIGURE 6. Reflector Rod Bank (12 rods) Worth Versus ^{10}B Enrichment

rods. A homogeneous rod ring containing 13.5 vol% B_4C was chosen for this study. Figure 1 shows the location of this ring. The worth of the fully inserted ring (153.8 cm high) was 0.0545 Δk . This does not correspond to the Δk one would expect from Figure 3, since the radial and R- θ calculations treat the axial effects only approximately.

Inserting the ring one-fourth of the way into the core from the top yielded a Δk of 0.0116. The flux perturbation associated with this rod is shown in Figures 7 and 8. A rod worth curve as a function of degree of insertion was obtained from a two-dimensional perturbation code⁽⁶⁾ and is shown in Figure 9. The calculated value for

one-fourth insertion is shown on the figure and agrees quite well with the perturbation result.

IV. IN-CORE CONTROL ROD CALCULATIONS AND RESULTS

Effect of Rod Composition

The worths of control rods in the core were determined from one-dimensional transport theory calculations employing the full 26 energy group cross-section set. In all of the calculations the rods were placed directly on the core axis (see Figure 1). The worth of three characteristic rods, (fully inserted), are shown in Table III.

FIGURE 7. Total Flux Versus Height as a Function of Core Radius

FIGURE 8. Total Flux Versus Radius as a Function of Core Height

FIGURE 9. Reflector Rod Bank Worth
Versus Degree of Insertion

TABLE III. In-Core Control Rod Worths

	Rod		
	50 vol% B ₄ C	25 vol% B ₄ C	50 vol% TA
Δk	0.029	0.018	0.019

The flux depressions associated with these rods are shown in Figure 10.

The variations in the worth of the base rod (50 vol% B₄C) with changes in the ¹⁰B content of the B₄C are shown in Figure 11.

Effect of Rod Axial and Radial Position

Two-dimensional perturbation theory was used to obtain the worth of B₄C rod material as a function of radius and core height. The radial worth distribution can be used to estimate the approximate worth of rods located off the core axis. A rod worth curve as a function of degree of insertion of the rod was obtained from the axial worth distribution. The results are shown in Figures 12 and 13.

V. DISCUSSION

The results presented in this report should provide an adequate basis for determining the FTR reference control rod configuration. From the information given, the worth of a variety of rods and rod patterns as a function of position (both radial and axial) and composition can be estimated. In addition, the perturbations in the total neutron flux near such rods can also be ascertained.

Several assumptions are inherent in these calculations, and thus care must be exercised in utilizing the results. The assumptions and their effects are listed below.

- 1) The rod worth profiles were obtained from two-dimensional perturbation theory. In these calculations, the radial and axial fluxes were assumed to be separable. The errors caused by this assumption are most pronounced where the two reflectors (axial and radial) meet. Thus the portion of the axial reflector rod worth curve which lies above and below the core may be quite inaccurate. While the two-dimensional calculation (R-Z geometry) of the worth of a partially inserted rod bank agrees quite well with the perturbation theory worth curve, this agreement may be the result of cancelling errors since there are other significant effects (i.e., flux depressions near the end of the rod bank) which are ignored in the perturbation calculations.
- 2) The utility of the radial B₄C worth curve (Figure 12) for estimating off-center rod worths may also be somewhat questionable. For instance, if this curve is used to estimate reflector rod worths by extrapolating the worth of the central rod, a significant overestimate results. Hence, at best, the curve should only be used for estimating the worth of control rods located not too far from the core center.
- 3) The R-θ and one-dimensional radial calculations approximate the neutron leakage in the axial direction by including a fictitious absorption term in the neutron balance equation. This term is calculated from diffusion theory assuming that the axial leakage is characteristic of a bare core. The height of the bare

FIGURE 10. Total Flux Versus Radius Near In-Core Control Rods

FIGURE 11. Control Rod Worth Versus ^{10}B Enrichment

FIGURE 12. Worth of B_4C Rod Material (50 vol% B_4C) Versus Core Radius

FIGURE 13. Rod Worth Versus Degree of Insertion for Rod on Core Axis

core is determined by adding a reflector savings to the actual core height. Inherent in this approximation is the assumption that the reflector savings for the core material and the control rod material are identical and that this savings does not change when rods are added to

the core. The R-Z calculation described on page 8 yields a worth 9% higher than a one-dimensional radial case for the same rod ring composition. This deviation is a measure of the error associated with the axial neutron leakage assumption. This comparison cannot be made

directly since the height of the rods in the R- θ and radial calculations is somewhat obscured in the approximation used. If it is assumed that in the R- θ and radial calculations the rods were actually 117.8 cm long (the bare core height) and that the rod worth curve (Figure 9) is correct, then the R-Z calculation (with rods 153.8 cm high) should yield a worth $\sim 3.73\%$ higher. The remaining deviation ($\sim 5.3\%$) could then be attributed to the inaccuracies in the neutron leakage approximation. In any event, the rod worths shown in this report are a function of rod height and to a first approximation the height dependence can be determined from Figure 9.

- 4) The arrangement of the reflector rods was generally chosen to minimize interactions between rods. A measure of the effect of choosing other than optimal spacing is shown by the two, 18-rod cases. If the rods in this situation are bunched in groups of two, the worth of the bank is reduced by 9%. Bunching in groups of 3 or more is expected to result in even greater reductions in the values shown in this report.

- 5) No effort was made to include the fine detail of the control rod construction since this has not yet been defined. Based upon calculations of in-core rods in ZPR-III Assembly 48,⁽¹⁾ the inclusion of typical rod detail would not grossly alter the rod worth.

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