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## ANALYSES OF EIGENVALUE BIAS AND CONTROL ROD WORTHS IN FFTF

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### ABSTRACT

The Fast Flux Test Facility (FFTF) core loading during its ninth operating cycle was significantly different from that of previous cycles because of the presence of the Core Demonstration Experiment (CDE). The CDE consists of a number of axially blanketed fuel assemblies and internal blankets prototypic of advanced oxide cores in Liquid Metal Reactors (LMR). In preparation for the Cycle 9 reload design effort, a careful assessment of control rod worth and reactivity calculations for Cycles 1 through 8 was made. The goal of this study was to establish calculational biases and reduce uncertainties factored into the reload design calculations. These analyses helped assure that the operational objectives for Cycle 9 were met.

### INTRODUCTION

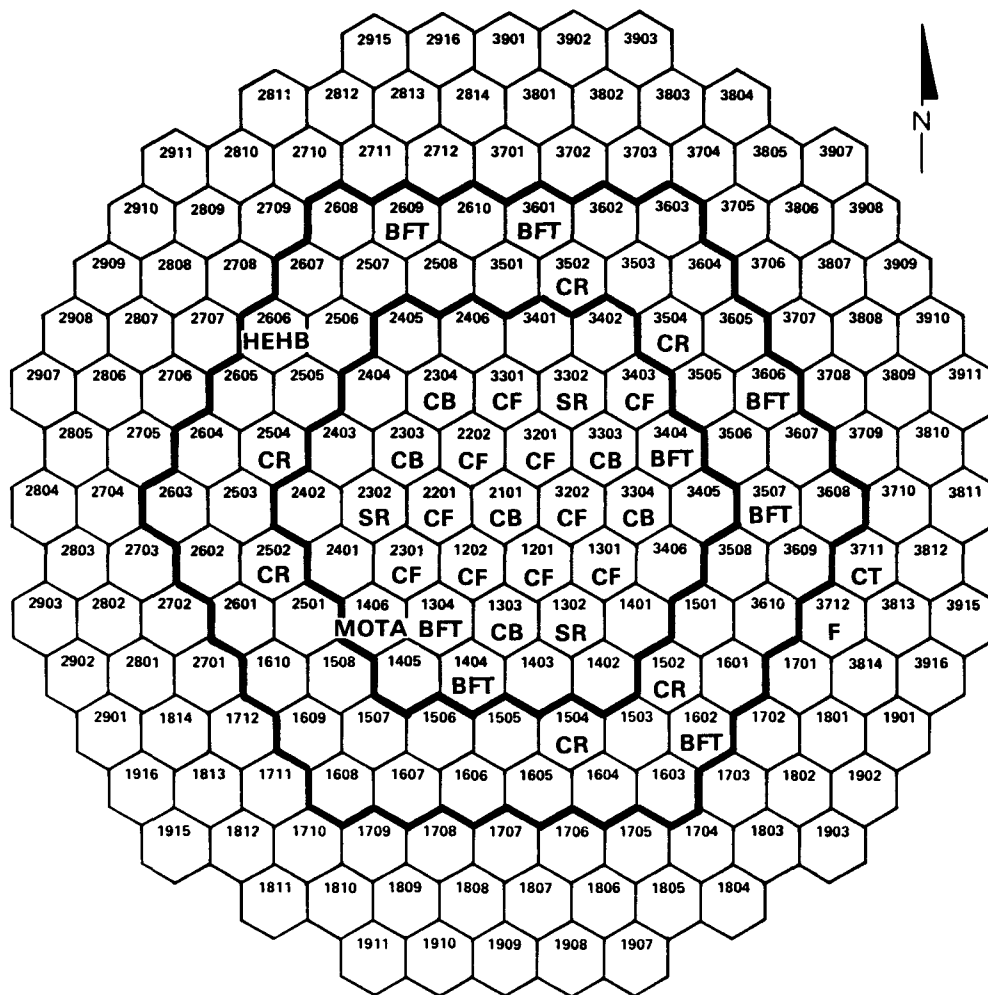
The Fast Flux Test Facility (FFTF) is a 400 MW thermal, sodium cooled fast reactor designed to test fuels and materials in support of the U.S. Liquid Metal Reactor program. It is currently (May 1987) in its ninth operating cycle and has accumulated over 1000 effective full power days (EFPD). This ninth cycle represents a significant change from previous operation because it is devoted primarily to the irradiation of the Core Demonstration Experiment (CDE). The CDE loading, shown in Figure 1, contains a central zone of ten long-life mixed oxide fuel assemblies and six blanket assemblies prototypic of a large scale breeder reactor. To achieve prototypic operating conditions, the reactor power level was reduced from 400 MW to 291 MW, and the cycle length was extended from nominally 100 days to 150 days. The CDE represented a major challenge in core physics predictions of power distributions, control and safety rod worths, burnup reactivity loss rates and criticality due to the added complications of the central

region of internal blanket assemblies and fresh axially blanketed fuel assemblies. The transition to the CDE core without the benefit of critical experiments was made through a careful evaluation of biases and uncertainties for previous cores and a calculational assessment of the differences projected for the CDE.

### METHODS

Twelve group cross section data used in all calculations were generated by the MIDX<sup>1</sup> program from the Set 500 library.<sup>2</sup> Set 500, which is based on ENDF/B-V.2, contains 53 group data in the Bondarenko<sup>3</sup> format. To reduce differences between measured and calculated parameters, the twelve group cross sections were adjusted based on analysis<sup>4</sup> of reaction rate data measured as part of the FFTF Reactor Characterization Program.<sup>5</sup> The adjustments were particularly important for predicting reactivity changes with burnup in heterogeneous configurations like the CDE test zone because <sup>238</sup>U capture was the principal cross section adjusted. The adjusted cross section set was used in performing neutronic and burnup analyses for Cycles 1 through 9 based on standard FFTF reload design methods. That is, the 2DB<sup>6</sup> diffusion theory program was used with two-dimensional (2D) triangular mesh models to perform neutronic analyses. Fuel depletion in the 2D models was computed either directly in 2DB or by the ORIGEN<sup>7</sup> program. For each cycle, calculations of the worth of individual control and safety rods and  $K_{eff}$  for the zero power critical state were made.

For 2DB calculations through Cycle 8, space-energy independent bucklings were used to account for axial neutron leakage. The buckling was varied with control and safety rod configuration, but small changes in buckling from cycle to cycle were neglected. Because of the increased heterogeneity in the CDE core, space dependent, energy independent buckling



- |     |                                      |      |                             |
|-----|--------------------------------------|------|-----------------------------|
| CB  | CDE BLANKET ASSEMBLY                 | SR   | SAFETY ROD                  |
| CF  | CDE FUEL ASSEMBLY                    | CR   | CONTROL ROD                 |
| BFT | OTHER FUEL TESTS WITH AXIAL BLANKETS | MOTA | MATERIAL OPEN TEST ASSEMBLY |
| CT  | COBALT TEST ASSEMBLY                 | HEHB | ABSORBER TEST ASSEMBLY      |
|     |                                      | F    | FUEL ASSEMBLY IN ROW 7      |

UNLABELLED LOCATIONS IN ROWS 1 - 6 CONTAIN STANDARD DRIVER FUEL OR FUEL TESTS WITH AXIAL REFLECTORS. UNLABELLED LOCATIONS IN ROWS 7, 8 AND 9 CONTAIN RADIAL REFLECTOR ASSEMBLIES.

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Figure 1. FFTF Core Loading for Cycle 9A

values were used in 2DB calculations on Cycle 9.

In addition, three-dimensional diffusion theory (3DB)<sup>8</sup> calculations with the same cross sections were made for the High Power Physics Test (HPPT) loading (an early FFTF core) and for a preliminary CDE core design to provide a basis for determining axial bucklings and corrections to the 2DB calculations for control rod burnout and axial burnup variations in the fuel. The 3DB calculations were also used in conjunction with corresponding 2DB calculations to determine absorber fraction curves that are needed to represent partially withdrawn control rod configurations in 2D models. These curves relate an axial control rod position to an absorber volume fraction required in a 2D model to obtain the correct control strength.

#### CONTROL AND SAFETY ROD WORTHS

Individual control and safety rod reactivity worths are measured at the beginning of each FFTF operating cycle to verify compliance with technical specification limits. These measurements also provide data to compare with calculated worths and, thus, identify cycle-to-cycle trends.

The FFTF experience with individual rod worths is shown in Table 1. As indicated in this table, control rod worths and safety rod worths decreased during the early operating cycles until an equilibrium was reached. This equilibrium continued until the CDE core was installed in Cycle 9A. Over the same period, calculation to experiment (C/E) ratios for control rod worths increased somewhat, particularly from Cycle 1A to Cycle 2A where C/E values increased by an average of 4%. Safety rod worth C/E values showed no significant trends. The insertion of the CDE did not appear to have a major effect on control rod worths, but the proximity of the CDE blanket assemblies to the safety rods (see Figure 1) decreased their worth by an average of 9%.

The most likely reason for the control rod worth decrease during the first three cycles was the removal of in-core shim assemblies (ICSAs). The initial core loading required reactivity adjustment to compensate for the unirradiated condition of the fuel. This adjustment was accomplished by the use of seven stainless steel ICSAs, which were located in the core such that they enhanced the control rod worth. Several ICSAs were removed each cycle for the first three cycles as the average core burnup approached equilibrium.

There are several reasons for the C/E value increase during the first three cycles. The two-dimensional nuclear analysis model neglects boron depletion in the rods. Calculational estimates show that this depletion

decreases the worths of each control rod by approximately 0.1\$ ( $\$ = 0.00318 \Delta k/k$  for FFTF) over three cycles. Although a control rod burnout correction is factored into the C/E values in Table 1, there is a high degree of uncertainty in its accuracy. The C/E trend could also be related to the axial variation of fuel burnup which is not considered in the two-dimensional mid-plane nuclear analysis model.

The presence of an experimental control rod (ADVAB-2), beginning irradiation in Cycle 2A, perturbed the relatively uniform C/E rod worth values. Unlike the reference rods, ADVAB-2 used 62% enriched boron and had a short pellet stack that was offset 28.6 cm from the bottom of the core. The C/E values for the ADVAB-2 rod were consistently larger than the average values for other rods, and the C/E for the worths of the two rods closest to ADVAB-2 were smaller than the average.

There were two shortcomings in the 2D reload design model that contributed largely to these trends. First, the microscopic cross section data that were used for ADVAB-2 were generated for FFTF reference rods containing natural boron carbide. Spatial self shielding effects in reference FFTF control rods are negligible, whereas in ADVAB-2 they are substantial. Second, the absorber fraction curve that was generated for FFTF reference control rods was also used for ADVAB-2. In fact, the curve for ADVAB-2 was found to be significantly different.

#### REACTIVITY BIAS

Reactivities obtained from 2DB calculations on planar models of the zero power critical states were corrected for differences in core temperature and control rod bank position between calculated and measured conditions. The resulting 2DB reactivity biases, listed in Table 2, are defined as:

$$\Delta k/k = [k_{eff}(\text{calc.}) - 1]/k_{eff}(\text{calc.}).$$

Also listed in Table 2 are corrected biases, and corrections applied, that account for deficiencies in the treatment of ADVAB-2 (discussed above) and three-dimensional effects. These effects, which were evaluated by performing 3DB calculations, include:

- \* Unaccounted for changes in axial buckling from cycle to cycle.
- \* control rod burnout, and
- \* axial variation in the rate of fuel depletion

The ADVAB-2 correction (0.0019  $\Delta k/k$ ) was determined in the following way. First, spatial self shielding factors in the enriched

Table 1

Individual Control and Safety Rod Worths

<u>Safety Rods</u>	<u>Cycle 1A</u>		<u>Cycle 2A</u>		<u>Cycle 3</u>		<u>Cycle 8A</u>		<u>Cycle 9A</u>	
	<u>Worth(\$)</u>	<u>C/E<sup>a</sup></u>	<u>Worth(\$)</u>	<u>C/E</u>	<u>Worth(\$)</u>	<u>C/E<sup>a</sup></u>	<u>Worth(\$)</u>	<u>C/E</u>	<u>Worth(\$)</u>	<u>C/E</u>
1	5.67 ±0.04	1.01	5.98 ±0.07	0.99	5.74 ±0.06	1.03	5.36 ±0.03	1.04	5.73	1.06
2	5.81 ±0.03	0.99	4.99 ±0.04	0.94	4.80 ±0.04	0.99	5.31 ±0.04	1.01	4.50	1.03
3	5.91 ±0.04	1.02	5.34 ±0.04	0.99	5.20 ±0.04	1.02	5.43 ±0.04	1.04	4.42	1.06
Control Rods										
4	3.90 ±0.02	0.95	3.96 ±0.05	0.98	3.84 ±0.03	1.01	3.02 ±0.02	1.05	3.65	1.06
5	3.54 ±0.02	0.97	3.76 ±0.05	1.00	4.00 ±0.04	0.99	2.94 ±0.02	1.04	3.96	1.01
6	3.44 ±0.02	0.93	3.48 <sup>b</sup> ±0.04	1.07	3.87 <sup>b</sup> ±0.04	1.02	3.08 ±0.02	0.97	3.12	0.98
7	3.94 ±0.02	0.92	2.98 ±0.03	0.91	2.74 ±0.03	0.91	3.21 ±0.03	0.97	2.43	0.95
8	3.57 ±0.02	0.94	2.95 ±0.03	0.95	2.97 ±0.03	0.97	2.88 ±0.02	0.99	2.81	1.06
9	4.06 ±0.02	0.93	3.54 ±0.04	0.96	3.62 ±0.03	0.99	3.10 ±0.02	1.02	3.07	1.08
Total Safety Rod Worth		<u>Cycle 1A</u>	<u>Cycle 2A</u>	<u>Cycle 3</u>	<u>Cycle 8A</u>	<u>Cycle 9A (CDE)</u>				
Average Safety Rod C/E		17.39	16.31	15.74	16.10	14.65				
Total Control Rod Worth		1.01	0.97	1.00	1.03	1.05				
Average Control Rod C/E		22.45	20.67	21.04	18.23	19.04				
		0.94	0.98	0.98	1.01	1.02				

<sup>a</sup> C/E - Calculated Rod Worth/Measured Rod Worth

boron carbide pins were computed using the Monte Carlo program, MCNP.<sup>9</sup> These factors were then applied to the <sup>10</sup>B capture cross sections by energy group. Finally, the corrected cross section data were employed in a series of 3DB and 2DB calculations on FFTF models with ADVAB-2 at various axial positions. From these calculations, the effect of using spatially self shielded cross sections and an absorber fraction curve for ADVAB-2 were obtained.

In arriving at a  $k_{eff}$  bias to be used in the Cycle 9A reload design, corrected biases for Cycles 1 through 8 were averaged. However, all available data were not included in the averaging process. Instead, only one data point per major operating period was used, as indicated in the last column of Table 2. This was done to keep the average from being weighted in favor of short cycles with very similar loadings. For example, there was only one assembly changed between Cycles 1A and 1B.

The reactivity bias used in the Cycle 9A reload design analysis was  $-0.0009 \Delta k/k$ , which was very close to the bias of  $-0.0011 \Delta k/k$  inferred from Cycle 9A measurements and calculations. Computing and applying corrections to the 2DB biases not only resulted in a more accurate prediction of reactivity bias for Cycle 9A, but also significantly reduced the uncertainty which was important in optimizing the loading.

There are a number of possible explanations for the remaining variance in the corrected biases, including:

- \* uncertainties in the correction factors applied,
- \* fuel rod bowing,
- \* axial expansion of the fuel columns, and
- \* a historical tendency to over calculate fuel worths (see Reference 10 for example).

No attempt was made to evaluate the contributions of these or other possible causes of bias variation.

#### TRANSITION TO CDE

Replacing the central zone of FFTF with the CDE, along with other new tests added for Cycle 9, created greater uncertainty in the estimate of control rod worths, secondary control rod system shutdown margin (SSSM) and cycle length. The  $k_{eff}$  bias, bias uncertainty and control rod worth C/Es, discussed earlier, were used to establish a beginning of Cycle 9A (BOC9A) loading that optimized the chance of

having sufficient SSSM and reasonable cycle length. It was important to maintain reactor schedule with a refueling that required no extra time for reshimming after closing the reactor vessel and proceeding to the zero power physics testing state.

Driver fuel was added in the calculations to establish an excess reactivity, as computed with 2DB, of 8.14\$. This loading had a computed SSSM of 8.52\$, 4.50\$ more than required. Using a one sigma uncertainty of 2.60\$ on the SSSM, there was a 95% probability that the loading would have sufficient SSSM. The cycle length was estimated to be  $125 \pm 40$  EFPD (291 MW).

The techniques employed to optimize the fuel load for FFTF Cycle 9A proved to be adequate. Upon reactor startup, the SSSM was measured as 7.70\$ with a projected cycle length of  $135 \pm 15$  EFPD. Fission rate and heat deposition calculations were validated by the fact that measured sodium outlet temperatures were all within predicted allowances. Cycle 9A was completed on February 5, 1987, after 137.7 EFPD operation.

In summary, the objectives of the Cycle 9A refueling were achieved because of the extensive effort in establishing biases and uncertainties in the calculational methods based on past experience and careful projections to new conditions.

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Table 2

Summary of Reactivity Bias Calculations<sup>a</sup>

Cycle	Fuel <sup>b</sup>	Av. Exposure (EFPD)		2DB Bias	Fuel <sup>d</sup>	ADVAB-2 Adjust.	Buckling <sup>e</sup> Adjust.	CRC, <sup>f</sup> Burnup Adjust.	Adjusted Bias	Data <sup>g</sup> Points Used
	Assy.s	Fuel	CR.s <sup>c</sup>		Burnup Adjust.					
HPPT	72	11	14	-0.0039	-0.0003	0	0.0000	0.0001	-0.0041	
1A	72	25	32	-0.0038	-0.0007	0	0.0000	0.0002	-0.0043	-0.0043
1B	72	59	66	-0.0021	-0.0016	0	0.0000	0.0004	-0.0033	
2A	73	110	112	-0.0026	-0.0030	0.0019	-0.0001	0.0007	-0.0032	-0.0032
2B	74	135	139	-0.0021	-0.0037	0.0019	-0.0003	0.0009	-0.0033	
3	76	120	166	-0.0018	-0.0033	0.0019	-0.0005	0.0010	-0.0027	-0.0027
4	77	155	51	0.0028	-0.0043	0.0019	-0.0007	0.0003	0.0001	0.0001
5B	80	251	156	0.0065	-0.0069	0.0019	-0.0010	0.0010	0.0014	0.0014
6B	80	250	206	0.0053	-0.0069	0	-0.0010	0.0013	-0.0013	-0.0013
6C	80	302	260	0.0052	-0.0083	0	-0.0010	0.0016	-0.0025	
6D	80	337	297	0.0061	-0.0093	0	-0.0010	0.0019	-0.0024	
7A	81	251	278	0.0048	-0.0058	0.0019	-0.0012	0.0018	0.0015	0.0015
8A	80	239	65	0.0071	-0.0055	0	-0.0010	0.0004	0.0010	0.0010
9A	74	169	252	0.0012	-0.0039	0	0.0000	0.0016	-0.0011	
			Avg.	0.0016					-0.0017	-0.0009
			St. Dev.	0.0040					0.0019	0.0021

<sup>a</sup>Reactivity data are in units of  $\Delta k/k$ .

<sup>b</sup>Includes number of fuel assemblies in rows 1 through 6 only. Cycles 3 through 6D and 9A each had one Row 7 fuel assembly.

<sup>c</sup>CR = control rod.

<sup>d</sup>Fuel burnup adjustment =  $-2.76 \times 10^{-5} \Delta k/k/EFPD$  for 2DB and  $-2.30 \times 10^{-5} \Delta k/k/EFPD$  for ORIGEN, which was used for Cycles 7A, 8A and 9A.

<sup>e</sup>Buckling adjustment =  $-0.00013 \Delta k/k$  for each nonfuel to fuel exchange.

<sup>f</sup>Estimated control rod burnout effect =  $6.3 \times 10^{-6} \Delta k/k/EFPD$ .

<sup>g</sup>Data points used in establishing a target reactivity for Cycle 9A reload design calculations.