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**Flux and Power Distributions in BWR
Multi-Bundle Fuel Arrays**

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Table of Contents

Abstract

1. Introduction

2. Analysis

3. Results

3.1 Four-Bundle Supercell Calculations

3.2 Eight-Bundle Supercell Calculations

3.3 A Semi-empirical Correlation

4. Conclusions

References

ABSTRACT

Multi-bundle calculations have been performed in order to shed some light on an abnormal TIP trace recently discovered in a BWR/3. Transport theory was employed to perform the calculations with ENDF/B-IV data. The results indicate that a strong variation of the TIP reading does exist along the narrow water gap of a BWR due to the steep gradient of the thermal neutron flux; the maxima occurring at the intersections of the water gaps and the minima in between.

Using this characteristic behavior of the TIP reading, together with the observed normal TIP trace, the abnormal behavior of the affected TIP trace exhibiting three peaks along the channel was roughly simulated. The calculations confirmed that the observed TIP trace anomaly was caused by the severe bending of the affected instrument tube as was actually discovered.

The effect of hot water intrusion into the TIP guide tube, as well as that of loading the new 8 x 8 reload bundles, was also evaluated.

1. INTRODUCTION

Local flux anomalies were noted on Traversing Incore Probe (TIP) traces of a BWR/3 shortly after reloading with some new 8 x 8 fuel bundles late last year.¹ At a pair of symmetric TIP locations the two axial TIP traces were found strikingly different; one of them exhibiting three unusual peaks (see Fig. 1f). The large discrepancy in TIP readings was later identified as caused by a bent instrument tube as shown in Fig. 1. In the interim, BNL was asked to perform multi-bundle calculations to evaluate the effect of large tube displacements on the TIP reading.

In addition, there was some indication of hot water leakage into the affected TIP guide tube. Consequently, the effect of hot water intrusion into the TIP was also evaluated.

The calculational model employed in the present work was similar to that of a previous work² except that both 4-bundle and 8-bundle supercells were considered in this study. Transport theory was used with ENDF/B-IV data. An attempt was made to reproduce qualitatively the abnormal behavior of the affected TIP trace from the results of the 8-bundle supercell calculation in conjunction with the observed normal TIP trace. The synthesized TIP trace of the affected instrument tube resembles the observed one, suggesting that the severe bending of the affected instrument tube was responsible for the TIP trace anomalies.

This report describes the analysis made and documents the important results obtained in the present work.

2. ANALYSIS

The calculational procedure consists of a multigroup, one-dimensional, unit cell calculation with HAMMER³ to generate eight-group cell-averaged cross sections using ENDF/B-IV data, followed by an eight-group, two-dimensional, multi-bundle supercell calculation with TWOTRAN-II⁴ to obtain the incore detector reading. Further details concerning the calculational procedure may be found in Reference 2.

Because of time constraints, the supercell calculations employed the eight-group cell-averaged cross sections that were generated in the previous work² at normal conditions for full power operation, namely, an average fuel temperature of 1200° F, a moderator temperature of 286°C and an effective in-channel void fraction of 40%. These cross sections represent the bundle characteristics of the BWR/4 class rather than a BWR/3. For this reason, the results of this work should be taken as being typical of a modern BWR rather than a specific plant. However, an effort was made to simulate the new 8 x 8 reload bundle with an equivalent 7 x 7 bundle by preserving the important characteristics of the 8 x 8 reload bundle such as the enrichment distribution with approximately the same bundle-average enrichment and the presence of a water hole and extra gadolinia rod.

Both 4-bundle and 8-bundle configurations were used for the supercell calculations. In the 4-bundle representation, a simulated reload bundle was placed in the fourth quadrant as illustrated in Fig. 2, and two separate supercell calculations were performed: one with the incore detector located at its normal position (at center of the narrow-narrow gap) and the other with the detector displaced two fuel rows down. It should be mentioned that no control rod is present in the 4-bundle case. Figure 3 shows the detailed representation of the displaced detector for the second case. In addition, the first case was also recalculated with the TIP guide tube filled with hot water (without voids) to see the significance of water intrusion into the TIP chamber.

For a more realistic representation, a supercell calculation was also performed in an 8-bundle environment as shown in Fig. 4 where only the two control blades at the lower left and lower right corners were inserted. It was assumed that the perturbation of neutron flux distributions by the presence of incore detector was of secondary importance so that only a single 8-bundle supercell calculation was done to provide the desired spatial variation of the TIP reading by editing the U-235 fission activity along the water gap. This was a matter of practical necessity for, otherwise, a series of lengthy 8-bundle supercell calculations would be required. The effect of perturbation by the incore detector could be estimated, if necessary, from the results of the previous work.²

3. RESULTS

3.1 Four-Bundle Supercell Calculations

The 4-bundle supercell calculations were performed to evaluate the effect of hot water intrusion into the TIP guide tube and that of an abnormally displaced incore detector. Table I summarizes the effect of hot water leakage into the TIP tube. An increase of about 7% in TIP reading could result from the hot water intrusion due to the increase of thermal group fluxes by the slowing-down and thermalization effects of H_2O .

The effect of loading the new 8 x 8 reload bundle was also studied. The results are presented in Table II. The new 3 x 8 reload bundle has a minor effect on the TIP reading, reducing it by only 3%.

Table III summarizes the results of drastically moving the incore detector from its normal position to two fuel rows down (see Fig. 3). It is seen that the TIP reading tends to decrease substantially (~ 23%) as the detector moves into the narrow water gap between fuel bundles. This is due to the reduction of thermal group fluxes as is evident from Table IV.

3.2 Eight-Bundle Supercell Calculations

In order to represent more closely the actual situation at the affected BWR/3, a supercell calculation was also carried out in an 8-bundle environment as shown in Fig. 4. Typical computer-generated curves of the thermal neutron flux as a function of both the horizontal and vertical positions are given in Figs. 5 through 11; the curves are identified by the coordinate system (J_y or I_x) as illustrated in Fig. 4. These plots provide a much better perspective of the thermal neutron behavior across the supercell, and manifest the effects of control rods, water gaps, gadolinia rods, and water holes.

Note, in particular, the strong spatial variation of the thermal flux along the water gaps ($J_y = L$, $I_x = 12$) with the maxima occurring at the intersections and the minima in between. This implies that a substantial reduction in TIP reading is possible if the detector is moved from the intersection into the interior of the water gaps as was found in the previous 4-bundle supercell calculations.

Figures 12 and 13 show, respectively, the normalized local power distributions in the left 4-bundle cell and the right 4-bundle cell of the 8-bundle supercell. The normalization is such that the average 8-bundle power density be unity. The numbers listed in the spaces between dotted lines are the relative U-235 fission activities along the water gaps that were obtained by summing over eight groups and integrated over the volume of the incore detector. Thus, they represent the unperturbed detector readings that would be obtained without the presence of the detector.

It should be noted that, if the detector is displaced two fuel rows away from its normal position at the center of the narrow-narrow gap, the detector reading decreases by about 22-24% in good agreement with the previous finding that resulted from 4-bundle supercell calculations with an explicit representation of the detector. Also, if the detector is moved further away from its normal position, the detector reading first reduces to a minimum (~ 37% decrease) and then rises to a maximum (~ 40% increase) at the wide-wide gap intersection, and repeats the cycle as it travels along the narrow water gap.

3.3 A Semi-Empirical Correlation

It would be of interest to synthesize the TIP trace anomalies from the normal trace, if possible. We shall attempt to accomplish this in a qualitative way with a view to showing that the large lateral displacement of the affected instrument tube was responsible for the TIP trace anomalies. To do this, we need to know the extent of the tube displacement. Reference 1 provides a top view (horizontal projection) of the

affected instrument tube as shown in Fig. 14. Note that the bent tube traversed the face of three pairs of fuel bundles. This means that the affected detector would see three peaks as it passed through the three water gap intersections as can be inferred from the curve $J_y = L$ in Fig. 6. This was also borne out by the observed TIP trace.⁵

Let $N(z)$ denote the normal TIP trace and $A(z)$ represent the abnormal trace of the affected TIP tube. We may write

$$A(z) = CN(z) F_l(z(x)) F_{xy}(z(x)),$$

where $F_l(z(x))$ is the local peaking factor to account for the lateral displacement of the affected TIP, $F_{xy}(z(x))$ is the global radial peaking factor to account for the appropriate environment surrounding the 8-bundle array, and C is a constant normalization factor.

The local peaking factors are defined as the ratios of the relative fission activities along the narrow water gap in an 8-bundle fuel array to that at the normal TIP position. They can be computed from the results presented in Figs. 12 and 13. Note that F_l 's thus obtained are a function of local position (x). Assume that the dislodged instrument tube was bent linearly and that the bottom three feet were not affected (see Fig. 1). Thus, starting from approximately the notch position 36, the horizontal local positions along the narrow water gap can be converted to a set of equally spaced axial positions by a linear transformation.

The global radial peaking factors are not available without a global core calculation. Because of the lack of information we shall assume that F_{xy} is fairly constant so that it can be lumped into the normalization constant C . We then derive the normalization constant by forcing the areas under the synthesized and actual abnormal TIP traces to be equal.

The synthesized and normalized TIP readings of the dislodged instrument tube are shown as triangles in Fig. 15. It does exhibit three unusual peaks as was actually observed.^{1,5} This further confirms that the observed TIP trace anomalies were caused by the large displacement (through bending) of the affected instrument tube and that the affected detector was simply responding to its environment.

4. CONCLUSIONS

There exists a steep thermal flux gradient along the narrow water gap of a BWR. As a result, the incore detector reading would exhibit a strong spatial variation if the detector is allowed to move along the water gap in the horizontal direction. The present study indicates that the detector reading would exhibit maxima at the intersections of the water gaps and minima in between. Relative to the normal position of the incore detector, the maximum could be as large as a 40% change and the minimum could amount to a 37% change.

Using this characteristic behavior of the detector reading, we have shown that the observed TIP trace anomalies at a BWR/3 were caused by the severe bending of the affected instrument tube and that the affected detector was simply responding to its environment.

The effect of hot water intrusion into the TIP guide tube is to increase the TIP reading by about 7%.

The effect of loading the new 8 x 8 reload bundles is relatively insignificant, reducing the TIP reading by only 3%.

REFERENCES

1. Docket No. 50-245; Unusual Event UE-50-245/75-2, Letter dated Dec. 3, 1975 from William G. Council (Plant Superintendent of Millstone Nuclear Power Station) to James P. O'Reilly, Director, Region 1 Office of Inspection and Enforcement, U.S. Nuclear Regulatory Commission.
2. H. S. Cheng, "A Study of the Effect of Position and Voids on BWR In-core Detector Readings", BNL-20547, Brookhaven National Laboratory (1975).
3. J. E. Suich and H. C. Honeck, "The HAMMER System - Heterogeneous Analysis by Multigroup Methods of Exponentials and Reactors", DP-1064, Savannah River Laboratory (1967).
4. K. D. Lathrop and F. W. Brinkley, "TWOTRAN-II: An Interfaced, Exportable Version of TWOTRAN Program for Two-Dimensional Transport", LA-4848-MS, Los Alamos Scientific Laboratory (1973).
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Table I

The Effect of Hot Water Intrusion on TIP Reading
(Normal Operating Conditions and Normal Detector Position)

		<u>Relative U-235 Fission Activity at TIP</u>	
	<u>Group Index</u>	<u>With Hot H₂O</u>	<u>No Hot H₂O</u>
Fast Groups	1	0.059	0.061
	2	0.117	0.117
	3	1.676	1.661
Thermal Groups	4	1.270	1.221
	5	4.690	4.424
	6	6.357	5.926
	7	5.072	4.637
	8	1.271	1.081
	SUM:	<u>20.512</u>	<u>19.128</u>

Percent Increase: +7.2%

Table II

The Effect of New 8 x 8 Reload Bundle on TIP Reading
 (Normal Operating Conditions, Normal Detector Position, and Hot
 Water Intrusion)

		<u>Relative U-235 Fission Activity at TIP</u>	
	<u>Group Index</u>	<u>8 x 8 Reload</u>	<u>7 x 7 Bundle</u>
Fast Groups	1	0.058	0.059
	2	0.114	0.117
	3	1.666	1.676
Thermal Groups	4	1.249	1.270
	5	4.547	4.690
	6	6.151	6.357
	7	4.909	5.072
	8	1.232	1.271
	SUM:	<u>19.926</u>	<u>20.512</u>

Percent Decrease: -2.9%

Table III

The Effect of a Drastic Detector Displacement on TIP Reading
(Normal Operating Conditions and Detector Moved Two
Rows Down)

		<u>Relative U-235 Fission Activity at TIP</u>	
	<u>Group Index</u>	<u>Displaced Position</u>	<u>Normal Position</u>
Fast Groups	1	0.062	0.058
	2	0.118	0.114
	3	1.639	1.666
Thermal Groups	4	1.128	1.249
	5	3.526	4.547
	6	4.490	6.151
	7	3.476	4.909
	8	0.869	1.232
SUM:		<u>15.308</u>	<u>19.926</u>
Percent Decrease: -23.2%

Figure 2. The 4-Bundle Environment for the Incore Detector Calculations.

Fig. 4. The 8-Bundle Supercell Representation for Milstone.

Fig. 5

Fig. 6

Fig. 7

Fig. 8

Fig. 9

Fig. 10

Fig. 11

Fig.12. Local Power Distribution Calculated by TWOTRANII (8-Group, S_4 Approximation)

Cell Position: Left Half of the 8-Bundle Supercell.

Void Content: EIV = 40 %, BPV = 0 %, GDV = 0 %.

1.230	1.175	1.086	1.206	1.228	1.324	1.359	.006337	1.382	1.373	1.307	1.298	1.320	1.279	1.350	
1.161	0.285	1.192	1.210	1.223	1.329	1.171	.005037	1.192	1.381	1.332	1.343	1.321	0.465	1.277	
1.053	1.166	1.004	0.950	0.942	0.403	1.345	.004303	1.370	0.421	1.099	1.195	1.199	1.320	1.318	
1.139	1.154	0.924	0.367	0.875	0.992	1.274	.004015	1.282	1.039	1.080	0.00	1.194	1.341	1.296	
1.119	1.128	0.895	0.852	0.926	1.065	1.320	.004059	1.280	1.026	1.022	1.080	1.099	1.330	1.304	
1.145	1.159	0.368	0.927	1.030	1.185	1.036	.004343	1.345	0.411	1.026	1.039	0.422	1.380	1.372	
1.102	0.973	1.163	1.153	1.248	1.015	1.208	.004984	1.168	1.345	1.281	1.283	1.371	1.193	1.383	
.004658	.003916	.003554	.003524	.003791	.004263	.005015	.005625	.005020	.004345	.004062	.004019	.004309	.005045	.006411	.007882
0.851	0.830	1.060	1.089	1.199	0.986	1.185	.005016	1.208	1.036	1.321	1.275	1.347	1.174	1.362	
0.635	0.818	0.315	0.818	0.938	1.105	0.986	.004264	1.015	1.186	1.066	0.994	0.404	1.332	1.327	
0.462	0.648	0.622	0.678	0.787	0.938	1.200	.003793	1.250	1.031	0.927	0.876	0.944	1.227	1.232	
0.394	0.576	0.569	0.281	0.678	0.818	1.090	.003527	1.154	0.928	0.853	0.368	0.952	1.213	1.210	
0.313	0.510	0.538	0.569	0.623	0.316	1.061	.003558	1.164	0.369	0.897	0.927	1.007	1.196	1.090	
0.288	0.159	0.510	0.576	0.649	0.819	0.831	.003922	0.974	1.162	1.131	1.157	1.170	0.286	1.180	
0.250	0.288	0.313	0.394	0.162	0.635	0.852	.004705	1.105	1.147	1.122	1.142	1.057	1.165	1.236	

CONTROL BLADE

Fig.13. Local Power Distribution Calculated by TWOTRANII (8-Group, S_4 Approximation)

Cell Position : Right Half of the 8-Bundle Supercell.

Void Content: EIV = 40 %, BPV = 0 %, GDV = 0 %.

1.351	1.281	1.173	1.287	1.294	1.371	1.391	.006408	1.381	1.357	1.270	1.248	1.257	1.207	1.269
1.281	0.312	1.291	1.296	1.295	1.373	1.199	.005093	1.190	1.366	1.288	1.285	1.252	0.437	1.194
1.173	1.291	1.098	1.024	1.006	0.418	1.380	.004348	1.364	0.415	1.051	1.134	1.126	1.227	1.221
1.287	1.295	1.023	0.398	0.935	1.030	1.306	.004057	1.276	1.022	1.030	0.000	1.109	1.231	1.182
1.293	1.292	1.005	0.935	0.994	1.113	1.355	.004102	1.272	1.005	0.967	1.006	1.005	1.195	1.163
1.366	1.369	0.417	1.032	1.116	1.247	1.066	.004389	1.331	0.399	0.955	0.951	0.381	1.199	1.181
1.382	1.192	1.376	1.309	1.368	1.076	1.247	.005035	1.153	1.297	1.184	1.149	1.182	0.995	1.129
.006414	.005052	.004329	.004076	.004206	.004551	.005190	.005680	.004944	.004147	.003722	.003536	.003605	.003990	.004753
1.363	1.176	1.354	1.290	1.348	1.061	1.231	.005113	1.184	0.981	1.195	1.095	1.074	0.844	0.866
1.329	1.335	0.405	1.003	1.080	1.203	1.029	.004301	0.990	1.108	0.941	0.823	0.320	0.831	0.645
1.233	1.229	0.948	0.883	0.936	1.041	1.262	.003824	1.208	0.944	0.792	0.683	0.630	0.657	0.469
1.211	1.216	0.956	0.370	0.859	0.935	1.163	.003554	1.098	0.824	0.683	0.284	0.575	0.583	0.399
1.091	1.198	1.011	0.931	0.902	0.371	1.172	.003584	1.069	0.318	0.628	0.575	0.543	0.516	0.317
1.181	0.287	1.174	1.162	1.137	1.168	0.980	.003948	0.837	0.825	0.654	0.582	0.515	0.161	0.291
1.238	1.168	1.060	1.147	1.128	1.154	1.111	.004736	0.858	0.640	0.466	0.398	0.316	0.291	0.253

CONTROL BLADE

Fig. 15 THE SYNTHESIZED ABNORMAL TIP TRACE
OF THE AFFECTED INSTRUMENT TUBE.