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Reactivity Analysis of
Core Distortion Effects in the FFTF

by

Bradley James Knutson

A thesis submitted in partial fulfillment
of the requirements for the degree of

Master of Science
In Nuclear Engineering

University of Washington

1982

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Approved
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(Chairperson of Supervisory Committee)

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to Offer
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Master's Thesis

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University of Washington

Abstract

REACTIVITY ANALYSIS OF CORE DISTORTION
EFFECTS IN THE FFTF

By Bradley James Knutson

Chairperson of the Supervisory Committee:

Professor Norman J. McCormick

Department of Nuclear Engineering

An improved technique for evaluating core distortion reactivity effects was developed using reactivity analyses of two core geometry models (R-Z and HEX). This technique is incorporated into a new processor code called CORDIS. The advantages of this technique over existing reactivity models are that it preserves core heterogeneity, provides a control rod insertion effect model, uses row-dependent axial shape functions, and provides a flexible and cost efficient core distortion reactivity analysis method.

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CHAPTER I

INTRODUCTION

Analytical predictions of the Fast Flux Test Facility (FFTF) reactivity feedback effects are necessary to accurately predict core behavior. One important reactivity feedback effect is due to core distortion resulting from mechanical, thermal and neutronic interactions in the core. This reactivity effect is particularly important in liquid metal fast reactors, such as the FFTF, where leakage effects are important.

One existing core distortion reactivity analysis model is contained in a three-dimensional structural analysis code, NUBOW-3D.^[1] In this model, NUBOW-3D first calculates subassembly displacements for specified reactor conditions. It then integrates those displacements axially over each subassembly using a chopped cosine function to represent the axial flux and adjoint flux distribution; i.e., cosine-squared weighting, for the reactivity calculations. The displacement integral is then multiplied by the appropriate input average radial duct (subassembly) displacement worth gradient ($\rho/\text{unit displacement}$) and normalized by the integral of the axial cosine-weighting function. A sum over all rows gives the reactivity response of the core model.

The goals of this study were to develop improved techniques for the analysis of core distortion reactivity effects, to evaluate the adequacy of simpler reactivity models currently used in codes like NUBOW-3D, to evaluate the relative importance of axial effects and core heterogeneities on feedback reactivity, and to develop a method/approach for calculating core distortion reactivity effects in the FFTF.

This thesis presents the core distortion reactivity analysis in two parts. The first describes the reactivity analysis which was made using an R-Z (radial/axial) core model and the existing reactivity model incorporated in NUBOW-3D. The R-Z model analysis provided necessary input for use in the NUBOW-3D reactivity model. It also allowed the calculation of axial worth shape functions for use in evaluating the importance of axial effects on feedback reactivity.

The second part discusses the reactivity analysis made using a detailed HEX (plane) core model combined with the R-Z axial model. This HEX/R-Z model allowed the development of a more comprehensive reactivity analysis method. The new method uses the displacements calculated by NUBOW-3D as input into a more detailed reactivity analysis model contained in a processor code called CORDIS,

which was developed as a part of this thesis. This reactivity model incorporated the axial effects determined in the R-Z core analysis, a control rod insertion effect model not present in the NUBOW-3D reactivity model and a more accurate representation of core heterogeneity effects. The accuracy of this new comprehensive reactivity model was tested against diffusion theory calculations for a uniform core expansion case. It was also used to evaluate the accuracy of the NUBOW-3D reactivity model.

CHAPTER II

REACTIVITY ANALYSIS USING R-Z CORE MODEL

An R-Z model was first chosen for this analysis because it provided a whole core model with radial representation needed to calculate radial row worth gradients (reactivity per radial movement). These worth gradients are required as input to the NUBOW-3D code for use in its reactivity analysis model. A description of this R-Z core model is given in Appendix A.

The following sections describe the reactivity analysis made using the R-Z core model to calculate the row worth gradients needed by NUBOW-3D. Also, an evaluation of the adequacy of the axial worth weighting function used by NUBOW-3D is discussed.

R-Z Model Assumptions

The reactivity model in NUBOW-3D requires the input of radial row worth gradients. Several assumptions are necessary to calculate these worth gradients using the R-Z core model. These are as follows:

- the core expands uniformly in the radial direction (no axial expansion);

- . the entire subassembly is displaced radially during core expansion;
- . since control rod insertion effects are difficult to model in an homogenized radial core model, an all rods out (ARO) case is used;
- . since reactivity effects are due mostly to distortion of the fueled core region, radial reflector regions are not explicitly modeled.

Also assumed in this analysis is that first-order perturbation (FOP) theory can adequately predict core material worths (reactivity coefficients) at each core position. A verification of the adequacy of FOP theory for use in this analysis is discussed in the second part of this thesis. It uses the HEX/R-Z reactivity model developed using the results of the R-Z and HEX reactivity analyses.

Calculational Steps

A flow diagram outlining the calculational steps used in the R-Z reactivity analysis is shown in Figure 1. To begin the analysis, the two-dimensional diffusion theory code, 2DBS,^[2] was used to calculate direct and adjoint flux distributions in the R-Z core geometry.

FIGURE 1. FLOW CHART OF THE CALCULATIONAL STEPS
USED IN THE R-Z REACTIVITY ANALYSIS.

CALCULATIONAL STEPS USED IN R-Z REACTIVITY ANALYSIS

The flux output was then used in a two-dimensional, first-order perturbation theory code, PERTV.^[3] PERTV was modified to write specific subassembly material reactivity coefficient traverses (i.e., the worth of subassembly materials at each core mesh point ($\Delta K/K/KG$)) to files.

The material reactivity coefficient files were then used by a processor code called WORRAD, which was written for this analysis. WORRAD computed radial row worth gradients based on the uniform core expansion assumptions discussed in the previous section.

And finally, the row worth gradients were used in the NUBOW-3D structural analysis code. NUBOW-3D calculated subassembly displacements for specified reactor conditions. Then, using the row worth gradients, NUBOW-3D calculates average subassembly worth gradients and uses these with the subassembly displacements to compute the reactivity response of the core model (the method is described in Chapter I).

Calculational Method

This section describes the details of the R-Z model reactivity analysis incorporated in the WORRAD processor code. Using uniform core expansion assumptions along with

calculated core material reactivity coefficients, WORRAD calculates radial row worth gradients for use in the NUBOW-3D reactivity model.

To begin the analysis, WORRAD calculates subassembly worths ($\Delta K/K$) at each core radial mesh point. This calculation is done by multiplying typical fuel subassembly material masses (KG) by their associated material worths ($\Delta K/K/KG$), as calculated by PERTV. These material worths are calculated at each core matrix location. Combining these material worths axially at each radial mesh point gives subassembly worths radially across the core model. In this analysis, typical inner and outer zone fuel subassembly compositions were considered as well as empty control rod ducts.

Several assumptions are made to ease the calculation of the radial row worth gradients. The first assumption is that the sodium coolant (for a liquid metal fast reactor) acts like a gas in which fuel materials (including structure) can move. In other words, the sodium fills in areas void of fuel materials. Thus, the 'fuel' movement and sodium backfill contributions to the reactivity effect of subassembly displacement are both considered.

The next assumption is that the direction of subassembly motion can be either hexagonal flat to flat or corner to corner. In the analysis, a typical displacement of 1 mil in either direction was assumed to calculate the amount of subassembly volume displaced with uniform expansion. The displacement of 1 mil was chosen to give reactivity effect units of (β /mil).

With the calculation of the amount of subassembly volume displaced, the reactivity contributions of the 'fuel' and sodium are then calculated using the equations shown in Figure 2. Note that the first equation is shown using 'fuel' only. A similar equation is used for sodium. The combination of both the 'fuel' and sodium effects (second equation) yields a subassembly worth gradient for each row. Since an all rods out case is assumed, the reactivity effect of empty control rod duct displacement is also included by using the duct structure material (stainless steel) in place of 'fuel' in the first equation of Figure 2. To preserve continuity of the radial worth gradient calculations at the interface between different subassembly zones (e.g., inner and outer enrichment zone fuel subassemblies) linear extrapolation is used to calculate subassembly worths across the interface.

FIGURE 2. R-Z MODEL APPROACH IN CALCULATING SUBASSEMBLY WORTH GRADIENTS.

R-Z MODEL APPROACH:

REACTIVITY EFFECT - 'FUEL' MOTION

$$G_F = (W_{F_{i+1}} - W_{F_i}) * V * F$$

G = WORTH GRADIENT ($\text{¢}/\text{mil}$)

W = 'FUEL' WORTH (¢)

V = VOL. FRACT. DISPLACED - PER mil

F = 'FUEL' FRACTION

$$\therefore G_{SUB} = G_F - G_{Na}$$

The radial row worth gradients are calculated by multiplying the number of subassemblies in each row by the appropriate subassembly worth gradient for that row. Both peak (core midplane) and average (averaged over axial dimension) material worths are used in the reactivity calculations. These radial row worth gradients are then normalized to yield experimental results from core expansion tests performed in the EMC.^[4] This experimentally derived value was -0.81% /mil due to uniform radial core expansion.

The normalized radial row worth gradients are then used by the NUBOW-3D code to calculate the core distortion reactivity effect based on calculated subassembly displacements. The subassembly displacements are calculated for various thermal/hydraulic reactor conditions.

Preliminary Results

This section discusses the WORRAD calculational results in determining the radial row worth gradients for use in the NUBOW-3D reactivity model. Also, typical core distortion reactivity effects calculated by the NUBOW-3D model are shown.

Table 1 shows the subassembly worths calculated by WORRAD at each radial mesh interval (see Appendix A for

TABLE 1

SUBASSEMBLY WORTH CALCULATIONS

<u>Radial Mesh Interval</u>	<u>Average Assy-Worth ($\Delta K/K$)</u>	<u>Peak Assy-Worth ($\Delta K/K$)</u>
1	.7986-02	.1027-01
2	.7915-02	.1019-01
3	.7860-02	.9991-02
4	.7657-02	.9736-02
5	.7413-02	.9428-02
6	.7099-02	.9150-02
7	.6921-02	.8930-02
8	.0000	.0000
9	.0000	.0000
10	.6430-02	.8253-02
11	.6305-02	.8113-02
12	.6134-02	.7834-02
13	.5770-02	.7390-02
14	.5373-02	.6901-02
15	.6618-02	.8819-02
16	.5361-02	.8506-02
17	.0000	.0000
18	.0000	.0000
19	.5519-02	.7346-02
20	.5287-02	.7070-02
21	.4929-02	.6623-02
22	.4396-02	.5964-02
23	.3855-02	.5284-02

mesh interval spacing). Both average and peak material worths were used in the calculations. Figure 3 shows these subassembly worths as a function of the radial mesh interval. The discontinuities at radial mesh intervals 8, 9, 17 and 18 are due to the modeling of empty control rod ducts in the R-Z model (see Appendix A). The discontinuity across mesh intervals 14 and 15 represents the change in fuel enrichment. The R-Z reactivity analysis model did not extend past mesh interval 23 (end of core without reflector region).

Table 2 shows the subassembly worth gradient calculations using average and peak material worths with the two different subassembly directions of displacement. The 'corner-to-corner' worth gradients are 15.5% higher than the 'flat-to-flat' worth gradients due to the differences in volume displaced in each case. The worth gradient contribution of the empty control rod (C-rod) ducts are over an order of magnitude smaller in effect as the fuel subassemblies.

Table 3 shows the row worth gradient calculations based on the average and peak subassembly worths for both subassembly displacement directions from Table 2. These values show the reactivity effect of moving an entire subassembly row a radial distance of 1 mil. They are

FIGURE 3. SUBASSEMBLY WORTHS AS A FUNCTION OF THE RADIAL MESH INTERVAL.

TABLE 2
SUBASSEMBLY WORTH GRADIENT CALCULATIONS*

Based on Average Material Worth Values

Row	Worth Gradients Flat-to-Flat		Worth Gradients Corner-to-Corner	
	Fuel Assy (Cents/Mil)	C-Rod Assy (Cents/Mil)	Fuel Assy (Cents/Mil)	C-Rod Assy (Cents/Mil)
2	-.3517-02	.0000	-.4061-02	.0000
3	-.4776-02	-.5357-04	-.5515-02	-.6186-04
4	-.5944-02	.0000	-.6864-02	.0000
5	-.8223-02	-.2158-03	-.9495-02	-.2492-03
6	-.8035-02	.0000	-.9278-02	.0000

Based on Peak Material Worth Values

2	-.4836-02	.0000	-.5584-02	.0000
3	-.6443-02	-.1631-03	-.7439-02	-.1883-03
4	-.8145-02	.0000	-.9404-02	.0000
5	-.1127-01	-.4420-03	-.1302-01	-.5104-03
6	-.1092-01	.0000	-.1261-01	.0000

*1\$ = 0.00318 $\Delta K/K$

Note: Control rod (C-Rod) subassemblies are located only in Rows 3 and 5. Hence, the C-Rod worth gradients for Rows 2, 4 and 6 are always zero.

TABLE 3
ROW WORTH GRADIENT CALCULATIONS

Based on Average Material Worth Values

Row	<u>Worth Gradients Flat-to-Flat</u>		<u>Worth Gradients Corner-to-Corner</u>	
	<u>Fuel Assy (Cents/Mil)</u>	<u>C-Rod Assy (Cents/Mil)</u>	<u>Fuel Assy (Cents/Mil)</u>	<u>C-Rod Assy (Cents/Mil)</u>
2	-.2110-01	.0000	-.2437-01	.0000
3	-.4299-01	-.1607-03	-.4963-01	-.1856-03
4	-.1070+00	.0000	-.1235+00	.0000
5	-.1480+00	-.1295-02	-.1709+00	-.1495-02
6	-.2411+00	.0000	-.2783+00	.0000

Based on Peak Material Worth Values

2	-.2902-01	.0000	-.3351-01	.0000
3	-.5799-01	-.4893-03	-.6695-01	-.5650-03
4	-.1466+00	.0000	-.1693+00	.0000
5	-.2029+00	-.2652-02	-.2343+00	-.3062-02
6	-.3276+00	.0000	-.3782+00	.0000

calculated by multiplying the average subassembly worth for a particular row by the number of subassemblies in that row.

Table 4 shows the row worth gradients of Table 3 normalized to yield the EMC experimental value of -0.81% /mil for uniform core expansion. These values are calculated by assuming a uniform core expansion occurs which produces a 1 mil displacement in the outer core radius (end of Row 6). The 1 mil displacement was chosen simply to allow a reactivity effect calculation. Multiplying each row worth gradient from Table 3 by the amount of radial displacement of its mean row radius gives the reactivity effect of each row. Summing the reactivity effect contributions from each row gives a total core reactivity effect. Based on this total reactivity effect value the individual row worth gradients are then normalized to yield the EMC result of -0.81% for a mil of radial core expansion.

Table 5 shows the row worth gradients which were used in the NUBOW-3D code. They represent the average row worth gradients normalized to yield the experimental EMC result of -0.81% /mil for uniform radial core expansion (see Table 4). Note that for Rows 3 and 5, the control rod (C-rod) and fuel subassembly reactivity effects are combined. Also shown are the individual duct (subassembly) worth gradients which represent the average worth gradient

TABLE 4

NORMALIZED ROW WORTH GRADIENTS
 [Normalization Value = $-.8100$ Cents/Mil for Total Core Worth]

Based on Average Material Worth Values

Row	<u>Worth Gradients Flat-to-Flat</u>		<u>Worth Gradients Corner-to-Corner</u>	
	<u>Fuel Assy (Cents/Mil)</u>	<u>C-Rod Assy (Cents/Mil)</u>	<u>Fuel Assy (Cents/Mil)</u>	<u>C-Rod Assy (Cents/Mil)</u>
2	$-.4207-01$	$.0000$	$-.4207-01$	$.0000$
3	$-.8568-01$	$-.3203-03$	$-.8568-01$	$-.3203-03$
4	$-.2133+00$	$.0000$	$-.2133+00$	$.0000$
5	$-.2950+00$	$-.2581-02$	$-.2950+00$	$-.2581-02$
6	$-.4805+00$	$.0000$	$-.4805+00$	$.0000$

Based on Peak Material Worth Values

2	$-.4237-01$	$.0000$	$-.4237-01$	$.0000$
3	$-.8466-01$	$-.7144-03$	$-.8466-01$	$-.7144-03$
4	$-.2140+00$	$.0000$	$-.2140+00$	$.0000$
5	$-.2963+00$	$-.3872-02$	$-.2963+00$	$-.3872-02$
6	$-.4782+00$	$.0000$	$-.4782+00$	$.0000$

TABLE 5

REACTIVITY EFFECTS-UNIFORM RADIAL CORE EXPANSION*
(R-Z GEOMETRY)

<u>Row</u>	<u>Motion of Entire Row (ϵ/Mil)</u>	<u>Individual Duct Motion (ϵ/Mil)</u>
2	-0.0421	-0.00702
3	-0.0860	-0.00717
4	-0.213	-0.0118
5	-0.298	-0.0124
6	-0.480	-0.0160

*Fuel and control rod duct (rods out) worths
have been homogenized for rows 3 and 5.

of a subassembly in a particular row. These are obtained by dividing the row worth gradient by the number of subassemblies in that row.

Figure 4 shows the reactivity effects calculated by NUBOW-3D using the radial row worth gradients calculated by WORRAD. The core distortion reactivity response is calculated for various core thermal/hydraulic conditions as indicated by the power-to-flow ratio (% of full power/% of full flow). The calculated reactivity response shown in Figure 4 is approximate due to the following effects:

. the cosine-squared axial model used in NUBOW-3D;

FIGURE 4. CORE DISTORTION REACTIVITY EFFECTS CALCULATED BY
NUBOW-3D FOR VARIOUS THERMAL/HYDRAULIC
CONDITIONS.

- . masking of core heterogeneities by the R-Z model;
- . uncertainties in the subassembly displacements calculated by NUBOW-3D.

To determine the adequacy of the NUBOW-3D axial model, an evaluation was made using WORRAD. This evaluation is discussed in the next section.

Axial Worth Shapes

The evaluation of the axial worth shapes consisted of using material worths at different axial levels to calculate the radial row worth gradients. By normalizing these worth gradients to the average row worth gradients and the EMC experimental result, an axial distribution is determined. The resultant normalized radial row worth gradients are shown in Table 6 at the axial position from which the material worths are taken. These worth gradients are plotted in Figure 5 as a function of the axial dimension.

To model the axial worth distribution exhibited in Figure 5, a row-dependent axial weighting function was determined using a new processor code called PARAM. PARAM finds the best fit to the axial data between a parabolic and chopped cosine function based on input variables and the resultant percent deviation of each fit from the actual

TABLE 6

NORMALIZED ROW WORTH GRADIENTS BY AXIAL LEVEL
(CENTS/MIL)

Axial Level of Material Worths	Row 2	Row 3	Row 4	Row 5	Row 6
average	-.4207-01	-.8600-01	-.2133+00	-.2976+00	-.4805+00
peak	-.5784-01	-.1166+00	-.2922+00	-.4097+00	-.6529+00
8*	-.2328-01	-.4625-01	-.1101+00	-.1545+00	-.2480+00
9	-.2975-01	-.5791-01	-.1377+00	-.1935+00	-.3159+00
10	-.3553-01	-.7012-01	-.1695+00	-.2377+00	-.3852+00
11	-.4119-01	-.8198-01	-.2004+00	-.2812+00	-.4528+00
12	-.4641-01	-.9288-01	-.2291+00	-.3214+00	-.5153+00
13	-.5093-01	-.1022+00	-.2540+00	-.3561+00	-.5693+00
14	-.5446-01	-.1095+00	-.2734+00	-.3835+00	-.6116+00
15	-.5682-01	-.1144+00	-.2865+00	-.4017+00	-.6401+00
16	-.5784-01	-.1166+00	-.2922+00	-.4097+00	-.6529+00
17	-.5747-01	-.1159+00	-.2905+00	-.4074+00	-.6494+00
18	-.5576-01	-.1124+00	-.2814+00	-.3946+00	-.6300+00
19	-.5278-01	-.1062+00	-.2655+00	-.3721+00	-.5958+00
20	-.4870-01	-.9763-01	-.2440+00	-.3408+00	-.5493+00
21	-.4379-01	-.8685-01	-.2188+00	-.3018+00	-.4946+00
22	-.3759-01	-.7415-01	-.1937+00	-.2567+00	-.4382+00
23	-.2999-01	-.6398-01	-.1615+00	-.2183+00	-.3662+00
24	-.2248-01	-.5420-01	-.1269+00	-.1800+00	-.2950+00
25**	-.1240-01	-.4484-01	-.1038+00	-.1460+00	-.2392+00

*Bottom of active fuel (see Appendix A)

**Top of active fuel (see Appendix A)

FIGURE 5. AXIAL DISTRIBUTIONS OF THE ROW WORTH GRADIENTS.

AXIAL WORTH SHAPES

data. The functions modeled in PARAM and the deviation equation are shown below.

Parabolic FCN: $W_i = aZ^2 + W_{PK}$

W_i = row worth gradient @ axial position Z_i

W_{PK} = peak row worth gradient (FCN)

$Z = (Z_i - Z_{MID})$

Z_i = axial position i

Z_{MID} = axial midpoint position (FCN)

a = parabolic factor (TBD)

FCN = function dependent

TBD = to be determined

Cosine FCN: $W_i = W_{PK} \cos^{\alpha} \left[\frac{\pi Z}{H'} \right]$

W_i = row worth gradient @ axial position Z_i

W_{PK} = peak row worth gradient (FCN)

$Z = (Z_i - Z_{MID})$ as defined above

H' = extrapolated core height (FCN)

α = cosine FCN power (TBD)

FCN = function dependent

TBD = to be determined

Both functions were compared by using the standard deviation normalized to the peak row worth gradient (W_{PK}).

$$\% \text{ of peak} = \left(\frac{100}{W_{PK_{FCN}}} \right) \left[\sum_{i=1}^k \left(\frac{W_i_{\text{actual}} - W_i_{FCN}}{k-1} \right)^2 \right]^{1/2}$$

k = number of axial levels.

PARAM results showed that a cosine function best fit the axial worth distribution (see Figure 5). The best fit row-dependent cosine function variables are shown in Table 7. Also shown is the percent deviation comparisons between the best fit cosine function and the cosine-squared model as incorporated in the NUBOW-3D code. This comparison was made by setting $\alpha=2$.

TABLE 7
BEST FIT ROW-DEPENDENT COSINE FUNCTION VARIABLES

Row	Midpt.	Extrap. Height	α	Functional Peak Worth	Actual Peak Worth	%	% $\alpha=2$
2	16.10	21.0	.9620	.05785	.05784	1.61	18.1
3	16.25	31.0	2.332	.1167	.1166	1.27	3.57
4	16.40	30.0	2.278	.2928	.2922	0.89	2.96
5	16.35	31.0	2.502	.4103	.4097	1.17	5.00
6	16.35	31.0	2.368	.6539	.6529	0.56	3.78

In view of the results shown in Table 7, a cosine-squared, axial weighting function is not the best fit for modeling the axial worth dependence.

R-Z Model Conclusions

From the results of the R-Z reactivity analysis, several conclusions were made:

- . the adequacy of the R-Z core model in describing core distortion reactivity effects of heterogeneous hexagonal components is questionable;
- . the chopped cosine-squared model used by NUBOW-3D to represent the axial shape of the distortion reactivity is not completely correct; the axial shape depends on radial position;
- . the sodium backfill contribution to the reactivity effects was small compared to the 'fuel' (subassembly materials excluding sodium) movement contribution;
- . in general, the reactivity effects of small displacements of the inner core subassemblies are smaller than those in the outer enrichment zones;

This is due to the steeper flux gradient and higher enrichment in the outer fuel regions.

The overall conclusion is that a more comprehensive core distortion reactivity model is needed which is more accurate in modeling core heterogeneities. Also, this new model should include row-dependent axial worth weighting functions and model control rod insertion effects.

CHAPTER III

REACTIVITY ANALYSIS USING HEX/R-Z CORE MODEL

To provide a more comprehensive core model which accurately represents core heterogeneities, a HEX (plane) core model was chosen to evaluate both the azimuthal and radial components of core distortion reactivity. A description of this core model is given in Appendix B. This core model also allowed an evaluation of control rod effects on core distortion reactivity.

To model the axial core dimension, the axial worth distribution functions determined in the R-Z analysis are used to extend subassembly worth gradient components from the HEX analysis axially. Using this HEX/R-Z core model, a new core distortion reactivity analysis method was developed. This new method uses displacements calculated by NUBOW-3D as input to a separate reactivity analysis model contained in a new processor code called CORDIS. The CORDIS reactivity model incorporates the axial effects determined in the R-Z core analysis, a control rod insertion effect model not present in the NUBOW-3D reactivity model, and a more accurate representation of core heterogeneity effects.

The following sections describe the reactivity analysis made using the HEX/R-Z core model and the development of the new core distortion reactivity analysis method (CORDIS). Also, a comparison of CORDIS and NUBOW-3D reactivity response calculations is discussed.

HEX Model Assumptions

To perform a reactivity analysis using the HEX core model, several assumptions are necessary. These are as follows:

- . the HEX model represents the average core midplane (i.e., it's necessary to include row-dependent peak-to-average factors in the axial worth distribution cosine function);
- . the control rod insertion effects can be adequately modeled using a simple synthesis approach -- material worths calculated with all rods out (ARO) will be used below the control rod bank height; and material worths calculated with all rods in (ARI-secondary control rods only -- Row 5) will be used above the control rod bank height;

- . the subassembly worth gradients can be adequately represented by two X and Y components.

As in the R-Z analysis, it is assumed that FOP theory can adequately predict core material worths (reactivity coefficients) at each core position. A verification of the adequacy of FOP theory for use in this analysis is made using the HEX/R-Z reactivity model. This model is developed from a combination of the R-Z and HEX reactivity analyses and is discussed in the following sections.

Calculational Steps

A flow diagram outlining the calculational steps used in the HEX/R-Z reactivity analysis is shown in Figure 6. To begin the analysis, the two-dimensional diffusion theory code, 2DBS, was used to calculate direct and adjoint flux distributions in the HEX core geometry.

The flux output was then used in the two-dimensional, first-order perturbation theory code, PERTV. Also used in PERTV were collapsed cross-sections calculated using a one-dimensional diffusion theory code, 1DX.^[5] These effective cross-sections were calculated for only seven main subassembly types as shown in Appendix B. The sodium contained in each subassembly type was represented by seven

FIGURE 6. FLOW CHART OF THE CALCULATIONAL STEPS USED IN
THE HEX/R-Z REACTIVITY ANALYSIS.

additional effective cross-sections. These 14 effective cross-sections reduced the amount of calculations done by PERTV in determining material reactivity coefficients and was very cost efficient.

Due to the reduced number of input materials, PERTV was modified to calculate subassembly worths at each core mesh point. This was done by having PERTV 'fold' the masses of each core material (KG) into their respective material worths ($\Delta K/K/KG$) at each core mesh point.

To maintain the necessary continuity of the material worths across interfaces, the material masses representing each subassembly type were uniformly spread over each core mesh point. The subassembly worths were then calculated at each mesh point by summing the 'fuel' and sodium component worths of each subassembly type. These subassembly worths, along with the material core map used in PERTV, were then written to a file for use in a new core distortion reactivity analysis model.

This new model embodies the HEX and R-Z reactivity analyses and is contained in a processor code called CORDIS. CORDIS uses subassembly displacement data calculated by NUBOW-3D (or ABAQUS)⁽⁶⁾ and subassembly worth data calculated by PERTV to calculate a core

distortion reactivity effect. NUBOW-3D was modified to write subassembly displacements in X and Y components, oriented with the HEX core model, to files. These displacements also extend in the axial dimension due to the three-dimensional structure of NUBOW-3D. To represent the axial subassembly worth distribution, CORDIS uses the row-dependent axial functions calculated by PARAM in the R-Z reactivity analysis.

Note that the reactivity model contained in NUBOW-3D is no longer needed for reactivity effect calculations. Only the displacements calculated by NUBOW-3D are needed for use in the new reactivity model, CORDIS.

Calculational Method

This section discusses the details of the new reactivity analysis method incorporated in the CORDIS processor code. The CORDIS code description, input instructions and the code listing are given in Appendix C.

CORDIS begins the analysis by first resolving the subassembly worths calculated by PERTV into X and Y component subassembly worth gradients. The method of calculating these component worth gradients is outlined in Figure 7 for the X-component. CORDIS makes these calculations for both

FIGURE 7. HEX MODEL APPROACH IN CALCULATING SUBASSEMBLY
WORTH GRADIENT COMPONENTS.

HEX MODEL APPROACH:

WORTH GRADIENT X-COMPONENT:

$$\begin{aligned} G_x = & [G_5 + G_7 - G_1 - G_{11}] * \text{COS. } 30 \\ & + [G_8 + G_4 - G_2 - G_{10}] * \text{COS. } 60 \\ & + G_6 - G_{12} \end{aligned}$$

the ARO and ARI cases for use in a control rod insertion reactivity effect synthesis model described later.

As shown in Figure 7, there are 12 worth gradients (G_i) calculated for each subassembly. These gradients are then resolved into X and Y components. The individual gradients are calculated by taking the change in subassembly worth across the subassembly HEX perimeter divided by the distance between the calculational mesh points. There are six mesh points per subassembly HEX, located in the centroid of each triangular region.

Thus, for subassemblies which do not lie on the HEX core edge, 24 mesh points are involved in calculating the 12 subassembly worth gradients (i.e., across the HEX faces, two mesh points are used; at the corners, four mesh points are used). At the core edge, appropriate modifications are made to use as many mesh points as possible.

For comparison purposes, CORDIS also calculates the radial subassembly worth gradients for each subassembly type. Combining these for a particular row gives a row worth gradient. These results can be compared directly to the radial row worth gradients calculated by the R-Z model when allowance is made for the different types of subassemblies contained in the individual rows.

After computing the subassembly worth gradient components and their radial worths, CORDIS computes the 'true' X and Y subassembly displacement components using NUBOW-3D displacement output. The term 'true' refers to a combination of isothermal expansion and duct bowing effects, which are calculated separately by NUBOW-3D. A description of the NUBOW-3D displacement data file format is given in Appendix D. If a uniform radial expansion test case is desired, CORDIS calculates the displacement data per user specifications (see Appendix C).

An important assumption regarding the NUBOW-3D displacement data was necessary for the reactivity effect calculations. Due to cost and convergence limitations, NUBOW-3D only analyzed an all fuel, twelfth-core sector model (12 subassemblies) out to row six (no reflectors included). The displacement data calculated for those 12 subassemblies was assumed to be representative of all subassemblies in a full core model.

The NUBOW-3D sector model also required a no azimuthal motion boundary condition on the subassemblies located on the sector edge. This may have limited the displacement response calculations since the true subassembly interaction effects were not explicitly modeled. A description of the NUBOW-3D core model is given in Appendix D.

It should be noted that CORDIS is also able to accept displacement data from other core structural analysis codes like ABAQUS. It is only necessary that the displacement data file be formatted as shown in Appendix D. NUBOW-3D was chosen for this analysis because of its inherent reactivity analysis model.

With both subassembly worth gradient and true displacement X and Y components calculated, CORDIS then sets up the axial dimension. Since NUBOW-3D uses a three dimensional core model, the displacement data are already calculated over the axial dimension. Therefore, CORDIS need only extend the worth gradients axially. This is done by using the row-dependent axial weighting functions calculated by PARAM in the R-Z analysis. For reflector rows 7, 8 and 9, a cosine-squared axial worth distribution is assumed along with the row 6 axial function, since these rows were not explicitly modeled in the R-Z analysis.

An additional row-dependent peak-to-average factor is included in the chopped cosine models to account for the average core midplane representation in the worth calculations using the HEX model. This factor is also derived from the R-Z analysis directly from the ratios of the peak-to-average row worth gradients calculated by WORRAD.

To model the control rod insertion effect, CORDIS uses the subassembly worth gradient components calculated from the ARO case below the secondary control rod bank height. Above the bank position, CORDIS uses the ARI case worth gradient data. Since control rod effects are difficult to model, this synthesis approach was thought to be a good first step in characterizing control rod effects. Later analyses could provide a more detailed model if needed. Figure 8 shows the control rod insertion effect model used by CORDIS over the core region.

With the axial modeling setup, CORDIS finally calculates the reactivity effect of core distortion. This is done by integrating the subassembly worth gradient components, multiplied by the displacement components, axially over each subassembly. The integration is done numerically using the trapazoidal method. The integration is then normalized by the integral of the axial worth distribution functions (the row-dependent cosine models from PARAM). The summation of the computed subassembly reactivity effects then gives the total core model reactivity effect. This integration method is also shown in Figure 8.

If the core model used in CORDIS is only a partial core sector, CORDIS will automatically calculate a complete core reactivity effect based on computed average row

FIGURE 8. CONTROL ROD INSERTION EFFECT MODEL AND NUMERICAL
INTEGRATION MODEL USED BY CORDIS.

NUMERICAL INTEGRATION MODEL:

$$\frac{\Delta K}{K} = \sum_{j=1}^{\text{ALL NODES}} \frac{\int W_x(Z) \cdot D_x(Z) + W_y(Z) \cdot D_y(Z) dZ}{\int \cos^{\alpha} \left(\frac{\pi (Z - Z_{MID})}{2 Z_D} \right) dZ}$$

$$W_x(Z) = G_x A(Z)$$

reactivity effects. CORDIS can model various core sectors or a whole core model. Sector modeling is convenient when establishing the bounds of the calculated core distortion reactivity response for various heterogeneity models.

By running NUBOW-3D for different thermal/hydraulic and/or time dependent inelastic (creep and swelling) affected reactor states, subassembly displacement files for the various states can be calculated. Using CORDIS, the core reactivity response at each reactor state can be calculated. Thus, a prediction of the duct bowing reactivity effect on the FFTF reactivity feedbacks is possible by evaluating the slope of the reactivity response curve for the various reactor states.

An additional capability of CORDIS to model uniform core expansion also allows direct comparison of the CORDIS reactivity results to $(\Delta K/K)$ calculations using the 2DBS code for the same core expansion case. This comparison can also be made to experimental results from core expansion tests such as those in the EMC.

Using a uniform core expansion test case, CORDIS calculations were compared to 2DBS calculations to verify the adequacy of FOP theory for use in this analysis. This verification is discussed in Appendix E.

Results

Using the CORDIS code, the influence of heterogeneous structure on reactivity response due to core distortion effects in the FFTF was evaluated. This evaluation used different FFTF twelfth-sector core configurations representing a range of possible sector models involving various core heterogeneities (shown in Figure 9). The reactivity results calculated with CORDIS for various core sector models and reactor conditions are also shown in Figure 9. These reactivity results have been adjusted for FOP theory modeling criteria as discussed in Appendix E. The comparative cases shown in the table between CORDIS and NUBOW-3D indicate the versatility of the CORDIS code. Thus, CORDIS represents a very cost efficient way of making such reactivity calculations.

Allowing for the differences in core components between the R-Z and HEX models, the CORDIS average radial row worth gradients are shown in Table 8, compared to the R-Z results from Table 7.

As evidenced by Table 8, heterogeneity effects gave overall positive radial row worth gradients to Rows 2 and 4 in the HEX model. This was mainly due to the movement of in-core shims into fuel regions and fuel into empty control

FIGURE 9. COMPARISON OF HEX/R-Z REACTIVITY ANALYSIS
RESULTS (CORDIS) WITH NUBOW-3D RESULTS.

HEX/R-Z REACTIVITY ANALYSIS RESULTS:

CR CONTROL ROD
 ICS IN-CORE SHIM
 SR SAFETY ROD
 PSR PERIPHERAL SHIM ROD
 IRT IN-CORE REACTOR THIMBLE
 VOTA VIBRATION OPEN TEST ASSEMBLY

<u>REACTIVITY CHANGE, ρ</u>			
<u>CORDIS</u>			<u>NUBOW 3-D*</u>
<u>CONTROL ROD BANK HEIGHT</u>			
<u>TWELFTH CORE</u> <u>CONFIGURATION</u>	<u>18 INCHES</u>	<u>36 INCHES</u> <u>(FULL OUT)</u>	<u>36 INCHES</u> <u>(FULL OUT)</u>
SECTOR 1	-23.6	-19.6	
SECTOR 2	-32.6	-35.1	
SECTOR 3	-31.7	-26.1	
ALL FUEL SECTOR	-39.9	-32.7	-44.0

*NUBOW-3D DOES NOT HANDLE CONTROL ROD INSERTION CASES.

TABLE 8

REACTIVITY EFFECTS-UNIFORM RADIAL CORE EXPANSION
(HEX and R-Z Geometry)Motion of Entire Row (ϕ /mil)

<u>Row</u>	<u>HEX</u>	<u>R-Z</u>
2	+.00840	-.0421
3	-.0511	-.0860
4	+.0168	-.213
5	-.257	-.298
6	-.594	-.480

rod duct channels. Thus, core heterogeneity must be accurately accounted for in distortion reactivity calculations.

HEX/R-Z Model Conclusions

From the results of the HEX/R-Z reactivity analysis, several conclusions were made:

- . the azimuthal heterogeneity effect on distortion reactivity is substantial and should not be ignored;
- . core heterogeneity must be accounted for in core distortion reactivity effect calculations; in fact, the HEX model shows net positive reactivity contributions from individual core rows, which is

in contrast to the R-Z model prediction of a negative reactivity effect for each row;

- . the presence of control rods in the core increases (in the negative direction) distortion reactivity; however, this effect is not large.

CHAPTER IV

SUMMARY

An improved technique for evaluating core distortion reactivity effects was developed using reactivity analyses of two core geometry models (R-Z and HEX).

The reactivity analysis using an R-Z core model provided radial row worth gradients (reactivity per radial movement). These were needed for use in an existing reactivity model contained in a three dimensional structural analysis code, NUBOW-3D. The R-Z representation also allowed an evaluation of axial worth shapes. Based on this R-Z reactivity analysis it appeared that a radial smear model was inadequate in treating core heterogeneities. Also, row-dependent axial shape functions were more appropriate than the chopped cosine-squared model present in NUBOW-3D.

A more comprehensive reactivity analysis was then made by using a HEX (plane) core model. This model preserved core heterogeneity effects by accounting for both azimuthal and radial reactivity effects.

To develop an improved core distortion reactivity analysis method, the R-Z axial model and the HEX (plane) model

were combined into a HEX/R-Z reactivity analysis model. This HEX/R-Z model represents a new analysis method and is contained in a new processor code called CORDIS. CORDIS incorporates the row-dependent axial worth shape functions determined in the R-Z analysis, contains a control rod insertion effect model, preserves core heterogeneity effects, and provides a flexible and cost efficient analysis method. CORDIS can also accept displacement data calculated by either the NUBOW-3D code or the ABAQUS structural analysis code.

Core distortion reactivity response calculations made using CORDIS were compared to diffusion theory calculations for a uniform core expansion case. The CORDIS results, which are based on first-order perturbation (FOP) theory, were in good agreement with diffusion theory results when allowance was made for radial leakage effects unaccounted for in FOP theory. To account for these leakage effects, appropriate scaling factors were used in later CORDIS calculations. When NUBOW-3D calculations were included in the comparison, it was evident that core distortion reactivity calculations should be made using the more comprehensive CORDIS reactivity model.

Conclusions

Three main conclusions can be drawn from this work.
For the FFTF and similar liquid metal fast reactors:

- (1) A simple "ring-wise" worth gradient does not adequately describe distortion reactivity effects of heterogeneous hexagonal components.
- (2) The chopped cosine-squared model for the axial shape of the distortion reactivity is not completely correct; the axial shape depends on radial position.
- (3) The presence of control rods in the core increases (in the negative direction) distortion reactivity, however, this effect is not large.

The CORDIS code represents a cost efficient reactivity model which accounts for the core heterogeneity and control rod effects and also contains an improved axial model.

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APPENDIX A

R-Z CORE MODEL DESCRIPTION

The core geometry used in the R-Z analysis is shown in Figure 10. A reflective boundary condition at the core centerline was used in this analysis. Compositions are given in Table 9 for core components and for homogenized zones. The material compositions used in this R-Z analysis were based on the most current FFTF design data at the time as given in Reference 7. One exception was the stainless steel composition for the control rod and peripheral shim rod which was updated to reflect design changes. All densities are for beginning of life (BOL) hot core conditions (mean core temperature of approximately 830°F).

The core was fully loaded with several closed loop and material tests included. All control rods were withdrawn with the resultant sodium channel zones represented separately from the fuel zones (see Figure 10). The R-Z core matrix consisted of 33 radial mesh points with 40 axial mesh points.

The neutron energy spectrum was represented by a twelve-group structure with five downscatter groups and is shown in Table 10. This energy structure was evaluated in

FIGURE 10. R-Z FULL CORE GEOMETRY WITH ZONE NUMBER
DESIGNATIONS AND MESH STRUCTURE.

TABLE 9

CORE COMPONENT COMPOSITIONS
(atoms/bn-cm)

Inner Zone Driver (ID) (Fueled Region)		Outer Zone Driver (OD) (Fueled Region)	
Pu-239	0.0013873		0.0016965
Pu-240	0.0001880		0.0002294
Pu-241	0.0000268		0.0000327
U-235	0.0000390		0.0000366
U-238	0.0055380		0.0051960
O	0.0140750		0.0141020
Na	0.0089717		0.0089717
S/S(a)	0.0194070		0.0194070
General Purpose Fueled Closed Loop Test (GCLT) -- Row 2/Row 4		Special Purpose Fueled Closed Loop Test (SCLT) -- Row 4/Row 6	
Pu-239	0.0002360		0.0000447
Pu-240	0.0000322		0.0000061
Pu-241	-		-
U-235	0.0000381/0.0000678		0.0000229/0.0000507
U-238	0.0009132/0.0008835		0.0001571/0.0001292
O	0.0024030		0.0004546
Na	0.0142480		0.0155415
S/S	0.0184580		0.0171720
Radial Reflector (RR)		Axial Reflector (AR)	Radial Shield (RS)
	Row 7	Rows 8&9	
Na	0.003083	0.0020355	0.004408
S/S(a)	0.018055	0.0265936	0.065476
Inc(b)	0.055596	0.0506141	-

TABLE 9 (Cont'd)

	Lower Radial Shield (LRS)	Upper Radial Shield (URS)	
	Row 7	Row 7	Rows 8&9
Na	0.0046564	0.0030544	0.0020047
S/S (a)	0.0642352	0.0701666	0.0740530

	Lower Axial Shield (LAS)	Above/Below Control Rod (ABCR)	Gas Plenum (GP)
Na	0.0055895	0.007024	0.0088881
S/S (a)	0.0607807	0.029495	0.0239782

	Sodium Channel (NaCh)	Material Test (MT)	Drive Line (DL)
Na	0.019889	0.009022	0.0166076
S/S (a)	0.007838	0.046441	0.0199859

Control Rod and Peripheral Shim Rod (CR&PSR)

Na	0.007024
S/S (a)	0.029495
B-10	0.006351
B-11	0.025723
C	0.008018

(a) Composition of Stainless Steel 316 (atom percent)

64.38% Fe
19.08% Cr
13.05% Ni
1.47% Mo
1.80% Mn
0.22% C

TABLE 9 (Cont'd)

(b) Composition of Inconel 600 (atom percent)

7.44% Fe
17.52% Cr
74.64% Ni
0.21% Mn
0.19% C

TABLE 9 (Cont'd)

<u>Zone Number</u>	<u>Material</u>	<u>Volume Fraction</u>
1	ID	1.000
2	ID	0.833
	GCLT2	0.167
3	ID	1.000
4	ID	0.833
	GCLT4	0.056
	SCLT4	0.056
	MT	0.056
5	OD	1.000
6	OD	0.933
	SCLT6	0.033
	MT	0.033
7	RR7	0.958
	PSR	0.042
8	RR89	1.000
9	RS	1.000
10	NaCh	1.000
11	ABCR	1.000
12	LAS	1.000
13	LRS7	1.000
14	AR	1.000
15	RR7	0.917
	ABCR	0.083
16	CR	0.700
	NaCh	0.300
17	GP	1.000
18	URS7	0.917
	DL	0.083
19	URS89	1.000

TABLE 10
TWELVE-GROUP ENERGY STRUCTURE^[7]

<u>Group # for Twelve-Group Set</u>	<u>Energy Boundaries (eV)</u>	<u>Lethargy Interval</u>
1	6.065+06 to 1.000+07	.500
	3.679+06 to 6.065+06	.500
2	2.231+06 to 3.679+06	.500
	1.353+06 to 2.231+06	.500
3	8.209+05 to 1.353+06	.500
	4.979+05 to 8.209+05	.500
4	3.877+05 to 4.979+05	.250
	3.020+05 to 3.877+05	.250
5	1.832+05 to 3.020+05	.500
	1.111+05 to 1.832+05	.500
6	6.738+04 to 1.111+05	.500
	4.087+04 to 6.738+04	.500
7	2.554+04 to 4.087+04	.470
	1.989+04 to 2.554+04	.250
	1.503+04 to 1.989+04	.280
8	9.119+03 to 1.503+04	.500
	5.531+03 to 9.119+03	.500
9	3.355+03 to 5.531+03	.500
	2.840+03 to 3.355+03	.167
	2.404+03 to 2.840+03	.167
	2.035+03 to 2.404+03	.167
10	1.234+03 to 2.035+03	.500
	7.485+02 to 1.234+03	.500

TABLE 10 (Cont'd)

<u>Group # for Twelve-Group Set</u>	<u>Energy Boundaries (eV)</u>	<u>Lethargy Interval</u>
11	4.540+02 to 7.485+02	.500
	2.754+02 to 4.540+02	.500
12	1.301+02 to 2.754+02	.750
	6.144+01 to 1.301+02	.750
	1.371+01 to 6.144+01	1.500
	6.826-01 to 1.371+01	3.000
	2.520-2	--

Reference 7 and was considered to be more than adequate for a detailed analysis of this kind.

Cross sections were taken from previous work in which the FTR-300S cross section set was collapsed to twelve energy groups using the 1DX computer code.^[7] The materials used are shown in Table 11.

TABLE 11

MATERIALS USED IN 2-D, R-Z CALCULATIONS*
 (cross sections are read-in for the following materials)

1	Pu239	1300K, Zone 1
2	Pu240	1300K, Zone 1
3	Pu241	1300K, Zone 1
4	U235	1300K, Zone 1
5	U238	1300K, Zone 1
6	0	1300K, Zone 1
7	NA	750K, Zone 1
8	SSID	Stainless Steel Inner Driver
9	Pu239	1300K, Zone 2
10	Pu240	1300K, Zone 2
11	Pu241	1300K, Zone 2
12	U235	1300K, Zone 2
13	U238	1300K, Zone 2
14	0	1300K, Zone 2
15	NA	750K, Zone 2
16	SSOD	Stainless Steel Outer Driver
17	NA	750K, Sr Na Channel
18	SSSR	Stainless Steel Sr Na Channel
19	SSRRI	Stainless Steel Radial Refl Row 7
20	INCR7	Inconel Radial Refl Row 7
21	NA	750K, Row 7 Radial Refl
22	SSLS	Stainless Steel Lower Shield
23	NA	650K, Lower Shield
24	SSMT	Stainless Steel Material Test
25	NA	750K, Material Test
26	Pu239	1300K, GPCL Row 2
27	Pu240	1300K, GPCL Row 2
28	U235	1300K, GPCL Row 2
29	U238	1300K, GPCL Row 2
30	0	1300K, GPCL Row 2
31	NA	750K, GPCL Row 2
32	SSGP2	Stainless Steel GPCL Row 2
33	SSTAR	Stainless Steel Axial Refl Top
34	INTAR	Inconel Axial Refl Top
35	NA	800K, Axial Refl Top
36	SSPL	Stainless Steel Plenum
37	NA	800K, Plenum
38	SSCR	Stainless Steel Control Rod Row 5
39	NA	750K, Row 5 CR
40	B10	1050K, Row 5 CR
41	B11	1050K, Row 5 CR
42	C	1050K, Row 5 CR
43	ID	Inner Driver, NA In, U238 T=1300K
44	OD	Outer Driver, NA In, U238 T=1300K
45	IDNAO	Inner Driver, NA Out, U238 T=1300K
46	ODNAO	Outer Driver, NA Out, U238 T=1300K

TABLE 11 (Cont'd)

47	IDDOP	Inner Driver, NA In, U238 T=1650K
48	ODDOP	Outer Driver, NA In, U238 T=1650K
49	FP	1300K, Zone 1

*Temperature designations represent the temperature at which the cross sections were evaluated.

APPENDIX B

HEX CORE MODEL DESCRIPTION

The core geometry used in the HEX analysis is shown in Figure 9 of the main text, where the inner zone fuel extends through row 4. This core differs from the R-Z analysis core because it was desired that the HEX core show the current FFTF core loading. At the time, this core was representative of test period T-16, which was the core loading prior to the first full power ascent in FFTF. This was because CORDIS would be used to predict the duct bowing effect on the FFTF reactivity feedbacks for this test period core loading. Thus, it was convenient to do the reactivity analysis using this core model.

The material compositions were updated from the R-Z model to reflect as-built compositions. These compositions are given in Table 12. All densities are for the BOL hot core conditions (mean core temperature of approximately 830°F), representative of full power operation in FFTF. As explained in the HEX/R-Z analysis section, both an ARO (primary and secondary control rods) and an ARI (secondary control rods only -- row 5) core model case was used.

To account for axial leakage, a modified space and energy independent buckling term (B^2) was used in the

TABLE 12

CORE COMPONENT COMPOSITIONS
(atoms/bn-cm)

<u>Isotope</u>	<u>Inner Drivers</u>	<u>Outer Drivers</u>	<u>In-Core Shims</u>	<u>VOTA*</u>	<u>Radial** Shield</u>
Pu-239	0.001394	0.001706			
Pu-240	0.000200	0.000245			
Pu-241	0.000027	0.000033			
U-235	0.000039	0.000037			
U-238	0.005590	0.005262			
Oxygen	0.014211	0.014211			
SS	0.019419	0.019419	0.046234	0.018655	0.065184
Na	0.009068	0.009068	0.009068	0.016970	0.004415

<u>Isotope</u>	<u>Absorber</u>	<u>Absorber Channel</u>	<u>Row 7 Reflector</u>	<u>Rows 8&9 Reflector</u>
B-10	0.006323			
B-11	0.025608			
C	0.007982			
SS	0.027984	0.007803	0.017974	0.026475
Inconel			0.055348	0.050388
Na	0.007035	0.019919	0.003255	0.002039

*In the HEX model, the Vibration Open Test Assembly (VOTA) was represented by an In-Core Shim to reduce the number of core materials modeled.

**In the HEX model, the radial shield was represented by Row 7 reflector material.

2DBS and PERTV calculations for each core model. This buckling term was taken from Reference 8 for a standard all control rods out case, which gave a value of 550 E-6 cm^{-2} . This B^2 value was used uniformly over the entire calculational mesh, which was a 51×30 mesh matrix with a sub-assembly pitch (flat-to-flat) of 4.74 inches. Since the calculations involved changes between mesh points (gradients), adjustments to B^2 to account for control rod insertion should not affect the calculational results.

As in the R-Z model, a twelve-group energy spectrum was used with five down-scatter groups (see Appendix A). Cross sections were taken from a twelve-group file prepared by work in Reference 7. The materials used are shown in Table 13.

TABLE 13

MATERIALS USED IN 2-D, HEX CALCULATIONS*
 (cross sections are read-in for the following materials)

1	Pu239	1300K, Zone 1
2	Pu240	1300K, Zone 1
3	Pu241	1300K, Zone 1
4	U235	1300K, Zone 1
5	U238	1300K, Zone 1
6	0	1300K, Zone 1
7	NA	750K, Zone 1
8	SSID	Stainless Steel Inner Driver
9	Pu239	1300K, Zone 2
10	Pu240	1300K, Zone 2
11	Pu241	1300K, Zone 2
12	U235	1300K, Zone 2
13	U238	1300K, Zone 2
14	0	1300K, Zone 2
15	NA	750K, Zone 2
16	SSOD	Stainless Steel Outer Driver
17	NA	750K, Sr Na Channel
18	SSSR	Stainless Steel Sr Na Channel
19	SSRRI	Stainless Steel Radial Refl Row 7
20	INCR7	Inconel Radial Refl Row 7
21	NA	750K, Row 7 Radial Refl
22	SSLS	Stainless Steel Lower Shield
23	NA	650K, Lower Shield
24	SSMT	Stainless Steel Material Test
25	NA	750K, Material Test
26	CR	750K, Material Test
27	NI	750K, Material Test
28	FE	750K, Material Test
29	MO	750K, Material Test
30	MN	750K, Material Test
31	C	750K, Material Test
32	Pu242	1300K, Zone 1
33	Pu242	1300K, Zone 2
34	FP	1300K, Zone 1
35	FP	1300K, Zone 2
36	SSPL	Stainless Steel Plenum
37	NA	800K, Plenum
38	SSCR	Stainless Steel Control Rod Row 5
39	NA	750K, Row 5 CR
40	B10	1050K, Row 5 CR
41	B11	1050K, Row 5 CR
42	C	1050K, Row 5 CR
43	SSPSR	Stainless Steel Peripheral Shim Rod
44	NA	750K, Row 7 PSR
45	B10	1050K, Row 7 PSR
46	B11	1050K, Row 7 PSR

TABLE 13 (Cont'd)

47	C	750K, Row 7 PSR
48	SSOD	Stainless Steel Outer Driver

*Temperature designations represent the temperature at which the cross sections were evaluated.

APPENDIX C

CORDIS REACTIVITY ANALYSIS CODE

Code Description

The CORDIS code is capable of calculating individual subassembly as well as whole core reactivity effects due to core distortion. It operates on core subassembly displacement files calculated by core analysis codes such as NUBOW-3D or ABAQUS and subassembly worth files calculated using FOP theory in the PERTV code in HEX geometry. The displacement file format is discussed in Appendix D. The worth files (ARO and ARI) contain the PERTV material core map at the beginning, followed by the material worths for each subassembly type in succession for all core mesh points (e.g., $51 \times 30 = 1530$). These files are created by using a modified version of PERTV. The user may also specify a test case mode whereby CORDIS will calculate the subassembly displacements based on uniform core expansion assumptions.

The axial worth distribution is represented in CORDIS by row-dependent, axial worth shape function variables calculated by an R-Z core model (described in the main text). These variables are part of the CORDIS input

parameters. CORDIS also models control rod effects using a synthesis approach with two worth gradient files:

- 1) An all rods out (ARO) case;
- 2) An all rods in (ARI-secondary rods only) case.

Above the secondary bank, CORDIS uses worth gradients from the ARI file and below the bank, CORDIS uses the ARO file.

The actual reactivity effect calculation is done by integrating the displacement components, multiplied by the worth gradient components, over the axial dimension of each subassembly. The integration is then normalized by the integral of the axial worth shape functions over the axial dimension. A summation of all subassembly reactivity effects then gives the core model reactivity effect which is extended to a full core model if a sector model was used.

The CORDIS code operation is performed by six sub-routines as described in the code listing which follows. A sample input parameter deck is shown at the end of the listing. The CORDIS input instructions are discussed below.

Input InstructionsCard 1: Format (9I6)

JROWS - number of radial rows represented in HEX core model.

JROWN - number of subassemblies in last row.

NZONE - number of subassembly zones in HEX core model
(1 subassembly = 1 zone).

IM - number of x-mesh points in HEX core model.

JM - number of y-mesh points in HEX core model.

Note: The HEX core model should be oriented such that the x-mesh points follow the corner-to-corner subassembly direction at the core midplane; the y-mesh points should follow the flat-to-flat subassembly direction at the core midplane (see Figure 9 and note Card 6 description).

NELM - number of core materials modeled (e.g., each subassembly type and their sodium components

accounted for a total of 14 materials in the HEX model used in this analysis).

ICALC - if nonzero, reactivity effect calculations will be done; if zero, only the worth gradients are calculated.

IARI - the file unit number of the worth gradients calculated for the ARI case.

IARO - the file unit number of the worth gradients calculated for the ARO case.

Card 2: Format (4F12.6)

XCTR - core center x-mesh number.

YCTR - core center y-mesh number.

BETA - delayed neutron fraction ($\Delta K/K/\$$).

PITCH - subassembly pitch (flat-to-flat distance in inches).

Card 3: Format (10I6)

- IPR1 - if nonzero, material HEX core map used in PERTV is printed -- materials by zone (the modified version of PERTV used in this analysis stored the core map as the first record on the worth gradient files (ARI and ARO)).
- IPR2 - if nonzero, subassembly material worths are printed ($\Delta K/K$) for each core mesh point.
- IPR3 - if nonzero, subassembly worths are printed ($\Delta K/K$) for each core mesh point.
- IPR4 - if nonzero, subassembly material worth gradients (12) are printed (cents/inch).
- IPR5 - if nonzero, subassembly worth gradients (12) are printed (cents/inch).
- IPR6 - if nonzero, subassembly worth gradient components (x and y) are printed (cents/inch).
- IPR7 - if nonzero, subassembly radial worth gradients are printed (cents/mil).

IPR8 - if nonzero, average subassembly and total radial row worth gradients are printed (cents/mil).

IPR9 - if nonzero, subassembly and total row reactivity effects (worths) are printed (cents).

IPR10 - if nonzero, axial integration variables from subroutine DKCALC are printed for program checking.

Card 4: Format (11I6, F6.3)

Assuming NUBOW-3D was used for calculating the displacements:

NSTEP - number of calculational time steps in NUBOW-3D calculation.

NNODE - number of geometric nodes in NUBOW-3D core model.

NASSY - number of subassemblies in NUBOW-3D core model.

NROW - number of radial rows in NUBOW-3D core model.

IFUEL - if an all fuel (inner and outer zone) CORDIS core model is desired in the reactivity calculations, then set = 1; otherwise, set = 0.

LASR - number of the last row which contains inner zone fuel.

ICOS - if uniform (over all rows) axial worth shape function variables are to be used, set = 0; if row-dependent function variables, set = 1.

NXI - number of axial intervals in axial cosine shape function model (from R-Z analysis).

NXB - number of the base (lowest) axial interval in axial cosine shape function model.

(See Figure 5 of main text for an example of these last two variables.)

ITEST - if a uniform expansion test case is desired (CORDIS calculates the subassembly displacements), set = 1; otherwise, set = 0.

ICOREX - row number which uniform radial expansion is based on (used if ITEST = 1).

EXPANS - displacement of the outer radius of row 'ICOREX' due to uniform core expansion (inches) (used if ITEST = 1).

Card 5: Format (4F12.6, 2I6)

ZB - bottom of core (axial position in inches); should be set corresponding to NUBOW-3D axial model.

ZT - top of core (axial position in inches); should be set corresponding to NUBOW-3D axial model.

AROT - NUBOW-3D core sector model axis rotation angle necessary to orient the displacement components with the CORDIS core sector model (degrees).

XCR - average secondary control rod bank height (all primary rods fully withdrawn) (inches withdrawn).

INFU - inner zone fuel material number (from PERTV core material map).

IOUTFU - outer zone fuel material number (from PERTV core material map).

Card 6: (I=1,NZONE); Format (I5, 4(1X,I3))

ASSID(I) - subassembly identification numbers corresponding to those in the CORDIS core model (these numbers are variable depending on individual choice).

ASSX(I) - subassembly x-mesh number based on diagram below:

ASSY(I) - subassembly y-mesh number based on the diagram above.

ASSR(I) - subassembly row numbers.

ASSP(I) - subassembly position indicators for CORDIS core model:

0 = located off of the core model edge.

1 = located on the right core model edge.

- 2 = located on the left core model edge.
- 3 = located on the top core model edge.
- 4 = located on the bottom core model edge.
- 5 = located in the corner of core model.

Card 7: (I=1, NASSY); Format (12I6)

AMODEL(I) - subassembly identification numbers in NUBOW-3D core sector model. If ICOS = 0, go to **.

Card 8: (I=1, NROW); Format (6E12.6)

RMID(I) - midpoint (axial interval number) in cosine shape function (input a dummy variable for Row 1).

Card 9: (I=1, NROW); Format (6E12.6)

REXT(I) - extrapolation distance (number of axial intervals) in cosine shape function (input a dummy variable for Row 1).

Card 10: (I=1, NROW); Format (6E12.6)

RALP(I) - cosine shape function power ($\cos^\alpha$) (input a dummy variable for Row 1).

Card 11: (I=1, NROW); Format (6E12.6)

PAV(I) - peak-to-average ratios for each new row (input
a dummy variable for Row 1).

If ICOS = 1, go to ***.

**Card 8; Format (4E12.6)

RMID(1) = see definition above.

REXT(1) = see definition above.

RALP(1) = see definition above.

PAV(1) = see definition above.

***Card 12 (or 9 depending on ICOS value)

...(I=1, NNODE); Format (6F12.6)

ZND(I) - axial geometric node positions in NUBOW-3D
model (inches) (see Appendix D).

CORDIS will read in displacement data off of file unit
number 11. Format specifications are explained in
Appendix D. Subassembly material worth data from PERTV is
assumed created by binary 'writes.' CORDIS will read off
those worth files using binary 'reads.'

CORDIS Code Listing:

```

C      * * DESCRIPTION OF CORDIS SUBROUTINES * *
C
C      MAIN *READS IN NECESSARY VARIABLES TO SET UP MASTER ARRAY,
C            ALLOWING FOR EXECUTION TIME DIMENSIONING
C            *PRINTS INPUT
C            *CONTROLS CODE OPERATION
C
C      ASSIGN *READS IN SUBASSEMBLY INFORMATION
C             *CALCULATES CORE POSITION PARAMETERS FOR EACH SUBASSEMBLY
C             *PRINTS INPUT
C
C      GRAD1 *COMPUTES SUBASSEMBLY MATERIAL WORTH GRADIENT COMPONENTS
C            (CENTS/IN)
C
C      ROWGRD *COMPUTES SUBASSEMBLY MATERIAL RADIAL WORTH GRADIENTS
C             (CENTS/MIL)
C            *COMBINES SUBASSEMBLY MATERIAL RADIAL WORTH GRADIENTS TO GIVE
C            AVERAGE ROW RADIAL WORTH GRADIENTS (CENTS/MIL)
C
C      NUBCOS *READS IN NUBOW-3D CORE MODEL DATA
C            *READS IN AXIAL WEIGHTING (FITTING) VARIABLES FOR
C            COSINE FUNCTION
C            *IF UNIFORM EXPANSION CASE IS CHOSEN, NUBCOS COMPUTES
C            SUBASSEMBLY DISPLACEMENTS BASED ON INPUT ROW DISPLACEMENT
C            DATA
C            *PRINTS INPUT
C
C      DKCALC *READS IN NUBOW-3D CALCULATED SUBASSEMBLY DISPLACEMENT
C            DATA
C            *COMPUTES THE DISPLACEMENT REACTIVITY EFFECTS FOR THE
C            FOLLOWING:
C            INDIVIDUAL SUBASSEMBLIES
C            INDIVIDUAL ROWS
C            ENTIRE CORE
C
C            *   *   *   *   *   *   *   *   *   *   *   *   *
C
C            * * MASTER ARRAY 'S' STORAGE ALLOCATIONS * *
C
C            REACTIVITY CALCULATION CORE MODEL:
C
C            SUBASSEMBLY INFORMATION
C
C      L1  ASSID--ID NUMBERS
C      L2  ASSX--X-COMPONENTS
C      L3  ASSY--Y-COMPONENTS
C      L4  ASSR--ROW NUMBERS
C      L5  ASSP--POSITION INDICATIONS
C      L6  ANGLE--ANGLES WITH RESPECT TO CORE CENTER (RADIAN)
C            AND X-AXIS OF MODEL

```

```

C   L7      ZPT--POSITION POINTS ON WORTH FILES
C
C           SUBASSEMBLY MATERIAL WORTH INFORMATION
C
C   L8      DELK--TEMPORARY STORAGE FOR MATERIAL WORTHS AS
C            CALCULATED BY PERTV (DELK/K/MATERIAL)
C   L8A     DELK2--SAME AS DELK ABOVE
C   L9      ZMATO--MATERIAL CORE MAP FOR THE ALL RODS OUT
C            (ARO) CASE
C   L10     GXO--MATERIAL WORTH GRADIENT X-COMPONENTS FOR THE
C            ARO CASE (CENTS/INCH)
C   L11     GYO--MATERIAL WORTH GRADIENT Y-COMPONENTS FOR THE
C            ARO CASE (CENTS/INCH)
C   L12     ZMATI--MATERIAL CORE MAP FOR THE ALL RODS IN (ARI,
C            SECONDARIES ONLY) CASE
C   L13     GXI--MATERIAL WORTH GRADIENT X-COMPONENTS FOR THE
C            ARI CASE (CENTS/INCH)
C   L14     GYI--MATERIAL WORTH GRADIENT Y-COMPONENTS FOR THE
C            ARI CASE (CENTS/INCH)
C   L15     RAY1--RADIAL MATERIAL ROW WORTH GRADIENTS
C            (CENTS/MIL)
C   L16     RAY2--NUMBER OF SUBASSEMBLIES IN EACH ROW
C
C           NUBOW CORE MODEL:
C
C           SUBASSEMBLY INFORMATION
C
C   L17     AMODEL--ID NUMBERS
C   L18     NASR--ROW NUMBERS
C   L19     NUMR--NUMBER OF SUBASSEMBLIES IN EACH ROW
C
C           CHOPPED COSINE FUNCTION VARIABLES:
C
C   L20     RMID--ROW DEPENDENT SHAPE MIDPOINTS
C   L21     REXT--ROW DEPENDENT EXTRAPOLATION DISTANCES
C   L22     RALP--ROW DEPENDENT FUNCTION POWER
C   L23     PAV--ROW DEPENDENT PEAK TO AVERAGE WORTH RATIOS
C   L24     ZND--NUBOW GEOMETRIC NODE POSITIONS (INCHES)
C
C           IF UNIFORM EXPANSION TEST CASE:
C
C   L25     RO--INITIAL ROW RADII (INCHES)
C   L26     RM--MEAN ROW RADII (INCHES)
C   L27     UR--MEAN RADII DISPLACEMENTS (INCHES)
C
C           IF NUBOW CALCULATED SUBASSEMBLY DISPLACEMENTS:
C
C   L27     UR--RADIAL SUBASSEMBLY DISPLACEMENTS (INCHES)
C   L28     VX--X-COMPONENTS OF SUBASSEMBLY DISPLACEMENTS (INCHES)
C   L29     VY--Y-COMPONENTS OF SUBASSEMBLY DISPLACEMENTS (INCHES)
C
C           REACTIVITY EFFECT INFORMATION:
C
C   L30     DKA--SUBASSEMBLY WORTHS (CENTS)
C   L31     RW1--ROW WORTHS (CENTS)
C   L32     TOTS--TOTAL CORE WORTHS FOR EACH NUBOW TIMESTEP (CENTS)
C   L33     PFS--POWER TO FLOW RATIOS FOR EACH NUBOW TIMESTEP

```



```

WRITE (6,350) ZB,ZT,AROT,XCR,INFU,IOUTFU
IF (INFU.GT.NELM) INFU=INFU-NELM
IF (IOUTFU.GT.NELM) IOUTFU=IOUTFU-NELM
FACT=ZT-ZB
XCR=XCR+ZB
ANGR=AROT*PI/180.0
RCOS=COS(ANGR)
RSIN=SIN(ANGR)
L18=L17+NASSY
L19=L18+NASSY
L20=L19+NROW
L21=L20+NROW
L22=L21+NROW
L23=L22+NROW
L24=L23+NROW
L25=L24+NNODE
L26=L25+NROW
L27=L26+NROW
L28=L27+NROW
L29=L28+NNODE
L30=L29+NNODE
L31=L30+NASSY
L32=L31+NROW
L33=L32+NSTEP
L34=L33+NSTEP
L35=L34+NSTEP
IMORE=L35
GO TO 110
100 IMORE=L17
C
C      EXTEND MASTER ARRAY S FILELENGTH TO IMORE--EXECUTION
C      TIME DIMENSIONING
C
110 CALL EXFL (S,IMORE)
    DO 120 I=1,IMORE
120  S(I)=0.0
    BETA=BETA/100.
C
    CALL ASSIGN (S(L1),S(L2),S(L3),S(L4),S(L5),NZONE,XCTR,YCTR,PI,S(L6
+),S(L7),IM,PITCH)
C
    DO 150 ITW=1,2
      IF (ITW.EQ.2) GO TO 130
      LA=L10
      LB=L11
      LC=L9
      LD=IARO
      GO TO 140
130  LA=L13
      LB=L14
      LC=L12
      LD=IARI
C
140  CALL GRAD1 (S(L7),NZONE,S(L8),IM,JM,NELM,PITCH,S(L1),IPR2,IPR4,I
+  PR5,IPR6,PI,S(LA),S(LB),NELM2,S(LC),LD,IARI,IPR3,IPR1,BETA,
+  S(L5),S(L8A),IMJM)
C

```

```

      CALL ROWGRD (S(LA),S(LB),NZONE,S(L15),S(L16),S(L6),S(L1),PI,NELM
+ 2,IPR7,IPR8,JROWS,S(L4),JROWN,ITW)
C
150 CONTINUE
      IF (ICALC.EQ.0) GO TO 180
C
      CALL NUBCOS (S(L18),S(L20),S(L21),S(L22),S(L24),NNODE,NROW,ICOS,S(
+L17),NASSY,S(L23),S(L19),ITEST,EXPANS,PITCH,PI,S(L27),S(L25),S(L26
+),ICOREX,JROWS,JROWN,S(L1),S(L4),NZONE)
C
      DO 160 IS=1,NSTEP
C
      CALL DKCALC (NNODE,NASSY,NROW,IS,PI,S(L24),S(L20),S(L21),S(L22),
+ S(L27),S(L28),S(L29),S(L31),S(L23),S(L30),FACT,ZB,S(L18),S(L1),N
+ ZONE,S(L17),S(L10),S(L11),S(L9),S(L13),S(L14),S(L12),NELM2,IM,JM
+ ,XCR,S(L7),S(L19),ITEST,S(L6),IPR10,IFUEL,IPR9,S(L32),NSTEP,RCOS
+ ,RSIN,S(L33),S(L34),NXI,NXB,JROWS,JROWN,LASR,NELM,INFU,IOUTFU)
C
160 CONTINUE
      WRITE (6,360)
      WRITE (6,370)
      DO 170 I=1,NSTEP
        IX=I-1
        I1=IX+L32
        I2=IX+L33
        I3=IX+L34
        WRITE (6,380) I,S(I3),S(I2),S(I1)
170 CONTINUE
180 STOP
190 FORMAT ('1',40(' '),20('*'))
200 FORMAT (' ',40(' '),18X, '*')
210 FORMAT (' ',40(' '),18X, '*')
220 FORMAT (' ',40(' '),20('*'))
230 FORMAT (9I6)
240 FORMAT (//////,T6,6H JROWS,T17,47HNUMBER OF RADIAL ROWS REPRESENTED
+ IN CORE MODEL,T105,I6,/,T6,6H JROWN,T17,35HNUMBER OF SUBASSEMBLIE
+S IN LAST ROW,T105,I6,/,T6,6H NZONE,T17,45HNUMBER OF SUBASSEMBLY Z
+ONES(1 SUBASSY=1 ZONE),T105,I6,/,T6,6H IM,T17,23HNUMBER OF X-ME
+SH POINTS,T105,I6,/,T6,6H JM,T17,23HNUMBER OF Y-MESH POINTS,T10
+5,I6,/,T6,6H NELM,T17,32HNUMBER OF CORE MATERIALS MODELED,
+T105,I6,/,T6,6H ICALC,T17,51HIF NONZERO,REACTIVITY CALCULATION WIL
+L BE PERFORMED,T105,I6)
250 FORMAT (T6,6H IARI,T17,69HWORTH VECTOR FILE UNIT NUMBER - ALL ROD
+S IN (ARI,SECONDARY RODS ONLY),T105,I6,/,T6,6H IARO,T17,50HWORTH
+VECTOR FILE UNIT NUMBER - ALL RODS OUT (ARO),T105,I6)
260 FORMAT (4F12.6)
270 FORMAT (T6,6H XCTR,T17,25HCORE CENTER X-MESH NUMBER,T105,F6.3,/,T
+6,6H YCTR,T17,25HCORE CENTER Y-MESH NUMBER,T105,F6.3,/,T6,6H BET
+A,T17,35HDELAYED NEUTRON FRACTION (DELK/K/$),T99,F12.6,/,T6,6H PIT
+CH,T17,51HSUBASSEMBLY PITCH (FLAT TO FLAT DISTANCE IN INCHES),T105
+,F6.3)
280 FORMAT (10I6)
290 FORMAT ('ODESIRED ADDITIONAL OUTPUT',//,T6,6H IPR1,T17,51HIF NONZ
+ERO,MATERIAL MAP PRINTOUT--MATERIALS BY ZONE,T105,I6,/,T6,6H IPR2
+,T17,47HIF NONZERO,SUBASSEMBLY MATERIAL WORTHS (DELK/K),
+T105,I6,/,T6,6H IPR3,T17,72HIF NONZERO,MAIN SUBASSEMBLY MATERIAL
+WORTHS (ELEMENTS COMBINED) (DELK/K),T105,I6,/,T6,6H IPR4,T17,65HI

```

```

+F NONZERO,SUBASSEMBLY MATERIAL WORTH GRADIENTS (12) (CENTS/INCH),
+T105,I6,/,T6,6H IPR5,T17,70HIF NONZERO,MAIN SUBASSEMBLY MATERIAL
+WORTH GRADIENTS (12) (CENTS/INCH),T105,I6,/,T6,6H IPR6,T17,
+80HIF NONZERO,SUBASSEMBLY MATERIAL WORTH GRADIENT COMPONENTS (X AN
+D Y) (CENTS/INCH),T105,I6)
300 FORMAT (T6,6H IPR7,T17,66HIF NONZERO,SUBASSEMBLY MATERIAL RADIAL
+WORTH GRADIENTS (CENTS/MIL),T105,I6,/,T6,6H IPR8,T17,81HIF NONZER
+O,AVERAGE AND TOTAL SUBASSEMBLY MATERIAL ROW WORTH GRADIENTS (CENT
+S/MIL),T105,I6,/,T6,6H IPR9,T17,72HIF NONZERO,SUBASSEMBLY AND TOT
+AL ROW REACTIVITY EFFECTS (WORTHS) (CENTS),T105,I6,/,T6,6H IPR10,T
+17,63HIF NONZERO,DKCALC AXIAL INTEGRATION VARIABLES FOR PROGRAM CH
+ECK,T105,I6)
310 FORMAT (11I6,F6.3)
320 FORMAT ('ONUBOW INPUT',/,T6,6H NSTEP,T17,20HNUMBER OF TIME STEPS,
+T105,I6,/,T6,6H NNODE,T17,25HNUMBER OF GEOMETRIC NODES,T105,I6,/,T
+6,6H NASSY,T17,31HNUMBER OF SUBASSEMBLIES MODELED,T105,I6,/,T6,6H
+ NROW,T17,29HNUMBER OF RADIAL ROWS MODELED,T105,I6,/,T6,6H IFUEL,T
+17,75H0/1= VARIED CORE SUBASSY TYPES/ ALL FUEL MODEL (INNER AND OU
+TER ZONES ONLY),T105,I6,/,T6,6H LASR,T17,41HLAST ROW WHICH CONTAI
+NS INNER DRIVER FUEL,T105,I6)
330 FORMAT (T6,6H ICOS,T17,76H0/1= UNIFORM AXIAL FITTING PARAMETERS/R
+OW DEPENDENT AXIAL FITTING PARAMETERS,T105,I6,/,T6,6H NXI,T17,49
+HNUMBER OF AXIAL INTERVALS IN COSINE FITTING MODEL,T105,I6,/,T6,6H
+ NXB,T17,66HNUMBER OF THE BASE (LOWEST) AXIAL INTERVAL IN COSINE
+ FITTING MODEL,T105,I6,/,T6,6H ITEST,T17,57H0/1= NONUNIFORM RADIAL
+ EXPANSION/UNIFORM RADIAL EXPANSION,T105,I6,/,T6,6HICOREX,T17,53HR
+OW NUMBER WHICH UNIFORM RADIAL EXPANSION IS BASED ON,T105,I6,/,T6,
+6HEXPANS,T17,20HDISPLACEMENT OF ROW ,I2,38H DUE TO UNIFORM CORE EX
+PANSION(INCHES),T105,F6.3)
340 FORMAT (4F12.6,2I6)
350 FORMAT (T6,6H ZB,T17,40HBOTTOM OF CORE(AXIAL POSITION IN INCHES
+),T105,F6.3,/,T6,6H ZT,T17,37HTOP OF CORE(AXIAL POSITION IN INC
+HES),T105,F6.3,/,T6,6H AROT,T17,52HNUBOW CORE SECTOR MODEL AXIS R
+OTATION ANGLE(DEGREES),T105,F6.3,/,T6,6H XCR,T17,46HAVG. CONTROL
+ ROD BANK HEIGHT(INCHES WITHDRAWN),T105,F6.3,/,T6,6H INFU,T17,33H
+INNER DRIVER FUEL MATERIAL NUMBER,T105,I6,/,T6,6HIOUTFU,T17,33HOUT
+ER DRIVER FUEL MATERIAL NUMBER,T105,I6,/)
360 FORMAT ('1TOTAL REACTIVITY EFFECT',/)
370 FORMAT (' ',15X,'TIME',21X,'REACTIVITY',/, 'TIMESTEP',6X,'(EFPD)',
+5X,'POWER/FLOW',7X,'(CENTS)',/, ' ',50(' '),/)
380 FORMAT (' ',13,7X,F7.1,8X,F6.4,6X,E11.4)
END

```

C

```

SUBROUTINE ASSIGN (ASSID,ASSX,ASSY,ASSR,ASSP,NZONE,XCTR,YCTR,PI,AN
+GLE,ZPT,IM,PITCH)
INTEGER
+ ASSID(NZONE), ASSP(NZONE), ASSR(NZONE), ASSX(NZONE),
+ ASSY(NZONE), ZPT(NZONE)
DIMENSION
+ ANGLE(NZONE)

```

C

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```

READ IN SUBASSEMBLY DATA--COMPUTE SUBASSEMBLY
ANGLE WITH CORE CENTER AND POSITION ON WORTH FILES

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```

UNITY=PITCH/2.
UNITX=UNITY/SQRT(3.)
WRITE (6,140)

```

```

WRITE (6,150)
DO 130 I=1,NZONE
  READ (5,160) ASSID(I),ASSX(I),ASSY(I),ASSR(I),ASSP(I)
  FX=FLOAT(ASSX(I))-XCTR+1.
  FY=FLOAT(ASSY(I))-YCTR+.5
  IF (FX.EQ.0.) GO TO 100
  FY=FY*UNITY
  FX=FX*UNITX
  FXY=FY/FX
  ANGLE(I)=ATAN(FXY)
  IF (FX.LT.0..AND.FY.GT.0.) ANGLE(I)=ANGLE(I)-PI
  IF (FX.LT.0..AND.FY.LT.0.) ANGLE(I)=ANGLE(I)+PI
  IF (FY) 120,110,120
100 IF (FX.EQ.0..AND.FY.EQ.0.) ANGLE(I)=0.
  IF (FX.EQ.0..AND.FY.GT.0.) ANGLE(I)=PI/2.0
  IF (FX.EQ.0..AND.FY.LT.0.) ANGLE(I)=3.0*PI/2.0
110 IF (FY.EQ.0..AND.FX.GT.0.) ANGLE(I)=0.
  IF (FY.EQ.0..AND.FX.LT.0.) ANGLE(I)=PI
120 ZPT(I)=(ASSY(I)-1)*IM+ASSX(I)
  ANG=ANGLE(I)*180./PI
  WRITE (6,170) ASSID(I),ASSX(I),ASSY(I),ASSR(I),ASSP(I),ANG,ZPT(I)
+ )
130 CONTINUE
  RETURN
140 FORMAT ('0',36X,'SUBASSEMBLY INFORMATION')
150 FORMAT (//,' ID NO.',5X,'X-COORD',5X,'Y-COORD',5X,'ROW NO.',5X,'PO
+SITION',5X,'ANGLE-CTR(DEG)',5X,'POSITION PT.',/,' ',94('-'),/)
160 FORMAT (15,4(1X,I3))
170 FORMAT (' ',15,8X,I2,2(10X,I2),11X,I2,10X,F7.1,13X,I4)
END

```

C

```

SUBROUTINE GRAD1 (ZPT,NZONE,DELK,IM,JM,NELM,PITCH,ASSID,IPR2,IPR4,
+IPR5,IPR6,PI,GX,GY,NELM2,ZMAT,IAR,IARI,IPR3,IPR1,BETA,ASSP,
+DELK2,IMJM)
  INTEGER
+   ASSID(NZONE),      ASSP(NZONE),      ZMAT(IM,JM),
+   ZPT(NZONE)
  DIMENSION
+   DELK(IM,JM),      GRAD(12),      GX(NELM2,NZONE),
+   GY(NELM2,NZONE),  DELK2(IMJM)
  IPRT=IPR1+IPR2+IPR3+IPR4+IPR5+IPR6
  IF (IPRT.EQ.0) GO TO 110
  IF (IAR.EQ.IARI) GO TO 100
  WRITE (6,530)
  GO TO 110
100 WRITE (6,540)
110 CONV=PI/180.0
  ANGLE1=CONV*60.0
  ANGLE2=CONV*30.0
  COS30=COS(ANGLE2)
  COS60=COS(ANGLE1)
  SIN60=SIN(ANGLE1)
  DX1=PITCH/3.0
  DX2=PITCH/SQRT(3.)
  DX3=DX1*2.0
  IF (IPR1.EQ.0) GO TO 120
  WRITE (6,550)

```



```

C
C      READ IN MATERIAL CORE MAP
C
120 DO 130 J=1,JM
    READ (IAR) (ZMAT(I,J),I=1,IM)
    IF (IPR1.EQ.0) GO TO 130
    WRITE (6,560) (ZMAT(IA,J),IA=1,IM)
130 CONTINUE
    ISTOP=NELM+1
    ISTOP2=NELM+NELM2
C
C      READ SUBASSEMBLY MATERIAL WORTHS (DELK/K)
C
DO 520 IN=1,ISTOP2
    IF (IN.GT.NELM2.AND.IN.LE.NELM) INJ=IN-NELM2
    IF (IN.GT.NELM) INJ=IN-NELM
    READ (IAR) ((DELK(IA,IB),IA=1,IM),IB=1,JM)
    IF (IN.LT.ISTOP) GO TO 140
    IF (IPR3.EQ.0) GO TO 180
    WRITE (6,570) IN
    GO TO 160
140 IF (IPR2) 180,180,150
150 WRITE (6,580) IN
160 DO 170 J=1,JM
    WRITE (6,590) J
    WRITE (6,600) (DELK(I,J),I=1,IM)
170 CONTINUE
180 IF (IPR4.EQ.0.AND.IPR5.EQ.0) GO TO 190
    WRITE(6,580)IN
    WRITE (6,610)
190 IF (IN.GE.ISTOP) GO TO 200
    IF (IPR4.EQ.0) GO TO 520
200 DO 220 J=1,JM
    KB=(J-1)*IM
    DO 210 I=1,IM
        KA=KB+I
        DELK(I,J)=DELK(I,J)/BETA
        DELK2(KA)=DELK(I,J)
210 CONTINUE
220 CONTINUE
    DO 510 I=1,NZONE
        ISET4=0
        ISET3=0
        ISET1=0
        ISET2=0
        ISET5=0
        IF (ASSP(I).EQ.0) GO TO 280
        IF (ASSP(I).EQ.1) GO TO 230
        IF (ASSP(I).EQ.2) GO TO 240
        IF (ASSP(I).EQ.3) GO TO 250
        IF (ASSP(I).EQ.4) GO TO 260
        IF (ASSP(I).EQ.5) GO TO 270
        WRITE (6,620) ASSID(I)
        GO TO 280
230 ISET1=1
    GO TO 280
240 ISET2=1

```

```

      GO TO 280
250   ISET3=1
      GO TO 280
260   ISET4=1
      GO TO 280
270   ISET5=1
C
C      SET UP SUBASSEMBLY WORTH FILE POSITION POINTS
C
280   K1=ZPT(I)
      K2=K1+1
      K3=K2+1
      K4=K3+IM
      K5=K4-1
      K6=K5-1
      IF (ISET5.GT.0) GO TO 470
      IF (ISET2.GT.0) GO TO 290
      K7=K1-1
      IF (ISET4.GT.0) GO TO 300
      K8=K7-IM
      K9=K8+1
290   K10=K9+1
      IF (ISET1.GT.0) GO TO 310
      K11=K10+1
      K12=K11+1
300   K13=K3+1
      K14=K13+1
      K15=K4+2
      K16=K4+1
      IF (ISET3.GT.0) GO TO 320
      K17=K16+IM
      K18=K17-1
310   K19=K18-1
      IF (ISET2.GT.0) GO TO 330
      K20=K19-1
      K21=K20-1
320   K22=K6-1
      K23=K22-1
      K24=K7-1
C
C      COMPUTE SUBASSEMBLY MATERIAL WORTH GRADIENTS
C      (TWELVE) (CENTS/INCH)
C
      GRAD(1)=(DELK2(K7)-DELK2(K1))/DX1
      IF (ISET4.GT.0) GO TO 340
      P89=(DELK2(K8)+DELK2(K9))*0.5
      P12=(DELK2(K1)+DELK2(K2))*0.5
      GRAD(2)=(P89-P12)/DX2
330   GRAD(3)=(DELK2(K10)-DELK2(K2))/DX1
      IF (ISET1.GT.0) GO TO 350
      P1112=(DELK2(K11)+DELK2(K12))*0.5
      P23=(DELK2(K2)+DELK2(K3))*0.5
      GRAD(4)=(P1112-P23)/DX2
340   GRAD(5)=(DELK2(K13)-DELK2(K3))/DX1
      P1415=(DELK2(K14)+DELK2(K15))*0.5
      P34=(DELK2(K3)+DELK2(K4))*0.5
      GRAD(6)=(P1415-P34)/DX2

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```

GRAD(7)=(DELK2(K16)-DELK2(K4))/DX1
IF (ISET3.GT.0) GO TO 380
P1718=(DELK2(K17)+DELK2(K18))*0.5
P45=(DELK2(K4)+DELK2(K5))*0.5
GRAD(8)=(P1718-P45)/DX2
350 GRAD(9)=(DELK2(K19)-DELK2(K5))/DX1
IF (ISET2.EQ.0) GO TO 370
DO 360 M3=10,12
360 GRAD(M3)=0.0
GRAD(1)=0.0
GRAD(2)=0.0
GO TO 450
370 P2021=(DELK2(K20)+DELK2(K21))*0.5
P56=(DELK2(K5)+DELK2(K6))*0.5
GRAD(10)=(P2021-P56)/DX2
380 GRAD(11)=(DELK2(K22)-DELK2(K6))/DX1
P2324=(DELK2(K23)+DELK2(K24))*0.5
P61=(DELK2(K6)+DELK2(K1))*0.5
GRAD(12)=(P2324-P61)/DX2
C
C      COMPUTE SUBASSEMBLY MATERIAL WORTH GRADIENT
C      X AND Y COMPONENTS (CENTS/INCH)
C
IF (ISET1.EQ.0) GO TO 400
DO 390 M2=4,8
390 GRAD(M2)=0.0
GO TO 450
400 IF (ISET4.EQ.0) GO TO 420
DO 410 N2=2,4
410 GRAD(N2)=0.0
GO TO 440
420 IF (ISET3.EQ.0) GO TO 440
DO 430 N3=8,10
430 GRAD(N3)=0.0
440 G1=GRAD(5)+GRAD(7)-GRAD(1)-GRAD(11)
G2=GRAD(4)+GRAD(8)-GRAD(2)-GRAD(10)
450 G3=GRAD(8)+GRAD(10)-GRAD(2)-GRAD(4)
G4=GRAD(7)+GRAD(11)-GRAD(1)-GRAD(5)
IF (ISET1.GT.0.OR.ISET2.GT.0) GO TO 460
GX(INJ,I)=G1*COS30+G2*COS60+GRAD(6)-GRAD(12)
460 GY(INJ,I)=G3*COS30+G4*COS60+GRAD(9)-GRAD(3)
470 GX2=(DELK2(K3)-DELK2(K1)+DELK2(K4)-DELK2(K6))/(2.0*DX2)
GY2=(DELK2(K5)-DELK2(K2))/DX3
IF (ISET4.GT.0) GY(INJ,I)=GRAD(9)
IF (ISET3.GT.0) GY(INJ,I)=GY2
IF (ISET1.EQ.0.AND.ISET2.EQ.0) GO TO 480
GX(INJ,I)=GX2
480 IF (ISET5.EQ.0) GO TO 490
GX(INJ,I)=GX2
GY(INJ,I)=GY2
490 IF (IPR4.EQ.0.AND.IPR5.EQ.0) GO TO 510
WRITE (6,630) ASSID(I),(GRAD(JK),JK=1,12)
510 CONTINUE
IF (IPR6.EQ.0) GO TO 520
WRITE (6,640) IN
WRITE (6,650) (ASSID(I),GX(INJ,I),GY(INJ,I),I=1,NZONE)
520 CONTINUE

```

```

      RETURN
530 FORMAT ('IARO DATA')
540 FORMAT ('IARI DATA')
550 FORMAT ('OMATERIALS BY ZONE',//)
560 FORMAT (' ',60I2)
570 FORMAT ('ITOTAL WORTH (DELK/K) VALUES FOR MATERIAL ',I2,/)
580 FORMAT ('IMATERIAL ',I3,/)
590 FORMAT (' ROW ',I3,'---MATERIAL WORTH (DELK/K) VALUES . . .',/)
600 FORMAT (' ',12E10.4)
610 FORMAT ('OWORTH GRADIENTS (CENTS/INCH)',/, 'O ASSY',3X,'GRAD 1',4X,
+ 'GRAD 2',4X,'GRAD 3',4X,'GRAD 4',4X,'GRAD 5',4X,'GRAD 6',4X,'GRAD
+ 7',4X,'GRAD 8',4X,'GRAD 9',4X,'GRAD 10',3X,'GRAD 11',3X,'GRAD 12',
+/, ' ',131('-',),//)
620 FORMAT ('OUNIDENTIFIED SUBASSEMBLY TYPE FOR SUBASSEMBLY ',I5,
+ ' ',TYPE=0 ASSUMED')
630 FORMAT (' ',1X,I4,12E10.4)
640 FORMAT ('OX&Y WORTH GRADIENT COMPONENTS (CENTS/INCH) FOR MATERIAL
+ ',I2,/, 'O ASSY',8X,'XCOMP',8X,'YCOMP',/, ' ',35('-',),//)
650 FORMAT (' ',1X,I4,5X,E10.4,5X,E10.4)
      END
C
      SUBROUTINE ROWGRD (GX,GY,NZONE,RAY1,RAY2,ANGLE,ASSID,PI,NELM2,IPR7
+ ,IPR8,JROWS,ASSR,JROWN,ITW)
      INTEGER
+      ASSID(NZONE),      ASSR(NZONE)
      DIMENSION
+      ANGLE(NZONE),      GX(NELM2,NZONE),      GY(NELM2,NZONE),
+      RAY1(JROWS),      RAY2(JROWS)
      IPRT=IPR7+IPR8
      IF (IPRT.EQ.0) GO TO 110
      IF (ITW.EQ.2) GO TO 100
      WRITE (6,200)
      GO TO 110
100 WRITE (6,210)
110 DO 190 IE=1,NELM2
      DO 120 J=1,JROWS
        RAY1(J)=0.
120   RAY2(J)=0.
        IF (IPR7.EQ.0) GO TO 130
        WRITE (6,220) IE
C
C      COMPUTE AVERAGE AND TOTAL SUBASSEMBLY RADIAL
C      WORTH GRADIENTS (CENTS/MIL)
C
130   DO 150 I=1,NZONE
        COSX=COS(ANGLE(I))
        SINX=SIN(ANGLE(I))
        S1=(GX(IE,I)*COSX+GY(IE,I)*SINX)/1000.0
        DO 140 J=1,JROWS
          IF (ASSR(I).NE.J) GO TO 140
          RAY1(J)=RAY1(J)+S1
          RAY2(J)=RAY2(J)+1.
140   CONTINUE
        IF (IPR7.EQ.0) GO TO 150
        ANGX=ANGLE(I)*180.0/PI
        WRITE (6,230) ASSID(I),ANGX,S1
150   CONTINUE

```

```

      DO 160 J=1,JROWS
160   RAY1(J)=RAY1(J)/RAY2(J)
      IF (IPR8.EQ.0) GO TO 190
      WRITE (6,240) IE
      WRITE (6,250)
      DO 170 IR=2,JROWS
        IR1=(IR-1)*6
        FLR=FLOAT(IR1)
        IF (IR.EQ.JROWS) FLR=FLOAT(JROWN)
        RAYT=RAY1(IR)*FLR
        WRITE (6,260) IR,RAY1(IR),RAYT
170   CONTINUE
190   CONTINUE
      RETURN
200   FORMAT ('1ALL RODS OUT (ARO) DATA')
210   FORMAT ('1ALL RODS IN (ARI) DATA')
220   FORMAT ('ORADIAL SUBASSEMBLY WORTH GRADIENTS (CENTS/MIL) FOR MATER
+IAL ',I2,/, 'O ASSY',8X, 'ANGLE(DEG)',7X, 'ASSY WTH',/, ' ',37('-'),//
+)
230   FORMAT (' ',I5,7X,E10.4,6X,E10.4)
240   FORMAT ('OAVG&TOT RADIAL SUBASSEMBLY WORTH GRADIENTS (CENTS/MIL) F
+OR MATERIAL ',I2,/, ' ',16X, 'MATL WORTH',8X, 'TOTAL ROW')
250   FORMAT (' ROW',13X, '(CTS/MIL)',8X, '(CTS/MIL)',/, ' ',43('-'),/)
260   FORMAT (' ',1X,I2,13X,E10.4,7X,E10.4)
      END

```

C
C

```

      SUBROUTINE NUBCOS (NASR,RMID,REXT,RALP,ZND,NNODE,NROW,ICOS,AMODEL,
+NASSY,PAV,NUMR,ITEST,EXPANS,PITCH,PI,UR,RO,RM,ICOREX,JROWS,JROWN,A
+SSID,ASSR,NZONE)
      INTEGER

```

```

+   AMODEL(NASSY), ASSID(NZONE), ASSR(NZONE)
      DIMENSION
+   NASR(NASSY),   NUMR(NROW),   PAV(NROW),   RALP(NROW),
+   REXT(NROW),   RM(NROW),   RMID(NROW),   RO(NROW),
+   UR(NROW),     ZND(NNODE)

```

C
C
C
C

```

      READ IN NUBOW CORE MODEL DATA AND COSINE
      AXIAL FITTING FUNCTION VARIABLES

```

```

      READ (5,210) (AMODEL(I),I=1,NASSY)
      WRITE (6,220)
      WRITE (6,230)
      WRITE (6,210) (AMODEL(I),I=1,NASSY)
      DO 120 K=1,NASSY
        DO 110 J=1,NZONE
          IF (AMODEL(K).NE.ASSID(J)) GO TO 110
          DO 100 I=1,NROW
            IF (ASSR(J).NE.I) GO TO 100
            NASR(K)=I
            NUMR(I)=NUMR(I)+1
100     CONTINUE
110     CONTINUE
120     CONTINUE
      WRITE (6,240)
      WRITE (6,210) (NASR(I),I=1,NASSY)
      WRITE (6,250)

```

```

WRITE (6,210) (NUMR(I),I=1,NROW)
WRITE (6,260)
IF (ICOS.EQ.0) GO TO 130
READ (5,270) (RMID(I),I=1,NROW)
READ (5,270) (REXT(I),I=1,NROW)
READ (5,270) (RALP(I),I=1,NROW)
READ (5,270) (PAV(I),I=1,NROW)
GO TO 150
130 READ (5,280) RMID(1),REXT(1),RALP(1),PAV(1)
DO 140 J=2,NROW
    RMID(J)=RMID(1)
    REXT(J)=REXT(1)
    RALP(J)=RALP(1)
    PAV(J)=PAV(1)
140 CONTINUE
150 DO 160 I=1,NROW
    WRITE (6,290) I,RMID(I),REXT(I),RALP(I),PAV(I)
160 CONTINUE
READ (5,300) (ZND(I),I=1,NNODE)
WRITE (6,310)
WRITE (6,320) (ZND(I),I=1,NNODE)
C
C             IF UNIFORM RADIAL EXPANSION TEST CASE,
C             COMPUTE ROW DISPLACEMENTS (INCHES)
C
IF (ITEST.EQ.0) GO TO 200
ASSYA=SQRT(3.0)*0.5*(PITCH**2.0)
DO 180 I=1,NROW
    I1=I-1
    INX=I1*6
    F11=FLOAT(INX)
    IF (F11.EQ.0.0) F11=1.0
    IF (I.EQ.JROWS) F11=FLOAT(JROWN)
    TOTA=F11*ASSYA
    IF (I1.EQ.0) GO TO 170
    RO(I)=SQRT((TOTA/PI)+RO(I1)**2.0)
    RM(I)=(RO(I)-RO(I1))/2.0+RO(I1)
    GO TO 180
170 RO(I)=SQRT(TOTA/PI)
    RM(I)=RO(I)/2.0
180 CONTINUE
FACTA=(RO(ICOREX)+EXPANS)/RO(ICOREX)-1.0
WRITE (6,330) EXPANS,ICOREX
WRITE (6,340)
DO 190 I=2,NROW
    UR(I)=RM(I)*FACTA
    WRITE (6,350) I,RO(I),RM(I),UR(I)
190 CONTINUE
200 RETURN
210 FORMAT (12I6)
220 FORMAT ('1NUBOW INPUT DATA')
230 FORMAT ('OASSY NUMBERS IN MODEL',/,' ',21('-'),/)
240 FORMAT ('OROW NUMBERS OF ASSEMBLIES',/,' ',25('-'),/)
250 FORMAT ('ONUMBER OF ASSEMBLIES BY ROW',/,' ',27('-'),/)
260 FORMAT ('OCOSINE FCN. MODEL PARAMETERS',/,'O ROW',5X,'MIDPT',4X,'E
+XTRAP',5X,'ALPHA',5X,'PK/AV',/,' ',45('-'),/)
270 FORMAT (6E12.6)

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```

280 FORMAT (4E12.6)
290 FORMAT (' ',2X,I2,1X,4E10.4)
300 FORMAT (6F12.6)
310 FORMAT ('OGEOMETRIC NODE POSITIONS',/, ' ',24('-'),/)
320 FORMAT (' ',6E12.4)
330 FORMAT ('OPROGRAM TEST---UNIFORM CORE EXPANSION PRODUCING A',E10.4
+,' INCH DISPLACEMENT IN THE OUTER RADIUS OF ROW',I3,/)
340 FORMAT (' ',10X,'OUTER RADIUS',6X,'MEAN RADIUS',5X,'DELTA RADIUS',
+/, ' ROW ',7X,'(INCHES)',2(9X,'(INCHES)'),/, ' ',55('-'),/)
350 FORMAT (' ',I4,3X,E12.4,2(5X,E12.4))
END

```

C

```

SUBROUTINE DKCALC (NNODE,NASSY,NROW,IS,PI,ZND,RMID,REXT,RALP,UR,VX
+,VY,RW1,PAV,DKA,FACT,ZB,NASR,ASSID,NZONE,AMODEL,GXO,GYO,ZMATO,GXI,
+GYI,ZMATI,NELM2,IM,JM,XCR,ZPT,NUMR,ITEST,ANGLE,IPR10,IFUEL,IPR9,TO
+TS,NSTEP,RCOS,RSIN,PFS,TIM,NXI,NXB,JROWS,JROWN,LASR,NELM,INFU,IOUT
+FU)

```

```

INTEGER

```

```

+ AMODEL(NASSY), ASSID(NZONE), ZMATI(IM,JM),
+ ZMATO(IM,JM), ZPT(NZONE)

```

```

DIMENSION

```

```

+ ANGLE(NZONE), DKA(NASSY), GXI(NELM2,NZONE),
+ GXO(NELM2,NZONE), GYI(NELM2,NZONE), GYO(NELM2,NZONE),
+ NASR(NASSY), NUMR(NROW), PAV(NROW),
+ PFS(NSTEP), RALP(NROW), REXT(NROW),
+ RMID(NROW), RW1(NROW), TIM(NSTEP),
+ TOTS(NSTEP), UR(NROW), VX(NNODE),
+ VY(NNODE), ZND(NNODE)

```

```

IPRT=IPR9+IPR10

```

```

IF (IPRT.EQ.0) GO TO 100

```

```

WRITE (6,440)

```

```

100 IF (ITEST.NE.0) GO TO 110

```

C

C

```

READ IN BURNUP (EFPD) AND POWER/FLOW RATIO

```

C

```

READ (11,450) TIME,PFR

```

```

PFS(IS)=PFR

```

```

TIM(IS)=TIME

```

```

110 FNXI=FLOAT(NXI)

```

```

UNIT=FACT/FNXI

```

```

DKSUMA=0.0

```

```

DO 120 I=1,NROW

```

```

120 RW1(I)=0.0

```

```

IF (ITEST.NE.0) GO TO 130

```

C

C

```

READ IN NUBOW SUBASSEMBLY RADIAL DISPLACEMENT

```

C

```

DATA IF NONUNIFORM RADIAL EXPANSION CASE

```

C

```

(INCHES)

```

C

```

READ (11,460) (UR(I),I=2,NROW)

```

```

130 DO 410 JA=1,NASSY

```

```

JR=NASR(JA)

```

```

DO 140 IA=1,NZONE

```

```

140 IF (AMODEL(JA).EQ.ASSID(IA)) GO TO 150

```

```

WRITE (6,470) AMODEL(JA)

```

```

GO TO 430

```

```

150 DO 170 JJM=1,JM

```

```

      JW=(JJM-1)*IM
      DO 160 JIM=1,IM
        JJ=JW+JIM
        IF (ZPT(IA).NE.JJ) GO TO 160
        JACT=JM-JJM+1
        IIZ=ZMATI(JIM,JACT)
        IOZ=ZMATO(JIM,JACT)
        IF (IIZ.GT.NELM) IIZ=IIZ-NELM
        IF (IOZ.GT.NELM) IOZ=IOZ-NELM
        GO TO 180
160    CONTINUE
170    CONTINUE
C
C      IF ALL FUEL MODEL--SET CORE MATERIALS TO FUEL
C      MATERIALS
C
180    IF (IFUEL.EQ.0) GO TO 200
        IF (JR.GT.LASR) GO TO 190
        IIZ=INFU
        IOZ=INFU
        GO TO 200
190    IIZ=IOUTFU
        IOZ=IOUTFU
200    DO 210 JD=1,NROW
        IF (JR.NE.JD) GO TO 210
        DIF=NUMR(JD)
        GO TO 220
210    CONTINUE
220    FJR=FLOAT(JR)
        FNXB=FLOAT(NXB)-.5
        ZMID=(RMID(JR)-FNXB)*UNIT+ZB
        ZMAX=REXT(JR)*UNIT/2.
        Z2=ZMID-ZMAX
        RAN=(FJR-1.0)*6.0
        IF (FJR.EQ.1.0) RAN=1.0
        FJROW=FLOAT(JROWS)
        IF (FJR.EQ.FJROW) RAN=FLOAT(JROWN)
        RF=RAN/DIF
        IF (IPR10.EQ.0) GO TO 230
        IF (IIZ.EQ.0) IIZ=1
        WRITE (6,480)
        WRITE (6,490) IIZ,IOZ,JR,JA,NASR(JA),RMID(JR),ZMID,REXT(JR),ZMAX
+      ,Z2,RAN,DIF,RF
230    IF (IPR9.EQ.0.AND.IPR10.EQ.0) GO TO 240
        IF (ITEST.NE.0) GO TO 240
        WRITE (6,500) IS,TIME,PFR
240    SUMA=0.0
        SUMB=0.0
        DEN=0.0
        F2A=0.0
        F2B=0.0
        P2=0.0
        COSX=COS(ANGLE(IA))
        SINX=SIN(ANGLE(IA))
        RGYI=GYI(IIZ,IA)*RCOS-GXI(IIZ,IA)*RSIN
        RGXI=GXI(IIZ,IA)*RCOS+GYI(IIZ,IA)*RSIN
        RGYO=GYO(IOZ,IA)*RCOS-GXO(IOZ,IA)*RSIN

```



```

      RGXO=GXO(IOZ,IA)*RCOS+GYO(IOZ,IA)*RSIN
      IF (ITEST.NE.0) GO TO 250
      READ (11,510) (VX(I),VY(I),I=1,NNODE)
250    IF (IPR9.EQ.0.AND.IPR10.EQ.0) GO TO 260
      WRITE (6,520) AMODEL(JA),JR,UR(JR)
      WRITE (6,530)
C
C      PERFORM AXIAL INTEGRATION OF REACTIVITY EFFECTS
C
260    DO 350 JN=1,NNODE
      ZC=ABS(ZMID-ZND(JN))
      IF (ZC.GT.ZMAX) GO TO 350
      ZC=PI*ZC/(2.0*ZMAX)
      F1A=F2A
      F1B=F2B
      P1=P2
      P2=COS(ZC)**RALP(JR)
      IF (IPR10.EQ.0) GO TO 270
      WRITE (6,540)
      WRITE (6,550) ZC,F1A,F1B,P1,RALP(JR),PAV(JR),P2
270    IF (ITEST.NE.0) GO TO 280
C
C      CALCULATE TRUE SUBASSEMBLY X AND Y COMPONENTS
C      OF DISPLACEMENT (INCHES)
C
      VXSQ=VX(JN)**2.0
      VYSQ=VY(JN)**2.0
      VXYS=(VXSQ+VYSQ)**0.5
      IF (VX(JN).EQ.0.0.AND.VY(JN).EQ.0.0) GO TO 290
      VXT=(UR(JR)/VXYS+1.0)*VX(JN)
      VYT=(UR(JR)/VXYS+1.0)*VY(JN)
      GO TO 300
280    VXT=UR(JR)*COSX
      VYT=UR(JR)*SINX
      GO TO 300
290    VXT=0.0
      VYT=0.0
300    IF (IPR9.EQ.0.AND.IPR10.EQ.0) GO TO 310
      WRITE (6,560) JN,ZND(JN),VX(JN),VY(JN),VXT,VYT
310    Z1=Z2
      Z2=ZND(JN)
      DZ=Z2-Z1
      FZI=0.0
      FZO=DZ
      DEN=DEN+(P1+P2)*DZ/2.0
C
C      CONTROL ROD BANK POSITION CHECK
C
      IF (ZND(JN)-XCR) 330,330,320
320    F2B=(RGXI*VXT+RGYI*VYT)*P2*PAV(JR)
      IF (F1B.EQ.0.0) F1B=F2B
      FZI=Z2-XCR
      FZO=XCR-Z1
      IF (FZO.LE.0.0) FZI=DZ
      SUMB=SUMB+(F1B+F2B)*FZI/2.0
330    F2A=(RGXO*VXT+RGYO*VYT)*P2*PAV(JR)
      IF (FZO.GT.0.0) GO TO 340
      FZO=0.0

```

```

      F2A=0.0
340   SUMA=SUMA+(F1A+F2A)*FZO/2.0
      IF (IPR10.EQ.0) GO TO 350
      WRITE (6,570)
      WRITE (6,580) Z1,Z2,DZ,DEN,ZND(JN),XCR
      WRITE (6,590)
      WRITE (6,600) GXI(IIZ,IA),GYI(IIZ,IA),GXO(IOZ,IA),GYO(IOZ,IA),
+      F2B,FZI,FZO,SUMB,SUMA,F2A
350   CONTINUE
      ZTOP=ZMID+ZMAX
      IF (XCR.LT.ZTOP.AND.XCR.GE.Z2) GO TO 360
      DZ=ZTOP-Z2
      IF (XCR.GE.ZTOP) SUMA=SUMA+F2A*DZ/2.0
      IF (Z2.GT.XCR) SUMB=SUMB+F2B*DZ/2.0
      GO TO 370
360   F2B=(RGXI*VXT+RGYI*VYT)*P2*PAV(JR)
      FZI=ZTOP-XCR
      FZO=XCR-Z2
      DZ=ZTOP-Z2
      SUMA=SUMA+F2A*FZO*(1+FZO/DZ)/2.
      SUMB=SUMB+F2B*FZI*(FZO/DZ)/2.
370   DEN=DEN+P2*DZ/2.0
      IF (IPR10.EQ.0) GO TO 380
      WRITE (6,610)
      WRITE (6,620) DZ,SUMA,SUMB,DEN
380   IF (DEN.EQ.0) GO TO 390
      DKA(JA)=(SUMA+SUMB)/DEN
390   IF (IPR9.EQ.0) GO TO 400
      WRITE (6,630) DKA(JA)
400   RW1(JR)=RW1(JR)+DKA(JA)*RF
      IF (IPR10.EQ.0) GO TO 410
      WRITE (6,640)
      WRITE (6,650) DKA(JA),RF,RW1(JR)
410   CONTINUE
      DO 420 JK=1,NROW
420   DKSUMA=DKSUMA+RW1(JK)
      TOTS(IS)=DKSUMA
      IF (IPR9.EQ.0) GO TO 430
      WRITE (6,660)
      WRITE (6,670) (JR,RW1(JR),JR=1,NROW)
      WRITE (6,680) DKSUMA
430   RETURN
440   FORMAT ('1')
450   FORMAT (F7.1,F6.4)
460   FORMAT (E12.4)
470   FORMAT ('OASSEMBLY NO. ',I5,' WAS NOT FOUND')
480   FORMAT ('O  IIZ',5X,'IOZ',5X,'JR',7X,'JA  NASR(JA) RMID(JR)',4X,'
+ZMID',4X,'REXT(JR)',4X,'ZMAX',8X,'Z2',8X,'RAN',6X,'DIF',7X,'RF')
490   FORMAT (' ',I5,4I8,3X,8E10.4)
500   FORMAT ('OSTEP',I4,/, ' TIME ',F7.1,/, ' POWER/FLOW ',F6.4,/)
510   FORMAT (2E12.4)
520   FORMAT ('OASSY NO.',I4,/, ' ROW NO.',I3,/, ' RADIAL DISPLACEMENT (IN
+) ',E10.4,/)
530   FORMAT ('O',8X,'AXIAL',14X,'DISPLACEMENT VECTORS',/, ' ',8X,'LEVEL'
+,5X,'X-COMP',4X,'Y-COMP',6X,'TRUE X-COMP TRUE Y-COMP',/, ' NODE',4X
+,'(IN)',7X,'(IN)',6X,'(IN)',10X,'(IN)',8X,'(IN)',/, ' ',65(' '),/)
540   FORMAT ('O      ZC',8X,'F1A',7X,'F1B',7X,'P1',5X,'RALP(JR)  PAV(JR)

```

•

4

APPENDIX D

DISPLACEMENT DATA FILE FORMAT

The NUBOW-3D displacement data were calculated for the twelfth-core sector model shown in Figure 11. The axial geometric node structure used is shown in Figure 12. The displacement file created by NUBOW-3D is formatted for use in the CORDIS reactivity analysis method as shown in Table 14. Listed below are definitions for the terms used in Table 14.

TIME = amount of core burnup (EFPD).

PFR = power-to-flow ratio (% full power/% full flow).

UR(i) = radial displacement of duct in row i due to core expansion in global cylindrical coordinate system (bottom of subassembly relative to core center).

NROW = number of rows in core model.

VX(i), VY(i) = X and Y displacement of geometric nodal point (j) of appropriate duct in local

FIGURE 11. NUBOW-3D, 30-DEGREE CORE SECTOR MODEL.

ID - INNER DRIVER FUEL
OD - OUTER DRIVER FUEL

FIGURE 12. NUBOW-3D AXIAL SUBASSEMBLY GEOMETRIC NODE
STRUCTURE.

TABLE 14

NUBOW-3D DISPLACEMENT DATA FILE FORMAT

CALCULATIONAL TIMESTEP 1	{	SUBASSY. DUCT 1	TIME, PFR	(F7.1, F6.4)
			UR(2)	(E12.4)
			.	
			.	
			.	
			.	
			.	
			UR(NROW)	
			VX(1), VY(1)	(2E12.4)
			.	
.	{	.	.	
.		.	.	
.		.	.	
.		.	.	
.		.	.	
.		.	.	
.		.	.	
.		.	.	
.		.	VX(NNODE), VY(NNODE)	
.		.		
.	{	SUBASSY. DUCT M		
.				
.				
.				
.				
.				
.				
.				
.				
.				
LAST CALCULATIONAL TIMESTEP (NSTEP)				

100

cartesian coordinate system (relative to
subassembly bottom radial displacement).

NNODE = number of geometric axial node points in
NUBOW-3D core model.

M = number of ducts in model.

NSTEP = number of calculation steps.

APPENDIX E

VERIFICATION OF THE ADEQUACY OF FIRST ORDER PERTURBATION (FOP) THEORY

There are two assumptions associated with using FOP theory to calculate the reactivity effect of subassembly movement. The first is that FOP theory does not take into account neutron spectrum changes due to core component movement. FOP theory assumes that a subassembly's worth at a new position is based on the initial unperturbed neutron spectrum at that new position. In reality the subassembly 'carries' its neutron spectrum along with it.

The second assumption is that FOP theory does not account for decreased leakage associated with a larger core dimension. Thus, a FOP theory reactivity effect calculation for a uniform core expansion case would be too large negative because of the unaccounted for decreased leakage (positive reactivity effect).

To verify the adequacy of FOP theory concerning spectral and leakage changes, an additional HEX geometry, 2DBS, eigenvalue problem was run with perturbed radial core dimensions. The perturbed core dimensions modeled a uniform core expansion resulting in a $\approx$ 100 mil expansion to the outer core dimension (Row 9). The 100 mil expansion was

chosen only to make a reactivity effect calculation. This problem was then compared to the unperturbed eigenvalue calculation used in the HEX core analysis. The resultant $\Delta K/K$ between the two cases was $2.085E-3$. Using a delayed neutron fraction equal to $0.00318 (\Delta K/K)/\beta$ as before, this becomes $6.557E-1\beta$, or 66% .

The adequacy of the CORDIS reactivity analysis method was demonstrated using test cases involving uniform core expansion. Comparison of CORDIS reactivity response calculations to two-dimensional diffusion theory calculations using the 2DBS code and EMC test results is summarized in Table 15.

TABLE 15
CORE REACTIVITY RESPONSE DUE TO UNIFORM CORE EXPANSION
(100 mils)

2DBS	$-.66\%/mil$ (HEX core model)
EMC	$-.81\%/mil$
CORDIS	$-.74\%/mil$ (whole core model)
CORDIS	$-.81\%/mil$ (one-twelfth sector model)

As shown in Table 15, CORDIS predicted the core reactivity response to uniform core expansion within approximately 12% of the diffusion theory calculation, using a whole-core representation. To quantify this difference, an

estimate was made regarding the amount of the reactivity effect that could be attributed to the leakage and spectrum assumptions inherent to FOP theory.

For a large reactor, the two-group equation defining the effective multiplication factor, K_{eff} , can be written as

$$K_{eff} = \frac{K_{\infty}}{1 + M^2 B_0^2}$$

where, $\frac{1}{1 + M^2 B_0^2}$ = total nonleakage probability

M^2 = migration area of the neutrons

B_0^2 = buckling (a measure of the binding (or buckling) of the spatial distribution of the neutron flux)

K_{∞} = effective multiplication constant in an infinite system (i.e., no leakage).

Considering only radial leakage in a cylindrical core, B_0^2 can be written as

$$B_0^2 \approx \left(\frac{2.405}{R_0} \right)^2$$

where, R_0 = radius of the cylindrical core.

Now, assuming a uniform core expansion, the perturbed core radius can be written as

$$\begin{aligned} R_p &= R_0 + \delta R \\ &= R_0 \left[1 + \frac{\delta R}{R_0} \right] \\ \therefore \left(\frac{1}{R_p} \right)^2 &= \left(\frac{1}{R_0} \right)^2 \left(1 + \frac{\delta R}{R_0} \right)^{-2} . \end{aligned}$$

Assuming that $\frac{\delta R}{R_0}$ is small compared to 1, this expression can be written as

$$\frac{1}{R_p^2} \approx \frac{1}{R_0^2} \left(1 - 2 \frac{\delta R}{R_0} \right).$$

Thus, the perturbed buckling B_p^2 can be written as

$$B_p^2 \approx B_0^2 \left(1 - 2 \frac{\delta R}{R_0} \right).$$

Therefore, an equation for the perturbed effective multiplication factor, K_{eff_p} , can be derived as follows:

$$K_{eff_p} = \frac{K_{\infty}}{1 + M^2 B_0^2 \left(1 - 2 \frac{\delta R}{R_0} \right)}$$

$$K_{eff_p} = \frac{(1 + M^2 B_0^2) K_{eff}}{1 + M^2 B_0^2 \left(1 - 2 \frac{\delta R}{R_0} \right)} = \frac{K_{eff}}{1 - 2 \frac{\delta R}{R_0} \left(\frac{M^2 B_0^2}{1 + M^2 B_0^2} \right)}.$$

Writing now the reactivity change between the perturbed and unperturbed multiplication factors, we see that

$$\begin{aligned} \frac{\Delta K}{K_{eff}} &= \frac{K_{eff_p} - K_{eff}}{K_{eff}} = \frac{K_{eff_p}}{K_{eff}} - 1 \\ &= \frac{1}{1 - 2 \frac{\delta R}{R_0} M^2 B_0^2 (1 + M^2 B_0^2)^{-1}} - 1 \\ &= \left[1 - 2 \frac{\delta R}{R_0} M^2 B_0^2 (1 + M^2 B_0^2)^{-1} \right]^{-1} - 1. \end{aligned}$$

Expanding the negative powers, since $M^2 B_0^2$ is small compared to 1, and the same is true for the entire quantity in the overall brackets compared to 1, we see that

$$\frac{\Delta K}{K_{eff}} \approx 2 \frac{\delta R}{R_0} M^2 B_0^2 (1 - M^2 B_0^2).$$

Ignoring higher power terms, the final expression is

$$\frac{\Delta K}{K_{\text{eff}}} \approx 2 \frac{\delta R}{R_0} M^2 B_0^2.$$

To obtain an estimate of the quantity $M^2 B_0^2$, the all rods out, 2DBS calculations were used. In particular, since $M^2 B_0^2$ represents the leakage fraction, it is approximately equal to the total leakage divided by the total source calculated by 2DBS. This value yielded an average result of 0.047 for $M^2 B_0^2$. Considering a 0.1-inch (100 mil) uniform radial expansion, $\delta R/R_0$ was calculated to be approximately 0.0028. Thus, $\Delta K/K_{\text{eff}}$ was calculated to be approximately 0.00026 $\frac{\Delta K}{K}$, or 8 cents. It is only fortuitous that this result agrees with the calculated change.

Thus, the CORDIS calculations, using FOP theory, are within the expected range of the 2DBS eigenvalue calculations when the decreased leakage due to an expanded core is considered.

To evaluate the effect of the energy spectrum changes, 2DBS was run for two cases involving uniform expansion. One case was for a 10-mil expansion and another for a 100-mil expansion. The resulting $\Delta K/K/\text{mil}$ calculation for both cases gave nearly identical results of approximately

-.66¢/mil. Since leakage was accounted for in both cases, only energy spectrum change effects would have influenced the $\Delta K/K/\text{mil}$ results. Thus, for uniform core expansion up to 100 mils, the energy spectrum effects on reactivity calculations, using FOP theory, are negligible.

To account for the leakage effect in the CORDIS reactivity calculations, a factor of $(.66/.74) = 0.892$ (from Table 15) was used to adjust all subsequent whole core calculations. The adjustment to sector models was made based on the individual sector reactivity result compared to that for the whole core calculation. Thus, for the particular sector shown in Table 15, the adjustment factor was $(.74/.81) (.892) = .815$. The sector referred to in Table 15 is Sector 1 in Figure 9.