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XENON-INDUCED SPATIAL INSTABILITIES

IN THREE-DIMENSIONS

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MASTER

By

Finn B. Skogen
Allan F. McFarlane

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Approved:

J. S. Moore, Manager
Core Engineering

Approved:

M. J. O'Boyle, Manager
Xenon Instabilities Program

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TABLE OF CONTENTS

Section	Title	Page
1	INTRODUCTION	1
2	CORE DESCRIPTION	1
3	ONE- AND TWO-DIMENSIONAL ANALYSES	3
4	THREE-DIMENSIONAL ANALYSIS	5
5	CONCLUSIONS	19
	APPENDIX A	A-1

LIST OF ILLUSTRATIONS

Figure	Title	Page
1.	X-Y Flow Channel Geometry and Fuel Loading Pattern	2
2.	X-Y Power Distribution in a Plane Four Feet from Bottom of Core	4
3.	X-Y Power Peaking versus Time after Perturbation in the Average Plane	6
4.	X-Y Power Peaking versus Time after Perturbation in the Inlet Plane	7
5.	Axial Peaking Factor versus Time after Perturbation	8
6.	Axial Power Shape (Equilibrium Xenon)	10
7.	Contour Plot of Flux Distribution for Y=0 Plane, Equilibrium Conditions	11
8.	Normalized Power Density at Two Points in a Plane versus Time after Perturbation	12
9.	Axially Integrated Power in Hot Channels versus Time after Perturbation	13
10.	Normalized Power Density at Two Points in a Channel versus Time after Perturbation	14
11.	Comparison of Power Density at a Point; from Three-dimensional and Combined One- and Two-Dimensional Calculation	
12.	Contour Plot of Flux Distribution for Y=0 Plane at 115 Hours	15
13.	Contour Plot of Flux Distribution for Y=0 Plane at 133 Hours	16
14.	Contour Plot of Flux Distribution for Y=0 Plane at 109 Hours	17

LIST OF ILLUSTRATIONS (CONT)

Figure	Title	Page
15.	Contour Plot of Flux Distribution for $Y=0$ Plane at 127 Hours	18
16 -44.	Contour Plots of Flux Distribution for $Y=0$ Plane	21-49
A-1	X-Y Coordinates	A-2
A-2	Axial Coordinates	A-3

ABSTRACT

Three-dimensional diffusion theory calculations have been performed to study xenon-induced spatial oscillations in large pressurized water reactor (PWR) cores. A typical core was represented and a steady-state, unperturbed condition was created, simulating normal, full-power operation. A perturbation representing the full insertion of one control rod for one hour was introduced and the subsequent behavior of the power distribution was studied. The perturbed core exhibited an identifiable X-Y oscillation which converged, and an axial oscillation which diverged.

The results of the three-dimensional calculation are compared with two-dimensional calculations for selected planes in the core and with a one-dimensional axial calculation representing the average channel. The predictions of the simpler models are generally consistent with the three-dimensional calculation.

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XENON-INDUCED SPATIAL INSTABILITIES IN THREE-DIMENSIONS

1. INTRODUCTION

The characteristics of xenon-induced spatial power oscillations are of interest to designers and operators of large, high-power-density, pressurized water reactors. Extensive studies have been made of these oscillations in the plane perpendicular to coolant flow in previously reported parts of this program^[1, 2]. In this and other work, the assumption is made that the behavior of the core can be represented in one-dimensional or two-dimensional geometry. It is important to verify the validity of this assumption and this requires measurements on operating reactors or realistic three-dimensional calculations. Currently, there are no commercial reactors operating with conditions which adequately duplicate the largest PWR's already committed to construction. Therefore, three-dimensional calculations serve a useful purpose even though they are expensive to perform and require or incorporate simplifying assumptions.

The calculations reported here represent a realistic treatment of a typical, large PWR core using three-dimensional diffusion theory with a sophisticated treatment of coolant flow, with interassembly mixing, and subcooled voids, giving a local moderator density which is fed back into the neutron calculation.

This three-dimensional calculation is compared with a two-dimensional representation of the horizontal plane and a one-dimensional representation of the average channel.

2. CORE DESCRIPTION

The reactor system selected for this study is a large PWR core with the fuel loading pattern shown in Figure 1. Slight modifications from a typical

Figure 1. X-Y Flow Channel Geometry and Fuel Loading Pattern

checkerboard core are necessary because of restrictions imposed by the thermal-hydraulic model presently available in the three-dimensional code, and the relatively long computer running time necessary. The latter dictates a reduction in the spatial mesh intensity to a point where it is necessary to do the analysis on a homogenized core model; i.e., all non-lattice regions are homogenized in with the fuel. The geometry chosen has two mesh intervals per fuel assembly and a total of 12 equally spaced axial intervals in the active core. The X-Y mesh width used is about 10.8 cm, which was found to be adequate when studying free-running xenon oscillations^[1]. The overall problem size is 40 x 20 x 18, including the baffle, upper, lower, and radial reflector regions; i.e., the core is described by a total of 14,000 mesh points. Details of the coordinate system are given in Appendix A.

The geometry shown in Figure 1 was arrived at by running a series of two-dimensional calculations in which the fuel enrichments and the loading patterns were varied until an acceptable power distribution was found. The enrichment sets 2.4, 2.65, and 3.1 w/o were selected. The core has burnable poison distributed uniformly throughout, with the equivalent of approximately six burnable poison pins per fuel assembly. With a critical boron concentration of 1,100 ppm, the resulting X-Y power distribution in a plane four feet from the bottom of the core is relatively flat, as shown in Figure 2, and compares favorably with that of a standard PWR design. The power density of the core is 104.5 W/cc.

3. ONE- AND TWO-DIMENSIONAL ANALYSES

As a preliminary to the study, a two-dimensional analysis for a core of identical geometry was carried out. Two calculations were performed; one investigated the behavior of xenon-induced oscillations in an average enthalpy plane while the other represented the inlet plane.

The method of analysis was identical to that used in the study of X-Y instabilities^[2]. In the average enthalpy plane each mesh rectangle has an enthalpy rise relative to the inlet conditions and proportional to the power generation in that rectangle. At the inlet plane no enthalpy rise is calculated so that the effect of moderator density change is not fed back into the

QUADRANT #1					QUADRANT #2				
2 1.044	3 1.179	4 1.165	5 1.220	6 1.152	7 1.220	8 1.165	9 1.179	10 1.041	
11 0.960	12 1.130	13 1.215	14 1.140	15 1.220	16 1.140	17 1.215	18 1.130	19 0.960	
20 0.680	21 0.951	22 1.017	23 1.215	24 1.165	25 1.215	26 1.017	27 0.951	28 0.680	
	29 0.386	30 0.729	31 0.951	32 1.130	33 1.179	34 1.130	35 0.951	36 0.729	37 0.386
	38 0.386	39 0.680	40 0.960	41 1.041	42 0.960	43 0.680	44 0.386		

NOTE:

NUMBERS IN UPPER LEFT
REPRESENT REGIONS.

NUMBERS IN CENTER ARE
NORMALIZED POWERS OF
REGION.

Figure 2. X-Y Power Distribution in a Plane Four Feet from Bottom of Core

neutron calculation. However, the power density for the purposes of generating xenon and Doppler effects was assumed to be 104.5 W/cc in each case. The results of this analysis show that while the average plane is stable, the inlet plane, which has no pointwise moderator density feedback, exhibits an unstable oscillation.

Figures 3 and 4 show the X-Y power peaking as a function of time following the perturbation for the average and inlet plane, respectively. The stability indices of the two oscillations are $-0.042 \text{ hours}^{-1}$ (stable) and $+0.037 \text{ hours}^{-1}$ (unstable). The definition of this stability index and its derivation for this type of oscillation is given in Reference 2.

Using a diffusion theory code with average channel enthalpy feedback effects, a one-dimensional axial calculation was also performed. In this calculation the perturbation introduced is equivalent to a one-hour insertion of a bank of control rods with a corresponding reduction in power. The control rods are withdrawn and a free-running oscillation results. Reactor power remains constant at 100 percent and the major part of the power generation oscillates from top to bottom of the core. The oscillation is depicted in Figure 5, which shows the axial peaking factor as a function of time. This oscillation is divergent and corresponds to the behavior typical of this size and type of PWR core. Part-length control rods are provided to prevent such oscillations leading to unacceptable power shapes; a discussion of the use of these rods can be found in Reference 3.

The conclusion from these preliminary calculations is that the core is expected to be stable to X-Y oscillations, as indicated by the average plane calculation; and unstable to axial oscillations, as indicated by the average channel calculation.

4. THREE-DIMENSIONAL ANALYSIS

The code used for this calculation computes the neutron flux distribution and local coolant enthalpies and densities. The nuclear model is a three-dimensional, two-group diffusion theory in which feedbacks due to coolant density and fuel pellet temperature are taken into account. The

Figure 3. X-Y Power Peaking versus Time after Perturbation in the Average Plane

Figure 4. X-Y Power Peaking versus Time after Perturbation in the Inlet Plane

Figure 5. Axial Peaking Factor versus Time after Perturbation

thermal-hydraulic model determines the flow and enthalpy rise in the various subchannels in the core as a function of the power distribution, and flow mixing between assemblies is allowed for. The main limitation encountered in this model is that the largest channel array that can be described at present is 9×9 and that does not allow at least one flow channel per fuel assembly in a 15×15 assembly core. Consequently, it is necessary to combine more than one (and as many as four) fuel assembly in each channel, and it becomes impossible to reproduce the identical checkerboard loading typical of large PWR's. Figure 1 shows the X-Y channel array selected.

A three-dimensional problem was set up with the core described in Section 2. An axial poisoned region was introduced in a central section of the core to represent the presence of part-length rods and burnup in an operating core. The resulting equilibrium xenon axial power shape is shown in Figure 6. A two-dimensional contour plot of the flux distribution for the $y = 0$ plane is shown in Figure 7.

A local poison equivalent to a full-length control rod was inserted into the core on the y-axis in region 3 of Figure 2. The poison remained in the core for one hour and was then withdrawn. The perturbed core exhibited an oscillation, identifiable as an X-Y oscillation, which converged and an axial oscillation which diverged. The axial oscillation occurred through the axially nonuniform effects of enthalpy rise even though the control rod insertion was an axially uniform perturbation. The oscillation is described in Figures 8 through 15.

The local power density at two points in a selected plane are shown in Figure 8 for a plane three feet from the bottom of the core. This figure illustrates the superposition of the axial oscillations, indicated by the general level of the curves and the X-Y oscillation, indicated by the crossing and recrossing of the curves.

Figure 9 shows the variation with time of the axially integrated power in two selected channels which are the hottest channels when the oscillation is at a peak. This integrated power is effectively an averaged X-Y behavior and therefore corresponds to the equivalent two-dimensional calculation. The

Figure 6. Axial Power Shape Equilibrium Xenon

NOTE: CONTOUR VALUES ARE RELATIVE TO PEAK FLUX

Figure 7. Contour Plot of Flux Distribution for Y = O Plane, Equilibrium Condition

Figure 8. Normalized Power Density at Two Points in a Plane
3 Feet from Bottom of Core versus Time after Perturbation

Figure 9: Axially Integrated Power in Hot Channels versus Time After Perturbation

Figure 10. Normalized Power Density at Two Points in a Channel versus Time after Perturbation

Figure 11. Comparison of Power Density at a Point; from Three-Dimensional and Combined One and Two-Dimensional Calculations

NOTE: CONTOUR VALUES ARE RELATIVE TO PEAK FLUX

Figure 12. Contour Plot of Flux Distribution for Y = O Plane at 115.0 Hours

NOTE: CONTOUR VALUES ARE RELATIVE TO PEAK FLUX.

Figure 13. Contour Plot of Flux Distribution for Y = O Plane at 133.0 Hours

NOTE: CONTOUR VALUES ARE RELATIVE TO PEAK FLUX.

Figure 14. Contour Plot of Flux Distribution for Y = O Plane at 109.0 Hours

NOTE: CONTOUR VALUES ARE RELATIVE TO PEAK FLUX.

Figure 15. Contour Plot of Flux Distribution for Y = O Plane at 127.0 Hours

period of the X-Y oscillation is 31.8 hours and as an indicator of the degree of convergence of the oscillation an exponential decay was assumed for which the coefficient was calculated to be $-0.016 \text{ hours}^{-1}$. In a pure oscillation this would be a stability index as defined in Reference 1. This compares with the two-dimensional result of Figure 3, which gives a period of 36.0 hours and a stability index of $-0.042 \text{ hours}^{-1}$ for the average plane. The three-dimensional case is therefore less rapidly convergent than the average plane calculation. The inlet plane calculation which has no thermal feedbacks, predicted a divergent oscillation. Thus, the average plane calculation more nearly represents the stability of the core, but the cases are not strictly comparable since the three-dimensional result is influenced by the diverging axial oscillation. In practice, part-length rod movement would be required to control the axial oscillation and such action must affect the X-Y oscillation.

The axial oscillation can be represented by plotting the power at two points in the core, one above the midplane and one below the midplane, as shown in Figure 10.

The behavior of the power density at a single point as calculated in three dimensions can be compared with a combination of the one-dimensional and two-dimensional calculations. This is shown in Figure 11 for a point which is close to the peak power in the unperturbed core. The index in an exponential envelope to these curves is $+0.015 \text{ hr}^{-1}$ for the three-dimensional case and $+0.027 \text{ hr}^{-1}$ for the combined one- and two-dimensional calculations.

The antinodes of the radial oscillation occur at approximately 115 hours and 133 hours; the perturbation was removed at 101 hours. Contour plots of the $y = 0$ plane are shown for these times in Figures 12 and 13. The antinodes of the axial oscillation occur at 109 hours and 127 hours and these contour plots are shown in Figures 14 and 15. A complete set of contour plots is shown in Figures 16 through 44.

5. CONCLUSIONS

The three-dimensional results indicate that a perturbation introduced in one side of the core can excite an X-Y oscillation and an axial oscillation. The character of these oscillations is generally consistent with the predictions of simpler one- and two-dimensional calculations.

NOTE: CONTOUR VALUES ARE RELATIVE TO PEAK FLUX

Figure 16. Contour Plot of Flux Distribution for Y=0 Plane at 0.0 Hours, Xenon Free

Figure 17. Contour Plot of Flux Distribution for Y=0 Plane at 100.0 Hours, Equilibrium Xenon.

NOTE: CONTOUR VALUES ARE RELATIVE TO PEAK FLUX

Figure 18. Contour Plot of Flux Distribution for Y=0 Plane at 100.0 Hours, Perturbing Control Rod Inserted

NOTE: CONTOUR VALUES ARE RELATIVE TO PEAK FLUX

Figure 19. Contour Plot of Flux Distribution for Y=0 Plane at 101.0 Hours, Perturbing Control Rod Inserted.

NOTE: CONTOUR VALUES ARE RELATIVE TO PEAK FLUX

Figure 20. Contour Plot of Flux Distribution for Y=0 Plane at 101.0 Hours, Perturbing Control Rod Removed.

NOTE: CONTOUR VALUES ARE RELATIVE TO PEAK FLUX

Figure 21. Contour Plot of Flux Distribution for Y=0 Plane at 103.0 Hours.

NOTE: CONTOUR VALUES ARE RELATIVE TO PEAK FLUX

Figure 22. Contour Plot of Flux Distribution for Y=0 Plane at 105.0 Hours.

NOTE: CONTOUR VALUES ARE RELATIVE TO PEAK FLUX.

Figure 23. Contour Plot of Flux Distribution for Y=0 Plane at 107.0 Hours.

NOTE: CONTOUR VALUES ARE RELATIVE TO PEAK FLUX.

Figure 24. Contour Plot of Flux Distribution for Y=0 Plane at 109.0 Hours.

Figure 25. Contour Plot of Flux Distribution for Y=0 Plane at 111.0 Hours.

NOTE: CONTOUR VALUES ARE RELATIVE TO PEAK FLUX.

Figure 26. Contour Plot of Flux Distribution for Y=0 Plane at 113.0 Hours.

NOTE: CONTOUR VALUES ARE RELATIVE TO PEAK FLUX.

Figure 27. Contour Plot of Flux Distribution for Y=0 Plane at 115.0 Hours.

NOTE: CONTOUR VALUES ARE RELATIVE TO PEAK FLUX.

Figure 28. Contour Plot of Flux Distribution for Y=0 Plane at 117.0 Hours.

NOTE: CONTOUR VALUES ARE RELATIVE TO PEAK FLUX

Figure 29. Contour Plot of Flux Distribution for Y=0 Plane at 119.0 Hours.

NOTE: CONTOUR VALUES ARE RELATIVE TO PEAK FLUX.

Figure 30. Contour Plot of Flux Distribution for Y=0 Plane at 121.0 Hours.

NOTE: CONTOUR VALUES ARE RELATIVE TO PEAK FLUX.

Figure 31. Contour Plot of Flux Distribution for Y=0 Plane at 123.0 Hours.

NOTE: CONTOUR VALUES ARE RELATIVE TO PEAK FLUX.

Figure 32. Contour Plot of Flux Distribution for Y=0 Plane at 125.0 Hours.

NOTE: CONTOUR VALUES ARE RELATIVE TO PEAK FLUX.

Figure 33. Contour Plot of Flux Distribution for Y=0 Plane at 127.0 Hours.

NOTE: CONTOUR VALUES ARE RELATIVE TO PEAK FLUX.

Figure 34. Contour Plot of Flux Distribution for Y=0 Plane at 129.0 Hours.

NOTE: CONTOUR VALUES ARE RELATIVE TO PEAK FLUX.

Figure 35. Contour Plot of Flux Distribution for Y=0 Plane at 131.0 Hours.

NOTE: CONTOUR VALUES ARE RELATIVE TO PEAK FLUX.

Figure 36. Contour Plot of Flux Distribution for Y=0 Plane at 133.0 Hours.

NOTE: CONTOUR VALUES ARE RELATIVE TO PEAK FLUX.

Figure 37. Contour Plot of Flux Distribution for Y=0 Plane at 135.0 Hours.

NOTE: CONTOUR VALUES ARE RELATIVE TO PEAK FLUX.

Figure 38. Contour Plot of Flux Distribution for Y=0 Plane at 137.0 Hours.

NOTE: CONTOUR VALUES ARE RELATIVE TO PEAK FLUX.

Figure 39. Contour Plot of Flux Distribution for Y=0 Plane at 139.0 Hours.

NOTE: CONTOUR VALUES ARE RELATIVE TO PEAK FLUX.

Figure 40. Contour Plot at Flux Distribution for Y=0 Plane at 141.0 Hours.

NOTE: CONTOUR VALUES ARE RELATIVE TO PEAK FLUX.

Figure 41. Contour Plot of Flux Distribution for Y=0 Plane at 143.0 Hours.

NOTE: CONTOUR VALUES ARE RELATIVE TO PEAK FLUX.

Figure 42. Contour Plot of Flux Distribution for Y=0 Plane at 145.0 Hours.

NOTE: CONTOUR VALUES ARE RELATIVE TO PEAK FLUX.

Figure 43. Contour Plot of Flux Distribution for Y=0 Plane at 147.0 Hours.

NOTE: CONTOUR VALUES ARE RELATIVE TO PEAK FLUX.

Figure 44. Contour Plot of Flux Distribution for Y=0 Plane at 149.0 Hours.

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APPENDIX A

DESCRIPTION OF COORDINATES

X-Y COORDINATES

The X-Y mesh used in both three-dimensional and two-dimensional calculations are shown in Figure A-1. Each mesh rectangle has dimensions 10.75 x 10.75 cm.

AXIAL (Z) COORDINATES

The axial mesh is shown in Figure A-2.

Figure A-1 X-Y Coordinates

Figure A-2 Axial Coordinates