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AZIMUTHAL XENON OSCILLATIONS IN A TYPICAL PWR

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AZIMUTHAL XENON OSCILLATIONS IN A TYPICAL PWR

by

V. D. Vandervelde

Approved by

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September 1970

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INTRODUCTION

Large reactors, operating at sufficiently high neutron flux, are subject to spatial oscillations in the power distribution caused by the cyclical redistribution of xenon-135. These "xenon oscillations" are associated with some particular dimension of the reactor. For cylindrical reactors, the two main types of oscillations are axial (oscillation about the midplane) and azimuthal (oscillation about a diameter). Other more complicated types of oscillations, such as shapes which change from "humped" to "dished," are of course possible; but they are usually more damped for a given set of conditions than simple axial or azimuthal oscillations and are not considered here.

Present generation pressurized water reactors (PWR) have developed to the point where serious consideration must be given to occurrence and control of both axial and azimuthal xenon oscillations. Because axial oscillations are effectively damped by appropriate motion of partial length control rods[1,2] and present control system designs are adaptable to this method of control, this report will not consider axial oscillations.

The objective of this study is to investigate, for a "typical" PWR, the effect of azimuthal xenon oscillations. This objective necessitates a choice of parameters to represent the type of reactor (held constant throughout the study), and a choice of parameters to vary.

Once the type of reactor has been established, there are four variables* which most affect the oscillations. Higher neu-

* Boiling water reactors (not considered here) have an additional mechanism--the void coefficient--which strongly affects xenon oscillations.

tron flux, larger reactor dimensions, less negative or more positive temperature coefficients, and more "dished" power shapes all tend to increase the instability of the oscillations. The first three of these may be conveniently expressed as a single linear variable, but the power shape does not, in general, lend itself to any such simple representation. Because of this, three radial power shapes were considered in this study representing a range of possible operating conditions.

SUMMARY

This study indicates that the typical present generation PWR, operating at powers less than 2800 MW, should not be susceptible to divergent azimuthal xenon oscillations provided that the coolant coefficient is less than $\sim+2 \times 10^{-4}$ $\Delta k/°F$.

DISCUSSION

The investigation of azimuthal xenon oscillations in a typical large pressurized water power reactor was made by a series of three-dimensional MAPLE SYRUP calculations (see Appendix for brief description of MAPLE SYRUP).

GEOMETRICAL REPRESENTATION AND MATERIAL PROPERTIES

The reactor model geometry consists of a group of rectangular parallelepipeds, each containing a material (represented by a material number) and each having the dimensions ΔX, ΔY, and ΔZ with a mesh point centrally located. For this study $\Delta X = \Delta Y = 21.508$ cm and $\Delta Z = 26.126$ cm. Axial symmetry exists about the central plane so that an extrapolated height of 418 cm (including 52 cm of reflector) is represented by 8 axial layers. The material overlay is shown below for each of the 8 axial layers; Z = 1 is the layer closest to the midplane.

```
MATERIALS FOR Z=   1

1010101010 8 8 8 8 8 8 81010101010
101010 8 8 6 6 6 6 6 6 6 8 8101010
1010 8 6 6 4 4 4 4 4 4 4 6 6 81010
10 8 6 4 4 3 3 3 3 3 3 3 4 4 6 810
10 8 6 4 3 3 2 2 2 2 2 3 3 4 6 810
 8 6 4 3 3 2 2 1 1 1 2 2 3 3 4 6 8
 8 6 4 3 2 2 1 1 1 1 1 2 2 3 4 6 8
 8 6 4 3 2 1 1 1 1 1 1 1 2 3 4 6 8
 8 6 4 3 2 1 1 1 1 1 1 1 2 3 4 6 8
 8 6 4 3 2 1 1 1 1 1 1 1 2 3 4 6 8
 8 6 4 3 2 2 1 1 1 1 1 2 2 3 4 6 8
 8 6 4 3 3 2 2 1 1 1 2 2 3 3 4 6 8
10 8 6 4 3 3 2 2 2 2 2 3 3 4 6 810
10 8 6 4 4 3 3 3 3 3 3 3 4 4 6 810
1010 8 6 6 4 4 4 4 4 4 4 6 6 81010
101010 8 8 6 6 6 6 6 6 6 8 8101010
1010101010 8 8 8 8 8 8 81010101010
```

```
MATERIALS FOR Z=   2

1010101010 8 8 8 8 8 8 81010101010
101010 8 8 6 6 6 6 6 6 6 8 8101010
1010 8 6 6 4 4 4 4 4 4 4 6 6 81010
10 8 6 4 4 3 3 3 3 3 3 3 4 4 6 810
10 8 6 4 3 3 2 2 2 2 2 3 3 4 6 810
 8 6 4 3 3 2 2 1 1 1 2 2 3 3 4 6 8
 8 6 4 3 2 2 1 1 1 1 1 2 2 3 4 6 8
 8 6 4 3 2 1 1 1 1 1 1 1 2 3 4 6 8
 8 6 4 3 2 1 1 1 1 1 1 1 2 3 4 6 8
 8 6 4 3 2 1 1 1 1 1 1 1 2 3 4 6 8
 8 6 4 3 2 2 1 1 1 1 1 2 2 3 4 6 8
 8 6 4 3 3 2 2 1 1 1 2 2 3 3 4 6 8
10 8 6 4 3 3 2 2 2 2 2 3 3 4 6 810
10 8 6 4 4 3 3 3 3 3 3 3 4 4 6 810
1010 8 6 6 4 4 4 4 4 4 4 6 6 81010
101010 8 8 6 6 6 6 6 6 6 8 8101010
1010101010 8 8 8 8 8 8 81010101010
```

```
MATERIALS FOR Z=   3

1010101010 8 8 8 8 8 8 81010101010
101010 8 8 6 6 6 6 6 6 6 8 8101010
1010 8 6 6 4 4 4 4 4 4 4 6 6 81010
10 8 6 4 4 3 3 3 3 3 3 3 4 4 6 810
10 8 6 4 3 3 2 2 2 2 2 3 3 4 6 810
 8 6 4 3 3 2 2 1 1 1 2 2 3 3 4 6 8
 8 6 4 3 2 2 1 1 1 1 1 2 2 3 4 6 8
 8 6 4 3 2 1 1 1 1 1 1 1 2 3 4 6 8
 8 6 4 3 2 1 1 1 1 1 1 1 2 3 4 6 8
 8 6 4 3 2 1 1 1 1 1 1 1 2 3 4 6 8
 8 6 4 3 2 2 1 1 1 1 1 2 2 3 4 6 8
 8 6 4 3 3 2 2 1 1 1 2 2 3 3 4 6 8
10 8 6 4 3 3 2 2 2 2 2 3 3 4 6 810
10 8 6 4 4 3 3 3 3 3 3 3 4 4 6 810
1010 8 6 6 4 4 4 4 4 4 4 6 6 81010
101010 8 8 6 6 6 6 6 6 6 8 8101010
1010101010 8 8 8 8 8 8 81010101010
```

```
MATERIALS FOR Z=   4

1010101010 8 8 8 8 8 8 81010101010
101010 8 8 6 6 6 6 6 6 6 8 8101010
1010 8 6 6 4 4 4 4 4 4 4 6 6 81010
10 8 6 4 4 3 3 3 3 3 3 3 4 4 6 810
10 8 6 4 3 3 2 2 2 2 2 3 3 4 6 810
 8 6 4 3 3 2 2 2 2 2 2 2 3 3 4 6 8
 8 6 4 3 2 2 2 2 2 2 2 2 2 3 4 6 8
 8 6 4 3 2 2 2 2 2 2 2 2 2 3 4 6 8
 8 6 4 3 2 2 2 2 2 2 2 2 2 3 4 6 8
 8 6 4 3 2 2 2 2 2 2 2 2 2 3 4 6 8
 8 6 4 3 2 2 2 2 2 2 2 2 2 3 4 6 8
 8 6 4 3 3 2 2 2 2 2 2 2 3 3 4 6 8
10 8 6 4 3 3 2 2 2 2 2 3 3 4 6 810
10 8 6 4 4 3 3 3 3 3 3 3 4 4 6 810
1010 8 6 6 4 4 4 4 4 4 4 6 6 81010
101010 8 8 6 6 6 6 6 6 6 8 8101010
1010101010 8 8 8 8 8 8 81010101010
```

```
MATERIALS FOR Z=   5

1010101010 8 8 8 8 8 8 81010101010
101010 8 8 6 6 6 6 6 6 6 8 8101010
1010 8 6 6 4 4 4 4 4 4 4 6 6 81010
10 8 6 4 4 3 3 3 3 3 3 3 4 4 6 810
10 8 6 4 3 3 3 3 3 3 3 3 3 4 6 810
 8 6 4 3 3 3 3 3 3 3 3 3 3 3 4 6 8
 8 6 4 3 3 3 3 3 3 3 3 3 3 3 4 6 8
 8 6 4 3 3 3 3 3 3 3 3 3 3 3 4 6 8
 8 6 4 3 3 3 3 3 3 3 3 3 3 3 4 6 8
 8 6 4 3 3 3 3 3 3 3 3 3 3 3 4 6 8
 8 6 4 3 3 3 3 3 3 3 3 3 3 3 4 6 8
 8 6 4 3 3 3 3 3 3 3 3 3 3 3 4 6 8
10 8 6 4 3 3 3 3 3 3 3 3 3 4 6 810
10 8 6 4 4 3 3 3 3 3 3 3 4 4 6 810
1010 8 6 6 4 4 4 4 4 4 4 6 6 81010
101010 8 8 6 6 6 6 6 6 6 8 8101010
1010101010 8 8 8 8 8 8 81010101010

MATERIALS FOR Z=   6

1010101010 8 8 8 8 8 8 81010101010
101010 8 8 6 6 6 6 6 6 6 8 8101010
1010 8 6 6 4 4 4 4 4 4 4 6 6 81010
10 8 6 4 4 4 4 4 4 4 4 4 4 4 6 810
10 8 6 4 4 4 4 4 4 4 4 4 4 4 6 810
 8 6 4 4 4 4 4 4 4 4 4 4 4 4 4 6 8
 8 6 4 4 4 4 4 4 4 4 4 4 4 4 4 6 8
 8 6 4 4 4 4 4 4 4 4 4 4 4 4 4 6 8
 8 6 4 4 4 4 4 4 4 4 4 4 4 4 4 6 8
 8 6 4 4 4 4 4 4 4 4 4 4 4 4 4 6 8
 8 6 4 4 4 4 4 4 4 4 4 4 4 4 4 6 8
 8 6 4 4 4 4 4 4 4 4 4 4 4 4 4 6 8
10 8 6 4 4 4 4 4 4 4 4 4 4 4 6 810
10 8 6 4 4 4 4 4 4 4 4 4 4 4 6 810
1010 8 6 6 4 4 4 4 4 4 4 6 6 81010
101010 8 8 6 6 6 6 6 6 6 8 8101010
1010101010 8 8 8 8 8 8 81010101010

MATERIALS FOR Z=   7

1010101010 8 8 8 8 8 8 81010101010
101010 8 8 6 6 6 6 6 6 6 8 8101010
1010 8 6 6 4 4 4 4 4 4 4 6 6 81010
10 8 6 4 4 4 4 4 4 4 4 4 4 4 6 810
10 8 6 4 4 4 4 4 4 4 4 4 4 4 6 810
 8 6 4 4 4 4 4 4 4 4 4 4 4 4 4 6 8
 8 6 4 4 4 4 4 4 4 4 4 4 4 4 4 6 8
 8 6 4 4 4 4 4 4 4 4 4 4 4 4 4 6 8
 8 6 4 4 4 4 4 4 4 4 4 4 4 4 4 6 8
 8 6 4 4 4 4 4 4 4 4 4 4 4 4 4 6 8
 8 6 4 4 4 4 4 4 4 4 4 4 4 4 4 6 8
 8 6 4 4 4 4 4 4 4 4 4 4 4 4 4 6 8
10 8 6 4 4 4 4 4 4 4 4 4 4 4 6 810
10 8 6 4 4 4 4 4 4 4 4 4 4 4 6 810
1010 8 6 6 4 4 4 4 4 4 4 6 6 81010
101010 8 8 6 6 6 6 6 6 6 8 8101010
1010101010 8 8 8 8 8 8 81010101010

MATERIALS FOR Z=   8

1010101010 8 8 8 8 8 8 81010101010
101010 8 8 9 9 9 9 9 9 9 8 8101010
1010 8 9 9 9 9 9 9 9 9 9 9 9 81010
10 8 9 9 9 9 9 9 9 9 9 9 9 9 9 810
10 8 9 9 9 9 9 9 9 9 9 9 9 9 9 810
 8 9 9 9 9 9 9 9 9 9 9 9 9 9 9 9 8
 8 9 9 9 9 9 9 9 9 9 9 9 9 9 9 9 8
 8 9 9 9 9 9 9 9 9 9 9 9 9 9 9 9 8
 8 9 9 9 9 9 9 9 9 9 9 9 9 9 9 9 8
 8 9 9 9 9 9 9 9 9 9 9 9 9 9 9 9 8
 8 9 9 9 9 9 9 9 9 9 9 9 9 9 9 9 8
 8 9 9 9 9 9 9 9 9 9 9 9 9 9 9 9 8
10 8 9 9 9 9 9 9 9 9 9 9 9 9 9 810
10 8 9 9 9 9 9 9 9 9 9 9 9 9 9 810
1010 8 9 9 9 9 9 9 9 9 9 9 9 81010
101010 8 8 9 9 9 9 9 9 9 8 8101010
1010101010 8 8 8 8 8 8 81010101010
```

Material 10 is a poison boundary simulating the area outside the reactor vessel. Materials 8 and 9 represent reflector (H_2O and iron) regions. Materials 1 through 7 represent fuel regions. The thermal absorption cross sections of materials 1, 2, 3, 4, and 6 were adjusted to achieve the desired equilibrium power shape, and materials 5 and 7 were exactly the same as material 6 except during the perturbation.

The input diffusion parameters (Table I) were obtained by private communication from G. S. Lellouche of Brookhaven National Laboratory; and, although they were calculated for a particular reactor, they are representative of the parameters calculated for the present generation PWR's.

TABLE I

Parameters Used in The MAPLE SYRUP Calculations

Groups	D	Σ_a	$\nu\Sigma_f$	Σ_R
Fuel Cells[a]				
Fast	1.470	0.0104	0.0070	0.0172
Thermal	0.393	$\sim$0.10[c]	0.1271	-
Reflector Cells[b]				
Fast	1.470	0.0009	0	0.0431
Thermal	0.393	0.0293	0	-

a. Materials 1 through 7

b. Materials 8 and 9

c. The thermal absorption cross sections of the various regions in the reactor were varied to achieve the desired radial power shape.

The code requires that all regions use the same diffusion coefficients (D); therefore, the fuel region D's were used for all regions. This assumption introduces some error in the leakage from the reflector (and, therefore, the neutron flux shape), but because the flux shape was adjusted by changing the fuel thermal absorption cross section, the net error in the oscillation from this assumption should be small.

The sensitivity of the resultant oscillations to changes in the few-group parameters, except $\nu\Sigma_f$, is secondary. Even though these parameters are different because of such things as exposure dependence, the net effect on the results shown here is small. Since the value of the neutron flux at a given reactor power is inversely proportional to $\nu\Sigma_f$, the results can be adjusted accordingly.

The other pertinent operating characteristics and parameters, used in the calculations and listed in Table II, are also representative of present generation PWR's.

TABLE II

Assumed Reactor Data and Operating Characteristics

Reactor power - 2760 MW

Reactor height - 12 ft

Equivalent reactor diameter - 11 ft

Effective xenon cross section[a] - 1.414×10^6 barns

a. The effective xenon cross section for the cell is the actual average cross section multiplied by the ratio of the average neutron flux in the fuel to the average neutron flux in the cell.

CALCULATIONAL PROCEDURES AND ASSUMPTIONS

Three equilibrium radial power shapes were chosen to represent various possible operating shapes. Table III lists the equilibrium relative powers at each X,Y mesh point for one quadrant (90° symmetry exists at equilibrium because of the symmetric input) for each of the three shapes. For convenience, these same shapes are plotted in Figure 1 as a function of radius perpendicular to the plane where the perturbation will occur.

TABLE III

Equilibrium Relative Powers for One Quadrant of the Reactor

(90° symmetry is calculated: number in lower left-hand corner is at reactor counter; plots are in Figure 1)

Dished Power Shape $Q_{max}/Q_{avg} = 1.18$

47.3	45.9	41.1	30.5				
64.7	63.4	59.3	51.9	42.9	28.9		
65.0	65.3	63.3	60.2	57.1	46.2	28.9	
61.8	61.7	61.7	63.3	61.5	57.1	42.9	
57.9	58.2	60.0	61.4	63.3	60.2	51.9	30.5
56.2	56.5	57.5	60.0	61.7	63.3	59.3	41.1
55.4	55.6	56.5	58.2	61.7	65.3	63.4	45.9
55.1	55.4	56.2	57.9	61.8	65.0	64.7	47.3

Flat Power Shape $Q_{max}/Q_{avg} = 1.21$

38.4	37.3	33.3	24.7				
58.1	56.8	52.9	45.7	35.9	23.6		
65.8	64.9	62.3	57.7	51.9	40.2	23.6	
67.4	67.0	65.9	64.8	59.9	51.9	35.9	
67.4	67.3	67.7	66.7	64.8	57.7	45.7	24.7
67.8	67.8	67.6	67.7	65.9	62.3	52.9	33.3
68.2	68.1	67.8	67.3	67.0	64.9	56.8	37.3
68.4	68.2	67.8	67.4	67.4	65.8	58.1	38.4

Humped Power Shape $Q_{max}/Q_{avg} = 1.49$

30.3	29.3	26.2	19.3				
50.8	49.6	45.8	38.8	28.9	18.4		
64.5	63.4	59.9	53.9	45.5	33.6	18.4	
72.9	72.0	69.3	64.9	56.8	45.5	28.9	
78.1	77.4	75.7	71.4	64.9	53.9	38.8	19.3
81.9	81.2	79.1	75.7	69.3	59.9	45.8	26.2
84.2	83.4	81.2	77.4	72.0	63.4	49.6	29.3
84.9	84.2	81.9	78.1	72.9	64.5	50.8	30.3

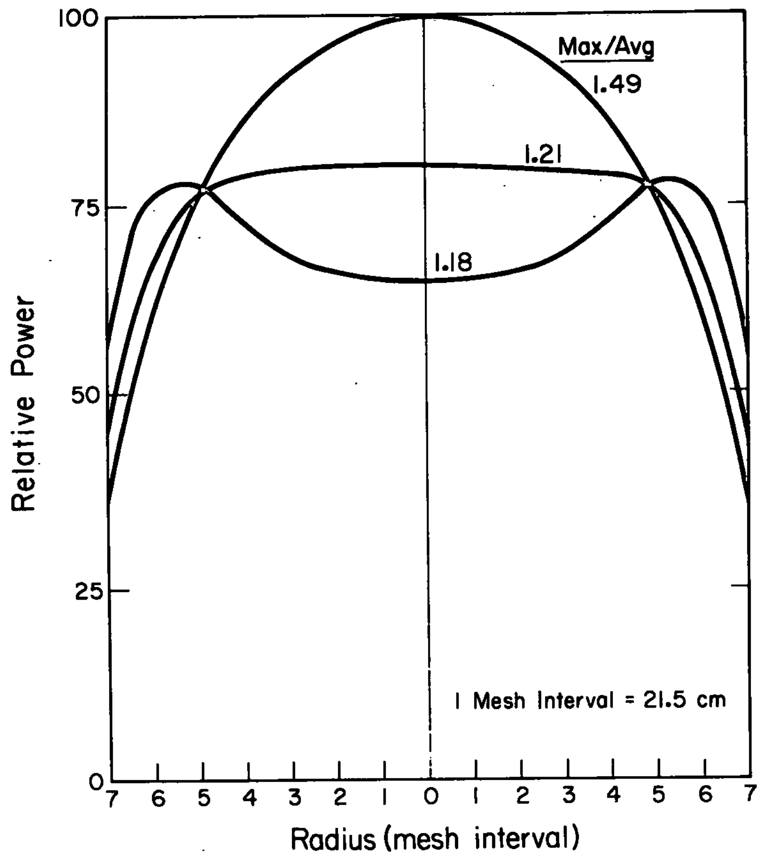

FIG. 1 HUMPED, FLAT, AND "DISHED" POWER DISTRIBUTIONS

The perturbation applied to the equilibrium radial power shape to initiate the oscillations was arbitrarily chosen as an increase in the thermal absorption cross section applied on one side of the reactor and an equal decrease applied to the opposite side. The perturbation was applied for a time period of 2 hours, after which time it was removed and the reactor was allowed to oscillate freely.

Criticality was maintained throughout the calculation by allowing the thermal absorption cross section of the central region of the reactor to change such that the eigenvalue was always 1.0. It may be noted that this type of control does tend to change the radial power shape about which the oscillation is occurring at any given time. Whether or not the resultant power shape tends to enhance or dampen the oscillations depends on the direction of the change in cross section. In any event, the changes were small (less than 1% in Σ_a of the central region, maximum to minimum) and represented a normal method of control during reactor operation. No nonsymmetric control (other than the perturbation itself) was used to enhance or dampen the oscillations.

For each radial power shape, the study consisted of choosing several damping coefficients* (α), which would represent the temperature coefficients of a typical PWR. For the PWR operating conditions, the range covered was:

Doppler coefficient = -1.1×10^{-5} $\Delta k/°F$, $\alpha = -2.2 \times 10^{-17}$

Coolant coefficient = -3×10^{-4} to $+2.3 \times 10^{-4}$ $\Delta k/°F$ representing a range in coolant coefficient of 5.3×10^{-4} $\Delta k/°F$ and a range in α of 1.6×10^{-17}

RESULTS

The results of the series of calculations are shown in Figure 2, where damping factor (D)** is plotted against α for the three radial shapes considered. As shown by the figure, the oscillations were generally quite damped (below the threshold for sustained oscillations); and, as expected, stability increases

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* The damping coefficient is the change in thermal cross section per change in thermal neutron flux. See Appendix for further information.

** Damping factor is defined as the ratio of the perturbed portion of the flux at the peak of an oscillation to the perturbed portion of the flux at the next peak.

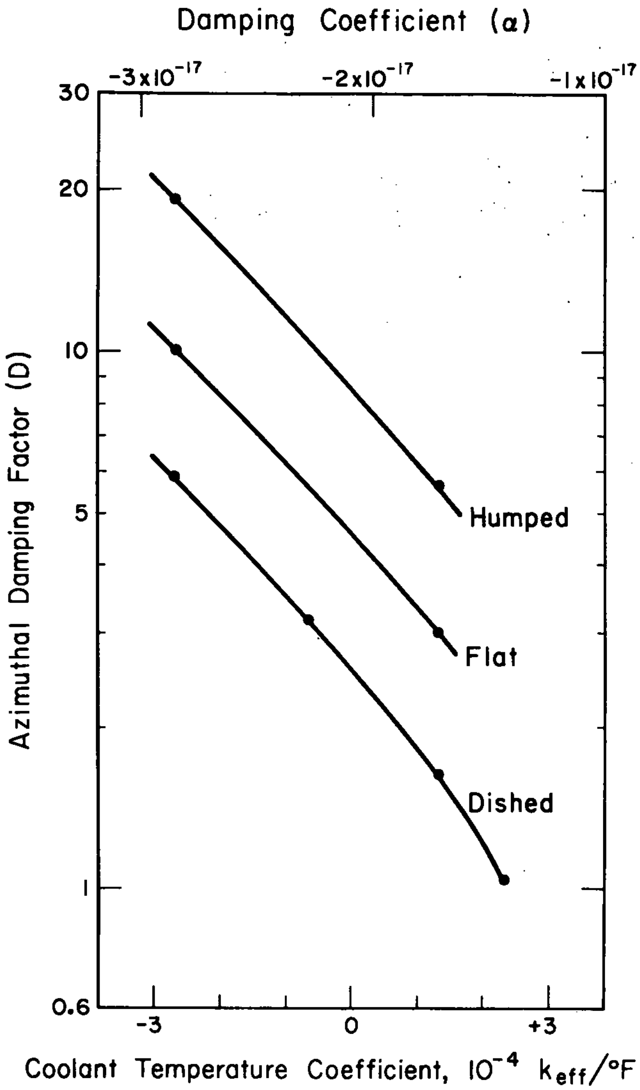

FIG. 2 DEPENDENCE OF DAMPING FACTOR ON COOLANT TEMPERATURE COEFFICIENT OF REACTIVITY

Reactor Power 2760 MW; Doppler Coeff -1.7 x 10^{-5} k_{eff}/°F as the temperature coefficient becomes more negative and as the radial power shape becomes peaked in the center. The threshold occurs for the dished shape at a coefficient of $+2.3 \times 10^{-4}$ $\Delta k/°F$. Positive coefficients as large as +3 or $+4 \times 10^{-4}$ are possible in power reactors under some conditions, so that some effort must be made to minimize positive coefficients to be sure that azimuthal xenon stability exists.

The above results are, of course, subject to some errors dependent upon the particular assumptions of the calculations. For instance, the main damping force to the oscillations is the relatively strong negative Doppler coefficient. If the magnitude of the Doppler coefficient is assumed to be lower by 32% (-0.75×10^{-5} $\Delta k/°F$ rather than -1.1×10^{-5} $\Delta k/°F$), threshold oscillations would be attained with a zero coolant coefficient and a dished radial shape; i.e., $\alpha = -1.5 \times 10^{-17}$ would be equivalent to a zero coolant coefficient.

Other assumptions that could change the damping factor are the neutron flux and the radial dimensions, which may be evaluated using one-dimensional analysis.[3] If, for instance, the average thermal flux is 40% greater or the effective reactor diameter is 10% greater, the damping factor will be approximately halved; i.e., the curves would be translated downward until the lowest curve passes through D = 1 at $\alpha = -2.0 \times 10^{-17}$.

To help determine the effect of axial flux shape (the third dimension in the three-dimensional study) upon azimuthal oscillations, a calculation was made using a different axial flux shape with the same radial power shape.

The conditions at which this change was made was at the threshold ($\alpha = -1.5 \times 10^{-17}$ with a 20% "dished" power shape).

The axial flux shape at which this condition is at the threshold is "dished" (Figure 3). The calculation was repeated, however, with an axial shape which was strongly "humped" (Figure 3).

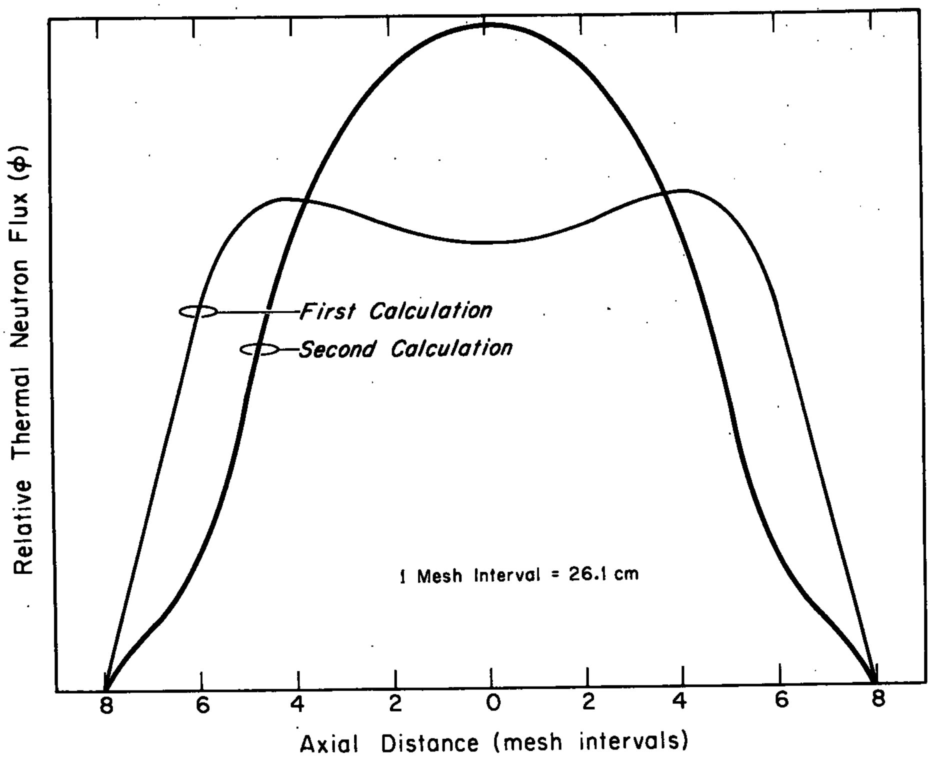

FIG. 3 EQUILIBRIUM AXIAL FLUX SHAPE AT X=3, Y=9
Radial Power Shape = 20% "Dished"

The results of this calculation indicated a slightly divergent oscillation with a damping factor of 0.8 or a decrease in damping factor of 20% from the original calculation.

Because the radical change in axial shape produced such a small change in damping factor, it is inferred that the results shown in Figure 2 are not strongly affected by changes in axial flux shape.

APPENDIX A

MAPLE SYRUP - A FORTRAN IV CODE FOR THE CALCULATION OF SPATIAL XENON TRANSIENTS

MAPLE SYRUP[4] uses a two-energy group neutron diffusion model to calculate the space-dependent neutron flux transient in a nuclear reactor operating under the influence of xenon-135 and iodine-135 fission product poisoning. The code, developed at Oak Ridge National Laboratory, is written in FORTRAN IV and treats one-, two-, and three-dimensional reactor geometries in rectangular coordinates. The initial two-group reactor parameters and the reactor power level are specified as input data from which the code calculates equilibrium steady-state neutron flux, xenon and iodine distributions, and the critical thermal absorption cross section at specified controller positions. This initial reactor state is perturbed in a specified manner by the removal of a specified fraction of the equilibrium xenon and iodine distributions over specified regions of the core or by a specified change in the two-group nuclear parameters, or by both methods. The code then generates neutron flux and xenon distributions at specified values of time over a specified time interval. The version of MAPLE SYRUP now operational at SRL maintains criticality at constant reactor power during the transient by use of "ganged" controllers. (The more general ORNL version allows the use of various space-dependent control algorithms that may be used in an attempt to damp spatial xenon oscillations.) Delayed neutron effects are neglected. Power feedback to the thermal absorption cross section is included as a coefficient (α, the "damping" coefficient) which is multiplied by the change in neutron flux from equilibrium, i.e., $\Sigma_a = \Sigma_{a_o} + \alpha(\phi_o - \phi)$.

To convert from a temperature coefficient ($\Delta k/^\circ F$) to the damping coefficient ($\Delta\Sigma_a/\Delta\phi$), the following assumptions and relations were used:

- Change in Σ_a per change in $k_{eff} = \frac{\Delta\Sigma_a}{\Delta k} = 0.142$

  This constant is a function of the core parameters and is representative of present generation PWR's.

- An average change in coolant temperature per change in flux* = $\Delta T_c/\Delta\phi = 3 \times 10^{-13}$

- An average change in fuel temperature per change in flux* = $\Delta T_f/\Delta\phi = 2 \times 10^{-11}$

  These constants are dependent upon the reactor power and the operating temperatures as well as the core parameters and are calculated by determining the average temperature rise occurring from hot standby (zero power and zero flux) to full power (and operating flux).

The total damping coefficient is then the sum of the effects of the coolant coefficient (A_c) and the Doppler coefficient (A_D):

$$\alpha = \Sigma_a/\Delta k \; (A_c \times \Delta T_c/\Delta\phi + A_D \times \Delta T_F/\Delta\phi)$$

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* The flux as used here is the average thermal neutron flux in a cell.

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3. V. D. Vandervelde. *Xenon Oscillation Dependence on Reactor Parameters.* E. I. du Pont de Nemours & Co., Savannah River Laboratory, Aiken, S. C. DPST-68-372 (1968).

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