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RELATIVE XENON INSTABILITY IN THE HANFORD K AND N REACTORS

D. K. McDANIELS

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RELATIVE XENON INSTABILITY IN THE HANFORD K AND N REACTORS

I. INTRODUCTION

The combination of a large reactor core with a sufficiently high flux level results in complications of the dynamic behavior of the core due to asymmetric xenon and temperature instabilities. In both phenomena, a local increase in neutron flux causes an increase in neutron multiplication in a surrounding zone. We consider here the instability associated with the delayed production of Xe^{135} , an isotope with a very high thermal neutron cross section. In order for this instability to result in flux oscillations, the neutron production in one part of the core must be independent of conditions in another part. Said in another way this means that the neutron migration area must be considerably less than the square of any core dimension. Thus, even though the total reactor power is held constant, it may be possible that neutron leakage from one part of the reactor to another is insufficient to counteract the tendency of the local flux to continue increasing in the part of the reactor where it is already high. An asymmetry in the distribution of reactor power may thus tend to increase in an unstable manner.

Troublesome flux oscillations due to the delayed xenon production were first observed at Hanford in late 1955¹. Similar disturbances were also noted at the Savannah River Reactors² in December of the same year. After some initial confusion, it has been found that close monitoring of the local power trends over the reactor volume permits satisfactory control. It is useful, however, to know quantitatively just how severe the problem is at a given reactor. Furthermore, an understanding of the possible flux variations can help considerably in visualizing what is actually going on inside the reactor in order to counteract the tendency towards flux distortions. This report gathers together the principal theoretical work on the problem, emphasizes the qualitative aspects to aid in giving a visual picture, and applies these results to K-Reactor and NPR.

II. SUMMARY AND CONCLUSIONS

The important features of xenon oscillations are discussed and a resume of the existing theoretical treatment of them is given. The theoretical calculations treat the disturbance as a small perturbation of the equilibrium flux distribution, analyzing the instability in terms of the relative excitation of radial and axial modes. It is found that only the first radial and axial modes are appreciably excited. A short variational calculation is outlined which simplifies some of the numerical work involved. The principal result of the theory is the prediction of the threshold flux for xenon instability below which no divergent oscillations are possible.

The threshold fluxes for the principal modes were estimated for K-Reactor and NPR. It is found that the xenon-instability problem will be less severe at NPR than it is at K-Reactor for a given total pile power. This is mainly due to the lower average flux at NPR, an advantage which is accentuated by the absence of a positive overall power coefficient. A zero coefficient was also assumed for K-Reactor, which strengthens the conclusion of lessened instability at N compared to K-Reactor since the actual overall coefficient at K-Reactor is positive. It must be strongly emphasized that a negative overall coefficient at N-Reactor will greatly reduce the instability; the positive coefficient at K-Reactor accentuates their problem.

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III. THEORYA. General

Consider a reactor operating at constant total power and at xenon equilibrium. The introduction of a small tilt in the equilibrium flux slope, for example from front to rear, causes the xenon to burn out more rapidly at the front and less rapidly at the rear, while the production of xenon from iodine decay remains relatively constant for sometime. The reactivity then increases at the front of the reactor and decreases at the rear amplifying the flux tilt. Ultimately the growth of xenon from the iodine that is now forming more rapidly at the front and the loss of xenon by decay at the rear reverses the trend, giving rise to oscillations which will persist unless control poisons are moved so as to counteract them. This qualitative explanation shows the possibility of instability in the flux shape and reactivity of the reactor.

In order to establish the criteria for instability and study the qualitative features of the oscillations it is common to analyze any flux variation into modes.

$$(1) \quad \delta\phi = \sum_{lmn} a_{lmn}(t) \bar{J}_m(\lambda_{lm} \frac{r}{R}) \sin \frac{n\pi z}{H}$$

where R is the reactor radius and H is the overall length from front to rear. The assumption is then made, and this is approximately true in the case of xenon instability, that the time behavior of each mode is independent of the others. In this analysis it is also necessary to assume that the disturbance is small, a condition which is usually not valid in practice. However, a large disturbance is unacceptable practically, and the results of an analysis based on the assumption that the disturbances are mathematically small will indicate correctly whether the system is stable or not. Thus, the first stage in a stability analysis is to rewrite the equations in terms of the differences between the actual and steady-state values. (In order to study the effects of a very large disturbance, numerical solutions of the appropriate differential equations must be obtained. Some results obtained in this manner² will be used later to give a semi-quantitative estimate of the actual flux distortions when considerably above the threshold for instability.)

B. Threshold Flux

From equation (1) above we see that the coefficients a_{lmn} determine the importance of each mode of excitation. Because the higher modes imply more curvature of the flux distribution, hence more leakage, (leakage is always a stabilizing factor) only the lower modes contribute. The calculation of the threshold for each mode of oscillation (separating into radial and axial modes as noted above) is outlined in Appendix A and gives us the fundamental relation for xenon instability

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$$(2) \quad f(\phi) = \left[\frac{M^2 B_g^2}{\alpha_x} \right] \Lambda_j - \frac{\alpha_T}{\alpha_x} \phi = \frac{\frac{1}{1 + \frac{\lambda_x}{\alpha_x \phi}} - \gamma_x}{1 + \frac{\lambda_x + \lambda_i}{\alpha_x \phi}}$$

where γ_x is the xenon capture cross section, M^2 is the migration area, B_g^2 is the geometrical buckling, α_x is the reactivity held by the equilibrium xenon,

$$\Lambda_j = \frac{\mu_j^2}{B_g^2}, \quad \alpha_T = \frac{\alpha_T}{M^2}, \quad \alpha_x = \frac{\alpha_x}{M^2}, \quad \alpha_T \text{ AND } \alpha_x$$

are coefficients which express the dependence of the material buckling, B_g^2 , on changes in flux (temperature) and xenon, λ_i and λ_x are the decay constants of I^{135} and Xe^{135} . The difference between the perturbed and unperturbed material buckling, μ_j^2 , is determined from solving

$$(3) \quad (\nabla^2 + B_0^2 + \mu_j^2) \phi_j = 0$$

where B_0^2 is the unperturbed material buckling and ϕ_0 corresponds to the unperturbed flux. For a three-dimensional reactor the oscillations can occur about any axis, and as noted earlier we assume that we can treat the radial and axial oscillations separately. The calculation of μ_j^2 (or Λ_j) is outlined in Appendix B, where a simple variational method is also discussed.

C. Modes of Oscillation

In the above analysis the flux is given by the sum of the unperturbed flux plus the contribution from equation (1). Any flux distribution can be expressed as a sum of such harmonics (eigenfunctions of the reactor). These are analogous to the terms of a fourier series describing, for instance, the vibrations of a stretched string. The first few radial and axial eigenfunctions are shown in Figure 1 for the case of an unflattened pile. We see from the figure that the higher harmonics have more internal leakage, are progressively more stable and so more difficult to perturb.

D. Severity of Power Distortions

The possible distortions in the power distribution during xenon oscillations which were discussed above can be very large; the severity increasing with the ratio of operating power to threshold power. We can illustrate this for the axial case, for which the differential equations have been

RADIAL

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$$\phi_{00} \sim J_0(\lambda_{00}r)$$

FUNDAMENTAL

$$\phi_{01} \sim J_1(\lambda_{01}r) \cos \theta$$

1ST AZIMUTHAL

$$\phi_{02} \sim J_2(\lambda_{02}r) \cos 2\theta$$

2ND AZIMUTHAL

$$\phi_{03} \sim J_3(\lambda_{03}r) \cos 3\theta$$

3RD AZIMUTHAL

$$\phi_{10} \sim J_0(\lambda_{10}r)$$

1ST RADIAL

$$\phi_{11} \sim J_1(\lambda_{11}r) \cos \theta$$

1ST RADIAL, 1ST AZIMUTHAL

AXIAL

$$\phi_0 \sim \sin \frac{\pi z}{H}$$

FUNDAMENTAL

$$\phi_1 \sim \sin \frac{2\pi z}{H}$$

1ST AXIAL

$$\phi_2 \sim \sin \frac{3\pi z}{H}$$

2ND AXIAL

FIG. 1 FLUX PERTURBATION HARMONICS FOR A THREE DIMENSIONAL CYLINDRICAL REACTOR. EIGENFUNCTIONS FOR THE UNFLATTENED REACTOR ARE INDICATED TO CLARIFY THE PATTERN AND ITS DESCRIPTION.

numerically solved² for the case of severe distortions where the perturbation analysis fails. This severity of the flux distortion can be put in quantitative terms by defining the "roof top ratio", as the ratio of the fluxes at one-fourth and three-fourths of the reactor length. This ratio should be near unity if we want to avoid severe local power distortions. Figure 2 shows the amplitude of the oscillation in the rooftop ratio as a function of the ratio of operating to threshold power levels. The inset figure shows graphically the definition of the ratio.

Even when the operating power level is below the threshold for sustained oscillation, it is important to examine the possibility and consequences of damped oscillations. At power levels only slightly below the threshold, large perturbations in the xenon distributions can be changed into oscillations of serious amplitude that are damped only slowly. This is one reason why severe oscillations will occur after startup even though full power is not reached since the damping of the oscillations near threshold can be quite slow.

IV. APPLICATION TO K-REACTOR AND NPR

We now apply the results of this analysis to estimating the threshold flux at K-Reactor and NPR. To do this we list in Table I the necessary parameters⁶ used in the fundamental relation given in Equation (2).

Table I

Parameters

<u>Item</u>	<u>K-Reactor</u>	<u>NPR</u>	<u>Common to Both</u>
Power	4000 MW	4000 MW	
Average Flux*	3.28×10^{13}	2.85×10^{13}	$x = 3.08 \times 10^{-18}^{**} \text{ cm}^2$ $\lambda_1 = .10584 \text{ HR}^{-1}$
H	946 cm	1163 cm	
R	712 cm	576 cm	$\lambda_x = .0756 \text{ HR}^{-1}$
M ²	600 cm ²	660 cm ²	$\gamma_x = .0487$
α_x	-.026	-.030	
α_T	.000	.000	
% Radial Flatt.	82%	80%	

*Conventional fluxes in fuel, averaged over the pile.

**2200 meter cross section for xenon, for use with conventional flux.

The overall power coefficient, α_T , is assumed to be zero and the effect on the results of the actual coefficient at the two reactors is discussed at the end of this section. Figures 3 and 4 show the threshold fluxes calculated for the various axial and radial modes at K-Reactor and NPR respectively. We can make a number of qualitative statements from these results. In both

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FIG. 2 AMPLITUDE OF ROOFTOP RATIO AS A FUNCTION OF THE EXTENT THE EQUILIBRIUM POWER IS ABOVE THE THRESHOLD POWER LEVEL. THE INSERT SHOWS THAT THE ROOFTOP RATIO IS B/A , WITH THE DISTORTED FLUXES MEASURED $1/4$ AND $3/4$ OF THE AXIAL LENGTH.

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FIG. 3 THRESHOLD FLUX AS A FUNCTION OF THE EXTENT OF THE FLATTENED ZONE AT K-REACTOR. ONLY THE FIRST AXIAL AND THE FIRST TWO RADIAL MODES ARE APPRECIABLY EXCITED. THE AVERAGE FLUX, $\bar{\phi}$, CORRESPONDS TO A POWER OF 4000 MW.

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FIG. 4 THRESHOLD FLUX AS A FUNCTION OF THE EXTENT OF THE FLATTENED ZONE AT NPR. ONLY THE FIRST AXIAL AND RADIAL MODES CAN BE EXCITED AT AN AVERAGE FLUX, $\bar{\phi}$, CORRESPONDING TO 4000 MW.

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reactors only the first axial and radial modes are primarily excited. (At K-Reactor the second azimuthal radial mode has its threshold below the average flux for a flattening efficiency greater than 80%.) This also means that calculations based on the picture of a two-region pile are quite valid,⁷ since these two lowest modes separate the reactor into two regions which act in opposition to each other.

The axial oscillations have a lower threshold for a given flattening efficiency than do the radial oscillations at NPR. Since normal operating conditions typically have 20-30% axial flattening and 70-80% radial flattening, thresholds are $1.8 - 2.1 \times 10^{13}$ n/cm²-sec. for the axial mode and $1.4 - 1.8 \times 10^{13}$ n/cm²-sec. for the first radial. Thus, at normal operating conditions either oscillation is almost equally probable. Since the average flux, ϕ is proportional to the full pile power, the xenon oscillations problem should start making itself felt above 2000 MW.

At K-Reactor the situation is somewhat reversed since the radial oscillations have a lower threshold than the axial ones for all operating conditions. The rapid change of the axial threshold with flattening indicates the large gain in stability to be made by peaking the flux.¹ (This is in addition to the easier control of the axial oscillations possible with upstream and downstream rods because of the moment arm involved.) For small flattening the axial mode is actually below threshold, but the assumption of separate axial and radial oscillations starts to fail here since a severe radial oscillation will tend to excite the axial one.

Finally, we note from equation (1) the effect of a power coefficient on the oscillation threshold. A positive coefficient will reduce the threshold. A negative coefficient will raise the threshold, and if large enough can eliminate the possibility of xenon oscillations altogether. In this connection it must be noted that only those temperatures that change in proportion to the local power level are effective. Since the over-all coefficient is positive at K-Reactor and zero or slightly negative⁶ at NPR, the xenon instability will also be decreased due to this factor.

V. MATHEMATICAL APPENDIX

A. Fundamental Relation for Threshold Flux⁴

The distribution of thermal flux is treated by one group diffusion theory

$$(A.1) \quad (\nabla^2 + B^2) \phi = 0$$

where ϕ is the neutron flux and B^2 is the space-and time-dependent material buckling of the hot, poisoned pile. The equations governing the concentration of Xe¹³⁵ at any point in the reactor are

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$$(A.2) \quad \frac{di}{dt} = \phi \alpha_i \gamma_i - \lambda_i i$$

$$\frac{dx}{dt} = \phi \alpha_x \gamma_x + \lambda_i i - \lambda_x x - \phi \alpha_x x$$

where i is the concentration of I^{135} relative to the equilibrium concentration of Xe^{135} at infinite flux, x is the concentration of Xe^{135} relative to the infinite flux saturation value, and the other factors have been defined earlier.

The perturbation solution for ϕ which simultaneously satisfies the above equations is carried out in detail in reference 4 and we will not repeat it here. However, we will describe the procedure used to provide the reader with an insight into the mathematical treatment.

Firstly, the time dependence is factored out by assuming that all quantities of interest vary exponentially with time with the same frequency, ω . This period ($\frac{2\pi}{\omega}$) turns out to be 25-30 hours for most cases of xenon instability. The quantities ϕ , B^2 , x and i are then expanded in terms of their equilibrium values plus the perturbation and the resulting differential equations for the perturbation amplitudes obtained.

The crucial step is now to expand the perturbation amplitudes in terms of the orthonormal eigenfunctions, g_{lmn} of the boundary-value problem that has the unperturbed flux shape as its fundamental solution. The eigenfunctions, g_{lmn} , satisfy

$$(A.3) \quad (\nabla^2 + B_0^2 + \mu_{lmn}^2) g_{lmn} = 0$$

We must remember that the g_{lmn} are not eigenfunctions of the reactor geometry, i.e., the unflattened reactor. The use of the actual reactor eigenfunctions, g_{lmn} , makes the theory considerably more exact. In the next section, we also include a less-accurate solution of (A.3) using a variational procedure employing the eigenfunctions of the reactor geometry.

In what follows it is assumed that the radial and axial oscillations can be treated separately. The differential equations (for example for the axial part) in the g_n are then multiplied by g_k and integrated over the reactor volume, resulting in a set of linear homogeneous equations. The usual requirement that the determinant vanish define possible values of ω defined by the quadratic form

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$$(A.4) \quad w^2 + bw + c = 0$$

The threshold for sustained oscillations is given by the condition that the damping term b is zero. If we make the further assumption (a very good one as it turns out) that the cross terms involving $g_n g_k$ are zero we get the fundamental relationship given by equation (2). For a flattened unperturbed reactor it is the use of the eigenfunctions given by (A.3) which assures that the cross terms will be small.

B. Exact Evaluation of μ (μ^2)

The primary problem of this analysis is the solution of

$$(B.1) \quad (\nabla^2 + B_0^2 + \mu^2)g = 0$$

for the flattened reactor where B_0^2 is zero in the flattened region. We first give the exact solutions for the buckling and then outline a variational treatment which greatly simplifies the calculations and which is accurate for a reactor with a flattened zone $< 40\%$ of the pertinent dimension.

Axial Case

The unperturbed flux has the following shape,

with L the total length of the flattened zone. For the unperturbed flux, B_0^2 is zero in the flattened region. The problem is thus the usual one of matching slopes and fluxes at $Z = +L/2$, with the flux extrapolating to zero at $Z = +H/2$. This must be done separately for both the even and odd solutions,

$$(B.2) \quad g_n = A_n \begin{cases} \sin \frac{2\lambda_n z}{H} & , n \text{ ODD} \\ \cos \frac{2\lambda_n z}{H} & , n \text{ EVEN} \end{cases} \quad |z| \leq \frac{L}{2}$$

$$g_n = B_n \sin \frac{2\lambda_n z}{H} + C_n \cos \frac{2\lambda_n z}{H} \quad , \quad \frac{L}{2} \leq |z| \leq \frac{H}{2}$$

where $\lambda_n = \mu_n H/2$. The criticality equations are then given as,

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$$(B.3) \quad \lambda_n \tan \lambda_n \alpha = \lambda'_n \cot \lambda'_n (1-\alpha) \quad , \quad n \text{ EVEN}$$

$$\lambda_n \cot \lambda_n \alpha = \lambda'_n \cot \lambda'_n (1-\alpha) \quad , \quad n \text{ ODD}$$

where $\alpha = L/H$ gives the fraction of the reactor which is flattened. The solution of (B.3) for the first two excited modes is given in Figure 5.

Radial Case

Consider a cylindrically flattened reactor of radius R_0 and flattened radius R_1 . We wish to solve the partial differential equation (B.1) with $B_0^2 = 0$ for $r \leq R_1$, and constant for $R_1 \leq r \leq R_0$. The boundary condition that $g(R_0) = 0$ along with the matching of flux and slope at $r = R_1$ leads to the criticality relation in the usual manner.

The modal solutions are

$$(B.4) \quad g_{1m} = A_{1m} J_m(\mu_{1m} r) \cos m\theta \quad , \quad r \leq R_1$$

$$g_{2m} = (B_{2m} J_m(\mu_{2m} r) + C_{2m} Y_m(\mu_{2m} r)) \cos m\theta \quad , \quad R_1 \leq r \leq R_0$$

where $\mu_{2m}^2 = B_0^2 + \mu_{1m}^2$

The criticality determinant for determining μ_{1m} is complicated⁵ and only the results will be discussed here. The quantity μ_{1m} is plotted in Figure 6 as a function of the percent flattening for the first and second azimuthal and the first radial modes.

C. Variational Method for Calculating $\mu(\mu)$

The above calculations can be quite tedious, especially for the radial oscillations. We give here a simple calculational method which is quite accurate out to a flat zone of about 40% of the pertinent pile dimension, using a variational approach⁸. If we let G_1 be the first variational approximation to the true function g_1 , we have (where the subscript, i, refers to whichever axial or radial mode is under consideration)

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FIG. 5 THRESHOLD PARAMETER FOR THE FIRST TWO MODES FOR AXIAL OSCILLATIONS AS A FUNCTION OF THE FLUX SHAPE. THE DOTTED CURVE SHOWS THE RESULTS OF A VARIATIONAL CALCULATION.

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FIG. 6 THRESHOLD PARAMETER FOR THE FIRST THREE MODES FOR RADIAL OSCILLATIONS AS A FUNCTION OF THE FLUX SHAPE. THE DOTTED CURVE SHOWS THE RESULTS OF A VARIATIONAL CALCULATION

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$$(B.5) \quad \int \mu_i^2 \phi_i^2 dV = - \int \phi_i \nabla^2 \phi_i dV \\ = \mu_i^0 \int \phi_i^2 dV$$

where μ_i^0 corresponds to G_1 and we have taken the simplest approximation for G_1 , i.e., G_1 is the eigen function of the reactor geometry. Since,

$$\mu_i^2 = B_0^2 + \mu_i^2$$

where B_0^2 is zero over the flat region we have,

$$(B.6) \quad \mu_i^2 = \mu_i^0{}^2 - \frac{B_0^2 \int \phi_i^2 dV_{\text{UNFLATTENED REGION}}}{\int \phi_i^2 dV_{\text{REACTOR}}}$$

This is the same result as that originally obtained by Ward⁹ where he used perturbation theory and expanded the perturbation in terms of the geometric eigenfunctions.

Axial Case

HERE,

$$G_n \sim \sin \frac{(n+1)\pi z}{H}$$

letting the origin of coordinates be at one end of the reactor. If, as before, we let L be the length of the flattened zone, $\Lambda_n = \mu_n^2 / B_g^2$, and $B_g^2 = (\pi/H)^2$, we obtain

$$(B.7) \quad \Lambda_n = (n+1)^2 - \frac{2}{(n+1)\pi} \left[\frac{H}{H-L} \right]^2 \left[\alpha - \frac{\sin 2\alpha}{2} \right]$$

where $\alpha = (n+1)\pi \frac{L}{H}$. The dotted curves in Figure 5 show the results of calculating Λ_1 and Λ_2 in this manner and indicates that the variational calculations is accurate to $L/H = 0.4$.

Radial Case

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$$(E.8) \quad \lambda_{am} = \frac{1}{(2.405)^2} \left[\lambda_{am}^2 - \left\{ 1 - \frac{\left(\frac{R_1}{R_0}\right)^2 \left(J_m^2\left(\lambda_{am}^0 \frac{R_1}{R_0}\right) - J_{m+1}\left(\lambda_{am}^0 \frac{R_1}{R_0}\right) J_{m-1}\left(\lambda_{am}^0 \frac{R_1}{R_0}\right) \right)}{J_m^2\left(\lambda_{am}^0 \frac{R_1}{R_0}\right)} \right\} B_0^2 R_0^2 \right]$$

where G_{lm} is the unperturbed eigenfunctions for the unflattened case,

$$G_{am} \sim J_m\left(\lambda_{am}^0 \frac{R_1}{R_0}\right) \cos m\theta$$

The dotted curve in Figure 6 shows the result for the λ_{01} mode.

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Reactor Physics
Process and Reactor Development Subsection

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