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ONE-GROUP XENON REACTIVITY CALCULATIONS

By

J. R. Fredsall
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March 2, 1964

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ONE-GROUP XENON
REACTIVITY CALCULATIONS

I. INTRODUCTION AND PURPOSE

The effect of xenon poisoning in the uniformly loaded reactor is fairly well known, and has been adequately documented. Transient behavior has been well tabulated for many years, and there has been little difficulty in applying xenon calculations to the progressively flattened reactor, since the loading remained predominately natural uranium. However, recent operating changes (e.g., higher graphite temperatures, solid enrichment loadings, and unintentional, adverse flux distortions) have prompted a review of current calculational techniques. In addition, in the area of nuclear safety, xenon calculations for the water loss case are based upon tables generated for much lower neutron temperatures, and do not directly allow for reductions in the absorption cross section at the high temperatures of the dry reactor.

A study was initiated in the Pile Physics Unit to evaluate current methods in light of the newer and supposedly more influential operating conditions, and thus possibly improve critical prediction accuracy. Particular areas considered included the following:

1. Validity and limitations of the flux-squared-weighting technique for homogenizing localized xenon effects.
2. Effect of elevated graphite and fuel temperature on xenon poisoning.
3. Xenon poisoning in the dry lattice.
4. Xenon-control rod interaction and mutual shadowing.
5. Effects of moderate to severe flux distortions.

This document comprises the results of that study. Theoretical checks on calculational accuracy utilized results from the computer programs, the MOFDA¹, IDIOT², and VITABUCK³ codes. Basic xenon constants and equations were identical with those of previous similar work⁴.

II. SUMMARY

It is concluded that xenon effects for all cases studied may be calculated, with no change in the present calculational methods, to an accuracy of seven per cent; this includes flux distortions of any degree, so long as xenon and iodine concentrations are modified by an obvious (flux-squared weighting) correction factor.

Noteworthy conclusions and specific disagreements between current hand calculational methods of Reference 4 and the more sophisticated (i.e., a combination P-3 Buckling Approach) technique utilized in this study are summarized as follows:

1. Local xenon poisoning versus local power
 - the current simplified approach underestimates xenon poisoning by less than 6% (a conservative error)

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2. Xenon poisoning in the dry lattice
 - the current approach underestimates xenon poisoning by 5% (a conservative error)
3. Local reactivity (poisoning) effects converted to full pile effects
 - the technique of Reference 1 overestimates xenon local (tube) poisoning by less than 5% for the peak xenon effect at 10 hours after shutdown (a nonconservative error of, at most, 2 mk); the overestimation decreases to 1% at equilibrium and 35 hours down (or ~ 0.25 mk)
4. There is some degree of mutual shadowing between rods and xenon (discussed in section B-2)

The disagreements are, in general, conservative, and are not serious enough to warrant a change in calculational approach; in short, the presently employed method of calculating xenon reactivity (which is based upon a uniform loading with simple corrections for flux distribution) is satisfactorily accurate for most practical purposes. The inherent consistency of xenon transient behavior and the substantial accuracy of calculational techniques indicate that the traditional use of pile xenon as the standard for reactivity calculations is still appropriate.

Calculational details and appropriate constants are included in the body of this report, and may be useful in cases considerably outside the normal range.

The reader is referred to the Pile Physics Manual of Standard Practices if further insight is desired.

III. DISCUSSION

A. Local Xenon Reactivity Calculations

1. Cold Reactor Calculations

a. The Flux Weighting Approximation

Local xenon reactivity can be calculated by modified one-group diffusion theory in two different ways: the first assumes that the presence of xenon affects k_{∞} ($k_{\infty} = \eta \epsilon p f$) by perturbing both η and f ; the second considers that the presence of xenon changes f only (the approach presently used at Hanford).

In the standard definition of the thermal utilization,

$$f = \frac{\int_u \Sigma_u \phi dv}{\int_o \Sigma_a \phi dv + \int_u \Sigma_a \phi dv} \quad (1)$$

where the subscript u indicates fuel and o indicates all other cell materials. On introduction of xenon, the flux is perturbed,

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and the thermal utilization is changed to f' :

$$f' = \frac{\int_u \Sigma_a \phi' dv}{\int_o \Sigma_a \phi' dv + \int_u (\Sigma_a + \Sigma_{xe}) \phi' dv}, \quad (2)$$

where ϕ' is the perturbed flux.

The reactivity change can then be defined as

$$\rho_{xe} = \frac{\delta k}{k} \approx \frac{\Delta f}{f} = \frac{f' - f}{f}, \quad (3)$$

or substituting

$$\rho_{xe} = \frac{-(\int_u \Sigma_a \phi dv)(\int_o \Sigma_a \phi' dv) + (\int_u \Sigma_a \phi' dv)(\int_o \Sigma_a \phi dv) - \int_u \Sigma_a \phi dv \int_u \Sigma_a \phi' dv}{\int_u \Sigma_a \phi dv (\int_o \Sigma_a \phi dv + \int_u \Sigma_a \phi dv)} \quad (4)$$

Now, the simplifying assumption is made that the cell flux distribution does not change, or that $\phi(v) = \phi'(v)$; then,

$$\rho_{xe} = - \frac{\int_u \Sigma_x \phi dv}{\int_o \Sigma_a \phi dv + \int_u \Sigma_a \phi dv}. \quad (5)$$

This is the equation used in reference 4 to calculate the local xenon reactivity. The resultant computational equation for the old reactors is (after a suitable approximation for $\int_u \Sigma_x \phi dv$ is made):

$$\rho_{xe} = - \frac{31.375 w}{w + 325.37} \text{ mk}, \quad (6)$$

where w is the local power in watts/cm. (Note use of the linear unit watts/cm, which replaces the more common specific power unit watts/cm³; this linearization is valid for fuel columns of constant cross section.) Equation (5) can similarly be applied to iodine potential poisoning; for the old reactors reference 4 has

$$I = -0.06646 w \text{ mk}. \quad (7)$$

The xenon reactivity effect determined with these equations is given in Figures 1 and 2.

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b. P3 Calculations

Comparison calculations were made with a computer code used on the P3 approximation Boltzmann equation. This code employed the same nomenclature as is used in equations (6) and (7). This nomenclature and the corresponding values used is summarized in the following table:

Name	Symbol	Value
Xenon decay constant	λ_x	$2.091 \times 10^{-5} \text{sec}^{-1}$
Iodine decay constant	λ_I	$2.882 \times 10^{-5} \text{sec}^{-1}$
Fission yield of xenon	γ_x	0.0032
Fission yield of iodine	γ_I	0.0608
U-235 atoms concentration	N_{25}	$0.03396 \times 10^{22} \text{ atoms/cm}^3$
Energy of fission	k	$3.222 \times 10^{-11} \text{ watt-sec/fission}$
U-235 fission to xenon capture	σ_f/σ_x	1.627×10^{-4}
Thermal utilization	f	0.873
Fast fission factor	ϵ	1.056
Uranium absorption to xenon capture	$\Sigma_a^u \sigma_x$	1.0355×10^{17}
Inside radius of fuel*		0.5283 cm
Outside radius of fuel*		1.7221 cm

These constants were used in the following equations to calculate the macroscopic xenon and iodine cross sections through the fuel.

$$\Sigma_x = \frac{\sigma_x (\gamma_I + \gamma_x) P/K}{\lambda_x + \frac{\sigma_x}{\sigma_f} \frac{P}{KN_{25}\epsilon}} \quad (8)$$

$$\Sigma_I = \frac{\sigma_x \gamma_I P}{\lambda_I K} \quad (9)$$

*These radii are slightly different from those used in reference 4; i.e., $r_i = 0.61 \text{ cm}$, $r_o = 1.74 \text{ cm}$, but these differences mean only a 3.8 per cent difference in volume and a practically negligible effect on xenon poisoning.

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Where P is the specific power in watts/cm³. The power distribution through the fuel was approximately that used in reference 1. To mathematically approximate this condition, the fuel absorption cross section Σ_a was systematically varied until the ratio of maximum to minimum flux in the fuel (as calculated by the P3 code) was the same as that of reference 4 (0.753). Similarly, the input graphite cross section was varied to obtain the value $f = 0.873$, consistent with current "best calculated" parameters.

In order to simulate the effect of the variation in the xenon concentration through the fuel, ten concentric fuel regions were used. The macroscopic xenon cross sections for each of these regions were then calculated for the various values of local power (watts/cm) and the times after shutdown being investigated. The xenon concentration changes with time after shutdown according to the equation

$$X(t) = I_0 (e^{-\lambda_x t} - e^{-\lambda_I t}) + X_0 e^{-\lambda_x t} \quad (10)$$

The reactivity effects of the various xenon distributions were then calculated with the P3 calculated values of f and equation (3). These values are shown in Figures 1 and 2; note that they are approximately six per cent greater than those found from equations (6) and (7).

This difference of six per cent is probably the result of the assumption used in deriving equations (6) and (7), that the cell flux distributions do not change appreciably with addition of xenon to the fuel. However, as is shown in Figure 3, some change in the fuel flux distribution does occur; in general, the change is small enough so that the equilibrium xenon distribution can be calculated directly from the xenon-free flux distribution. The ratios $(\phi_{\min})_{\text{fuel}}/(\phi_{\max})_{\text{graphite}}$ and $(\phi_{\min})_{\text{fuel}}/(\phi_{\max})_{\text{fuel}}$ change by approximately 0.3% for a 1% δk xenon poisoning effect. Figure 3 also shows the actual xenon distributions through the fuel at equilibrium and at ten hours down.

2. Temperature Effect on Local Xenon Reactivities

Further P3 calculations were made to determine the effect of actual operating temperatures on the local xenon reactivity. One of the main effects of high graphite temperatures is the attendant change in individual material cross sections. Cross section changes are in turn reflected in higher values for the thermal utilization and the flattening of the fuel flux distribution.

The xenon cross section changes drastically with reactor neutron temperature as is shown in Figure 4 (data taken from MOFDA runs). Based on this data, a maximum local xenon effect is expected as the local power is increased. (For these calculations, the uranium density was reduced by seven per cent to account for the presence of fuel slug end caps; this correction was not made in reference 4.

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Basic calculations were made with the IDIOT² Code for several graphite temperatures. The cross sections generated by IDIOT were then used in the P3 Code determinations of the xenon reactivity effects. An empirical relationship between local power and graphite temperature was deduced from operating data taken at B Reactor; this relationship is:

$$T_{\text{graphite}}(^{\circ}\text{K}) = 283 + 0.28 W, \quad (13)$$

where W is in watts/cm. The graphite temperature to fuel neutron temperature relationship found in the IDIOT calculations is approximately:

$$T_{\text{fuel neutrons}}(^{\circ}\text{K}) = 91.0 + 0.67 T_{\text{graphite}}(^{\circ}\text{K}). \quad (14)$$

IDIOT calculated local xenon reactivity values, based on temperatures from equations (13) and (14), are shown in Figures 5, 6, and 7. The results indicate that equations (6) and (7) describe the local xenon reactivity to within six per cent accuracy; however, note that the reduction in cross section due to increasing fuel temperature from ambient to operating temperature results in as much as 10% loss in poisoning effect.

Calculations to determine the change in xenon worth on water loss showed that there is about a two per cent increase in xenon reactivity on water loss, assuming negligible neutron spectral changes. This coincides with what one would expect from equation (5), since f increases by about two per cent on water loss.

B. Tube Average Xenon Reactivities

1. Calculational Methods

a. The Flux Squared Weighting Approximation

In reference 1 the tube xenon and iodine reactivities are calculated by flux squared weighting the relationships of equations (6) and (7). The resulting equations are:

$$\rho_{\text{Xe}}(\text{mk}) = -31.375 \frac{\int \frac{w^3}{w+325.37} dy}{\int w^2 dy} = \frac{-160.78 P_T}{1+5.125 P_T} \quad (15)$$

$$\rho_{\text{I}}(\text{mk}) = -0.06646 \frac{\int w^3 dy}{\int w^2 dy} = -110.79 P_T, \quad (16)$$

where P_T is the tube power in megawatts.

b. Buckling Calculations

Tube xenon reactivities were calculated by the buckling technique as incorporated in the VITABUCK Code³. These results are compared

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to the relationships of equations (12) and (13) in Figures 8, 9, and 10. The buckling calculation of xenon reactivities involves dividing the fuel charge length into segments, calculating the average local power in each segment, determining the local xenon poisoning effect (in microbucks) for each segment, and applying a standard buckling calculation along the length of the tube to find the tube average effect. For these calculations, a 43 cm reflector augmentation, a 32-piece charge length, and a conversion factor of 1.618 $\mu\text{b}/\text{mk}$, were used.

Figures 8, 9, and 10 show that the flux squared weighting technique for finding the tube average xenon reactivity agrees with the buckling calculations to within 1.3 per cent for equilibrium and 35 hours after shutdown, and to within five per cent for ten hours after shutdown, the time of maximum xenon. In all of these instances, the buckling calculations gave lower values for the xenon reactivity.

Buckling calculations were also made using the hot reactor local xenon reactivities given in Figure 5; the results are shown in Figure 8. A comparison of these values with those of equations (15) and (16) shows agreement to within five per cent.

2. Flux Distribution and Xenon-Rod Shadowing Effects

An attempt was made to determine the effects of flux distribution and rod shadowing on xenon reactivities. Although the results of this study are admittedly limited in applicability, they do give some idea of the magnitude of these effects.

The magnitude of the change in xenon worth with flux distribution was established in the calculated flux distribution of the control-rods-inserted case, an axial distribution of common interest. In the smaller reactors, the local control strength of the HCR's is 59.5 μb and the front-to-rear spacing of the control rods is about 64 inches⁵. In order to simulate more closely the actual flux distribution present with the HCR's inserted, the zone of action of the control rods was shortened to 20 cm, and the "local control strength" accordingly increased to 550 μb for an equivalent pile reactivity effect. The flux distribution obtained for this poison configuration, shown in Figure 11, matches the actual (observed) distribution reasonably well. Also, shown in Figure 11 are the xenon distributions for a 1 MW tube at equilibrium and 35 hours after shutdown for the rods in and rods out states. The results of these calculations show that with the rods out, the pile reactivity effect (poisoning) of the xenon generated in the perturbed (rods in) flux distribution is +0.59 per cent, +1.80 per cent, and -0.62 per cent larger than that of the unperturbed distribution at equilibrium, 10 hours after shutdown, and 35 hours after shutdown, respectively. A comparison of the cases (1) rods in, perturbed xenon distribution, and (2) rods out, unperturbed distribution, shows that

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the perturbed xenon distribution poisoning is +1.53 per cent, +6.28 per cent, and +7.50 per cent lower in magnitude than that of the unperturbed case at equilibrium, 10 hours and 35 hours after shutdown, respectively. (A distinction must be made between the reactivity values with and without the rods in because of shadowing by the rods.)

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Figure 1

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Figure 2

Local Xenon Reactivities

———— Xenon Reactivity from Equations 6 and 7

- - - - - Xenon Reactivity by P3

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Figure 3
Flux Distribution Change in Fuel
with Xenon Poisoning
Local Power Level = 2.7 KW/Cm

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Figure 4

Cross Section Variation
with Neutron Temperature

σ_x = Microscopic xenon absorption cross section

Σ_u, Σ_f = Macroscopic uranium absorption cross sections

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Figure 5

Equilibrium Local Xenon Reactivities

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Figure 6

Local Xenon Reactivities
10 Hrs. After Shutdown

———— Xenon reactivity from equations 6 and 7
- - - - - Xenon reactivity by P3 - IDIOT Data

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Figure 7

Local Xenon Reactivities
35 Hrs. After Shutdown

- Xenon reactivity from equations 6 and 7
- - - - - Xenon reactivity by P3 - IDIOT Data

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- Xenon Reactivity from Equation 15
- - - - - Hot Xenon Reactivity from P3 - IDIOT Data (Buckling Calculations)
- Xenon Reactivity from equations 6 and 7 and Buckling Calculations

Equilibrium Tube Xenon Reactivities
(Cosine flux assumed)

Figure 8

Figure 9

Tube Xenon Reactivities 10 Hrs. After Shutdown
(Cosine Flux Assumed)

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Figure 10

Tube Xenon Reactivities
35 Hrs. After Shutdown
(Cosine Flux Assumed)

— Xenon Reactivity for Equations 15 and 16
 --- Xenon Reactivity from Equations 6 and 7 and Buckling Calculations

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Figure 11
The Effect of Control Rods on Xenon
Distribution for a 1 MW Tube

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