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CONTROL OF XENON INSTABILITIES

IN LARGE PWR'S

QUARTERLY PROGRESS REPORT

FOR THE PERIOD ENDING

MARCH 31, 1967

M. J. O'Boyle
Project Engineer

Prepared for the New York Operations Office
U. S. Atomic Energy Commission
Under AEC Contract AT(30-1)-3680

April 1967

WESTINGHOUSE ELECTRIC CORPORATION
Atomic Power Divisions
Box 355
Pittsburgh, Pennsylvania 15230

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PROGRAM DESCRIPTION

This program investigates the characteristics and control of spatial instabilities in large pressurized-water reactors (large PWR's), with particular emphasis on azimuthal xenon instabilities (x-y plane). The program consists of the following technical tasks:

Task EUXE-200 - Effect of Core Parameters on Spatial Oscillations

The aim of this task is to analyze the effect of variations in core design and operating parameters on the propensity for spatial oscillations, with emphasis on those resulting from xenon redistribution. Parameters to be analyzed include, but are not limited to, core dimensions, fuel and moderator temperature feedbacks, and power distributions.

Task EUXE-300 - Remedial Control Procedures

Under this task, two-dimensional x-y calculations will be performed to establish control methods and detector locations which will prevent divergent oscillations. Calculated results will be used to develop criteria for the application of remedial measures to large pressurized-water reactors.

Task EUXE-400 - Three-Dimensional Analysis

Under this task, either direct or synthesized three-dimensional calculations will be performed to further study spatial instabilities in large PWR cores with conditions conducive to oscillations. If a three-dimensional oscillation develops after perturbations have been introduced, selected remedial methods (as developed under Task EUXE-300) will be applied and evaluated. The unique characteristics of three-dimensional oscillations (if observed) will be identified and the criteria for the application of remedial measures will be developed.

PROGRESS SUMMARY

Major progress is summarized below for the three-month period ending March 31, 1967:

Calculations were performed with Xe-135 thermal absorption cross section and total fission yield varied by $\pm 10\%$ to evaluate the sensitivity of the stability characteristics to uncertainties in basic nuclear physics data. Whereas the stability characteristics were relatively insensitive to changes in the xenon cross section, the sensitivity to the total xenon yield was more pronounced.

A spatial stability analysis was performed for an 11-ft core with a checkerboard fuel loading pattern. The oscillation characteristics were very similar to those for cores with three-zone loading.

To evaluate the tendency of a large core to undergo precessing oscillations, full-core calculations were performed on an 11-ft core with two perturbations located 90 degrees apart on the principal axes. Results indicate that precessing oscillations can be excited when the second perturbation is introduced one-quarter cycle after the first.

Stability characteristics were evaluated for 11-ft cores with triple-peak steady-state power distributions. The core with the central peak of lesser magnitude than the outer two peaks was relatively more unstable than the "standard" core with a flat steady-state power distribution. Stability characteristics improved when the central peak was larger than the outer peaks.

Calculations were performed for an 11-ft core with a flat power distribution where local fuel temperature feedback effects were accounted for. These calculations showed the 11-ft core to be stable with Doppler feedback, and the magnitude of the converging oscillation following the perturbation to be approximately one-third that of the no-feedback case.

DETAILED PROGRESS REPORTS

EUXE-100

PROGRAM MANAGEMENT

M. J. O'Boyle, Project Engineer

Development Projects
PWR Plant Division

This is the third in a series of technical progress reports on the U.S.-Euratom program titled "Control of Xenon Instabilities in Large PWR's". The preceding reports in this series are:

EURAEC-1721 "Control of Xenon Instabilities in Large PWR's", Technical Progress Report for the Period Ending September 30, 1966

EURAEC-1781 "Control of Xenon Instabilities in Large PWR's", Quarterly Progress Report for the Period Ending December 31, 1966

Program management is not discussed in this technical progress report, since separate reports emphasizing the administrative aspects of the program are published monthly for limited distribution.

EFFECT OF CORE PARAMETERS ON SPATIAL OSCILLATIONS

R. J. French, Manager	Nuclear Engineering PWR Plant Division
G. H. Minton, Manager	Reactor Physics and Mathematics Section
J. E. Olhoeft, Manager	Reactor Physics
C. G. Poncelet	
A. M. Christie	

A. Introduction and Summary

This report continues the stability analysis which was discussed in previous quarterlies^{/1,2}. In the last report^{/2}, xenon oscillations were examined in the x-y plane using TURBO*^{/3}, a two-dimensional few-group diffusion code. After determining suitable values for certain parameters such as mesh size, several stability problems were investigated. In no part of this was fuel or moderator temperature feedback introduced. The investigation included:

(a) Core Size

Core sizes from 8-ft to 15-ft in diameter were examined and it was found that a core with a diameter of 8.8-ft was on the stability threshold for azimuthal oscillations while 11, 13 and 15-ft cores exhibited increasingly strong oscillations of this type. In particular, the 15-ft core very quickly produced large non-linear oscillations.

-
- ^{/1} M. J. O'Boyle, et al, "Control of Xenon Instabilities in Large PWR's Technical Progress Report for the Period Ending September 30, 1966" WCAP-3680-1 (1966)
- ^{/2} M. J. O'Boyle, et al, "Control of Xenon Instabilities in Large PWR's Quarterly Progress Report for the Period Ending December 31, 1966" WCAP-3680-2 (1966)
- ^{/3} S. M. Hendley and R. A. Mangan, "TURBO* -- A Two-Dimensional Few-Group Depletion Code for the IBM-7090", WCAP-6059 (1964).

(b) Initial Power Distribution

Several different power distribution shapes were investigated to find how they influenced azimuthal instabilities. It was concluded that stability was very sensitive to the unperturbed power distribution.

(c) Perturbation Location

It appeared that the spatial oscillations were of predominantly the same combination of spatial modes independent of the position of the perturbation. The magnitude of the oscillations was not very dependent upon perturbation position so long as the perturbation was not introduced too close to the center of the core or in a non-fueled region.

In the current report, the initial power distribution analysis was continued. A variety of other parameters was also investigated and a brief outline of these is given below. Except where specified, calculations were done on an 11-ft symmetrical half-core with flat power distribution and no temperature feedback.

(1) Power Density

The power density was varied from $2/3$ to $4/3$ of the standard value and the resulting oscillations were found to be quite dependent on the corresponding flux level.

(2) Initial Power Distribution

The unperturbed steady-state power distribution was varied in two ways. In the first, the oscillations from a checkerboard pattern of enrichment were investigated. As might be expected, the spatial power distribution was somewhat different from the conventional core, however, its stability characteristics were similar. In the second, enrichments were found so as to produce two concentric power peaks. The subsequent stability was again found to be very sensitive to the power distribution. With the outer peaks of relatively larger magnitude than the central peak, the core was relatively more unstable than with a flat power distribution.

(3) Perturbation Size

The perturbation was reduced to 1/2, 1/5 and 1/10 of its original size. These corresponded to reactivity worths of approximately 6×10^{-4} , 3×10^{-4} and 1×10^{-4} , respectively, the full perturbation being 9×10^{-4} . In the first case the perturbation did not produce a very significant change in the magnitude of the oscillations, however, reducing it to 1/10 had an appreciable effect. Subsequent oscillations were maintained in the linear range for an appreciable time.

(4) Variation of Basic Parameters

The absorption cross-section and the iodine yield were varied by $\pm 10\%$ at full and 1/10 perturbation in order to determine the sensitivity of the reactor power to these physics parameters. It was found that the stability was affected by both of the above but more so to the iodine yield. The sensitivity to direct xenon yield was also investigated, but stability appeared to be almost independent of this parameter.

(5) Fuel Temperature Feedback

One case with Doppler feedback was run in this series of calculations. Without fuel temperature feedback, the 11-ft core was quite unstable, but with fuel temperature feedback, the oscillations were convergent.

(6) Perturbation Left In

One case was run to investigate the effect on the oscillations if the perturbation was left in the core for the duration of the calculation. Although oscillations were not symmetric across the core, stability was not greatly affected.

(7) Full Core Calculations

Calculations in this section were performed with an 11-ft full core (all others were performed with a symmetrical half-core -- see section B) in order to find the response to two perturbations, one on each principal axis in the x-y plane. When the two perturbations were introduced and removed simultaneously, the power oscillated across a diagonal. When they were inserted out of phase in time (16 hours apart) the power peak precessed round the core.

(8) Radial Oscillations

Radial oscillations were investigated by placing a perturbation at the center of a 15-ft core (a previous 11-ft core produced no oscillations). For this size of core, radial oscillations were observed but they quickly converged.

B. Description of the Core

For all calculations except (7) and (8) above, an 11-ft core which was symmetrical about a principal axis was used. The corresponding full core had 193 assemblies each of size 21.5 cm., the calculation mesh length being half this, i.e., 10.75 cm/1. For this standard core a power density of 84.5 watts/cm was used, corresponding to an average thermal flux of approximately 4×10^{13} n/cm²-sec.

In all cases the core was burned for 100 hours to obtain an equilibrium xenon distribution and except for (6) above, the perturbation was introduced for one hour. Subsequent oscillations were observed every four hours, each of these time intervals being called a time-step. In no calculation was moderator feedback introduced, nor, except for case (5), was there any fuel temperature feedback.

/1 M. J. O'Boyle, et al, "Control of Xenon Instabilities in Large PWR's Quarterly Progress Report for the Period Ending December 31, 1966", WCAP-3680-2 (1966).

C. Limits of Accuracy

In the majority of the calculations, non-linear saturation effects became quite noticeable after the first few oscillations and it was consequently difficult to calculate accurate decay (or growth) constants as these are applicable only to linear theory. Consequently, figures stated here in tables tend to be very approximate and are only meant to be taken as a rough guide to comparing results.

Since the calculations are performed in two dimensions, it happens that the power maxima are sometimes shifted from the axis of symmetry. For most cases, the difference between the maximum power value and the peak on the axis of symmetry is less than 1% and, to be consistent, all graphs of power against time use the latter values. In a few cases, the discrepancy in the power values is substantial and, in those cases, only spatial contour plots are used.

There will be some measure of error incurred in the calculation due to the large grid mesh used for the spatial calculation and also possibly from the length of time step. The first of these two was investigated and discussed in the previous report/1 and it did not appear that the large mesh would substantially alter the results.

The use of a finite time-step length introduces a degree of uncertainty in the calculations. This effect will be discussed in a future report.

D. Detailed Analysis of Results

1. Effect of Change in Power Density on Spatial Stability

It is known that spatial stability is dependent on, among other things, reactor power/2. Since power density is a design parameter which will vary from core to core, an investigation of the sensitivity of spatial oscillations to power density was made.

/1 M. J. O'Boyle, et al, "Control of Xenon Instabilities in Large PWR's Quarterly Progress Report for the Period Ending December 31, 1966", WCAP-3680-2 (1966)

/2 D. Randall and D. S. St. John, "Xenon Spatial Oscillations", Nucleonics, 16, 3, 82-86 (1958)

The power of the core was varied about the standard value by $\pm 1/3$ of this value. Since the standard value was 84.5 watts/cm, two calculations were made; one at 56.3 watts/cm and the other at 112.7 watts/cm. The oscillations resulting from these are shown in Figures 200.1 and 200.3, respectively, and can be compared to the standard 11-ft core shown in Figure 200.2. The size of the initial oscillations and, to a lesser extent, their subsequent growth rate are sensitive to variation in power density.

2. Effect of Initial Power Distribution on Spatial Stability

As discussed in the previous report^{/1}, spatial stability of the core is very sensitive to the unperturbed power distribution. This is because leakage from the core and coupling between regions are sensitive to the power distribution. Since in future reactors it is possible that certain fuel management schemes may require that a core has a checkerboard enrichment pattern, this was looked at from the point of view of xenon instabilities. The stability characteristics of a reactor with a triple peak in the unperturbed power distribution (i.e., a dished power distribution with an added peak in the center) were also examined. Sensitivity to this kind of distribution is important in that recycled cores can exhibit triple peaks in their power distribution.

In both cases an 11-ft core was used. For the checkerboard core the assemblies in the two inner regions alternated in enrichments 2.5 and 3.0% (see Figure 200.4). Two cores with different shapes of triple peak were examined (see Figures 200.5 and 200.6) and for both, the inner peak was produced by adding an extra region of enrichment in the center of a core whose power distribution was already dished. The cores were all perturbed in the same manner as described

^{/1} M. J. O'Boyle, et al, "Control of Xenon Instabilities in Large PWR's Quarterly Progress Report for the Period Ending December 31, 1966", WCAP-3680-2 (1966).

Figure 200.1 Xenon-Induced Oscillations at 2/3 Full Power

Figure 200.2 Xenon-Induced Oscillations at Full Power

Figure 200.3 Xenon-Induced Oscillations at $4/3$ Full Power

Figure 200.4 Enrichment Pattern for Checkerboard Core

Figure 200.5 Initial Power Distribution for Triple Peak Core #1

Figure 200.6 Initial Power Distribution For Triple Peak Core #2

in section B and the power distribution observed every subsequent four hours.

The resulting power distribution from the checkerboard core does not differ greatly from the corresponding conventionally enriched core although it exhibits discontinuities in power at the assembly interfaces. Figure 200.7 compares the unperturbed power distribution for the checkerboard core with that of the equivalent standard 11-ft core. It can be seen that, averaging over the discontinuities of the checkerboard, the power distribution would be fairly flat. Figures 200.8 and 200.9 show the checkerboard spatial power distributions for 8 and 32 hours after the perturbation has been removed. The equivalent spatial plots for the standard 11-ft core (defined in section B) are also shown in these figures for comparison. From these and the graph of the power oscillations in time (Figure 200.11), it appears that the stability characteristics of the checkerboard core are quite similar to the standard 11-ft core. Figure 200.11 shows the power oscillations in two adjacent assemblies. Graphs A and A' correspond to assemblies of enrichment 2.6% while B and B' correspond to adjacent assemblies of enrichment 2.1%. The position of all these assemblies is shown in the core diagram of Figure 200.11. Figure 200.10 is the equivalent plot for the standard 11-ft core.

Contour plots of power for 20 and 32 hours after the removal of the perturbation are shown in Figures 200.12 and 200.13 for the checkerboard core. Because of the sharply fluctuating nature of the power distribution, these curves appear very different from the corresponding curves for the standard 11-ft core.

The unperturbed power distributions for the two triple peaks can be seen in Figures 200.5 and 200.6. The subsequent oscillations for the first of these are considerably weaker than for the latter as its initial power distribution is much closer to a cosine curve.

Figure 200.7 Initial Power Distribution for Checkerboard Core

Figure 200.8

Power Distribution for Checkerboard Core Eight Hours after Removal of Perturbation

Figure 200.9 Power Distribution for Checkerboard Core 32 Hours After Removal of Perturbation

Figure 200.10 Xenon-Induced Oscillations for Standard Core

Figure 200.11 Xenon-Induced Oscillations for Checkerboard Core

Figure 200.12 Contour Power Plot for Checkerboard Core 16 Hours after Removal of Perturbation

Figure 200.13 Contour Power Plot for Checkerboard Core 28 Hours after Removal of Perturbation

The responses of the power in time are shown in Figures 200.14 and 200.15. Figures 200.16 to 200.18 and 200.19 to 200.21 show the respective contour plots of the power distribution across the core for 8, 16 and 28 hours after perturbing the reactor. From these it can be seen that the peak stays on the 0-180 degree axis and consequently should not be excessively difficult to control. With the triple peak shown in Figure 200.6, the core is relatively more unstable than with a flat power distribution.

Table 200.1 shows some results for the checkerboard core and the two triple peak cores.

3. The Effect of Perturbation Size on Xenon-Induced Oscillations

With the size of perturbation used in most of the calculations, the oscillations diverged quite rapidly and soon were in the non-linear range. In order to evaluate the sensitivity of the core to perturbation size, three calculations were performed which had poisons that were reduced in strength to 1/2, 1/5 and 1/10 of the original. The reactivity worth equivalents for these perturbations were 6×10^{-4} , 3×10^{-4} , and 1×10^{-4} , respectively, that for the full perturbation being 9×10^{-4} . The results of these were also useful in determining a suitable poison to produce linear oscillations in the investigation of certain parameters (see section 4).

From the results shown in Figures 200.22 to 200.25, it can be seen that 1) the period is not affected much by perturbation size and 2) it requires a reactivity worth of 1×10^{-4} or less to keep the first few oscillations in the linear range.

4. The Effect of Varying Certain Core Parameters on Core Stability

Due to approximations in theory and inaccuracies in basic physical data, results of calculations may have some degree of uncertainty in their value. To determine the sensitivity of results to changes

Figure 200.14 Xenon-Induced Oscillations for Triple Peak #1

Figure 200.15 Xenon-Induced Oscillations for Triple Peak #2

Figure 200.16 Contour Power Plot for Triple Peak Core #1, 8 Hours after Removal of Perturbation (all power values in figure above are relative).

Figure 200.17. Contour Power Plot for Triple Peak Core #1, 16 Hours after Removal of Perturbation (all power values in figure above are relative).

Figure 200.18 Contour Power Plot for Triple Peak Core #1, 28 Hours after Removal of Perturbation (all power values in figure above are relative)

Figure 200.19 Contour Power Plot for Triple Peak #2, 8 Hours after Removal of Perturbation (all power values in figure above are relative)

Figure 200.20. Contour Power Plot for Triple Peak #2, 16 Hours after Removal of Perturbation (all power values in figure above are relative)

Figure 200.21 Contour Power Plot for Triple Peak #2, 28 Hours after Removal of Perturbation (all power values in figure above are relative)

Table 200.1

The Effect of Initial Power Distribution on Spatial Stability

	<u>Enrichments</u> <u>3 or 4 Zone</u>	<u>Period of</u> <u>Oscillation</u> <u>(Hrs)</u>	<u>Damping</u> ^{/2} <u>Factor</u>	$\left(\frac{\bar{P}_{\text{assembly}}}{\bar{P}_{\text{core}}} \right)^{1/3}_{\text{max.}}$
^{/1}				
Standard Core	2.4/2.5/3.0	23	1.45	1.22
Checkerboard	2.4/2.5/3.0	23-1/2	1.49	1.27
Triple Peak #1	2.6/2.3/2.8/2.7	23	1.21	1.65
Triple Peak #2	2.5/2.3/2.8/2.8	24	1.50	1.41

¹ All cores 11-ft in diameter

² Defined as the ratio of the second-to-first peak

³ Peak-to-average power for initial power distribution

Figure 200.22 Xenon-Induced Oscillations for Poison of Reactivity Worth 9×10^{-4}

Figure 200.23 Xenon-Induced Oscillations for Poison of Reactivity Worth 6×10^{-4}

Figure 200.24 Xenon-Induced Oscillations for Poison of Reactivity Worth 3×10^{-4}

Figure 200.25 Xenon-Induced Oscillations for Poison of Reactivity Worth 1×10^{-4}

in the relevant parameters, calculations were performed in which these parameters were varied about their mean value and the solutions compared. The parameters investigated were:

- (a) Thermal absorption cross section of Xe-135
- (b) Iodine yield from fissions
- (c) Direct xenon yield from fissions

The Xe-135 absorption cross section and the iodine yield were varied by $\pm 10\%$ both at full perturbation and a perturbation $1/10$ that size.

The case with the smaller poison was examined to determine if the response in the linear region was more or less sensitive to changes in these parameters. In (c) above, the direct xenon yield was changed from 0.002 to 0.0 and 0.004.

Cases (a) and (b) were investigated particularly because the values given to these quantities will vary over the lifetime of the core. In the first case, the microscopic absorption cross-section will change because of spectrum variations in the core with time. The iodine yield will also change with time because of the buildup of plutonium.

The direct xenon yield has a stabilizing influence, since it contributes to the direct formation of xenon, and therefore increased parasitic absorption, following a local increase in the flux.

Figures 200.26 and 200.27 show the power oscillations for 10% changes in thermal absorption cross section. These can be compared with the appropriate graph of the standard 11-ft core (Figure 200.2).

The results for variation in Xe-135 absorption at a perturbation strength $1/10$ that of the previous two cases are shown in Figures 200.28 and 200.29.

Figure 20C.26 Xenon-Induced Oscillations for 10% Increase in Absorption Cross-Section at a Poison Reactivity Worth of 9×10^{-4}

Figure 200.27. Xenon-Induced Oscillations for 10% Reduction in Absorption Cross-Section at a Poison Reactivity Worth of 9×10^{-4}

Figure 200.28 Xenon-Induced Oscillations for 10% Increase in Absorption Cross-Section and at a Poison Reactivity Worth of 1×10^{-4}

Figure 200.29 Xenon-Induced Oscillations for 10% Reduction in Absorption Cross-Section and at a Poison Reactivity Worth of 1×10^{-4}

The power oscillations for changes of $\pm 10\%$ in the iodine yield are shown in Figures 200.30 and 200.31. From these and the results in Table 200.2, it is evident that stability is more dependent on this factor than on changes in Xe-135 absorption cross section.

Variation of yield at 1/10 perturbation is shown in Figures 200.32 and 200.33. In this case, all oscillations appear to be in the linear range — the exponential growth of the oscillations has not yet been saturated. Because of the apparent sensitivity of the core to changes in iodine yield, care would have to be taken in interpreting results for a reactor near the stability threshold.

Some data relating to stability for change in Xe-135 absorption cross-section and changes in iodine yield are shown in Table 200.2.

The third parameter to be varied was the direct xenon yield. Increasing this quantity should have a stabilizing influence. The results are shown in Figures 200.34 and 200.35. These are for direct xenon yields of 0.0 and 0.004, the value of the standard core being 0.002. It can be seen that the stability is almost completely insensitive to this parameter and its value is of little importance as far as spatial xenon oscillations are concerned.

Table 200.2

The Effect of Varying Certain Physical Parameters on Core Stability

1. Variation of Absorption Cross-Section

Case	Reactivity Worth of Poison	Absorption Cross-Section (% Deviation from Standard Core)	Damping Factor
1. (Standard Core)	9×10^{-4}	0%	1.45
2.	9×10^{-4}	+10%	1.53
3.	9×10^{-4}	-10%	1.36
4.	1×10^{-4}	+10%	1.07
5.	1×10^{-4}	-10%	1.04

2. Variation of Iodine Yield from Fissions

Case	Reactivity Worth of Poison	Yield (% Deviation from Standard Core)	Damping Factor
1. (Standard Core)	9×10^{-4}	0%	1.45
2.	9×10^{-4}	+10%	1.54
3.	9×10^{-4}	-10%	1.28
4.	1×10^{-4}	+10%	1.17
5.	1×10^{-4}	-10%	1.02

Figure 200.33 Xenon-Induced Oscillations for a 10% Reduction in Iodine Yield
at a Poison Reactivity Worth of 1×10^{-4}

Figure 200.34 Xenon-Induced Oscillations for Direct Xenon Yield of 0.004.

Figure 200.35 Xenon-Induced Oscillations for Direct Xenon Yield of 0.000.

5. The Effect of Fuel Temperature Feedback on Core Stability

Using the standard 11-ft core (described in section B), the effect of local fuel temperature feedback was investigated. With the addition of appropriate fuel temperature feedback parameters derived from a typical core design, TURBO* calculations produced oscillations which were considerably reduced in size. This can be seen from Figure 200.36, which compares the standard core with Doppler feedback (curves B and B'), and without Doppler feedback (curves A and A'). The difference in power level across the core is lowered to about 1/3 of its original value with the addition of fuel temperature feedback. It also shows that the core which without Doppler feedback was quite unstable, now exhibits convergent oscillations, and is therefore stable.

An earlier calculation reported in the June 1966 progress report^{/1} indicated that even with Doppler feedback the oscillations were initially as large as in the case without any feedback, and that they were slightly divergent. This case, however, differs from that reported herein in respect to the fact that feedback was only introduced after the perturbation had been removed and that the initial power distribution was more dished hence producing a more unstable core.

6. The Effect on Stability of Leaving the Perturbation in the Core

The stability of a core in which the poison was left in for all time steps was investigated. The power fluctuations on the side of the perturbation were considerably depressed while on the opposite side the oscillations were not greatly affected. This is shown in Figure 200.38 and can be compared to the standard 11-ft core shown in Figure 200.37. It can be seen from Figure 200.38 that the bulk of the power is produced from the side away from the perturbation.

^{/1} M. J. O'Boyle, et al, "Control of Xenon Instabilities in Large PWR's Technical Progress Report for the Period Ending September 30, 1966" WCAP-3680-1 (1966)

Figure 200.36 Xenon-Induced Oscillations With and Without Doppler Feedback

Figure 200.37 Xenon-Induced Oscillations with Direct Xenon Yield at 0.004

Figure 200.38 Xenon-Induced Oscillations with Direct Xenon Yield at 0.000.

7. The Effect on Spatial Stability of Two Perturbations in a Full Core

Three full-core calculations were run in order to investigate the nature of oscillations originating from two perturbations, one on each of the principal axes (i.e. the axes which divide the core into four quadrants).

In the first of these using a full core version of the standard 11-ft half core (defined in section B), two perturbations were placed at right angles to each other as described above. The two perturbations were left in for the usual time, one hour, and the subsequent oscillations observed every four hours. The power oscillated along the diagonal between the perturbations and although, in effect, there was twice as much poison in this core than in the half core, these oscillations peaked only slightly larger than in the half core (see Figures 200.39 and 200.40). The contour plots in Figures 200.41 to 200.44 show how the peak oscillates across the core.

A similar core was set up differing only in that the second perturbation was introduced 16 hours after the first had been removed. This was done in an attempt to make the power peak precess round the core. As can be seen from Figure 200.45, this was indeed what happened. In this figure each time step is shown (see section B for description of time steps) along with the relative magnitude of the power peak. Figures 200.46 to 200.51 show in more detail how the peak actually precesses. A second calculation was done at half power and the results are shown in Figure 200.52. The precession is still evident but the peaks appear to bunch up across a diagonal just off the $0-180^\circ$ axis. It appears that as the power is decreased, there is less of a tendency for the peak to precess round the core.

Figure 200.39 Xenon-Induced Oscillations for Standard 11-ft Symmetric Half Core

Figure 200.40 Xenon-Induced Oscillations for Full Core with Two Perturbations Introduced Simultaneously and at Right Angles

Figure 200.41 Contour Power Plot of Xenon Oscillations-Steady State Flux Distribution for Full Core Calculation

Figure 200.42 Contour Power Plot of Xenon Oscillations-Power Distribution 4 Hours after Perturbations have been Removed

Perturbation Positions Shown by Dotted Squares

Figure 200.43 Contour Power Plot of Xenon Oscillations. Power Distribution 12 Hours after Perturbations have been Removed.

Figure 200.44 Contour Power Plot of Xenon Oscillations. Power Distribution 24 Hours after Perturbations have been Removed.

Perturbation Positions Shown by Dotted Squares

Figure 200.45 Precession of Xenon-Induced Power Peak in Full Core at Full Power

Figure 200.46 Contour Power Plot for Xenon-Induced Oscillations after First Perturbation (shown in dotted square) has been Removed.

Figure 200.47 Contour Power Plot for Xenon-Induced Oscillations after Second Perturbation (shown in dotted square) has been Removed.

Figure 200.48 Contour Power Plot for Xenon-Induced Oscillations 12 Hours after Second Perturbation has been Removed.

Figure 200.49 Contour Power Plot for Xenon-Induced Oscillations 20 Hours after Second Perturbation has been Removed.

Figure 200.50 Contour Power Plot for Xenon-Induced Oscillations 28 Hours after Second Perturbation has been Removed.

Figure 200.51 Contour Power Plot for Xenon-Induced Oscillations 40 Hours after Second Perturbation has been Removed.

Figure 200.52 Precession of Xenon-Induced Power Peak in Full Core at Half-Power

8. Stability of Radial Oscillations in a 15-ft Core

In a previous report^{/1} the response to a perturbation located at the center of an 11-ft core was shown (Figure 200.16). It was seen that there is in effect no response to a poison located in this position. The same calculation was carried out for a 15-ft core and convergent radial oscillations were observed. These are shown in Figure 200.53.

^{/1} M. J. O'Boyle, et al, "Control of Xenon Oscillations in Large PWR's Quarterly Progress Report for the Period Ending December 31, 1966" WCAP-3680-2 (1966)

Figure 200.53 Xenon-Induced Radial Oscillations in 15-ft Core

EUXE-300

REMEDIAL CONTROL PROCEDURES

R. J. French, Manager

Nuclear Engineering
PWR Plant Division

D. L. Miller, Manager

Nuclear Core Design

R. F. Barry

T. D. Knight

A. Summary

Analysis of an 11-foot diameter core shows that xenon spatial stability depends on the magnitude of the initial perturbation. Small perturbations give rise only to convergent spatial transients even though larger perturbations instigate divergent transients in the same core. This conclusion is significant because it means that minor random fluctuations in core parameters cannot initiate divergent transients.

B. Analysis

The analysis reported here is for an 11-ft diameter Zircaloy-clad, ~ 2.5 w/o enriched core, known (and shown here) to be xenon unstable for large perturbations. The calculations were done in one dimension along a diameter of the core; this model, using a space-independent transverse buckling, is a conservative approximation since it has too little leakage.

Small asymmetric changes were made in a series of cases to start a transient. The perturbation was left in the reactor for one hour, and then withdrawn. The maximum-to-average power density ratio was then observed at four-hour intervals. Results are shown in Figures 300.1, 300.2, and 300.3. In these figures, the magnitude of the perturbation is shown by the change in over-all core reactivity.

It will be seen in these figures that the core is unstable for large perturbations and becomes stable as the magnitude of the perturbation is decreased.

Figure 300.1 Xenon Transient Peaking Factor - 0.034% Δk Perturbation

Figure 300.2 Xenon Transient Peaking Factor - 0.085% Δk Perturbation

Figure 300.3 Xenon Transient Peaking Factor - 0.170% Δk Perturbation

EUXE-400

THREE-DIMENSIONAL ANALYSIS

This sub-task was inactive during this report period.