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CONTROL OF XENON INSTABILITIES
IN LARGE PRESSURIZED WATER
REACTORS

SUMMARY REPORT

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SEPTEMBER 1969

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ABSTRACT

Detailed analyses, both theoretical and analytical, were performed to study fully the characteristics of free-running xenon oscillations in Large Pressurized Water Reactors (PWR's) and to evaluate the effects of variations of individual core parameters on core stability. Included in that evaluation were such parameters as core size, fuel enrichment, power distribution, power coefficient, power density, iodine and xenon yields, and thermal xenon absorption cross section. This work provided a sound basis for proceeding with engineering studies on remedial control procedures for X-Y xenon oscillations and the three-dimensional analyses.

Strategies for controlling divergent xenon oscillations in the X-Y plane in large PWR cores were investigated using one- and two-dimensional digital simulation techniques. A three-zone core typical of the largest present-day PWR was used in the control studies. Unstable xenon oscillations had to be achieved artificially by eliminating moderator temperature feedback effects because such cores, although axially unstable, are inherently stable in the X-Y plane. A general procedure was successfully developed to damp divergent xenon oscillations in the X-Y plane. Three dimensional calculations incorporating nuclear, thermal, and hydraulic feedback effects were performed to substantiate the validity of one- and two-dimensional calculations. The predictions of the simpler models are generally consistent with the three-dimensional calculation.

SECTION 1

INTRODUCTION

In response to the need for Pressurized Water Reactors (PWR's) with improved economics and greater efficiency, cores have become larger, power densities have increased, and power distributions have been made more uniform. Each of these improvements has, however, made the core inherently less stable to the slow spatial power oscillations called xenon oscillations, which are caused by redistribution of xenon-135 within the core.

The incentives for improved economics in nuclear power remain as strong as ever; and there is little reason to believe that the current trend to larger, more efficient PWR's will change, even though such advances will eventually make cores unstable to xenon oscillations--first to axial oscillations, then to diametral oscillations. The trend will continue because the period of xenon oscillations is long, relative to control mechanism and operator reaction time, being of the order of 30 hours; and, accordingly, it appears to be more practical and economic to design for detection and control of such oscillations, rather than to accept the size and rating constraints imposed by the design of a stable core.

Xenon oscillations in large PWR's were first investigated by Westinghouse in the early 1960's under AEC Contract AT(30-1)-3070 in connection with a feasibility study for a 1000 MWe PWR.^[1] That work was followed in the mid-1960's with detailed diffusion-depletion calculations under AEC Contract AT(30-1)-3269 which led to the development of a workable control strategy for stabilizing large PWR cores against axial (Z-axis) xenon instabilities.^{[2][3]}

This report summarizes the work performed by Westinghouse in the period March 1966 through July 1969 under the US-Euratom sponsored Control of Xenon Instabilities in Large PWR's (EUXE) Program, AEC Contract AT(30-1)-3680.

The aim of the EUXE Program was to extend logically the previous work on xenon oscillations by studying the characteristics and control of xenon instabilities in the X-Y plane -- the plane perpendicular to the direction of coolant flow. To facilitate accomplishing that objective in a systematic and complete manner, the EUXE Program was divided into the following three technical tasks:

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

Detailed analyses, both theoretical and analytical, were performed under this task to study fully the characteristics of free-running xenon oscillations in large PWR's and to evaluate the effects of variations of individual core parameters on core stability. Included in that evaluation were such parameters as core size, fuel enrichment, power distribution, power coefficient, power density, iodine and xenon yields, and thermal xenon absorption cross section.

The work performed under this task provided a sound basis for the engineering studies which followed under Tasks EUXE-300 and EUXE-400, inasmuch as it led to a fuller understanding of the physical phenomenon of spatial oscillations in large cores, as well as to a better appreciation of the capabilities and limitations of the various calculational methods used in spatial stability analysis.

Task EUXE-300: Remedial Control Procedure

Strategies for controlling divergent xenon instabilities in the X-Y plane in large PWR cores were examined under this task, using one- and two-dimensional digital simulation techniques. A three-zone core typical of the largest present-day PWR was used in the control studies. Unstable xenon oscillations had to be achieved artificially by eliminating moderator temperature feedback effects because such cores, although axially unstable, are inherently stable in the X-Y plane.

A general procedure was successfully developed to damp divergent xenon oscillations in the X-Y plane. The procedure is straight forward and it entails the full insertion of one appropriate full-length control rod when X-Y power tilt approaches a predetermined limit, and the subsequent withdrawal of that rod after a specified period of time.

Task EUXE-400: Three-Dimensional Analysis

Three-dimensional calculations incorporating nuclear, thermal, and hydraulic feedback effects were performed under this task to substantiate the validity of earlier one- and two-dimensional digital calculations. A typical large PWR core equivalent to that used in the control study was represented, and a perturbation representing the insertion of one control rod was introduced. The perturbed core exhibited an oscillation which was stable in the X-Y plane but divergent in the axial direction. The results of the two-dimensional calculations for selected core planes and the one-dimensional axial calculation representing the average channel are generally consistent with the three-dimensional calculation.

Sections 2, 3, and 4 of this report summarize the technical results obtained under Task EUXE-200, Task EUXE-300, and Task EUXE-400, respectively. Detailed descriptions of the work performed in those tasks may be found in the following topical reports:

EUXE-200: C. G. Poncelet and A. M. Christie, "Xenon-Induced Spatial Instabilities in Large Pressurized Water Reactors," WCAP-3680-20 (EURAE-1974), March 1968.

EUXE-300: F. B. Skogen and A. F. McFarlane, "Control Procedures for Xenon-Induced X-Y Instabilities in Large Pressurized Water Reactors," WCAP-3680-21 (EURAE-2111), February 1969.

EUXE-400: F. B. Skogen and A. F. McFarlane, "Xenon-Induced
Spatial Instabilities in Three Dimensions,"
WCAP-3680-22 (to be issued).

A listing of all technical progress reports issued under this program is provided as part of the references. The technical progress reports describe the above work as it was in progress during the program.

SECTION 2

TASK EUXE-200

EFFECT OF CORE PARAMETERS ON SPATIAL OSCILLATIONS

The characteristics of free-running xenon oscillations in large PWR's^[4] were examined in detail, both from a phenomenological point of view and from the standpoint of the theoretical and calculational methods employed in their analysis. The space-time characteristics of xenon oscillations in the X-Y plane, perpendicular to the direction of reactor coolant flow, were studied for a variety of core sizes, power distributions, and temperature feedback effects. The influence of perturbation size and location was evaluated. Extensive parametric and sensitivity analyses were performed using linearized modal expansion theory. Parameters investigated included core size, power distribution, power density, power coefficient, fuel enrichment, Xe-135 absorption cross section, I-135 fission yield and direct Xe-135 fission yield. Comparisons were made between modal theory results and numerical results from direct digital simulation, which demonstrated satisfactory agreement between the two techniques.

2.1 Numerical Approximations

In view of the geometrical complexity of large PWR's, and the importance of including realistic feedback mechanisms, the use of digital simulation in the analysis of spatial xenon instabilities was preferred over alternate methods. One- and two-dimensional diffusion theory codes were found to adequately exhibit the spatial instability associated with xenon redistribution. A number of possible sources of error were investigated within the context of digital simulation and their effect on xenon stability characteristics evaluated with the following results:

- a. The space-time behavior of gross power distribution can be reasonably well calculated using a relatively crude spatial mesh. A spatial mesh of 10 cm was demonstrated to be adequate for two-dimensional X-Y stability calculations.

- b. Finite time-step lengths during which the flux is assumed constant can introduce significant errors in the calculation of the period of the oscillation and the stability index, the definition of which is provided in Appendix A of this report. Figure 2-1 shows the effect of time-step error on the stability index of free-running oscillations in cores with a power density of 84.5 watts/cc. Note that a core that is very unstable will appear significantly more stable as longer time-step lengths are used; and, conversely, a core that is very stable will appear significantly less stable as longer time-step lengths are used. Time-step lengths of one-hour or less are recommended for calculating stability characteristics.
- c. The finite convergence criterion introduces an error which is not random in relation to stability characteristics. That error operates in the same direction as the time-step error in very unstable cores, and in the opposite direction of the time-step error in very stable cores. A convergence criterion of 10^{-5} is recommended for calculating stability characteristics.
- d. In the treatment of fuel temperature feedback, it was observed that the non-linear characteristics of the power coefficient affect somewhat the stability characteristics of the core. The effect of fuel temperature on the fast absorption and fast removal cross sections should be accounted for in xenon-oscillation calculations.
- e. Two energy groups are sufficient to adequately simulate xenon-induced spatial instabilities in large PWR's. The presence of delayed neutrons was shown to have no noticeable effect on stability characteristics.
- f. In the treatment of temperature feedback effects, the temperature time constant can be taken as zero. A moderator temperature time constant of the order of a few minutes is required before the temperature time lag influences spatial xenon stability characteristics.

Figure 2-1. Effect of Time-Step Length on Spatial Stability Index

2.2 Parametric Studies

Parametric studies were performed using linearized modal expansion theory to evaluate the effect of changes in various core parameters and physical constants on the characteristics of diametral xenon oscillations in large PWR's. This was accomplished by deriving analytic expressions that related the stability index, as defined in Appendix A, and the period of oscillation to the parameters under study. The standard core conditions used as a basis for that study were those of an 11-foot diameter core (12-foot active fuel length) with an average U-235 enrichment of 2.6 a/o, an average power density of 84.5 watts/cc, and a flat power distribution.

Figures 2-2 through 2-9 delineate the results of the parametric study. From the figures it is readily apparent that the most important parameters influencing core stability are power coefficient, fuel enrichment, steady-state power distribution, and core diameter. Of somewhat less importance are xenon absorption cross section, iodine yield, power density, and direct xenon yield.

The merit of the parametric results lies in the trends rather than the specific numerical results, due to the approximate nature of linearized modal analysis. The trends provide important insight into the many interacting physical processes that produce the phenomenon of xenon oscillations. Limited parametric studies were performed using direct digital simulation techniques to substantiate the extensive modal theory results. The agreement was satisfactory, indicating acceptable consistency, as shown by the X's plotted on Figures 2-2, 2-3, 2-4, 2-7, 2-8 and 2-9. The Zest numerical calculations (the X's in the Figures) were all done with a value of $\partial\rho/\partial p = -3.10 \times 10^{-6}/\text{MWt}$.

2.3 Space-Time Characteristics of Xenon Oscillations

A series of one- and two-dimensional digital calculations were performed to study the space-time characteristics of xenon oscillations in the plane perpendicular to reactor coolant flow. More specifically, perturbation size and location, non-linearities, fuel temperature feedback, and very small (noise) perturbations were investigated to determine how they influenced the space-time characteristics of xenon oscillations.

Figure 2-2. Variation of Stability Index with U-235 Enrichment - Modal Analysis

Figure 2-3. Variation of Stability with Core Diameter - Modal Analysis

Figure 2-4. Variation of Stability Index with Average Power Density - Modal Analysis

Figure 2-5. Variation of Stability Index with Power Distribution - Modal Analysis

Figure 2-6.. Variation of Stability Index with Net Power Coefficient - Modal Analysis

Figure 2-7. Variation of Stability Index with I-135 Yield - Modal Analysis

Figure 2-8. Variation of Stability Index with Xenon Absorption Cross Section-Modal Analysis

Figure 2-9. Variation of Stability Index with Direct Xe-135 Yield - Modal Analysis

Summarized below are the key conclusions drawn from that study:

- a. The diametral oscillation is the most readily excited mode of oscillation in the X-Y plane. A typical example of the characteristics of that type of oscillation in time and space is provided in Figures 2-10 through 2-13. Figure 2-10 shows the time-dependent variations of the amplitude of the oscillation, whereas Figures 2-11 through 2-13 show the relative X-Y power distribution for 28 hours, 36 hours, and 52 hours, respectively, after the perturbation. The distribution in Figure 2-12 is essentially the steady state power distribution.
- b. The spatial mode characteristics of xenon oscillations in the X-Y plane are relatively insensitive to variations in the location or the magnitude of short duration reactivity perturbations. A small effect, due to the non-linear nature of the fuel temperature feedback, was observed to detract from stability somewhat as the size of the perturbations was increased.
- c. Precessing oscillations can be excited purposely by a particular sequence of asymmetric local perturbations. However, control rod movement in an actual reactor would be such that precessing oscillations of the type described in Reference 4 would be extremely difficult to produce.
- d. Very small (noise) perturbations of the order of the convergence criterion in diffusion-theory calculations may excite oscillations in an inherently unstable core.
- e. The major stabilizing influence for azimuthal or diametral oscillations in a PWR is the fuel temperature feedback arising from the Doppler effect. The moderator density feedback is also important and should be accurately accounted for in calculating stability characteristics.

Figure 2-10. Xenon-Induced Oscillations for Poison of Reactivity Worth of 1×10^{-4}

Figure 2-11. Contour Power Distribution
28 Hours after Removal of Perturbation

Figure 2-12. Contour Power Distribution
36 Hours after Removal of Perturbation

Figure 2-13. Contour Power Distribution
52 Hours after Removal of Perturbation

SECTION 3

TASK EUXE-300

REMEDIAL CONTROL PROCEDURES

Digital simulation techniques were used to investigate the general behavior of X-Y xenon oscillations in response to control action and to demonstrate that successful control of divergent oscillations in the plane perpendicular to reactor coolant flow can be achieved by the insertion of an appropriate full-length control rod for some specified period of time. [5]

3.1 Analytical Model

Digital simulation techniques were the basic analytic tool used in the X-Y control studies. Although that approach has certain drawbacks, it was preferred over other methods because it readily accommodates a realistic treatment of reactivity feedback mechanisms and it facilitates a detailed spatial description of the relatively complex geometry of large PWR's.

The core model on which the control study was performed is representative of the largest PWR presently under design, consisting of 193 fuel assemblies in the three-zone checkerboard pattern shown in Figure 3-1. The active height of the core is 12 ft, the equivalent diameter is 11 ft, and the average power density is 104.5 watts/cc.

3.2 X-Y Xenon Oscillations without Control

The initial phase of the study was concerned with determining the stability characteristics of the above mentioned core without control action. The analysis showed that this core is stable with respect to X-Y xenon oscillations when pointwise Doppler and moderator feedback effects are accounted for, having a stability index, as defined in Appendix A, of -0.03 hr^{-1} . The analysis further indicated that the core could be made unstable by

Figure 3-1. Checkerboard Fuel Loading Pattern in Large PWR Cores

eliminating moderator density feedback effects, and that was done for the purposes of the control study. Accordingly, the reference core used as the basis for all the following control studies was a half-core mockup of the core just described with moderator density feedback effects intentionally neglected to make it unstable to xenon oscillations in the X-Y plane. Diagonal symmetry was used in the half-core mockup because previous work^[5] had shown that the core is slightly less stable across the diagonal than it is across the flats (main axes).

The reference core, was perturbed by inserting a local poison in the form of a control rod in the peripheral region of the core. The poison was retained in the core for one hour and then withdrawn. That action sufficiently perturbs the flux across the core to initiate the spatial xenon transient. Figure 3-2 shows the resulting X-Y power peaking in symmetrically opposite assemblies plotted as a function of time following the removal of the perturbation. The oscillation is divergent with a calculated stability index of $+0.014 \text{ hr}^{-1}$.

3.3 Control with a Single Insertion Period

In PWR cores of this type the means available for the control of xenon-induced spatial oscillations in a plane at right angles to the coolant flow are limited to the insertion of one, or possibly two, full-length control rods.

Initial attempts to control the diagonal mode of oscillation indicated that the magnitude of the effect of the control rod on the core radial hot-channel factor was sensitive to the particular location of the rod. Figure 3-3 shows the control rods which have proved the most effective for xenon control in the cores studied. Consider these rods to be designated X-Y xenon control rods, then the following procedure is defined:

- a. When the power in one quadrant of the core exceeds the average of the four quadrants by a set amount, fully insert the X-Y xenon control rod closest to the peak.

Figure 3-2. X-Y Power Peaking versus Time after Perturbation
(104.5 W/cc Core, Diagonal Symmetry, No Moderator Density Feedback)

Figure 3-3. X-Y Xenon Control Rod Arrangement

- b. When the power tilt again approaches the set limit, withdraw the rod. (The rod may be withdrawn at any earlier time but a repetition of the procedure may be required.)

The effectiveness of the procedure is demonstrated by applying control to the divergent oscillation shown in Figure 3-2. For the diagonal mode of oscillation, the xenon control rod located on the diagonal in the quadrant where the power was increasing, was inserted. The xenon was then allowed to redistribute for four hours before the corrective rod was withdrawn. The subsequent behavior of the system is illustrated in Figure 3-4 which shows the power peaking in a horizontal plane as a function of time throughout the operation. The oscillation following the withdrawal of the rod is seen to be damped and the stability index computed from these results is changed from $+0.014 \text{ hr}^{-1}$ to -0.004 hr^{-1} .

The fact that the oscillation converges after the rod has been removed from the core indicates that the new power shape, or xenon distribution, is such that the stability characteristics of the core are significantly altered. This is presumably a temporary state brought about by the redistribution of xenon and iodine and is a phenomenon which is very important to the reactor operator. The significance of this effect, if confirmed, is that repeated and continual action to control an unstable system is not required, but corrective action need only be taken once following a significant perturbation.

3.4 Control with Repeated Insertion Period

Clearly, the case described above needs no further corrective action for the time duration investigated. It is seen that the four-hour time interval allowed for xenon redistribution had a sufficient effect on the oscillation to change it from divergent to convergent, at least temporarily. Note, however, that the four-hour time interval used in these calculations represents a maximum time rather than an optimum time. By a maximum time is meant that any rod insertion extending beyond four hours would, in this

Figure 3-4. X-Y Power Peaking versus Time after a Perturbation
 (Xenon Rod, 4 Hour, Diagonal Mode)

case, result in a violation of the operational restrictions imposed on power distribution. It is possible therefore that when the corrective rod is withdrawn the oscillation persists and is divergent. Intuitively, if there is a single control action that tends to damp out a diverging oscillation, then there should exist a set of repeated actions that will accomplish a greater effect.

The consequences of a shorter period of insertion were evaluated on the diagonal mode of oscillation when the initial corrective action was terminated after two hours. The resulting oscillation has a stability index of approximately zero; i.e., a sustained oscillation is created where the X-Y power peaking factor oscillates between 1.20 and 1.40. To return this system to a steady-state condition further action is required and two possibilities have been examined. First, the same control rod was inserted again two hours after the initial action was terminated and left inserted for two additional hours. This proved unsuccessful as a more divergent oscillation resulted following the withdrawal of the rod. In the second case, the control action was commenced half an oscillation period later; i.e., the control was applied to the peak when it had shifted over to the symmetric quadrant of the core. This proved highly successful as the subsequent behavior of the core indicates that the system has been returned to steady state. The power peaking as a function of time for this case is plotted in Figure 3-5.

An alternate control procedure can therefore be defined, namely;

- a. When the power in one quadrant of the core exceeds the average of the four quadrants by a set amount, fully insert the X-Y xenon control rod closest to the peak for a period of two hours.
- b. When the power is growing in the opposite quadrant, insert the symmetrically placed rod for a period of two hours.
- c. Repeat as necessary.

Figure 3-5. X-Y Power Peaking versus Time after Perturbation
(Xenon Rod, Two 2-Hour Insertions, Diagonal Mode)

For the amplitude of oscillation described above it has been demonstrated that successful control can be achieved with insertion times ranging from two to four hours, and within this range success is not critically dependent upon time duration of rod insertion.

3.5 Other Procedures

It was mentioned that part of this study was concerned with identifying the most suitable xenon control rods. The results of this effort are illustrated in Figure 3-3 which shows possible xenon control rod positions. This analysis also considered the use of other rods. It was found that any outer rod located on a diagonal depressed the quadrant power to such an extent that the power tilt became intolerable after a relatively short period of time. In addition, a divergent oscillation resumed following the withdrawal of these rods. Control was also attempted by inserting a rod in the quadrant where the power density was decreasing, the object being to burn out the xenon peak more rapidly. This procedure failed primarily because unacceptable power asymmetry conditions resulted when the rod was inserted.

Other procedures were investigated involving the use of rods not on the axis of symmetry, and the simultaneous use of two rods. These procedures either produced an initially unacceptable power distribution or failed to alter the divergent character of the oscillation.

3.6 Limitations in the Method of Analysis

Throughout this analysis the approach of digital simulation was consistently employed when studying xenon-induced spatial oscillations. Although digital simulations facilitate detailed descriptions of core geometries, loading patterns, and control rods, there are definite disadvantages to this method. The most important sources of error in this type of an analysis are the finite length time-step and the pointwise convergence criterion.^[4]

In most of the cases studied the stability index was deduced from a calculation which was terminated after one cycle. The index which is deduced in this way could be quite inaccurate, particularly if modes

other than the fundamental are present to any significant degree. The calculation did not cover a sufficient period of time to establish this point.

In spite of the indicated limitations to the model employed throughout this work, a good quantitative feeling for the problem of controlling xenon-induced spatial oscillations is realized. The significance of these limitations is somewhat reduced because the unstable system studied was artificially created by eliminating any moderator density effects in the calculations and the purpose of the study is to identify problems of a general nature.

SECTION 4

TASK EUXE-400

THREE-DIMENSIONAL ANALYSIS

Three-dimensional diffusion theory calculations incorporating nuclear, thermal, and hydraulic feedback effects have been performed to study xenon-induced spatial oscillations in large PWR cores.^[6] A PWR core typical of the largest core now under design, was represented and a steady-state equilibrium condition was created, simulating normal full power operation. A perturbation representing the insertion of one control rod for one hour was introduced and the subsequent behavior of the power distribution was studied. The perturbed core exhibited an oscillation which was identifiable as an X-Y oscillation which converged and an axial oscillation which diverged.

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

4.1 Core Description

The reactor system selected for this study was a large PWR core with the fuel loading pattern shown in Figure 4-1. Slight modifications from a typical checkerboard core were necessary due to restrictions imposed by the thermal-hydraulic model presently available in the three-dimensional code, and the relatively long computer running time necessary. The latter dictated a reduction in the spatial mesh intensity to a point where it was necessary to do the analysis on a homogenized core model; i.e., all non-lattice regions were homogenized in with the fuel. The geometry chosen has two mesh intervals per fuel assembly and a total of 12 equally spaced axial intervals in the active core. The overall problem size is 40 x 20 x 18 including baffle, upper, lower, and radial reflector regions; i.e., the core is described by a total of 14,000 mesh points. Details of the coordinate system are given in Appendix B. The core had burnable poison distributed uniformly throughout with the equivalent of approximately six burnable poison pins per fuel assembly. With a critical boron concentration of 1100 ppm, the resulting X-Y power distribution in a plane four feet from the bottom of the core was relatively flat, as shown in Figure 4-2, and compared favorably with that of a standard PWR design. The power density of the core was 104.5 watts/cc.

Figure 4-1. The X-Y Flow Channel Geometry and Fuel Loading Pattern

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

NOTE:

NUMBERS IN UPPER LEFT REPRESENT REGIONS.

NUMBERS IN CENTER ARE NORMALIZED POWERS OF REGION.

Figure 4-2. X-Y Power Distribution in a Plane 4 Feet from Bottom of Core

4.2 One- and Two-Dimensional Analyses

As a preliminary to the three-dimensional study, a two-dimensional analysis of a core of identical geometry was carried out. Two calculations were performed; one with moderator density feedback effects and the other without. The power density assumed in both calculations for the purposes of generating xenon and Doppler effects was 104.5 watts/cc.

The method of analysis was identical to that used previously in the study of X-Y instabilities.^[5] The results of this analysis show that the core is stable with and unstable without moderator temperature feedback, as was the core model used in the control study described in Section 3.

Figures 4-3 and 4-4 show the X-Y power peaking as a function of time following the perturbation for calculations with and without feedback, respectively. The stability indices of the two oscillations are $-.042 \text{ hours}^{-1}$ (stable) and $+0.37 \text{ hours}^{-1}$ (unstable).

A one-dimensional axial calculation was also performed using a diffusion theory code with average channel enthalpy feedback effects. In this calculation the perturbation introduced is equivalent to a one-hour insertion of a bank of control rods with a corresponding reduction in power. The control rods are withdrawn and a free running oscillation results. Reactor power remains constant at 100% and the major part of the power generation oscillates from top to bottom of the core. The oscillation is depicted in Figure 4-5 which shows the axial peaking factor as a function of time. This oscillation is divergent and corresponds to the behavior typical of this size and type of PWR core. Part-length control rods are provided to prevent such oscillations leading to unacceptable power shapes; a discussion of the use of these rods can be found in Reference 7.

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

Figure 4-3. X-Y Power Peaking versus Time After Perturbation with Moderator Temperature Feedback Effect

Figure 4-4. X-Y Power Peaking versus Time after Perturbation without Moderator Temperature Feedback Effect

Figure 4-5. Axial Peaking Factor versus Time after Perturbation

4.3 Three-Dimensional Analysis

The code used for this calculation computes the neutron flux distribution and local coolant enthalpies and densities. The nuclear model is a three-dimensional two-group diffusion theory code in which feedbacks due to coolant density and fuel pellet temperature are taken into account. The thermal-hydraulic model determines the flow and enthalpy rise in the various subchannels in the core as a function of the power distribution, and flow mixing between assemblies is allowed for. The main limitation encountered in this model is that the largest channel array that can be described at present is 9 x 9 and that does not allow at least one flow channel per fuel assembly in a 15 x 15 assembly core. Consequently, it is necessary to combine more than one (and as many as four) fuel assemblies in each channel, and it becomes impossible to reproduce the identical checkerboard loading typical of large PWR's. Figure 4-1 shows the X-Y channel array selected.

A three-dimensional problem was set up with the core described in Section 4.1. An axial poisoned region was introduced in a central section of the core to represent the presence of part-length rods and burnup in an operating core. The resulting equilibrium xenon axial power shape is shown in Figure 4-6. A two-dimensional contour plot of the flux distribution for the $y=0$ plane is shown in Figure 4-7.

A local poison equivalent to a full-length control rod was inserted into the core on the y -axis in region 3 of Figure 4-2. The poison remained in the core for one hour and was then withdrawn. The perturbed core exhibited an oscillation which was identifiable as an X-Y oscillation which converged and axial oscillation which diverged. The resulting oscillation is described in Figures 4-8 through 4-10.

The axial oscillation can be represented by plotting the power at two points in the core, one above and one below the mid-plane, as shown in Figure 4-8. In practice, part-length rod movement would occur to control the axial oscillation.

Figure 4-6. Axial Power Shape (Equilibrium Xenon)

NOTE: CONTOUR VALUES ARE RELATIVE TO PEAK FLUX.

Figure 4-7. Contour Plot of Flux Distribution for $Y = 0$ Plane.
Equilibrium Condition

Figure 4-8. Normalized Power Density at Two Points in a Channel versus Time after Perturbation

Figure 4-9. Normalized Power Density at Two Points in a Plane 3 Feet From Bottom of Core versus Time after Perturbation

Figure 4-10. Axially Integrated Power in Hot Channels versus Time After Perturbation

The local power density at two points in a selected plane are shown in Figure 4-9 for a plane three feet from the bottom of the core. This figure illustrates the superposition of the axial oscillations, indicated by the general level of the curves and the X-Y oscillation, indicated by the crossing and recrossing of the curves.

Figure 4-10 shows the time-dependent variation of axially integrated power (normalized $F_{\Delta H}$) in two symmetrically opposite channels, which are the hottest channels when the oscillation is at a peak. The period of the X-Y oscillation is 31.8 hours, and as an indication of the degree of convergence of the oscillation an exponential decay was assumed from which the stability index was calculated to be -0.016 hr^{-1} . Since the axially integrated power represents closely the condition that one tries to predict with two-dimensional, average-core calculations, results so obtained can be considered equivalent to and can be compared against earlier two-dimensional stability calculations of the same core. Such a comparison shows that the two-dimensional average-core calculation was consistent with but converged somewhat more rapidly than, the three dimensional calculation. This small difference in results is probably due to such dissimilarities between the two-dimensional and the three-dimensional codes as slight differences in numerical techniques and the possible interaction in the 3-D model of the divergent axial oscillation on the observed X-Y behavior.

The behavior of the power density at a single point as calculated in three dimensions can be compared with a combination of the one-dimensional and two-dimensional calculations. This is shown in Figure 4-11 for a point which is close to the peak power in the unperturbed core. The index in an exponential envelope to these curves is $+0.015 \text{ hr}^{-1}$ for the three-dimensional case and is $+0.027 \text{ hr}^{-1}$ for the combined one- and two-dimensional calculations.

4.4 Conclusions

The three-dimensional results indicate that a perturbation introduced in one side of the core can excite an X-Y oscillation and an axial oscillation. The predictions of less-costly one- and two-dimensional calculations are generally consistent with the results of the three-dimensional analysis.

Figure 4-11. Comparison of Power Density at a Point Obtained from Three-Dimensional and Combined One and Two-Dimensional Calculations

SECTION 5

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The following is a listing of all the published technical progress reports on the US-Euratom program titled "Control of Xenon Instabilities in Large PWR's":

EURAECE-1721 WCAP-3680-1	"Control of Xenon Instabilities in Large PWR's, Technical Progress Report for the Period Ending September 30, 1966"
EURAECE-1781 WCAP-3680-2	"Control of Xenon Instabilities in Large PWR's, Quarterly Progress Report for the Period Ending December 31, 1966"
EURAECE-1830 WCAP-3680-3	"Control of Xenon Instabilities in Large PWR's, Quarterly Progress Report for the Period Ending March 31, 1967"
EURAECE-1880 WCAP-3680-4	"Control of Xenon Instabilities in Large PWR's, Quarterly Progress Report for the Period Ending June 30, 1967"

REFERENCES (Continued)

EURAEC-1925 WCAP-3680-5	"Control of Xenon Instabilities in Large PWR's, Quarterly Progress Report for the Period Ending September 30, 1967"
EURAEC-2008 WCAP-3680-6	"Control of Xenon Instabilities in Large PWR's, Semi-Annual Progress Report for the Period Ending March 31, 1968"
EURAEC-2045 WCAP-3680-7	"Control of Xenon Instabilities in Large PWR's, Quarterly Progress Report for the Period Ending June 30, 1968"
EURAEC-2067 WCAP-3680-8	"Control of Xenon Instabilities in Large PWR's, Quarterly Progress Report for the Period Ending September 30, 1968"
EURAEC-2080 WCAP-3680-9	"Control of Xenon Instabilities in Large PWR's, Quarterly Progress Report for the Period Ending December 31, 1968"
EURAEC-2098 WCAP-3680-10	"Control of Xenon Instabilities in Large PWR's, Quarterly Progress Report for the Period Ending March 31, 1969"

APPENDIX A

DEFINITION OF STABILITY INDEX

With the assumption that the oscillation can be approximated by one mode, the flux or power perturbation $\delta\phi$ can be written as a function of time t as,

$$\delta\phi = Ae^{bt} \sin \frac{2\pi t}{\tau}$$

where A is a constant and τ is the period of the oscillation, and b is called the stability index. Therefore:

$$b = \frac{1}{t_2 - t_1} \ln \frac{\delta\phi_2}{\delta\phi_1}^*$$

where $t_2 - t_1$ is the time differential between successive flux peaks, and $\delta\phi_1$ and $\delta\phi_2$ are consecutive maxima in the perturbed flux at times t_1 and t_2 . Properly used, this relationship should be applied to consecutive peaks in the same region of the core. Although this definition of stability index was applied in the analysis performed under Task EUXE-200, it was not feasible to use this definition in the detailed two- and three-dimensional analyses performed under Tasks EUXE-300 and EUXE-400 for cost reasons. Therefore, instead of using consecutive maxima, the work performed under Task EUXE-300 and Task EUXE-400 defined $\delta\phi_1$ as:

$$\delta\phi_1 = \frac{\phi_{\max} - \phi_{\min}}{0.5(\phi_{\max} + \phi_{\min})},$$

where $\phi_{\max}$ and $\phi_{\min}$ are the maximum and the minimum values of the flux at time t_1 at symmetrically opposed points on the axis of perturbation. $\delta\phi_2$ is similarly defined at time t_2 , which is one-half cycle later. This definition reduces the calculation required by one-half cycle, although the result could be quite inaccurate in the presence of higher modes.

* A stable core would have a negative stability index while an unstable core would have a positive stability index.

Note that the definition of the stability index given in WCAP-3680-20 (Reference 4, Appendix B), had $\delta\phi_1$ and $\delta\phi_2$ inadvertently inverted.

APPENDIX B
DESCRIPTION OF COORDINATES

X-Y Coordinates

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

Axial (Z) Coordinates

The axial mesh is shown in Figure B-2.

X-AXIS

Figure B-1. X-Y Coordinates

Figure B-2. Axial Coordinates