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CONTROL OF XENON INSTABILITIES IN LARGE PWR'S

QUARTERLY PROGRESS REPORT

FOR THE PERIOD ENDING

DECEMBER 31, 1966

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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 December 31, 1966:

An evaluation of the sensitivity of space-time flux response to mesh spacing in the x-y plane has demonstrated that the presently employed mesh spacing of about 10 cm is adequate for instability studies in large cores.

Stability characteristics in the x-y plane were evaluated for different size cores with equivalent (flat) power distributions. The 8.8 ft diameter Zircaloy-clad core was just on the threshold of instability with temperature feedbacks neglected. In the larger cores, where the magnitude of the oscillations is greater for the same perturbing influence, non-linear effects were quite pronounced.

The effect of the unperturbed steady-state power distribution on core stability was also investigated. Results indicate the spatial stability characteristics of the core are very sensitive to the initial, unperturbed power distribution.

Initial studies were completed on the effect of perturbation location on the behavior of xenon-induced power oscillations. These studies suggest that the magnitude of the oscillations is dependent on perturbation location whereas the spatial characteristics are not, as long as the perturbing influence is withdrawn from the core shortly after causing the perturbation.

DETAILED PROGRESS REPORTS

PROGRAM MANAGEMENT

M. J. O'Boyle, Project Engineer

Development Projects
PWR Plant Division

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

EURAEC-1721 WCAP-3680-1	"Control of Xenon Instabilities in Large PWR's", Technical Progress Report for the Period Ending September 30, 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.

EUXE-200

EFFECT OF CORE PARAMETERS ON SPATIAL OSCILLATIONS

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G. H. Minton, Manager — Reactor Physics and Mathematics Section

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A. M Christie

A. Summary

1. The evaluation of the two-dimensional x-y diffusion-depletion computer program TURBO*, initiated in the last period[1], was completed with an evaluation of the sensitivity of results to the spatial mesh description. It was concluded that a relatively coarse mesh of 10 cm is satisfactory to analyze the spatial oscillations associated with xenon distribution in large PWR cores.

2. Stability characteristics in the x-y plane were evaluated for different size cores. Calculations were performed for cores ranging from 8.8 ft to 15 ft in diameter. All cores had an approximately flat power distribution and the same average enrichment. Temperature feedback effects were not accounted for in these calculations. The 8.8 ft (Zircaloy clad) core was approximately on the threshold for xenon-induced azimuthal oscillations. The large cores underwent very large oscillations and exhibited strong non-linear effects.

---

[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).

3. The effect of the steady-state (unperturbed) power distribution on core stability was studied for a large, 11 ft core. Initial core loading patterns were varied to give rise to widely different power distributions in the x-y plane. The stability characteristics of the core were found to be very sensitive to the unperturbed power distribution.

4. Calculations were performed for a large, 11 ft core, with the perturbation located at different positions along a diameter. It appears that for this particular core, with a perturbation inserted for only a short time, xenon-induced azimuthal oscillations can be described in terms of essentially the same spatial mode, independent of the location of the perturbation, with only the magnitude of the oscillations a function of the perturbation location.

B. Effect of Spatial Mesh Size in Diffusion-Depletion Calculations of Spatial Oscillations

Diffusion-depletion calculations of spatial oscillations have the one advantage that realistic core configurations and perturbations can be analyzed, providing space-time flux responses that can be used directly in developing control procedures. Multi-dimensional calculations are, however, costly, since a relatively large number of time steps are required for each calculation. In two-dimensional, x-y geometry, half-core or full-core calculations are required to adequately treat azimuthal oscillations.

To maintain computing time within reasonable limits, it is necessary to use a coarse spatial mesh description of the core. Initial calculations of azimuthal xenon oscillations used a spatial mesh width of 10.8 cm for an 11 ft diameter core, for a total of 648 mesh points in half-core gemoetry[1]. A calculation was performed with a spatial mesh width of 5.4 cm, for a total of 2592 mesh points, to evaluate the sensitivity of results to the mesh size.

Figure 200.1 compares the ratio of assembly average power to core average power following the introduction of a perturbation, for the 10.8 cm and 5.4 cm meshes. The figure shows this ratio for two assemblies symmetrically located along a diameter (0° and 180°). The core selected for comparison has an initial power distribution which is dished toward the center of the core, with an average enrichment of 2.5%, resulting in relatively large oscillations. The use of the relatively coarser mesh tends to overestimate the power peak by a few per cent, with a negligible effect on the period of oscillation. The errors introduced by the use of this relatively coarse mesh (10.8 cm) are of the same order of magnitude as those introduced by the use of a finite time step length[2] (four hours in these calculations).

---

[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] L. E. Strawbridge, E. C. Allard, and C. P Bhalla, "Xenon-Induced Core Instabilities", WCAP-3209-48 (1965).

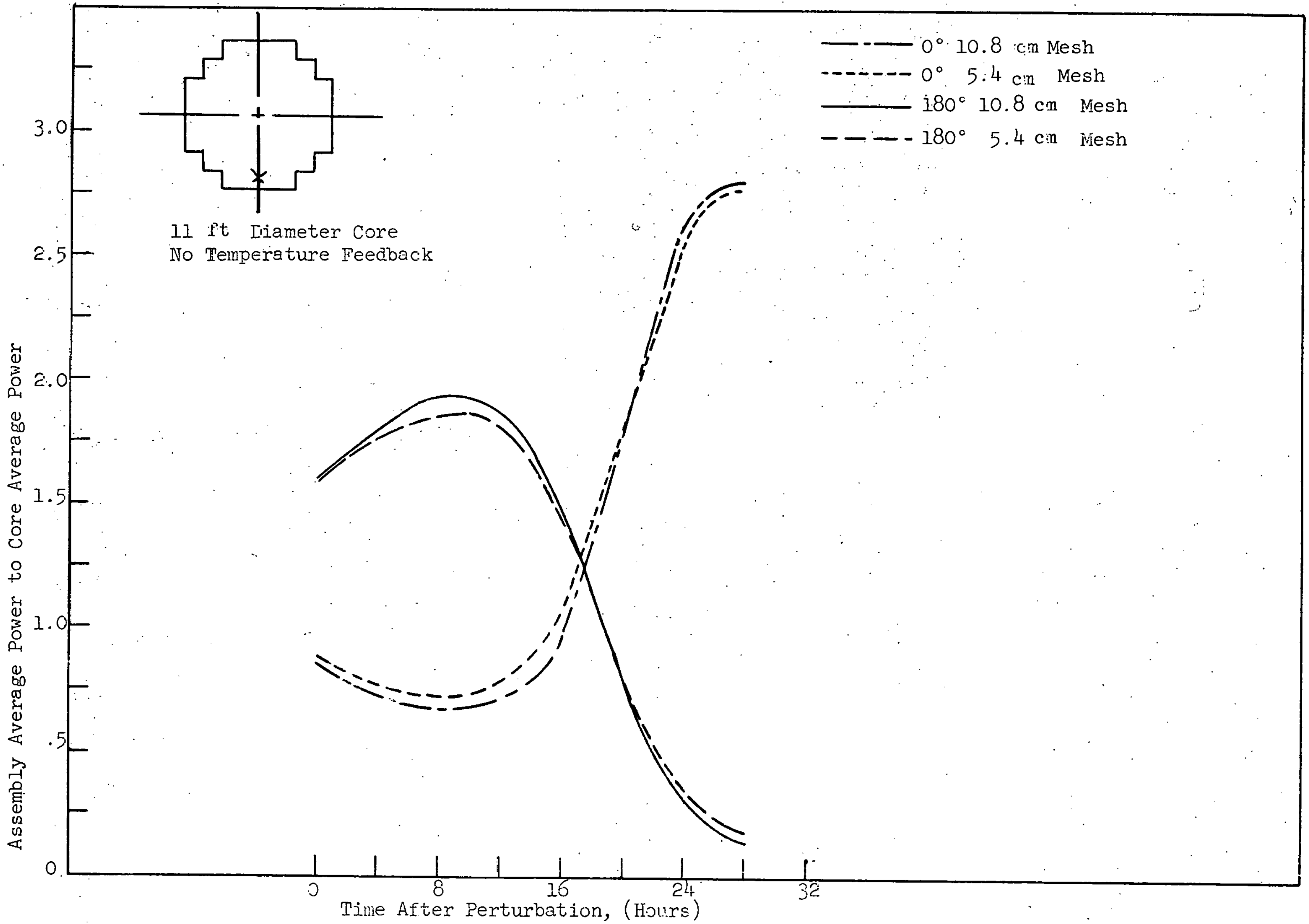

Figure 200.1 Effect of Spatial Mesh Size on Xenon-Induced Oscillation.

Figure 200.2 shows the steady-state power distributions, and the power distributions eight hours following the perturbation, taken along the axis 0° - 180°. The calculations using both spatial mesh widths predict similar oscillation characteristics, with the relatively coarser mesh tending to overestimate slightly the peak in one side of the core, and to underestimate the depression in the other side of the core.

The calculations with the finer mesh (5.4 cm) required more than three times as much computation time than the calculations with the coarser mesh (10.8 cm). Because of the relatively small errors introduced by the use of the coarser mesh, this mesh specification has been selected for subsequent x-y geometry calculations.

C. Effect of Core Size on Core Stability - Xenon-Induced Azimuthal Oscillations

As the linear dimensions of a nuclear system increase, leakage from the core decreases, and coupling between the regions of the core is decreased. The efficiency of neutron leakage to counteract a local change in multiplication due to a local perturbation decreases as core size increases, and the inherent instability to spatial xenon oscillations is enhanced. Linearized perturbation analyses lead to threshold criteria when the oscillations are small./1,2,3 Quantitative data, however, can only be

---

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

[2] A. S. Lellouche, "Space-Dependent Xenon Oscillations", Nuclear Science and Engineering, 12, 482-489 (1962).

[3] A. S. Lellouche, "Reactor Size Sufficient for Stability Against Spatial Xenon Oscillations", Nucl. Sci. and Eng., 13, 60-62 (1962).

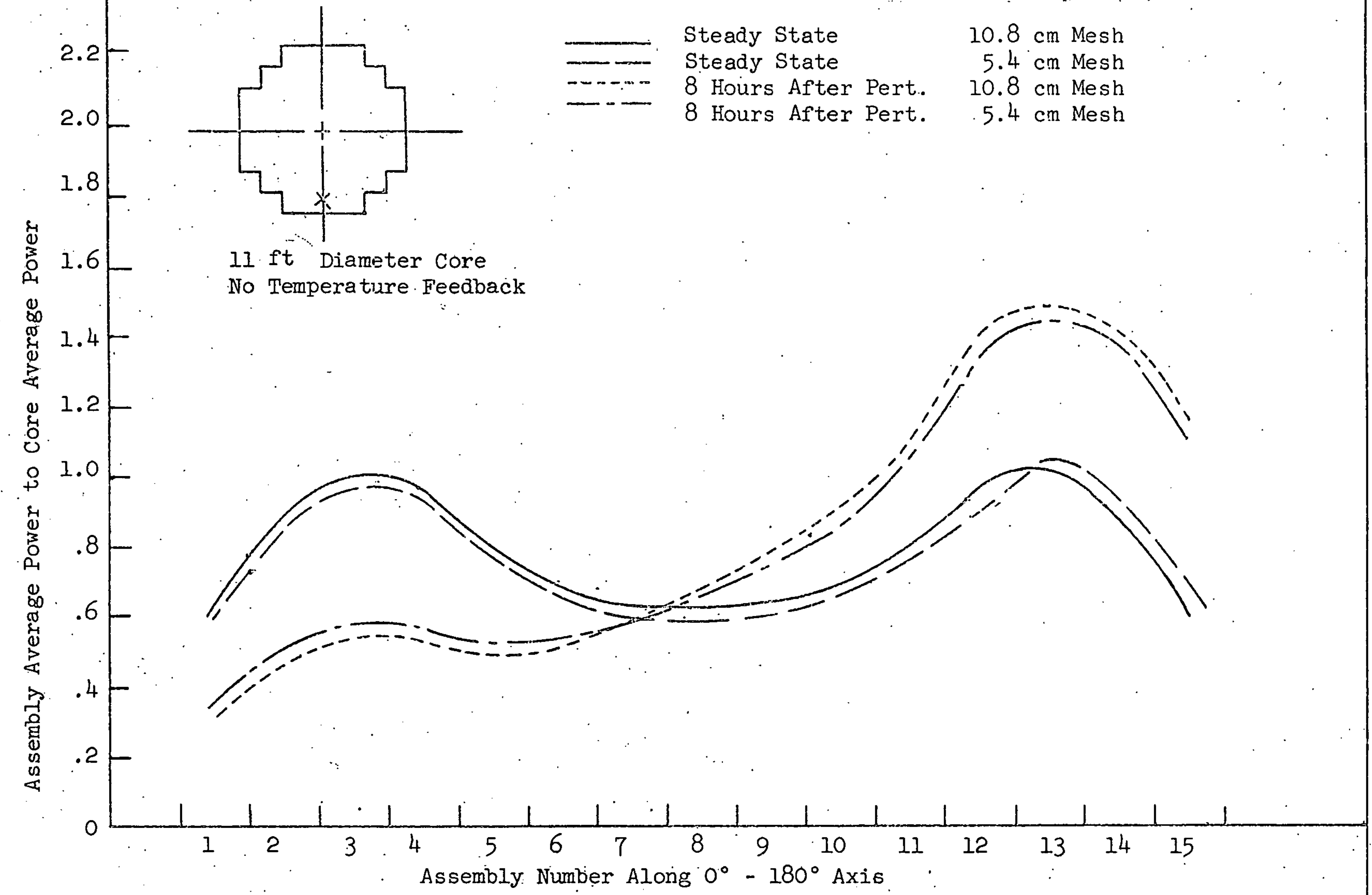

Figure 200.2 Effect of Spatial Mesh Size on Power Distribution

obtained for idealized geometries and fuel loadings. PWR cores, although they approximate a right circular cylinder, exhibit a non-circular, staggered boundary in the x-y plane, with non-uniform zoning inside the boundary. The stability characteristics and the nature of spatial oscillations in such a system are best studied through actual simulation using multidimensional diffusion codes.

Calculations were performed with the diffusion-depletion code TURBO*[1,2] in x-y geometry for a number of core sizes varying from approximately 8 to 15 feet in equivalent diameter. Core configurations were selected to correspond to actual PWR designs and, in the case of the very large cores, to anticipated designs[3]. Since the spatial stability characteristics of a core are sensitive to the steady-state, unperturbed flux distribution (see section D), three-zone enrichments were selected to yield an approximately flat distribution in all cores, such that the effect of size only on xenon-induced azimuthal oscillations could be studied. The average enrichment for all cores was approximately 2.6%, and the same power density was used (85 w/cc) in all cases, thus resulting in approximately the same flux level for all sizes.

---

[1] S. M. Hendley and R. A. Mangan, "TURBO* - A Two-Dimensional Few-Group Depletion Code for the IBM-7090", WCAP-6059 (1964).

[2] 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).

[3] D. L. Miller. Personal Communications. Westinghouse Atomic Power Divisions, PWR Division, Nuclear Core Design.

Table 200.1 lists the various core sizes used in the analysis. All cores had the same size of assembly (8.5 in x 8.5 in). The last column in the table lists the maximum ratio of assembly-average-power to core-average-power for the steady-state, unperturbed distribution.

All cores were perturbed in a similar fashion. Each core was burned for 100 hours to build equilibrium xenon. A single control rod was introduced along an axis of the core (0^{o} - 180^{o}), at a distance of approximately 2/3 from the core center. The core was depleted for an additional hour, and the control rod was removed. Time steps of four hours each were used to analyze the ensuing oscillation/1.

Figures 200.3 through 200.7 show the resulting oscillations as assembly-average-power to core-average-power for three core locations (0, 90, and 180 degrees), for the five cores described in Table 200.1. It is to be stressed that the effects of temperature feedback were not included in these calculations, such that the spatial oscillations which were observed do not correspond to actual core operation. However, these calculations exhibit clearly the effect of core size on xenon-induced azimuthal instabilities.

---

[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).

Table 200.1

Core Configurations Used in the Evaluation of the Effect of Core Size on Xenon-Induced Azimuthal Oscillations

Case	Number of Assemblies	Equivalent Core Diameter (ft)	Equivalent Core Diameter (m)	Three Zone Enrichments	$\left(\frac{\overline{P}_{assy}}{\overline{P}_{core}}\right)$ Max.
1	121	8.8	2.67	2.3/2.6/3.0	1.30
2	157	10.0	3.04	2.4/2.6/2.9	1.32
3	193	11.0	3.37	2.4/2.5/3.0	1.22
4	269	13.1	3.98	2.5/2.6/2.9	1.30
5	349	14.9	4.53	2.5/2.6/2.7	1.39

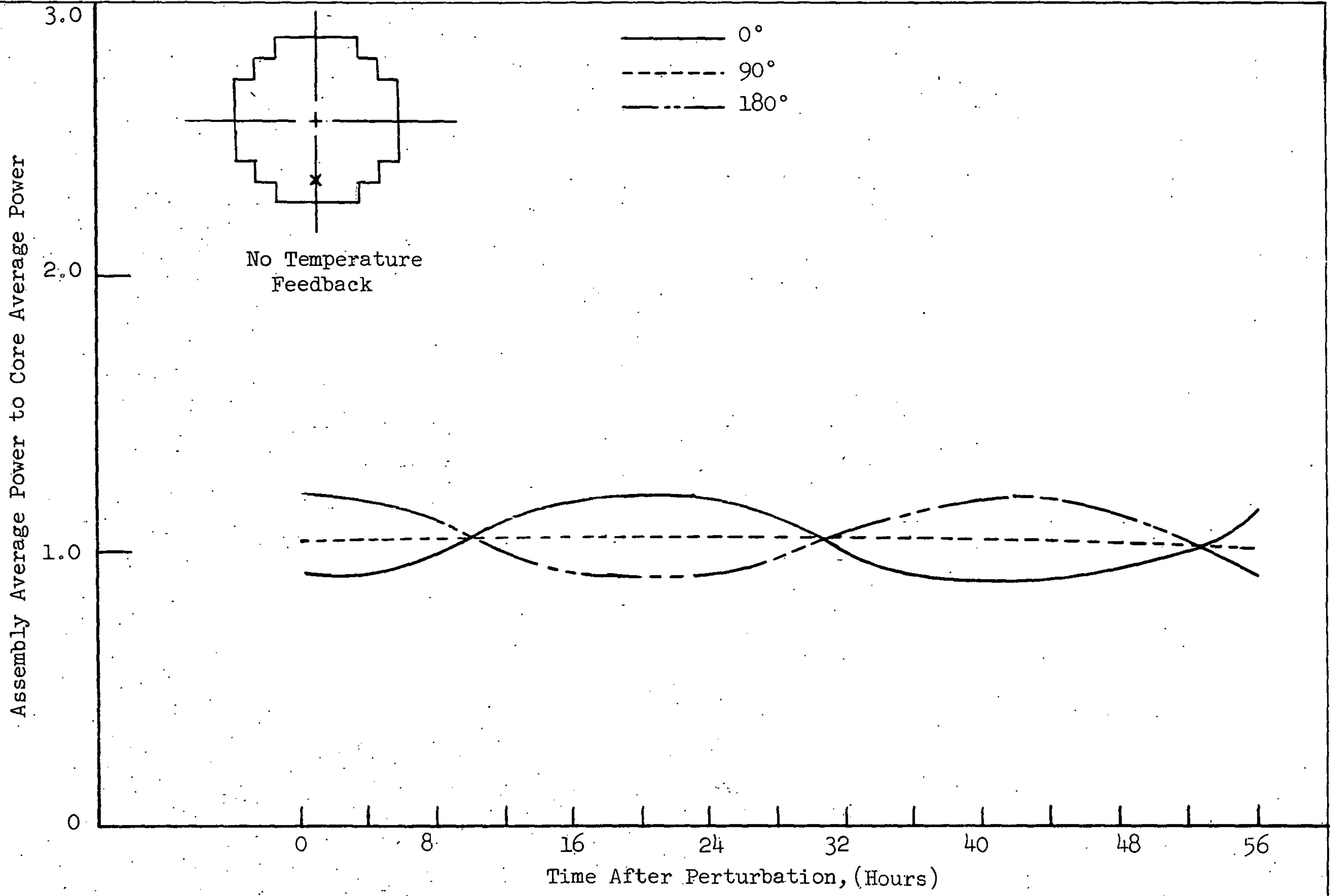

Figure 200.3 Xencn-Induced Oscillations in 8.8 ft Diameter Core

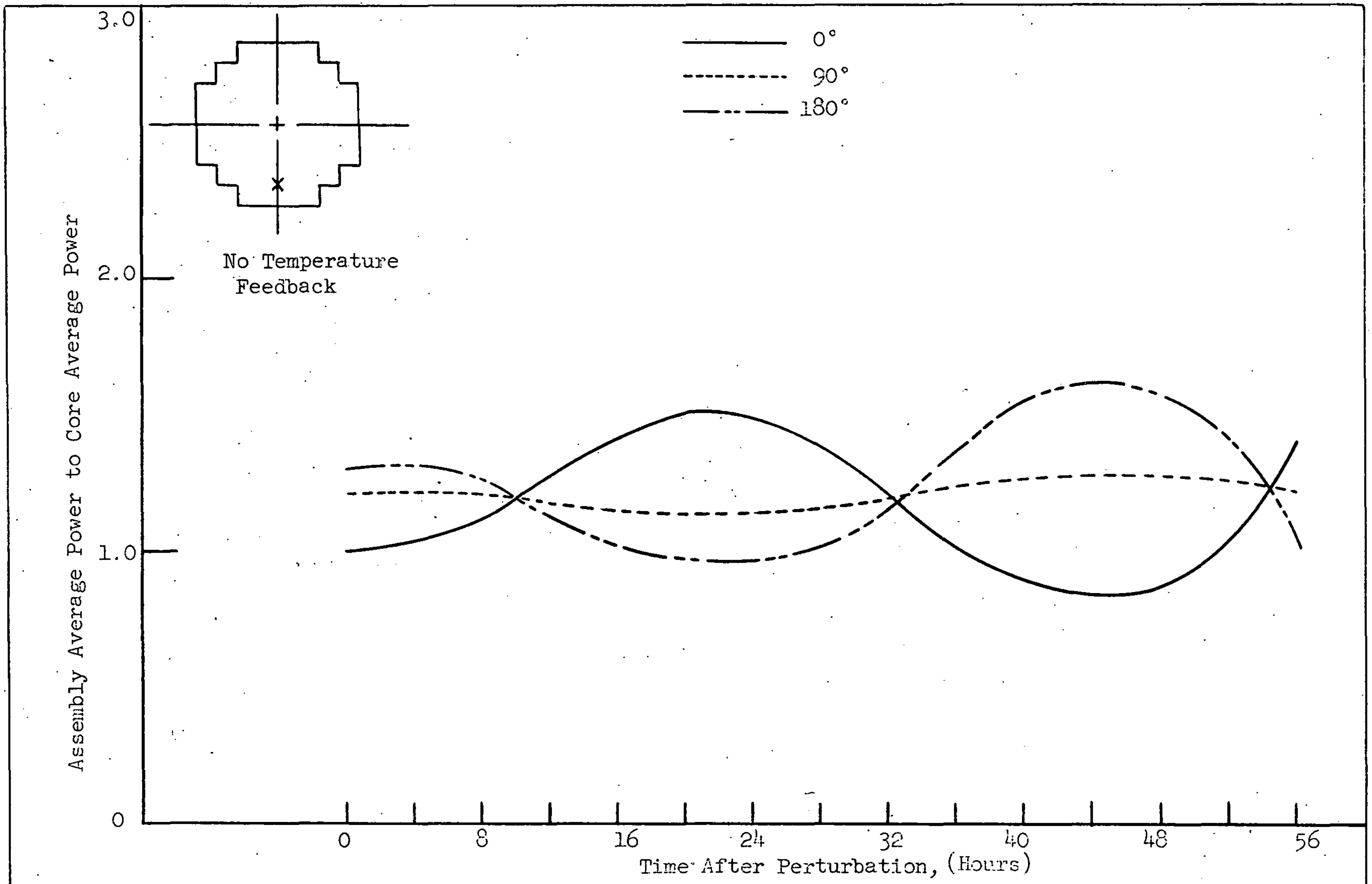

Figure 200.4 Xenon-Induced Oscillations in 10 ft Diameter Core

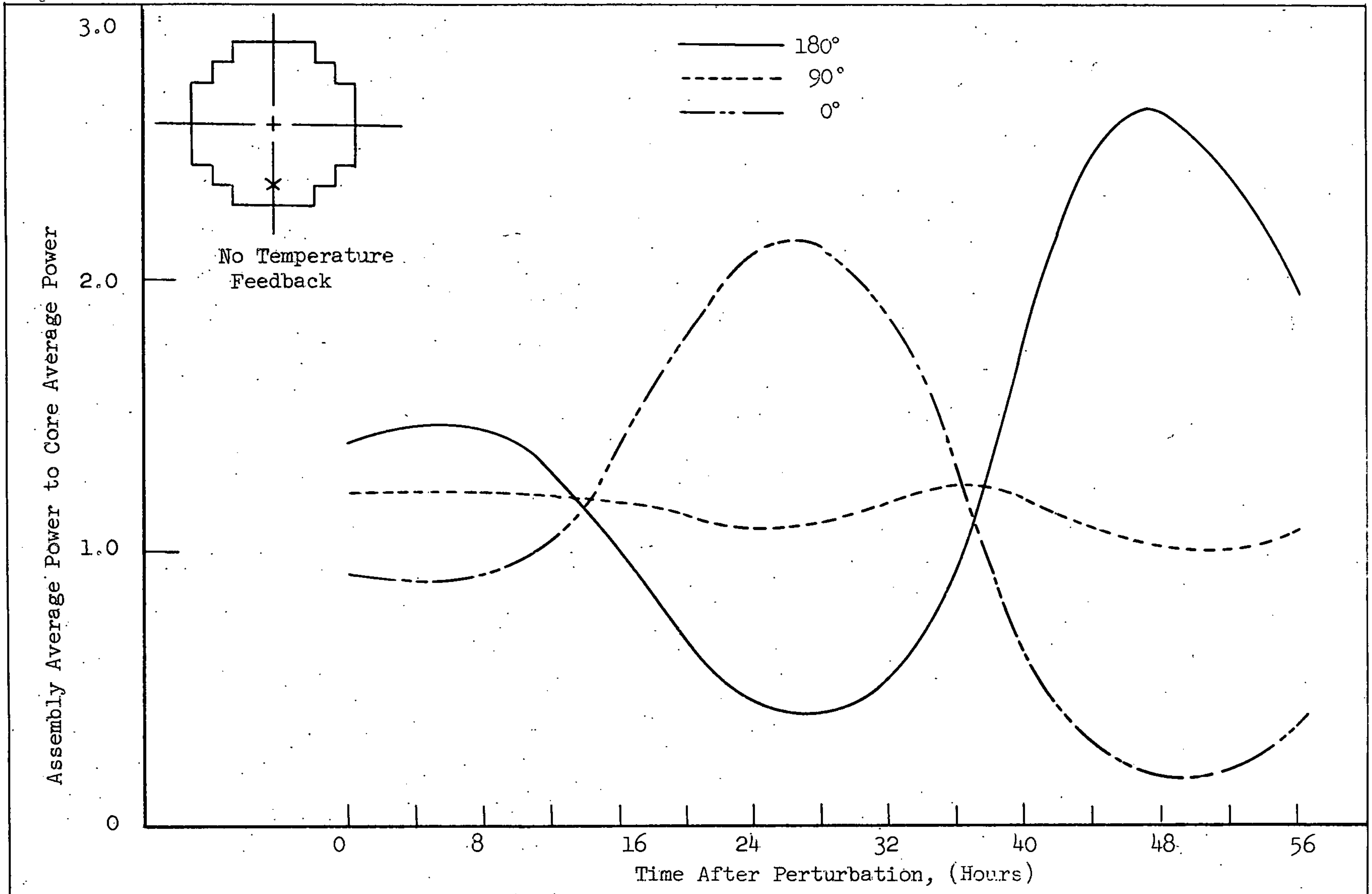

Figure 200.5 Xenon-Induced Oscillations in 11 ft Diameter Core

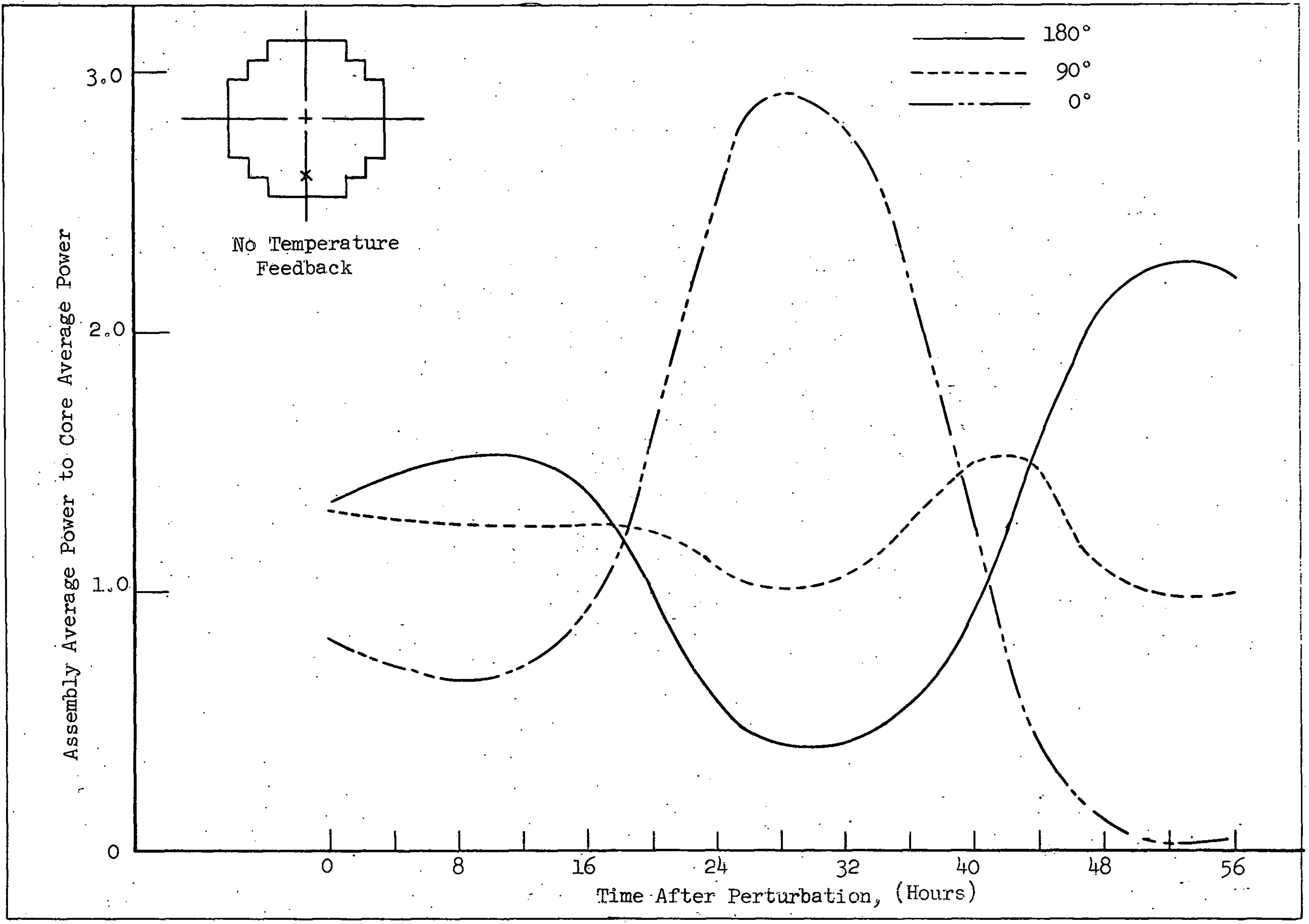

Figure 200.6 Xenon-Induced Oscillations in 13 ft Diameter Core

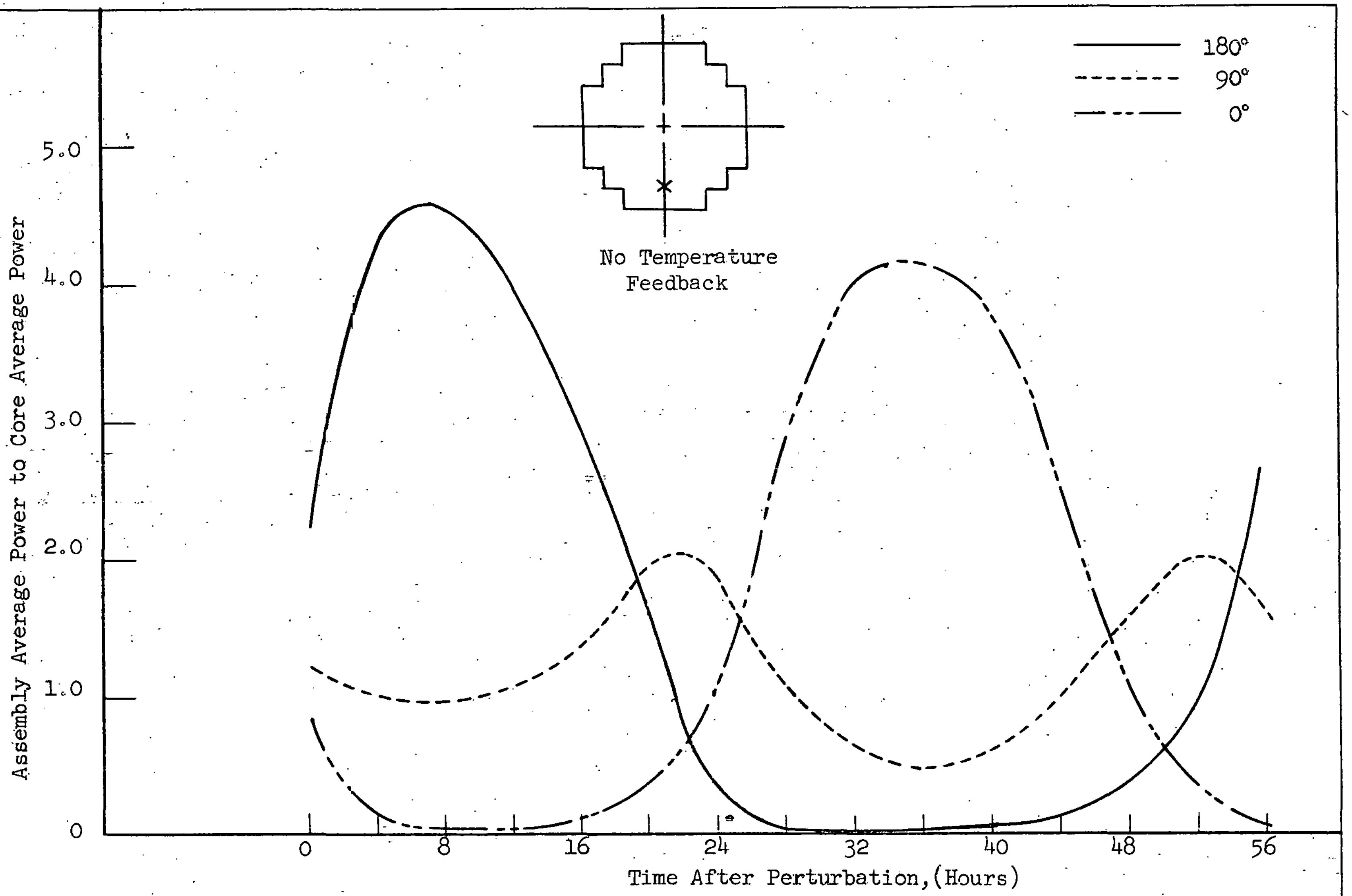

Figure 200.7 Xenon-Induced Oscillations in 15 ft Diameter Core

Figure 200.3 shows that the 8.8-ft diameter core (Zircaloy clad), with a flat power distribution, is close to the threshold of instability to azimuthal oscillations. The average thermal flux in the calculations is of the order of 4.5 x 10^{13}. Stability threshold calculations based on the Randall and St. John perturbation modal analysis[1], predicts that a 10-ft core would be on threshold for azimuthal oscillations in the first harmonic. This number was obtained by associating a factor (1/1.5) with the difference in eigenvalue between the first and the fundamental mode, to account for flux flattening. There is a large uncertainty in this number, such that the threshold prediction bears a large uncertainty. Note that Figure 200.4 shows a small divergent behavior for the 10-ft core.

Table 200.2 lists the periods and damping factors for the 8.8, 10, and 11-ft cores. The slight increase in oscillation period with core size agrees qualitatively with simple modal analyses[1]. For the 11-ft core, the oscillations are large, and non-linear effects become important. There is a tendency for the flux oscillations to saturate. The damping factor in Table 200.2 was calculated as the ratio of the first two peaks.

---

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

Table 200.2

Effect of Core Size on Oscillation Characteristics - Xenon-Induced Azimuthal Oscillations

Case	Equivalent Core Diameter (ft)	Oscillation Period (hours)	Damping Factor[a]
1	8.8	41	~ 1
2	10.0	43	1.12
3	11.0	46	1.45

---

[a] Defined here as the ratio of the second-to-the-first peak.

For the 13-ft and 15-ft cores, oscillations are very large and non-linear effects are dominant. Note the strong saturation effects. For cores of this dimension, it is apparent that higher modes are excited. Moreover, there appears to be a strong coupling between modes. Note that in the 15-ft core, for a period of approximately 15-20 hours, half of the core produces almost no power, while the other half carries the entire load.

Such oscillations are not realistic since feedback and control effects are neglected. However, they are characteristic of xenon-induced spatial power oscillations in the limit of very large cores with very large perturbations.

Figures 200.8 through 200.10 show the x-y power distribution (contour maps) for the 11-ft core, 24 hours, 36 hours, and 48 hours, respectively, after the perturbation. These plots are very useful in determining the spatial characteristics of the oscillations in time in the two-dimensional plane. As such, they are ultimately useful in specifying the spatial control requirements of the core.

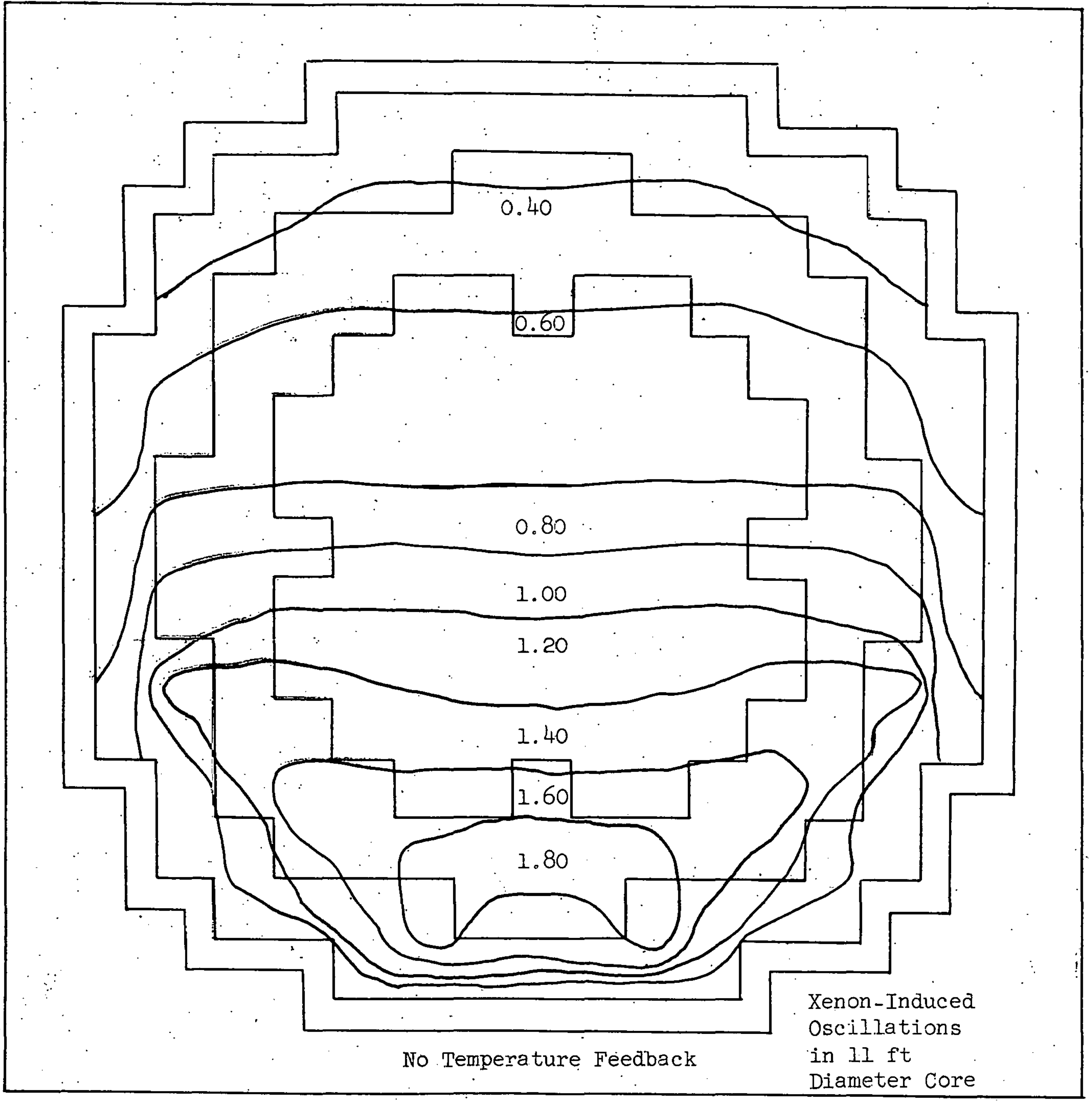

Figure 200.8 XY Power Distribution 24 Hours After Perturbation

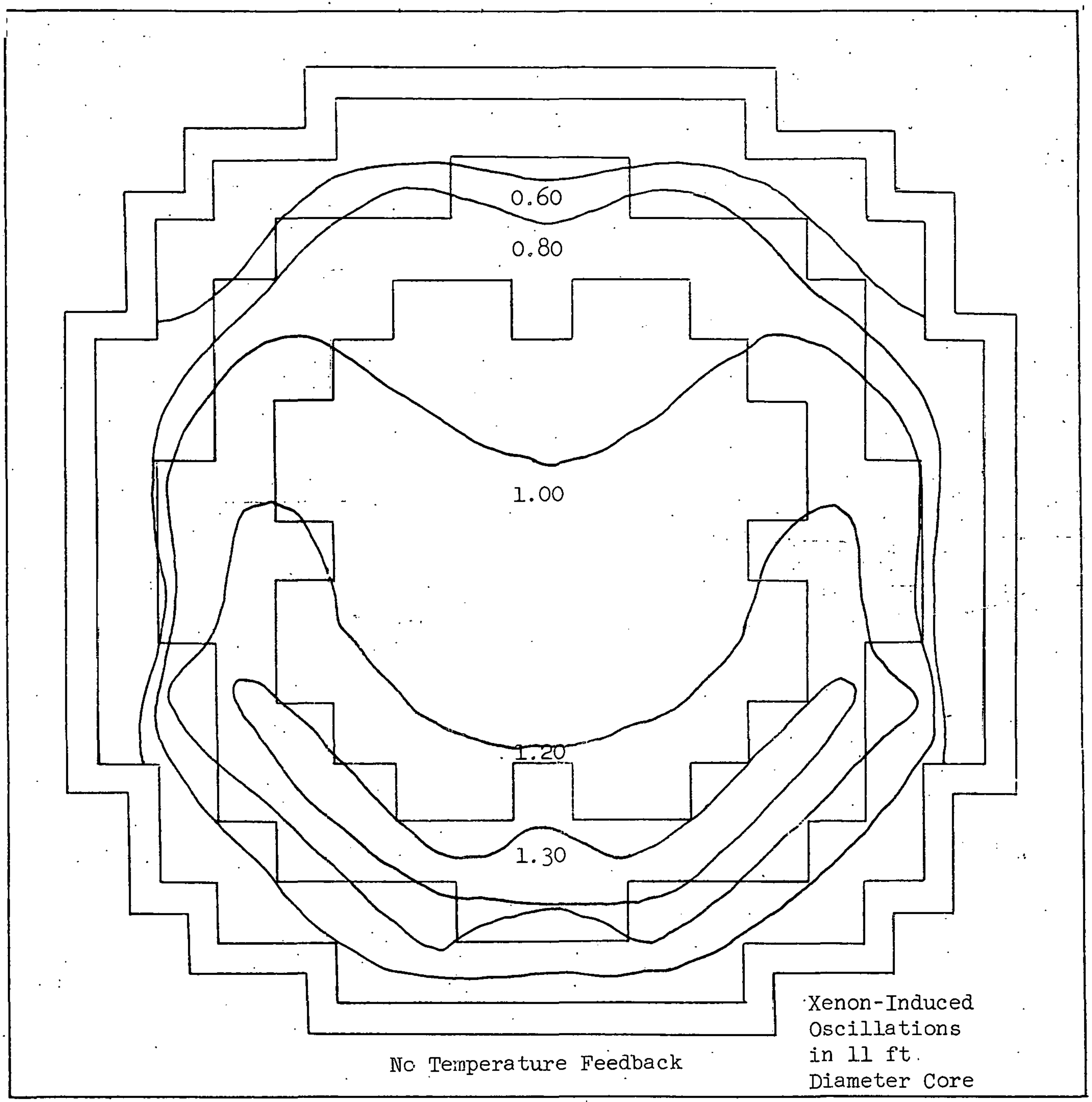

Figure 200.9 XY Power Distribution 36 Hours After Perturbation

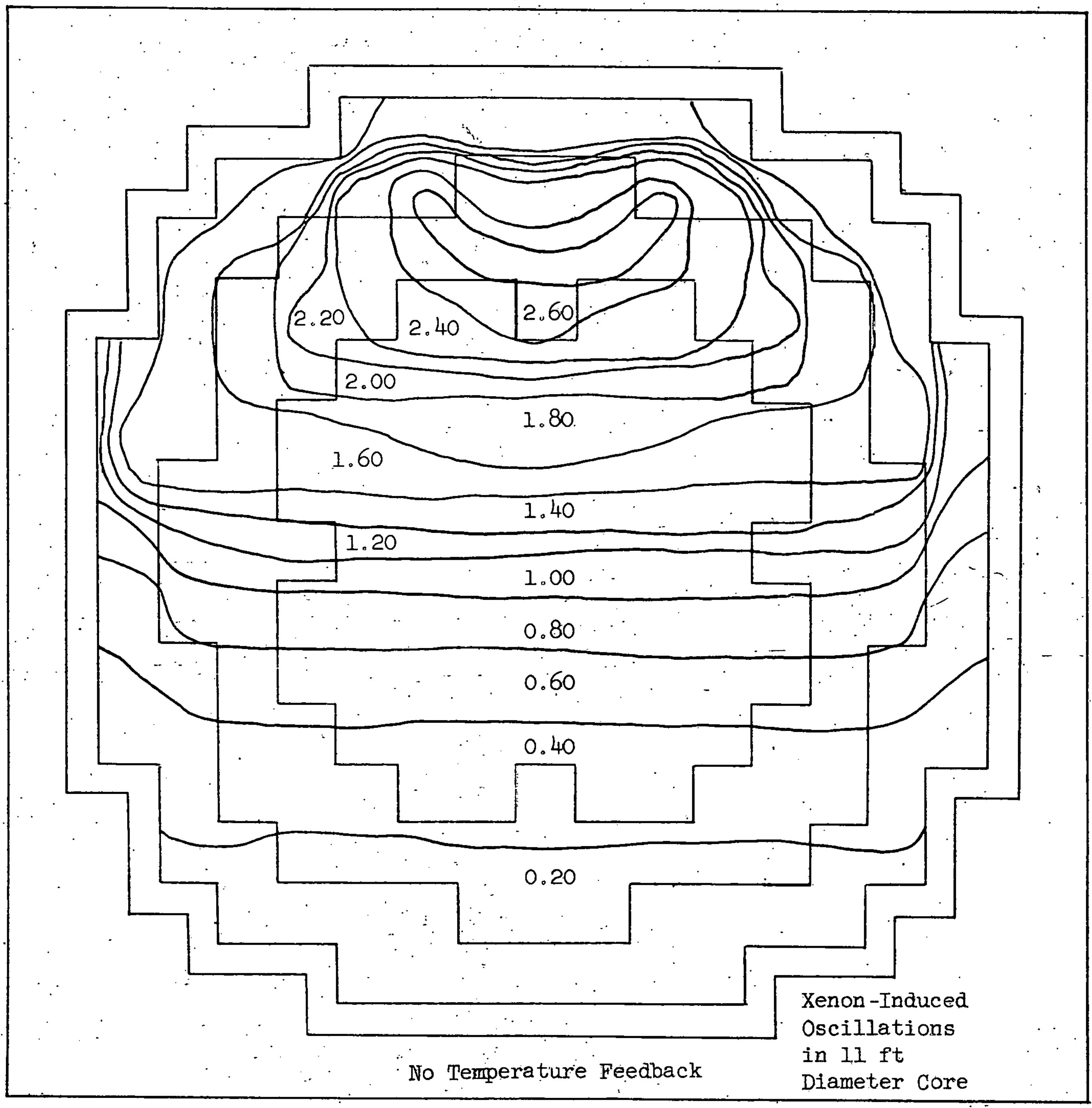

Figure 200.10 XY Power Distribution 48 Hours After Perturbation

D. Effect of Steady-State (Unperturbed) Power Distribution on Core Stability - Xenon-Induced Azimuthal Oscillations

The spatial stability characteristics of the core are very sensitive to the initial, unperturbed power distribution, since leakage and the coupling between core regions are very sensitive to the spatial flux distribution. In a given size core, fuel management requirements lead to varying power distributions from the initial core loading to achievement of the equilibrium cycle. Moreover, design optimizations naturally require flattened power distributions, which tend to decrease the stability characteristics of a core. It is important to evaluate the sensitivity of xenon-induced azimuthal oscillations to power distributions in the x-y plane.

An 11-ft core was selected for analysis. Three-zone enrichments were selected to yield x-y power distributions ranging from a distribution peaked at the center (batch loading) to a power distribution dished in the center of the core. Table 200.3 lists the four cases chosen for analysis. Approximately the same average enrichment ($\sim$2.6%) was maintained in all cases and the cores were operated at the same power density (85 w/cc). Figure 200.11 shows the steady-state power distributions taken along the axis 0° - 180°. Case C is identical to core 3 analyzed in section C.

All cores were perturbed in the same fashion as described in section C. Figures 200.12 through 200.14 show the resulting power oscillations for case A, B, and D, respectively. The figures show the power oscillations at the location of the perturbation and at the point symmetrically opposite along the 0° - 180° axis. The oscillations in case C are shown in

Table 200.3

Cases Selected for the Evaluation of the Effect of Steady-State Power Distribution on Xenon-Induced Azimuthal Oscillations

Case	Equivalent Core Diameter (ft)	Three Zone Enrichments	$\left(\frac{\overline{P}_{assy}}{\overline{P}_{core}}\right)$ Max.
A	11.0	2.6/2.6/2.6	2.16
B	11.0	2.5/2.5/2.9	1.75
C	11.0	2.4/2.5/3.0	1.22
D	11.0	2.3/2.6/2.9	1.33

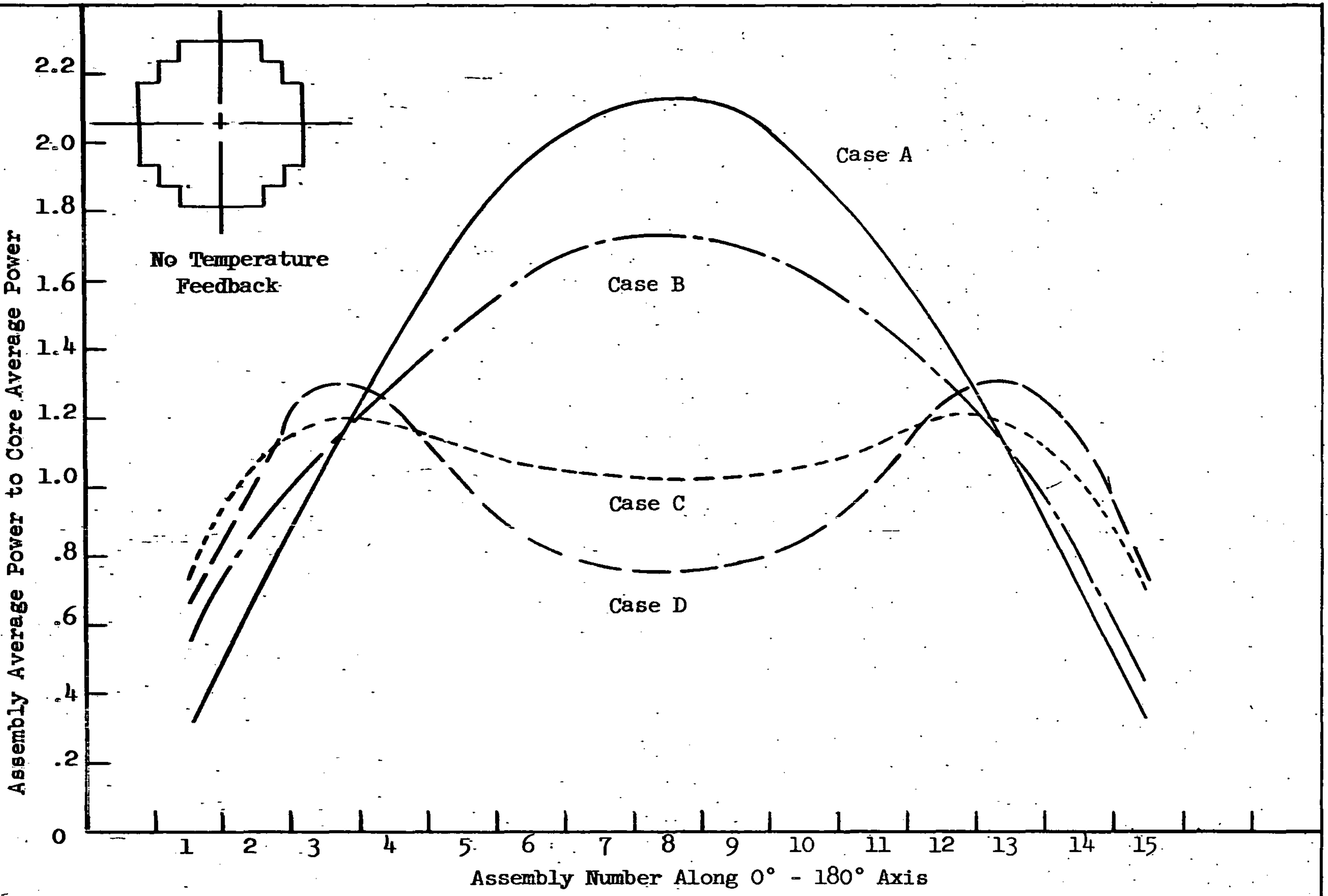

Figure 200.11 Steady State Power Distributions in 11 ft Diameter Core

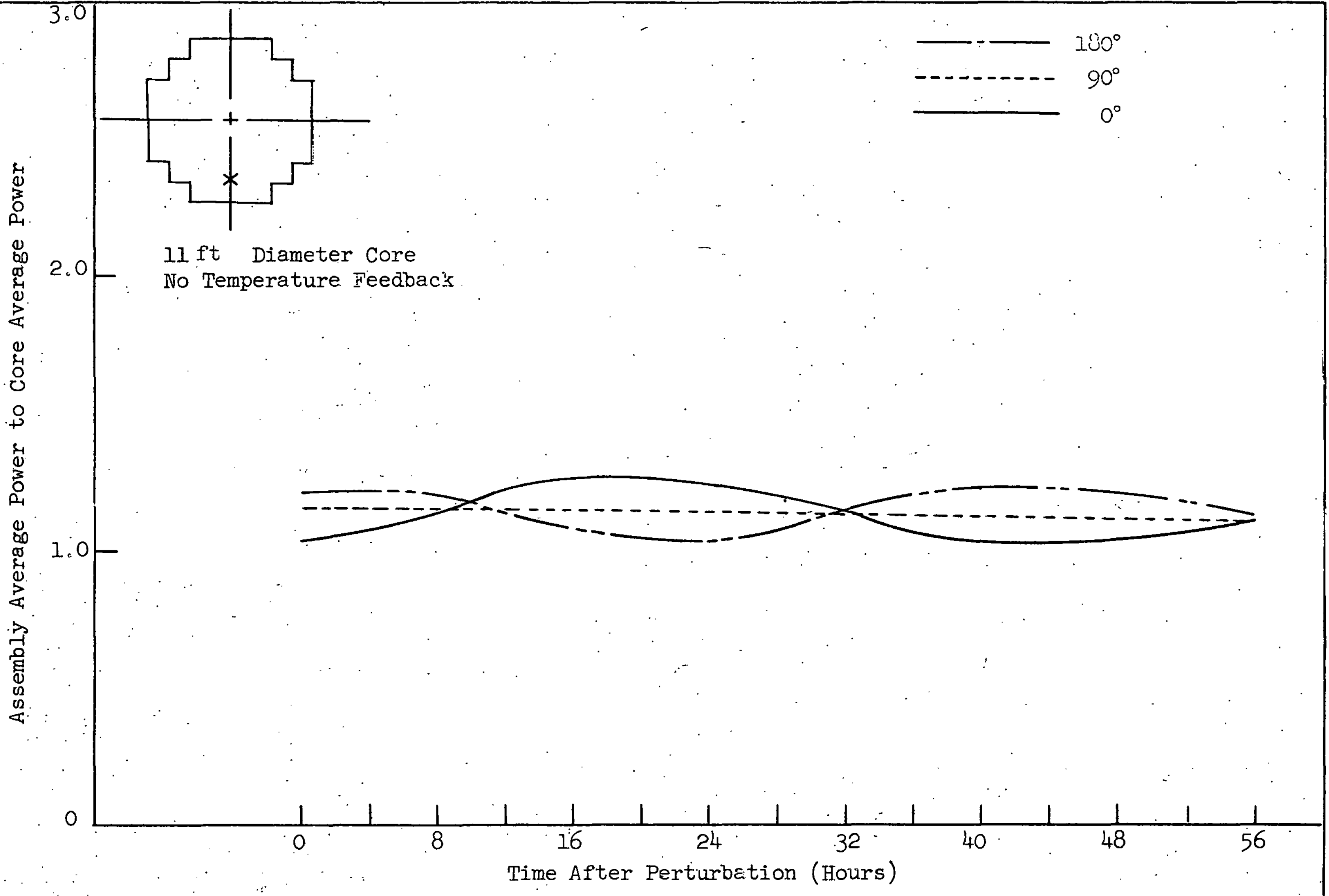

Figure 200.12 Effect of Initial Power Distribution on Xenon-Induced Oscillations — Case A

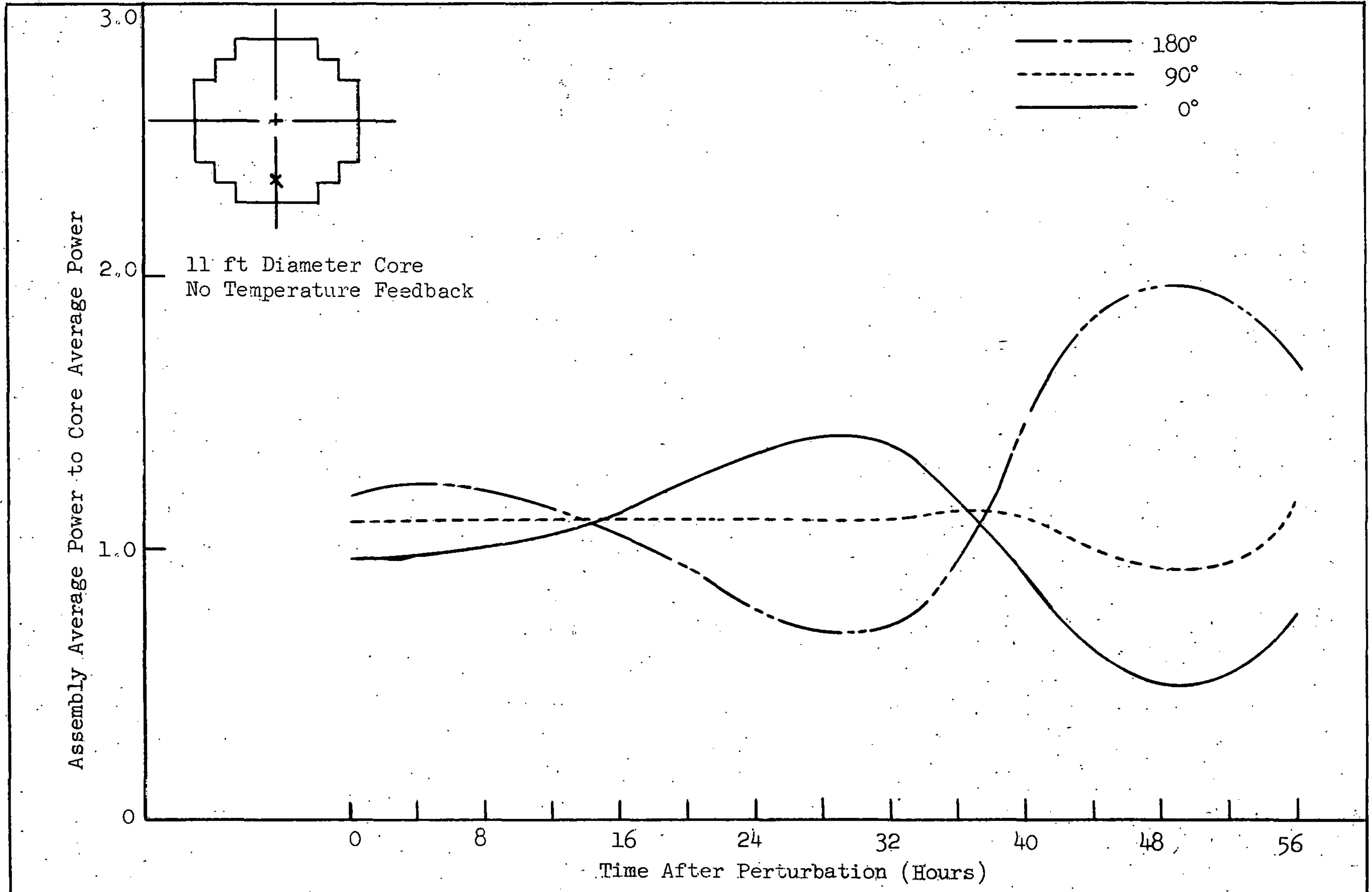

Figure 200.13 Effect of Initial Power Distribution on Xenon-Induced Oscillations — Case B

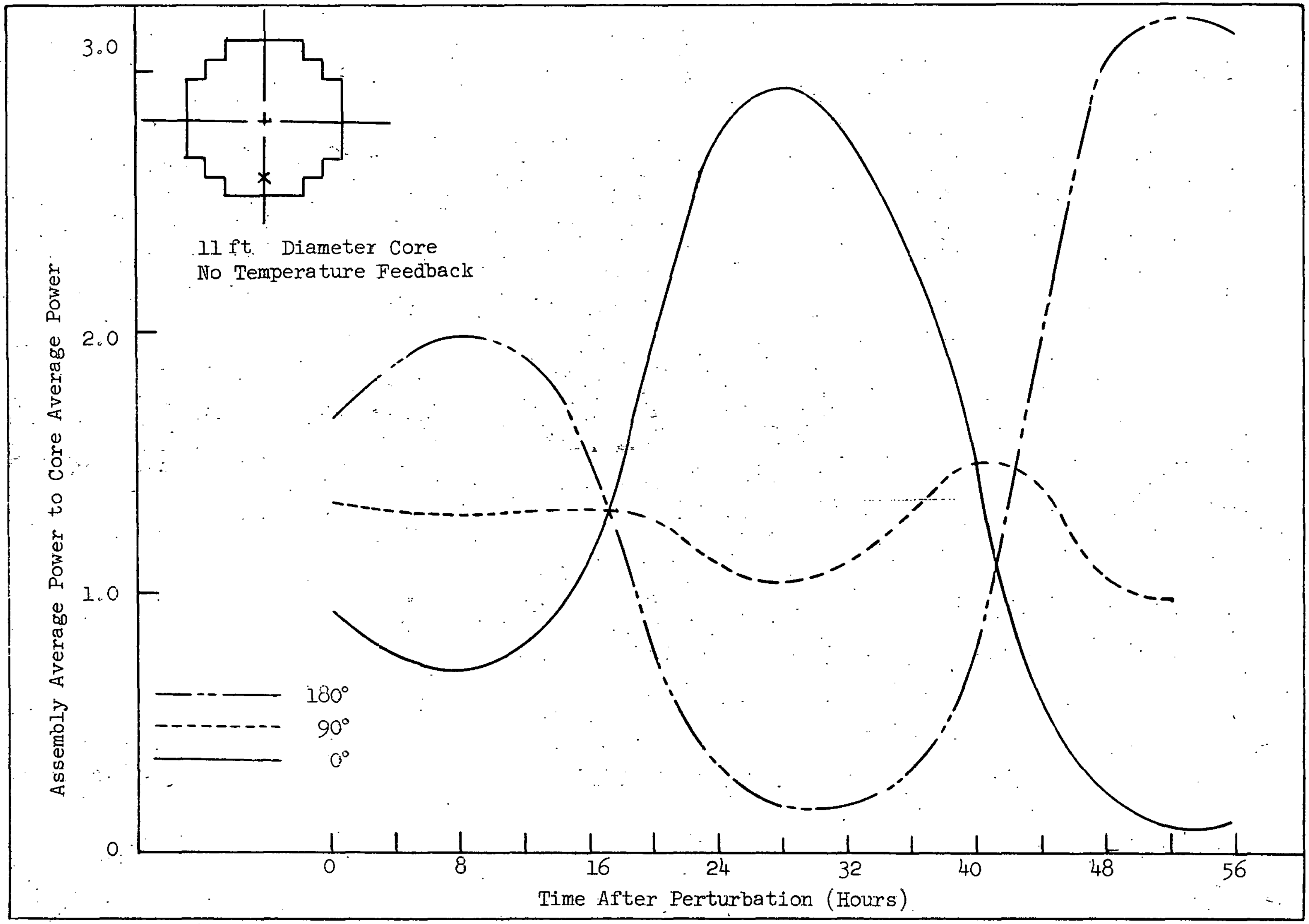

Figure 200.14 Effect of Initial Power Distribution on Xenon-Induced Oscillations — Case D

Figure 200.5. Temperature feedbacks were not accounted for in these calculations. Figure 200.12 shows that in the batch-loaded core, the oscillations are convergent and of relatively small magnitudes. The oscillations are divergent for the other three cases, and increase in magnitude from case B to case D. For case D, non-linear effects introduce large distortions in the oscillations.

Table 200.4 lists the periods and damping factors for cases A, B, and C. The period of oscillation is approximately independent of the initial flux distribution. This is predicted for large size cores by simple modal analyses[1].

The above results show that the spatial stability characteristics of a given size core are very sensitive to the unperturbed power distribution in the x-y plane. Thus one would expect the stability characteristics of a core to vary with plant lifetime, with the most unstable conditions occurring at the beginning of each fuel cycle. Because of the relatively long periods associated with xenon-induced oscillations, and in view of the success achieved in controlling axial xenon oscillations[2], no major problem is anticipated in the control of azimuthal xenon oscillations.

---

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

[2] L. E. Strawbridge, E. C. Allard, and C. P. Bhalla, "Xenon-Induced Core Instabilities", WCAP-3260-48 (1965).

Table 200.4

Effect of Steady-State Power Distribution on Oscillation Characteristics — Xenon-Induced Azimuthal Oscillations

Case	Equivalent Core Diameter (ft)	Oscillation Period (hours)	Damping Factor
A	11.0	46	0.99
B	11.0	46	1.39
C	11.0	46	1.45

E. Effect of Perturbation Location on Xenon-Induced Azimuthal Oscillations

The steady-state (unperturbed) conditions of a core are important for the determination of the inherent spatial stability characteristics of the core. For a given core, however, the characteristics of the oscillation which follows a perturbation, are dependent on the magnitude and location of the perturbation. In terms of a classical modal expansion of the flux shape, only those modes can be excited which are present in a modal expansion of the perturbation. A series of calculations were performed in a given core to evaluate the flux responses in space-time to perturbations at different locations along a diameter. The 11-ft core with a flat power distribution (case 3 in section C) was selected for analysis. The perturbation was located at four different positions along the axis 0° - 180°.

Figure 200.15 shows the power oscillations following a perturbation at a position 2/3 from core center along a radius (case i), and at the edge of the core (case iv). The power oscillations in this and the following figure are those occurring at the symmetric points 2/3 from core center along the axis 0° - 180°. Note that with the perturbation located at the edge of the core, the magnitude of the oscillations is still relatively large. Figure 200.16 shows the power oscillations following a perturbation at a position 1/3 from core center (case iii), and at the

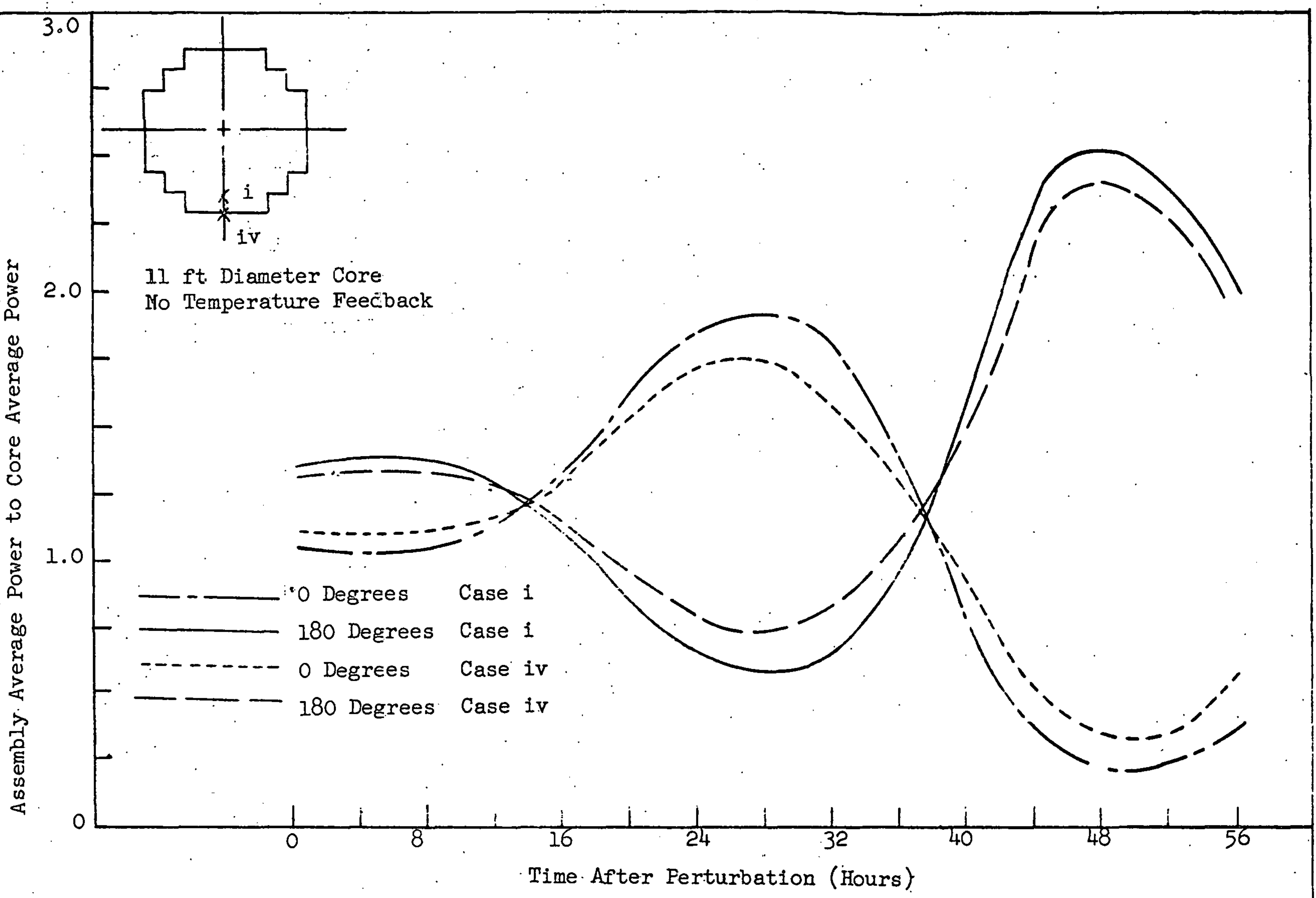

Figure 200.15 Effect of Perturbation Location on Xenon-Induced Oscillations (Cases i and iv)

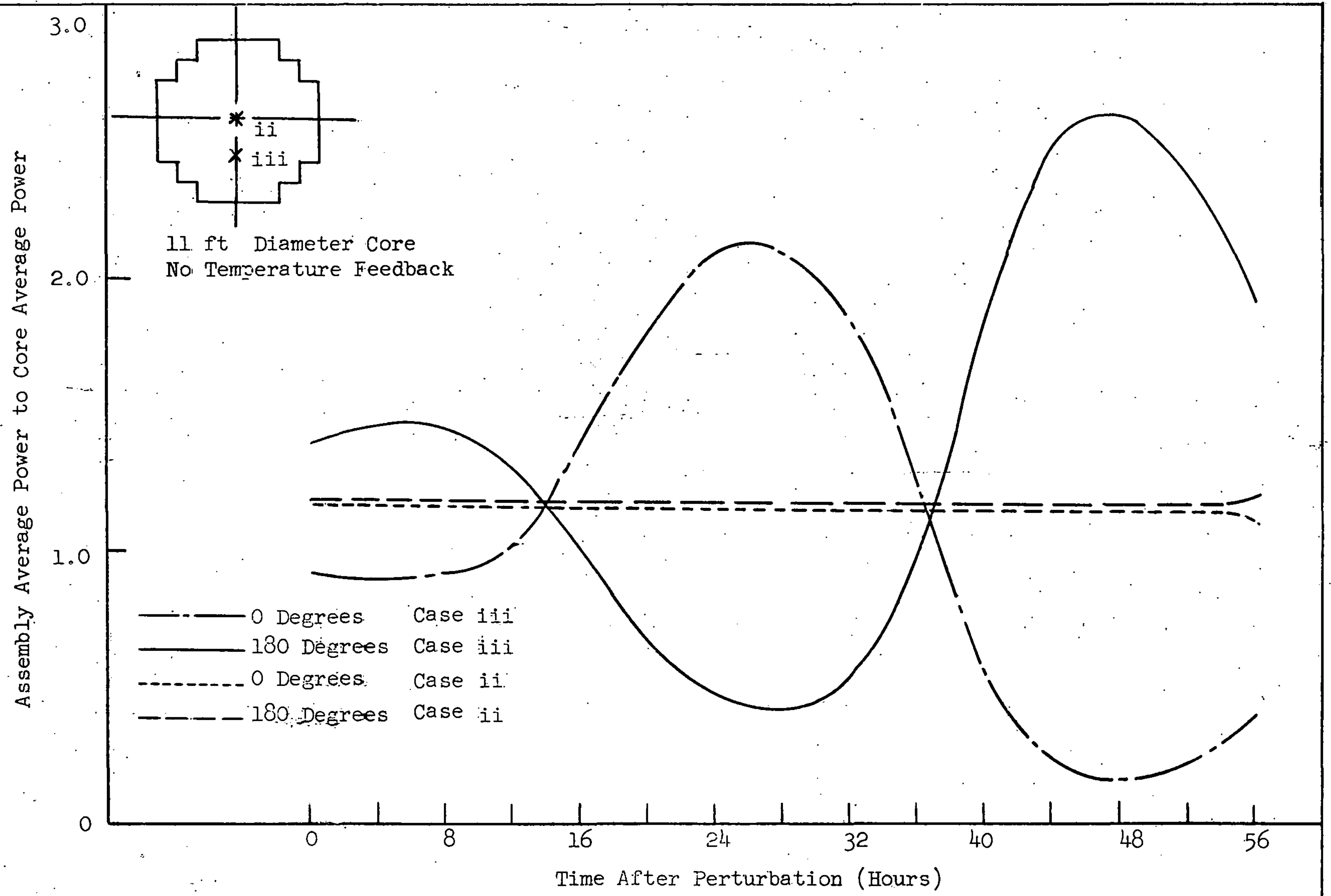

Figure 200.16 Effect of Perturbation Location on Xenon-Induced Oscillations (Cases ii and iii)

core center (case ii). The core center is located at a nodal point of the first geometric azimuthal mode, and it is seen that this particular mode is not excited in case ii. Note also that, with the perturbation located at the core center, the core is stable to radial oscillations.

Figure 200.17 shows the power distribution taken along the 0° - 180° axis, 28 hours after the perturbation, for case i through iv. Note the dependence of the oscillation magnitude on the location of the perturbation.

The above results, together with the earlier results comparing the power oscillations following perturbations located at different azimuthal positions[1], show that for this particular core (11-ft, flat power distribution), with the perturbation inserted for only a short time, xenon-induced azimuthal oscillations can be described in terms of essentially the same spatial mode, independent of the location of the perturbation. The relationship between the magnitude of the oscillations and the location of the perturbation can be obtained from the above results and those in reference 1.

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[1] O'Boyle, M. J., et al, "Control of Xenon Instabilities in Large PWR's Technical Progress Report for the Period Ending September 30, 1966", WCAP-3080-1 (1966).

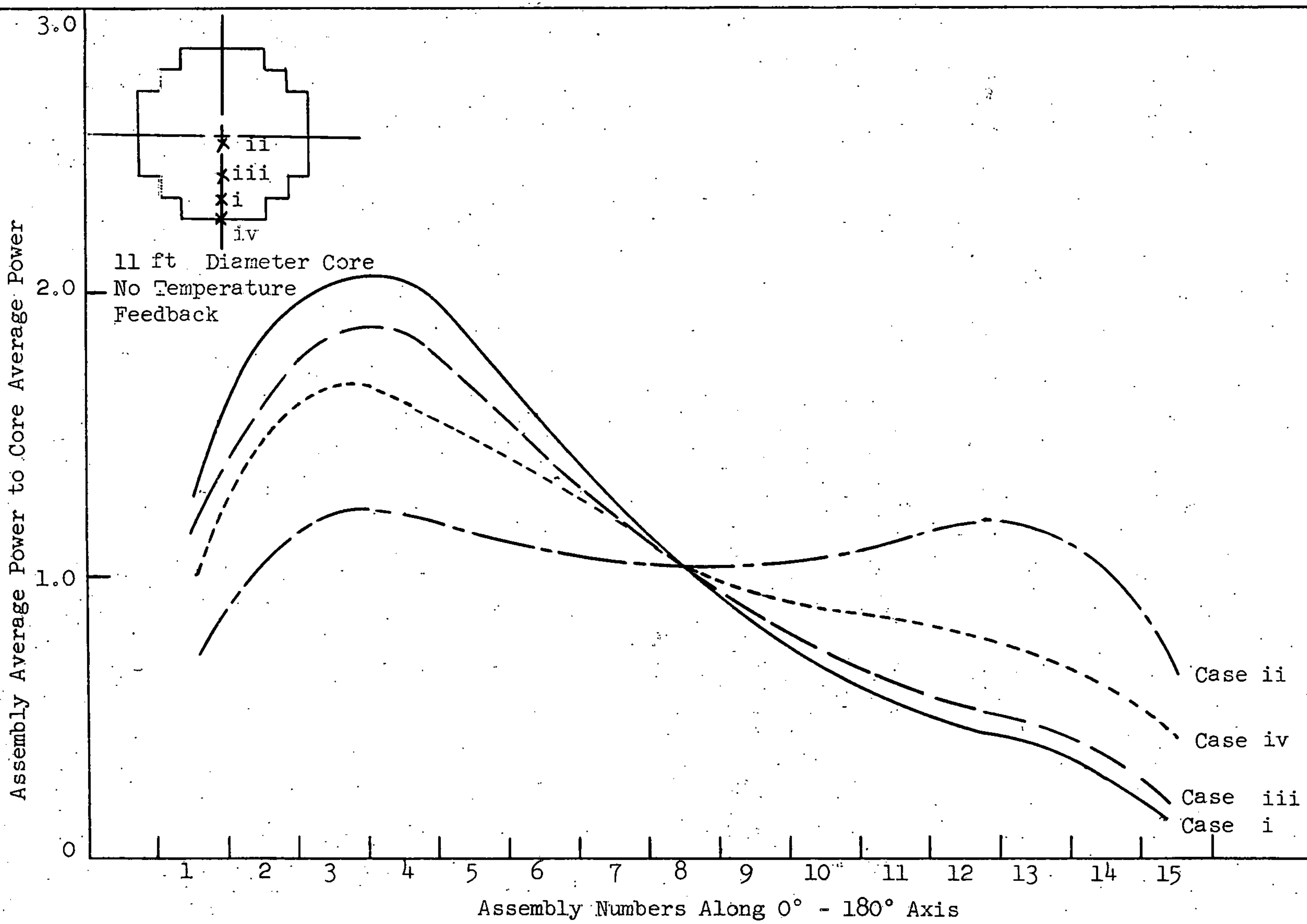

Figure 200.17 Effect of Perturbation Location on Power Distribution 28 Hours After Perturbation

EUXE-300

REMEDIAL CONTROL PROCEDURES

There were no significant accomplishments on this task during this report period.

EUXE-400

THREE-DIMENSIONAL ANALYSIS

This sub-task was inactive during this report period.

WCAP-3680-2

UNITED STATES MISSION
TO THE
EUROPEAN COMMUNITIES

35, BOULEVARD ROYAL
LUXEMBOURG

23, AVENUE DES ARTS
BRUSSELS

March 29, 1967.

Dr. Pierre Kruys
Joint R&D Board
EURATOM
51-53, rue Belliard
Brussels 4.

Dear Dr. Kruys:

We have received the following notification of Patent Clearance for the following U.S. reports:

Project 0198 - General Atomics - Contract AT(04-3)-167 P.A. 28 - Q.7 Report #GA-7618 - EURAEC 1807 - forwarded to you on Feb 28 1967.

Project 0253 - Westinghouse - Contract AT(30-1)-3696 - Q.2 - Report #WCAP-3696-2 - EURAEC 1779 - forwarded to you on Jan 31 67.

Project 0272 - Westinghouse - Contract AT(30-1)-3680 - Q.2 - Report #WCAP-3680-2 - EURAEC 1781 - forwarded to you on Jan 25 67.

Project 0260 - Westinghouse - Contract AT(30-1)-3677 - Q.2 - Report #WCAP-3677-2 - EURAEC 1780 - forwarded to you on Jan 31 67.

Enclosed are the following reports pertaining to Joint Program Research and Development work underway in the United States:

Project 029A - General Electric - Contract AT(04-3)-189 P.A. 38 - Plutonium Subcritical Experiment Program - Q.10 for Oct/Dec 66 - Report #GEAP-5428 - EURAEC 1818 - Patent Cleared (Z).

Project 0213 - General Atomics - Contract AT(04-3)-167 P.A. 32 - Lattice Physics Studies - Q. for period ending Oct 66 - Report #GA-7562 - EURAEC-1821 - Patent Cleared (Z). ✓

Project 0213 - General Atomics - Contract AT(04-3)-167 P.A. 32 - Lattice Physics Studies - Q. for period ending Dec 66. Report #GA-7683 - EURAEC-1822 - Not Patent Cleared(X). ✓

JUN 1 2 1967

Project 0214 - Babcock & Wilcox - Corrosion and Hydriding of Zircaloy - Contract AT(30-1)-3675 - Q.1 for Sep/Dec 66 Report #BAW-3765-1 - EURAEC 1819 - Patent Cleared (Z).

Project 0282 - General Electric - Power Reactor High Performance UO2 Project - Q.1 for Jul/Oct 66 - Contract AT(04-3)-189 P.A. 50 - Report #GEAP-5402 - EURAEC 1820 - Patent Cleared (Z).

Project 00116 - General Electric - Development Program on the Garigliaho Nuclear Reactor - Q.16 & 17 - Contract AT(04-3)-189 P.A. 33 - Report #GEAP-5277 - EURAEC 1823 - Not Patent Cleared (X).

Sincerely yours,

(Heidy G. Mercer) for:
Dixon B. Hoyle
Senior AEC Representative
and
Deputy for Euratom Affairs.

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