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ANALYSIS OF XENON OSCILLATION EXPERIMENTS

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ANALYSIS OF XENON OSCILLATION EXPERIMENTS

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ABSTRACT

Time-dependent, three-dimensional neutron flux calculations have been performed to compare with experimental results of axial xenon oscillations in a Savannah River production reactor. The results of the calculations predict the oscillation behavior for those experiments that were least affected by other driving forces, such as control rod motion. This study indicates that MAPLE SYRUP (the code used for this report) and other similar codes are applicable for predicting the threshold for and the period of xenon oscillations.

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INTRODUCTION

Large reactors operating at high neutron flux are subject to spatial oscillations in the power distribution associated with the periodic redistribution of xenon-135. The Savannah River production reactors are subject to these "xenon oscillations."

Normally, when xenon oscillations occur, corrective control rod action (to damp the oscillations) complicates the oscillation such that analysis of the observed results is very difficult. In May and June 1969, a series of axial and azimuthal xenon oscillations were initiated in one of the AEC production reactors at the Savannah River Plant and were allowed to progress without corrective action for several cycles.[1-3] The objective of these tests was to provide an experimental basis for comparison of techniques used to calculate xenon oscillations.

This report discusses the three-dimensional MAPLE SYRUP calculations for the axial xenon oscillation experiments.

SUMMARY

Three-dimensional neutron flux calculations using the MAPLE SYRUP code have been compared with measurements in production reactor xenon oscillation experiments. Results of these calculations are summarized in Table I. Although the calculations do not agree exactly with the experimental results, they are sufficiently accurate to indicate that MAPLE SYRUP or similar codes may be used for applications of three-dimensional calculations. Because of the strong sensitivity of xenon oscillations to flux shape, any degree of accuracy could have been achieved by arbitrarily adjusting the equilibrium flux shapes used in the calculations. The equilibrium flux shapes actually used in the calculations were, within the accuracy of the code, those that existed in the reactor at the time of the experiments.

Only those experiments that could be accurately represented by the Savannah River version of MAPLE SYRUP are compared with calculations. Tests in which the experimental results were influenced by control rod motion during the test are omitted as are the azimuthal tests in which the results are strongly influenced by the moderator temperature coefficient and therefore by the complex moderator flow pattern in the Savannah River production reactors.

TABLE I

Comparison of Three-Dimensional MAPLE SYRUP Calculations with Experimental Results

Experiment	Relative Reactor Power[a]	Equilibrium Flux Shape	Damping Factor		Period, hr	
			Calc	Exp	Calc	Exp
3	0.721	Symmetric	2.1	2.5	31	30
4	1.000	Symmetric	1.0	1.0	29	26
6	1.182	Symmetric	0.6	0.8	27	25
7	1.182	Asymmetric	3.2	2.7	33	25

a. Relative to Experiment 4. The absolute values for the experiments are given in classified DP report.[2]

DESCRIPTION OF REACTOR

The Savannah River C reactor is contained within a stainless steel tank ∿18-1/2 ft in diameter and ∿15 ft high surrounded on the sides by an iron and light water thermal shield. The basic lattice pattern of the core is triangular on a 7-inch pitch center-to-center between primary lattice positions. In the central region of the core (controlled zone), every seventh lattice position is occupied by a septifoil control assembly, and the remaining positions are occupied by fuel or special assemblies. The outer region of the core (buckled zone) is composed of fuel on a 7-inch pitch. The lattice is surrounded by a radial reflector (D_2O) ∿1.1 ft thick.

A control position is occupied by a housing, which has positions for seven rods. Five of the rod positions are occupied by full length rods, and the other two by partial length rods that can be used for axial flux shape control.

Reactivity control is accomplished by ganged full rod motion (Gangs I, II, and III) with individual trim in any control assembly as required to flatten the radial power shape. The control rods are inserted from the top of the reactor.

Axial flatness is accomplished by inserting the partial length rods and adjusting their position to obtain a nearly symmetric axial flux shape. For the xenon oscillation experiments, the number of partial length rods in the control assemblies varied from zero (in some Gang III assemblies) to two (in some Gang I and II assemblies) to obtain a flat radial power shape with approximately the same full control rod insertion in all gangs.

The reactor is D_2O moderated and cooled. The flow comes into a plenum at the top of the reactor and goes down through the coolant annuli of the fuel assemblies and out into the bulk moderator. The flow then circulates through the bulk moderator, and exits at the bottom of the reactor tank. The flow pattern is significant to the xenon effect, because it determines the degree to which temperature coefficients affect xenon oscillations. In the radial direction, during azimuthal oscillations, both the Doppler coefficient and the moderator temperature coefficient act to oppose the oscillation. In the axial direction, only the Doppler coefficient opposes the oscillations; the moderator temperature coefficient is ineffectual.

The instrumentation for determining the axial distribution during the tests was a system of nine rods, each containing seven iron pins attached to thermocouples for measurement of the heat generated by gamma ray interactions with the iron. These axial power monitors (APM) are located at centroids of triangles whose vertices lie on control positions. The monitors are calibrated periodically with a traveling wire flux monitor at the same location.

The second thermocouple from the top (Sensor 2) is located 42 inches above the reactor midplane. The signal from Sensor 2 of the centermost APM (APM 1) was chosen, for this report, to describe the progress of the xenon oscillation experiments.

DESCRIPTION OF EXPERIMENTS

Only the axial xenon oscillations have been calculated. The azimuthal oscillations are affected by the complicated flow pattern of the bulk moderator, and no model has been developed that adequately describes the complex interaction.

For convenience, the seven axial xenon oscillation tests can be grouped in order of complexity:

- Group 1 — Experiments 3, 4, 5, and 6
- Group 2 — Experiments 2 and 7
- Group 3 — Experiments 1 and 2

Group 1 represents the simplest type of tests in terms of ease of calculation and accuracy of assumptions in the MAPLE SYRUP calculations. Common characteristics for Experiments 3, 4, 5, and 6 are:

- The perturbation was achieved by moving the partial length rods down a short distance and leaving them for 1-1/2 hours, then returning them to their original position and allowing the oscillation to proceed about a nearly symmetric axial flux shape.
- The reactivity control to maintain constant reactor power during these tests was as uniform as conveniently feasible. Approximately half of the full control rods (every other one) were in the top portion of the reactor, and the other half had the rod tips in the bottom portion of the reactor. The result of this alternating pattern was such that any net reactivity change that occurred during the tests was compensated for by approximately equal changes in the top and bottom halves of the reactor so that the axial flux shape was nearly unaffected by the small full control rod motion. This allowed the flux to oscillate about an axial flux shape that was affected only by changing xenon concentration.

The primary differences between the experiments within Group 1 were the reactor power and starting flux shapes. Table II lists

these parameters. In Experiment 5, the perturbation occurred in Gang I only (central 31 control clusters); in Experiments 3, 4, and 6, the perturbation occurred in Gangs I and II (central 55 control clusters). The main observable difference in the results between Experiments 4 and 5 was the magnitude of the oscillation. Because both the damping factor (1.0) and the oscillation period (26 hr) were the same for Experiments 4 and 5 (within experimental error), no separate calculations were made for Experiment 5.

Group 2 can be differentiated from Group 1 by the form of the perturbation. As with the Group 1 tests, the perturbation was initiated by lowering the partial rods. In this case, however, the partial rods were moved in Gang I only, and they remained in the perturbed position throughout the test. This resulted in an oscillation about a highly nonsymmetric axial flux shape. As might be expected, the resultant oscillation was more damped than the oscillation at the same power and starting flux shape done by the method described for Group 1.

Experiment 2, contained in Group 2, is also contained in Group 3.

TABLE II

Axial Xenon Oscillation Experiments

Experiment	Relative Reactor Power, MW	Fractional Axial Flatness[a]	Perturbation			Asymptotic APR[c]	Damping Factor[d]	Full Control[e]
			Gang Moved	Perturbation APR[b]	APR after 1-1/2 hr			
1	0.72	0.55	I, II	1.30	1.20	1.0 to 0.8	N.A.	0.3
2	0.72	0.55	I	1.68	*f*	1.62	∿10.0	0.3
3	0.72	0.55	I, II	1.30	1.20	1.06	∿2.5	0.3, 0.74
4	1.00	0.52	I, II	1.20	1.17	1.02	1.0	0.3, 0.74
5	1.00	0.52	I	1.78	1.45	1.03	1.0	0.3, 0.74
6	1.18	0.50	I, II	1.24	1.30	1.04	∿0.8	0.3, 0.74
7	1.18	0.50	I	1.68	*f*	1.62	∿2.7	0.3, 0.74

a. Fractional axial flatness as defined for this report is the fraction of the axial shape (extrapolated zero to extrapolated zero) over which the flux is essentially constant. The values listed are for the central portion of the reactor (APM 1) and differ from those listed in References 2 and 3 because of a different definition.

b. APR is for the center of the reactor. The axial power ratio (APR) is the ratio of the flux at sensor positions 2 and 6. These sensors are separated vertically by 84 inches and are symmetric about the axial midplane.

c. APR about which the oscillation occurs.

d. Damping factor = $\Delta\phi_n/\Delta\phi_{n+1}$, where $\Delta\phi_n$ is the maximum change in the flux from its asymptotic value at some axial point for the n^{th} peak of the oscillation and $\Delta\phi_{n+1}$ is the maximum change one cycle later.

e. Full rod insertion is approximate. When two values of insertion are listed, every other control cluster had enough trim to yield the larger insertion.

f. Not applicable.

Group 3 is different from the others in that the reactivity control during the tests was nonuniform axially. The full control rods were evenly banked (by gang) with the rod tips at approximately 1/4 the way down from the top of the reactor. The effect of this type of control is to distort the axial flux shape. As the flux becomes lower at the top, the worth of the rods is reduced, requiring that they be driven in further to maintain constant power. This further reduces the flux at the top. The inverse occurs as the flux becomes larger at the top. The resultant oscillation is one that is affected not only by changing xenon but also by changing rod motion. The oscillation during Experiment 1 appeared to be nearly a sustained oscillation. This occurred at the same power and equilibrium flux shape as Experiment 3, which, with nearly uniform control and affected only by xenon, was quite well damped.

An attempt was made to modify MAPLE SYRUP to accept a control that changed position with time to simulate the full control rod motion that occurred in Experiments 1 and 2. Although the results could be qualitatively reproduced, it became apparent that a more sophisticated model was required to mock up the actual test. No calculational results are reported for those experiments.

DESCRIPTION OF MAPLE SYRUP CODE

GENERAL

MAPLE SYRUP uses a two-energy-group neutron diffusion model to calculate the space-dependent neutron flux transient in a nuclear reactor operating under the influence of xenon-135 and iodine-135 fission product poisoning. The code, developed at Oak Ridge National Laboratory, is written in FORTRAN IV and treats one-, two-, and three-dimensional reactor geometries in rectangular coordinates. The initial two-group reactor parameters and the reactor power level are specified as input data from which the code calculates equilibrium, steady-state neutron flux; xenon and iodine distributions; and the thermal absorption cross section in a specified material required for criticality. This initial reactor state is perturbed by changing the material in specified regions of the reactor. The code then calculates neutron flux and iodine and xenon distributions at specified time intervals. Delayed neutron effects are neglected, but power feedback is included and acts directly upon the thermal absorption cross section of the materials affected.

The neutron diffusion equations at each time step are solved by a difference method, and the xenon and iodine equations at each point in space are solved explicitly assuming constant neutron flux during each time interval. Total power of the reactor (the sum of the fission neutrons) is held constant throughout the calculations.

GEOMETRY

The geometry specification in MAPLE SYRUP consists of overlaying material numbers in a one-, two-, or three-dimensional array (X,Y,Z) to mock up the various reactor regions. Symmetry (neutron current = 0) is allowed at boundaries. Mesh lines (possible material boundary lines) are generated by increasing X, Y, and Z by ΔX, ΔY, and ΔZ, respectively. Mesh points (where all calculations are done) occur at the centers of the rectangular parallelepipeds thus formed.

For the representation of the three-dimensional calculations considered in this report, $\Delta X = \Delta Y = 26.40$ cm with symmetry at the planes defined by X = 1 and Y = 1 and a total of 10 mesh points in each direction. $\Delta Z = 10.16$ cm with 45 mesh points and no symmetry

requirement. One-dimensional calculations used a single value of X (X = 1) and a single value of Y (Y = 1) with the same 45 mesh points in the Z direction.

Figure 4 shows the material overlay for a typical calculation. Material 1 represents a poison boundary, 2 represents D_2O reflector, 3 represents buckled zone fuel, and 4 through 9 represent controlled zone fuel with varying values of thermal absorption cross section.

The perturbation is introduced by changing the material number in any of the 4500 regions. In the example shown in Figure 4, the central region (representing control Gangs I and II) was changed at Z layers 12 and 35 to represent partial rod motion to achieve a particular change in the axial flux shape. After 1-1/2 hours (for Experiments 3, 4, and 6), a second perturbation is optionally introduced to return the material numbers back to the original values; this perturbation represents the return of the partial rods to their original position.

The nearly cylindrical reactor has been represented by a number of square prisms; i.e., the 60° symmetric hexagonal lattice pattern has been represented by a 90° symmetric series of squares in the X-Y plane. The variation in individual control assemblies has been homogenized over these regions. In the axial direction, the nonsymmetric control rod positions have been made axially symmetric before the perturbation to represent the nearly symmetric axial flux shape that existed at the beginning of each of the tests. These simplifying assumptions obviously introduce some error into the calculations. The amount of error, however, is believed to be relatively small, but an analysis of the error is beyond the scope of this report.

PARAMETERS

The material parameters used in the calculations were obtained by cell calculations using the HAMMER[5] code combined with a code which calculates individual isotope depletion and buildup. One-dimensional calculations indicated that no significant change in the xenon oscillations occurred for parameters obtained at a wide range of exposures for the lattice used in the experiments, so the parameters chosen for all calculations were obtained at an exposure equivalent to the exposure at the beginning of Experiment 4.

Input parameters are discussed in Classified DP report.[6]

MATERIALS FOR Z= 1

```
4 4 4 4 4 4 4 3 3 2
4 4 4 4 4 4 4 3 3 2
4 4 4 4 4 4 4 3 3 2
4 4 4 4 4 4 4 3 2 2
4 4 4 4 4 4 3 3 2 1
4 4 4 4 4 4 3 3 2 2 1
4 4 4 4 3 3 2 2 1 1
3 3 3 3 3 2 2 1 1 1
3 3 3 2 2 2 1 1 1 1
2 2 2 2 1 1 1 1 1 1
```

MATERIALS FOR Z= 2

```
4 4 4 4 4 4 4 3 3 2
4 4 4 4 4 4 4 3 3 2
4 4 4 4 4 4 4 3 3 2
4 4 4 4 4 4 4 3 2 2
4 4 4 4 4 4 3 3 2 1
4 4 4 4 4 3 3 2 2 1
4 4 4 4 3 3 2 2 1 1
3 3 3 3 3 2 2 1 1 1
3 3 3 2 2 2 1 1 1 1
2 2 2 2 1 1 1 1 1 1
```

MATERIALS FOR Z= 3

```
4 4 4 4 4 4 4 3 3 2
4 4 4 4 4 4 4 3 3 2
4 4 4 4 4 4 4 3 3 2
4 4 4 4 4 4 4 3 2 2
4 4 4 4 4 4 3 3 2 1
4 4 4 4 4 3 3 2 2 1
4 4 4 4 3 3 2 2 1 1
3 3 3 3 3 2 2 1 1 1
3 3 3 2 2 2 1 1 1 1
2 2 2 2 1 1 1 1 1 1
```

MATERIALS FOR Z= 4

```
4 4 4 4 4 4 4 3 3 2
4 4 4 4 4 4 4 3 3 2
4 4 4 4 4 4 4 3 3 2
4 4 4 4 4 4 4 3 2 2
4 4 4 4 4 4 3 3 2 1
4 4 4 4 4 3 3 2 2 1
4 4 4 4 3 3 2 2 1 1
3 3 3 3 3 2 2 1 1 1
3 3 3 2 2 2 1 1 1 1
2 2 2 2 1 1 1 1 1 1
```

MATERIALS FOR Z= 5

```
4 4 4 4 4 4 4 3 3 2
4 4 4 4 4 4 4 3 3 2
4 4 4 4 4 4 4 3 3 2
4 4 4 4 4 4 4 3 2 2
4 4 4 4 4 4 3 3 2 1
4 4 4 4 4 3 3 2 2 1
4 4 4 4 3 3 2 2 1 1
3 3 3 3 3 2 2 1 1 1
3 3 3 2 2 2 1 1 1 1
2 2 2 2 1 1 1 1 1 1
```

MATERIALS FOR Z= 6

```
4 4 4 4 4 4 4 3 3 2
4 4 4 4 4 4 4 3 3 2
4 4 4 4 4 4 4 3 3 2
4 4 4 4 4 4 4 3 2 2
4 4 4 4 4 4 3 3 2 1
4 4 4 4 4 3 3 2 2 1
4 4 4 4 3 3 2 2 1 1
3 3 3 3 3 2 2 1 1 1
3 3 3 2 2 2 1 1 1 1
2 2 2 2 1 1 1 1 1 1
```

FIG. 1 TYPICAL THREE-DIMENSIONAL MATERIAL OVERLAY FOR MAPLE SYRUP CALCULATIONS

MATERIALS FOR Z= 7

```
4 4 4 4 4 4 4 3 3 2
4 4 4 4 4 4 4 3 3 2
4 4 4 4 4 4 4 3 3 2
4 4 4 4 4 4 4 3 2 2
4 4 4 4 4 4 3 3 2 1
4 4 4 4 4 3 3 2 2 1
4 4 4 4 3 3 2 2 1 1
3 3 3 3 3 2 2 1 1 1
3 3 3 2 2 2 1 1 1 1
2 2 2 2 1 1 1 1 1 1
```

MATERIALS FOR Z= 8

```
6 6 6 6 6 6 6 3 3 2
6 6 6 6 6 6 6 3 3 2
6 6 6 6 6 6 6 3 3 2
6 6 6 6 6 6 6 3 2 2
6 6 6 6 6 6 3 3 2 1
6 6 6 6 6 3 3 2 2 1
6 6 6 6 3 3 2 2 1 1
3 3 3 3 3 2 2 1 1 1
3 3 3 2 2 2 1 1 1 1
2 2 2 2 1 1 1 1 1 1
```

MATERIALS FOR Z= 9

```
6 6 6 6 6 6 6 3 3 2
6 6 6 6 6 6 6 3 3 2
6 6 6 6 6 6 6 3 3 2
6 6 6 6 6 6 6 3 2 2
6 6 6 6 6 6 3 3 2 1
6 6 6 6 6 3 3 2 2 1
6 6 6 6 3 3 2 2 1 1
3 3 3 3 3 2 2 1 1 1
3 3 3 2 2 2 1 1 1 1
2 2 2 2 1 1 1 1 1 1
```

MATERIALS FOR Z= 10

```
6 6 6 6 6 6 6 3 3 2
6 6 6 6 6 6 6 3 3 2
6 6 6 6 6 6 6 3 3 2
6 6 6 6 6 6 6 3 2 2
6 6 6 6 6 6 3 3 2 1
6 6 6 6 6 3 3 2 2 1
6 6 6 6 3 3 2 2 1 1
3 3 3 3 3 2 2 1 1 1
3 3 3 2 2 2 1 1 1 1
2 2 2 2 1 1 1 1 1 1
```

MATERIALS FOR Z= 11

```
6 6 6 6 6 6 6 3 3 2
6 6 6 6 6 6 6 3 3 2
6 6 6 6 6 6 6 3 3 2
6 6 6 6 6 6 6 3 2 2
6 6 6 6 6 6 3 3 2 1
6 6 6 6 6 3 3 2 2 1
6 6 6 6 3 3 2 2 1 1
3 3 3 3 3 2 2 1 1 1
3 3 3 2 2 2 1 1 1 1
2 2 2 2 1 1 1 1 1 1
```

MATERIALS FOR Z= 12

```
7 7 7 7 7 7 5 3 3 2
7 7 7 7 7 7 5 3 3 2
7 7 7 7 7 7 5 3 3 2
7 7 7 7 7 5 5 3 2 2
7 7 7 7 5 5 3 3 2 1
7 7 7 5 5 3 3 2 2 1
5 5 5 5 3 3 2 2 1 1
3 3 3 3 3 2 2 1 1 1
3 3 3 2 2 2 1 1 1 1
2 2 2 2 1 1 1 1 1 1
```

FIG. 1 (Continued)

MATERIALS FOR Z= 13

7	7	7	7	7	7	5	3	3	2
7	7	7	7	7	7	5	3	3	2
7	7	7	7	7	7	5	3	3	2
7	7	7	7	7	5	5	3	2	2
7	7	7	7	5	5	3	3	2	1
7	7	7	5	5	3	3	2	2	1
5	5	5	5	3	3	2	2	1	1
3	3	3	3	3	2	2	1	1	1
3	3	3	2	2	2	1	1	1	1
2	2	2	2	1	1	1	1	1	1

MATERIALS FOR Z= 14

7	7	7	7	7	7	5	3	3	2
7	7	7	7	7	7	5	3	3	2
7	7	7	7	7	7	5	3	3	2
7	7	7	7	7	5	5	3	2	2
7	7	7	7	5	5	3	3	2	1
7	7	7	5	5	3	3	2	2	1
5	5	5	5	3	3	2	2	1	1
3	3	3	3	3	2	2	1	1	1
3	3	3	2	2	2	1	1	1	1
2	2	2	2	1	1	1	1	1	1

MATERIALS FOR Z= 15

7	7	7	7	7	7	5	3	3	2
7	7	7	7	7	7	5	3	3	2
7	7	7	7	7	7	5	3	3	2
7	7	7	7	7	5	5	3	2	2
7	7	7	7	5	5	3	3	2	1
7	7	7	5	5	3	3	2	2	1
5	5	5	5	3	3	2	2	1	1
3	3	3	3	3	2	2	1	1	1
3	3	3	2	2	2	1	1	1	1
2	2	2	2	1	1	1	1	1	1

MATERIALS FOR Z= 16

7	7	7	7	7	7	5	3	3	2
7	7	7	7	7	7	5	3	3	2
7	7	7	7	7	7	5	3	3	2
7	7	7	7	7	5	5	3	2	2
7	7	7	7	5	5	3	3	2	1
7	7	7	5	5	3	3	2	2	1
5	5	5	5	3	3	2	2	1	1
3	3	3	3	3	2	2	1	1	1
3	3	3	2	2	2	1	1	1	1
2	2	2	2	1	1	1	1	1	1

MATERIALS FOR Z= 17

7	7	7	7	7	7	5	3	3	2
7	7	7	7	7	7	5	3	3	2
7	7	7	7	7	7	5	3	3	2
7	7	7	7	7	5	5	3	2	2
7	7	7	7	5	5	3	3	2	1
7	7	7	5	5	3	3	2	2	1
5	5	5	5	3	3	2	2	1	1
3	3	3	3	3	2	2	1	1	1
3	3	3	2	2	2	1	1	1	1
2	2	2	2	1	1	1	1	1	1

MATERIALS FOR Z= 18

7	7	7	7	7	7	5	3	3	2
7	7	7	7	7	7	5	3	3	2
7	7	7	7	7	7	5	3	3	2
7	7	7	7	7	5	5	3	2	2
7	7	7	7	5	5	3	3	2	1
7	7	7	5	5	3	3	2	2	1
5	5	5	5	3	3	2	2	1	1
3	3	3	3	3	2	2	1	1	1
3	3	3	2	2	2	1	1	1	1
2	2	2	2	1	1	1	1	1	1

FIG. 1 (Continued)

MATERIALS FOR Z= 19

7	7	7	7	7	7	5	3	3	2
7	7	7	7	7	7	5	3	3	2
7	7	7	7	7	7	5	3	3	2
7	7	7	7	7	5	5	3	2	2
7	7	7	7	5	5	3	3	2	1
7	7	7	5	5	3	3	2	2	1
5	5	5	5	3	3	2	2	1	1
3	3	3	3	3	2	2	1	1	1
3	3	3	2	2	2	1	1	1	1
2	2	2	2	1	1	1	1	1	1

MATERIALS FOR Z= 20

7	7	7	7	7	7	5	3	3	2
7	7	7	7	7	7	5	3	3	2
7	7	7	7	7	7	5	3	3	2
7	7	7	7	7	5	5	3	2	2
7	7	7	7	5	5	3	3	2	1
7	7	7	5	5	3	3	2	2	1
5	5	5	5	3	3	2	2	1	1
3	3	3	3	3	2	2	1	1	1
3	3	3	2	2	2	1	1	1	1
2	2	2	2	1	1	1	1	1	1

MATERIALS FOR Z= 21

7	7	7	7	7	7	5	3	3	2
7	7	7	7	7	7	5	3	3	2
7	7	7	7	7	7	5	3	3	2
7	7	7	7	7	5	5	3	2	2
7	7	7	7	5	5	3	3	2	1
7	7	7	5	5	3	3	2	2	1
5	5	5	5	3	3	2	2	1	1
3	3	3	3	3	2	2	1	1	1
3	3	3	2	2	2	1	1	1	1
2	2	2	2	1	1	1	1	1	1

MATERIALS FOR Z= 22

7	7	7	7	7	7	5	3	3	2
7	7	7	7	7	7	5	3	3	2
7	7	7	7	7	7	5	3	3	2
7	7	7	7	7	5	5	3	2	2
7	7	7	7	5	5	3	3	2	1
7	7	7	5	5	3	3	2	2	1
5	5	5	5	3	3	2	2	1	1
3	3	3	3	3	2	2	1	1	1
3	3	3	2	2	2	1	1	1	1
2	2	2	2	1	1	1	1	1	1

MATERIALS FOR Z= 23

7	7	7	7	7	7	5	3	3	2
7	7	7	7	7	7	5	3	3	2
7	7	7	7	7	7	5	3	3	2
7	7	7	7	7	5	5	3	2	2
7	7	7	7	5	5	3	3	2	1
7	7	7	5	5	3	3	2	2	1
5	5	5	5	3	3	2	2	1	1
3	3	3	3	3	2	2	1	1	1
3	3	3	2	2	2	1	1	1	1
2	2	2	2	1	1	1	1	1	1

MATERIALS FOR Z= 24

7	7	7	7	7	7	5	3	3	2
7	7	7	7	7	7	5	3	3	2
7	7	7	7	7	7	5	3	3	2
7	7	7	7	7	5	5	3	2	2
7	7	7	7	5	5	3	3	2	1
7	7	7	5	5	3	3	2	2	1
5	5	5	5	3	3	2	2	1	1
3	3	3	3	3	2	2	1	1	1
3	3	3	2	2	2	1	1	1	1
2	2	2	2	1	1	1	1	1	1

FIG. 1 (Continued)

MATERIALS FOR Z= 25

7	7	7	7	7	7	5	3	3	2
7	7	7	7	7	7	5	3	3	2
7	7	7	7	7	7	5	3	3	2
7	7	7	7	7	5	5	3	2	2
7	7	7	7	5	5	3	3	2	1
7	7	7	5	5	3	3	2	2	1
5	5	5	5	3	3	2	2	1	1
3	3	3	3	3	2	2	1	1	1
3	3	3	2	2	2	1	1	1	1
2	2	2	2	1	1	1	1	1	1

MATERIALS FOR Z= 26

7	7	7	7	7	7	5	3	3	2
7	7	7	7	7	7	5	3	3	2
7	7	7	7	7	7	5	3	3	2
7	7	7	7	7	5	5	3	2	2
7	7	7	7	5	5	3	3	2	1
7	7	7	5	5	3	3	2	2	1
5	5	5	5	3	3	2	2	1	1
3	3	3	3	3	2	2	1	1	1
3	3	3	2	2	2	1	1	1	1
2	2	2	2	1	1	1	1	1	1

MATERIALS FOR Z= 27

7	7	7	7	7	7	5	3	3	2
7	7	7	7	7	7	5	3	3	2
7	7	7	7	7	7	5	3	3	2
7	7	7	7	7	5	5	3	2	2
7	7	7	7	5	5	3	3	2	1
7	7	7	5	5	3	3	2	2	1
5	5	5	5	3	3	2	2	1	1
3	3	3	3	3	2	2	1	1	1
3	3	3	2	2	2	1	1	1	1
2	2	2	2	1	1	1	1	1	1

MATERIALS FOR Z= 28

7	7	7	7	7	7	5	3	3	2
7	7	7	7	7	7	5	3	3	2
7	7	7	7	7	7	5	3	3	2
7	7	7	7	7	5	5	3	2	2
7	7	7	7	5	5	3	3	2	1
7	7	7	5	5	3	3	2	2	1
5	5	5	5	3	3	2	2	1	1
3	3	3	3	3	2	2	1	1	1
3	3	3	2	2	2	1	1	1	1
2	2	2	2	1	1	1	1	1	1

MATERIALS FOR Z= 29

7	7	7	7	7	7	5	3	3	2
7	7	7	7	7	7	5	3	3	2
7	7	7	7	7	7	5	3	3	2
7	7	7	7	7	5	5	3	2	2
7	7	7	7	5	5	3	3	2	1
7	7	7	5	5	3	3	2	2	1
5	5	5	5	3	3	2	2	1	1
3	3	3	3	3	2	2	1	1	1
3	3	3	2	2	2	1	1	1	1
2	2	2	2	1	1	1	1	1	1

MATERIALS FOR Z= 30

7	7	7	7	7	7	5	3	3	2
7	7	7	7	7	7	5	3	3	2
7	7	7	7	7	7	5	3	3	2
7	7	7	7	7	5	5	3	2	2
7	7	7	7	5	5	3	3	2	1
7	7	7	5	5	3	3	2	2	1
5	5	5	5	3	3	2	2	1	1
3	3	3	3	3	2	2	1	1	1
3	3	3	2	2	2	1	1	1	1
2	2	2	2	1	1	1	1	1	1

FIG. 1 (Continued)

MATERIALS FOR Z= 31

```
7 7 7 7 7 7 5 3 3 2
7 7 7 7 7 7 5 3 3 2
7 7 7 7 7 7 5 3 3 2
7 7 7 7 7 5 5 3 2 2
7 7 7 7 5 5 3 3 2 1
7 7 7 5 5 3 3 2 2 1
5 5 5 5 3 3 2 2 1 1
3 3 3 3 3 2 2 1 1 1
3 3 3 2 2 2 1 1 1 1
2 2 2 2 1 1 1 1 1 1
```

MATERIALS FOR Z= 32

```
7 7 7 7 7 7 5 3 3 2
7 7 7 7 7 7 5 3 3 2
7 7 7 7 7 7 5 3 3 2
7 7 7 7 7 5 5 3 2 2
7 7 7 7 5 5 3 3 2 1
7 7 7 5 5 3 3 2 2 1
5 5 5 5 3 3 2 2 1 1
3 3 3 3 3 2 2 1 1 1
3 3 3 2 2 2 1 1 1 1
2 2 2 2 1 1 1 1 1 1
```

MATERIALS FOR Z= 33

```
7 7 7 7 7 7 5 3 3 2
7 7 7 7 7 7 5 3 3 2
7 7 7 7 7 7 5 3 3 2
7 7 7 7 7 5 5 3 2 2
7 7 7 7 5 5 3 3 2 1
7 7 7 5 5 3 3 2 2 1
5 5 5 5 3 3 2 2 1 1
3 3 3 3 3 2 2 1 1 1
3 3 3 2 2 2 1 1 1 1
2 2 2 2 1 1 1 1 1 1
```

MATERIALS FOR Z= 34

```
7 7 7 7 7 7 5 3 3 2
7 7 7 7 7 7 5 3 3 2
7 7 7 7 7 7 5 3 3 2
7 7 7 7 7 5 5 3 2 2
7 7 7 7 5 5 3 3 2 1
7 7 7 5 5 3 3 2 2 1
5 5 5 5 3 3 2 2 1 1
3 3 3 3 3 2 2 1 1 1
3 3 3 2 2 2 1 1 1 1
2 2 2 2 1 1 1 1 1 1
```

MATERIALS FOR Z= 35

```
6 6 6 6 6 6 6 3 3 2
6 6 6 6 6 6 6 3 3 2
6 6 6 6 6 6 6 3 3 2
6 6 6 6 6 6 6 3 2 2
6 6 6 6 6 6 3 3 2 1
6 6 6 6 6 3 3 2 2 1
6 6 6 6 3 3 2 2 1 1
3 3 3 3 3 2 2 1 1 1
3 3 3 2 2 2 1 1 1 1
2 2 2 2 1 1 1 1 1 1
```

MATERIALS FOR Z= 36

```
6 6 6 6 6 6 6 3 3 2
6 6 6 6 6 6 6 3 3 2
6 6 6 6 6 6 6 3 3 2
6 6 6 6 6 6 6 3 2 2
6 6 6 6 6 6 3 3 2 1
6 6 6 6 6 3 3 2 2 1
6 6 6 6 3 3 2 2 1 1
3 3 3 3 3 2 2 1 1 1
3 3 3 2 2 2 1 1 1 1
2 2 2 2 1 1 1 1 1 1
```

FIG. 1 (Continued)

MATERIALS FOR Z= 37

6 6 6 6 6 6 6 3 3 2
6 6 6 6 6 6 6 3 3 2
6 6 6 6 6 6 6 3 3 2
6 6 6 6 6 6 6 3 2 2
6 6 6 6 6 6 3 3 2 1
6 6 6 6 6 3 3 2 2 1
6 6 6 6 3 3 2 2 1 1
3 3 3 3 3 2 2 1 1 1
3 3 3 2 2 2 1 1 1 1
2 2 2 2 1 1 1 1 1 1

MATERIALS FOR Z= 38

6 6 6 6 6 6 6 3 3 2
6 6 6 6 6 6 6 3 3 2
6 6 6 6 6 6 6 3 3 2
6 6 6 6 6 6 6 3 2 2
6 6 6 6 6 6 3 3 2 1
6 6 6 6 6 3 3 2 2 1
6 6 6 6 3 3 2 2 1 1
3 3 3 3 3 2 2 1 1 1
3 3 3 2 2 2 1 1 1 1
2 2 2 2 1 1 1 1 1 1

MATERIALS FOR Z= 39

4 4 4 4 4 4 4 3 3 2
4 4 4 4 4 4 4 3 3 2
4 4 4 4 4 4 4 3 3 2
4 4 4 4 4 4 4 3 2 2
4 4 4 4 4 4 3 3 2 1
4 4 4 4 4 3 3 2 2 1
4 4 4 4 3 3 2 2 1 1
3 3 3 3 3 2 2 1 1 1
3 3 3 2 2 2 1 1 1 1
2 2 2 2 1 1 1 1 1 1

MATERIALS FOR Z= 40

4 4 4 4 4 4 4 3 3 2
4 4 4 4 4 4 4 3 3 2
4 4 4 4 4 4 4 3 3 2
4 4 4 4 4 4 4 3 2 2
4 4 4 4 4 4 3 3 2 1
4 4 4 4 4 3 3 2 2 1
4 4 4 4 3 3 2 2 1 1
3 3 3 3 3 2 2 1 1 1
3 3 3 2 2 2 1 1 1 1
2 2 2 2 1 1 1 1 1 1

MATERIALS FOR Z= 41

4 4 4 4 4 4 4 3 3 2
4 4 4 4 4 4 4 3 3 2
4 4 4 4 4 4 4 3 3 2
4 4 4 4 4 4 4 3 2 2
4 4 4 4 4 4 3 3 2 1
4 4 4 4 4 3 3 2 2 1
4 4 4 4 3 3 2 2 1 1
3 3 3 3 3 2 2 1 1 1
3 3 3 2 2 2 1 1 1 1
2 2 2 2 1 1 1 1 1 1

MATERIALS FOR Z= 42

4 4 4 4 4 4 4 3 3 2
4 4 4 4 4 4 4 3 3 2
4 4 4 4 4 4 4 3 3 2
4 4 4 4 4 4 4 3 2 2
4 4 4 4 4 4 4 3 3 2 1
4 4 4 4 4 4 3 3 2 2 1
4 4 4 4 3 3 2 2 1 1
3 3 3 3 3 2 2 1 1 1
3 3 3 2 2 2 1 1 1 1
2 2 2 2 1 1 1 1 1 1

FIG. 1 (Continued)

MATERIALS FOR Z= 43

```
4 4 4 4 4 4 4 3 3 2
4 4 4 4 4 4 4 3 3 2
4 4 4 4 4 4 4 3 3 2
4 4 4 4 4 4 4 3 2 2
4 4 4 4 4 4 3 3 2 1
4 4 4 4 4 3 3 2 2 1
4 4 4 4 3 3 2 2 1 1
3 3 3 3 3 2 2 1 1 1
3 3 3 2 2 2 1 1 1 1
2 2 2 2 1 1 1 1 1 1
```

MATERIALS FOR Z= 44

```
4 4 4 4 4 4 4 3 3 2
4 4 4 4 4 4 4 3 3 2
4 4 4 4 4 4 4 3 3 2
4 4 4 4 4 4 4 3 2 2
4 4 4 4 4 4 3 3 2 1
4 4 4 4 4 3 3 2 2 1
4 4 4 4 3 3 2 2 1 1
3 3 3 3 3 2 2 1 1 1
3 3 3 2 2 2 1 1 1 1
2 2 2 2 1 1 1 1 1 1
```

MATERIALS FOR Z= 45

```
4 4 4 4 4 4 4 3 3 2
4 4 4 4 4 4 4 3 3 2
4 4 4 4 4 4 4 3 3 2
4 4 4 4 4 4 4 3 2 2
4 4 4 4 4 4 3 3 2 1
4 4 4 4 4 3 3 2 2 1
4 4 4 4 3 3 2 2 1 1
3 3 3 3 3 2 2 1 1 1
3 3 3 2 2 2 1 1 1 1
2 2 2 2 1 1 1 1 1 1
```

FIG. 1 (Continued)

CALCULATIONAL PROCEDURE

The procedure for calculating the various xenon oscillation experiments was divided into three parts:

- Calculating the proper equilibrium flux and power shape
- Calculating the proper perturbation
- Allowing the calculation to proceed so the resultant oscillation could be observed

The most difficult phase of the calculation was the first: obtaining the proper equilibrium axial and radial flux shapes. To obtain reasonable agreement between experimentally observed shapes and calculated shapes, it was necessary to adjust the thermal cross section of each of a number of regions. This was an iterative procedure, with each change in a given region resulting in a change in both the axial and radial shape. The iterative procedure was arbitrarily stopped when further changes did not significantly improve agreement between calculation and experiment.

The perturbation in the calculation involved changing the thermal cross section in two axial regions (simulating movement of the top and bottom of the partial rods) so that the resultant axial power ratio (APR) agreed with the experimentally observed axial power ratio. Since it also seemed desirable to match the APR after 1-1/2 hours when the partial rods were returned to the original position, the calculated perturbation was usually a compromise between a match in APR at time = 0 and a match in APR at time = 1-1/2 hr.

Because of the long running time of the three-dimensional calculations, some one-dimensional calculations were made to reduce the running time (Appendix A). Certain parameters required in the three-dimensional calculations were studied with one-dimensional calculations. These studies are reported in Appendix B; results indicate a convergence criterion of 2×10^{-4} is adequate, and that a time step as short as can be afforded should be used. The time step of 1/2 hour used for these calculations could produce the difference between the calculated and observed periods.

RESULTS AND CONCLUSIONS

A summary of the three-dimensional calculational results is shown in Table I in the Summary section. Plots comparing the calculations with measurements are in Figure 2. Best agreement with experiment occurs with Group 1 (Experiments 3, 4, and 6), where the calculational model most nearly corresponds to the actual experiment. Reasonable agreement in the damping factor occurs with all calculations, but the calculated period is always greater than the experimental period. The period discrepancy is discussed in Appendix B.

In general, it may be concluded that this method of analyzing xenon oscillations yields results that adequately predict the reactor stability behavior due to xenon without complicating factors such as control rod motion (detailed time behavior is not as well predicted). Since these complicating factors are usually different for each type of reactor, they require specialized treatment for any particular situation.

Other codes could be used to analyze the xenon oscillation tests. MAPLE SYRUP was chosen for this analysis on the basis of availability, but is representative of the three-dimensional "marching through time" technique used in other codes.

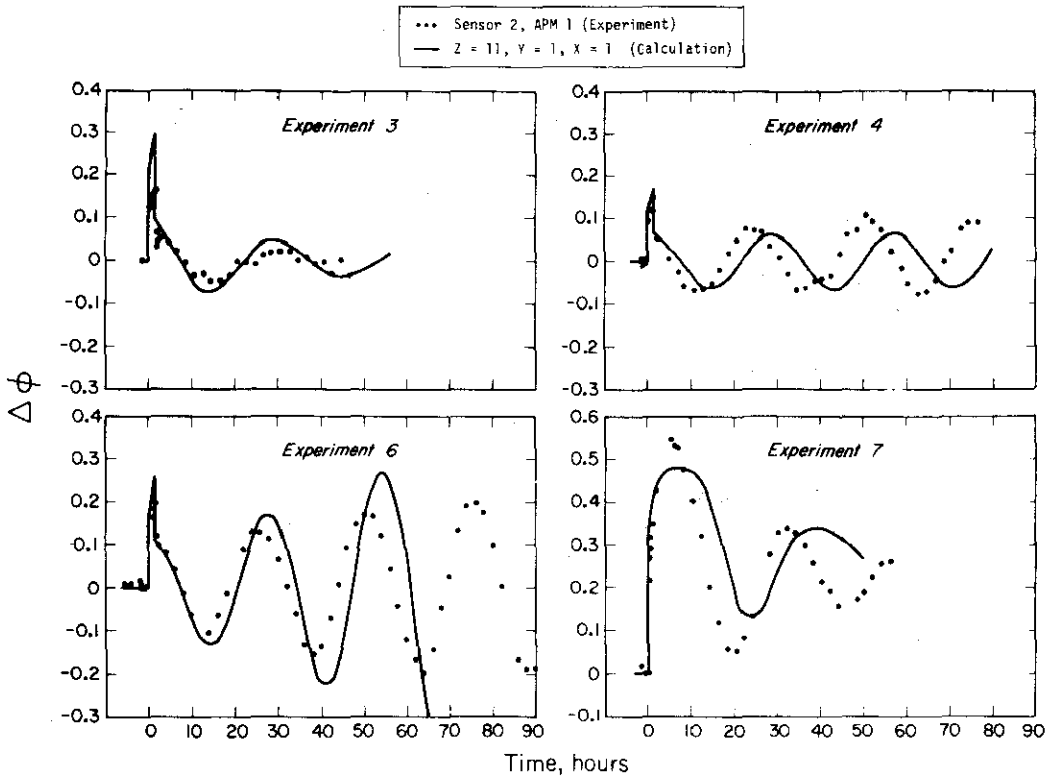

FIG. 2 RELATIVE CHANGE IN FLUX WITH TIME

APPENDIX A

ONE-DIMENSIONAL CALCULATIONS

In addition to the three-dimensional calculations, which are the main concern of this report, one-dimensional calculations were also made. The advantage of the one-dimensional studies is primarily savings in computer time, because of the use of fewer space points.

Most of the one-dimensional work was done using the axial flux shape representative of the radial center of the reactor. The results of these calculations* were consistently pessimistic in calculating a smaller damping factor than was observed. For example, the one-dimensional calculations predict a threshold oscillation (damping factor = 1) at a reactor power approximately 3/4 of the observed threshold power.

Since the axial flux shape at the radial center of the reactor is not representative of the whole reactor (axial flux shapes during the xenon tests tend to become more rounded as one proceeds radially outward), a more properly weighted choice of axial neutron flux shape would reduce the error in the one-dimensional calculations.

---

* One-dimensional modal analysis calculations using the Randall-St. John[7] model agreed with one-dimensional MAPLE SYRUP calculations.

APPENDIX B

NUMERICAL STUDIES

Variation of some of the parameters in the numerical techniques was studied to determine the influence on the calculated results. To reduce computer time required for the study, one-dimensional calculations were used. The initial flux shape for the one-dimensional calculations was chosen to give results in agreement with the three-dimensional calculations for the threshold oscillation of Experiment 4.

Convergence Criterion

An investigation of the effect of the convergence criterion used in MAPLE SYRUP was made. The convergence criteria in the code are based on the maximum change of the pointwise flux for any iteration. A value of 2×10^{-4} (that is, when no flux point changes by more than 0.02% during an iteration) was used for all three-dimensional calculations.

To determine the error introduced by this criterion, a problem was repeated with a reduced value of 5×10^{-5}. The maximum change in axial power ratios during the first 18 hours of the oscillation was 0.84%. No change in the time behavior was observed during this limited time which indicates a change in period of less than 1/2 hour.

The incentive for using the looser criterion is shorter computer running time. The increase in the running time using the tighter criterion was a factor of more than 3, an intolerable increase.

Time Step

The effect of the time step used in the MAPLE SYRUP calculations was investigated by running a series of one-dimensional calculations with various time steps. A constant time step of 1/4 hour was used for the first 1-1/2 hours; then, in a series of problems, the time step was varied from 4 to 1/4 hours.

Figure 3 shows the resultant oscillation for the five different time steps.

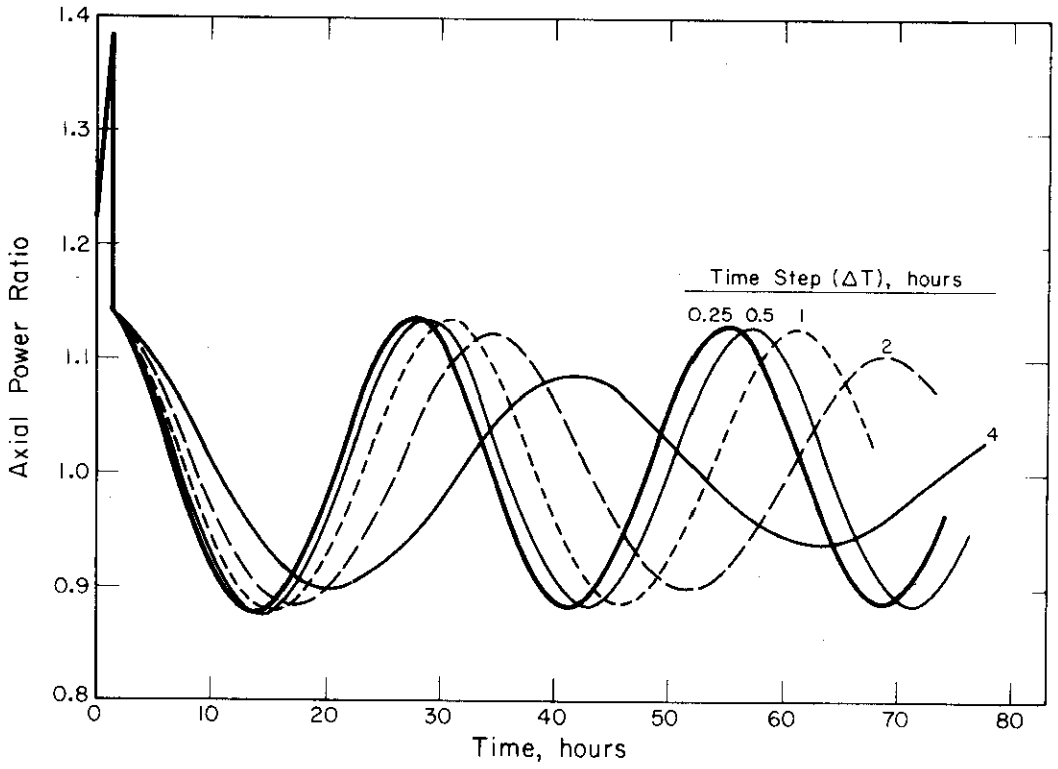

FIG. 3 EFFECT OF TIME STEP ON OSCILLATIONS

Calculated damping factors (D) as a function of time step are plotted in Figure 4. The damping factor is about the same for time steps less than 1 hour.

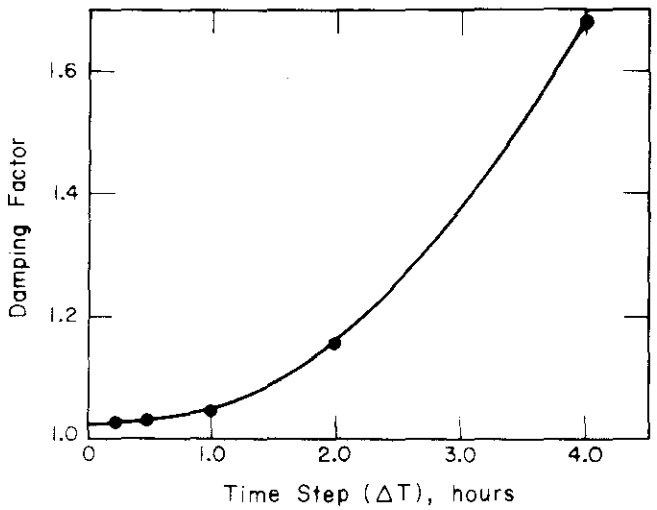

FIG. 4 EFFECT OF TIME STEP ON DAMPING FACTOR

There are two features of the time characteristics: the time between successive maxima or minima (the period τ), and the time at which the first minimum is reached. Figure 5 is a plot of the calculated period (τ) as a function of time step (ΔT). A linear extrapolation predicts a 2-hour reduction in calculated period for a zero time step as compared with a 1/2-hour time step (all three-dimensional calculations used a 1/2-hour time step). Figure 6 shows the time to the first minimum versus the time step. The one-dimensional calculations extrapolated to zero time step indicate a reduction of one hour in the calculated time to the first minimum.

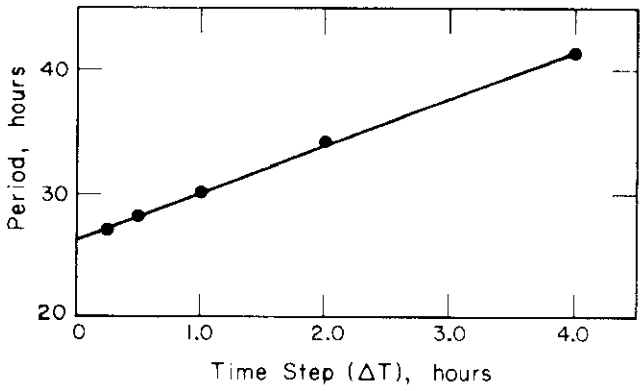

FIG. 5 EFFECT OF TIME STEP ON PERIOD

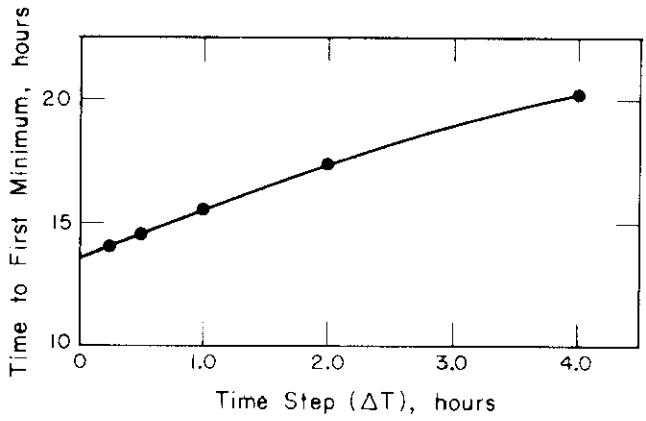

FIG. 6 EFFECT OF TIME STEP ON TIME TO FIRST MINIMUM AMPLITUDE

The conclusions of this study are:

- The convergence criterion of MAPLE SYRUP is satisfactory.
- The time step should be as small as possible with respect to computer usage.

These conclusions are in agreement with more detailed studies of numerical errors, such as reported by Poncelet and Christie.[8]

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