

CONF-850809--36

CONF-850809--36

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Seismic Analysis of a Large LMFBR with Fluid-Structure Interactions

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Abstract

The seismic analysis of a large LMFBR with many internal components and structures is presented. Both vertical and horizontal seismic excitations are considered. The important hydrodynamic phenomena such as fluid-structure interaction, sloshing, fluid coupling and fluid inertia effects are included in the analysis. The results of this study are discussed in detail. Information which are useful to the design of future reactors under seismic conditions are also given.

1. Introduction

This paper describes the seismic fluid-structure interaction analysis of a large LMFBR reactor vessel containing many internal components. Two mathematical models are developed. An axisymmetrical model is used for the vertical seismic excitation analysis, whereas a three-dimensional model (one-half of the reactor) is used for the horizontal seismic excitation analysis. In both models, the reactor vessel and internals are represented by shell elements and the sodium coolant by the continuum fluid elements. The important hydrodynamic phenomena such as fluid-structure interaction, sloshing, fluid coupling, and fluid inertial effects are fully accounted in the analysis. This is quite different from the conventional analysis which treats the fluid as added mass attached to the vessel and internals [1,2].

Five sections are contained in this paper. The introduction is given in Section 1. Section 2 describes the configuration of the reactor and the internal components. The mathematical models and results of the vertical and horizontal excitation analyses are presented in Section 3 and 4, respectively. The conclusions and recommendations are given in Section 5.

2. Description of the Reactor System

The reactor configuration used in the analysis is shown in Fig 1. It consists of a reactor core, a core support plate, a core support structure, a thermal baffle plate, and a reactor vessel filled with sodium coolant. The reactor core is enclosed by a 7.62 cm (3 in.) thick core barrel in the circumferential direction and supported on a core support plate which is supported by a core support structure and connected to the reactor vessel wall. The thickness of the cylindrical vessel wall is 8.90 cm (3.5 in.), whereas the thickness of the dished bottom head is 6.35 cm (2.5 in.). The core support plate and core support structure are complicated box-girder type of structures. However, in the mathematical models they are represented by a 3 in. thick plate and a 3.5 in. thick conical shell which have the same stiffness as the actual structure. Similarly, the skirt support is also simulated by a 4 in. thick plate with equivalent stiffness. The hot and cold sodium is separated by a horizontal thermal baffle plate which spans from the top of the core barrel to the reactor vessel

wall. The thermal baffle plate is only 3.81 cm thick (1.5 in.) and is very flexible. since the core support structure is a box-girder type of structure, the sodium coolant below the thermal baffle plate between the core barrel and vessel wall and that in the reactor lower plenum underneath the core support structure are interconnected. Therefore, a large amount of sodium is trapped between the core barrel, reactor vessel wall, thermal baffle plat, and reactor bottom head. It should be mentioned that in the mathematical model the fluids on both sides of the conical core support structure are allowed to flow through the core support structure freely.

3. Vertical Seismic Excitation Analysis

A concern in the reactor design is the maximum vertical acceleration of the reactor core during seismic disturbances. If the vertical accelerations at the reactor core exceed the gravitational acceleration during the seismic event, the subassemblies may lift off. Another concern is the interaction forces acting on the submerged components due to the fluid coupling effect. This is especially important in this case, since the thermal baffle is relatively thin. Thus, determination of the vertical response of LMFBR reactor is necessary in the seismic safety analysis.

The mathematical model used in the vertical excitation analysis is shown in Fig. 2. It is an axisymmetrical model. Thin fluid elements are placed at the fluid-structure interfaces to accommodate the contact-sliding boundary conditions. Three percent (3%) structural damping is used for all shell elements. Since fluid damping is insignificant, it is ignored in the analysis. The input seismic excitation is a 20-s, 0.52 g, vertical acceleration time history applied at the reactor skirt support. This input motion is obtained from the reactor building safe shutdown earthquake (SSE) analysis. The response spectrum of the input motion is depicted in Fig. 3. It can be seen that the spectrum has a very wide range of the strong amplification region (2-10Hz). A time history analysis is carried out using the fluid-structure interaction finite element program-FLUSTR. The time step at is 0.0025 s. The computed seismic responses consist of the relative displacements and accelerations (with respect to the fixed point, i.e. the skirt support) vs. time plots at points of interest; the fluid dynamic pressures vs. time; the shell stresses at selected locations. The significant results and findings are discussed below.

(1) The reactor system has three dominant vibration modes which can be seen in the vertical displacement time history plots at the centers of the horizontal thermal baffle (node 70), bottom head (node 168), and core support plate (node 126) shown in Figs. 4, 5, and 6, respectively. The 0.3 Hz frequency shown in Fig. 4 is believed to be the fundamental mode of the thermal baffle plate. Another two modes, 8.5 Hz and 11.5 Hz, which can be seen from Figs. 5 and 6 are the vibration modes of the bottom head and core support structure. It is noted that the frequency of the bottom head is within the strong amplification region of the input excitation, 2-10 Hz.

(2) Inspection of Fig. 4 indicates the vibration of the thermal baffle is strongly influenced by the vibration of the bottom head. The displacement history at the center of the thermal baffle consists of two components. The 0.3 Hz low frequency component is due to the vibration of the thermal baffle plate itself, whereas the 8.5 Hz high frequency component is due to the vibration of the bottom plate, which contributes about 60% of the total response. Similarly, the influence of thermal baffle vibration on the bottom head and core support plate can be observed in Figs. 5 and 6, respectively.

(3) The maximum relative accelerations at various locations are given in Fig. 7. The maximum acceleration at the junction of core support structure and vessel wall is 0.11 g, at the core barrel is 0.31 g and at the center of core support plate is 0.64 g. Using the acceleration at the junction of the core support structure and vessel wall as a reference point, the acceleration of the core is amplified three times through the core support structure and two times through the core support plate. These values provide useful information to reactor designers for controlling the acceleration at the reactor core to be within

allowable limit.

(4) The maximum shear stress is 138 MPa (20 ksi) which occurs at the junction of thermal baffle plate and the vessel. The maximum fluid pressure is 0.158 MPa (23 psi) which occurs at the bottom head. The fluid pressures above the thermal baffle plate are less than those below the thermal baffle plate.

In summary, the results indicate that the bottom head plays a very important role in the seismic design of large LMFBR reactors. This is because the fundamental frequency of the bottom head falls into the strong amplification range of the reactor support motion (2-10 Hz). The vibrational motion of the bottom head also strongly influences the motions of other submerged components and structures through the fluid coupling effects especially to flexible structures. This is clearly demonstrated from the vibrations of the horizontal thermal baffle plate.

4. Horizontal Seismic Excitation Analysis

Of particular interest in the seismic design of large LMFBRs subjected to horizontal seismic excitation is the sloshing response. The mathematical model used in horizontal analysis is a 180° sector of a three-dimensional model as shown in Fig. 8. Thin fluid elements are also used at fluid-structure interfaces to facilitate the calculation. The input seismic motion at the reactor skirt support is a 0.6 g, 20 s horizontal acceleration time history. The corresponding response spectrum is depicted in Fig. 9, which has a strong amplification region between frequencies 3-6 Hz.

The analysis indicated that the seismic response of the system is dominated by a beam-type vibrational mode with a frequency of 9 Hz. The maximum horizontal displacement (0.35 cm) and acceleration (1.16 g) are at the bottom of the reactor.

The maximum wave height is 104 cm (41 in.) which occurs at node 43 (see Fig. 8). The time history plot of sloshing at node 43 is shown in Fig. 10. The observed fundamental sloshing frequency is about 0.25 Hz which agrees with the theoretical solution (0.257 Hz) based on Housner's theory [3] for the portion of liquid coolant situated above the thermal baffle plate. The maximum pressure at the free surface is 0.017 MPa (2.5 psi); it occurred at the location (fluid element 1) where the maximum wave height occurs. The plot of pressure time history at fluid element 1 is depicted in Fig. 11. As indicated in [4], the fluid pressure in a flexible tank under sloshing motion consists of three components, two harmonic and one random. The lower frequency harmonic component is due to sloshing, the higher frequency harmonic component is due to tank wall vibration, and the random component is directly proportional to the input acceleration. The first two components can be clearly identified from Fig. 11. Also, the correlation of the lower frequency component of sloshing pressure and the free surface wave motions can be seen from Figs. 10 and 11. The maximum sloshing pressure at fluid element 1 is about 0.0055 MPa (0.8 psi). It occurs at 19 s when the maximum wave height occurs. The computed sloshing motion at $t = 19$ s is shown in Fig. 11. The fluid pressures and shell stresses are much smaller compared with those induced by the vertical seismic excitation. This is attributed to the high frequency of the fundamental vibration mode (9 Hz), which is beyond the strong amplification region of the input motion (3-6 Hz).

5. Conclusions and Recommendations

Seismic fluid-structure interaction analysis has been performed for a large LMFBR reactor with many internal components and structures. Much valuable information is obtained. This study is very useful for the design and safe evaluation of LMFBR reactors during seismic events. The major conclusions and recommendations drawn from this study are as follows:

(1) Seismic design of a large LMFBR reactor seems to have more problems associated with the vertical seismic excitation than with the horizontal excitation. This is primarily due to the wider range of the strong amplification region in the spectrum of vertical input motion. The narrow band in horizontal excitation is mainly due to the filter-out effect of the

reactor building.

(2) Due to wall flexibility and large fluid inertia, the reactor bottom head plays an important role in the overall seismic response of a large LMFBR reactor under vertical seismic excitation. Therefore, it is recommended that parametric study on the geometry and flexibility of the bottom head should be conducted during the preliminary design stage.

(3) Special attention should be given to those horizontal plate-like components or structures such as the thermal baffle plate. They could have a very large seismic response due to the inertia load of the surrounding large fluid mass and the fluid pressure induced by the vibrations of the neighboring structures. A conical-shaped baffle plate seems to be a better design for large LMFBRs.

(4) The magnitude of the vertical core acceleration under vertical seismic excitation depends on the flexibility of the core support structure and core support plate. In this study the acceleration at the center of the core is amplified three times through the core support structure and two times through the core support plate.

(5) The sloshing wave height under horizontal seismic excitation is significant. The maximum wave height is around 101 cm (40 in.). It occurs near the end of the seismic event (19 s). This indicates that the sloshing wave may become higher if an after-shock occurs.

(6) The seismic response of the LMFBR reactor under horizontal seismic excitation is primarily dominated by the beam-like vibrational mode. The frequency of the beam mode is beyond the range of the strong amplification region of the input motion. Therefore, the overall response is relatively small.

6. Acknowledgments

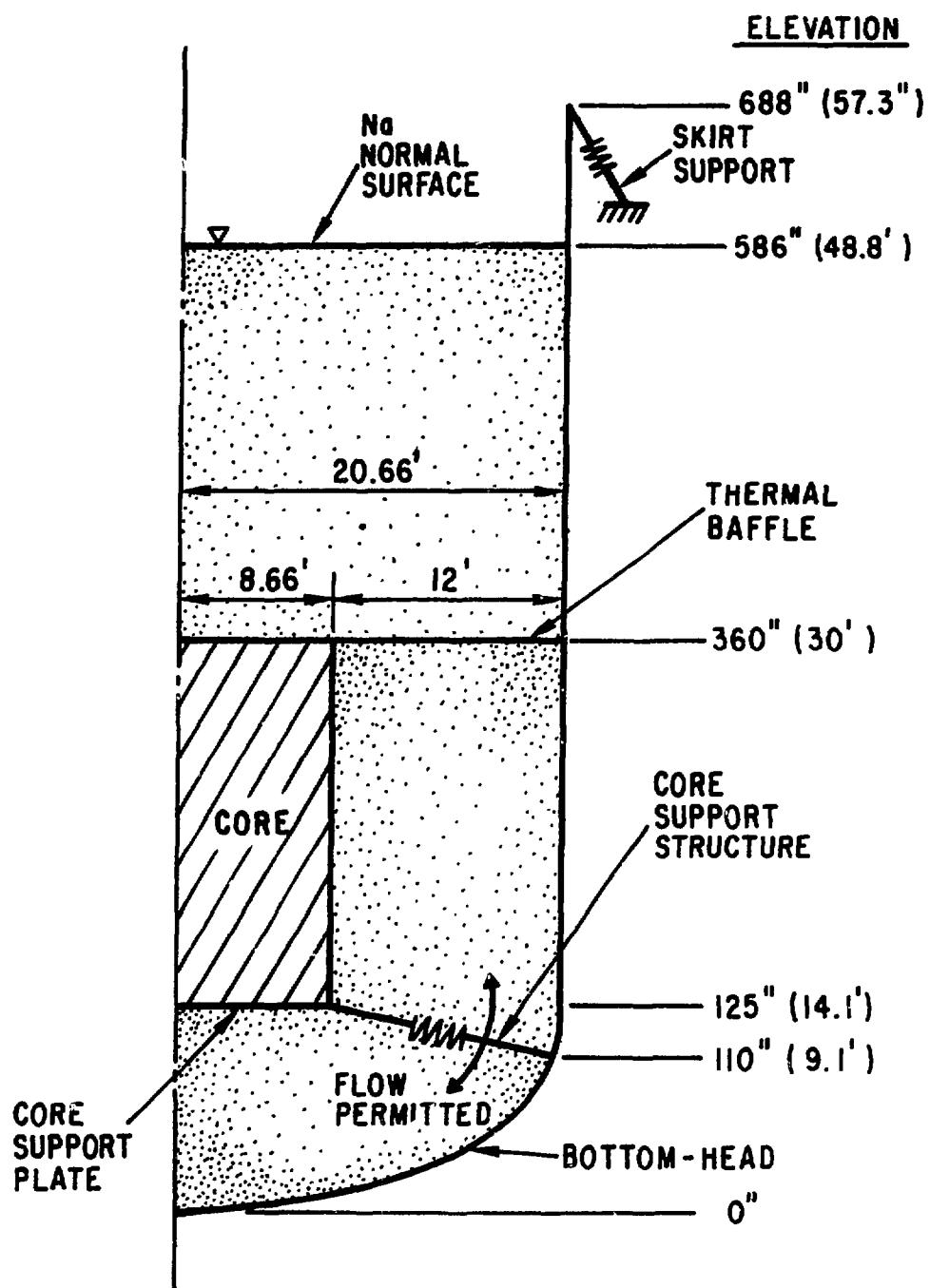
The author wishes to thank Drs. S. H. Fistedis and Y. W. Chang for their support during this study. This work was performed in the Engineering Mechanics Program of the Reactor Analysis and Safety Division at Argonne National Laboratory, under the auspices of the U.S. Department of Energy.

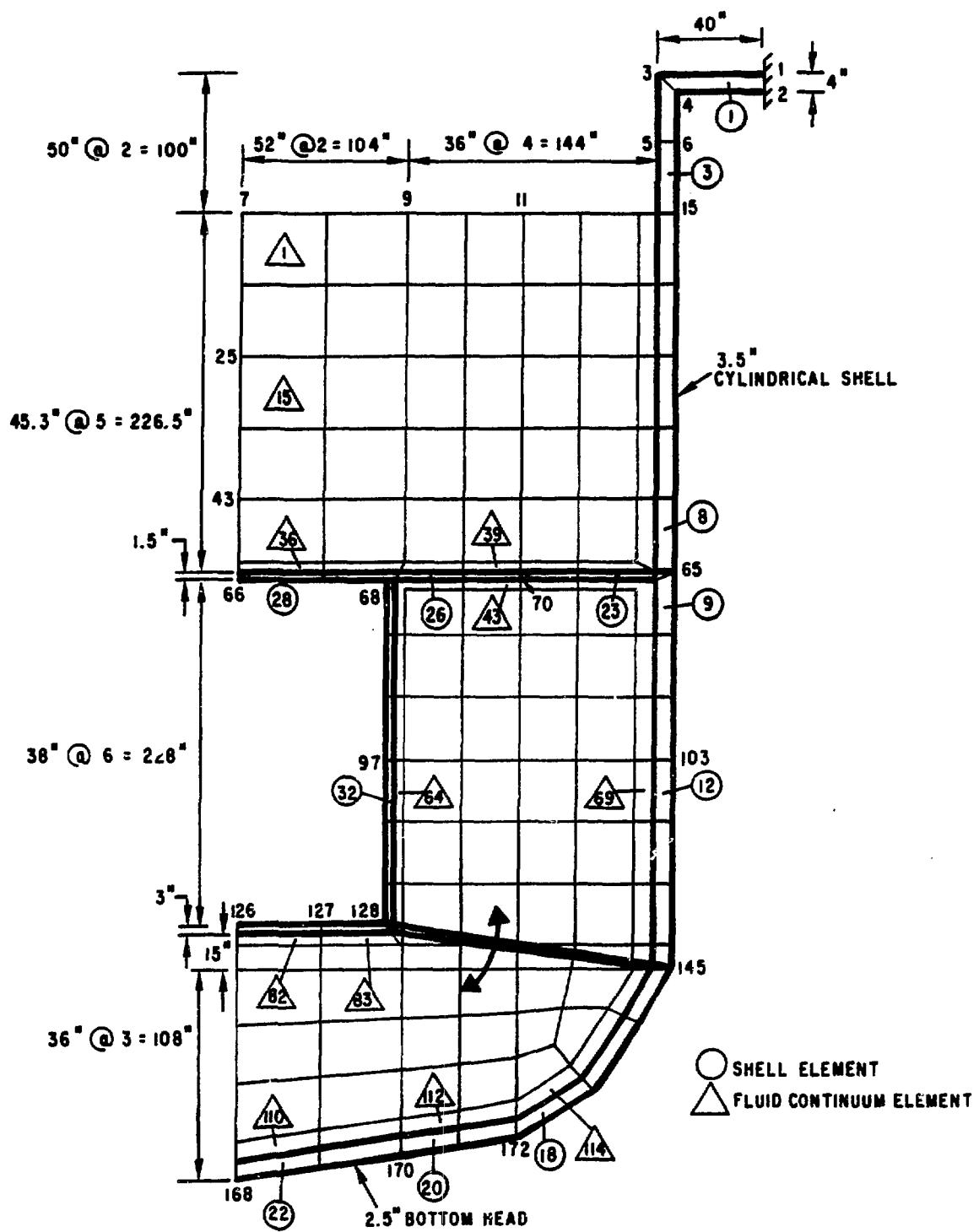
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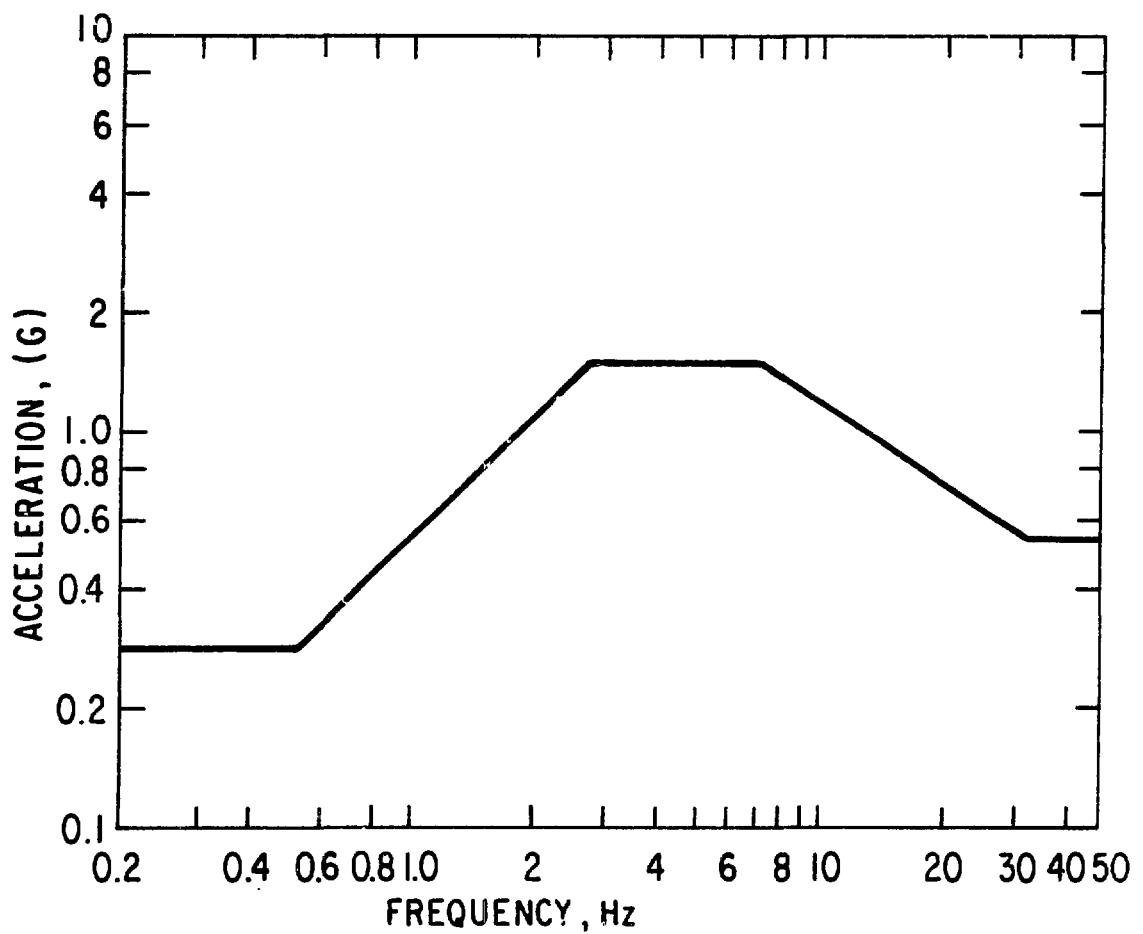
- [1] "Large Pool LMFBR Design," EPRI NP-883, Vol. 3 (August, 1978).
- [2] "Further Examination of the Pool-Type 1000 MWe LMFBR," EPRI, NP-881, Vol. 3, Appendix C (August, 1978).
- [3] HOUSNER, G. W., "Dynamic Pressures on Accelerated Fluid Containers," Bulletin of the Seismological Society of America, 47, pp. 15-35 (January, 1957).
- [4] MA, D. C., LIU, W. K., GVILDYS, J., CHANG, Y. W., "Seismic Behavior of Liquid-Filled Shells," Nuclear Engineering and Design, Vol. 70, pp. 437-455 (1982).

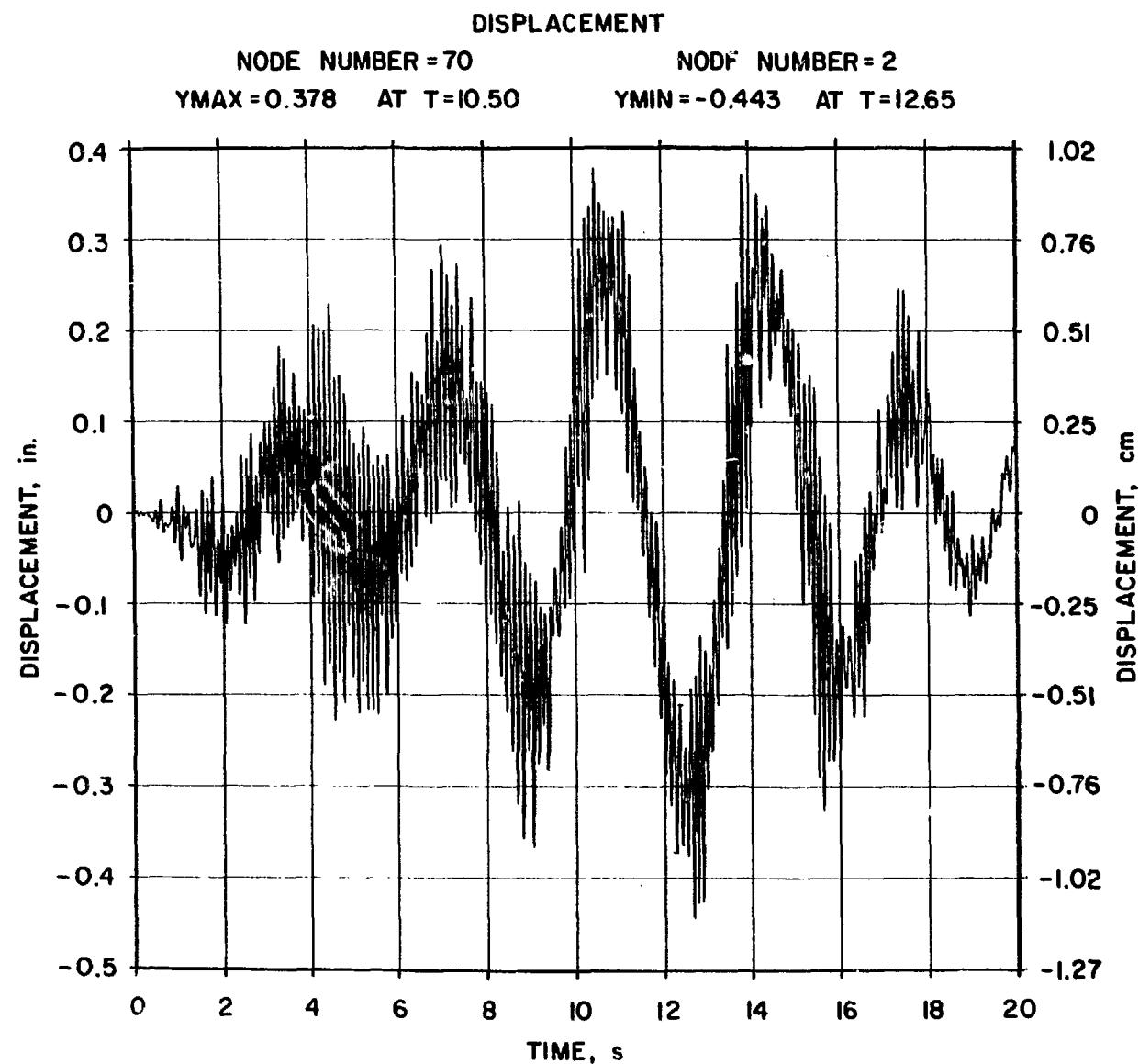
FIGURE CAPTIONS

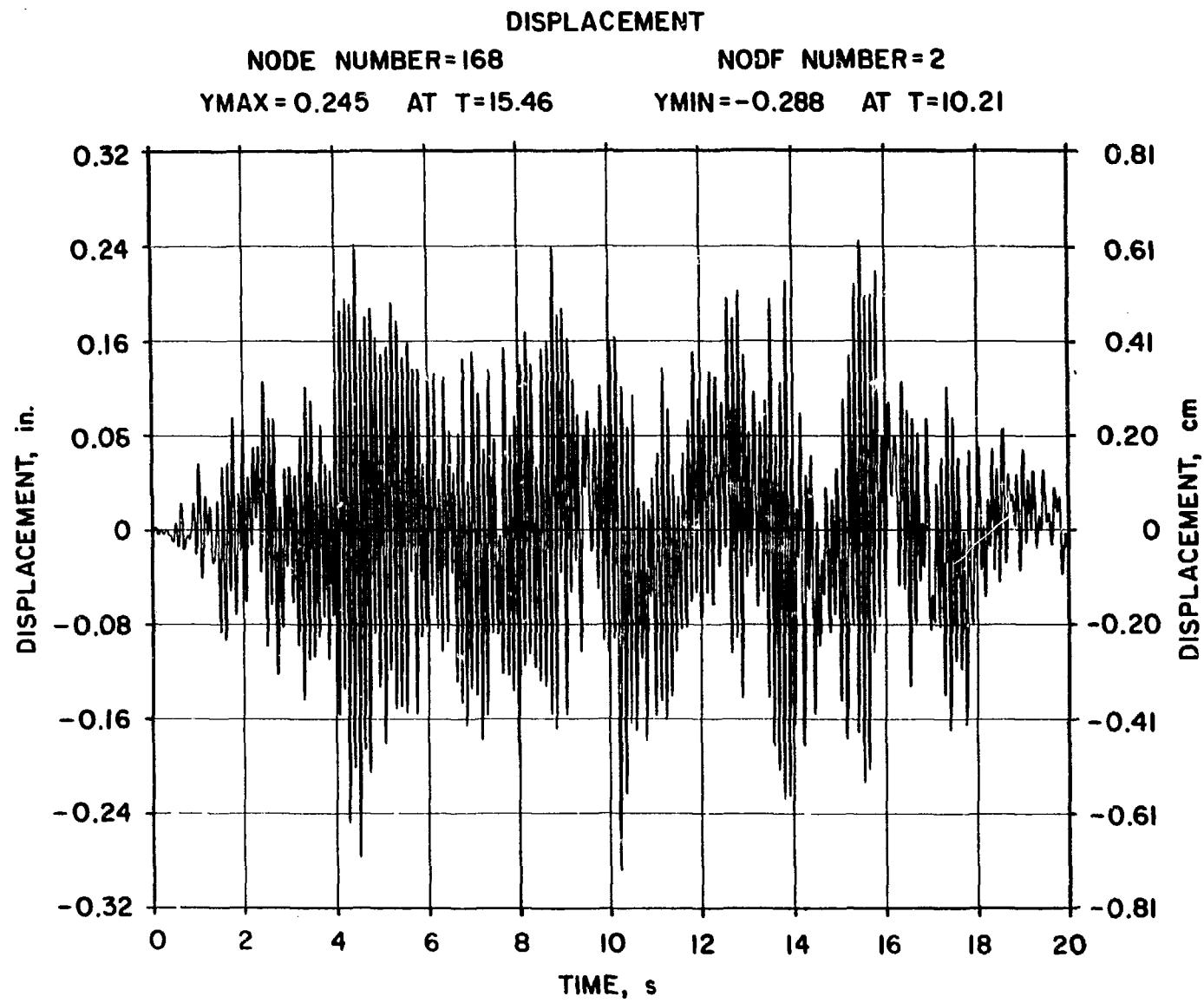
1. Configuration of a Large LMFBR reactor
2. Mathematical Model for Vertical Excitation Fluid-Structure Interaction Analysis
3. Response Spectrum of Vertical Acceleration Time History
4. Vertical Displacement Plot at Center of Baffle Plate
5. Vertical Displacement Plot at Center of Bottom Head
6. Vertical Displacement Plot at Center of Core Support Plate
7. Maximum Vertical Acceleration (g) at Various Locations
8. Mathematical Model of Horizontal Excitation Analysis
9. Response Spectrum of Horizontal Acceleration Time History
10. Free Surface (Node 43) Wave Height History
11. Free Surface (Fluid Element 1) Pressure History
12. Free Surface Sloshing Motion at $t=19$ s











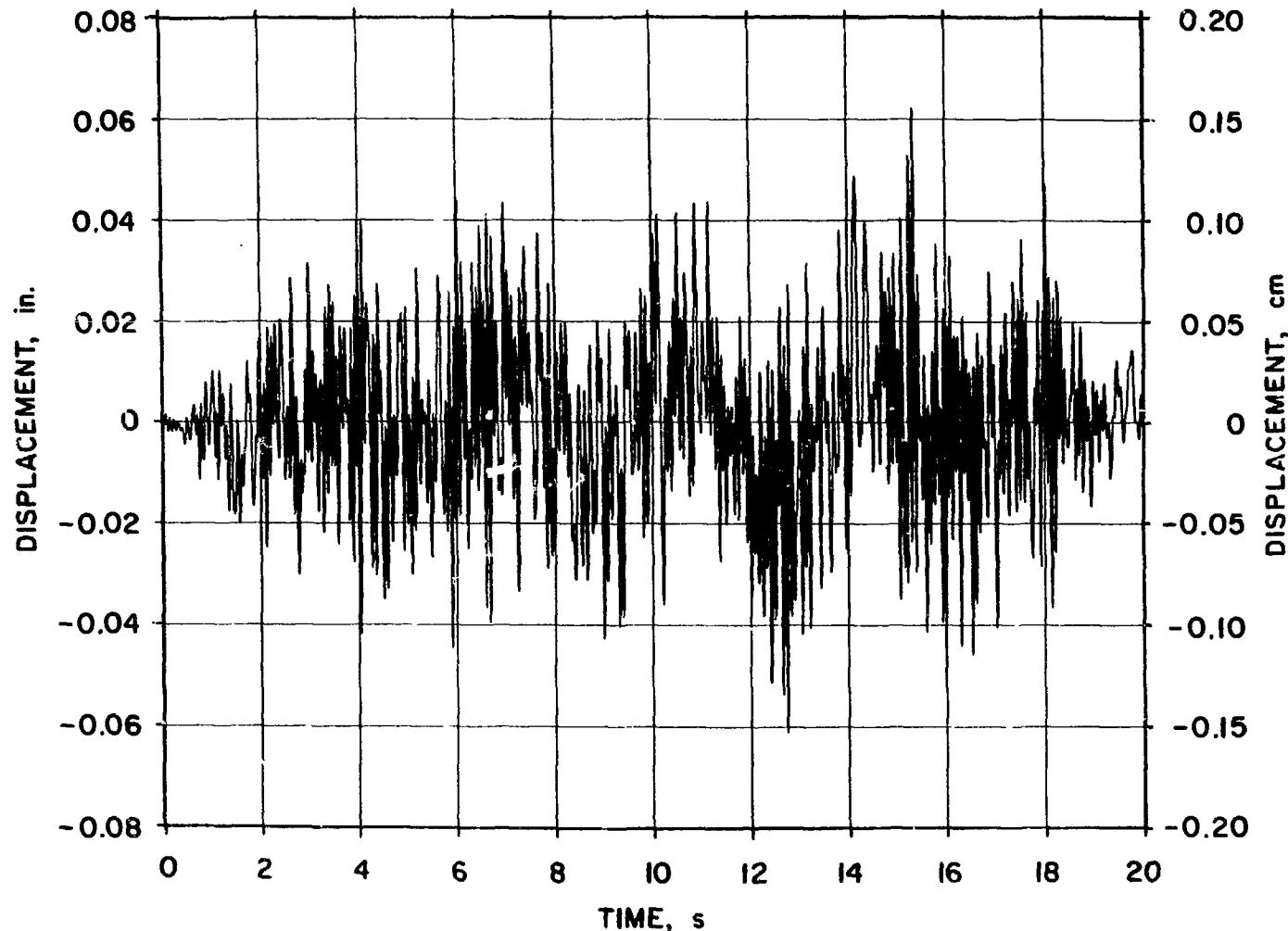
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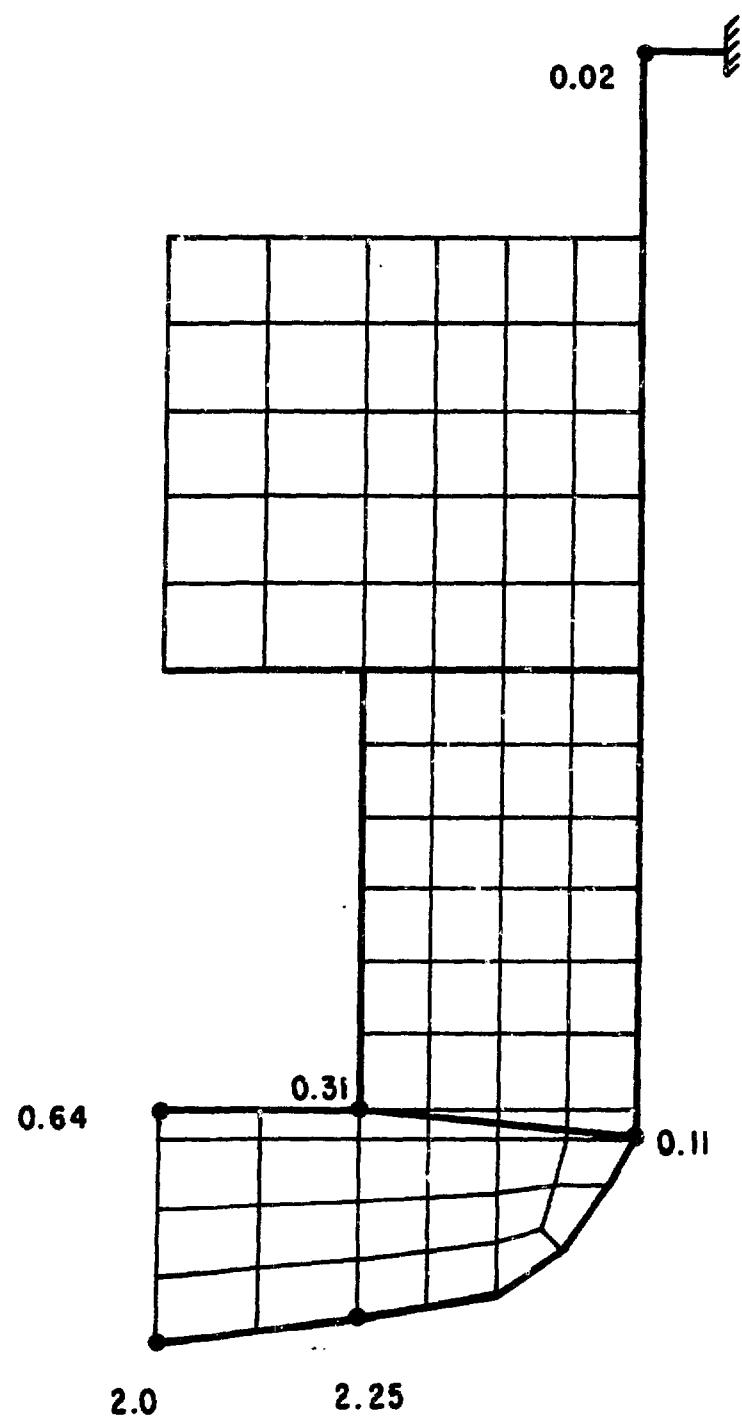
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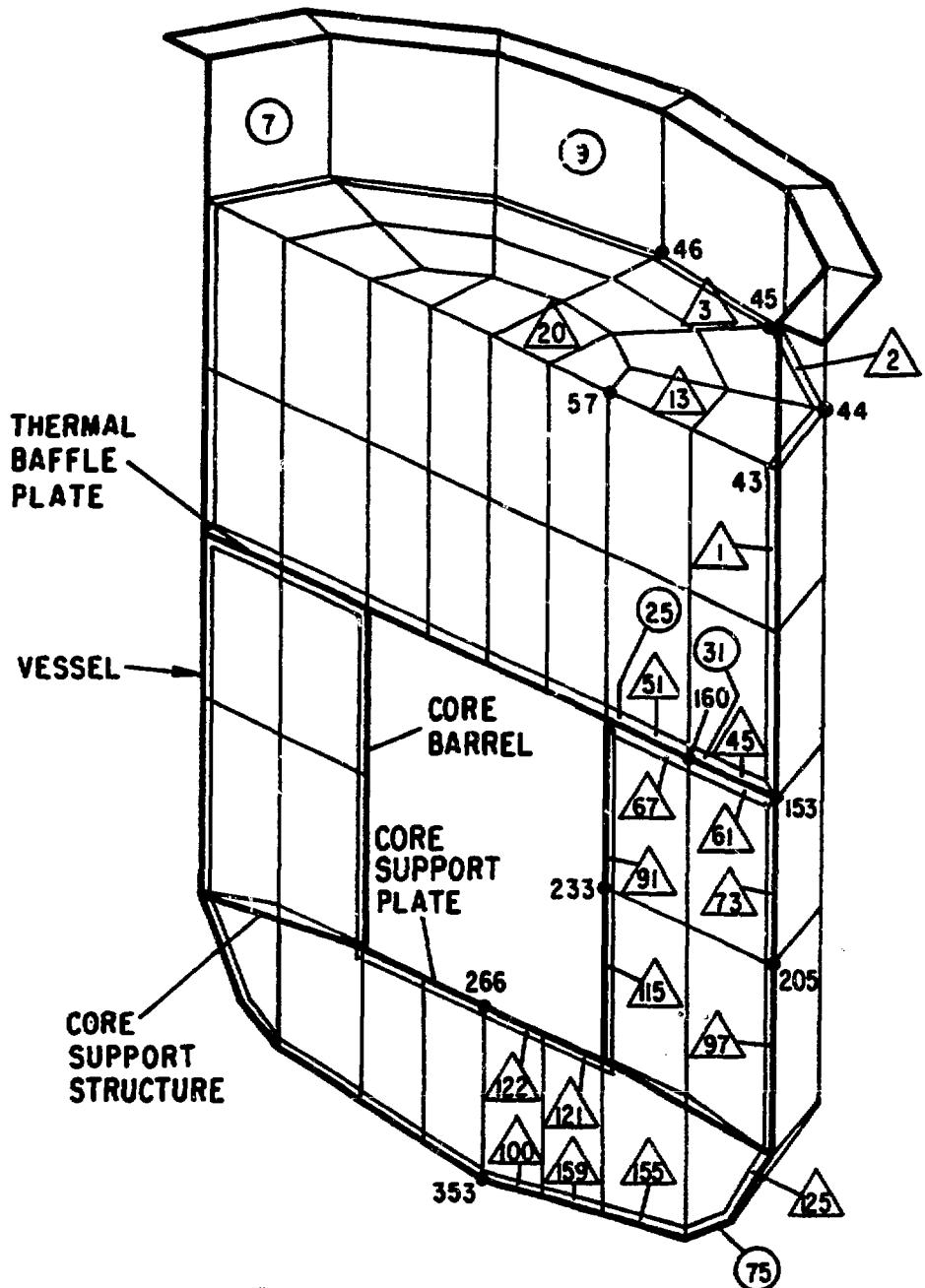
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NODF NUMBER = 2

YMIN = -0.061 AT T=12.71

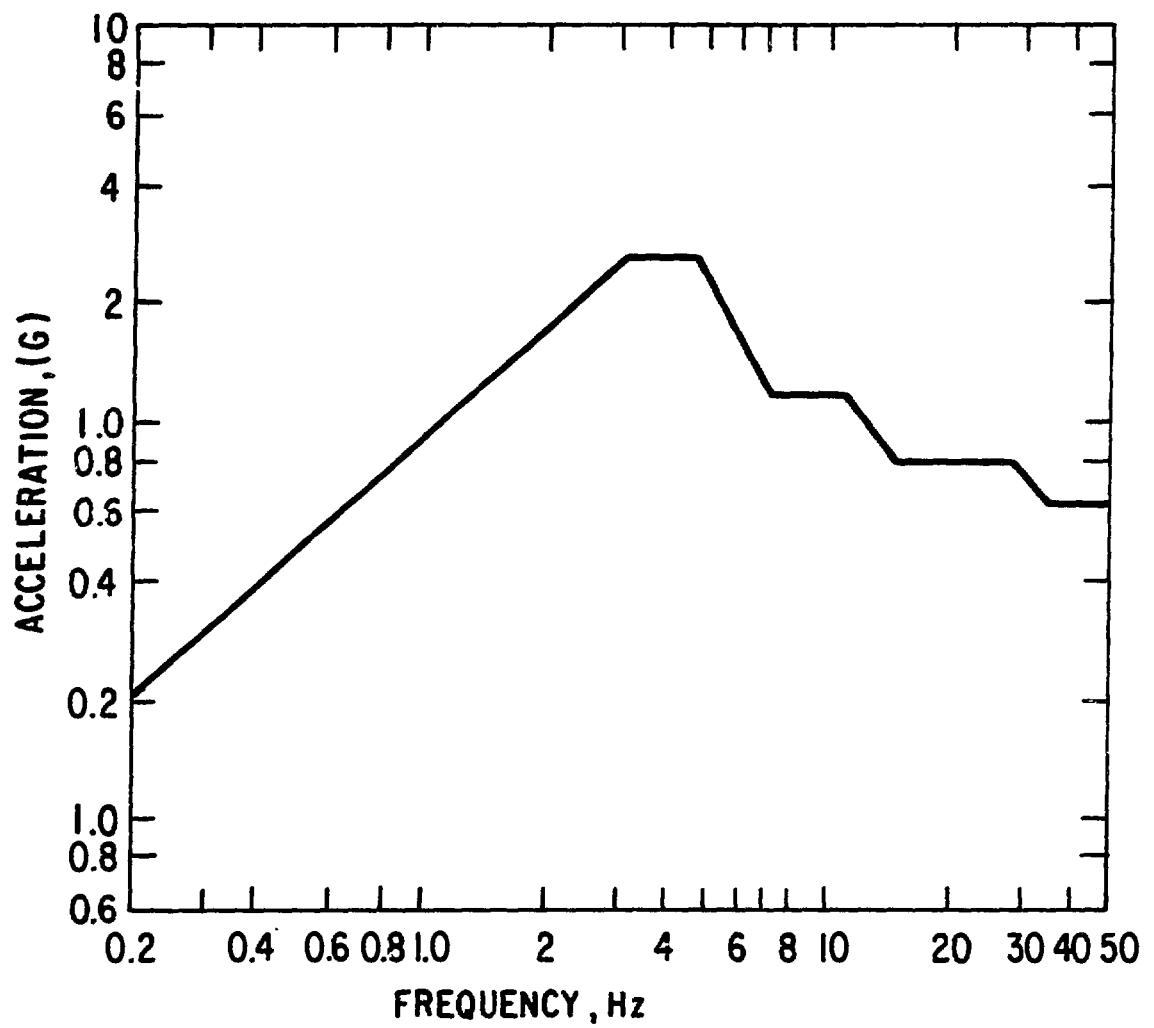






○ - SHELL ELEMENT

△ - FLUID ELEMENT



DISPLACEMENT

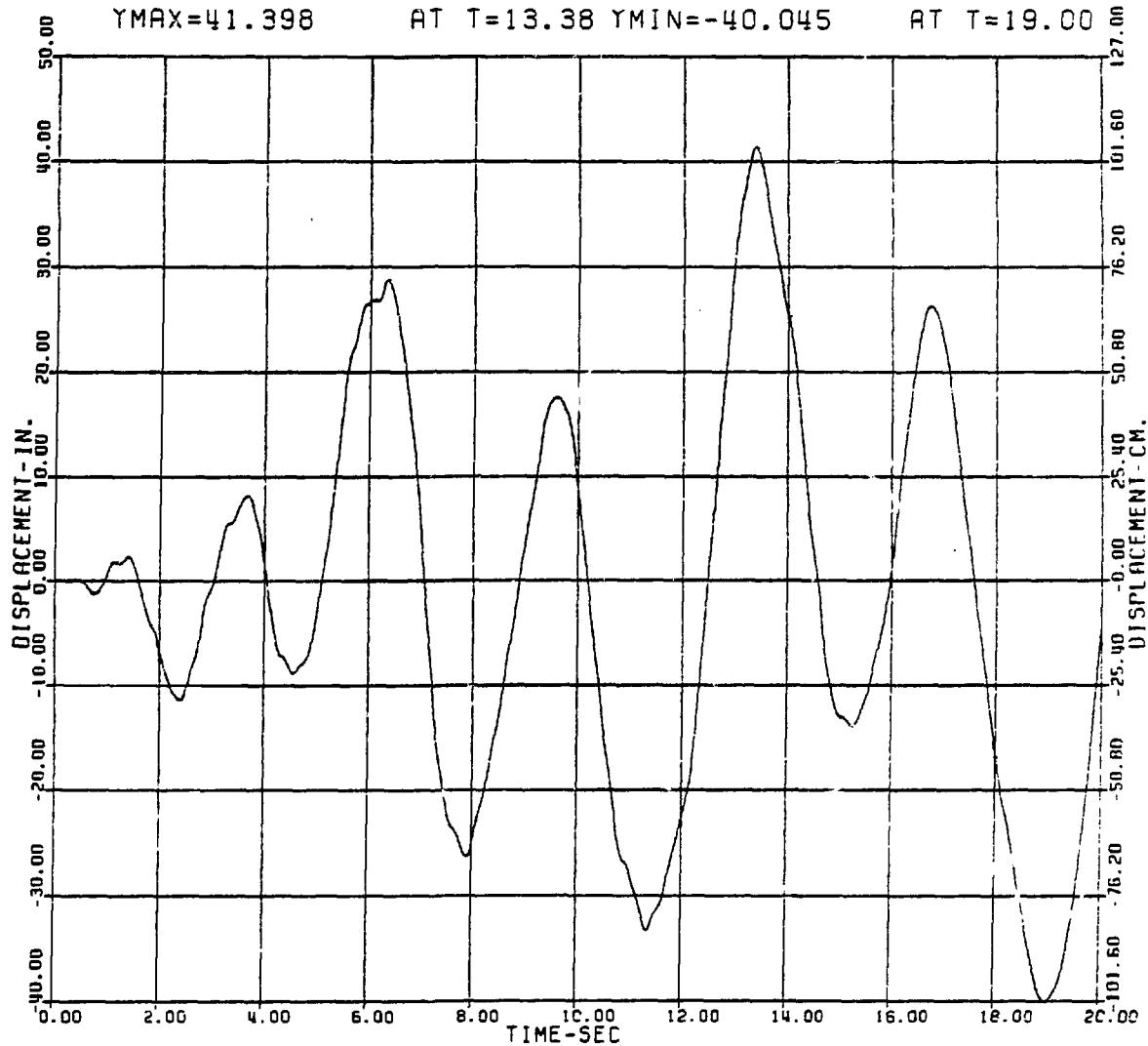
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NDOF NUMBER=3

YMAX=41.398

AT T=13.38 YMIN=-40.045

AT T=19.00



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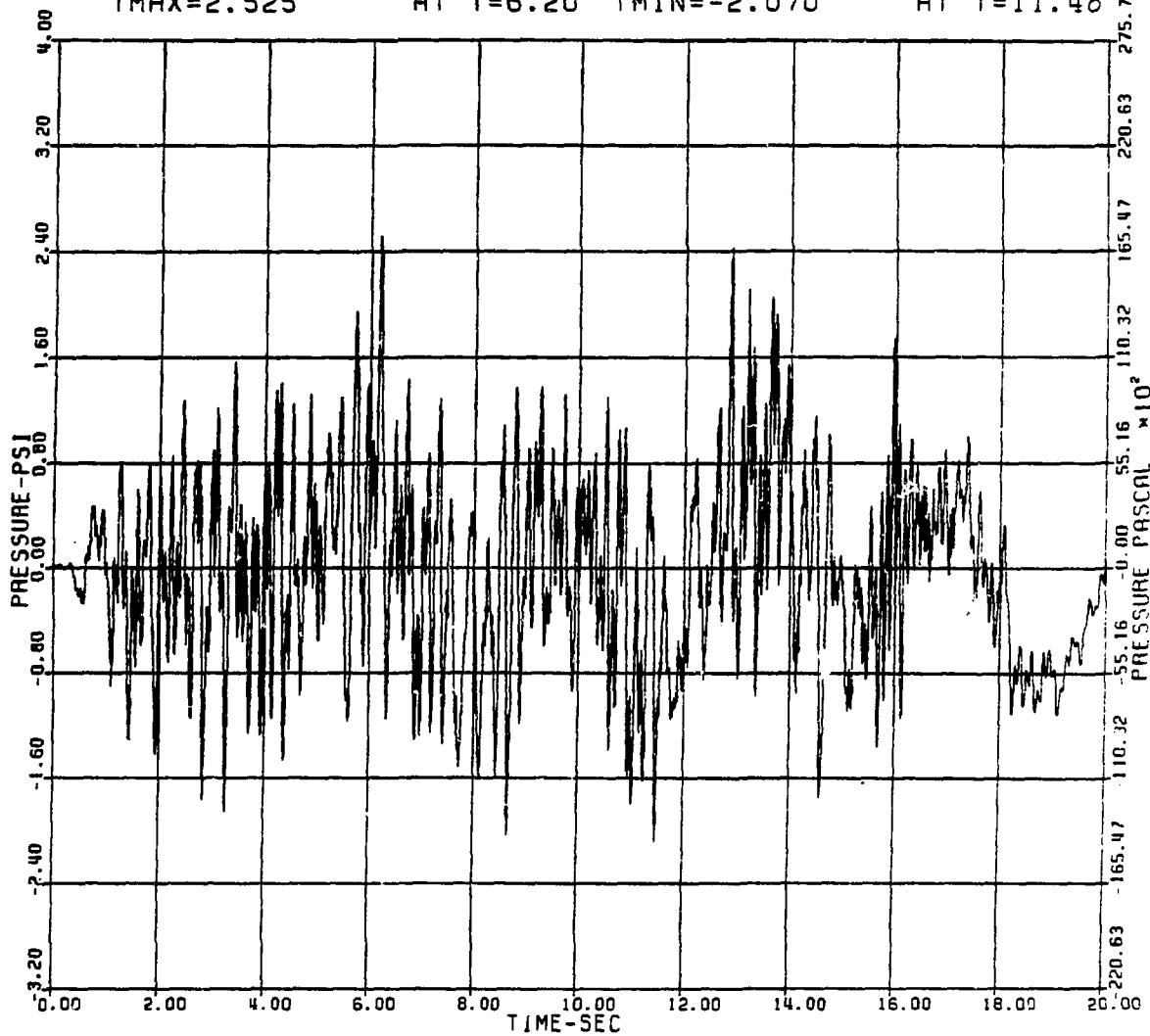
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NDOF NUMBER=7

TMAX=2,525

AT T=6.20 TMIN=-2.070

AT T = 11.48



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**COMPUTER SIMULATION OF SODIUM
COOLANT SLOSHING IN SEISMIC EVENT**

TIME = 19.000 second

