

Seismic Fluid-Structure Interaction Analysis  
of a Large LMFBR Reactor\*

by

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**MASTER**

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ABSTRACT

This paper describes a seismic analysis which includes fluid-structure interactions for a large LMFBR reactor with many internal components and structures. Two mathematical models were employed. An axisymmetrical model was used for the vertical excitation analysis whereas a three-dimensional model was used for the horizontal excitation analysis. In both analyses, the sodium coolant was treated by continuum fluid elements. Thus, important seismic effects such as fluid-structure interaction, free-surface sloshing, fluid coupling, etc. are included in the analysis. This study is useful to the design of future LMFBR reactors. The results of this study can be used to improve the margin of safety of LMFBR plants under seismic conditions.

## I. INTRODUCTION

Large LMFBR vessels contain a large amount of sodium coolant. For example, a reactor vessel of 40 ft in diameter contains 2,000,000 lbs of sodium coolant. Since most reactor components are submerged in the sodium coolant, the effects of fluid-structure interaction during seismic disturbances are of concern in the design of reactor components and reactor vessels.

Under horizontal seismic disturbances, a part of the coolant in the reactor vessel will participate in sloshing motions while the other part of the coolant will move together with the reactor vessel. The amount of fluid participating in sloshing motions depends on the vessel configuration and the fluid depth. If the vessel diameter is sufficiently large, sloshing motions can become important. Under vertical seismic disturbances, the coolant in the reactor vessel will not participate in sloshing motions. However, the reactor core may experience a very large vertical acceleration force at the core support, depending on the support conditions. This large acceleration force may cause subassemblies to lift off. Therefore, preventing the possibility of lift-off of subassemblies is a concern of safety analysis.

The response of LMFBR primary vessels subjected to horizontal ground motions has been reported in Refs. [1,2], where simple reactor vessels without internal components were studied in detail. The response of reactor vessels with simple core barrel as the internal component has been studied and reported in Ref. 3. This paper describes the seismic fluid-structure interaction analyses of a large LMFBR reactor vessel which contains many internal components such as core barrel, core support structure, thermal baffle plate, etc. The objectives of this study are (1) to accurately

determine the seismic response of the large LMFBRs which contain many internals, (2) to identify the critical areas that are overlooked in the conventional analysis, and (3) to provide recommendations for the design of future reactors.

Two mathematical models are constructed. 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 transient seismic response is obtained by solving the equations of fluid motion and structure dynamics simultaneously. Thus, important effects such as fluid-structure interaction, free-surface sloshing, fluid coupling, and fluid inertial effects can be fully accounted in the analysis. This is quite different from the conventional analysis which treats the fluid as added mass attached to the structure.

Five sections are contained in this paper. The introduction is given in Section I. Section II briefly introduces the methodology and the finite element code FLUSTR used in the coupled fluid-structure interaction analysis. Treatment of fluid-structure interfaces and utilization of thin fluid elements at the curved boundaries are also described. The vertical and horizontal fluid-structure interaction analyses are presented in Sections III and IV, respectively. The conclusions and recommendations on the design of future reactors are given in Section V.

## II. COUPLED FLUID-STRUCTURE INTERACTION ANALYSIS

For a coupled fluid-structure interaction analysis, the fluid is represented by finite fluid elements, whereas the reactor vessel and internal components are modeled by shell elements. The seismic response of the fluid-structure system is obtained by solving the equations of fluid motion and structural dynamics simultaneously. The governing equations of fluid dynamics are:

$$\dot{\rho} = -\rho v_{i,i} \quad (1)$$

$$\rho \dot{v} = \tau_{ij,j} + b_i \quad (2)$$

$$\tau_{ij} = -p\delta_{i,j} + \mu(v_{i,j} + v_{j,i}) \quad (3)$$

where  $\rho$  is the mass density,  $b$  is the body force,  $p$  is the pressure,  $v$  is the velocity vector, and  $\mu$  is the dynamic viscosity. The symbol " $\dot{\cdot}$ " denotes the material time derivative, and " $\cdot$ " denotes the spatial derivative. The equation of structural dynamics in matrix form is

$$[m] \ddot{\{q\}} + [c] \dot{\{q\}} + [k] \{q\} = \{P\} \quad (4)$$

where  $[m]$ ,  $[c]$ , and  $[k]$  are mass, damping, and stiffness matrix, respectively.  $\{q\}$  is the structural displacement vector and  $\{P\}$  is the fluid pressure acting on structures. At the fluid-structure interface, the fluid velocity normal to the structural surface is required to be equal to the normal component of the structural velocity:

$$v_n = q_n \tag{5}$$

whereas in the tangential direction of the fluid-structure interface, the fluid is allowed to slide freely. The detailed finite element formulations of FLUSTR code can be found in Refs. [4,5]. In this paper, only the treatment of fluid-structure interface is described.

#### Fluid-Structure Interface Treatment

The requirement of velocity continuity at the normal direction of fluid structure interfaces is implemented in the FLUSTR code by the contact/sliding element. The contact/sliding element is defined by three nodes, A, B, and C as shown in Fig. 1a. It has a spring with a constant of K at nodes A and B. The line connecting nodes A and B defines the "contact" direction, whereas the line joining nodes B and C denotes the "slide" direction. The local contact stiffness is first rotated to the global coordinates and then assembled into the system matrix by the standard procedure.

The contact/sliding element works well at the straight fluid-structure interfaces. However, when the interface becomes curved such as the reactor dished-bottom head, there exist two sliding directions (see Fig. 1a) and the contact/sliding element used has only one sliding direction. Therefore, it does not apply well to curved fluid-structure interfaces. To get around this difficulty, an alternative method is proposed in this study in which a thin layer of fluid element is placed at the interfaces to satisfy the requirements of fluid-structure coupling (see Fig. 1b). The thin fluid element is identical to the regular fluid element, except that it has a small dimension in the direction normal to the fluid-structure interface. The dashed lines in

Fig. 1b represent the deformed configuration of the thin fluid element. Numerical experimentation shows that the thin fluid elements can be effectively used in the curved fluid-structure interfaces.

### III. VERTICAL SEISMIC EXCITATION

#### Description of the LMFBR Reactor

The LMFBR reactor configuration used in this study is shown in Fig. 2. 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 all box-girder type of structures. They are very complicated. However, in the mathematical model, they are represented by a simple plate or shell which has the same stiffness as the actual structure. Thus, the core support plate is represented by a circular plate with a thickness of 7.62 cm (3 in.) and an adjusted elastic modulus of  $8.4 \times 10^8$  psi, whereas the core support structure is represented by a conical shell with a thickness of 8.90 cm (3.5 in.) and an adjusted elastic modulus of  $2 \times 10^{10}$  psi. Their effective stiffnesses were calculated from a detailed structural analysis. Similarly, the skirt support is also simulated by a shell of equivalent stiffness with a thickness of 10.16 cm (4 in.) and  $1.8 \times 10^9$  psi of adjusted elastic modulus. 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, and thermal baffle plate. It should be mentioned that fluids on both sides of the conical core support structure are allowed to flow through the core support structure freely.

An important 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. To prevent the possible lift offs of subassemblies is an important issue in the reactor safety analysis. Another major concern is the interaction forces between the submerged components through the fluid coupling effects. This is especially important in this case, since the thermal baffle is relatively thin. The vibrations of the reactor bottom head, vessel wall and core barrel will have a strong influence on the vibration of the baffle plate. They must be considered in the analysis.

#### Mathematical Model

The mathematical model used in vertical seismic analysis is shown in Fig. 3. It is an axisymmetrical model. The sodium coolant is represented by fluid elements, whereas the vessel and internal components are modeled by shell elements. Thin fluid elements are used at the fluid-structure interfaces to satisfy the requirements of fluid-structure coupling. A total of 36 shell elements and 110 fluid elements is used. The weight of reactor core, 1,684,000 lbs is uniformly distributed on the core support plate. Three percent structural damping is used for all shell elements. Damping of fluid is insignificant; hence it is ignored in this study.

The input seismic excitation is a 20-s duration vertical acceleration time history applied at the reactor skirt support. It has a maximum acceleration of 0.38 g. This input motion is obtained from the reactor building safe shutdown earthquake (SSE) analysis under a 0.3-g free-field motion. The input acceleration history and the corresponding response spectrum are depicted in Figs. 4 and 5, respectively. It can be seen from Fig. 5 that the maximum amplification region of the input motion is between the frequency range of 2-10 Hz.

### Discussion of Results

A time-history analysis with linear, small deflection option of FLUSTR code is carried out. The Newmark parameters are  $\beta = 1/4$  and  $\gamma = 1/2$ . The time step  $\Delta t$  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) Three dominant vibration modes are clearly shown 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) depicted in Figs. 6, 7, and 8, respectively. A low frequency of 0.3 Hz, which is believed to be the fundamental mode of the thermal baffle plate, can be seen from Fig. 6. Another two modes which can be seen from Figs. 7 and 8 are the vibration modes of the bottom head and core support structure. They have a frequency of 8.5 Hz and 11.5 Hz, respectively. It is noted that the frequency of the bottom head is within the strong amplification region of the input

excitation, i.e. 2-10 Hz (see Fig. 5).

(2) Inspection of Fig. 6 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. 7 and 8, respectively. This strong coupling existing between the thermal baffle plate and the bottom head can only be obtained in a coupled fluid-structure interaction analysis. In the conventional analysis, such as lumped mass model, this coupling effect is completely ignored.

(3) The maximum accelerations at various locations are given in Fig. 9. The maximum acceleration at the junction of core support structure and vessel wall is 0.11 g, under 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 ratios provide useful information to reactor designers for controlling the acceleration at the reactor core to be within allowable limit. The maximum absolute acceleration at the core should not exceed the gravitational acceleration. This is satisfied rather easily if one adds the maximum relative acceleration (0.64 g) and the maximum acceleration of the input excitation (0.38 g), the absolute acceleration at the reactor core is slightly more than the gravitational acceleration. If one further considers that the maximum relative acceleration and maximum

acceleration of the input motion are not always in-phase and occurring at the same time, the acceleration experienced by the reactor core should be well within the allowable limit. The maximum relative acceleration of the bottom head is 2.25 g.

(4) The maximum fluid pressures exerted on the vessel and internals are depicted in Fig. 10. In general, the fluid pressures in the fluid elements situated above the thermal baffle plate are less than those below the thermal baffle plate. The maximum pressure is 0.053 MPa (7.7 psi) at the fluid zone directly underneath the center of the thermal baffle and then increases to 0.069 MPa (10 psi) at the fluid zone about the midheight of the core barrel and reaches to 0.158 MPa (23 psi) at the bottom head. The time history plots of the fluid pressure directly underneath the baffle plate and at the center of the bottom head are depicted in Figs. 11 to 12, respectively. Again, strong coupling effect is observed between the thermal baffle and bottom head. The maximum shell stress is 138 MPa (20 ksi) at the thermal baffle plate.

(5) The fluid added mass or hydrodynamic mass can be obtained from the fluid pressure,  $p$ , and the structural acceleration normal to the fluid-structure interface,  $q_n$ ,

$$p = (m_s + m_a) q_n \quad (6)$$

in which  $m_s$  is the structural mass and  $m_a$  is the added mass. For example, from the values of the pressure and acceleration of the bottom head, one obtains the added mass on the bottom head.

$$m_a = \frac{p}{q_n} - m_s \quad (7)$$

This will greatly improve the usage of the lumped mass technique to lump the right amount of fluid onto the adjacent structures and to facilitate the seismic analysis for preliminary designs.

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 frequency range of the strong amplification region of a typical earthquake 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.

In order to further study the effects of bottom head geometry on the overall seismic response of the reactor system, the reactor bottom head is changed from a dished configuration to a flat configuration as shown in Fig. 13. The results indicate that the bottom head and thermal baffle are moving in unison with a vibrational frequency of 3.5 Hz. Because of the increased flexibility and the added mass effects of the bottom head, the overall seismic responses of a flat bottom head reactor are much larger than those in the dished-bottom head case.

This additional analysis further indicates that the configuration of the bottom head is very important to the overall seismic response. Therefore, it is recommended that parametric studies using the configuration of the bottom head as a parameter should be performed during the preliminary design stage for large LMFBR reactors. The proper amount of added mass on the bottom head can be obtained from the results of the fluid-structure interaction analysis.

#### IV. HORIZONTAL SEISMIC EXCITATION

##### Mathematical Model

Of interest to the seismic design of large LMFBRs subjected to horizontal seismic excitation is the free-surface sloshing response. For example, what is the maximum wave height? How big will be the sloshing pressures and the seismic-induced stresses at critical points?

The free-surface sloshing motion is an important seismically-induced hydrodynamic phenomenon in the large LMFBR reactors under horizontal seismic excitations. Due to the presence of large free surface, portions of the sodium coolant will participate the sloshing motions characterized by a low-frequency oscillation with standing waves on the free surface moving up and down. The amount of sodium coolant participating in sloshing motions depends on the vessel configuration and fluid depth. If the free-surface wave heights are large, the sloshing becomes nonlinear. A nonlinear formulation on the fluid motion is necessary. In general, if the wave heights exceed one tenth of the diameter of the tank, the sloshing response becomes nonlinear [6]. In the present study, we assume the sloshing response is small, i.e. linear sloshing. The surface wave effects are approximated by a perturbation method on the body force of the fluid. The detailed treatment of this method used in FLUSTR code can be found in Refs. 1 and 2.

The mathematical model used in horizontal analysis is a 180° sector of a three-dimensional model as shown in Fig. 14. The physical dimensions and material properties are identical to those of the axisymmetrical model used for vertical seismic excitation analysis. The weight of reactor core is uniformly distributed on the wall of the core barrel. 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 20 s horizontal acceleration time history shown in Fig. 15. The maximum acceleration is 0.45 g, which occurs at  $t = 6.2$  s. The corresponding response spectrum for that time history is depicted in Fig. 16, which has a strong amplification region between frequencies 3-6 Hz.

A seismic fluid-structure interaction analysis is carried out. It also uses the linear small deflection option of the FLUSTR code. Three percent structural damping is used for the shell elements. The time step is 0.005 s and Newmark parameters are  $\beta = 1/4$  and  $\gamma = 1/2$ . Important results of this analysis are discussed below.

#### Discussions of Results

The overall seismic response of the reactor vessel and the internals is dominated by a beam-type vibrational mode with a frequency of 9 Hz. The reactor vessel acts like a cantilever beam. The seismic response follows a  $\cos\theta$  distribution in the circumferential direction. The maximum horizontal displacement (0.35 cm) and acceleration (1.16 g) are at the bottom of the reactor. They are small and within the allowable limit. The core has a 0.97 g maximum horizontal acceleration. At the centerline of the reactor, such as center of the core, it has neither vertical displacement nor vertical acceleration during the horizontal excitation.

The maximum vertical displacements at the free surface (sloshing wave heights) are depicted in Fig. 17. The maximum wave height is 104 cm (41 in.) which occurs at the free surface vessel interface at the diametric direction of the vessel along the direction of horizontal excitation (node 43). However, the maximum wave height is less than 1/10 of the diameter (500 in.) of the vessel. This indicates that the small sloshing assumption used in the

analysis is valid. The free surface sloshing motions at intervals of 1 s are given in Fig. 18. Inspection of the sloshing motions indicate that the sloshing motion is dominated by the fundamental sloshing mode. However, higher modes are also participating in the sloshing motion. This can be seen from the sloshing motions at  $t = 8, 10, 15,$  and  $19$  s. The maximum sloshing waves occur at  $t = 19$  s. The time history plot of sloshing at node 43 is shown in Fig. 19. The observed fundamental sloshing frequency is about 0.25 Hz (period = 4 s) which agrees with the theoretical frequency value (0.257 Hz) calculated, based on Housner's theory [7] for the portion of liquid coolant situated above the thermal baffle plate. The maximum wave height, as can be seen from Fig. 19, occurs near the end of the seismic event. Since the damping of the fluid is small, the post-earthquake sloshing will last for a long time. Therefore, larger sloshing waves may build up in the reactor vessel if after shocks occur. The interaction of sloshing and tank vibration [1,2], i.e., the superposition of the tank wall vibration on the sloshing response, is very small. This is because the sloshing frequency (0.25 Hz) and vessel vibrational frequency (9 Hz) are well separated. Therefore, coupling between the two modes is unnoticeable. 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. 20. As indicated in the previous study of simple reactor tanks [1,2], 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. 20. Also, the correlation of the

lower frequency component of sloshing pressure and the free surface wave motions can be seen from Figs. 19 and 20. 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 pressure distribution at the free surface is found to be of  $\cos\theta$  type. The fluid pressures below the thermal baffle are generally higher than those above the thermal baffle. However they are small compared with those induced by the vertical seismic excitation. The maximum stress is 29 MPa (4.2 ksi) at the top of the vessel. This value is well below the allowable limit. It is in part attributed to the use of the thick-wall vessel (3.5 in.) and in part due to the high frequency of the fundamental vibration mode (9 Hz), which is beyond the strong amplifications region of the input motion (3-6 Hz).

## VI. CONCLUSIONS AND RECOMMENDATIONS

Seismic fluid-structure interaction analysis has been performed for a large LMFBR reactor with many internal components and structures. Two mathematical models are developed, one for vertical seismic excitation and the other for horizontal seismic excitation. 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 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. For example, the strong amplification region of the input motion used in this study is between 3-6 Hz for horizontal excitation and 2-10 Hz for vertical seismic excitation. The narrow band in horizontal excitation is mainly due to the filter-out effect of the reactor building. For this reason, the overall seismic response calculated from this study due to vertical excitation is generally larger than that induced by horizontal excitation.

(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. It is believed that the dished bottom head has a significant effect on the overall response of the LMFBR reactors. A flat bottom head will increase both the flexibility and fluid

inertia effect. Therefore, it cannot be used to represent a large-diametered LMFBR reactor in the mathematical model.

(3) Special attention should also be given to those horizontal plate-like components or structures such as the thermal baffle plate. They could have a very large seismic response, partly due to its own flexibility and large fluid inertia load, and partly due to the fluid pressure induced by the vibration of the bottom head. The latter is the well known "fluid coupling" effect. A conical-shaped baffle plate seems to be a better design for large LMFBRs.

(4) In this study, we found that a strong coupling existed between the vibrational motions of the bottom head and thermal baffle. Therefore, finite element representation of fluid is necessary. This coupling effect is ignored in the conventional lumped mass model in which an arbitrary amount of fluid mass is lumped to the bottom head and thermal baffle plate.

(5) The fluid added mass can be obtained through the relationship between the fluid pressure and structural acceleration time histories obtained from this study. They are very useful in the conventional lumped mass model calculation. For example, the correlation between the fluid pressure and structural acceleration time histories at the bottom head can be used for the parametric study of the bottom head.

(6) The primary concern in the design of an LMFBR reactor is the vertical acceleration at the reactor core caused by the vertical seismic excitation. The horizontal seismic excitation induces neither vertical acceleration nor vertical displacement at the center of the core. The magnitude of vertical core acceleration under vertical seismic excitation depends on the flexibility of the core support structure and core support plate. Based on the acceleration values obtained from this analysis, we found that 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.

(7) Fluid sloshing does not appear to be a problem in vertical seismic excitation. The free surface waves are mainly due to the vibration of the thermal baffle. They are negligibly small. The sloshing wave height under horizontal seismic excitation, however, 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. Also, higher sloshing modes do participate in the sloshing motion. These two facts are usually ignored in the conventional sloshing analysis.

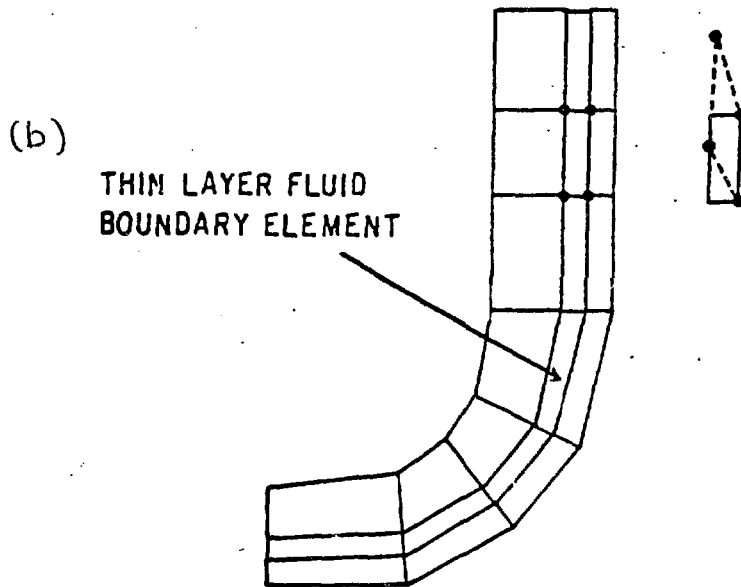
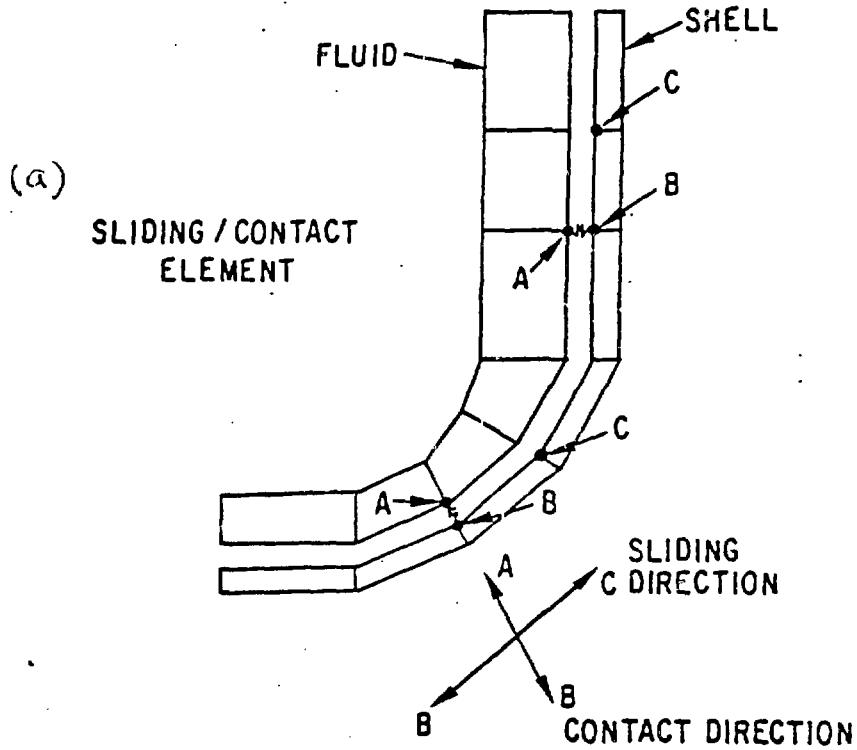
(8) The seismic response of the LMFB reactor under horizontal seismic excitation is primarily dominated by the beam-like vibrational mode. The frequency of the beam mode is 9 Hz which is beyond the range of the strong amplification region. Therefore, the overall response is relatively small. The maximum displacement and acceleration is at the bottom head. The maximum shell stress occurs at the top of the reactor vessel. All the response is well within the design limit.

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(a) (b)  
 Fig. 1. Contact/Sliding Element and Thin Fluid Element.

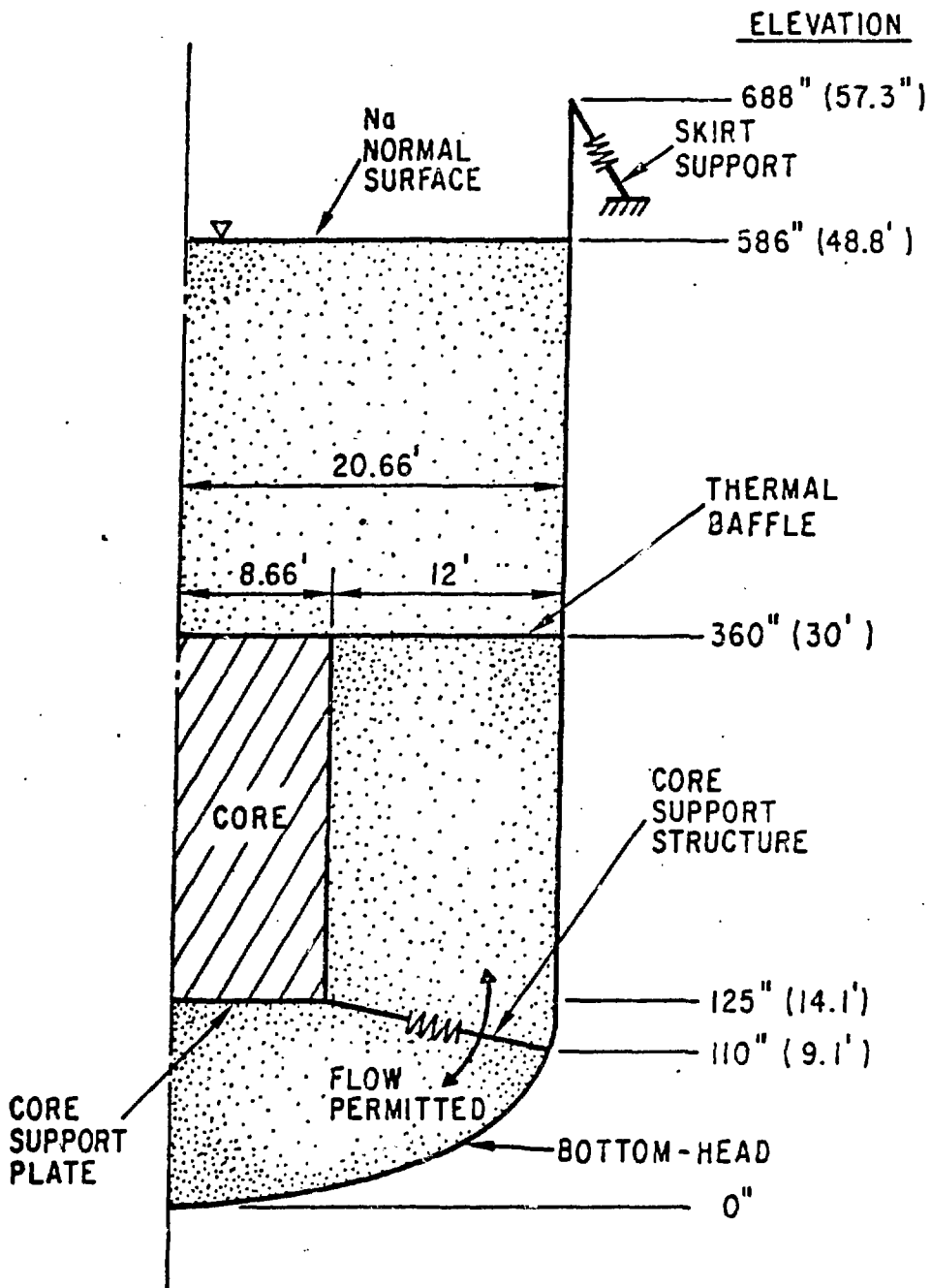


Fig. 2. Configuration of a Large LMFBR Reactor.

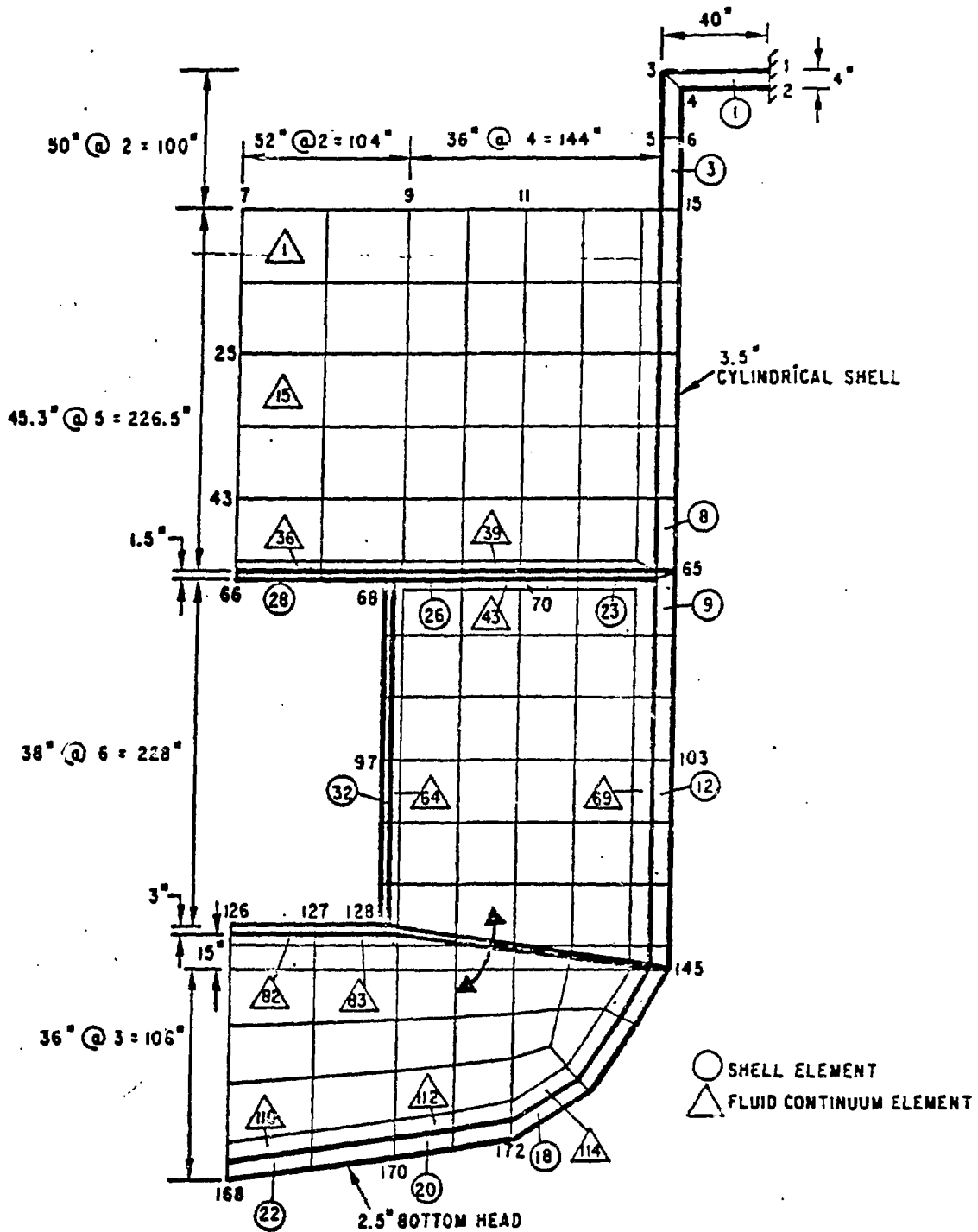


Fig. 3 . Mathematical Model for Vertical Excitation Fluid-Structure Interaction Analysis.

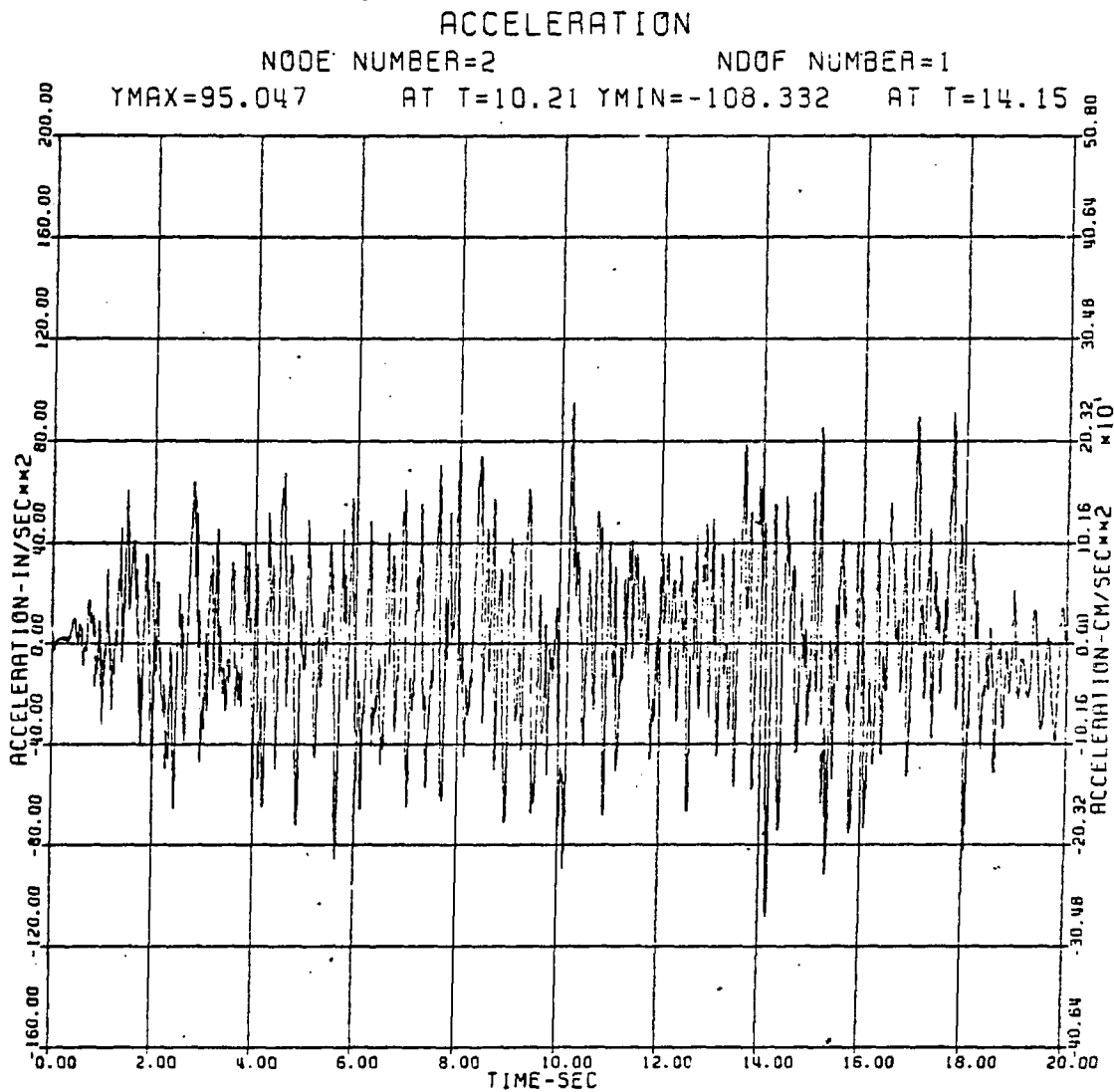


Fig.4. Twenty Second Duration Vertical Acceleration Time History.

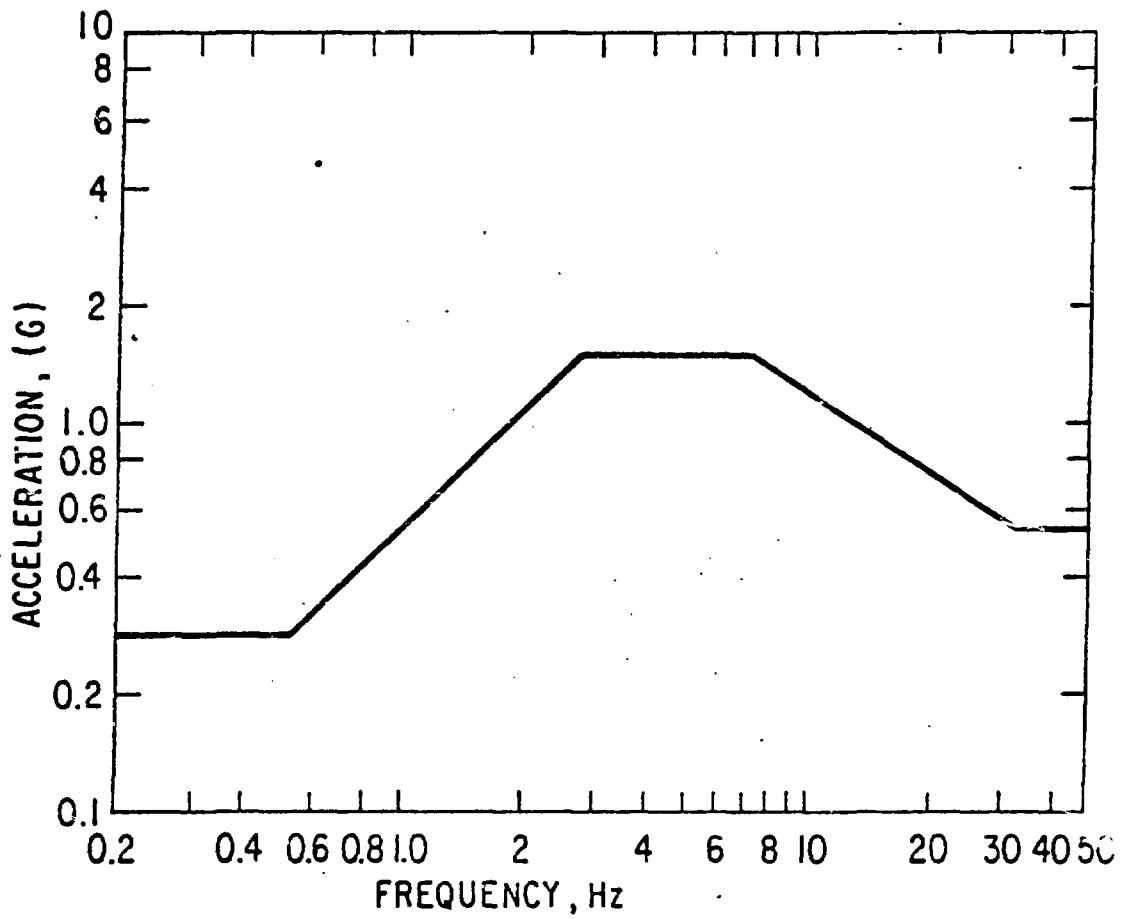


Fig. 5. Response Spectrum of Vertical Acceleration Time History.

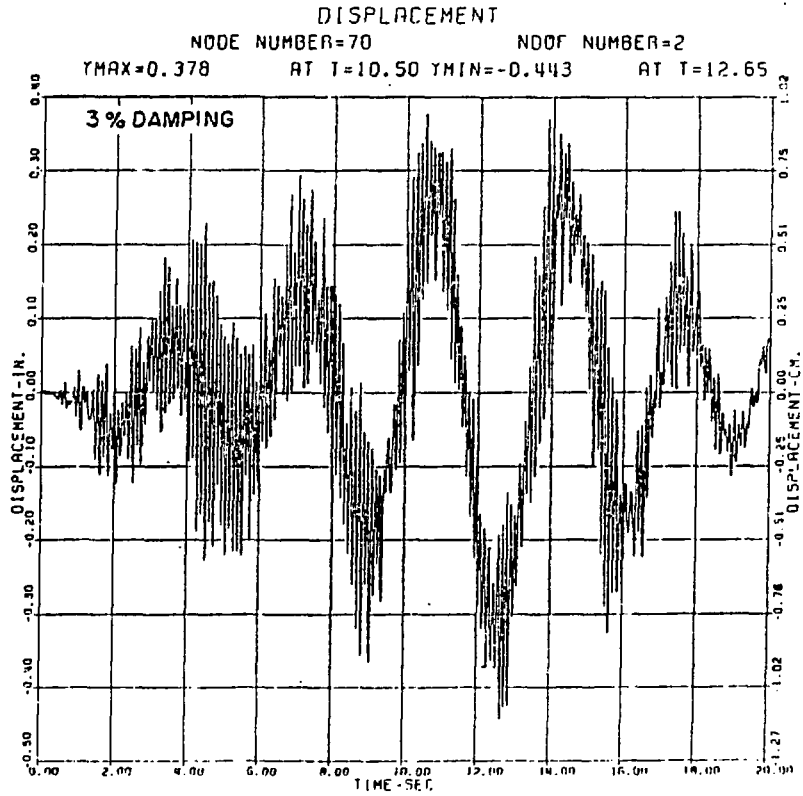


Fig. 6. Vertical Displacement Plot at Center of Baffle Plate.

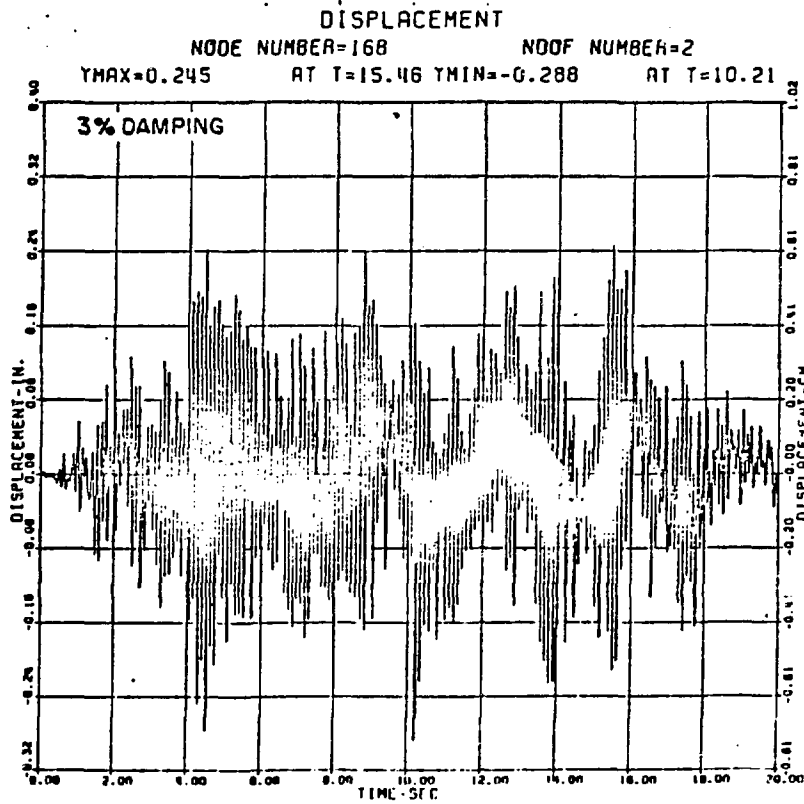


Fig. 7. Vertical Displacement Plot at Center of Bottom Head.

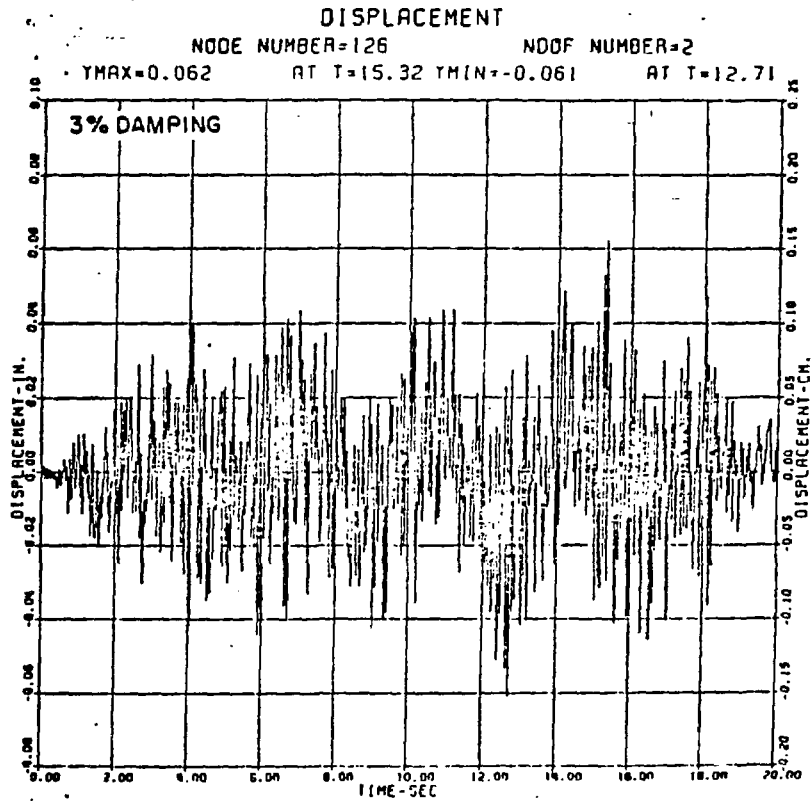


Fig. 8. Vertical Displacement Plot at Center of Core Support Plate.

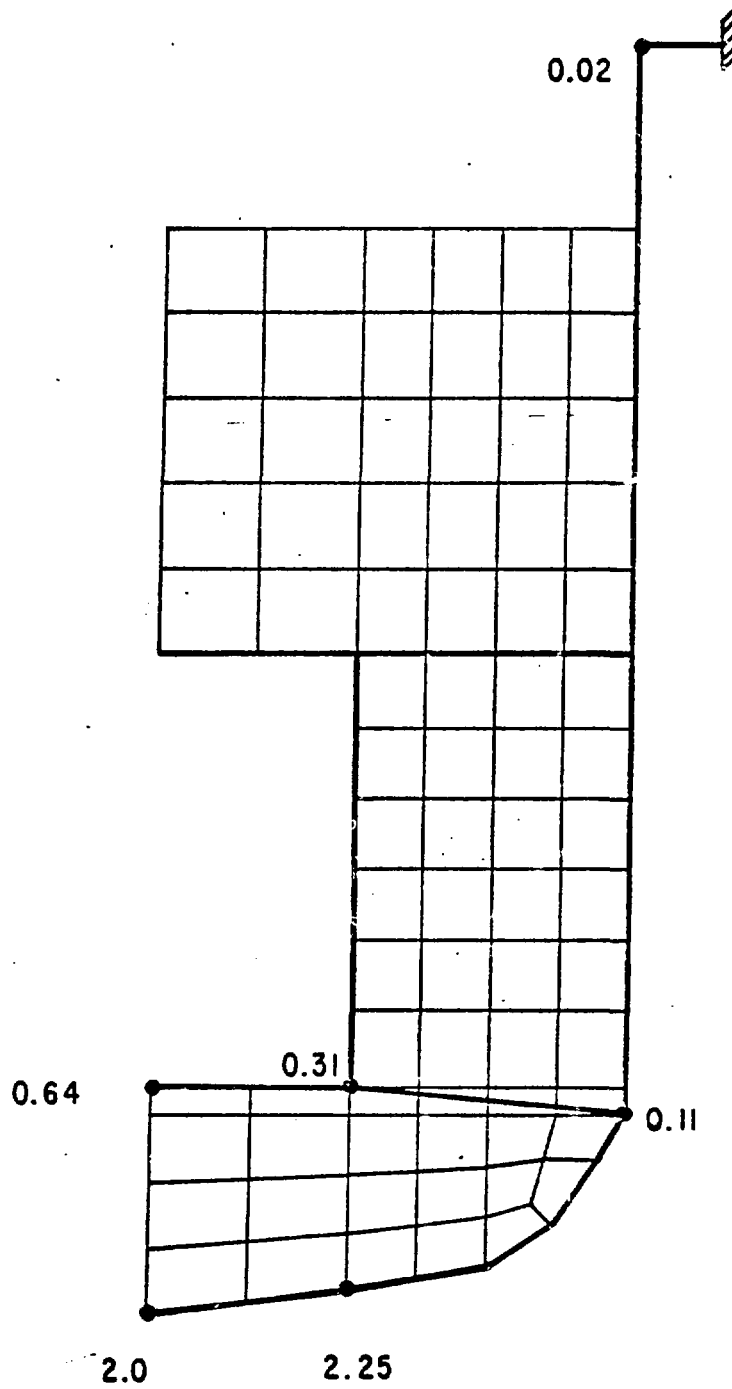


Fig. 9 . Maximum Vertical Acceleration (g) at Various Locations.

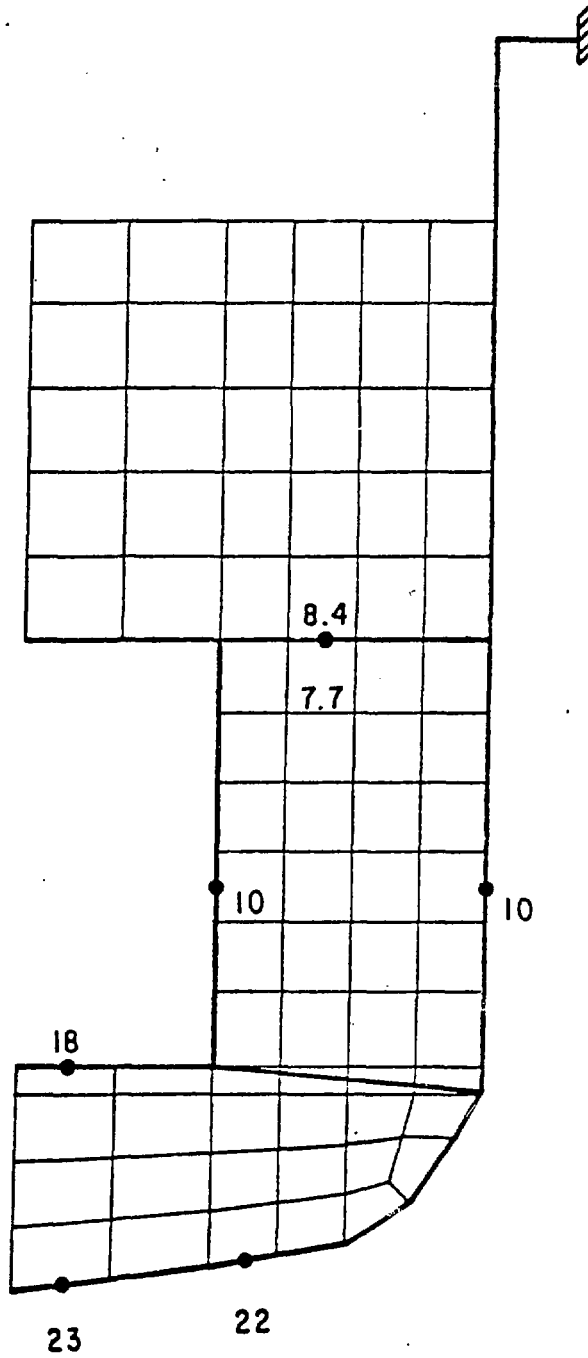


Fig. 10. Maximum Fluid Pressures (psf) at Various Locations.

CONTINUUM ELEMENT  
ELEMENT NUMBER=43      NOOF NUMBER=7

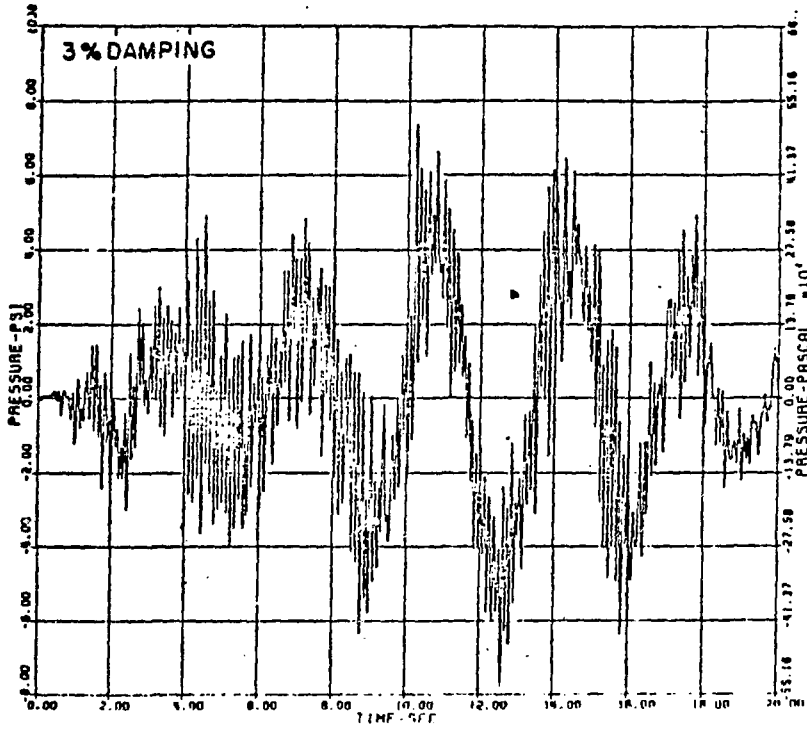


Fig. 11. Pressure Underneath Thermal Baffle.

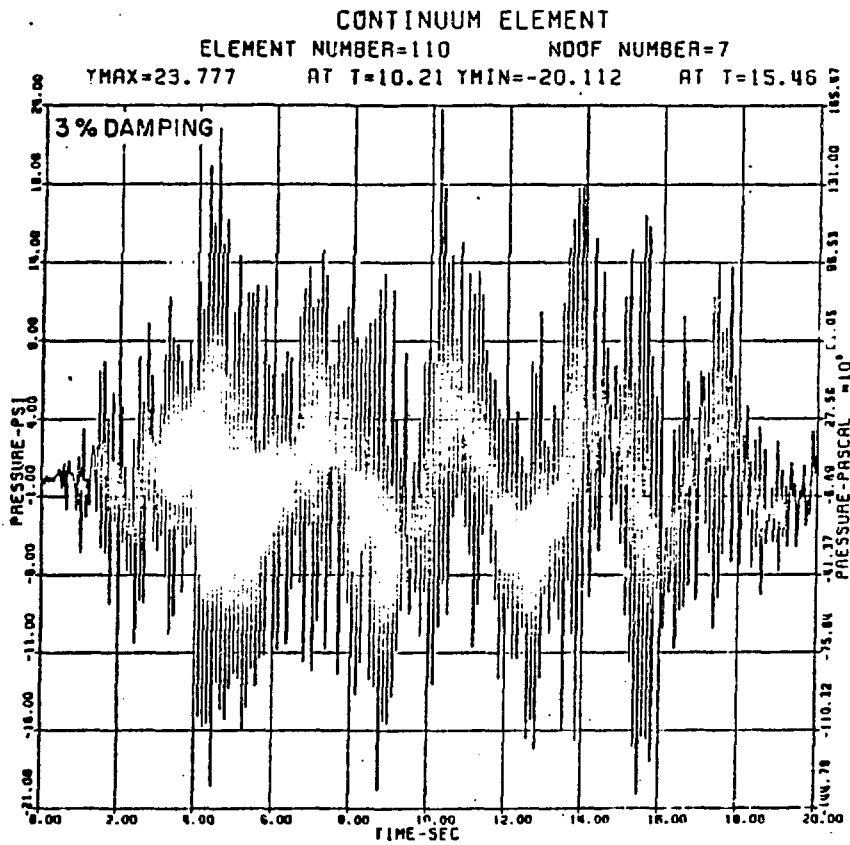


Fig./ 2. Pressure at Bottom Head.

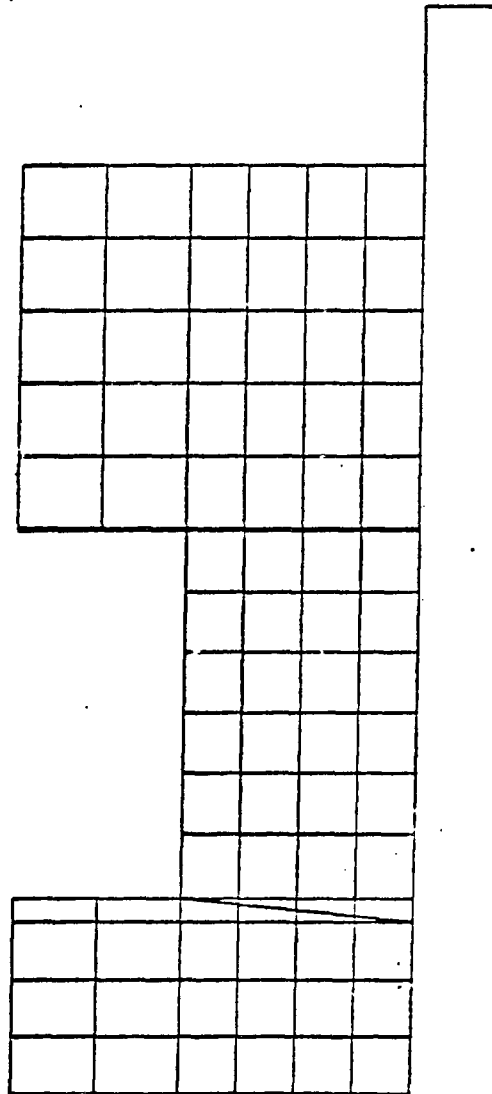
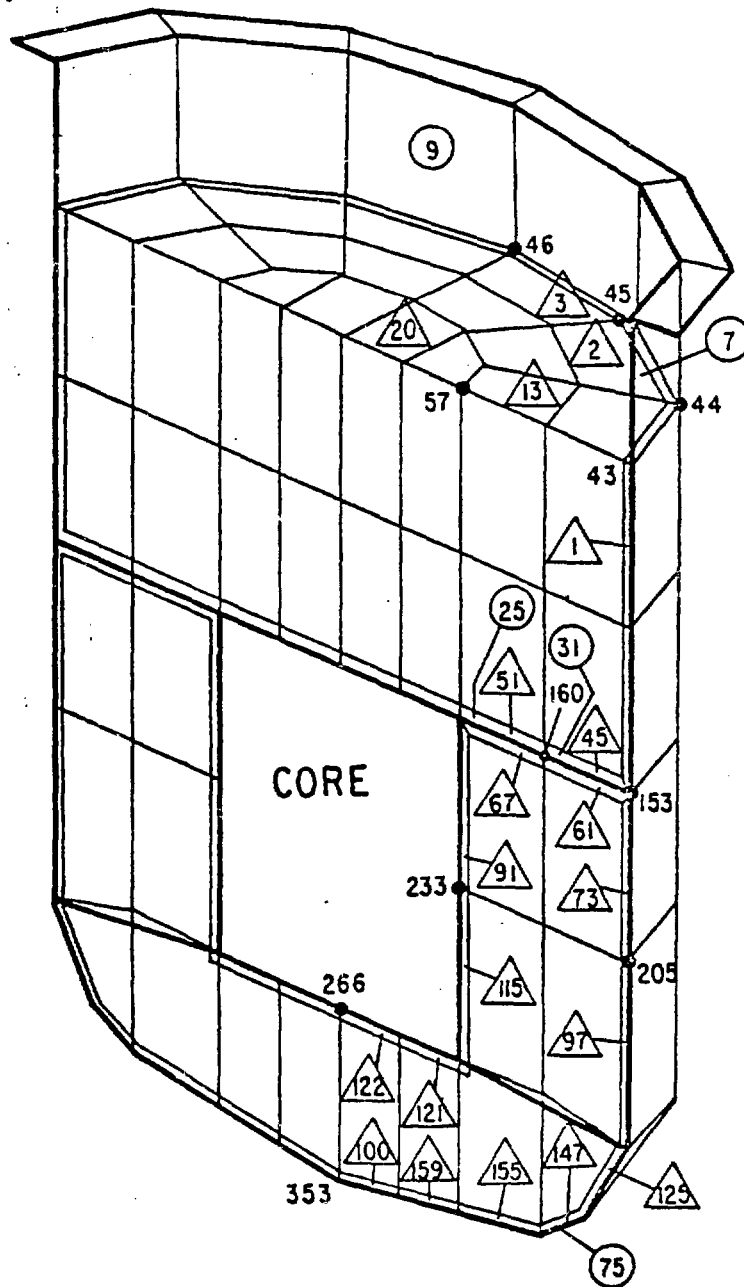


Fig. 13. Finite Element Mesh of a Flat-Bottom Reactor Vessel.



○ - SHELL ELEMENT

△ - FLUID ELEMENT

Fig. 14. Mathematical Model of a Large LMFBR Reactor Subjected to Horizontal Seismic Excitation.

ACCELERATION

NODE NUMBER=2

NDOF NUMBER=1

YMAX=124.712

AT T=5.62

YMIN=-127.576

AT T=6.20

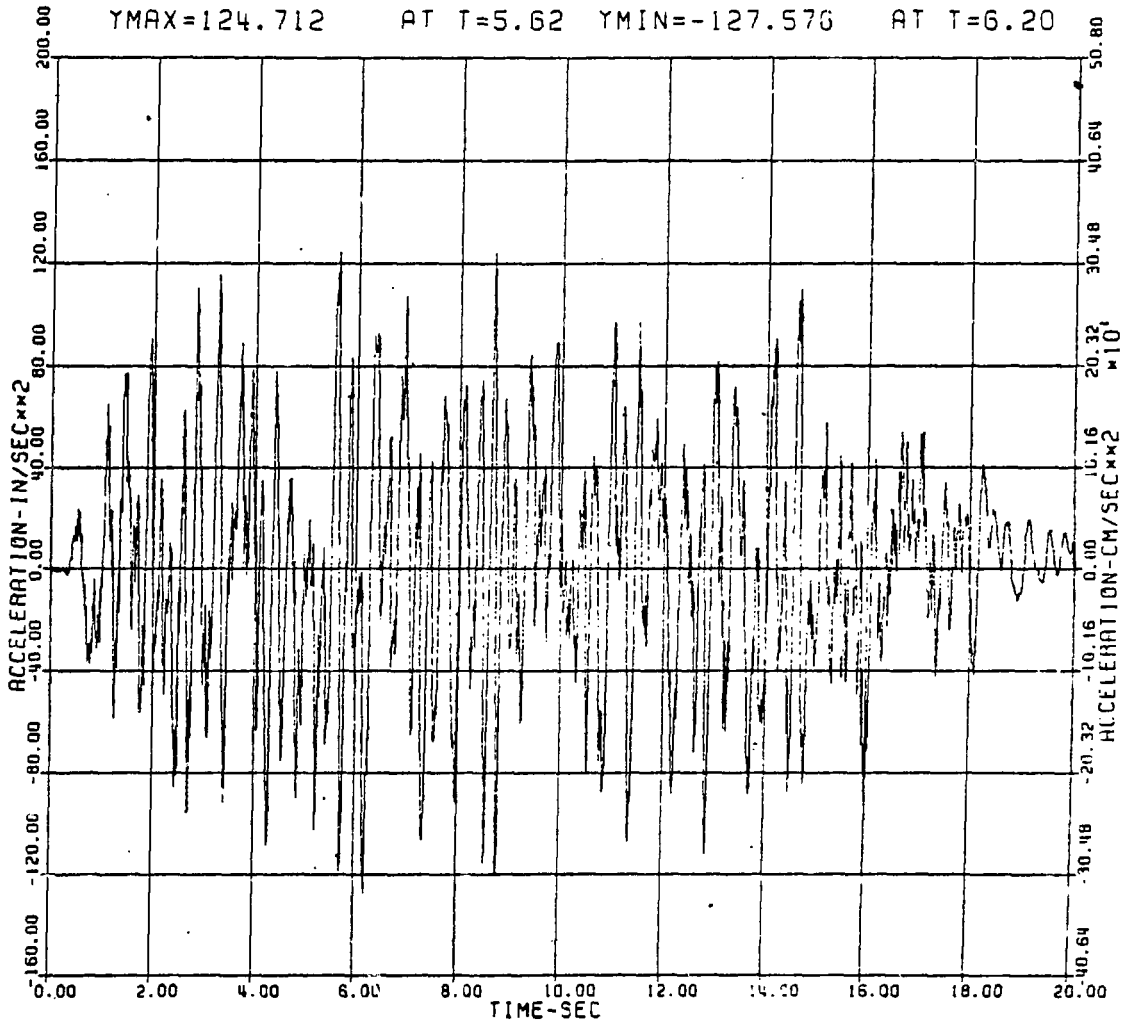


Fig. 15 Twenty Second Duration Horizontal Input Acceleration Time History.

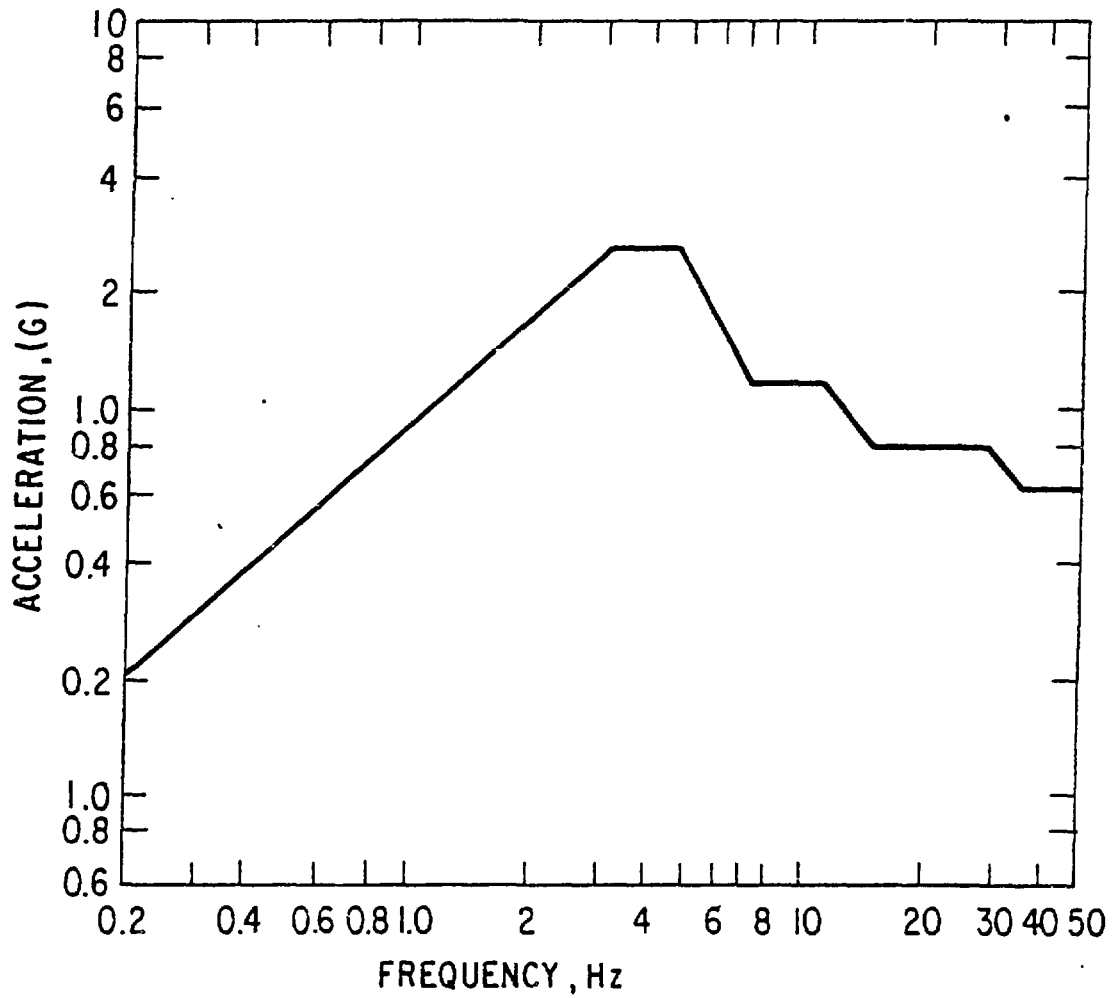


Fig. 16. Response Spectrum of Input Horizontal Acceleration Time History.

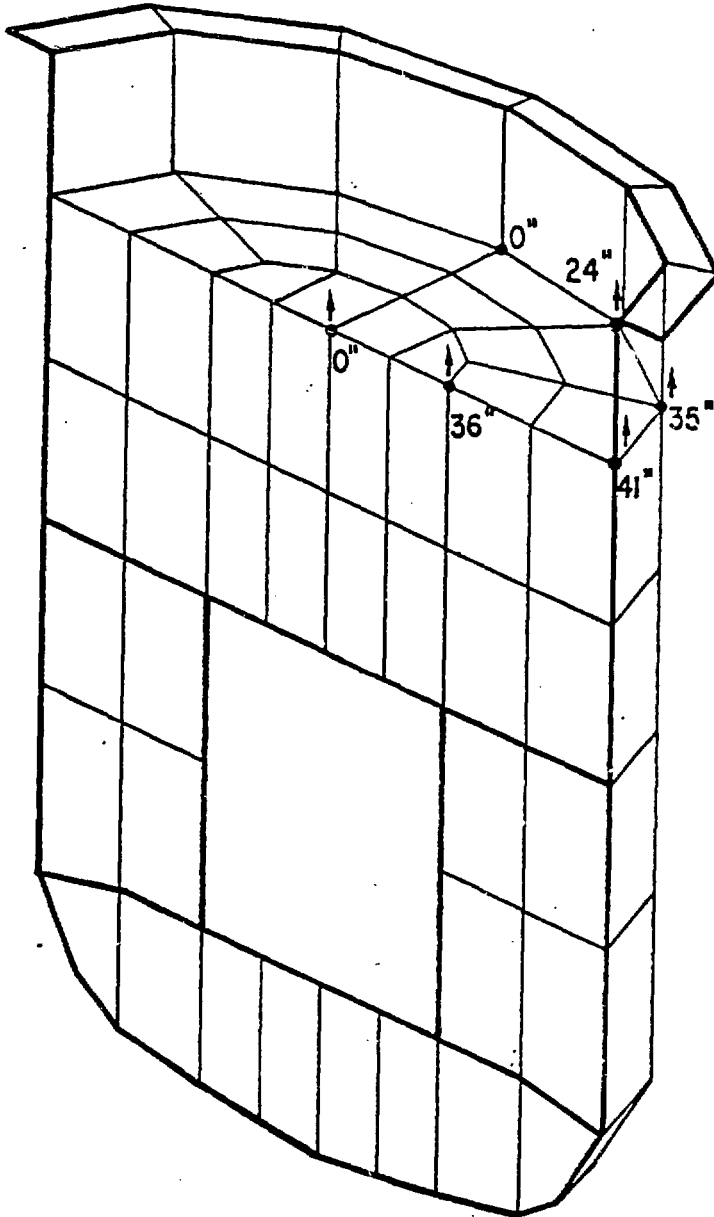


Fig. 1.7. Maximum Wave Heights at Free Surface.

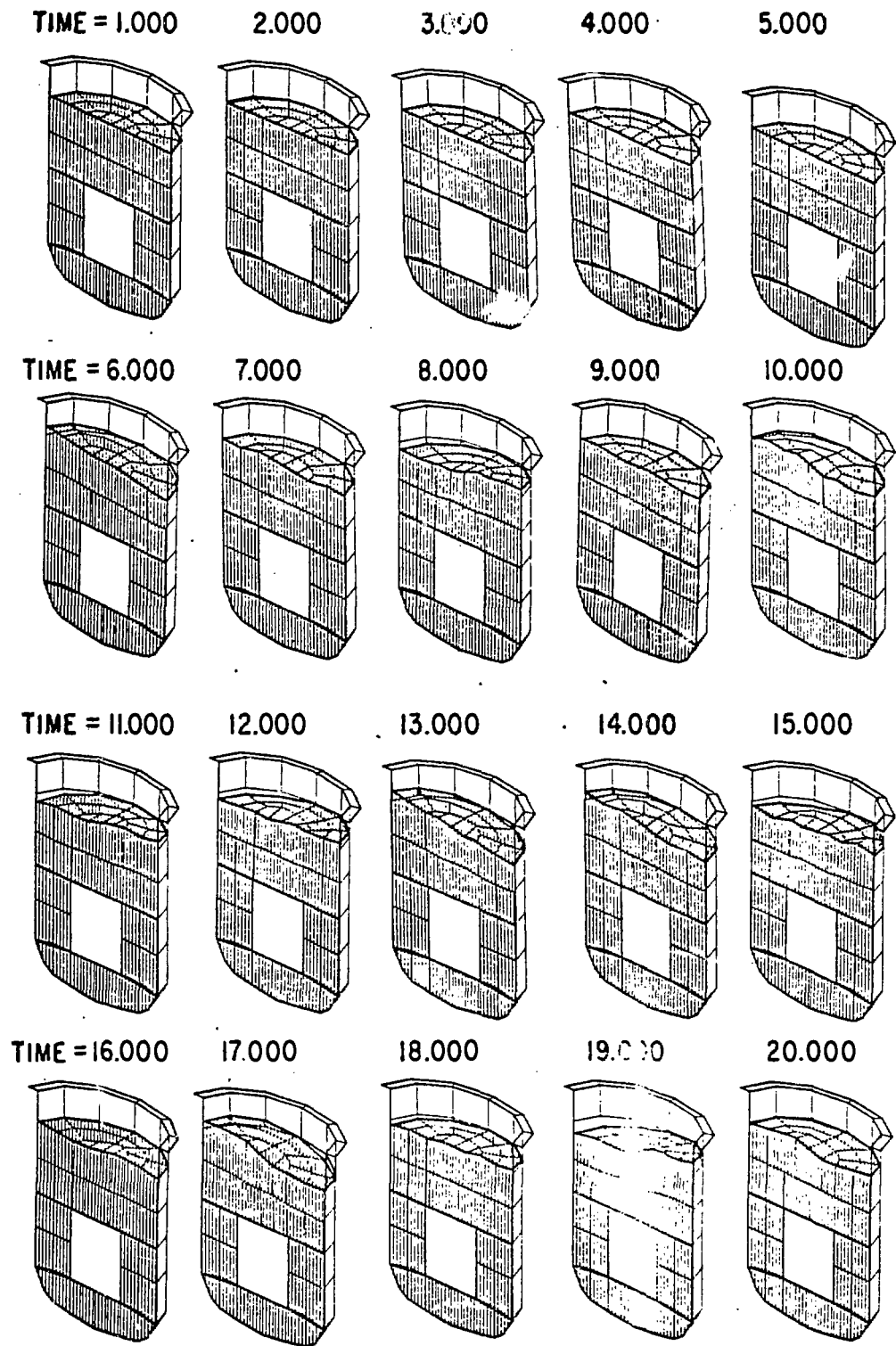


Fig. 18. *Slushing Response at Various Instant*

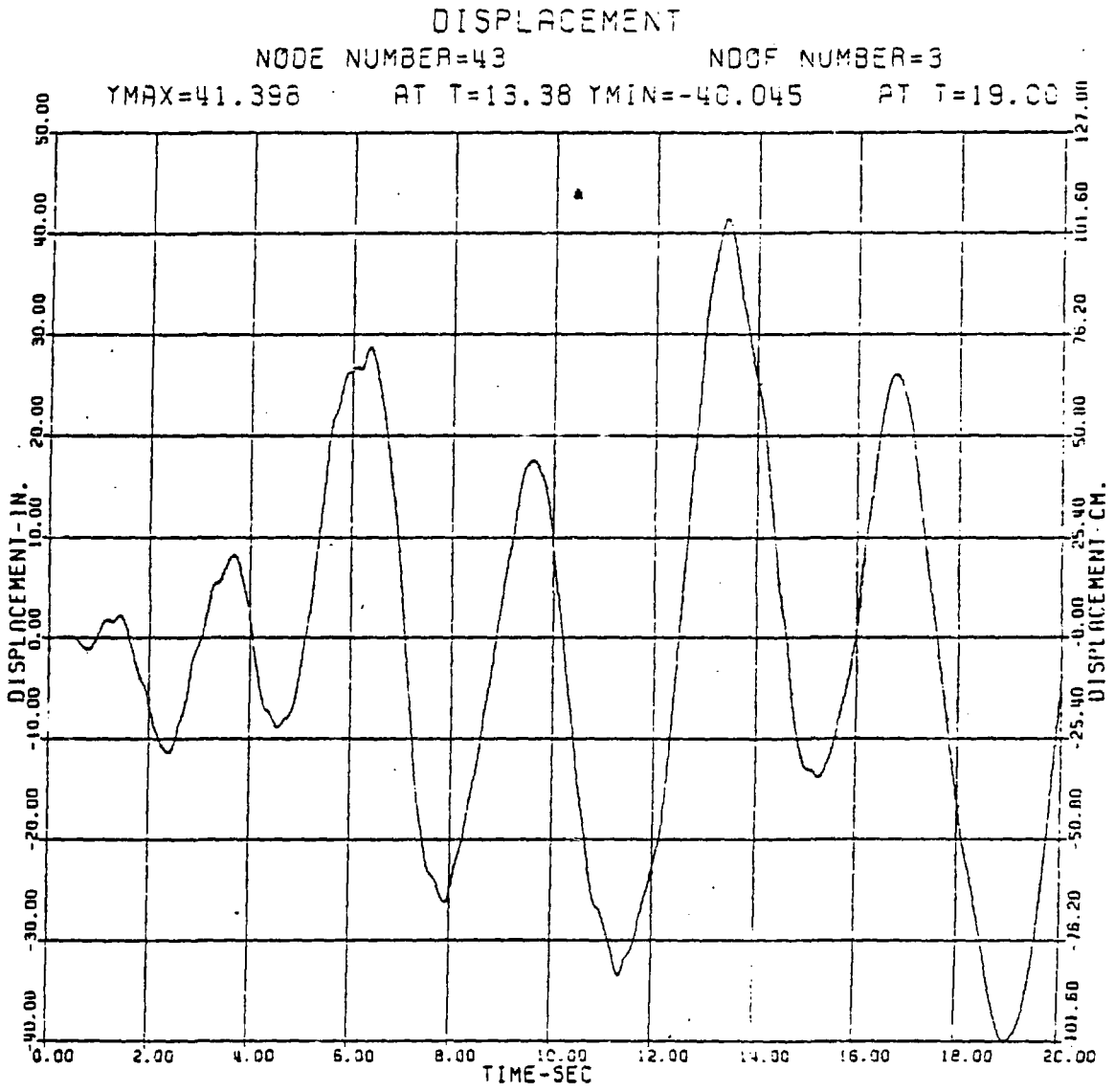


Fig./9. Wave Height History at Free Surface (Node 43).

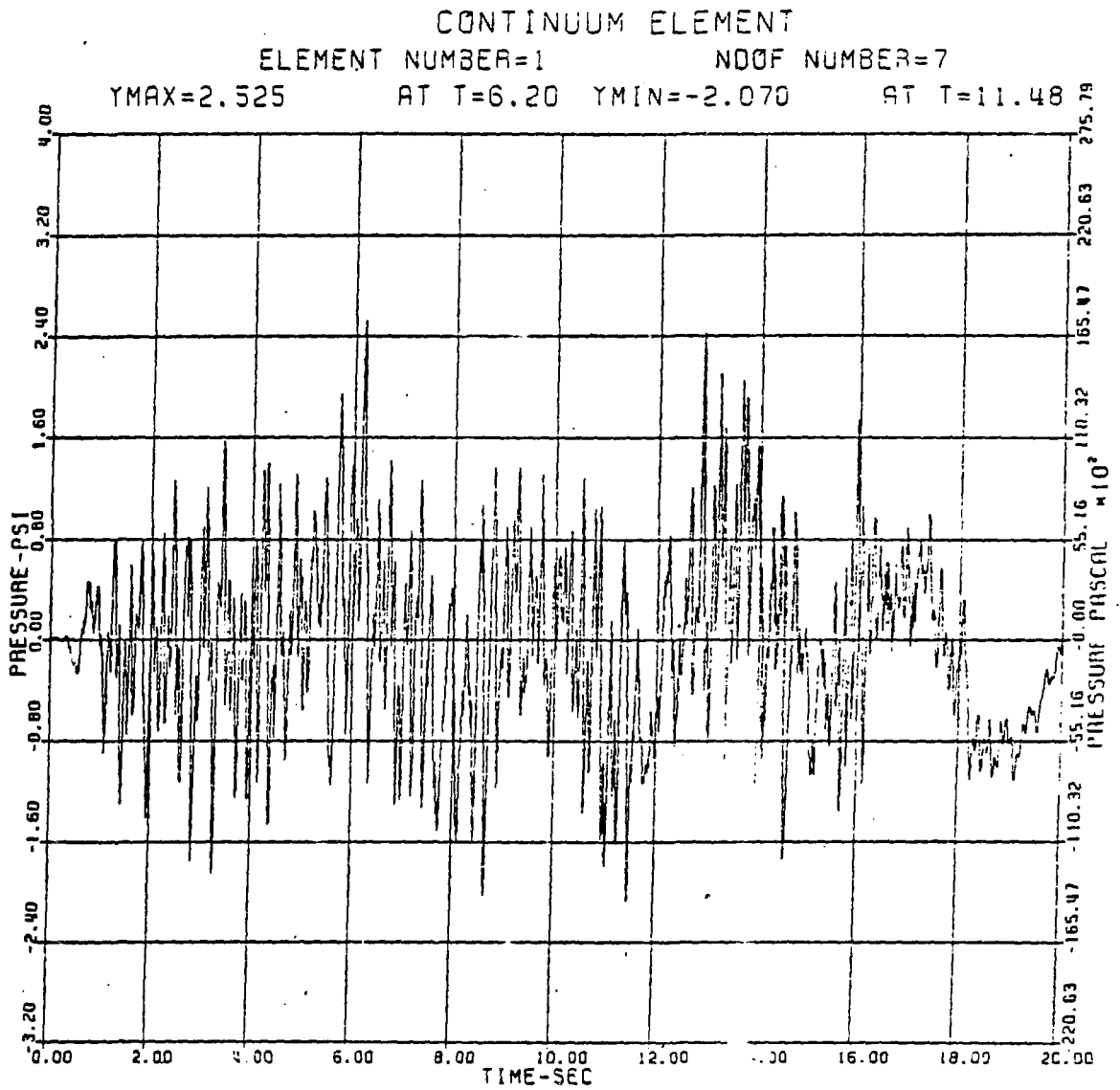


Fig. 20. Pressure History at Free Surface (Fluid Element 1).