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System Seismic Analysis of an Innovative Primary System for a Large Pool Type LMFBR Plant

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ABSTRACT

The system seismic analysis of an innovative primary system for a large pool type liquid metal fast breeder reactor (LMFBR) plant is presented. In this primary system, the reactor core is supported in a way which differs significantly from that used in previous designs. The analytical model developed for this study is a three-dimensional finite element model including one-half of the primary system cut along the plane of symmetry. The model includes the deck and deck mounted components, the reactor vessel, the core support structure, the core barrel, the radial neutron shield, the redan, and the conical support skirt. The sodium contained in the primary system is treated as a lumped mass appropriately distributed among various components. The significant seismic behavior as well as the advantages of this primary system design are discussed in detail.

INTRODUCTION

From the inception of nuclear power, there is a consensus that the most attractive breeder power system is the liquid metal cooled fast breeder reactor (LMFBR) (1). Two types of breeder system concepts, the pool type and the loop type systems, have been considered. In the pool type plant, the entire radioactive primary system sodium is contained in a very large primary vessel (typically about 22 m in diameter for a 1000 MWe plant). Major components which are submerged in this large pool of sodium are: the reactor core, blanket, reflector, lower internal structure, core support structure, upper internal structure, instrument tree, neutron shielding fuel handling equipment, primary pumps, intermediate heat exchangers (IHX) and the associated piping. In the loop type plant, the layout more closely resembles that of a conventional LWR plant, i.e., the primary pump, the IHX and the associated piping are located outside of the reactor vessel. Due to high boiling point of sodium (880°C) and its excellent heat transfer properties, a LMFBR plant is generally operated at low operating pressure and high operating temperatures around 500°C or higher. The combination of low pressure and high temperature leads to thin-walled vessel and piping design. Generally, it is quite a design challenge to meet simultaneously both thermal and seismic design criteria.

In this paper the system seismic analysis of an innovative primary system for a large pool type LMFBR plant is presented. Implied in this analysis are realistic design approaches and criteria developed in a joint effort between Atomic International (AI) and Argonne National Laboratory (ANL) which are employed to reduce the seismic load imposed on the structure. The nuclear island is considered embedded down into the basemat so that the vessel support is essentially at ground level. The safe shutdown earthquake (SSE) ground motion is chosen to be 0.25 g ZPA for sites having a shear wave velocity of 1220 m/s (4000 fps) which should cover about 75% of the potential sites in the

DISCLAIMER

U.S. Following an apparent trend in the nuclear industry for future reactor plants, the operating basis earthquake (OBE) is set to be one-third of the SSE.

Seismic Design Considerations and System Descriptions

In designing the primary system against the seismic loading, one of the most important safety considerations is the relative motion of the reactor core and the control rods. For maximum safety the movement of the reactor core should be minimized. In a design where the core support structure is supported from the reactor vessel bottom head, the displacement of the core is the sum of the relative displacement of the vessel head from the support flange and the relative displacement of the core from the vessel head. Although the net moment arm for the core is the same as compared to the case where the reactor core is supported directly from the vessel support point, these two components of the displacement generally do not move with the same frequency. Therefore, the vector sum of these two components is usually larger than the displacement in the case where the reactor core is supported directly from the vessel support point assuming the same structural stiffness.

Moreover, if the reactor core is supported off the vessel head, the reactor vessel carries both the reactor system and the entire sodium inventory. The motion due to the flexibility of the vessel is transmitted to the reactor core while the rocking of the reactor core induces bending stresses in the vessel head. In this case, failure of the reactor vessel would affect the reactor core. In the hanging core support structure design however, the reactor vessel only carries the weight of the sodium. There is no concentrated load at the vessel wall. This leads to a thinner reactor vessel. This design has an important safety advantage, i.e., the failure of the reactor vessel only means loss of sodium to the guard vessel which does not affect the hanging core support structure and the reactor core. Also, due to less displacement of the reactor core, the core support structure does not have to be as rigid as the bottom support design. However, the core support structure becomes more complex. Therefore, a trade off study was conducted. The hanging core support structure design was found to be more cost effective and was selected as the reference for the concept design.

The basic reactor layout is shown in Figs. 1 and 2. Unique to this design is the hanging core support structure and its backup support system. The hanging core support structure consists of four major parts. They are the skirt and its flange, 10 box beams, the core support basket and the inlet piping. The core support structure supports the reactor core, the core barrel, the support grid, the fixed neutron shield and the redan assembly. The reactor internals backup support system (RIBBS) consists of five columns supported from the deck by loading 10 "Belleville" springs and attached to the lower end of the core support structure by a breech type lock. The RIBBS is an additional redundant system provided for the highly unlikely event of the core support structure failure.

The reactor deck and the primary vessel form the primary system pressure boundary. An important design consideration is that the seismic events should not significantly affect the leak-tightness of the reactor deck. This is accomplished by a very stiff deck design. The deck is a stressed skin, circular box-beam type structure constructed of carbon steel. It supports the primary pump, the IHX, the three rotatable plugs thermal and neutron shieldings, the shut down heat removal systems and other equipments. The reactor vessel, the deck and the core support structure are supported by the conical support skirt through three bolted flanges.

ANALYSES OF THE PRIMARY SYSTEM

Preliminary structural and seismic analyses of the primary system described above are performed by using the ANSYS finite element computer program (2). The structural integrity of the primary system is assessed according to Section III of the ASME Boiler and Pressure Vessel Code (3). Additionally, the major seismic design criteria concerning reactivity control are:

- Limit the maximum differential vertical movement between control rod and core assemblies to 4.45 cm. (1.75 in.) for the SSE.
- Prevent liftoff of the assemblies during an OBE, which translates into a maximum vertical acceleration of 0.76 g during the OBE.
- No crushing of core assembly ducts under horizontal OBE and SSE.

The most stringent of these is the second item above, namely no liftoff of the subassemblies during the OBE. This criteria often resulted in very large increases in stiffness in the core support structure (CSS). It is noted, however, that even if a core assembly should lift off, such a displacement would be of the order of about 1.27 cm. (1/2 in.). In addition to assuring leaktightness of the deck, its maximum vertical displacement was limited to ±1.27 cm (1/2 in.).

The purposes of these analyses were to demonstrate the feasibility of the design, to identify problem areas, and to ensure sufficient safety margin. At this time, a rather coarse model of the entire primary system is set up so that the system response under various loadings can be evaluated. In areas where various design concepts are still under evaluation, such as the upper and lower internal structures and the details of deck mounted components, only approximate beam elements are used to represent the anticipated masses and stiffnesses of the structures. It is expected, however, that the overall response of the system will not be greatly altered by these local effects because their general characteristics have been included in the model.

Model Description

In the current practice of reactor seismic analysis, the axisymmetric model is often used. A major drawback in the axisymmetric model is that the cross sections of the components and structures remain undeformed during the earthquake excitation. As a result, the out-of-round vibrational modes are neglected. This drawback may not be severe for the bottom supported reactor core with the horizontal redan design. The current design with the hanging support structure and the vertical redan, however, is highly nonsymmetric. Therefore, a three-dimensional model provides a more attractive approach. All of the important vibration modes, including the out-of-round modes, can be predicted in the 3-D analysis. The interaction between the deck and deck-mounted components can also be considered.

The analytical model developed for this study is a three-dimensional finite element model including one-half of the primary system cut along the plane of symmetry. The sodium contained in the primary system is treated as a lumped mass properly distributed among various components. Plots of various parts of the model are given in Figs. 3 through 5. Figure 3 shows the deck model which consists of the top and bottom plates, the inner and outer rings, the radial support webs, the component penetration sleeves for the pumps and the IHXs, and the conical support skirt. The three rotatable plugs are considered as a lumped mass located at its center of gravity. The pumps, the IHXs and the upper internals structure are considered as circular cylindrical pipes with proper dimensions. The thermal and neutron shield of the deck are treated as evenly distributed in the bottom plate of the deck. Figure 4 shows the hanging core support structure which consists of the cylindrical skirt, the stiffener ring, the support beams, and the bottom core support hub. Figure 5 shows the core barrel, the radial neutron shield and the vertical redan. The IHX penetration shell is modeled as a pipe attached to the redan, whereas the core internals are treated as lumped mass. Finally, the reactor vessel is treated as a circular cylindrical pipe supported directly off the conical support skirt. Both dead weight and seismic loading are considered to make the primary stress evaluation complete.

Structural Response to Dead Load

Since all the masses of various components have been included in the model, the analysis of the primary system under dead load is straightforward. The gravitational force is applied to the model. The buoyancy force exerted on the structure submerged in the sodium is accounted for by reducing the density of the structure. The weight of the sodium in the region of the hot pool above the free surface of the cold pool is treated as lumped mass at appropriate nodel points. The deformed shapes of the deck and the reactor assembly components are shown in Figs. 6 and 7. From Fig. 6, it is noted that the maximum displacement in the deck occurs in the bottom plate which carries both the weight of the thermal insulation and the weight of the radiation shielding. The maximum displacement in the reactor assembly occurs at the bottom of the core support structure as shown in Fig. 7. The redan also has noticeable unsymmetric deformation due to the presence of the IHX penetration cylinders. All these displacements, however, are less than 1 in. Furthermore, the deformation of the core support structure can be reduced by refinement in the CSS skirt stiffener and the CSS base areas. The results of the analysis are summarized in Table 1. It is noted that the highest stress occurs in the beams of the core support structure. This stress is below the ASME code allowable stress.

System Seismic Response to Horizontal Earthquake Motion

The estimated seismic design spectra for this design effort are given in Fig. 8. The horizontal earthquakes with these design spectra are used as the loading for the model described above. Both the OBE and the SSE are considered. Prior to the analysis, a scoping calculation was performed. It was found that a horizontal earthquake motion in line with a core support beam results in higher stresses than an earthquake in a direction lying between two beams. Therefore, the direction of the seismic load is assumed to be parallel to the symmetry plane of the model in the analyses.

The calculated modal participation factors for the deck and deck mounted components are shown in Table 2. The mode shape plots of the typical modes are shown in Figs. 9 and 10. The most dominant vibrational mode is mode 2 which is the deck mounted component swinging mode. The pumps and the IHXs swing with the earthquake motion which causes mild local bending in the deck. This mode is the most common vibrational mode for the deck. It appears in several different frequencies with different magnitudes. The maximum displacement for the deck mounted components under the SSE is 3.43 cm. (1.35 in.). The deck distortional modes occur at freqencies greater than 8.7 Hz where local deck distortion is accompanied by mild swinging of the in-tank components.

The calculated modal participation factors for the hanging core support structure and its supported components under both OBE and SSE loadings are shown in Table 3. The mode shape plots of the typical modes are shown in Figs. 11 and 12. The most dominant vibrational mode in this case is mode 12 which is the reactor core rocking mode with a frequency of 3.9 Hz. The entire reactor core and core support assembly rocks back and forth. The maximum displacement of the reactor core reaches 0.64 cm. (0.25 in.) under SSE conditions. The redan in this case also rocks with some local out-of-round deformation at the in-tank-components region. The maximum displacement in the redan is 22.86 cm. (9 in.) under the SSE. At the present time, the IHX and the redan sleeve are not connected to each other in the model. However, since the displacement is not very large, no interference problem is expected. The other significant modes are generally related to the local out-of-round deformations of the redan. Generally, the redan out-of-round deformation is coupled with some mild rocking motion of the reactor core and the core support structure as shown in Fig. 11.

The stresses in various components under OBE and SSE loadings are summarized in Table 1 together with those for the dead load. The displacements of various components under seismic loads are summarized in Table 4. These stress and displacement values are summed over all modes with modal coefficient ratio greater than 0.1 by taking the square root of the sum of the squares. It is noted that the stress in the core support structure basket can be reduced by local stiffening.

System Seismic Response to Vertical Earthquake Motion

The vertical earthquake with the design spectra shown in Fig. 8 is used as the loading in the modal analysis of the primary system. Both OBE and SSE are again considered.

The calculated modal participation factors for the deck model are given in Table 5. The shapes of the typical modes are plotted in Figs. 13 and 14. The most significant vibrational mode for the deck is mode 5 which is the deck bouncing mode with a frequency of 8.7 Hz. The deck bounces up and down while the deck mounted components swing in and out. The vertical displacement at the inner ring of the deck is 0.76 cm. (0.3 in.) for SSE and 0.38 cm. (0.15 in.) for OBE. The horizontal displacement at the lower end of the deck mounted component is 0.64 cm. (0.25 in.) for the SSE. The maximum displacement and stress in the deck occurs in the lower deck plate where thermal and neutron shields are attached. The other vibrational modes are related to the local bending of the deck mounted components as shown in Fig. 14.

The calculated modal participation factors for the hanging core support structure and its supported componets under both OBE and SSE loadings are given in Table 6. The mode shape plots of significant modes are shown in Figs. 15 to 17. The most dominant vibrational mode in this case is mode 4 which is the reactor core bouncing mode with a frequency of 3.9 Hz. The entire core and the core support assembly bounce up and down while the redan rocks with local out-of-round deformation at the IHX sleeve region. Mode 3 is a less severe reactor core rocking mode with a frequency of 3.8 Hz. The reactor rocking motion is induced by the asymmetric distribution of the redan. The rest of the vibrational modes are associated with the redan out-of-round deformation accompanied by some mild vibration of the reactor core as shown in Fig. 17.

A summary of the stresses and displacements in various components under OBE and SSE conditions are given in Tables 1 and 4, respectively. It is noted that all stresses and displacements are below the design limits except the stress in the core support structure basket which can be reduced by local stiffening.

Summary and Conclusions

The system response of an innovative primary system to dead weight and seismic loading is presented. Unique to the design is a hanging core support structure and its backup support system. The design is highly redundant and versatile. The hanging core support structure is decoupled from the reactor vessel so that the vessel only has the function of containing the sodium. This has an important safety advantage, i.e., the failure of the reactor vessel only means loss of sodium to the guard tank which does not affect the hanging core support structure and the reactor core. As a result, the vessel can be made thinner which results in the overall commodity saving for the system. The bolted flange design has the advantage of ease of construction. Unlike the bottom support design where a great deal of work has to be done inside containment, the current core support structure including its supported reactor internals can be fabricated outside of the containment and installed in place without structural welding inside containment. Since in-containment construction is on the overall project critical path, this results in a significant saving in construction cost.

Besides providing backup support in a hypothetical case where the core support structure is assumed fail, the columns in the RIBBS can also serve as conduits for test cable for nuclear instrumentation. It is also possible to use the column as a monitoring device to continuously monitor the deflection of the reactor core.

System seismic analyses of the reference design indicate that the deck is basically a very stiff structure with little deformation due to seismic load. The in-tank components generally swing during earthquake with a maximum deflection of less than 5.08 cm. (2 in.) at the lower end of the component in a safe shutdown earthquake. Hence, no interference of the components is expected. The redan is the most flexible structure in the primary system in the current configuration, the deflection is localized near the IHX cylinder. The maximum deflection is approximately 25.4 cm. (10 in.) for a safe shutdown earthquake. Therefore, some local stiffening may be needed at the top of the redan. The reactor core and internals generally would bounce and rock during earthquake which cause the core support structure to become the high stress area in the system. However, sufficient safety margin can be designed into the core support structure to ensure safe reactor operation. As demonstrated in the analysis, the maximum stress can be expected to be less than 20 ksi for SSE loading after local stiffening of the core support basket. The relative horizontal displacement of the core and the control rod drive is expected to be less than 1.52 cm. (0.6 in.) for a safe shutdown earthquake. The vertical relative displacement is less than 2.54 cm. (1 in.). The vertical acceleration of the core is less than 0.76 g so that there is no lift off of the reactor subassembly. In conclusion, this primary system design offers substantial advantage over previous ones and warrants further development.

REFERENCES

(1) A. E. Waltar and A. B. Reynolds, Fast Breeder Reactors, Pergamon Press, NY, 1981.

(2) G. J. Desalvo and J. A. Swanson, ANSYS Engineering Analysis System User's Manual, Swanson Analysis Systems, Inc., Houston, Pennsylvania, 1979.

(3) ASME Boiler and Pressure Vessel Code, Section III, The American Society of Mechanical Engineers, NY, 1983.

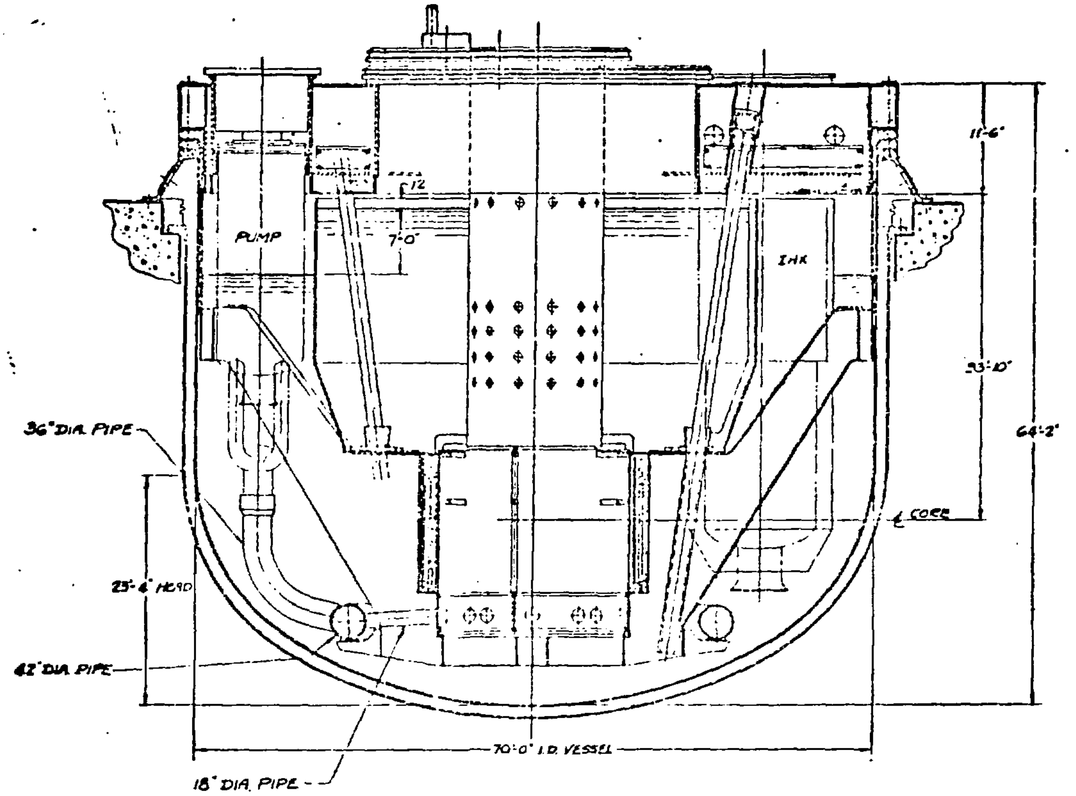

Fig. 1. Elevation View of the Primary System Layout.

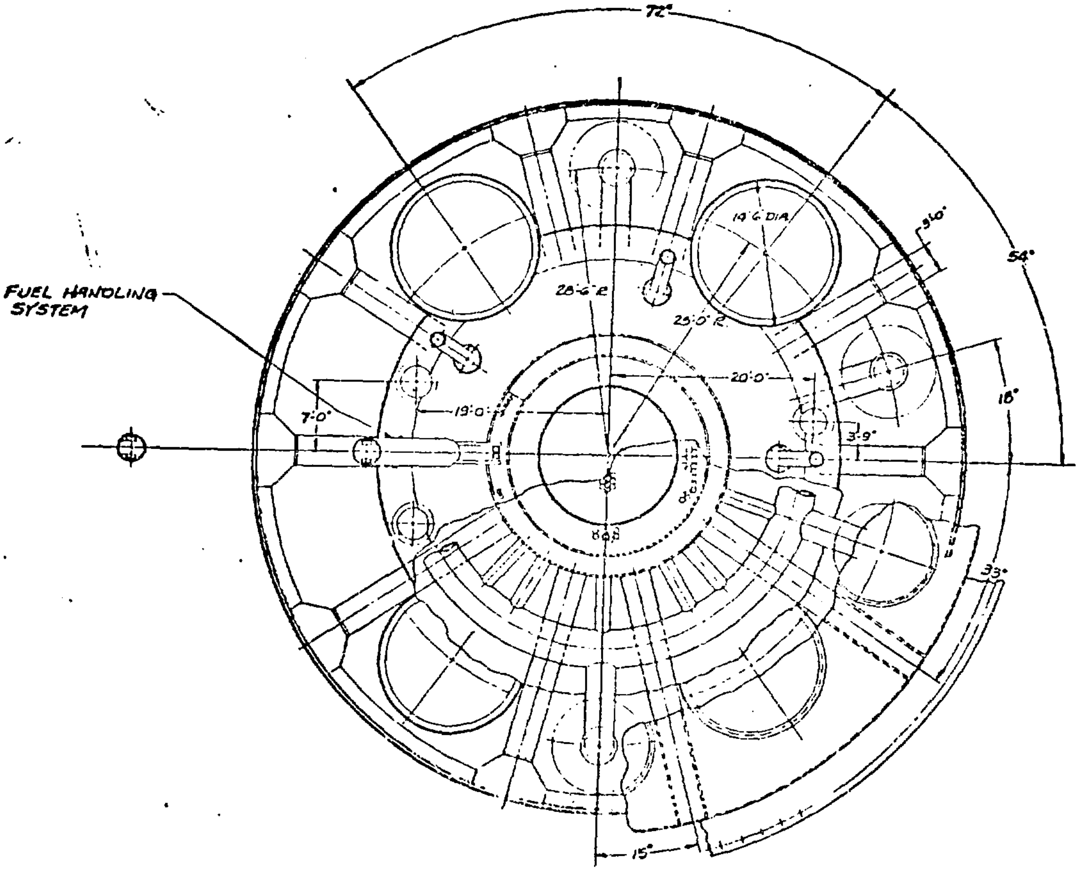

Fig. 2. Plan View of the Primary System Layout.

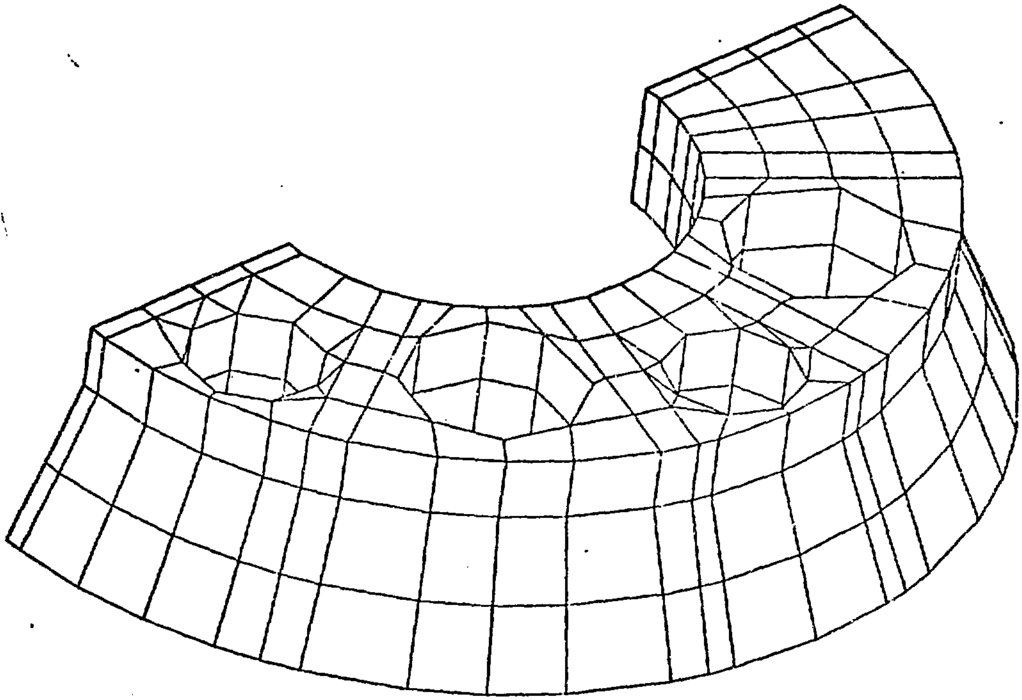

Fig. 3. The Deck Model.

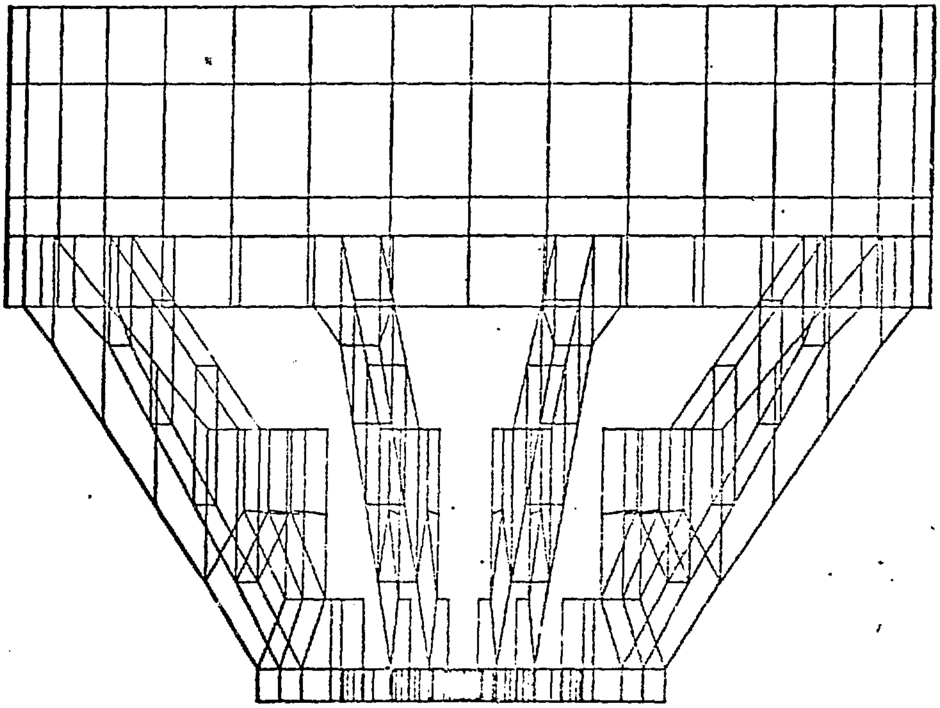

Fig. 4. The Hanging Core Support Structure Model.

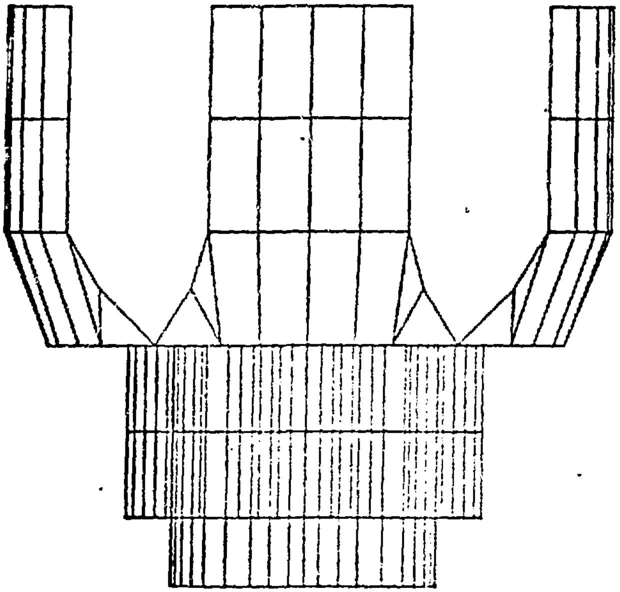

Fig. 5. The Core Barrel, the Radial Neutron Shield and the Vertical Redan Model.

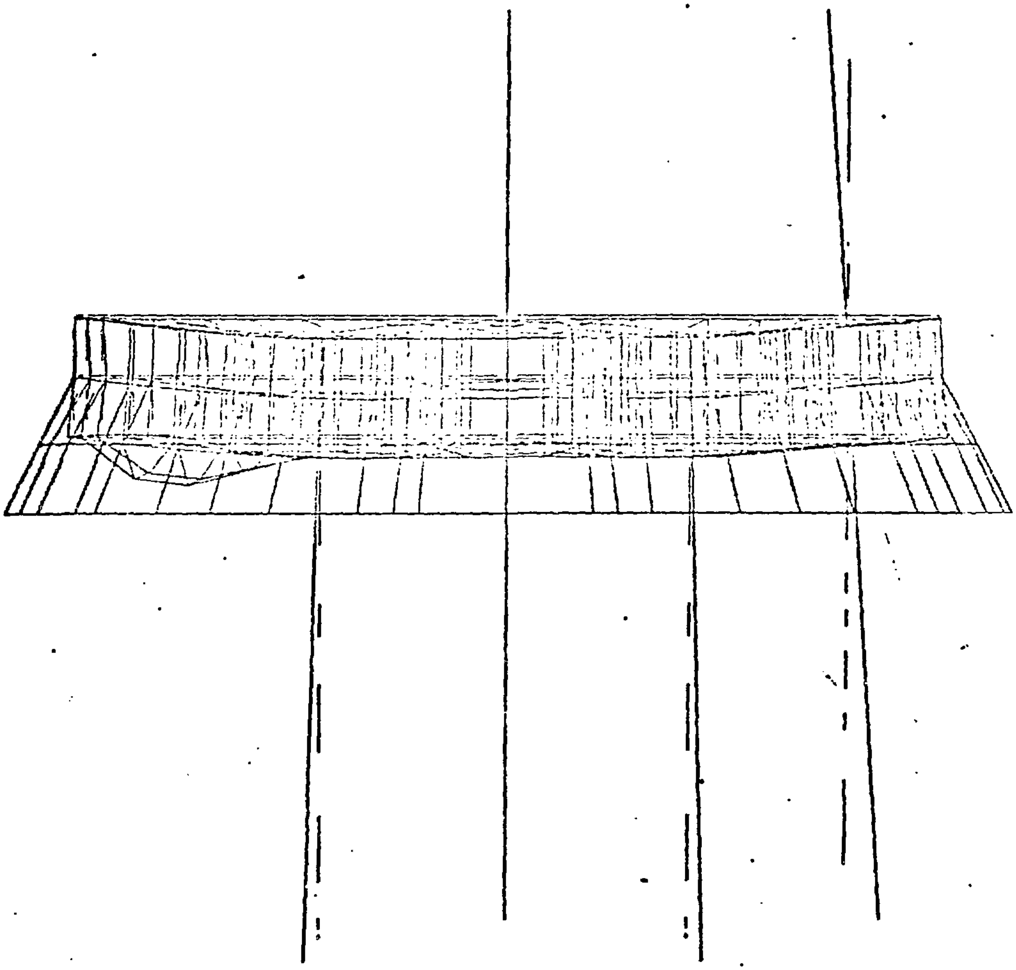

Fig. 6. Deformed Shape of the Deck under Dead Load.

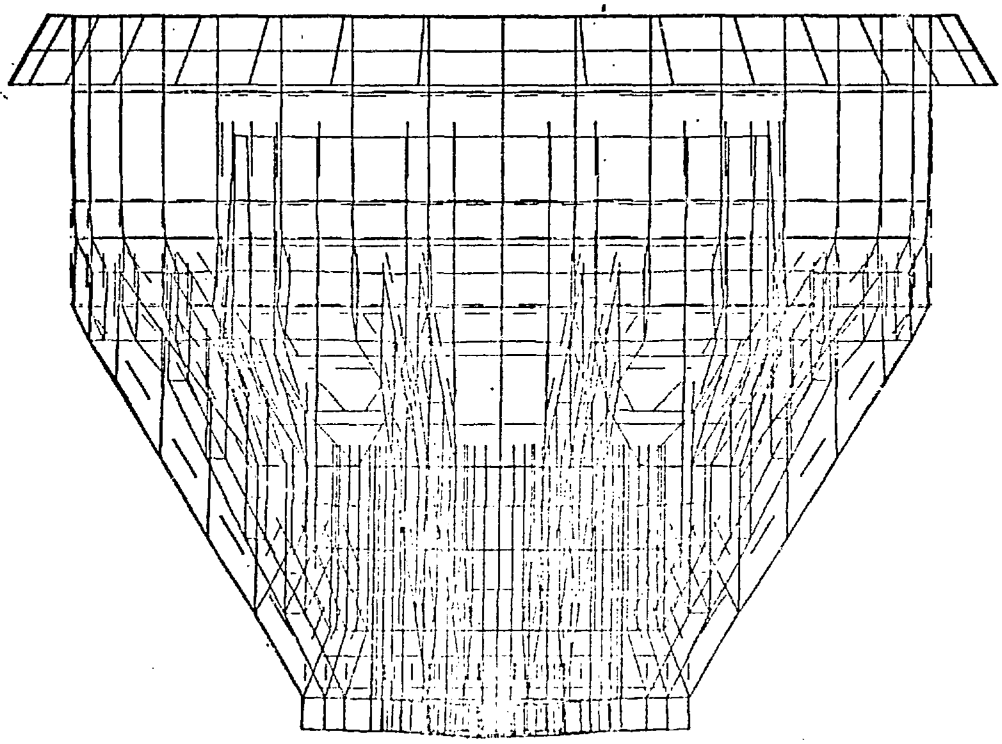

Fig. 7. Deformed Shape of the Core Support Structure and its Supported Components under Dead Load.

Table 1 Summary of stresses in the primary system and the ASME code allowable stresses

		Seismic	
	Dead Load σ_1, Ksi	OBE σ_2, Ksi	SSE σ_3 Ksi
Deck	7.2	7.4	13.6
Conical Skirt	3.5	3.7	7.6
CSS Skirt	10.0	8.5	16.3
CSS Beams	12.0	9.7	18.6
CSS Basket	11.5	23.6*	45.5*
Core Barrel and Radial Shield	1.1	2.3	8.8
Redan	1.1	15.4	30.2

*These high stresses will be reduced by local stiffeners.

ASME Code Allowable Stresses: $S_m = 16.2$ Ksi

Stress Combination: $\sigma_1 + \sigma_2 < 1.5 S_m$

$\sigma_3 < 1.5 (1.5 S_m)$

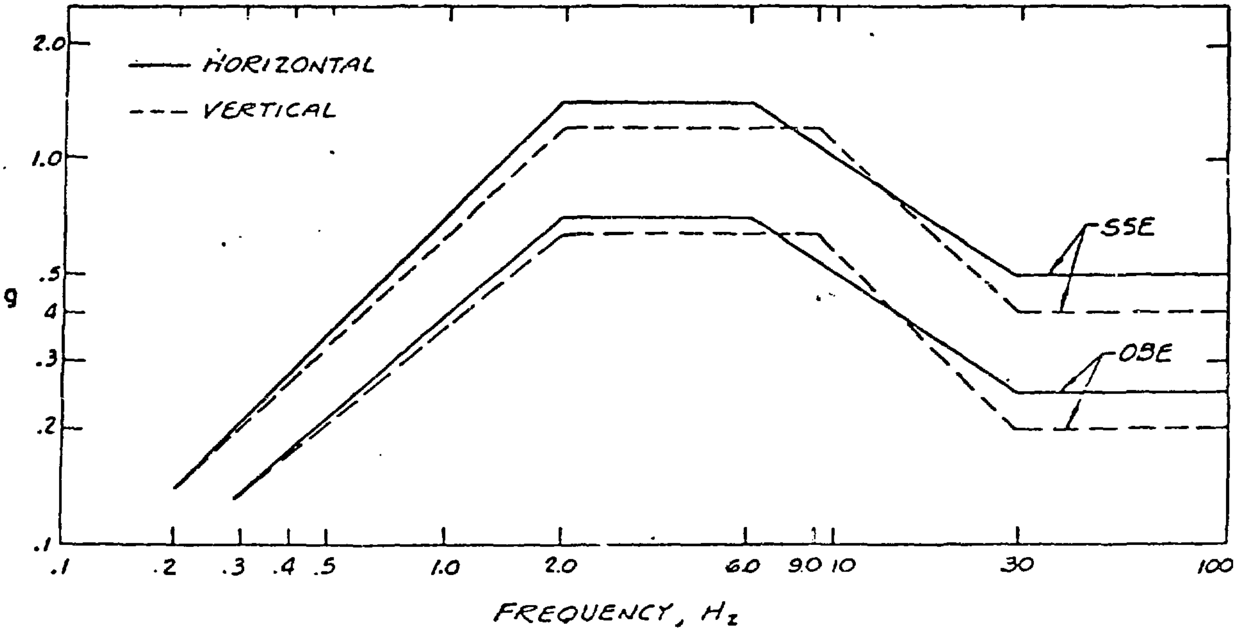

Fig. 8. Estimated Seismic Design Spectra for LPP Project. (SSE ~3% Damping, OBE ~2% Damping, SSE ZPA = 0.25 g at 4000 fps, OBE ZPA = 1/3 SSE ZPA)

Table 2. Calculated Modal Participation Factors for the Deck and Deck Mounted Components under Horizontal Seismic Loading.

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          ***** MODAL PARTICIPATION FACTORS *****

MODE     FREQUENCY          P.FACTOR       MODE COEF.      M.C. RATIO      EQUIV. MASS

  1        3.425              .7621          .4452          0.016819         585.7
  2        3.472             46.57          26.47           1.000000         550.0
  3        3.572             31.67          17.00           0.642337         823.5
  4        3.574             11.69           6.259          0.236814         427.5
  5        7.044             24.33           3.172          0.119324         378.1
  6        7.431            -16.35           1.877          0.070290         356.2
  7        7.624             26.39           2.840          0.107279         355.3
  8        7.771             -1.625          .1668          0.006302         348.6
  9        8.672            -15.16           1.183          0.044699         136.5
 10        9.152            -13.58           1.263          0.047714         684.4
 11        9.355             38.21           2.447          0.092452         308.6
 12        10.67              6.127          .2764          0.010443         718.8
 13        14.95             37.94           .6494          0.024533         1035.
 14        15.56             63.39           .9959          0.037623         840.3
 15        17.53             -8.653          .1011          0.003318         85.18
 16        19.76             -5.605          .4861D-01      0.001836         582.1
 17        21.07             -2.252          .1657D-01      0.000626         561.4
 18        21.44             -.9265          .6514D-02      0.000246         870.3
 19        21.50             -7.463          .5200D-01      0.001967         762.9
 20        23.70             -2.564          .1381D-01      0.000522         107.6
 21        24.67              .1592          .7685D-03      0.000029         36.04
 22        27.10              .8653          .3271D-02      0.000124         5.159
 23        27.13             16.51           .6046D-01      0.002284         18.21
 24        27.31              2.033          .7346D-02      0.000278         5.591
 25        27.43             -.6435          .2274D-02      0.000087         2.515
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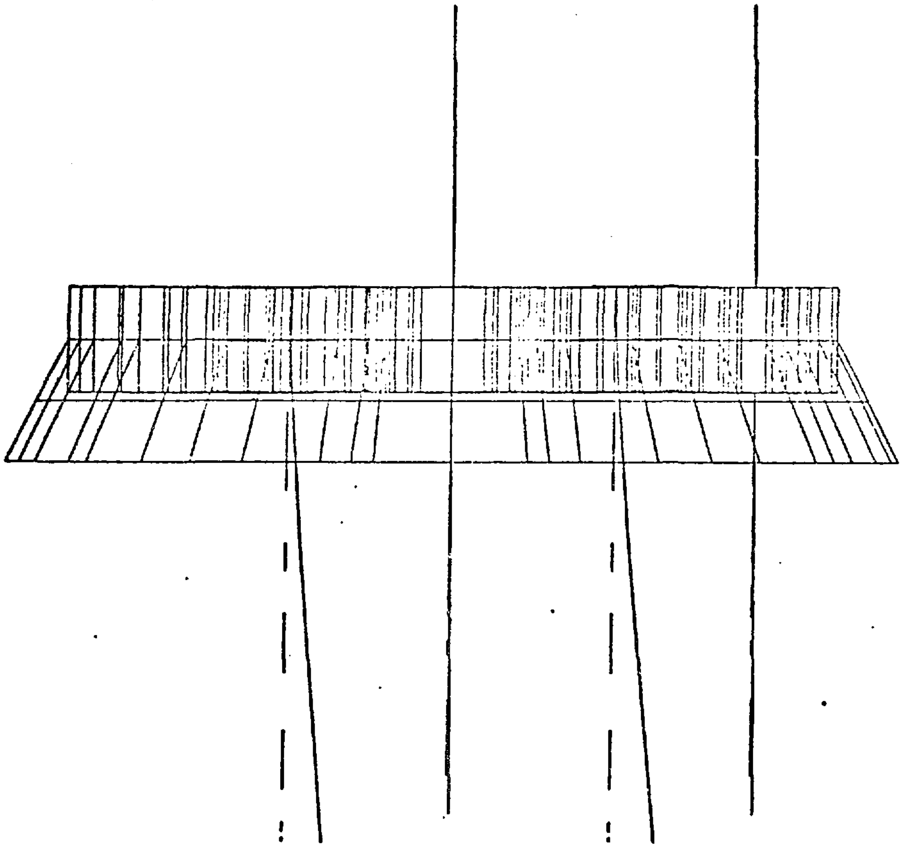

Fig. 9. Mode Shape Plot for the Deck-Mounted Components Swinging Mode in a Horizontal Earthquake.

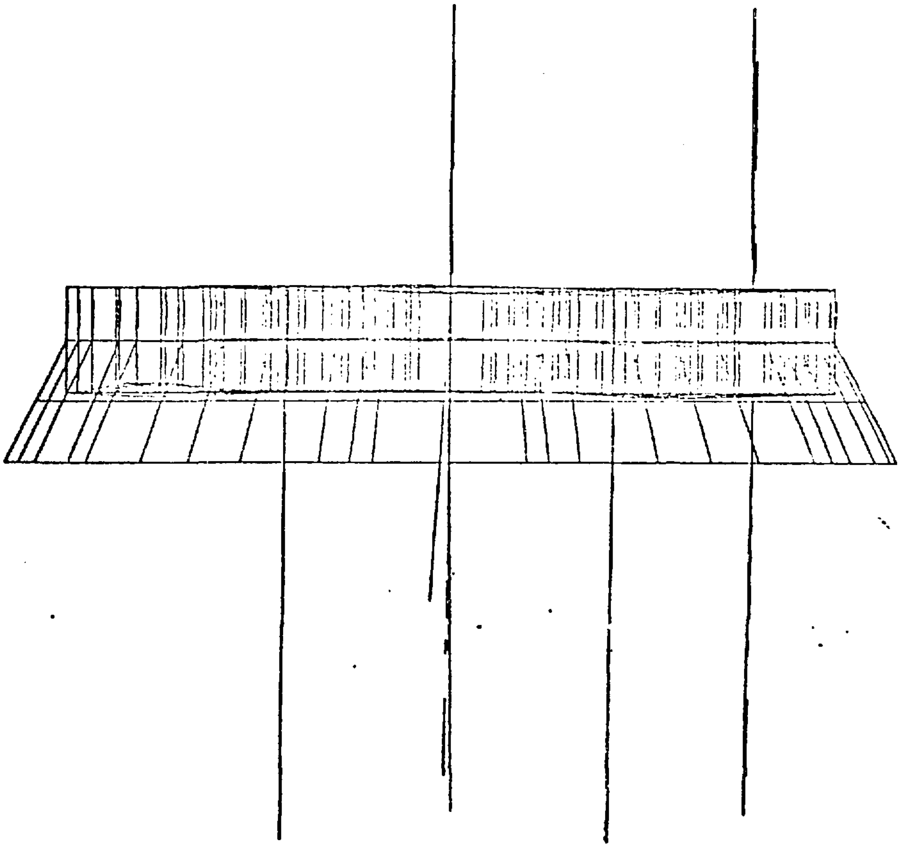

Fig. 10. Mode Shape Plot for the Deck Distortion Mode in a Horizontal Earthquake.

Table 3. Calculated Modal Participation Factors for the Hanging Core Support Structure and its Supported Components under Horizontal Seismic Loading.

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                ***** MODAL PARTICIPATION FACTORS *****

MODE    FREQUENCY        P.FACTOR      MODE COEF.     H.C. RATIO     EQUIV. MASS

  1       1.487           3.004          13.97         0.145362        24.11
  2       1.535           13.75          61.08         0.656951        23.16
  3       2.326           3.566          9.028         0.095045        48.94
  4       2.916           6.303          10.29         0.109285        74.88
  5       2.981           2.068          4.423         0.046955        59.34
  6       3.155           20.46          28.15         0.293904        73.19
  7       3.224          -.3633          .4796         0.005092        496.5
  8       3.269           6.259          8.026         0.085206        233.1
  9       3.355           5.725          6.971         0.074005        177.9
 10       3.451           2.798          3.218         0.034170        103.9
 11       3.485          -13.82          15.60         0.165573        35.75
 12       3.895           104.3          94.19         1.000000        699.9
 13       4.130          -.1716          .1378         0.001463        7349.
 14       4.147           9.746          7.764         0.082426        31.23
 15       4.315          -4.119          3.032         0.032195        500.9
 16       4.332          -.7042          .5142         0.005459        386.9
 17       4.641           .7206          .4583         0.004866        1528.
 18       4.680           3.693          2.311         0.024531        58.28
 19       5.183          -2.493          1.269         0.013473        49.28
 20       5.329           1.792          .8643         0.009131        69.04
 21       5.393           4.551          2.141         0.022727        91.92
 22       5.600           2.154          .9410         0.009991        85.41
 23       5.965           3.192          1.229         0.013053        41.74
 24       6.261           2.841          .9783         0.010386        46.01
 25       6.403           6.653          2.174         0.023979        45.40
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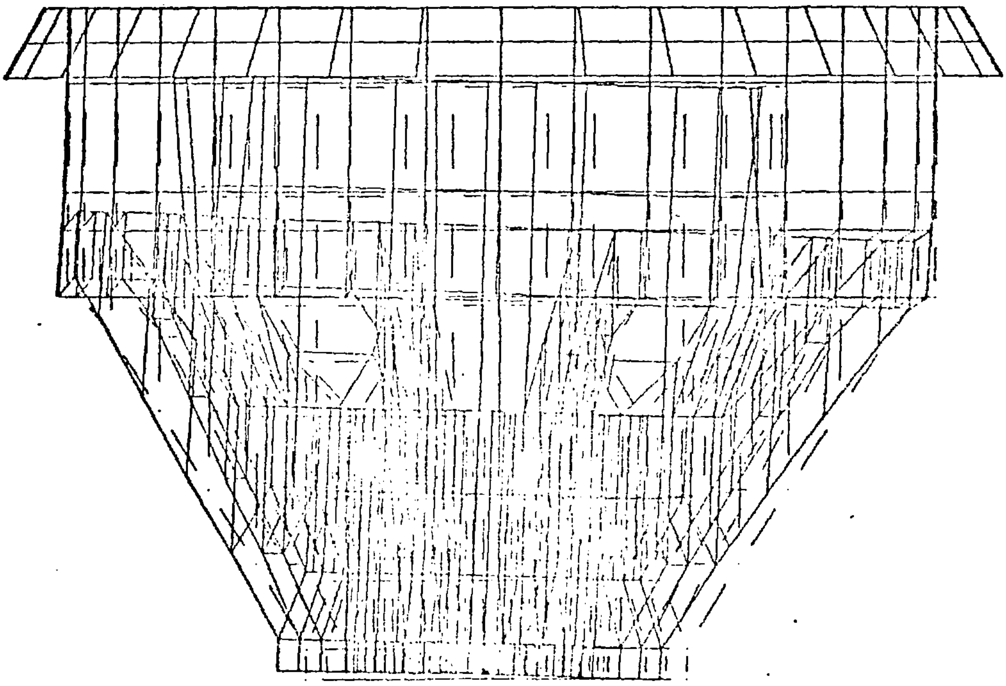

Fig. 11. Mode Shapt Plot for the Reactor Core Rocking Mode in a Horizontal Earthquake.

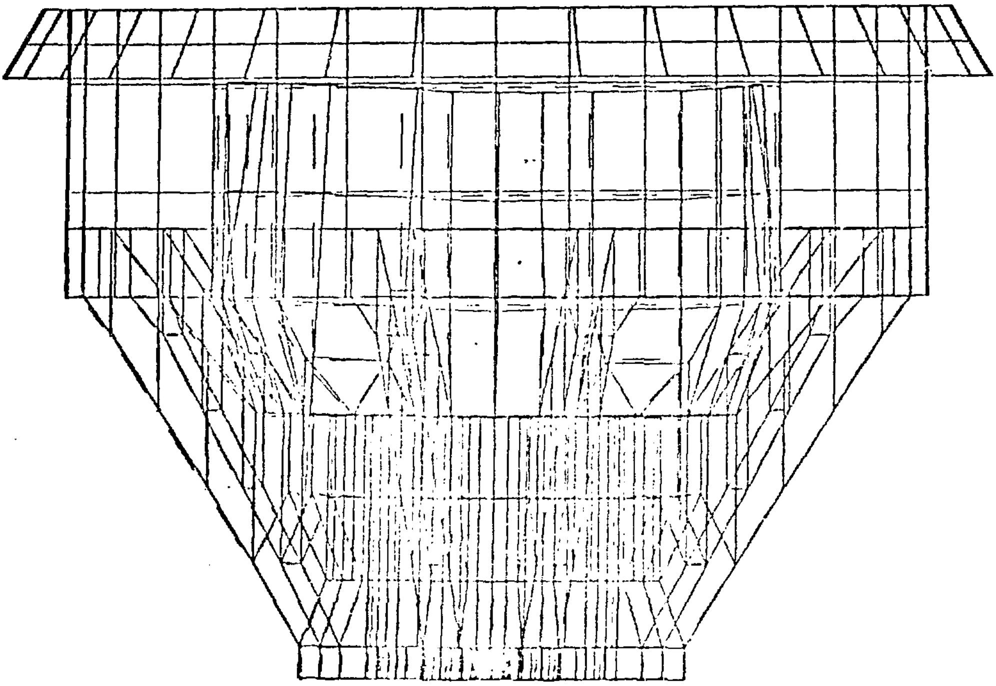

Fig. 12. Mode Shape Plot for the Redan Distortion Mode in a Horizontal Earthquake.

Table 4. Summary of Deformation in the Primary System under Seismic Load.

	OBE				SSE			
	Horizontal		Vertical		Horizontal		Vertical	
	Disp. (in)	Acc. (g)	Disp. (in)	Acc. (g)	Disp. (in)	Acc. (g)	Disp. (in)	Acc. (g)
Inner Ring of Deck*	0.01	0.22	0.03	0.31	0.03	0.42	0.06	0.60
Bottom of Pump	0.35	2.63	0.01	0.17	0.68	5.07	0.03	0.34
Bottom of IHX	0.92	1.09	0.03	0.49	1.84	2.38	0.07	0.92
Bottom of UIS	0.11	1.22	0.03	0.31	0.23	2.36	0.06	0.60
Top of Core Barrel*	0.27	0.38	0.39	0.61	0.53	0.77	0.74	1.20
Bottom of Core Barrel*	0.28	0.43	0.40	0.63	0.55	0.86	0.76	1.17
Top of Redan	4.99	2.66	0.48	0.65	9.75	5.44	0.93	1.24

*Design Limits:

	Core/Deck Disp. (in)		Core Acc. (g)	
	OBE	SSE	OBE	SSE
Horizontal	0.60	0.60	1.0-1.5	NA
Vertical	1.75	1.75	.76	NA

Table 5. Calculated Modal Participation Factors for the Deck and Deck Mounted Components under Vertical Seismic Loading.

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                ***** MODAL PARTICIPATION FACTORS *****

MODE     FREQUENCY        P.FACTOR      MODE COEF.     M.C. RATIO      EQUIV. MASS

  1        3.981          -6.920        2.693          0.627885         425.9
  2        4.035           .2417        .9154D-01      0.021347         413.4
  3        4.153           .8804D-01    .3148D-01      0.007340         341.0
  4        4.155           .8525        .3044          0.070992         532.9
  5        8.676          52.35         4.288          1.000000         128.8
  6        9.265         -30.60         2.156          0.502783         199.0
  7       10.01          -20.86         1.189          0.277323         220.6
  8       10.36           6.929         .3587          0.083559         201.0
  9       10.55          -1.254         .6154D-01      0.014350         243.9
 10       11.76          68.65          2.445          0.570055         489.6
 11       12.18         -35.68          1.139          0.265506         393.4
 12       12.71          -1.806         .5025D-01      0.011718         381.9
 13       16.02          -6.893         .9844D-01      0.022957         624.7
 14       17.14           4.465         .5364D-01      0.012509         247.5
 15       17.77          -4.356         .4766D-01      0.011113         108.7
 16       20.67          -1.308         .1306D-01      0.003046         619.5
 17       21.45           1.292         .1235D-01      0.002881         695.9
 18       21.68           .4849         .3069D-02      0.000716         997.3
 19       22.92          13.13          .7089D-01      0.016530         443.7
 20       24.45          -2.053         .9059D-02      0.002112         29.26
 21       26.21          -6.024         .2124D-01      0.004953         72.59
 22       27.22           .4383         .1360D-02      0.000317         2.806
 23       27.41          -.9463         .2863D-02      0.000668         3.426
 24       27.46          -2.092         .6291D-02      0.001467         4.877
 25       27.64          -.4469         .1314D-02      0.000306         3.578
```

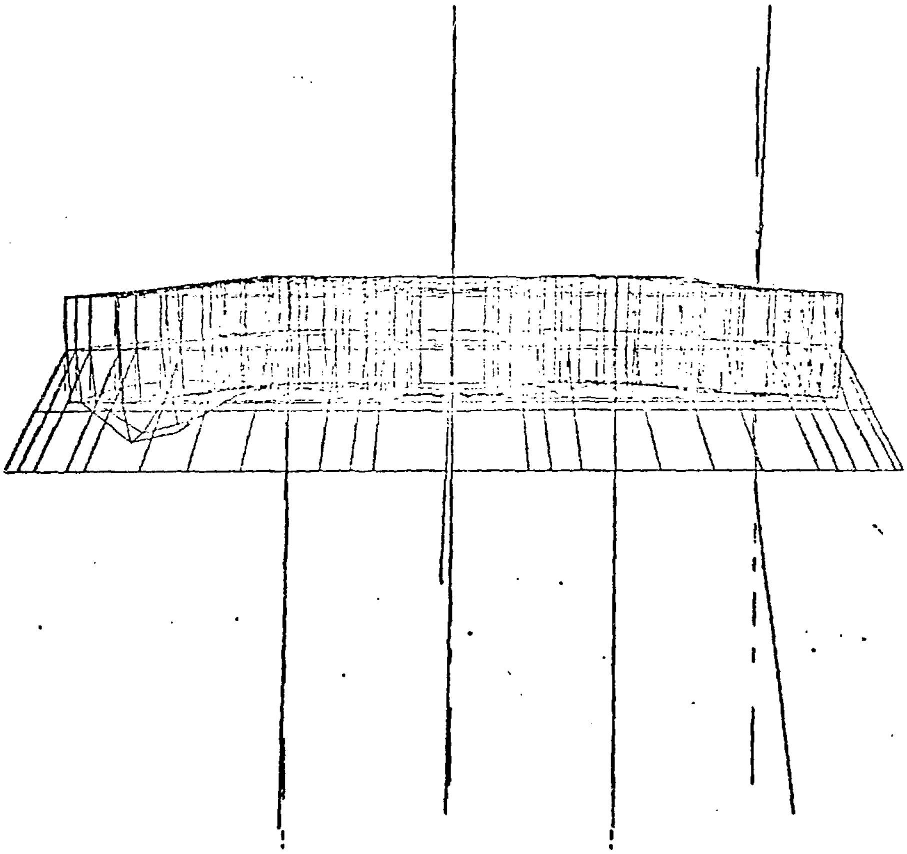

Fig. 13. Mode Shape Plot for the Deck Bouncing Mode in a Vertical Earthquake.

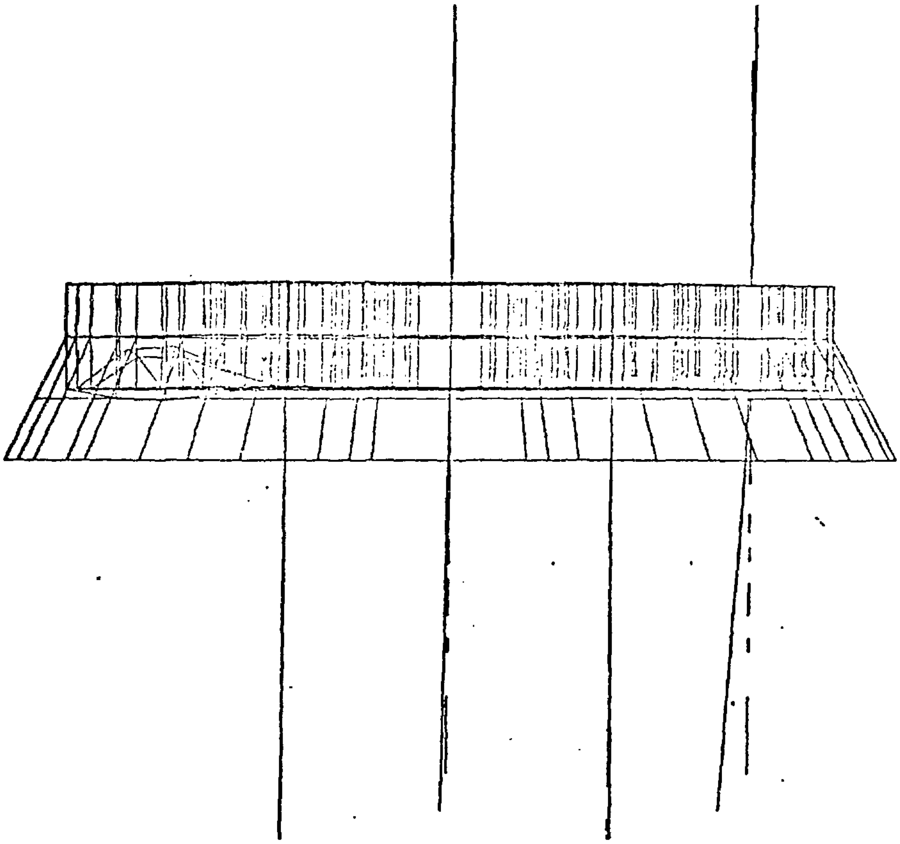

Fig. 14. Mode Shape Pot for the Deck Mounted Component Bending Mode in a Vertical Earthquake.

Table 6. Calculated Modal Participation Factors for the Hanging Core Support Structure and its Supported Components under Vertical Seismic Loading.

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              ***** MODAL PARTICIPATION FACTORS *****

MODE     FREQUENCY         P.FACTOR        MODE COEF.      M.C. RATIO       EQUIV. MASS

  1        1.972         -.1052D-02       .3136D-02         0.000061         .3438E+05
  2        2.069         -.5695           1.562             0.030238         .3723E+05
  3        3.784          13.52           11.09             0.214471         481.3
  4        3.927          67.89           51.71             1.000000         1056.
  5        5.000         -1.519           .6913             0.013369         9.943
  6        5.138          1.698           .7552             0.014605         60.61
  7        6.670         -.4320           .1141             0.002206         34.39
  8        8.033          .6750           .1228             0.002375         228.4
  9        8.679         -.9620           .1500             0.002901         171.8
 10        8.996         -.1000D-02       .1452D-03         0.000003         .6606E+08
 11        9.917          .4471           .4975D-01         0.000962         37.20
 12        12.24          .2776           .1655D-01         0.000320         132.1
 13        12.62         -.7804           .4210D-01         0.000814         74.15
 14        12.93          1.171           .5837D-01         0.001129         31.76
 15        13.32         -.2163           .9742D-02         0.000188         141.3
 16        13.44         -.7602D-02       .3324D-03         0.000006         183.6
 17        13.77         -.3390           .1380D-01         0.000268         214.2
 18        15.62          .9007           .2705D-01         0.000523         15.25
 19        17.77         -5.487           .1185             0.002292         141.1
 20        17.93          .4501           .9520D-02         0.000185         266.1
 21        18.21         -6.652           .1347             0.002604         237.4
 22        18.31         -.4502           .9141D-02         0.000177         893.3
 23        18.33         -.2020           .4017D-02         0.000078         902.5
 24        18.55          3.012           .5805D-01         0.001123         439.8
 25        19.05         -.9245           .1660D-01         0.000321         79.75
```

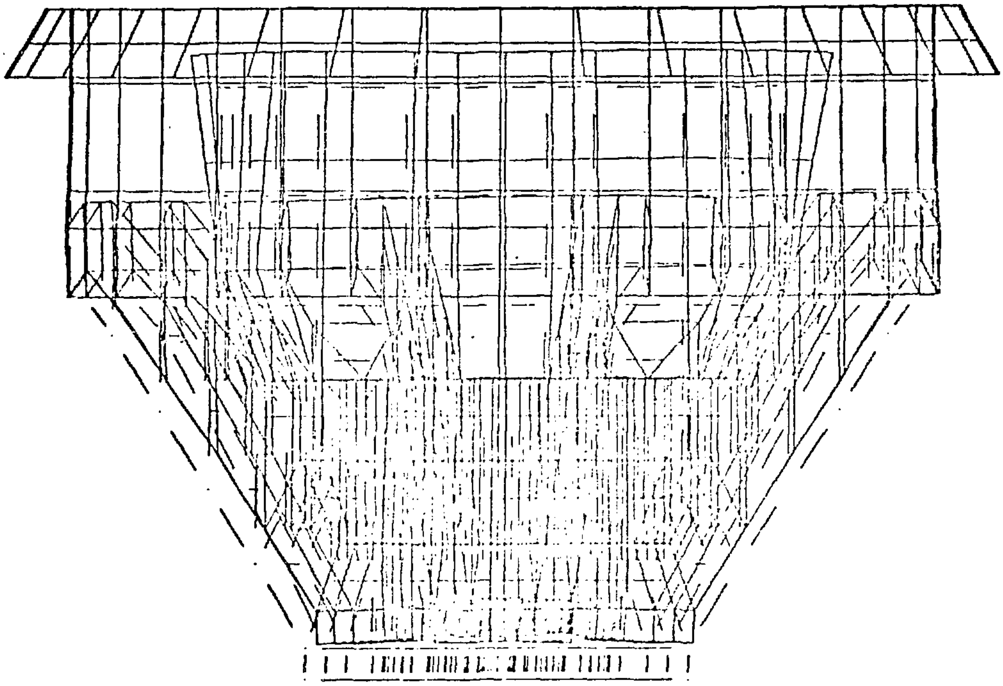

Fig. 15. Mode Shape Plot for the Reactor Core Bouncing Mode Associated with a Vertical Earthquake.

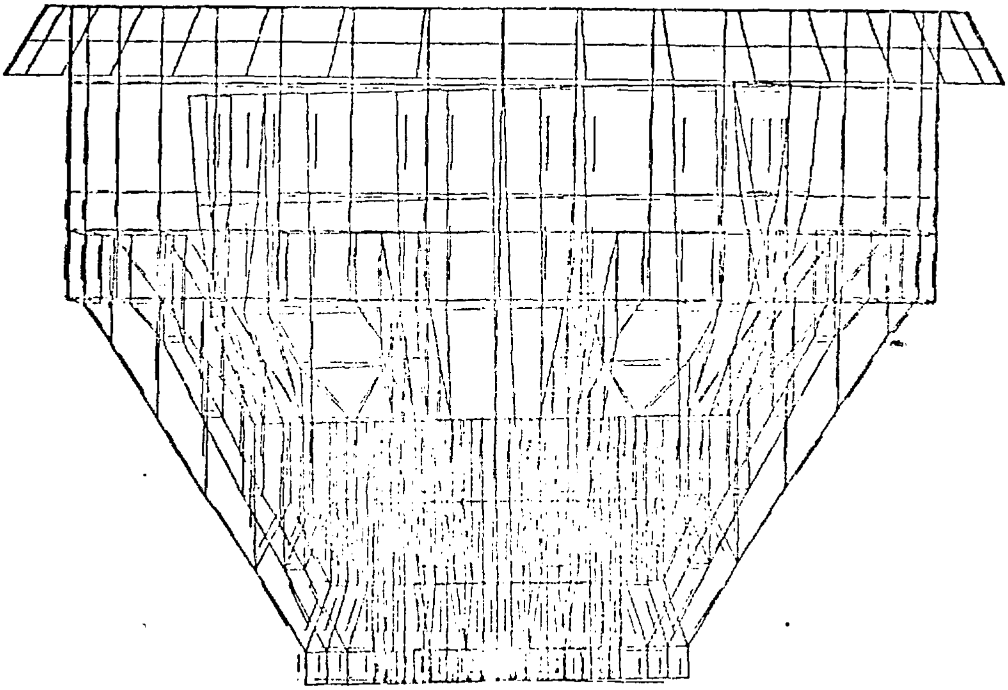

Fig. 16. Mode Shape Plot for the Reactor Core Rocking Mode Associated with a Vertical Earthquake.

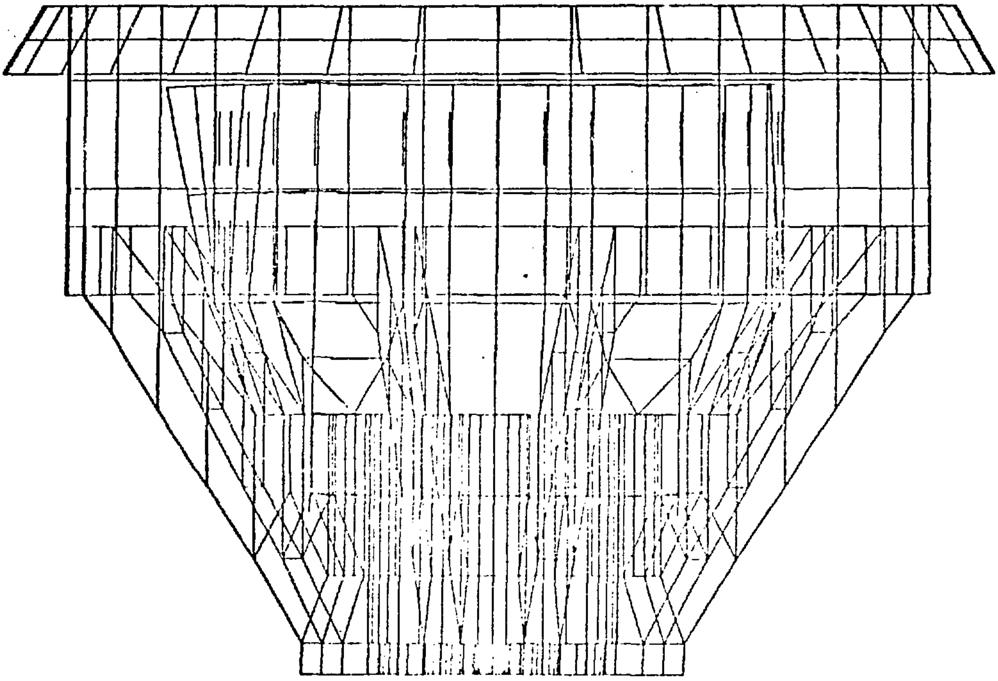

Fig. 17. Mode Shape Plot for the Redan Distortion Mode Associated with a Vertical Earthquake.