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A New Approach to the Design of Core Support Structures for Large LMFBR Plants*

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ABSTRACT

The paper describes an innovative design concept for a LMFBR Core Support Structure. A hanging Core Support Structure is described and analyzed. The design offers inherent safety features, constructibility advantages, and potential cost reductions.

INTRODUCTION

Throughout the world Liquid Metal Fast Breeder Reactors (LMFBR) are in various stages of design, construction and operation. A large pool-type plant, the 1200 MWe Super-Phenix reactor, is under construction in France at Creys-Malville, and is anticipated to begin operational testing next year. With the termination of the Clinch River Breeder Reactor project in the USA, the DOE is restructuring the fast breeder reactor program to develop advanced LMFBR concepts to support commercial introduction of inherently safe, reliable and cost-competitive breeders using both domestic programs and international collaboration. As part of a joint study (1) with Rockwell International, Argonne National Laboratory has introduced a new approach to the design of the core support structure of a large pool-type primary system.

In this paper a LMFBR core support structure that is independent from the reactor vessel is described and analyzed. It represents an attractive solution to accommodating seismic effects on the reactor core and offers some constructibility advantages that should help shorten the construction schedule for large LMFBR plants.

REACTOR ASSEMBLY

For a large pool-type LMFBR the reactor assembly (see Fig. 1) basically contains the core and the primary heat transfer system (piping, pumps and intermediate heat exchangers) along with approximately 3000 tons (2.7×10^6 Kg) of sodium. In most designs the deck, rotatable plugs and reactor vessel define the major part of the pri-

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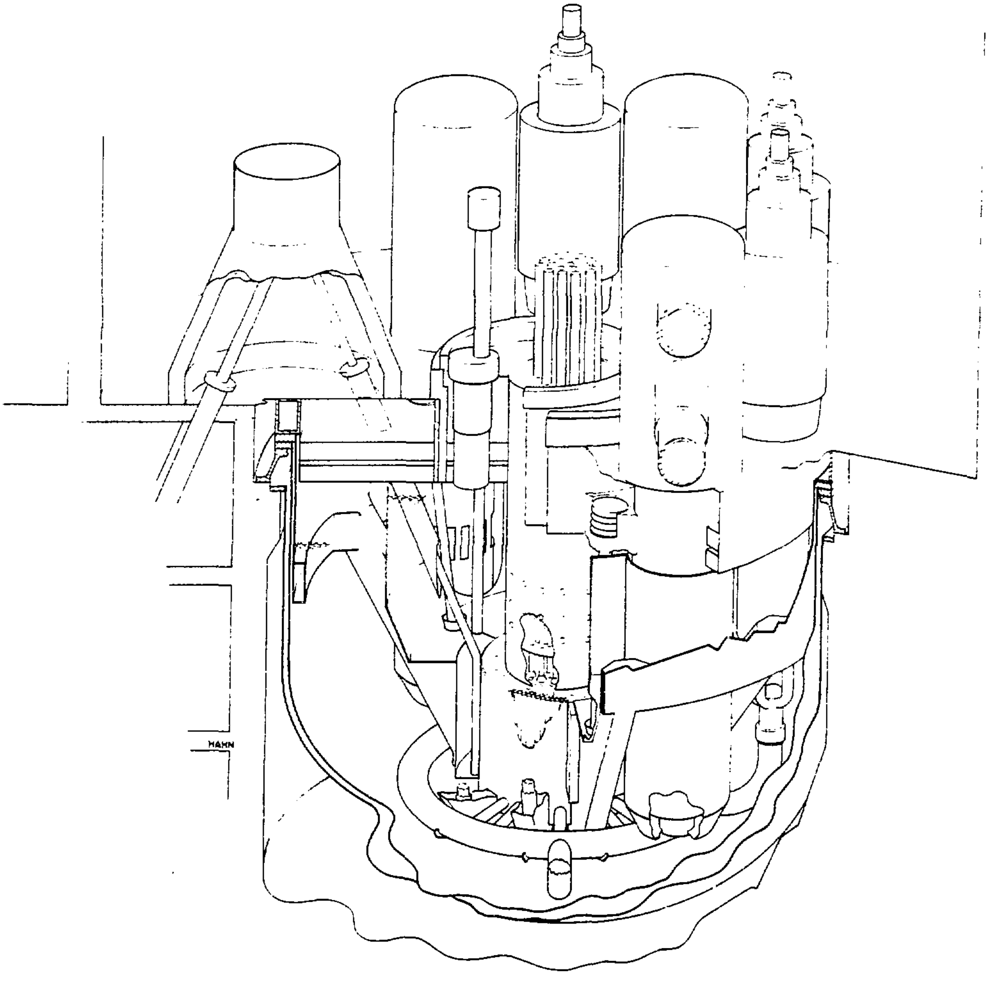

Figure 1. Reactor Assembly - Pictorial

mary system boundary and are generally supported at or near the deck-vessel interface. The core support structure supports the reactor fuel, blanket and reflector assemblies as well as the core barrel, radial neutron shield and the core support grid. The flow divider (sometimes called the redan) between the hot and cold sodium pools is also supported by the core support structure.

DESIGN GOALS

The core support features selected for the 3500 MWt sized reactor assembly and described in the next section has been strongly influenced by the following goals. The first is to accomodate the seismic loading of the core independent of any loads imposed on the reactor vessel. The intent here is to simplify the design of the reactor vessel and provide the safety advantage that any failure of the reactor vessel only means a loss of sodium to the guard tank and no degradation of the core support structure or the core. The second goal is to reduce the construction time in containment by taking a modular approach to assembly and reducing in-containment welding of reactor assembly components to essentially only seal welding. The third goal is to provide a backup support system for the core support structure that can provide an additional safety margin and can be used to continuously monitor deflections near the core support grid.

DESIGN FEATURES

For this investigation the core support structure is sized for a reactor assembly capable of supplying 3500 MW_t of heat to the intermediate heat transfer system. The reactor assembly, shown in Figs. 2 and 3 consists of: (1) the reactor vessel, guard vessel, and conical support skirt; (2) the reactor core assemblies; (3) the reactor internal structural components and (4) the reactor deck closure components. The reactor vessel and deck constitute the primary coolant and cover gas boundary. The pumps and intermediate heat exchangers are supported by the deck, as are portions of the shutdown heat removal and fuel handling systems.

REACTOR VESSEL

The reactor vessel contains essentially the entire inventory of the radioactive primary sodium coolant. In the present reactor configuration its only function is to contain the sodium coolant; support of the internals is provided by the core support structure. There are no penetrations in the reactor vessel; all equipment - intermediate heat exchangers, pumps, piping, instrumentation, fuel handling port, and other components - penetrate the primary coolant systems enclosure through the deck structure.

The vessel is suspended at its top flange from the same conical skirt (see Fig. 4) which provides support for the deck and core support structure.

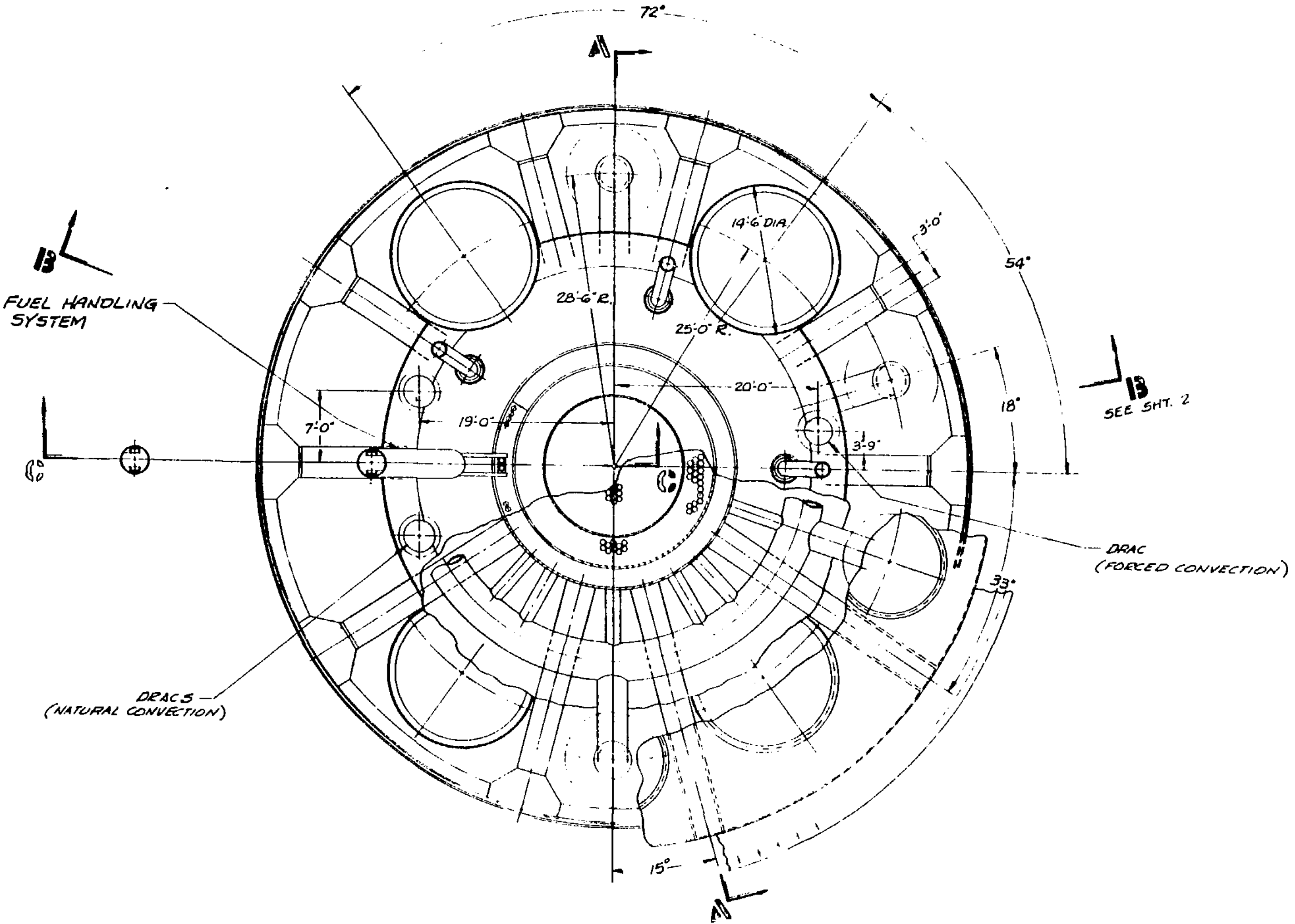

Figure 2. Reactor Assembly - Plan View

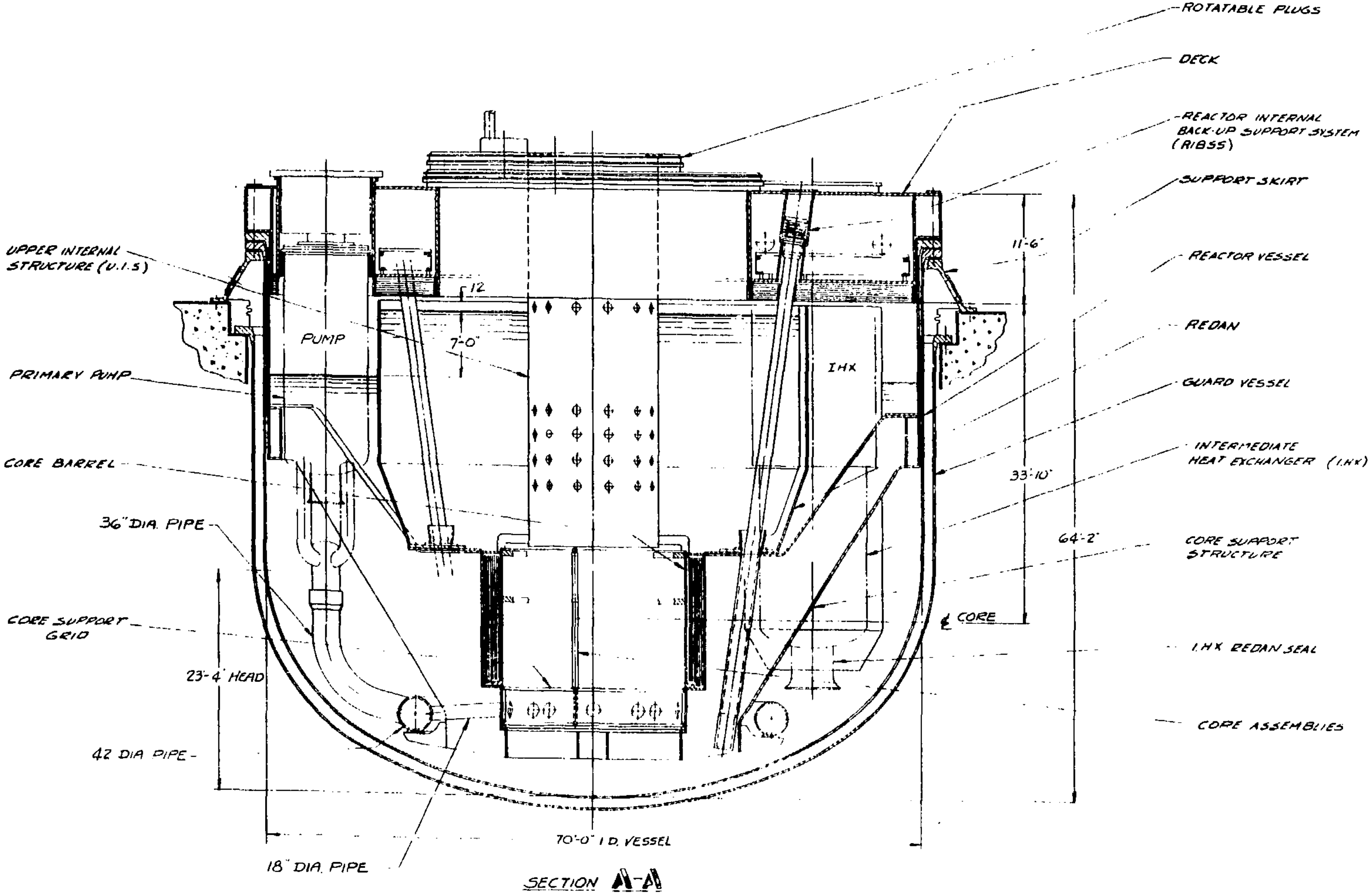

Figure 3. Reactor Assembly - Elevation View

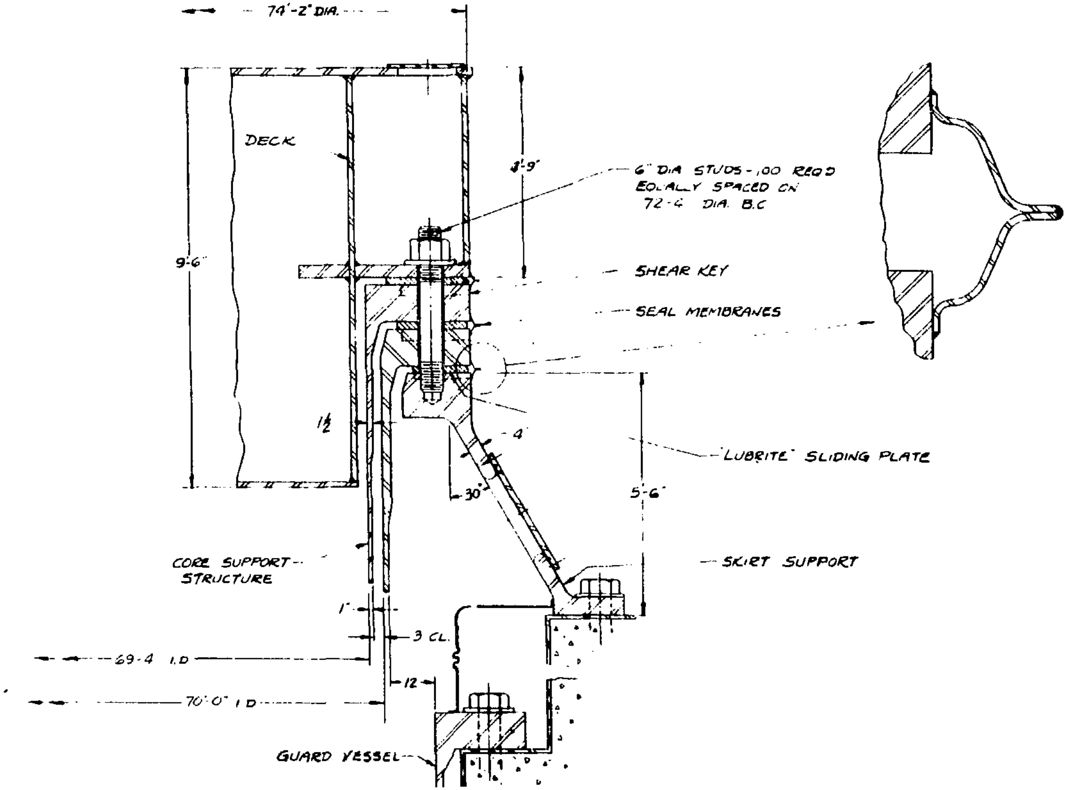

Figure 4. Vessel, Deck and Core Support Flange Interface

CORE SUPPORT ASSEMBLY

The core support assembly provides load support for the core assemblies, the support grid, the core barrel, the fixed radial neutron shield, and the redan assembly. It consists of the core support structure and the reactor internals backup support system (RIBSS).

Core Support Structure

The core support structure (CSS) provides the main support for the reactor primary system internals. As shown in Figs. 5 and 6 it consists of four integral components. They are the skirt (including its flange), 10 beams, the basket, and the inlet piping.

Skirt The skirt of the core support structure is a cylinder 69 ft 4 in. (21.3 m) inside diameter by 18 ft 6 in. (5.64 m) high with a nominal 1 in. (25 mm) thickness. As shown in Fig. 4 the flange is supported from the reactor vessel conical support skirt. The core support skirt is the main tie between the 10 beams. Attached to the skirt is a 1/8 in. (3.2 mm) thick thermal baffle, that is required to protect the skirt from excessive axial temperature gradients during normal operation.

Beams Attached to the bottom of the skirt are 10 box girder type beams. The beams are approximately 3 ft (915 mm) wide with a nominal depth of about 6 ft (1.8 m). The beams extend from below the cold sodium pool operating level to below the core zone. As shown in the plan view the center of the structure has a beam (wheel) arrangement with pads to support the core support grid.

Basket The basket zone of the core support structure is that area encompassing the fixed radial neutron shield and the core support grid. The basket is the inner diameter of the structure and is approximately 23 ft (7.0 m) in diameter and 18 ft 6 in. (5.64 m) high. It is stepped down at the top of the core support grid location. This step provides the platform for the core barrel flange and the accommodation for the core support grid outer diameter.

Inlet Piping Attached to the lower part of the core support assembly is the inlet piping. The inlet piping consists of four - 36 in. (915 mm) diameter pipes which are connected to the primary pump discharge pipes, a 42 in. (1.07 m) diameter distribution torus (which circles the lower end of the core support structure) and fourteen - 18 in. (457 mm) diameter core inlet pipes.

Reactor Internals Backup Support System (RIBSS)

Because the skirt and beams of the core support structure cannot be reliably inspected during service (even though the failure probability is considered very low) the design provides a backup load-bearing capability. As shown in Fig. 3, the five RIBSS are supported from the deck and attached to the lower end of the core support structure. The RIBSS concept is shown in Fig. 7. The RIBSS consists of 10

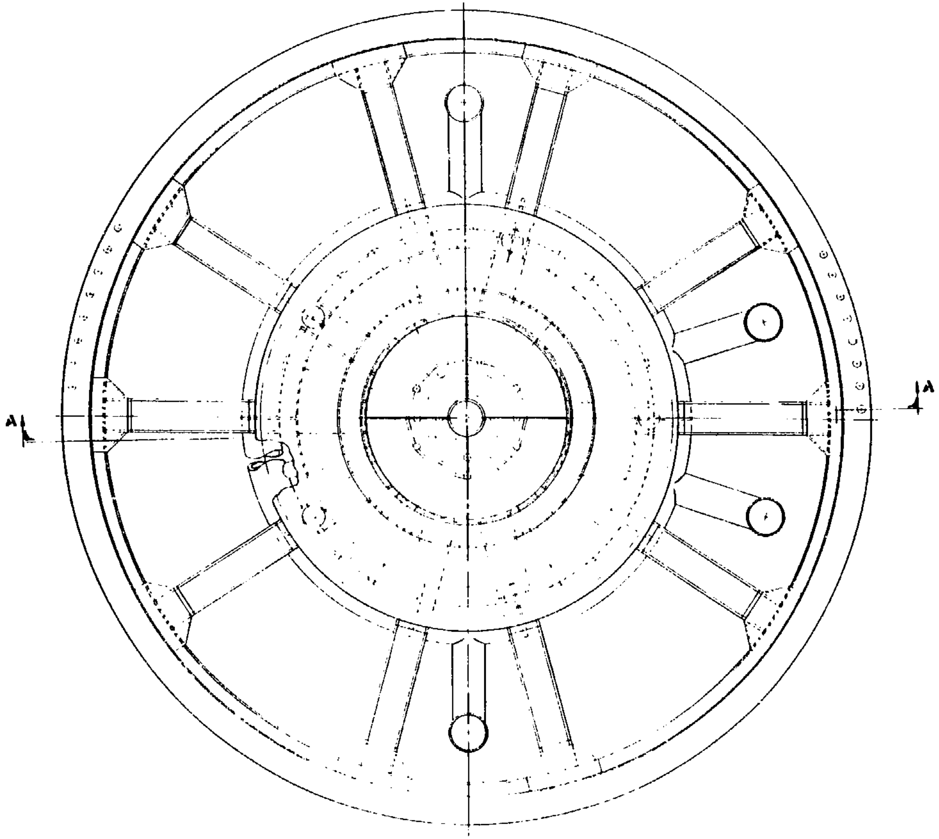

Figure 5. Core Support Structure - Plan View

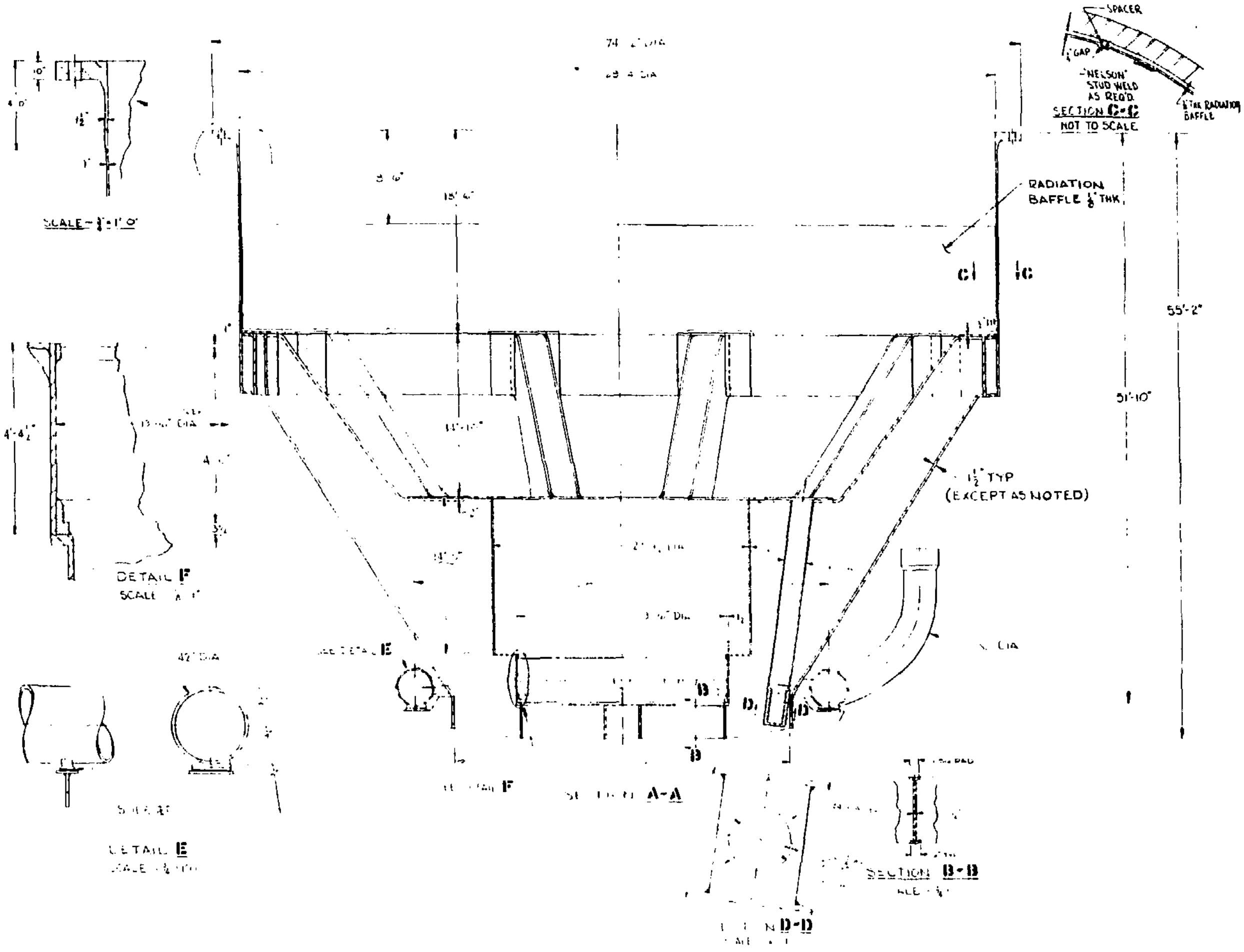

Figure 6. Core Support Structure - Elevation View

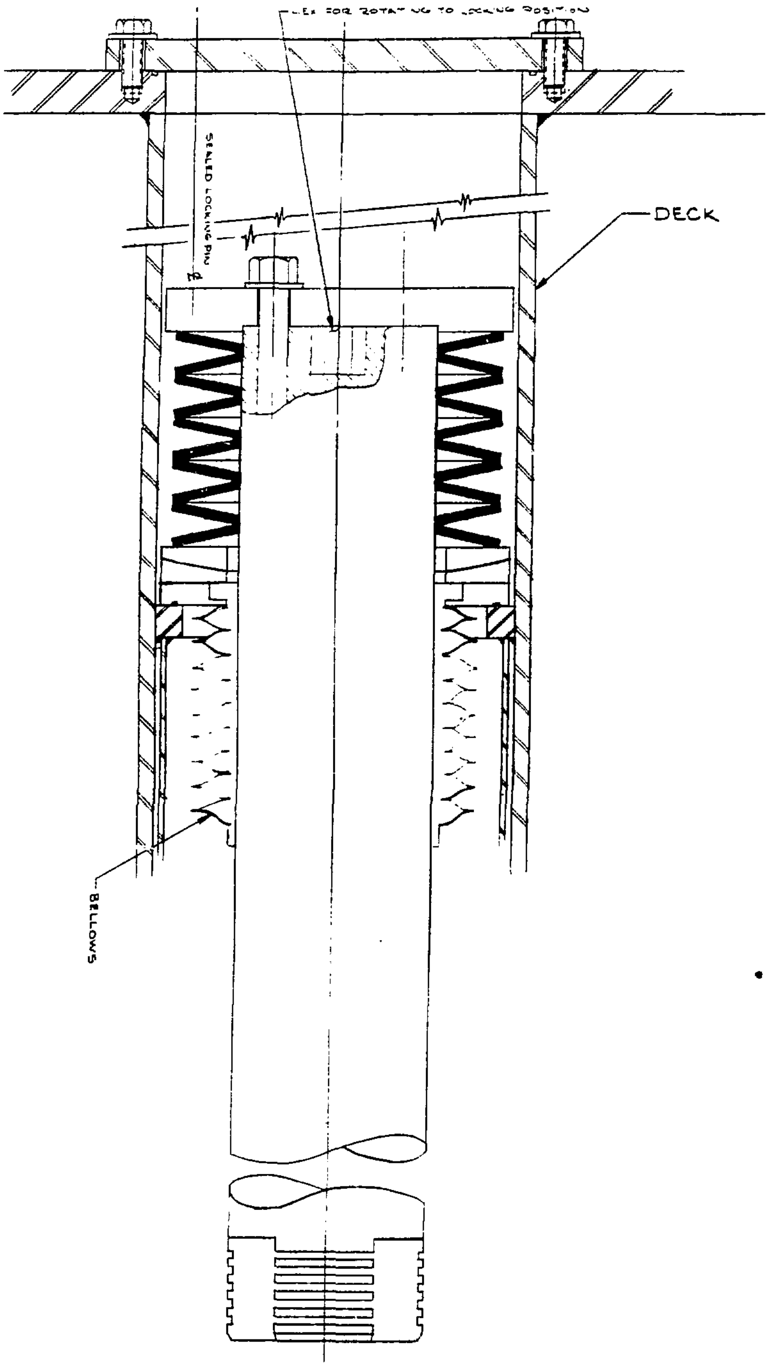

Figure 7. Reactor Internals Backup Support System (RIBSS)

"Belleville" springs, a column and a breech-type-lock at the lower end that fastens to the core support structure. In the very unlikely event of a core support beam failure, the RIBSS would act as the backup. The RIBSS will have stress monitoring capability and provisions for reactor instrumentation.

Constructibility Considerations

Most, if not all, of the studies of large pool-type LMFBR plants have concluded that reactor vessel field erection and installation lies on the construction critical path. These studies point out that considerable savings -- in both overall plant construction time and total cost -- can be achieved by finding ways to reduce the reactor vessel erection time within the containment building.

A major step in reducing field erection time was taken by the French in constructing Super Phenix, where much of the field fabrication of the reactor vessel, guard vessel, and deck was performed in an on-site field fabrication facility. However, a considerable amount of in-containment fitting and welding was still required to assemble the vessel internals once it was secured within the reactor containment building.

For the reactor assembly described in this paper, a major design goal was to further reduce vessel field work once it was installed in the containment. As was done in Super Phenix, an on-site fabrication facility is used to fabricate all components of the reactor vessel assembly. The major difference lies in two areas: (1) the completed components may all be pre-assembled in the field fabrication facility, thus reducing possible fitup errors in containment to a minimum; and (2) the vessel assembly is deliberately designed to virtually eliminate the need for any structural welding to take place within the containment. All flange-to-flange joints are bolted and seal-welded. This modular approach is expected to save several months of construction time within the containment building.

It is, of course, necessary to machine both faces of the core support structure (CSS), but this added cost will be more than offset by the time savings realized in assembly work performed inside the reactor containment building.

The use of the hanging core support structure is very compatible with the construction assembly just described. The CSS may be completely fabricated outside of containment, rough-machined, fitted onto the reactor vessel (top flange), and final machined. The stiffness and ruggedness of the beam-type CSS assures that machined tolerances will remain true until final assembly in the containment. The only work which must be performed within the containment is to lower the CSS into the reactor vessel, check tolerances, bolt the CSS to the vessel, and install the seal-weld assembly to the mating flanges.

The need for the RIBSS system does not add significantly to either total cost or construction time for the reactor vessel assembly. It will be necessary, of course, to make final adjustments after loads have been applied to assure proper preloading of each RIBSS support column.

All ASME Code required nondestructive examinations (NDE) and other inspections will be done in the on-site fabrication facility. Since no further welding is done in the containment building there is also no need to conduct any further NDE at that point.

The CSS design coupled with the other modular design components of the reactor vessel results in a clean, fast, and straightforward construction sequence within containment. This will result in a faster and less expensive erection project.

REACTOR ASSEMBLY ANALYSES

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 1.75 in. (44.5 mm) 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 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, 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

The analytical models developed for this study are three-dimensional finite element models 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 distributed among various components. Plots of various parts of the model are given in Figs. 8 and 9. Figure 8 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

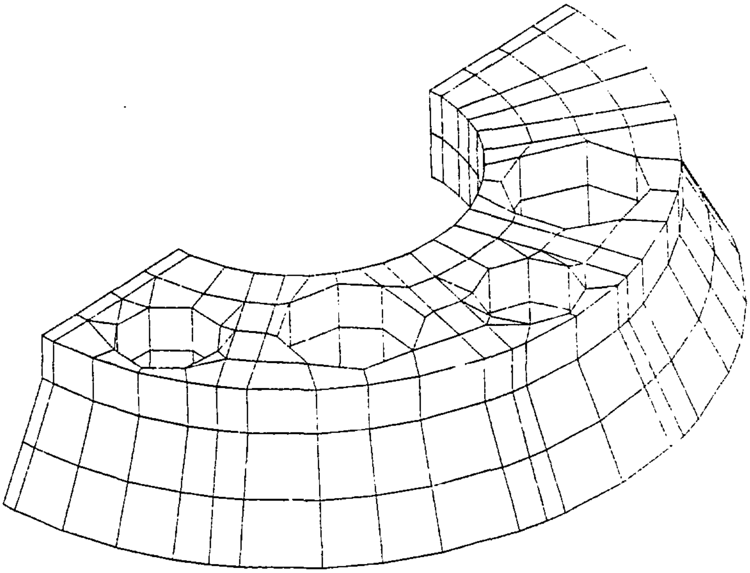

Figure 8. The Deck Model

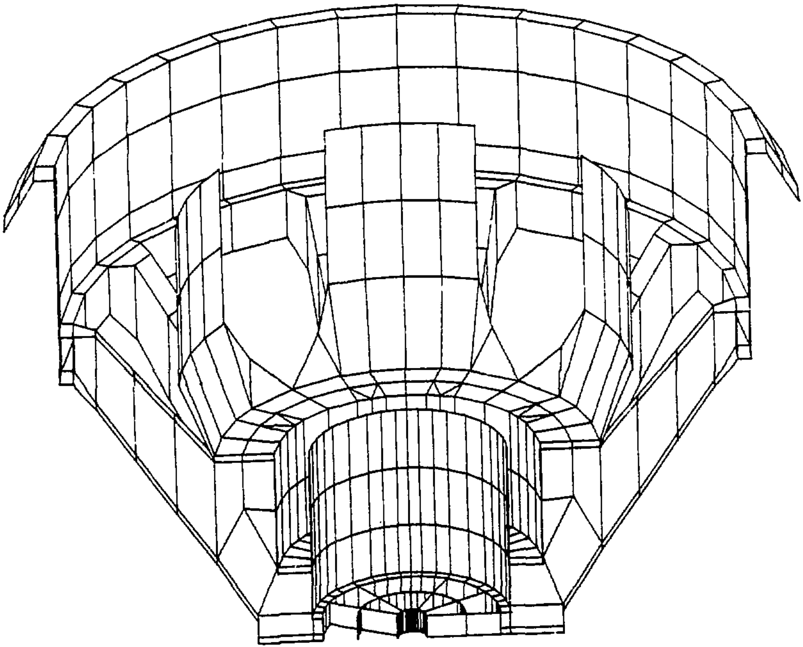

Figure 9. The Hanging Core Support Structure Model

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 9 shows the hanging core support structure model which consists of the cylindrical skirt, the stiffener ring, the support beams, the bottom core support hub, 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 nodal points. 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. 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 (25 mm). Furthermore, the deformation of the core support structure can be reduced by refinement in the CSS skirt stiffener and the CSS basket 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 seismic response spectra at reactor skirt support are given in Fig. 10. 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 mode shape plot of the most dominant vibrational modes for the deck and deck mounted components is shown in Fig. 11. This mode 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 also the most common vibrational mode for the deck. It appears in several different frequencies with different

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

$\sigma_3 < 1.5\ (1.5\ S_m)$

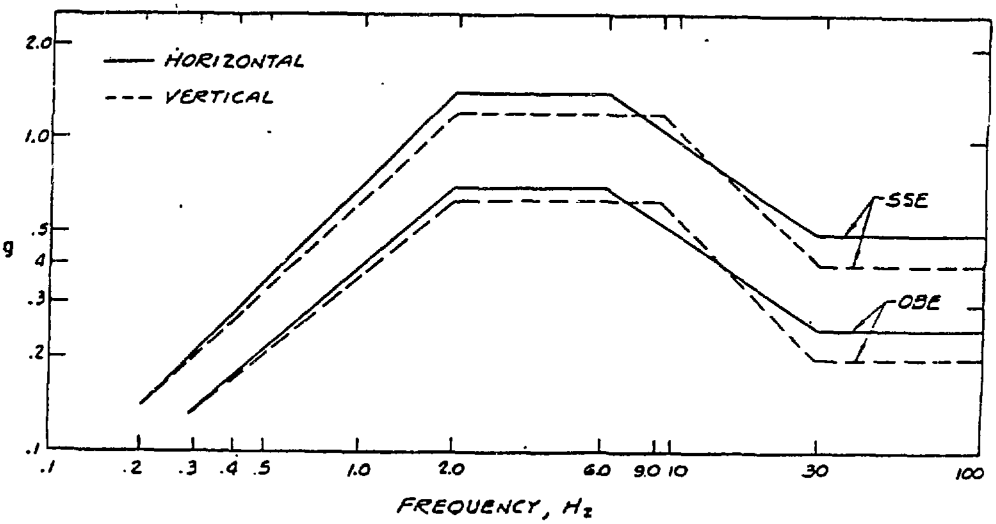

Figure 10. Estimated Seismic Design Spectra (SSE ~3% Damping, OBE ~2% Damping, SSE ZPA = 0.25 g at 4000 fps, OBE ZPA = 1/3 SSE ZPA)

magnitudes. The maximum displacement for the deck mounted components under the SSE is 1.35 in. (34.3 mm). The deck distortional modes occur at frequencies greater than 8.7 Hz where local deck distortion is accompanied by mild swinging of the in-tank components.

The mode shape plot of the most dominant vibrational mode for the core support structure model is shown in Fig. 12. This mode 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 0.25 in. (6.4 mm) 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 9 in. (229 mm) 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 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.

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 2. 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. 10 is used as the loading in the modal analysis of the primary system. Both OBE and SSE are again considered.

The mode shape of the most significant vibrational mode for the deck model are plotted in Fig. 13. This mode 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 0.3 in. (7.6 mm) for SSE and 0.15 in. (3.8 mm) for OBE. The horizontal displacement at the lower end of the deck mounted component is 0.25 in. (6.4 mm) 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 generally related to the local bending of the deck mounted components.

The mode shape plots of significant modes for the hanging core support structure and its supported components under both OBE and SSE loadings are shown in Figs. 14 to 15. 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 as shown in Fig. 14. Mode

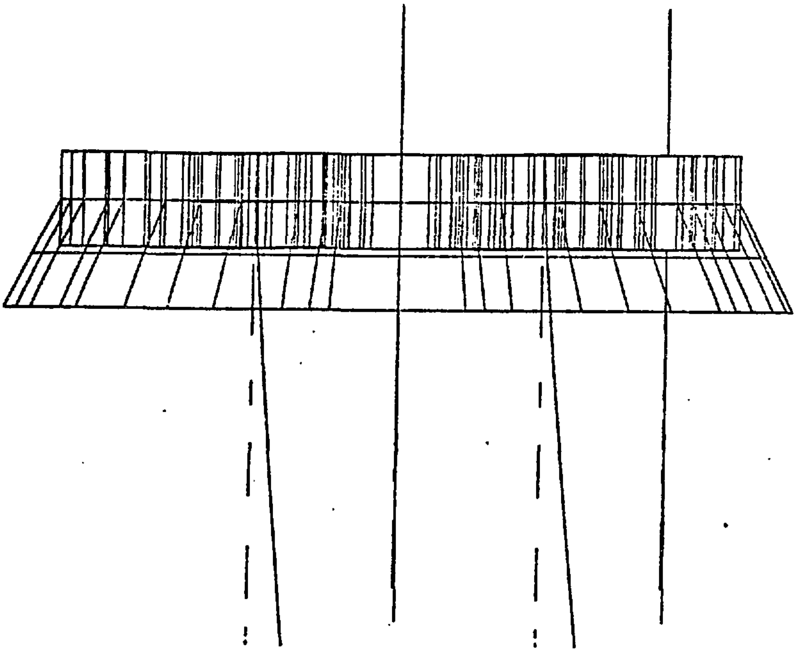

Figure 11. Mode Shape Plot for the Deck-Mounted Components Swinging Mode in a Horizontal Earthquake

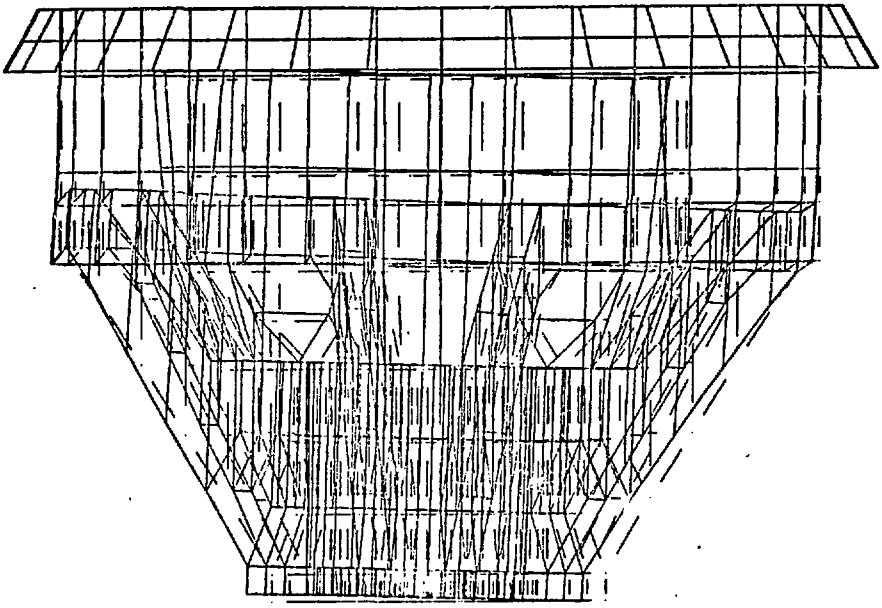

Figure 12. Mode Shape Plot for the Reactor Core Rocking Mode in a Horizontal Earthquake

Table 2. 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*	0.25	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

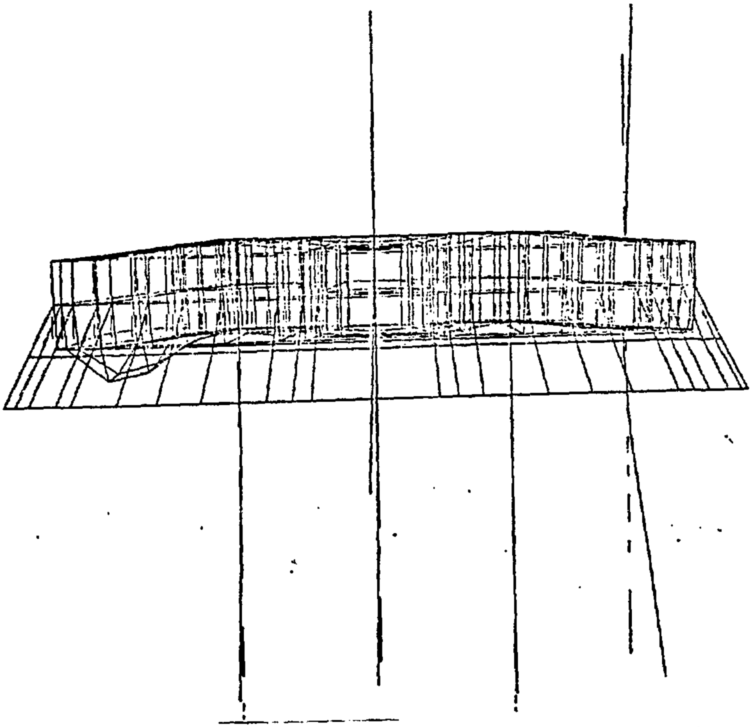

Figure 13. Mode Shape Plot for the Deck Bouncing Mode in a Vertical Earthquake

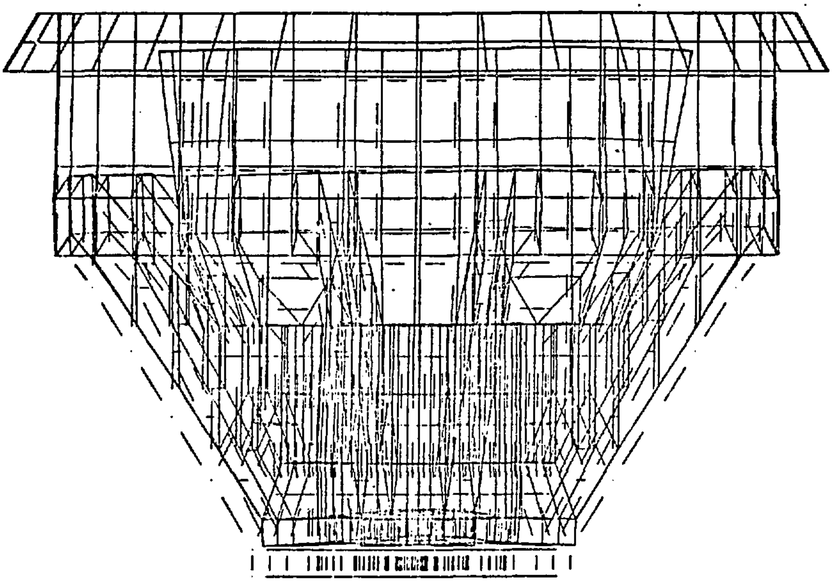

Figure 14. Mode Shape Plot for the Reactor Core Bouncing Mode Associated with a Vertical Earthquake

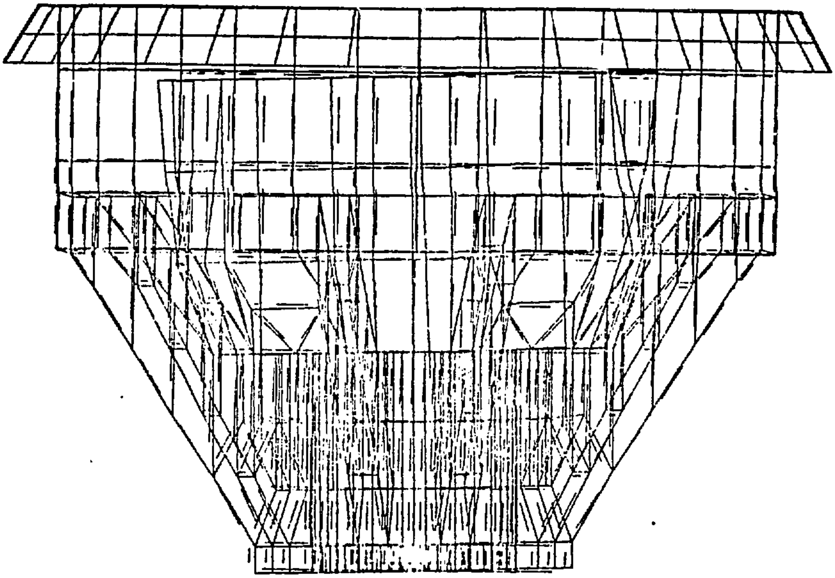

Figure 15. Mode Shape Plot for the Reactor Core Rocking Mode Associated with a Vertical Earthquake

3 is a less severe reactor core rocking mode with a frequency of 3.8 Hz. The reactor rocking motion shown in Fig. 15 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.

A summary of the stresses and displacements in various components under OBE and SSE conditions are given in Tables 1 and 2, 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

The hanging core support structure and its backup system is a unique concept. The design is highly redundant with regard to reactor safety. The hanging core support structure is decoupled from the reactor vessel, so that the reactor vessel's only function is to support and contain the primary sodium coolant. Constructibility, has been enhanced with the bolted multi-flange support system. Stress levels have been shown to be very reasonable for the overall concept.

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KEY WORDS

1. Beams, supports
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11. Nuclear energy
12. Powerplants
13. Reactors
14. Safety
15. Seismic
16. Structural engineering