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BENEFITS OF VERTICAL AND HORIZONTAL SEISMIC ISOLATION FOR LMR NUCLEAR REACTOR UNITS*

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by

Ting-shu Wu, Y. W. Chang and R. W. Seidensticker
Argonne National Laboratory
9700 South Cass Avenue
Argonne, IL 60439

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ABSTRACT

Seismic isolation has been shown to be able to reduce transmitted seismic force and lower response accelerations of a structure. When applied to nuclear reactors, it will minimize seismic influence on the reactor design and provide a design which is less site dependent. In liquid metal reactors where components are virtually at atmospheric pressure but under severe thermal conditions, thin-walled structures are generally used for primary systems. Thin-walled structures, however, have little inherent seismic resistance. The concept of seismic isolation therefore offers a viable and effective approach that permits the reactor structures to better withstand thermal and seismic loadings simultaneously. The majority of published work on seismic isolation deals with the use of horizontal isolation system only. In this investigation, however, local vertical isolation is also provided for the primary system. Such local vertical isolation is found to result in significant benefits for major massive components, such as the reactor cover, designed to withstand vertical motions and loadings. Preliminary estimations on commodity savings of the primary system show that, with additional local vertical isolation, the savings could be twice that estimated for horizontal isolation only. The degree of effectiveness of vertical isolation depends on the diameter of the reactor vessel. As the reactor vessel diameter increases, the vertical seismic effects become more pronounced and vertical isolation can make a significant contribution.

I. INTRODUCTION

Issues involving seismic design requirements have been identified as having contributed to an increased cost of nuclear power plants. Earthquakes are random, unpredictable, unpreventable natural phenomena, and they can be quite destructive. To assure that nuclear power plants are able to withstand earthquakes involving uncertainties in ground motion estimates, overconservatism has crept not only into the design requirements, but also in the interpretation of requirements for nuclear facilities. Different approaches have been pursued for potential reduction of this overconservatism and to explore ways to decrease uncertainties in seismic design, while increasing the seismic margin actually attained in the designs. One of these approaches which appears to have significant potential as a design strategy is the application of seismic isolation.

In recent years, base seismic isolation has been applied to various structures such as bridges [1], buildings [2], and nuclear power plants [3]. Seismic isolation has stimulated a great deal of interest both in nuclear power plants and other important structures. It differs from the conventional strategy where structures and components are provided with sufficient strength and ductility to cope with seismic loads. Seismic isolation is especially attractive to the nuclear industry since it can reduce design loads, minimize the effect of specific site environments, and contribute to the reduction of materials needed for the major components of the primary system.

Seismic isolation shifts the fundamental frequency of the isolated structure away from the more damaging frequency range of earthquakes, such that there will be reduction in the seismic loadings transmitted to the structure (and hence to the equipment located within the structure), as well as reduction in response accelerations of the structure.

Most applications of seismic isolation at present are used to reduce effects of horizontal ground motions of earthquakes. Vertical and/or simultaneous vertical and horizontal isolation are also of interest, particularly for thin-walled liquid metal reactor (LMR) structures and components. There are added concerns with the use of vertical isolation, such as rocking, life-off, etc., especially when used on large size structures. However, vertical isolation has considerable potential for contributions in certain types of LMR plants.

In LMRs, the primary system is subjected to low pressure combined with severe thermal environments and this results in relatively thin-walled components. It is a challenge to design the system against strong earthquakes and severe thermal loadings simultaneously. Seismic isolation has thus become especially attractive to use in LMR plants.

This paper reports the results from a preliminary study of incorporating horizontal isolation alone, and horizontal and partial vertical isolation to a LMR power plant. In the study, the entire nuclear island is isolated horizontally, while vertical isolation -- when provided -- is applied only to the primary system.

The results of this study are presented in three categories: without isolation (i.e., conventional design); horizontal isolation of the entire nuclear island; and horizontal isolation for the entire nuclear island and vertical isolation provided only for the primary system. The potential benefits of seismic isolation for a LMR plant are discussed, including rough estimates of savings possible of the of high-cost commodities used, such as stainless steel.

II. SYSTEM DESCRIPTION AND ANALYSIS MODEL

The nuclear power plant considered in this study is a LMR plant with a power level of 600 MWe. Diameter and height of the reactor vessel are approximately 20m x 20m, respectively. The nuclear island, which consists of the reactor containment building, the steam generator building, and associated reactor service building, is supported on a common basemat. In this investigation, the entire nuclear island is isolated horizontally. One of the benefits of full isolation is that it minimizes the number of components crossing the isolation boundary between the isolated strucutre and the non-isolated parts of the plant.

To isolate the entire nuclear island against horizontal ground motions caused by earthquakes, a large number of seismic isolation bearings are located under the upper basemat (Figure 1). These bearings in turn are

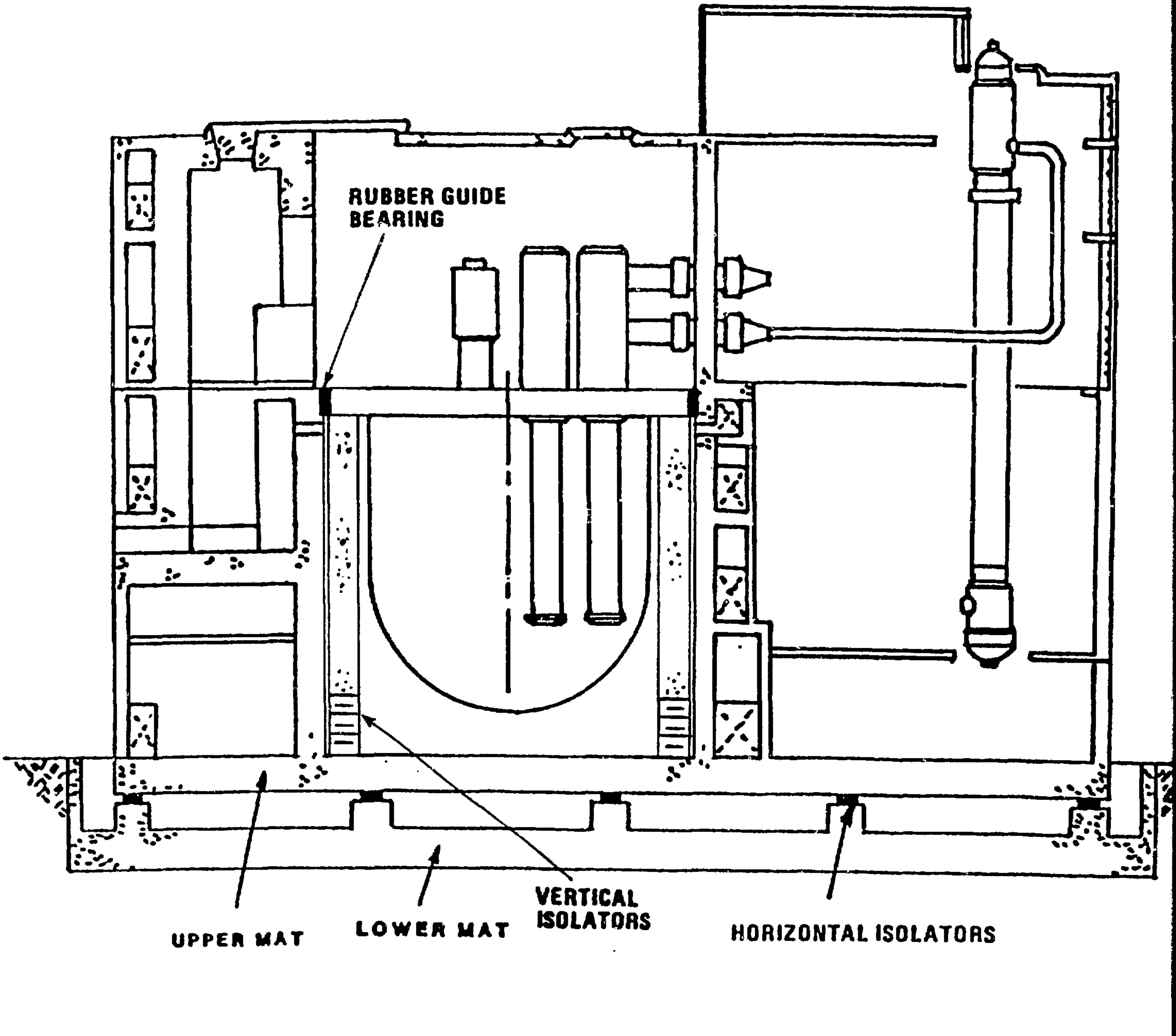


FIGURE 1. NUCLEAR ISLAND WITH SEISMIC ISOLATION

supported on the lower (additional) basemat. The isolation bearings are assumed to be very stiff in the vertical direction, while the overall stiffness in the horizontal direction is such that the isolated nuclear island will have a horizontal fundamental frequency (horizontal isolation frequency) of 0.5 Hz. The total damping ratio of the bearings in horizontal direction is assumed to be 5% of critical damping.

Also shown in Fig. 1 are the vertical seismic isolators which are used locally for the primary system only. These isolators can be of different design from the horizontal isolation bearings. For example, rubber bearings reinforced with steel plates may be used for horizontal isolation, while helical springs and viscodampers (such as the German GERB system) could be used for the vertical isolators. In this study, the vertical isolators have vertical isolation frequency and damping ratio of 1.5 Hz and 15% respectively.

Both the horizontal and vertical input ground motions are assumed synthetic time-histories whose response spectra envelop the USNRC design response spectra [4]. Peak accelerations of these time-histories are scaled to 0.3g.

Figure 2 shows the analytical model simulating the LMR plant when horizontal isolation only is used. The nine spring elements K1 through K9 simulate interconnections between structural portions of the plant. Included in the model are the containment building, the primary system, intermediate sodium pumps, and steam generators. The weight of floor, walls, equipment, and other components are lumped at appropriate floor levels.

The dynamic contributions of the foundation are represented by equivalent springs and dashpots (impedences). These impedences are generally functions of basemat geometry, embedment depth, elastic properties of the site, and excitation frequency. When the soil below the lower mat is uniform to a great depth (as assumed in this study), the impedence function can be represented by a frequency independent expression. These impedences are derived for a surface structure using elastic half-space theory.

The isolators are simulated by springs and dashpots. The springs are linear and are of such stiffness that they will yield the isolation frequencies described previously. The specific values used for the various

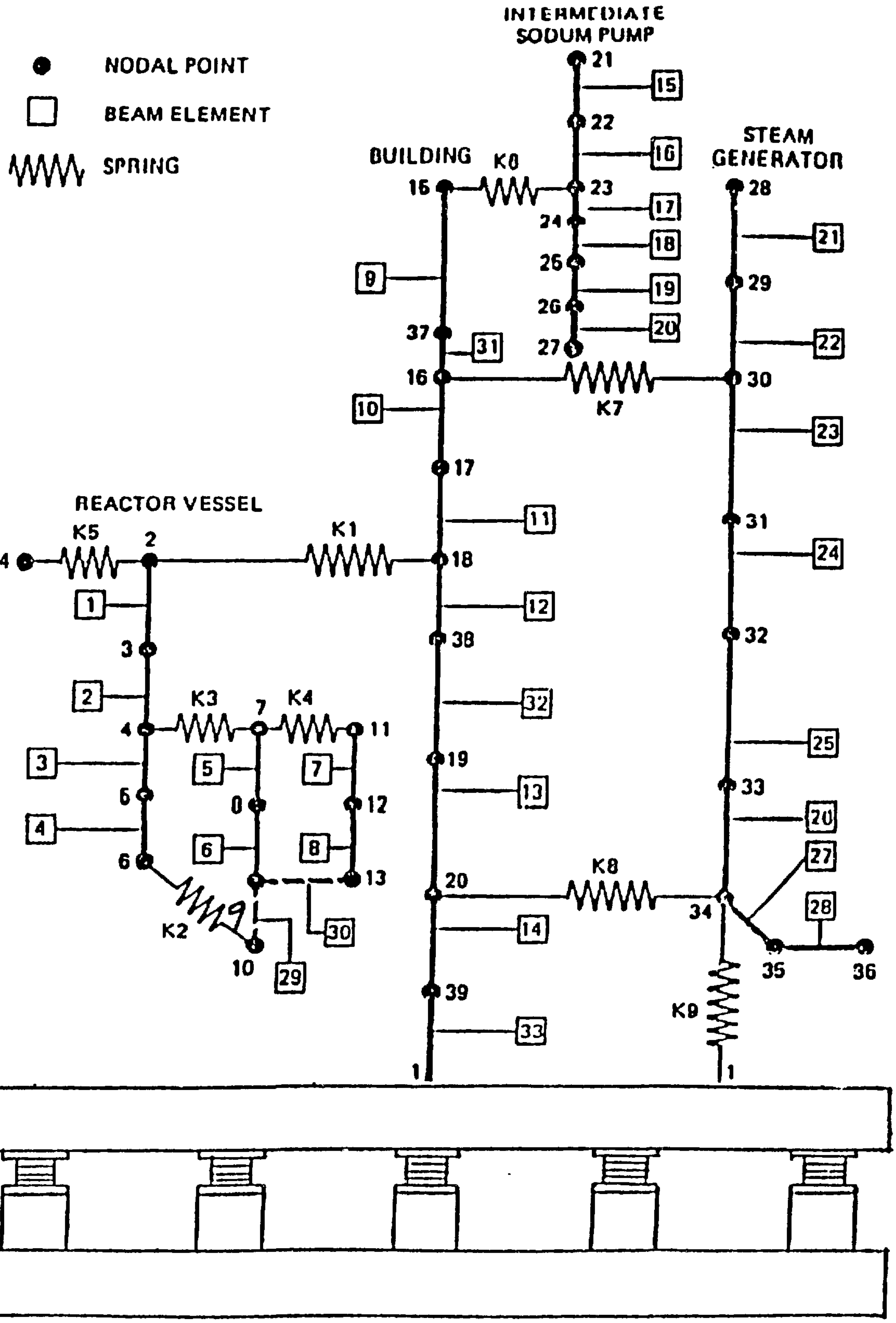


FIGURE 2
ANALYTICAL MODEL FOR A NUCLEAR ISLAND WITH HORIZONTAL SEISMIC ISOLATION

parameters, such as isolation frequency are for illustrative purposes only. They do not necessarily reflect values for any specific isolation system nor any specific isolated structure.

III. BASE ISOLATION AGAINST HORIZONTAL EARTHQUAKE GROUND MOTIONS

When the nuclear island of Fig. 1 is isolated against horizontal earthquake ground motions only with an isolation frequency of 0.5 Hz, its responses to the synthetic horizontal acceleration time-history with peak acceleration scaled to 0.3g show significant reduction when compared with results obtained from the same structure but without isolation. Figure 3 presents the spectral accelerations with and without horizontal isolation at mass nodal point 18, which is at the support for the primary system. It is observed that the isolation system reduces the peak spectral acceleration from 2.5g to less than 0.6g. The reduction is much greater within the frequency range 1 Hz to 10 Hz, which is the range of fundamental frequencies of most nuclear power plant structures. There are also significant reductions in horizontal forces transmitted to the nuclear island and in response accelerations at other mass nodes.

The results presented in Figure 3 are for relatively soft sites with a soil shear wave velocity of 610 m/s (2000 fps). Sites with a shear wave velocity of 1830 m/s (6000 fps) are observed to yield essentially the same responses as for the softer sites. This could be the result of the fact that the isolation system has a much lower stiffness than the stiffness of equivalent soil springs.

When there is no seismic isolation, relative horizontal displacement of the nuclear island with respect to the ground is expected to be trivial. With isolation, however, significant relative displacement will occur. Such relative displacement is of importance in the design of the seismic gap between the isolated nuclear island and the ground, and for design of piping or other items crossing the isolation boundary. The maximum relative horizontal displacement observed from this investigation is about 17cm (6.8 in), which also seem to have little dependence on the soil shear wave velocity.

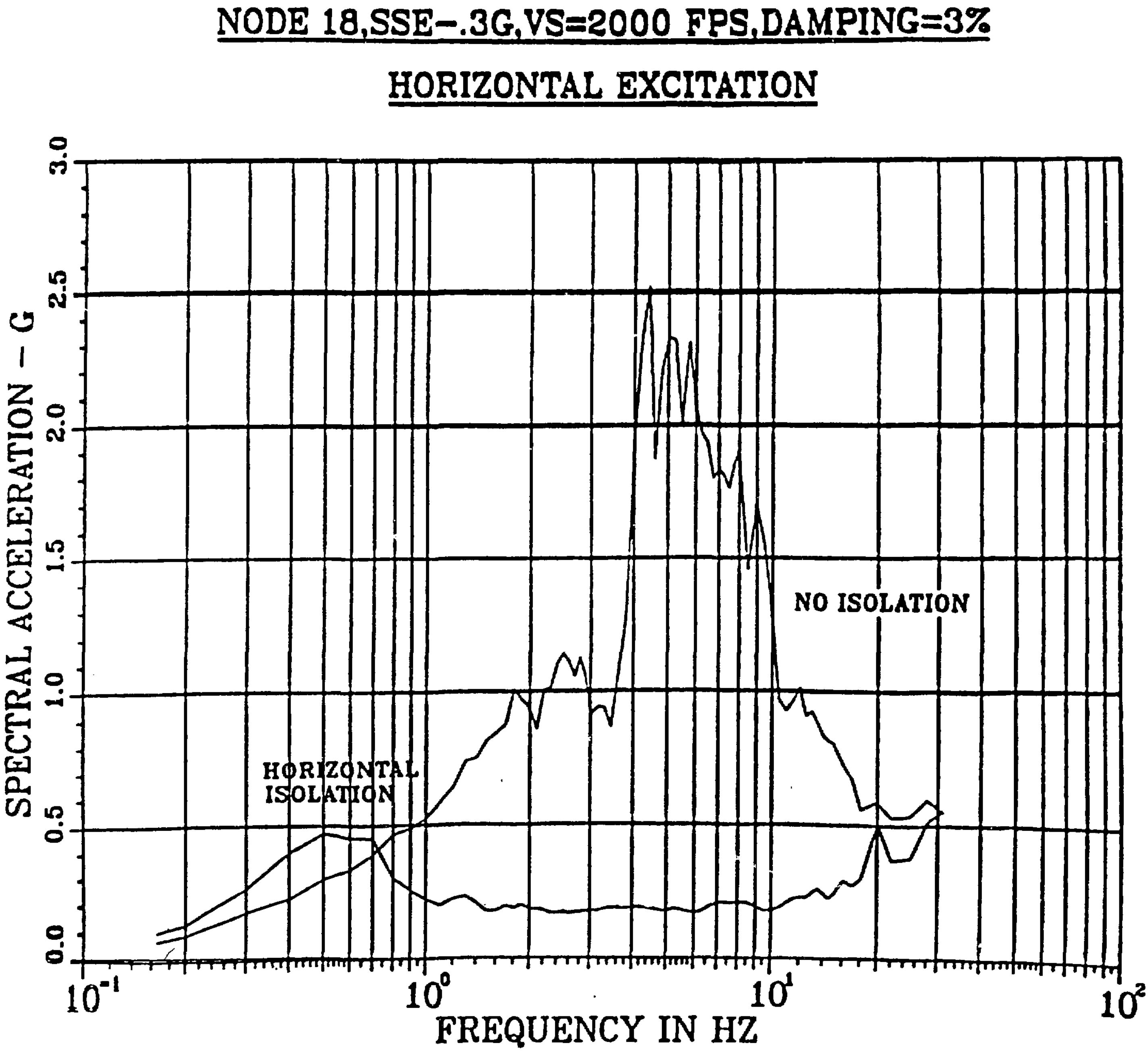


FIGURE 3
SPECTRAL ACCELERATION AT NODE 18 WITH AND WITHOUT SEISMIC ISOLATION
(Horizontal)

Displacements at different nodal points of the isolated plant have almost the same value. They are also of the same sign. It indicates that the isolated structure responds much like a rigid-body, and there is little differential movement between various parts of the isolated structure.

With reductions in transmitted shear force and response acceleration, it is possible that the thicknesses of certain components, such as the reactor vessel and guard vessel, can be reduced. Thinner components also could simplify fabrication and installation, with commensurate cost savings.

Rigid-body motion of the isolated nuclear island implies that isolation offers better protection not only to the structural elements but, probably more importantly, to the contents of the nuclear island, especially the equipment inside the buildings. There could also be less concern about relative displacements between critical internal components such as the control rods and the core.

With seismic isolation, analysis can be simplified since responses essentially remain elastic. In addition, reliability and design margins of structures in resisting seismic loads are increased. The reduced sensitivity of the structural responses to local soil environments makes the concept of standardizing LMR plants more feasible.

IV. LOCAL VERTICAL ISOLATION FOR PRIMARY SYSTEM

From the results of the previous section, horizontal isolation alone can only reduce responses in the horizontal direction. For components such as the large diameter reactor cover or deck, which is a massive structure and is designed mostly for vertical motions, horizontal isolation offers little advantage. Local vertical isolation offers isolation benefits to these components in the most effective way, and is provided for the primary system of the nuclear power plant considered here (Fig. 1). In a recent paper [5] which considers full horizontal isolation and partial vertical isolation for the nuclear steam supply system, it has been shown that the combined isolation systems reduces seismic responses very effectively.

The vertical isolators considered here are very stiff in the horizontal direction. Their total stiffness in the vertical direction yields a 1.5 Hz isolation frequency for the isolated primary system, and the vertical damping ratio is 15%.

The vertical input ground motion used in this study is a different synthetic acceleration time-history whose response spectra envelop the vertical design response spectra in NRC regulatory guides [4]. Maximum acceleration of the vertical input time-history is scaled to 0.3g, the same value used for horizontal input.

The analytical model shown in Figure 4 is modified from Fig. 2 by adding elements and mass nodes simulating the support necessary for the vertical isolators. For example, mass node 41, which has the same geometric location as node 18 of Fig. 2, is added in Fig. 3 to simulate the new support for the primary system. Node 18 which represents the reactor vessel in Fig. 2 is now simply a mass node for the building. Stiffnesses of the elements and magnitudes of the masses are all adjusted to reflect the vertical characteristics of the nuclear island.

Figure 5 shows the responses to vertical ground motion at the reactor support with and without local vertical isolation (i.e., at node 41 when there is local vertical isolation, and at node 18 when vertical isolation is absent). With this local vertical isolation, the frequency spectra is shifted to a lower frequency range in addition to a slight reduction in the peak spectral acceleration. Shifting the dominant spectral acceleration into a frequency range lower than the fundamental frequency of the structure results in lower dynamic amplification of the vertical ground motion input.

Lower dynamic amplification in the vertical direction means that components such as the reactor deck will be subjected to lower dynamic loadings. This means that the deck and other similar components can be designed with smaller thickness, thus resulting in substantial savings on material as well as fabrication costs.

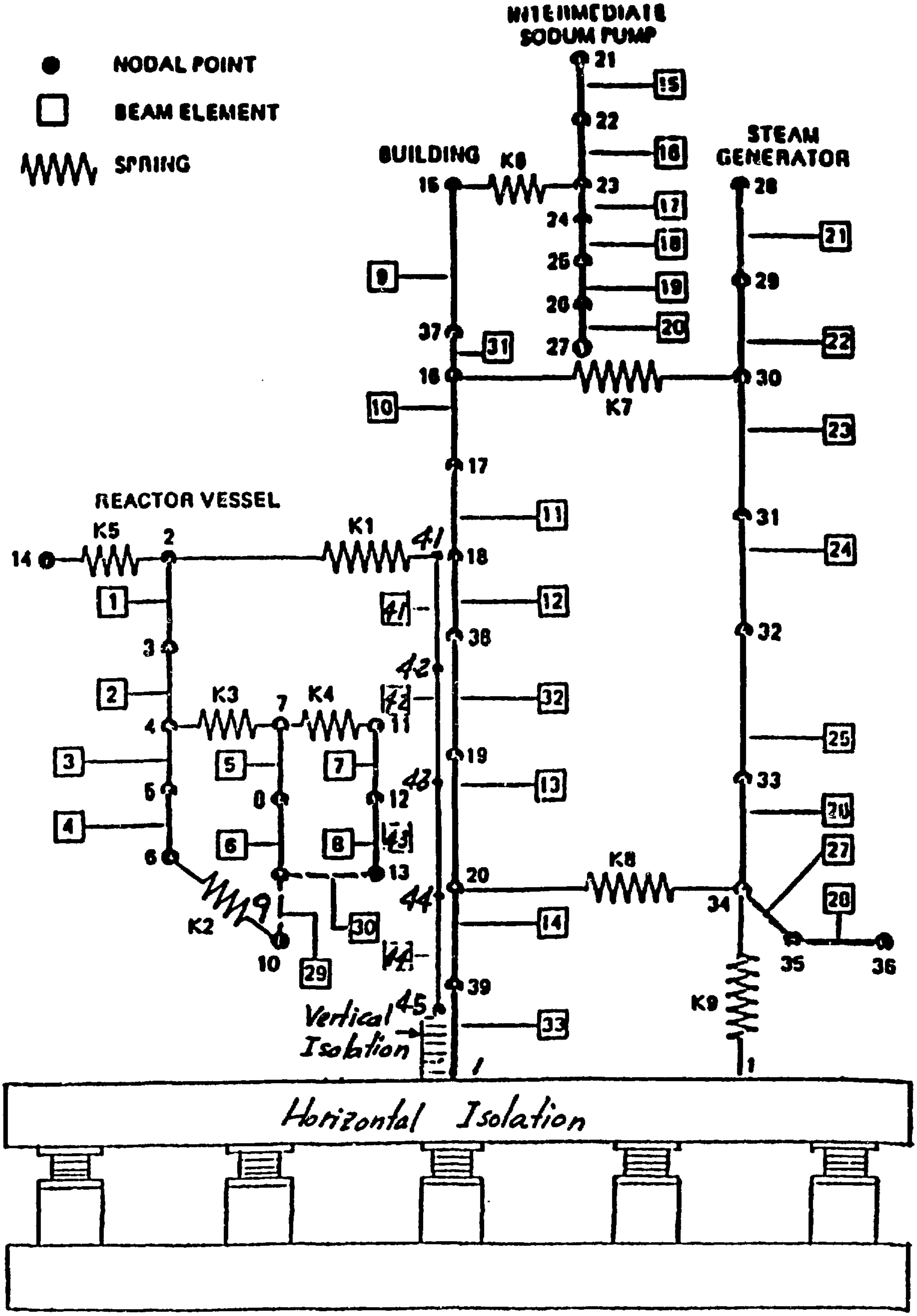


FIGURE 4
ISOLATION FOR THE ENTIRE NUCLEAR ISLAND
AND LOCAL VERTICAL ISOLATION FOR THE PRIMARY SYSTEM

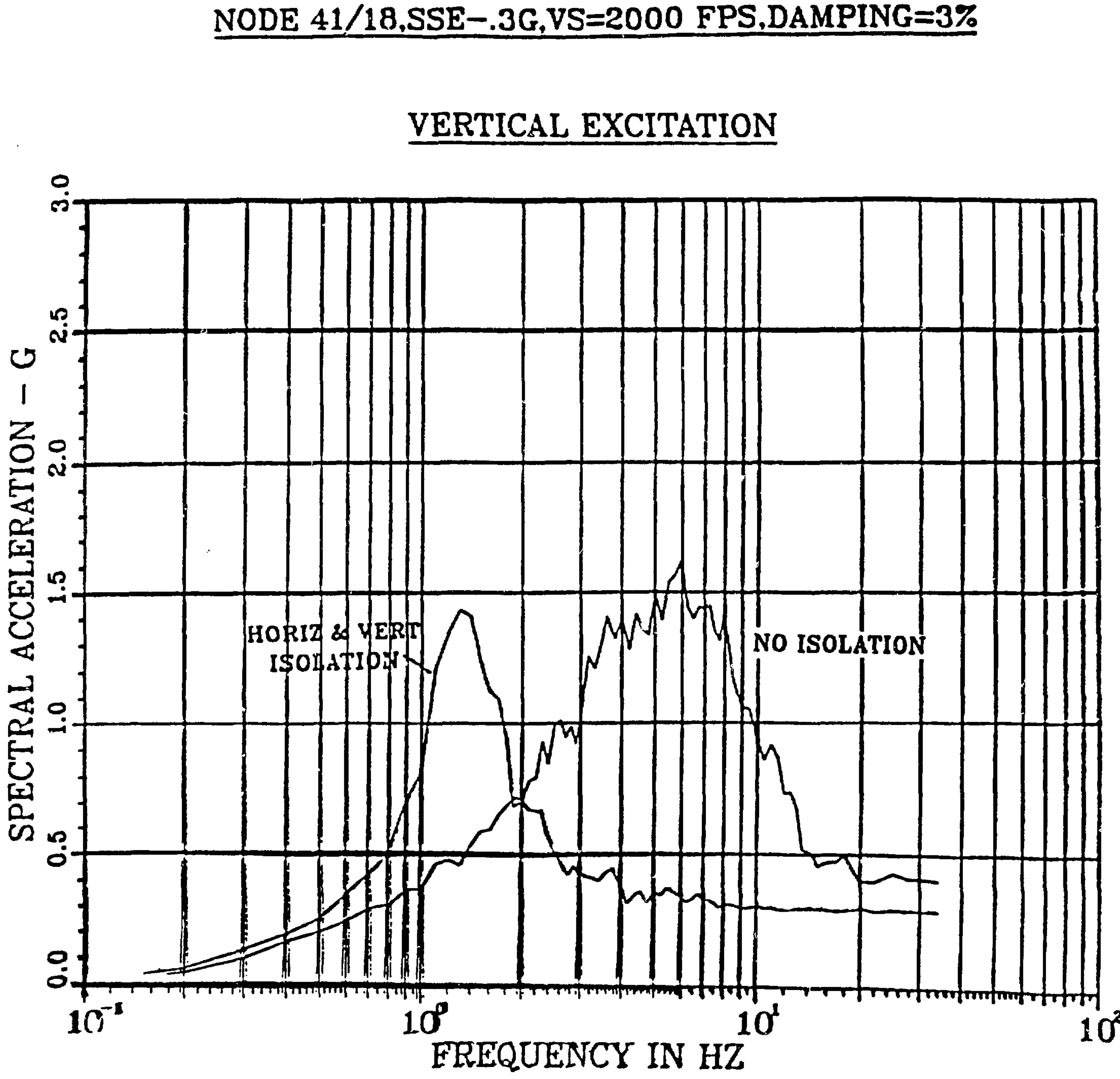


FIGURE 5. SPECTRAL ACCELERATION AT REACTOR SUPPORT (Node 41/18), WITH AND WITHOUT VERTICAL ISOLATION

V. ESTIMATIONS ON COMMODITY SAVINGS

As described in Section III, the use of seismic isolation requires not only the isolation system itself, but also introduces the need of additional structure. For example, full horizontal base isolation of the entire nuclear island requires an additional (lower) basemat, and also additional excavation and retaining walls. When local vertical isolation is provided for the reactor systems, installation of guides may be necessary to avoid rocking and other undesirable effects.

The use of seismic isolation results in reductions in response acceleration, less dependence on site properties, and lower transmitted loads. Most of these benefits have been discussed elsewhere, for example [6]. In this section, estimates are given on commodity reductions for some of the major primary system components resulting from seismic isolation.

When seismic loadings transmitted to components are reduced, there is potential that less strength is needed for components in resisting earthquakes. When the thickness of a critical component such as the reactor vessel, is reduced, there can be savings in material and fabrication costs. The estimates on commodity savings considered here are confined only to components of the primary system, namely the deck, reactor vessel (RV), guard vessel (CV), core support structure (CSS), and the RV/deck support structure.

The estimates were based on the maximum spectral acceleration within the frequency range of 1 Hz to 10 Hz. The estimated commodity savings are summarized in Table 1, where the weight of each component shown in the second column is based on the reference design used in this study (without seismic isolation). Column 3 gives the estimated weight when the entire nuclear island is isolated horizontally (Option 1). The last column of Table 1 shows the estimated weight when the nuclear island is isolated horizontally and the primary system is isolated vertically (Option 2). Without the local vertical isolation for the primary system, the deck does not benefit from isolation, since it is designed essentially to resist vertical loads. Local vertical isolation for the primary system also offers benefits to the RV/deck support structure and the reactor vessel.

TABLE 1

ESTIMATED COMMODITY REDUCTION

	WEIGHT (KIPS)		
COMPONENT	REFERENCE	OPTION 1*	OPTION 2**
DECK	1516	1516	884
RV	868	666	554
CV	288	216	216
CSS	770	523	523
RV/DECK SUP. STRUCT.	350	225	131
TOTAL	3792	3146	2308
SAVE	- -	646 (17%)	1484 (39%)

*NUCLEAR ISLAND ISOLATED HORIZONTALLY.

**NUCLEAR ISLAND ISOLATED HORIZONTALLY,
AND REACTOR ISOLATED VERTICALLY.

Figure 6 shows the responses at mass node 18 when major components have commodity reductions given by Option 1 of Table 1. When compared with the results without mass reduction the difference is almost trivial for frequencies below 9 Hz. Similar results (Fig. 7) are also observed for vertical excitation when the system commodities are reduced according to Option 2 (both horizontal and vertical).

From the estimates summarized in Table 1, horizontal isolation alone offers savings in materials required for about 17%. When local vertical isolation is also provided for the primary system, the large commodity reduction of the deck results in an overall savings of about 39% for the primary system.

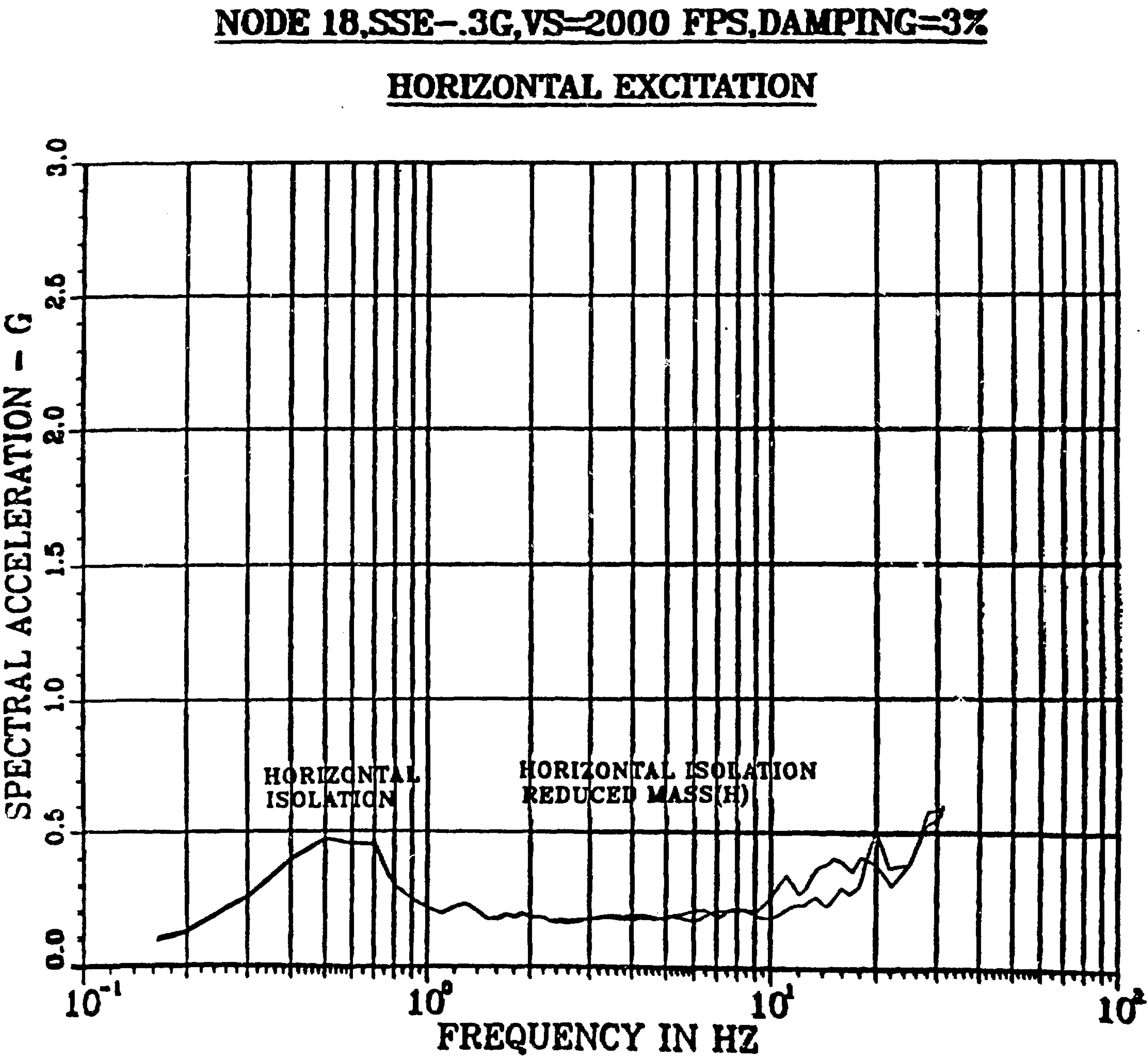
The above estimates are made only for the major reactor components of the primary system. They should not be extrapolated to overall cost savings for the entire LMR power plant, although additional savings not included here could be substantial.

VI. CONCLUSIONS

With recent advances in material and manufacturing technologies, seismic isolation is rapidly developing as a viable strategy for aseismic design. Aseismic is a subject of increasing interest among earthquake engineers world-wide. Such a concept has also been actually applied to various types of structures both in the United States and abroad. In a LMR plant where major reactor components are subjected to severe thermal environments, the concept of seismic isolation is especially attractive, and appears to have attractive properties for designing major LMR reactor components to withstand thermal and seismic loadings simultaneously.

Seismic isolation offers various benefits including: reduction in transmitted seismic loads, lower response accelerations, less site dependence for nuclear power plants and minimizing relative motions between the contents within the isolated structure.

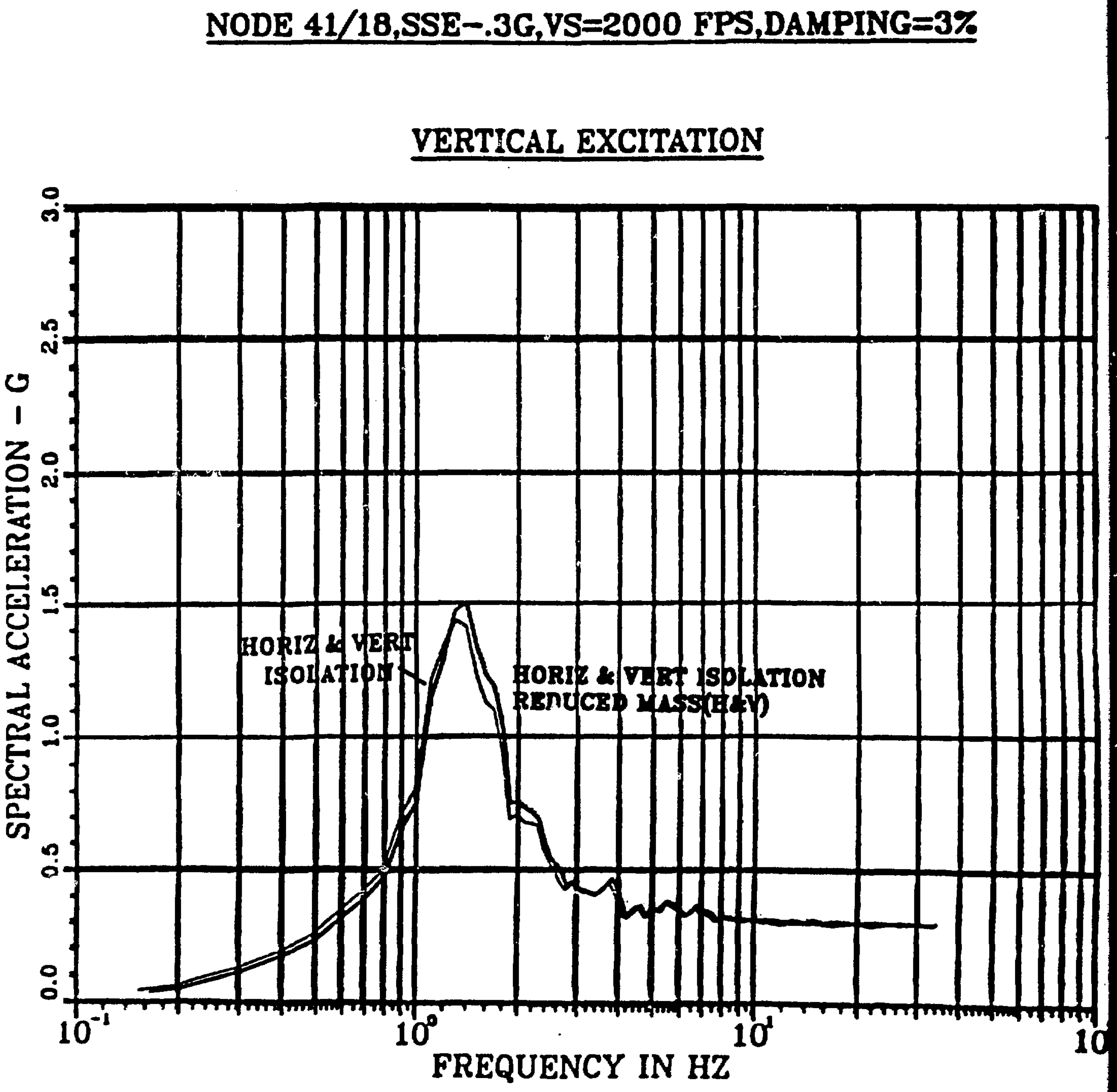
In a LMR, some massive components such as the reactor cover or deck are designed mainly for resisting vertical loads and movements. These components do not benefit from horizontal seismic isolation. In this investigation,



NODE 18,SSE-.3G,VS=2000 FPS,DAMPING=3%

HORIZONTAL EXCITATION

FIGURE 6. RESPONSES TO HORIZONTAL EXCITATION WITH AND WITHOUT MASS REDUCTION (Option 1 of Table 1)



NODE 41/18,SSE-.3G,VS=2000 FPS,DAMPING=3%

VERTICAL EXCITATION

FIGURE 7. RESPONSES TO VERTICAL EXCITATION WITH AND WITHOUT MASS REDUCTION
(Option 2 of Table 1)

local vertical seismic isolation was provided for the primary system. Estimated commodity savings for structural components of the primary system range from 17% for horizontal isolation alone to about 39% for local vertical isolation together with total horizontal isolation.

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