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IMPACT INDUCED RESPONSE SPECTRUM FOR THE SAFETY EVALUATION OF THE HIGH FLUX ISOTOPE REACTOR

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IMPACT INDUCED RESPONSE SPECTRUM FOR THE SAFETY EVALUATION OF THE HIGH FLUX ISOTOPE REACTOR[1]

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ABSTRACT

The dynamic impact to the nearby HFIR reactor vessel caused by heavy load drop is analyzed. The impact calculation is carried out by applying the ABAQUS computer code. An impact-induced response spectrum is constructed in order to evaluate whether the HFIR vessel and the shutdown mechanism may be disabled. For the frequency range less than 10 Hz, the maximum spectral velocity of impact is approximately equal to that of the HFIR seismic design-basis spectrum. For the frequency range greater than 10 Hz, the impact-induced response spectrum is shown to cause no effect to the control rod and the shutdown mechanism. An earlier seismic safety assessment for the HFIR control and shutdown mechanism was made by EQE. Based on EQE modal solution that is combined with the impact-induced spectrum, it is concluded that the impact will not cause any damage to the shutdown mechanism, even while the reactor is in operation. The present method suggests a general approach for evaluating the impact induced damage to the reactor by applying the existing finite element modal solution that has been carried out for the seismic evaluation of the reactor.

1. INTRODUCTION

The purpose of this calculation is to evaluate the consequences of a heavy drop load near the reactor and to estimate whether the impact caused by the drop may have the magnitude that is capable of damaging the HFIR reactor vessel and the reactor shutdown mechanism.

It is shown that none of these components will be damaged and the reactor can be shut down even after the heavy load is dropped to the concrete floor. This means that the heavy load can be lifted while the reactor is under operation. The total weight of the cask, including its contents, is approximately 25,000 lb from a height of 20 ft.

The pool slab on which the HFIR vessel stands and the surrounding concrete structure that receives the falling cask are approximately represented by a two-dimensional plane strain finite element model. The HFIR and its internal components are assumed to be one rigid body and their masses are assumed to be concentrated at four mass points along the axis of the vessel.

The cask that falls onto the bottom concrete slab of the HFIR pool is assumed to be rigid. Dynamic stress is generated and propagates through the concrete slab and the concrete walls to reach the reactor vessel and its internals. The ABAQUS computer code is applied to obtain the dynamic response and the time-dependent solution of this approximate model.

To evaluate the effect of the impact to the shutdown mechanism, an innovative approach to the problem is used. An earlier EQE finite element solution has shown that the shutdown mechanism will not be damaged by the HFIR design-basis seismic response spectrum. The present method of approach is to obtain the impact-induced response spectrum from the ABAQUS calculation. It is then compared to the design-basis seismic spectrum to show that the impact-induced response spectrum does not cause more damage to the shutdown mechanism. The impact-induced response spectrum is derived in this analysis by using the acceleration history of a surface point of the pool concrete slab close to the HFIR vessel.

2. ANALYSIS OF THE PROBLEM

The two-dimensional finite element model for the reactor and the nearby structure is sketched and shown in

[1]Based on work performed at Oak Ridge National Laboratory, managed by Lockheed Martin Energy Research Corp., for the U.S. Department of Energy under contract DE-AC05-96OR22464.

Fig. 1. The model describes the concrete slab, the concrete wall, the HFIR vessel, and the vessel supporting legs. The left end of the slab is fixed and the lower right end of the slab is simply supported. The upper right concrete slab on which the cask is impacted is assumed to be a cantilever beam. The GE-2000 cask and the fuel contained in the cask weigh approximately 25,000 lb. It is assumed to be dropped from a height of 20 ft above the bottom floor of the pool. This produces an end velocity of 430 in./s at the moment of impact to the concrete slab.

The impact solution of the drop problem is obtained by using the ABAQUS computer code with the dynamic contact option. The cask is assumed to be rigid as it is dropped from a height of 20 ft and strikes the bottom concrete slab of the pool. In the finite element model, the reinforced concrete medium is assumed to be homogenous and capable of carrying compressive stress as well as tensile stress. The calculation is an elastic-plastic analysis that provides an estimate of the amount of plastic strain to be generated at the region of the slab immediately underneath the falling cask. The result id shown in Fig. 2. The plastic strain is then used to estimate the amount of slab that may be damaged, or crushed, as a result of the impact of the cask. The concrete failure strain is 0.45%. It is used to measure the size of the concrete failure, or crushed, region.

Of particular concern is whether dropping the cask will damage the shutdown mechanism of the reactor. The present analysis is based on a modification of the EQE calculation shown in ref. 5.4. The EQE finite element calculation was performed by applying the SUPER-SAP computer code, and each problem case was carried out by two consecutive computer runs. They are the eigenvalue run and the modal superposition run. The eigenvalue run gives the basic modal properties of the model. The modal superposition run in the EQE calculation gives the resulting system excitation by a combination of the total modal contributions that are generated by using the seismic response spectrum as the driving force. In the present calculation, the EQE modal calculations are used and taken as granted. The driving force that was used in the EQE calculation is replaced by the impact spectrum obtained in this calculation. The resulting excitation of the reactor control and shutdown mechanism as a result of the impact by the drop of the cask is, therefore, obtained.

2.1 Two-Dimensional Impact Solution

The numerical results include the amount of penetration of the cask into the slab, the plastic strain distribution in the concrete slab directly underneath the cask, and the slab surface acceleration time history at a node that is located near the reactor vessel.

2.1.1 Displacement time history of the heavy load

Figure 3 shows the time history for the vertical displacement of the GE cask after it begins to contact the floor of the pool. It is seen that the impact begins at time equal to 0 s and the object remains in contact to the slab until time equal to 0.004 s. After 0.004 s, the object begins to bounce back and is separated from the slab. The maximum penetrated distance is approximately ½ in.

2.1.2 Time history solution of the responses at the surface of HFIR base slab

At the surface of the concrete slab where the HFIR reactor is located, the time history solutions of the horizontal and vertical accelerations at node point 786 are shown in Figs. 4a and b, respectively. Node point 786 is located on the surface of the concrete slab that is located two nodes away from the right side of the lower vessel wall.

2.1.3 Floor velocity response spectrum

Let *x(t)* be the solution of the differential equation of motion:

$$\ddot{x}\ (t)\ +\ 2\ \zeta\ \omega\ \dot{x}\ (t)\ +\ \omega^2\ x\ (t)\ =\ -a(t) \tag{2.1}$$

In the above equation, ω is the circular natural frequency of the above simple 1 degree of freedom oscillator, ζ is the damping ratio, and *a(t)* is the ground acceleration time history. The acceleration time histories *a(t)* shown in Figs. 4a and b are the driving force of the above differential equation. The displacement spectrum is defined as the maximum value of *x(t)* over the whole time interval vs the natural frequency *f* defined as ω/2π of the above one-dimensional harmonic oscillator. The solution *x(t)* is obtained by a finite difference algorithm. The horizontal and vertical velocity spectra, defined as the displacement spectra multiplied by ω, are plotted in Figs. 5a and b, respectively. The corresponding acceleration spectra are plotted in Figs. 6a and b. The solution algorithm requires the time interval to be equally spaced and the ratio of the time interval to the period of the spectrum to be less than 1. The time interval in this calculation is 0.0008 s. The valid period of the spectrum is less than 1/0.0008 or 1250 Hz. Here it reaches 3000 Hz without breaking down.

2.2 Interpretation and Implication of the Impact-Generated Response Spectra

The method to be used for the evaluation of the shutdown mechanism has been described in Section 2. As

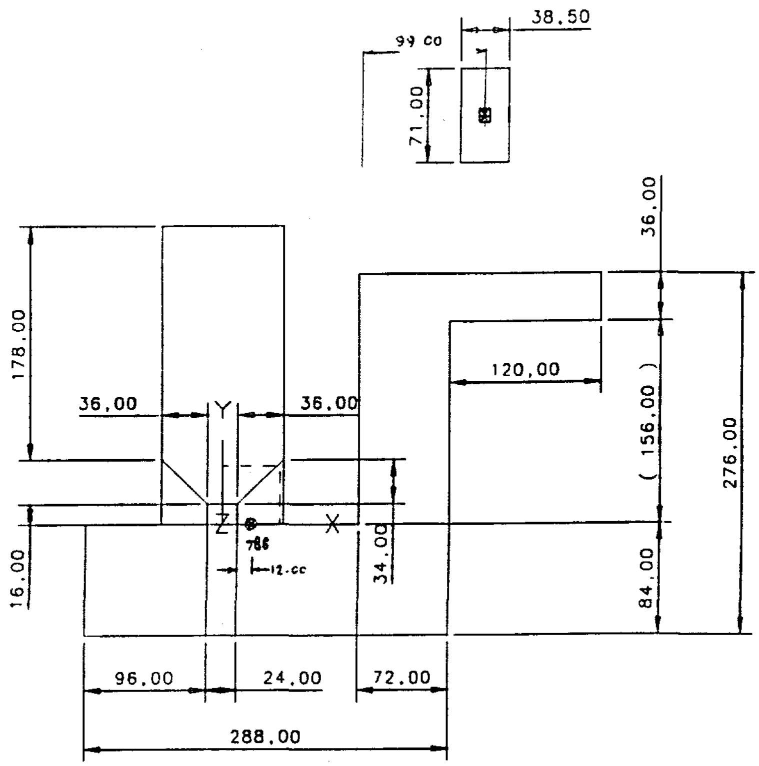

Fig. 1. Two-dimensional model of HFIR reactor vessel subjected to dynamic impact caused by a drop of the GE-2000 cask. The cask weighs 25,000 lb and the weight drops from a height of 20 ft.

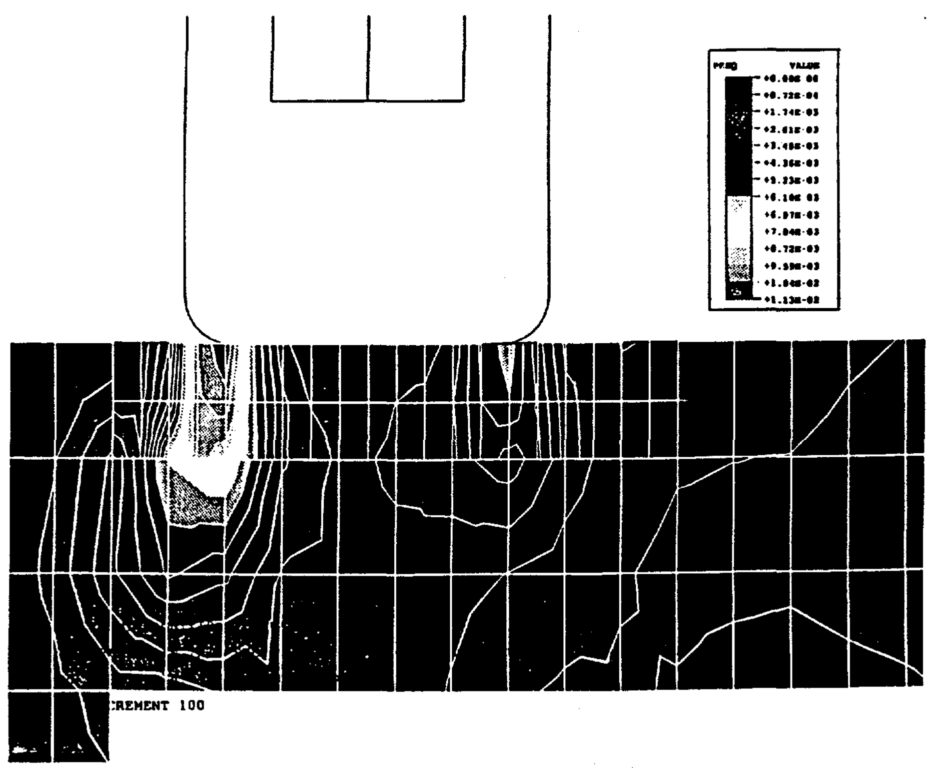

Fig. 2. Permanent damage of the concrete slab at the bottom of the HFIR pool underneath the surface of impact at time equal to 0.0054 s.

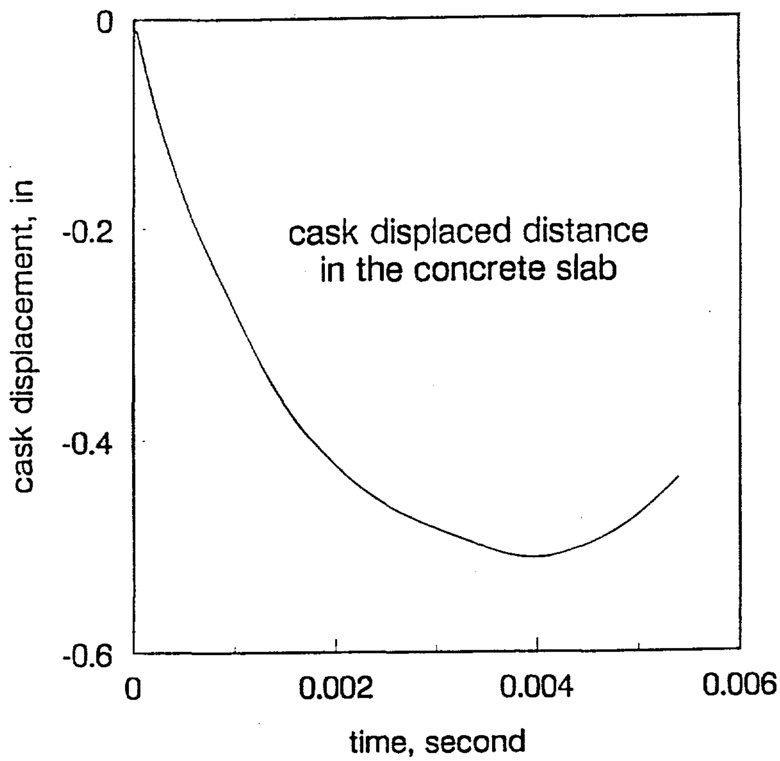

Fig. 3. Time histories of the displaced distance of the GE cask after it begins to contact the bottom of the pool. The maximum distance of cask penetration is 0.5 in.

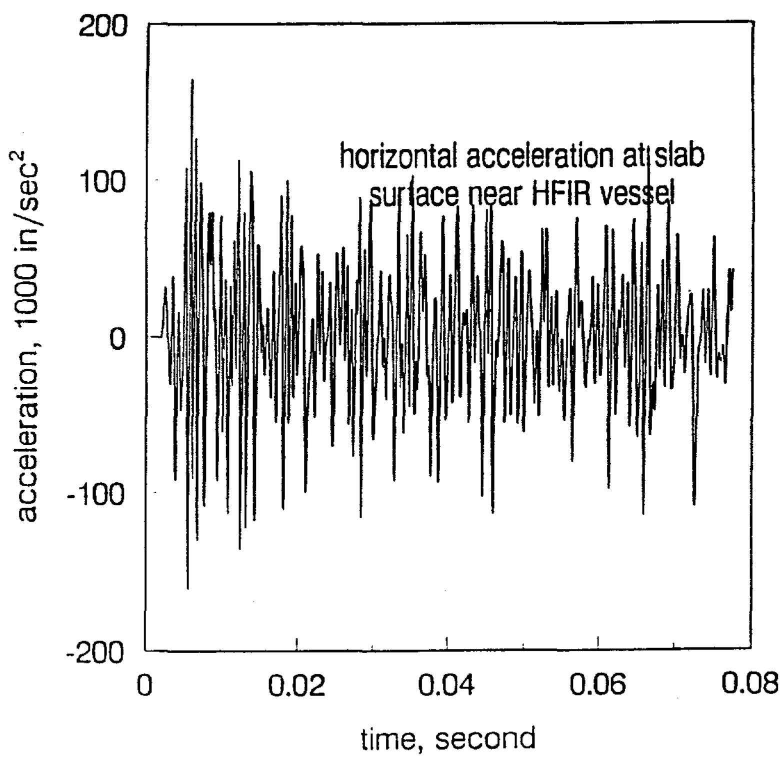

Fig. 4a. Horizontal acceleration at the surface of the reactor supporting concrete slab near the HFIR lower vessel wall at node 786.

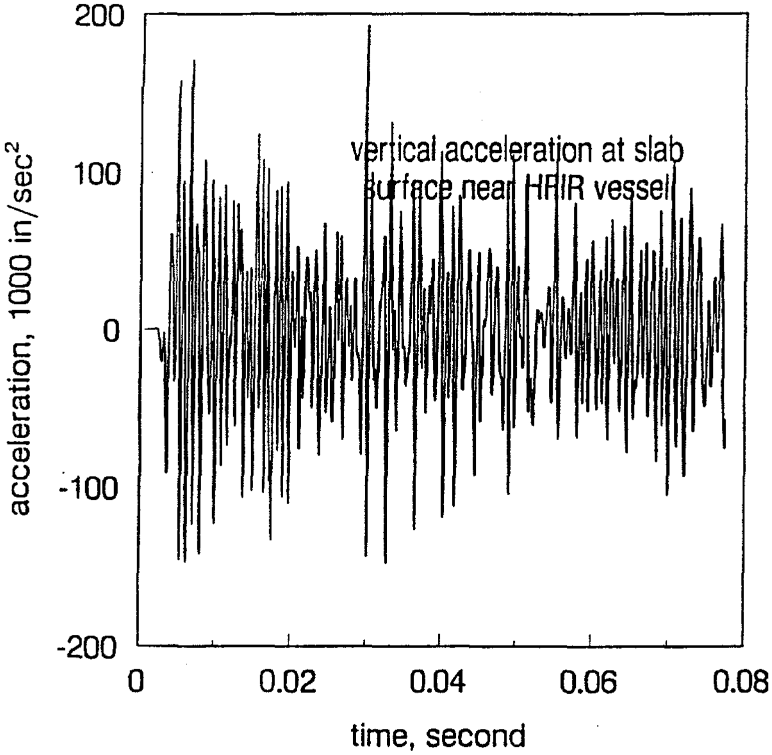

Fig. 4b. **Vertical acceleration at the surface of the reactor supporting concrete slab near the HFIR lower vessel wall at node 786.**

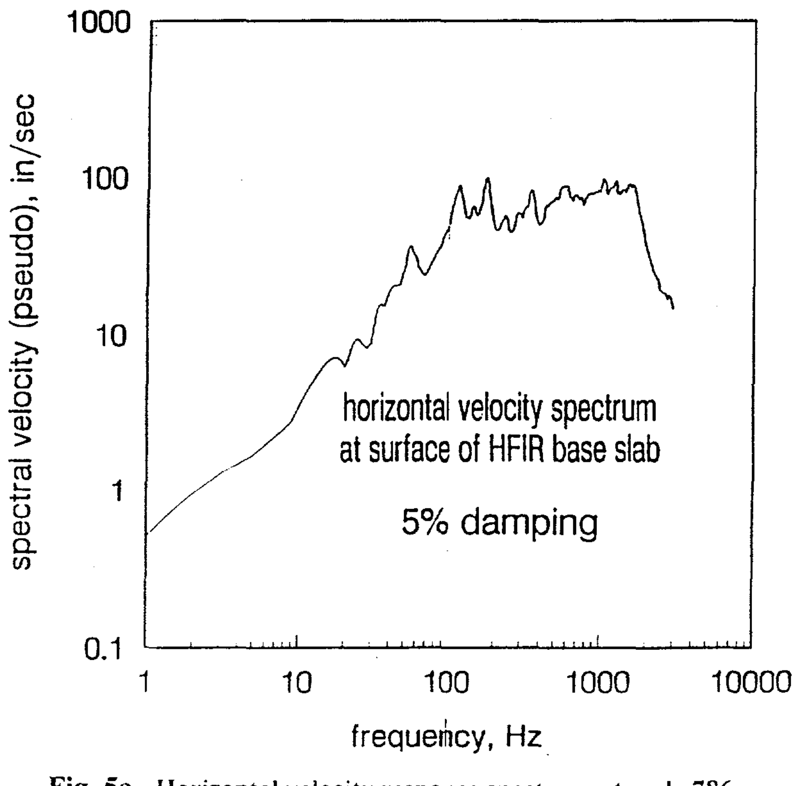

Fig. 5a. **Horizontal velocity response spectrum at node 786.**

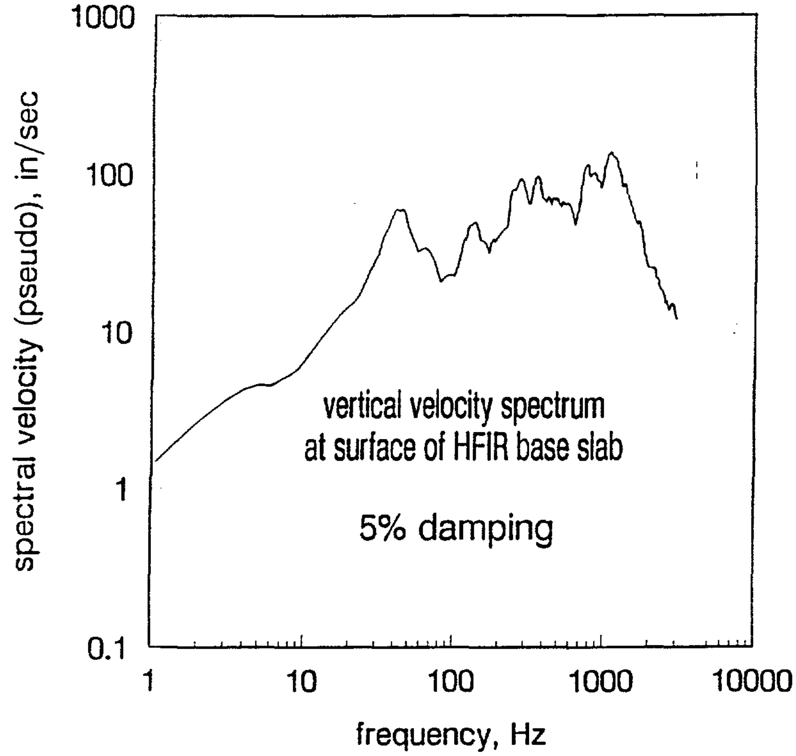

Fig. 5b. Vertical velocity response spectrum at node 786.

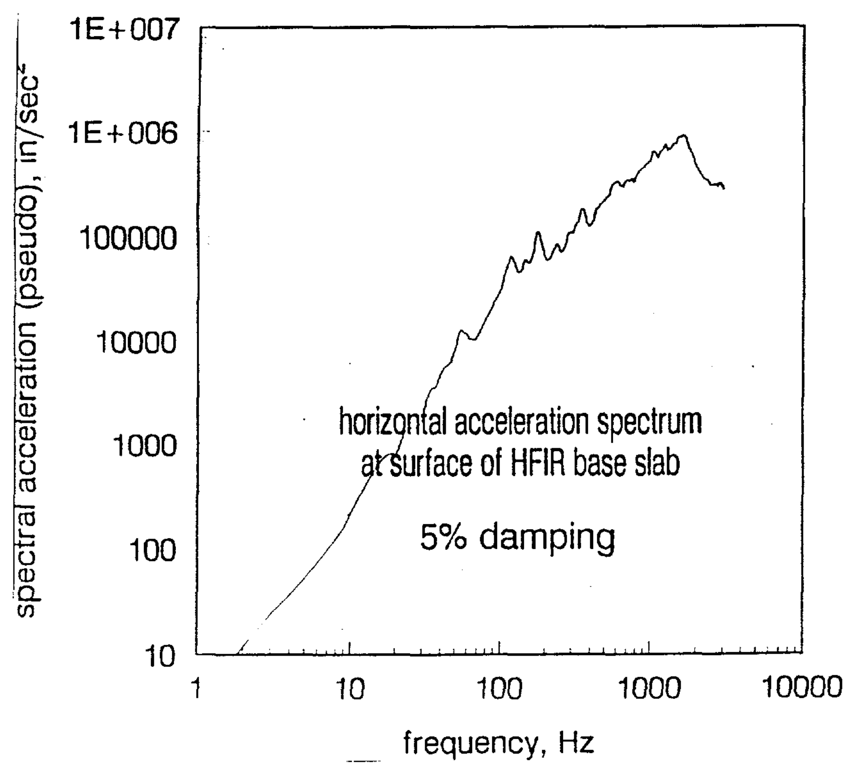

Fig.6a. Horizontal acceleration response spectrum at node 786.

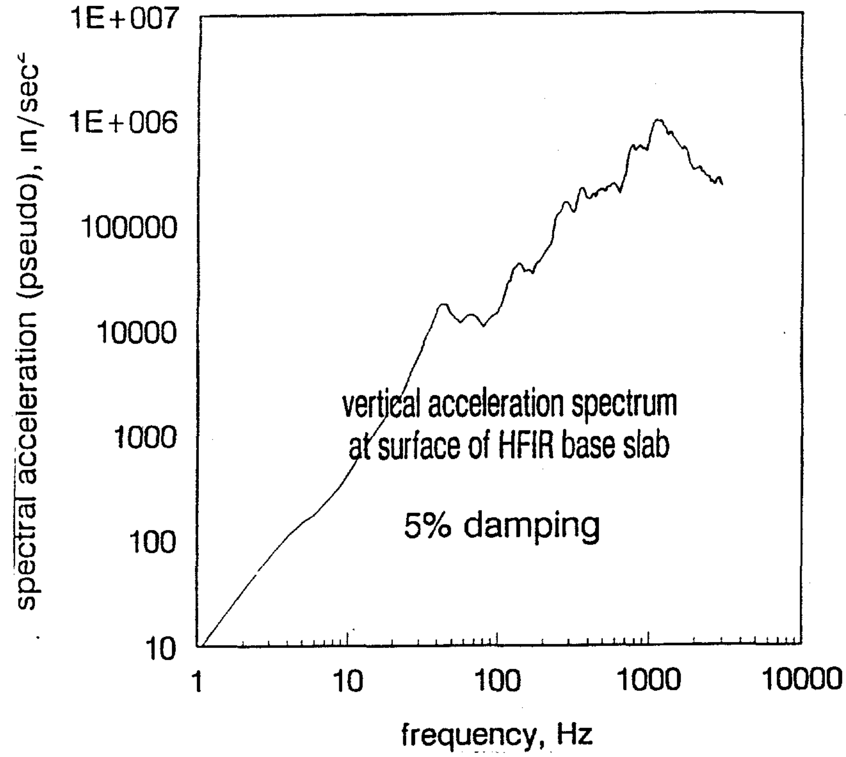

Fig. 6b. Vertical acceleration response spectrum at node 786.

described earlier, the EQE seismic assessment of the control made use of two runs by applying the SUPER-SAP finite element code. The first eigen run results are used here, but not the second modal superposition run. Nodes 4 and 8 in the EQE model are to be used as the main evaluation points for the maximum displacement distortion of the sliding track of the control rod, because these points represent the two narrow grips on which the control rod slides.

2.2.1 Impact spectrum and seismic design-basis spectrum

It is observed that both velocity spectra generated by impact shown in Figs. 5a and b in the frequency range smaller than 10 Hz have the maximum magnitude of approximately 10 in./s. The maximum magnitude approximately equals to 10 in./s is also shown in the HFIR design spectrum of 0.15-g peak ground acceleration with 3% damping used in ref. 5.8 as well as the newly established Oak Ridge spectrum (Fig. 7) with 0.26-g peak ground acceleration with 5% damping for a frequency range up to 5 Hz.

The above observation implies that the impact-response spectrum for the frequency range less than 10 Hz has the intensity that is not significantly more severe than the HFIR seismic design-basis spectrum. This is an indication that, if the control mechanism is safe against the design-basis spectrum, then it is likely to be safe against the impact-generated spectrum, provided that the impact spectrum in the high frequency range does not have the effect to the reactor shutdown mechanism. That the influence of the spectrum at the high frequency range does not have the effect to the shutdown mechanism will be shown in the following sections.

In Fig. 7, the Newmark spectrum is scaled up to 0.26 g for the purpose of comparison between the newly developed Oak Ridge spectrum and the standard Newmark spectrum that has been widely used in seismic design work in general.

2.2.2 EQE seismic analysis of control mechanism

The safety evaluation of the control and shutdown mechanism was analyzed by EQE calculation in Ref. 5.4. The EQE calculation was to estimate whether the control rod might be jammed during a hypothetical design earthquake event. As shown in EQE calculation, the horizontal displacement at node 4 was 0.133 in. and that at node 8 was 0.121 in. The difference between the two displacements was believed to contribute most of the distortion of the control rod track and, therefore, the smoothness of the possible sliding motion of the control rod. The control rod was assumed to be rigid. EQE concluded that this differential in displacements was not large enough to jam the rod for a shutdown operation after the earthquake.

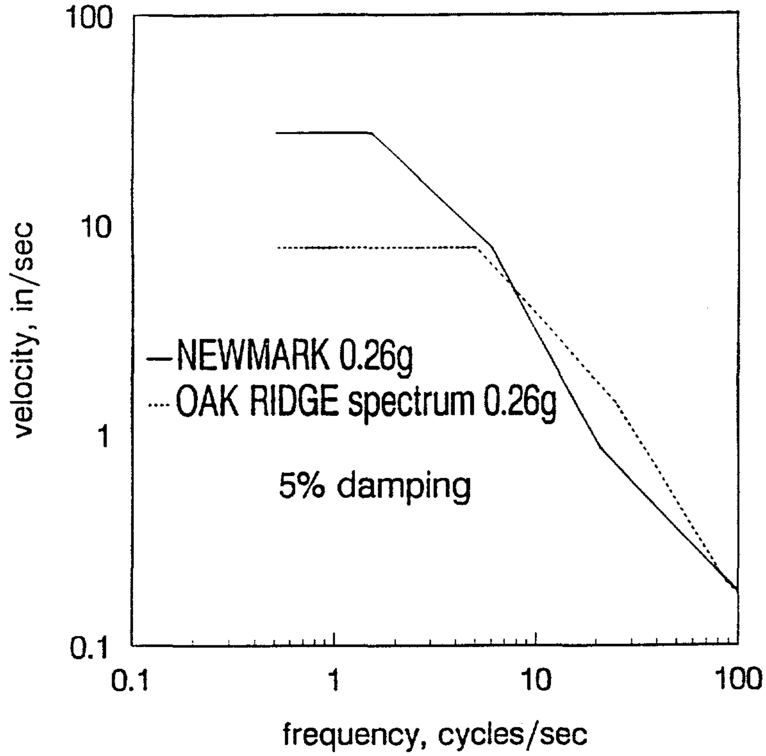

Fig. 7. Oak Ridge spectral velocity response with 0.26-g peak ground acceleration and 5% damping and the corresponding Newmark spectral velocity response spectrum.

The EQE calculation had the information for the first 10 natural frequencies and the corresponding 10 eigenvectors of the sliding track of the control rod. These results and their participation factors for the first ten modes are also listed in the following tables for the convenience of the subsequent calculations.

		Participation factor		
Mode	f, Hz	X	Y	Z
1	5.31	15.73	0.00	-12.42
2	5.33	12.40	0.00	15.73
3	9.65	-0.77	0.00	1.72
4	10.08	1.94	0.00	0.86
5	18.44	-0.83	0.00	1.91
6	18.47	-1.88	0.00	-0.82
7	32.30	0.12	0.00	-0.24
8	32.30	0.24	0.00	0.12
9	40.23	0.00	-20.03	0.00
10	42.55	-0.01	0.00	0.00

	Eigenvector	
Mode	ϕ (Node 4)	ϕ (Node 8)
1	4.09×10^{-2}	3.70×10^{-2}
2	3.23	2.92
3	0.37	0.09
4	-0.80	-0.13
5	0.45	-0.94
6	1.02	-2.17
7	0.14	0.60
8	0.30	1.24
9	0.00	0.00
10	0.00	0.00

The EQE calculation in ref. 5.8 showed that the displacement at node 4 is 0.133 in. and that at node 8 is 0.121 in. These values can be confirmed and obtained by applying the standard modal displacement equation

$$u_i = \frac{\gamma_i}{(2\ \pi\ f_i)^2} \times \Phi_i \times A_f \qquad (2.2)$$

The above equation reads that the i-th modal component of the displacement is equal to the participation factor γ divided by the square of the circular frequency $2\pi f$ multiplied by the modal eigenvector ϕ and the intercept of the acceleration spectrum A_f

2.2.3 Impact spectrum analysis of the control mechanism

The impact spectrum is applied to the control mechanism in the following calculation. It is seen from the acceleration spectra (Figs. 6a and b) that, in contrast to the seismic spectrum, these impact-induced spectral accelerations increase rapidly at the high frequency range. However, the high frequency part of the impact spectrum does not contribute to the response of node 4 and node 8 because the effective participation factor to the finite element model beyond the second mode of vibration decreases rapidly. This fact can be observed from the modal displacement equation shown in the last section and the impact spectra (Figs. 6a and b). It is shown in the following calculation that the impact-induced horizontal displacements at node 4 and node 8 for the first two modes are less than the values 0.133 in. and 0.121 in., respectively, caused by earthquake and the contribution to the total displacement from the higher modes is nearly zero. Therefore, the impact does not cause damage to the control mechanism worse than might be caused by the design-basis earthquake.

From the same equation of the modal displacement, the displacement at node 4 due to impact spectrum (Fig. 6a) is

$$u_1 = \frac{15.73}{(2\ \pi\ 5.31)^2} \times 0.041 \times 60.0 = 0.0348\ inch \qquad (2.3)$$

$$u_2 = \frac{12.4}{(2\ \pi\ 5.33)^2} \times 0.032 \times 60.0 = 0.0212\ inch \qquad (2.4)$$

and all higher modes do not have an effect. The total displacement at node 4 is

$$u = u_1 + u_2 = 0.056\ inch. \qquad (2.5)$$

To illustrate that all higher modes do not have significant effect, use the 10-th mode as an example. The frequency is 42.54 Hz, the participation factor is - 0.01523, the eigenvector at node 4 is 0.000021078, and the acceleration spectrum value is 7000 in/s^2. Then, from the modal displacement equation, the 10-th modal displacement at node 4 is

$$u_{10} = \frac{-0.01523}{(2\ \pi\ 42.54)^2} \times 0.000021078 \times 7000.0 = -3\times10^{-7}\ inch. \qquad (2.6)$$

Similarly, at node 8

$$u_1 = \frac{15.73}{(2\ \pi\ 5.31)^2} \times 0.037 \times 60.0 = 0.0314\ inch \qquad (2.7)$$

and the total displacement at node 8 is

$$u = u_1 + u_2 = 0.051\ inch. \qquad (2.8)$$

3.0 SUMMARY OF THE RESULTS

3.1 The plot shown in Fig. 2 for the damage of the pool bottom concrete slab as a result of the heavy load impact indicates that approximately half of the concrete slab would be damaged after the drop of the GE cask.

3.2 The impact-induced velocity response spectra Figs. 4a and b for frequency less than 10 Hz at the HFIR vessel supporting concrete slab has the magnitude approximately equal to the new Oak Ridge spectrum. The spectral velocity generated by the impact for frequency less than 10 Hz is no more then the design response spectrum. The Oak Ridge spectrum is formulated in compliance with the requirement of DOE Standard DOE-STD-1020-94.

3.3 The impact-induced vibration will not damage and jam the control rod. The damage to the control mechanism from the impact spectrum is less than that caused by the design-basis earthquake.

4.0 CONCLUSION

The HFIR pool bottom slab damage as a result of GE cask drop is the controlling factor for the damage evaluation in this safety analysis. Neither the reactor vessel nor the supporting legs are damaged. The impact-induced spectrum will not cause damage to the control rod worse than might be caused by the design-basis earthquake.

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