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Seismic Analysis of Submerged Spent Fuel Storage Structure

by Shih-Jung Chang
Research Reactors Division
Oak Ridge National Laboratory
Oak Ridge, TN 37831

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Abstract

The purpose of this calculation is to provide structural integrity analysis for the loaded new spent fuel rack arrays against possible seismic excitation. The seismic design calculation is based on the UCRL-15910 spectrum with peak ground acceleration of 0.32g and 5% damping. This spectrum may be considered as an upper bound of the newly developed Oak Ridge site-specific spectrum with 0.29g peak ground acceleration and 5% damping. Both are more conservative than the current design basis seismic acceleration of 0.15g for HFIR. The calculation is carried out by using ABAQUS version 5.2 and the response spectrum option. Since the new racks are to be submerged in HFIR pool, the pool water induced virtual mass has been conservatively taken into consideration. The result shows that if the silo buckling is regarded as failure then, with 95% confidence, the 5% probability of failure ground acceleration is as much as 2.334g. As compared with the design basis of 0.32g, the structure is very safe against earthquake.

1.0 INTRODUCTION

The purpose of this calculation is to provide a structural design analysis for the new spent fuel rack arrays against possible seismic excitation. Numerical analysis for the new spent fuel racks is based on the computer code ABAQUS 5.2. The analysis is made for the hourglass silo array and the diamond array, with and without the effect of the surrounding water. Seismic excitation is based on the UCRL-15910 spectrum with 0.32g peak ground acceleration and 5% damping. One of the horizontal seismic excitation is applied along the weakest direction of the structure. Seismic margin of safety or fragility analysis against peak ground acceleration is based on the maximum allowable buckling stress and yield stress of the rack array. Fluid-structure interaction is modeled by using the added-mass correction. Each jacketed spent fuel has an assumed weight of 600 lbs.

The 0.32g is based on the Lawrence Livermore Laboratory recommendation UCRL 15910 (ref. 1). It is more conservative as compared to the Oak Ridge site-specific spectrum of 0.29g that is recommended by the MMES Natural Phenomenon Engineering Center. A comparison of the two spectrums is shown in Fig. 1. The main difference of the two spectrums are shown in the frequency range f < 40 cps. Some minor difference happens between 16 cps to 50 cps. To choose UCRL 15910 spectrum for Oak Ridge area is on the conservative side. This is also more conservative than the current design basis seismic acceleration of 0.15g for HFIR.

2.0 CALCULATION AND ANALYSIS

2.1 Material properties

Stainless steel (304 SS)
- Modulus of elasticity — 28.10^6 psi
- Possion's ratio — 0.30
- Specific weight — 0.286 lbs/in^3 = $0.742.10^{-3}$ $lbs.s^2/in^4$
- Elongation in 2 in. — 30%
- Yield stress — 40.10^3 psi
- Ultimate stress — 90.10^3 psi

2.2 UCRL-15910 seismic response spectrum

A 0.32g peak ground acceleration with 5% damping is applied to the two horizontal directions and 2/3 of its magnitude applied to the vertical direction of the structure.

UCRL 15910 response spectrum is used in the calculation. A comparison of this spectrum to Oak Ridge site-specific spectrum is shown in the following table:

UCRL 19510 response spectrum and Oak Ridge site-specific spectrum

Period, sec	Frequency, cycle/sec	UCRL-15910 (0.32g) velocity, in/sec	Oak Ridge site-specific (0.29g) velocity, in/sec
2	0.50	22.0	6.5
1	1.00	22.0	6.5
0.5	2.00	22.0	6.5
0.4	2.50	17.0	6.5
0.2	5.00	9.0	5.0
0.1	10.00	3.8	3.8
0.06	16.67	1.9	2.4
0.04	25.00	1.1	1.6
0.02	50.00	0.48	0.50
0.015	66.67	0.32	0.25
0.010	100.00	0.22	0.17

2.3 Added-mass correction

The seismic induced vibration of the storage rack is affected by the surrounding pool water. Water tends to increase the apparent mass, the "added-mass" effect, of the structure. It reduces the natural frequency of the structure and, therefore, induces additional response. The amount of increase can be calculated by considering the induced fluid flow. A comprehensive review of the subject can be found in reference 2. A brief description of forces on the cylinder is shown in Appendix.

Forces on cylinder as induced by the surrounding fluid are expressed in terms of the coefficients α, β, σ, and τ. These coefficients were calculated by S. S. Chen of Argonne

National Laboratory on September 13, 1993. The numerical values are listed below. The index I and J denote the force acting on the i-th cylinder due to the motion of the j-th cylinder. The x-component force g_i and y-component force h_i for a total of N cylinders are

$$g_i = -\rho\pi R^2 \sum_{j=1}^{N} \left[\alpha_{ij} \frac{\partial^2 u_j}{\partial t^2} + \sigma_{ij} \frac{\partial^2 v_j}{\partial t^2} \right]$$

$$h_i = -\rho\pi R^2 \sum_{j=1}^{N} \left[\tau_{ij} \frac{\partial^2 u_j}{\partial t^2} + \beta_{ij} \frac{\partial^2 v_j}{\partial t^2} \right]$$

where ρ is the density of the fluid and R is the radius of the cylinder. u_j and v_j are displacement of j-th cylinder in x and y directions, respectively.

Added mass matrix for hourglass circular cylinder array

Number of cylinders = 5
Number of terms used = 10

Cylinder No.	Radius(in)	X(in)	Y(in)	
1	10.437	.000	.000	
2	10.437	-11.000	19.053	
3	10.437	11.000	19.053	
4	10.437	-11.000	-19.053	
5	10.437	11.000	-19.053	

Added matrix for alpha (I,J)

1.95510	.26789	.26789	.26789	.26789
.26789	1.73084	-.97068	.11162	.08704
.26789	-.97068	1.73084	.08705	.11162
.26789	.11162	.08704	1.73084	-.97068
.26789	.08705	.11162	-.97068	1.73084

Added matrix for tau (I, J)

0.00000	.56309	-.56309	-.56309	.56309
.88700	-.16987	-.25153	-.06522	.11023
-.88700	.25153	.16987	-.11023	.06522
-.88700	.06522	-.11023	.16987	.25153
.88700	.11023	-.06522	-.25153	-.16986

Added matrix for sigma (I, J)

0.00000	.88700	-.88700	-.88700	.88700
.56309	-.16986	.25153	.06522	.11023
-.56309	-.25153	.16987	-.11023	-.06522
-.56309	-.06522	-.11023	.16987	-.25153
.56309	.11023	.06522	.25153	-.16987

Added matrix for beta (I, J)

2.60924	-.56254	-.56254	-.56254	-.56254
-.56254	1.53605	.55296	-.27029	-.04270
-.56254	.55296	1.53605	-.04270	-.27029
-.56254	-.27029	-.04270	1.53605	.55296
-.56254	-.04270	-.27029	.55296	1.53605

Added mass matrix for diamond circular cylinder array

Number of cylinders = 4
Number of terms used = 10

Cylinder No.	Radius(in)	X(in)	Y(in)
1	10.437	.000	.000
2	10.437	-11.000	19.053
3	10.437	11.000	19.053
4	10.437	.000	38.106

Added matrix for alpha (I, J)

1.39091	.18660	.18660	.15571
.18660	2.44003	-1.66614	.18660
.18660	-1.66614	2.44003	.18660
.15571	.18660	.18660	1.39091

Added matrix for tau (I, J)

0.00000	.41910	-.41910	0.00000
1.12870	0.00000	0.00000	-1.12870
-1.12870	0.00000	0.00000	1.12870
0.00000	-.41910	.41910	0.00000

Added matrix for sigma (I,J)

0.00000	1.12870	-1.12870	0.00000
.41910	0.00000	0.00000	-.41910
-.41910	0.00000	0.00000	.41910
0.00000	-1.12870	1.12870	0.00000

Added matrix for beta (I,J)

1.89575	-.53529	-.53529	-.38023
-.53529	1.72182	.55168	-.53529
-.53529	.55168	1.72182	-.53529
-.38023	-.53529	-.53529	1.89575

2.4 Silo and pedestal dimensions

Each unit of the redesigned spent fuel racks consists of a circular cylindrical silo and a pedestal seating for the silo. A maximum of three packages of jacketed spent fuel can be stored in the silo part of the rack. Six hole openings are evenly distributed around the cylindrical wall of the pedestal to allow natural convection of pool water running through the rack.

Several key dimensions of the silo and pedestal (Figs. 2 to 4) are listed below with all units in inches:

Silo
- Height — 98
- Inner diameter — 20 1/2
- Wall thickness — 3/16

Fuel and jacket
- Height — 36 1/2
- Outer diameter — 20 9/16

Pedestal
- Height — 8 3/8
- Inner diameter — 6 × 5 1/4
- Wall thickness — 3/8
- Outer diameter — 20

Upper seating ring
- Inner diameter — 15 7/8
- Outer diameter — 21 1/4
- Thickness — 1/2

Lower seating plate
- Outer diameter — 20 3/4
- Thickness — 3/8

Base plate
- Thickness — 3/4

2.5 Apparent masses used in seismic analysis

The seismic analysis for the fuel loaded silo in air uses the dry fuel and jacket weight of 600 lbs. It will be seen later that the apparent mass needs at least to be doubled for the loaded rack that is submerged in water. The effect of the surrounding water in the event of seismic motion is substantial.

2.5.1 Dry mass

The mass of the fuel and jacket is assumed to be concentrated on two circular beams attached to the silo in the ABAQUS input file. The total mass density for the two beams is:

$$Mass = \frac{600}{1 \times \pi \times 20.6875 \times 386}$$

$$= \frac{600}{25087} = 0.023917 \; lbs.\, s^2/in.^4$$

In the above equation, the jacketed fuel weighs 600 pounds. The two circular beams are assumed to have a total cross section of one square inch and a diameter of 20.6875 inches.

2.5.2 Apparent mass of fuel and jacket in water

The fuel loaded silo is assumed to be submerged in HFIR pool when the earthquake takes place. The dry fuel and jacket have been assumed to be 600 pounds. When submerged, water is filled in all gaps for the jacketed fuel. In this analysis, the dry mass and the mass of the gap-filled water should altogether be considered as the mass inside the silo.

The weight of the gap-filled water weight can be estimated as the following. The displaced water by the jacket and fuel assembly is

Jacketed fuel	512.52
Jacketed fuel in water	– 356.68
Displaced water weight	155.84 lbs.

Gap-filled water weight is the water weight that would occupy the jacket volume of 36.5 inches long and 20.5 inches in diameter, subtracting the displaced water weight, i.e.,

Jacketed volume of water	443.04
Displaced water	– 155.84
Gap-filled water	287.20 lbs.

Therefore, inside the silo,

$$\text{Jacketed fuel and gap water} = 887.20 \text{ lbs.}$$

that should be used as the weight inside the silo to replace the 600 pounds dry weight in the seismic analysis.

The added-mass is expressed in terms of the coefficients shown in Appendix A multiplied by the displaced water mass of weight 443.04 pounds. The total apparent mass fraction of the submerged jacket and fuel in terms of the dry weight of 600 pounds is

$$\text{Apparent mass} = [887.20 + \text{coefficient} \times 443.04]/600$$

that is substantially greater than one. The effect is not negligible.

2.6 Response spectrum analysis of the spent fuel racks

All seismic response calculations are based on UCRL-19510 spectrum. The numerical results are calculated by applying the computer code ABAQUS with response spectrum option. Recall that the input of the calculation is based on two horizontal excitations and one vertical excitation with 2/3 of the magnitude given by the horizontal ones. The two horizontal excitations are perpendicular to each other. One of them is assumed to be applied along the weakest direction of the structure.

2.6.1 Natural frequencies for hourglass and diamond arrays

The natural frequencies for the two different arrays are listed in the following table. The effects of the surrounding water are shown for both arrays.

Mode No.	Hourglass frequency, cps		Diamond frequency, cps	
	w/o water	w/water	w/o water	w/water
1	21.678	13.783	21.483	13.755
2	21.718	13.801	21.968	14.072
3	45.790	29.997	58.219	36.656
4	58.263	39.178	77.028	48.410
5	71.231	47.585	80.931	51.524

It is observed in the above table that, as expected, the presence of water tends to reduce the magnitude of the natural frequency and to increase the response of the seismic excitation. The effect of water is significant.

2.6.2 Eigenvectors for the arrays

The eigenvectors that correspond to the first few eigenvalues are calculated from ABAQUS. These eigenvectors after multiplied by the corresponding magnitudes in the response spectrum and after square rooted the sum of the squares (SRSS) give the estimated response.

2.6.3 Stress distribution and maximum displacement

The principal stresses for both of the arrays are plotted by using the contour option. The von Mises stresses are also plotted. For the maximum displacement for the submerged hourglass array, u_x is 0.0359 inch and u_y is 0.0361 inch. For the submerged diamond array, u_x is 0.0358 inch and u_y is 0.0344.

2.6.4 Natural frequency obtained by a simplified method

In this section a simplified method is used to obtain the natural frequency of one silo to be attached on one pedestal. The simplified model is based on the assumption that the silo and pedestal assembly can be approximately represented by a cantilever beam with the equivalent mass and moment of inertia. By using this approach the natural frequency for the dry silo and pedestal assembly is found to be equal to 23.59 cps that is only about 10% higher than the ABAQUS solution of approximately 21.6 cps.

The fundamental frequency for a cantilever beam (ref. 4) is

$$f = \frac{(0.597\pi)^2}{2\pi l^2}\sqrt{\frac{EI}{m}} = 23.59\ cps$$

where l is the length of three fuel height and one pedestal height,

$$l = 36.5\times3 + 8.375 = 117.875\ in.$$

In the frequency equation the moment of inertia I is

$$I = \frac{\pi}{4}(r_0^4 - r_i^4) = 652.0\ in^4$$

The mass of the silo is

$$m_1 = 0.742\times10^{-3}\times\pi(r_0^2 - r_i^2) = 0.00904\ lbs.s^2/in^2$$

The mass of the three fuels is

$$m_2 = \frac{3\times600}{36.5\times3\times386} = 0.0426\ lbs.s^2/in^2$$

The total mass m is the sum of m_1 and m_2. Therefore, the fundamental frequency is 23.59 cps from the frequency equation.

2.7 Buckling of silo

The buckling stress for the silo shell is calculated by applying the cylindrical shell buckling formula (p. 462, ref. 3),

$$\sigma_{3cr} = \frac{0.3\times Eh}{a\sqrt{3(1 - \nu^2)}}$$

$$= 92.94\ ksi$$

where a is the radius of the cylindrical shell and h is its thickness,

$$\frac{a}{h} = \frac{10.25 \times 16}{3} = 54.7.$$

From the ABAQUS output, the axial stress is

$$\sigma_3 = 3.40 \; ksi \; < \; 92.94 \; ksi.$$

The yield stress is only 40 ksi. If no yielding is allowed, then the conservatism has a factor of safety

$$F = \frac{40}{3.40} = 11.76.$$

2.8 Seismic margin of safety or fragility

Peak ground acceleration of 0.32g for the safe shutdown earthquake has been used in the finite element seismic calculation. The median ground acceleration capacity A_m for the structure is

$$A_M = F_S \cdot F_\mu \cdot F_{RS} \cdot A_{SEE}$$

where

$$F_S = \textit{Structure strength factor}$$

$$F_\mu = \textit{inelastic response factor}$$

$$F_{RS} = \textit{structural response factor}$$

$$A_{SEE} = \textit{safe shutdown earthquake}$$

From the above buckling calculation, neglecting dead load stress from silo of 0.056 ksi,

$$F_S = 11.76.$$

If only elastic response is allowed and if the structure response factor 1.2 can be assumed than

$$F_{\mu} = 1.0 \quad and \quad F_{RS} = 1.2.$$

Then, the median ground acceleration capacity for the structure is

$$A_M = 11.76 \times 1 \times 1.2 \times 0.32 = 4.516g.$$

Since the structural analysis is based on elastic calculation, the random variability is small and the uncertainty is not large. Each of them is assumed to be 0.2., i.e.,

$$\beta_r = 0.2 \quad and \quad \beta_u = 0.2.$$

The fragility curve is shown in Fig. 5.

With 95% confidence, the 5% probability of failure for the structure is

$$A_{HCLPF} = A_M \cdot e^{-1.65(0.2+0.2)}$$

$$= 2.334g$$

that is larger than the design basis of 0.32g. Therefore, the structure has sufficient margin against seismic excitation.

3.0 SUMMARY OF RESULTS AND CONCLUSION

Added mass, or virtual mass, effect caused by the surrounding water must be considered in the seismic response analysis.

If the safe shutdown earthquake for HFIR is based on the peak acceleration of 0.32g, then the factor of safety for both of the arrays is at least equal to 11.76 with respect to the buckling failure and yielding of the structures due to earthquake excitation.

The probability of failure for the loaded spent fuel arrays is represented by the fragility curves in Fig. 5. The current design shows a good margin of safety.

4.0 APPENDIX

Added Mass Calculations

From section 2.3, the force of the i-th cylinder of a total N cylinders is g_i for the x-component and h_i for the y-component. Since, under earthquake excitation, the cylinders (or silos) are moving approximately in phase, their displacements may be assumed to be approximately equal, i.e., all u_i's are equal and so are v_i's.

Under this assumption, the equations for g_i and h_i can be simplified to

$$g_i = -\rho\pi R^2 \left[(\sum_{j=1}^{N} \alpha_{ij}) \frac{\partial^2 u}{\partial t^2} + (\sum_{j=1}^{N} \sigma_{ij}) \frac{\partial^2 v}{\partial t^2} \right]$$

$$h_i = -\rho\pi R^2 \left[(\sum_{j=1}^{N} \tau_{ij}) \frac{\partial^2 u}{\partial t^2} + (\sum_{j=1}^{N} \beta_{ij}) \frac{\partial^2 v}{\partial t^2} \right]$$

For the two different silo arrangements, the forces are calculated in the following:

1. <u>Hourglass array</u>

   From the added-mass matrix coefficients table, it can be shown that:

   - α — coefficients

$$\sum_j \alpha(1, j) = 1.95510 + 0.26789 \times 4 = 3.02666$$
$$\sum_j \alpha(2, j) = 1.22671$$
$$\sum_j \alpha(3, j) = \sum_j \alpha(4, j) = \sum_j \alpha(5, j) = \sum_j \alpha(2, j)$$

   - τ — coefficients

$$\sum_j \tau(1, j) = 0$$
$$\sum_j \tau(2, j) = 0.51061$$
$$\sum_j \tau(3, j) = -0.51061$$
$$\sum_j \tau(4, j) = -0.51061$$
$$\sum_j \tau(5, j) = 0.51061$$

- σ — coefficients

$$\sum_j \sigma(1,j) = 0$$
$$\sum_j \sigma(2,j) = 0.82021$$
$$\sum_j \sigma(3,j) = -0.82021$$
$$\sum_j \sigma(4,j) = -0.82021$$
$$\sum_j \sigma(5,j) = 0.82021$$

- β — coefficients

$$\sum_j \beta(1,j) = 2.60924 - 4 \times 0.56254 = 0.35908$$
$$\sum_j \beta(2,j) = 1.21348$$
$$\sum_j \beta(3,j) = \sum_j \beta(4,j) = \sum_j \beta(5,j) = \sum_j \beta(2,j)$$

The force on cylinder is, therefore,

$$\frac{-1}{\rho\pi R^2}\begin{bmatrix} g_1 & g_2 & g_3 & g_4 & g_5 \\ h_1 & h_2 & h_3 & h_4 & h_5 \end{bmatrix}$$

$$= \frac{\partial^2 u}{\partial t^2}\begin{bmatrix} 3.02666 & 1.22671 & 1.22671 & 1.22671 & 1.22671 \\ 0 & 0.51061 & -0.51061 & -0.51061 & 0.51061 \end{bmatrix}$$

$$+ \frac{\partial^2 v}{\partial t^2}\begin{bmatrix} 0 & 0.82021 & -0.82021 & -0.82021 & 0.82021 \\ 0.35908 & 1.21348 & 1.21348 & 1.21348 & 1.21348 \end{bmatrix}$$

The fraction of the displaced water weight to the dry fuel weight is

$$\frac{443.04}{600} = 0.7384$$

and that of the wet fuel to the dry fuel weight is

$$\frac{887.20}{600} = 1.4787.$$

The effect of the added-mass is estimated as

$$3.02666 \times 0.7384 = 2.2348$$

$$1.22671 \times 0.7384 = 0.9058.$$

The mass density for the fuel and jacket is modified to

$$0.023917 \times (1.4787 + 2.2348) = 0.08881$$

$$0.023917 \times (1.4787 + 0.9058) = 0.05703.$$

2. Diamond array

Similar calculation gives

$$\frac{-1}{\rho \pi R^2} \begin{bmatrix} g_1 & g_2 & g_3 & g_4 \\ h_1 & h_2 & h_3 & h_4 \end{bmatrix}$$

$$= \frac{\partial^2 u}{\partial t^2} \begin{bmatrix} 1.91982 & 1.14709 & 1.14709 & 1.91982 \\ 0.00000 & 0.00000 & 0.00000 & 0.00000 \end{bmatrix}$$

$$+ \frac{\partial^2 v}{\partial t^2} \begin{bmatrix} 0.00000 & 0.00000 & 0.00000 & 0.00000 \\ 0.44494 & 1.20292 & 1.20292 & 0.44494 \end{bmatrix}$$

Mass density of the fuel and jacket is modified to include the effect of added-mass as

$$0.023917 \times (1.4787 + 1.91982 \times 0.7384) = 0.023917 \times (2.8963) = 0.06927$$

$$0.023917 \times (1.4787 + 1.14709 \times 0.7384) = 0.023917 \times (2.3257) = 0.05562$$

5.0 REFERENCES

1. Design and Evaluation Guidelines for Department of Energy Facilities Subjected to Natural Phenomena Hazards, by Kennedy, R.P., Short, S.A., McDonald, J.R., McCann,Jr., M.W., Murray, R.C. and Hill, J.R. UCRL-15910, June 1990.

2. Flow-Induced Vibration of Circular Cylindrical Structures, by S. S. Chen, Hemisphere, New York, 1987.

3. Theory of Elastic Stability, by S. Timoshenko, McGraw-Hill, New York, 1936.

4. Structural Dynamics, by J. M. Biggs, McGraw-Hill, New York, 1964

Figure Captions

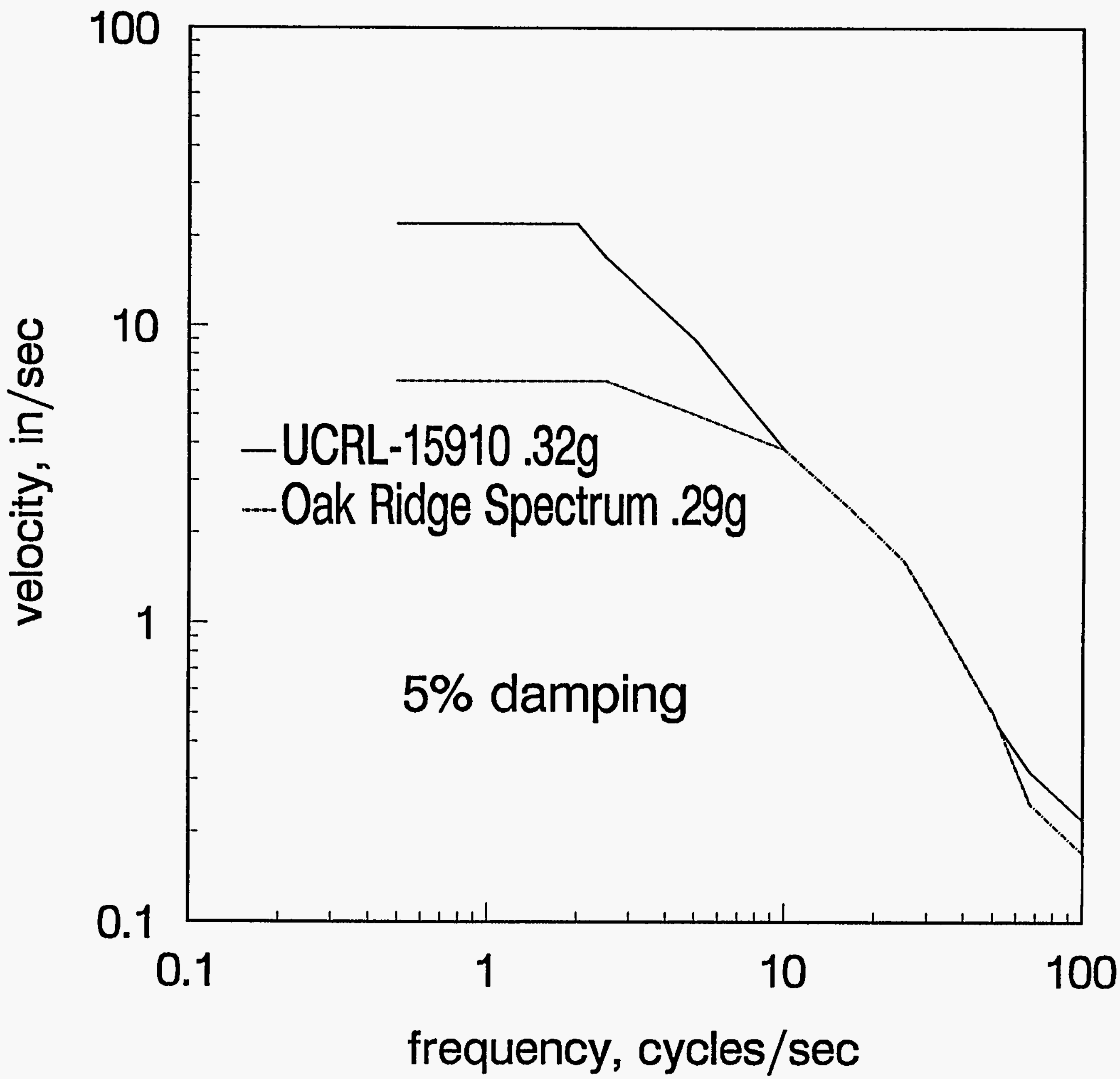
1. UCRL-15910 spectrum and Oak Ridge Site-Specific spectrum

2. Hourglass array

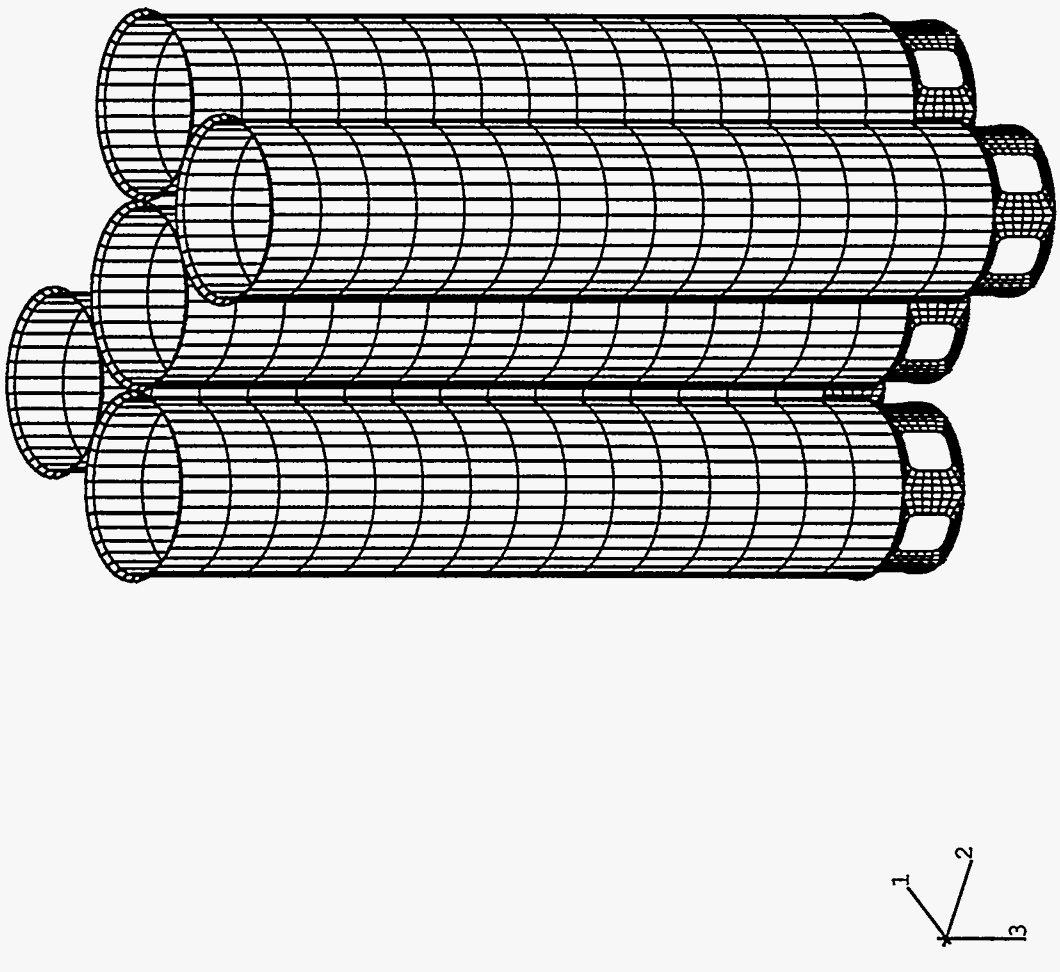
3. Hourglass pedestal array

4. Diamond array

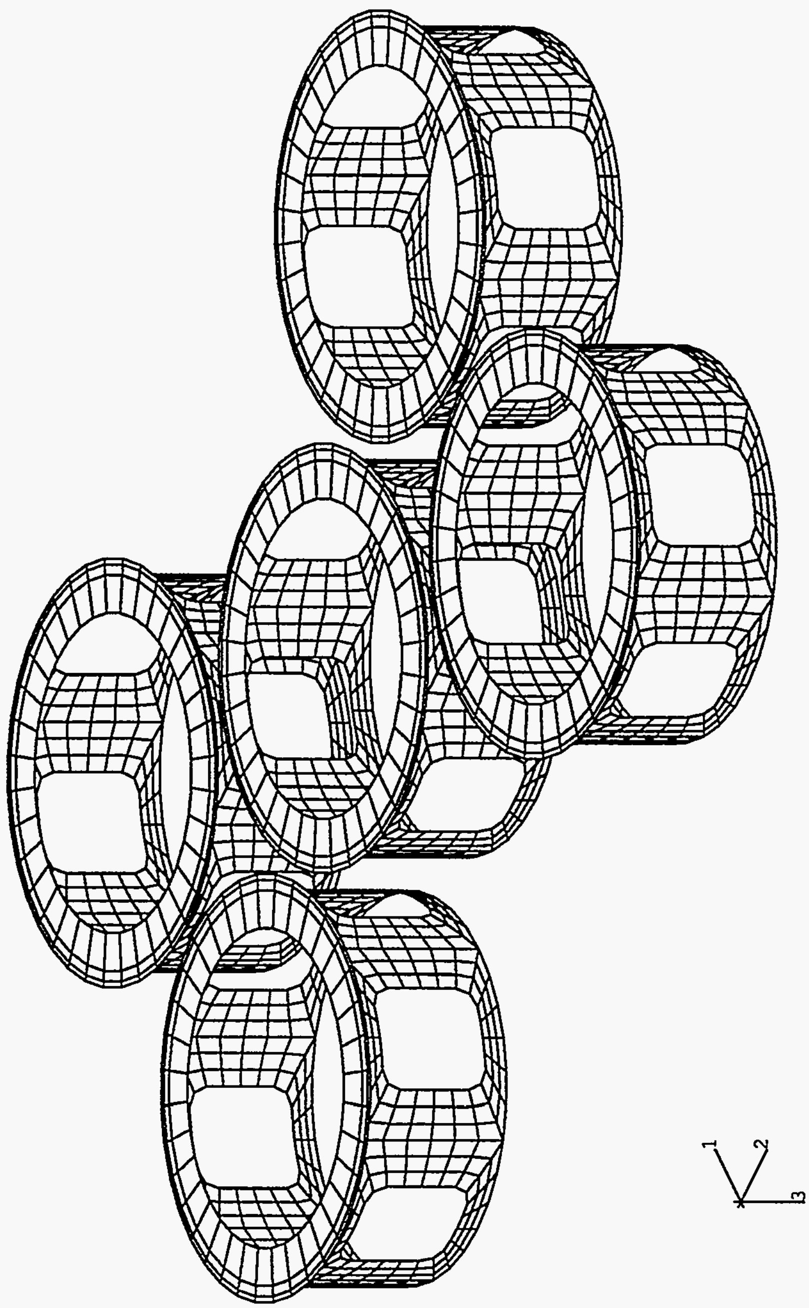
5. Seismic margin, or fragility, curves based on the submerged diamond array buckling failure analysis



100
10
1
0.1
velocity, in/sec
—UCRL-15910 .32g
---Oak Ridge Spectrum .29g
5% damping
0.1
1
10
100
frequency, cycles/sec



1
2
3


1
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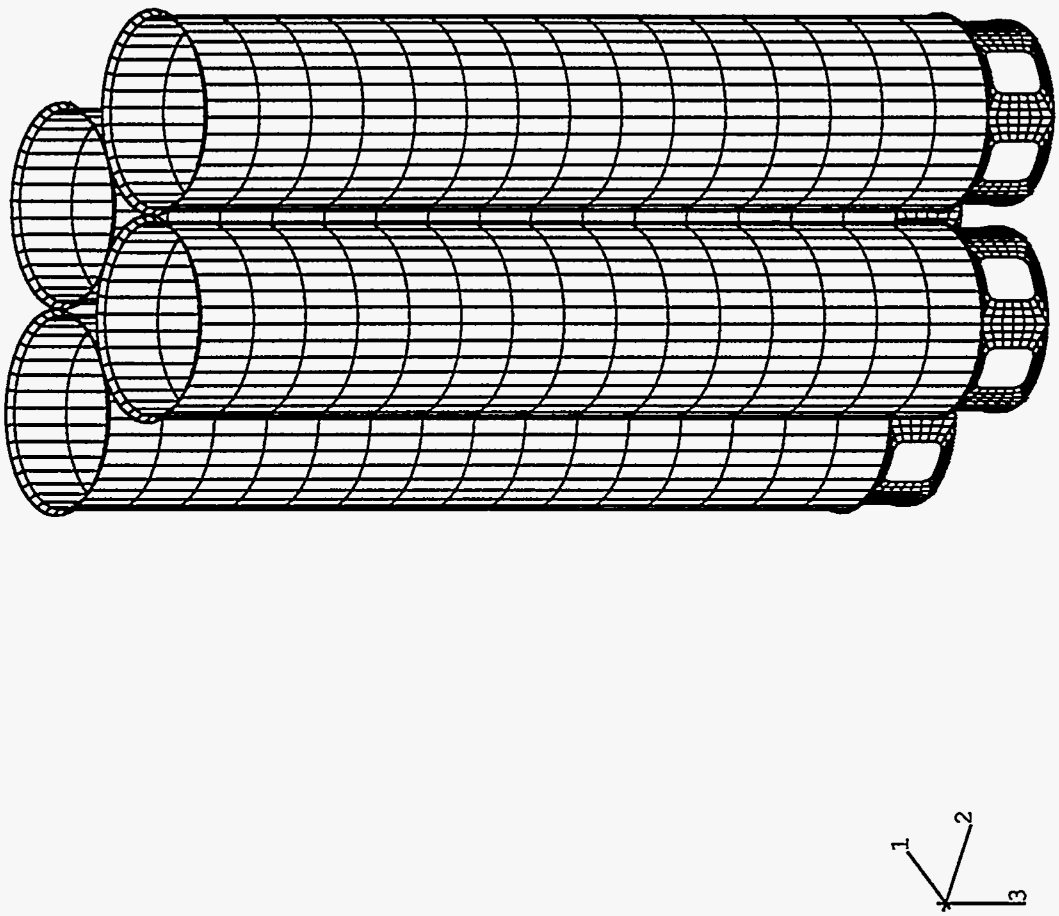
3


1
2
3

Spent Fuel Rack Probability of Failure Curves