Investigation of Seismic Limit States for LWR Containments

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INTRODUCTION

Sandia National Laboratories has led research into containment integrity under extreme loads (beyond design basis) for the U.S. Nuclear Regulatory Commission since 1982. The major thrust of the research has been on the effect of quasi-static pressure and temperature loads resulting from degraded core accidents. The investigation described in this paper represents a first attempt to quantify the behavior of containment buildings for seismic loading greater than the design safe-shutdown earthquake, or SSE.

An in-depth analytical study was conducted by Sargent and Lundy Engineers under contract to Sandia in order to determine typical values for seismic capacities and plausible seismic failure modes of LWR containments. This was a scoping study to determine if seismic events pose a significant threat to containment integrity. The seismic capacities of the containment buildings of four nuclear power plants located in the eastern United States were investigated for four different conditions of internal pressure and temperature. Sixteen potential limit states were postulated and structural calculations were conducted to identify the critical limit states for each containment.

In this investigation, load combinations well beyond the original design basis were considered. The results are interpreted in the context of generic seismic hazard curves, which are subject to large uncertainty, especially for the strong ground motion corresponding to levels beyond the SSE. Therefore, careful exercise of engineering judgement is required to evaluate seismic threat.

The results of Sargent and Lundy's study are described in detail by Amin, Agrawal, and Ahl (1989). This paper provides only a very brief summary of the results and a Sandia/NRC perspective of seismic threat to containment integrity.

ANALYSIS METHOD

Four containments in the eastern United States were studied: Clinton (Illinois), Fermi (Michigan), Sequoyah (Tennessee), and Zion (Illinois). These four containments were chosen to represent a range of containment, reactor, and foundation types. Table 1 lists some of the major characteristics and design parameters of the containments evaluated in this study. Although it is recognized that seismic capacity and limit states are dependent on the unique design features and site characteristics of a particular containment, some generality is obtained by considering containments that represent a range of the more important design and site characteristics.

Four load cases were considered for each containment as indicated in Table 2. Case 1 considers the effect of a main shock on the containment during normal operation, whereas Cases 2-4 consider the effect of an aftershock at various times during the progression of a severe (degraded core) accident, which might be triggered by the main shock. The pressure and temperature in Case 2 correspond to the design conditions, whereas the pressure in temperature in Case 3 represent a condition at which general yield of the containment wall is imminent. Case 4 provided an intermediate point between Case 2 and Case 3.

Table 1 - List of Containments Evaluated

			Design Parameters			
Containment	Type	Foundation	SSE (g)	Spectra Type	Pressure (psig)	Temp. (°F)
Fermi	BWR Mark I Steel	Rock	0.15	Housner	56.0	281
Clinton	BWR Mark III Reinforced Concrete	Soil	0.25	NRC Reg Guide 1.60	15.0	185
Zion	PWR Prestressed Concrete	Soil	0.17	Housner	47.0	271
Sequoyah	PWR Ice Condenser Steel	Rock	0.18	Housner	10.8	220

Table 2 - Load Cases[1]

	Case 1		Case 2		Case 3		Case 4[2]	
Containment	Pressure (psig)	Temp (°F)	Pressure (psig)	Temp (°F)	Pressure (psig)	Temp (°F)	Pressure (psig)	Temp (°F)
Fermi	0	150	56.0	281	74.0	550	NA	NA
Clinton	0	104	15.0	185	45.0	400	30.0	300
Zion	0	120	47.0	271	93.0	360	70.0	316
Sequoyah	0	120	10.8	220	24.8	360	NA	NA

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1. For each case, gravity, prestressing, and the pressure and temperature loads listed in this table were applied in that order, and then seismic load was applied.

2. Analysis of Case 4 was not conducted for Fermi and Sequoyah.

Sixteen potential limit states were postulated and appropriate evaluation criteria were developed as given in Table 3. The governing limit states and seismic capacity were determined by applying these criteria to the results of the structural analysis. The capacity was calculated in terms of the horizontal ground zero period acceleration, A_H, using input time histories for the horizontal and vertical acceleration that were consistent with NRC Reg Guide 1.60.

Table 3 - Limit States and Evaluation Criteria

Limit State Description	Evaluation Criterion	Applicability[1]
Ductile failure of steel liner	Mid-thickness strain >0.02 Surface strain >0.06	C/Z/S
Ductile failure of reinforcing bars	Strain > 10 x yield strain	F/C/Z/S
Failure of prestressing tendons	Strain > yield strain	Z
Ductile failure of steel shell	Mid-thickness strain >0.02 Surface strain >0.06	F/S
Buckling of steel containment shell	Membrane compression > buckling stress determined from ASME Code Case N-284 with factor of safety of 1.0	F/S
Transverse shear failure in wall or basemat	Nominal shear stress > capacity per ACI 318-83 Section 11.3	F/C/Z/S
Through-wall crushing of concrete	Average through wall compressive strain > 0.002	C/Z
Radial shear failure of penetrations	Force on penetration anchorage > capacity of penetration	C/Z
Failure of pretensioned bolted connections	Shear at connection > shear resistance at equipment hatch or drywell head	F/C/Z/S
Shear failure at buttress plate	Longitudinal shear flow > frictional plus shear resistances including rebars	Z
Failure of containment shell at beam seats or ice chest supports	Initiation of yielding according to Tresca criterion	F/S
Failure of suppression chamber supports	Stress > 1.60 AISC allowables or 1.0 stress limits, whichever is less.	F
Bearing failure of foundation	Average pressure on contact area > ultimate bearing capacity of foundation material	F/C/Z/S
Failure due to sliding of basemat	Horizontal force > frictional resistance plus side differential pressure	Z
Liquefaction of foundation soil	Average cyclic shear > average cyclic shear capacity	C
In-plane shear failure of walls near containment	Total shear force > strength per ACI 318.83 Section A-7.3	F/S

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1. F - Fermi; C - Clinton: Z - Zion; S - Sequoyah

A simplified structural analysis method, which consisted of the two basic steps outlined below, was adopted:

> Step 1: Nonlinear time-history analyses were conducted with lumped mass beam models, including consideration of soil nonlinearities and basemat uplift. The containment and other structures on the same basemat were represented with beam elements and the soil or rock foundation was represented with one-way springs and dampers. Bilinear moment curvature-diagrams were constructed for each beam element to account for the effect of non-seismic loads such as gravity, pressure, temperature, and prestressing loads. The strain-compatible soil shear modulus and damping values were obtained as a function of A_H using a one-dimensional vertical shear wave propagation model.
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> Step 2: Axisymmetric shell analyses of the containment, which combined the peak responses from the nonlinear time history analyses with gravity, pressure, temperature, and prestressing loads, were performed to determine stresses, displacements, and strains as required in the evaluation criteria. For the concrete containments, a cracked section element-level analysis was also conducted. For each limit state, margins were calculated by comparing the maximum response for a given A_H with the allowable level. The seismic capacities and governing limit states were found by identifying the lowest value of A_H that satisfies a limit state criteria.

SUMMARY OF RESULTS

The governing limit states and the conservative capacities obtained in Cases 1 and 3 are given in Table 4 for each containment. All four containments were found to have seismic capacities of at least three times their design-basis safe shutdown earthquake. Many of the critical limit states are not directly related to the containment pressure boundary and consequently, in these cases, the seismic capacity is not affected by the pressure and temperature in the containment. Results also suggest that the subsequent pressure and seismic capacity of a containment is not significantly affected by earthquakes of two times the SSE and possibly higher. Shear failure was a common governing limit state, but less conservative evaluation criteria for this limit state could result in a higher, more realistic estimate for the seismic margin on these limit states. This conclusion is supported by a study of tangential shear design provisions by Oesterle (1988), which shows that the criteria used for shear failure in the current study are quite conservative.

The effect of basemat uplift was relatively benign for containments at soil sites; however, for containments on rock sites, the hard impact condition between the basemat and rock foundation that occurs with uplift resulted in significant amplification of the in-structure response spectra relative to the input spectra for frequencies above 8 Hz. Although this amplification may have implications for equipment survivability in seismic events beyond the SSE, it did not significantly affect containment integrity.

Seismic capacities for the accident conditions involving elevated temperatures and pressures (at least up to levels at which general yielding of the containment shell initiates) were not markedly reduced from those obtained with normal operating pressures and temperatures. Comparison of the results shown in Table 4 indicate that there is no significant reduction in capacity for steel and reinforced concrete containments between Case 1 (normal operating pressure and temperature) and Case 3 (pressure and temperature loads sufficient to cause general yielding of the containment shell). Only in the Zion containment, where the applied internal pressure in Case 3 relieved the prestressing force, was capacity reduced. Even in this case, the conservatively estimated seismic capacity was still about four times the design SSE level when differences between the Housner spectra and NRC Regulatory Guide 1.60 spectra are considered.

SEISMIC HAZARD CURVES

Site specific seismic hazard curves were not available for all the plants considered in this study. However, Ravindra et al. (1985) developed generic seismic hazard curves for plants

Table 4 - Governing Limit States and Conservative Estimates of Capacities[1]

Containment	Design SSE and Spectra	Case 1[2]		Case 3[2]	
		Limit State	Capacity	Limit State	Capacity
Fermi	0.15g Housner[3]	Failure of biological shield wall	0.39g	Failure of biological shield wall	0.39g
		Failure of basemat in shear and bending	0.45g	Failure of basemat in shear and bending	0.45g
Clinton	0.25g RG 1.60	Liquefaction of soil under basemat	0.83g	Liquefaction of soil under basemat	0.83g
				Failure of wall reinforcing bars and liner	1.0g
Zion	0.17g Housner[3]	Failure by interference between containment and auxiliary buildings	0.75g	Failure of wall reinforcing bars	0.34g
				Failure of wall in transverse shear	0.39g
				Failure by interference between containment and auxiliary buildings	0.75g
				Shear failure at buttress plates	0.75g
Sequoyah	0.18g Housner[3]	Failure of shield building	0.30g	Failure of shield building	0.30g
		Failure of basemat in transverse shear	0.52g	Failure of basemat in transverse shear	> 1.0g[4]

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1. Capacities are given in terms of peak horizontal ground acceleration, A_H, and time histories consistent with Regulatory Guide 1.60 spectra.
2. The loads considered in Case 1 include dead load, prestress (if applicable), and seismic load. The loads considered in Case 3 include the same loads in Case 1 plus high pressure and temperature corresponding to a severe accident (see Table 2).
3. In the frequency range of interest to containment structural response, the Regulatory Guide 1.60 spectra are about a factor of two higher than the Housner spectra. This difference must be taken into account when calculating margins to failure relative to the original design basis.
4. The basemat shear capacity is higher in Case 3 than in Case 1 due to the beneficial effect of compression resulting from thermal loads in Case 3.

located in the eastern United States, which show the annual probability of exceedance as a function of a normalized acceleration (the peak ground acceleration divided by the SSE acceleration), as shown in Figure 1. These curves indicate that the median annual probabilities of exceedance for earthquakes with peak horizontal ground acceleration of two, three, and four times the SSE are approximately $2x10^{-5}$, $4x10^{-6}$, and $9x10^{-7}$, respectively. The 90% to 10% exceedance subjective probability bounds are roughly an order of magnitude plus and minus the median value at four times the SSE, respectively; the bounds are smaller for lower values of the normalized acceleration.

It must also be recognized that the characteristics of seismic motion associated with the acceleration required to cause containment failure are not well understood. There are few if any acceleration records of earthquakes of such magnitude in the eastern United States. In this study, time histories were consistent with the Reg Guide 1.60 spectra with 5% damping, which may not be applicable to earthquakes with horizontal ground zero period acceleration of two or more times the SSE level.

CONCLUSIONS

The results of the study suggest that containment buildings have significant capacity to sustain seismic loads well beyond design levels, even under the simultaneous action of beyond design basis pressures and temperatures. Very strong and unlikely earthquakes would be required to damage containment building pressure boundaries. These results tend to confirm those of previous, less exhaustive studies that attempted to estimate seismic margins for nuclear power plants, such as Budnitz, et al. (1985). However, it must be emphasized that for any given plant, the design details may incorporate a "weak link" that could limit seismic capacity, but which could only be identified by a plant-specific examination.

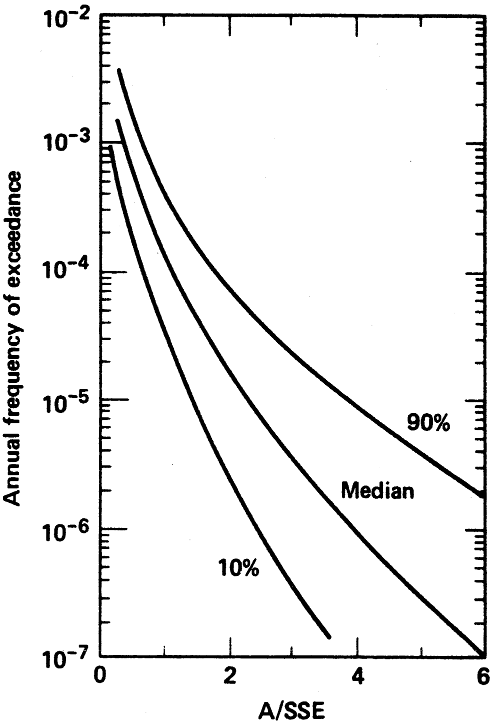

Figure 1
Generic Seismic Hazard Curve
for Plants Located in the Eastern U.S.,
from Ravindra et al. (1985)
(A is equivalent to A_H)

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