Seismic Risk Analysis of Spent Fuel Pools

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ABSTRACT

The objective of this study was to provide technical assistance to the NRC concerning the Generic Issue-82, Beyond Design Basis Accidents in Spent Fuel Pools. The realistic seismic capacity of spent fuel pools at two representative plants was estimated and the seismic failure probability from accidents in spent fuel pools was assessed using plant specific and site specific information. For this purpose, the spent fuel pools at Vermont Yankee (BWR) and H.B. Robinson Unit 2 (PWR) were studied.

INTRODUCTION

The major concern about accidents in spent fuel pools is the loss of water inventory and its capability to cool the radioactive fuel. Without sufficient water, some theoretical models suggest that the fuel's zircaloy cladding may initiate and sustain rapid oxidation (fire) that can spread to adjacent fuel assemblies (self-propagating) with the potential of releasing significant amounts of long-lived radioactive isotopes. Although these isotopes may not present a significant acute health hazard, their release could cause contamination of surrounding property comparable or larger than would occur from a reactor core melt accident.

Previous work [1] in support of the resolution of Generic Issue 82, "Beyond Design Basis Accidents in Spent Fuel Pools", indicated that the risk due to seismic induced failure of nuclear power plant spent fuel pools (SPF) may be significant and dominates the total risk resulting from SPF failures. This result was based on the use of generic seismic hazard and fragility data and resulted in calculated risk numbers with wide uncertainty ranges. To test the result, Lawrence Livermore National Laboratory was asked to determine seismically induced spent fuel pool failure probabilities for two specific plants, the Vermont Yankee Nuclear Power Station, a BWR, and the H.B. Robinson Plant, Unit 2, a PWR. Plant specific hazard and fragility information was used for each plant. The results of this work [2] are presented below.

The failure modes considered in this study were: (1) loss of liner integrity precipitated by gross structural failure of the SFP, (2) loss of function of the fuel pool support system (pool cooling and make-up) resulting in loss of water inventory, and (3) damage to fuel racks. The first failure mode turned out to be the dominant contributor to risk. The second failure mode, loss of pool cooling and make-up capability, was discounted since 3 to 8 days would be available to find alternate water sources before fuel damage could occur. The third failure was discounted after analysis showed that crushing of the fuel in the fuel racks could not result in a criticality accident.

VERMONT YANKEE SPENT FUEL POOL RISK ANALYSIS

Seismic Hazard Curves for Vermont Yankee

Under a separate program, LLNL had developed [3] seismic hazard curves for Vermont Yankee as shown in Figure 1. These curves were used in the seismic risk computation in the present study.

Structural Fragility of Pool Structure

The evaluation described below was performed to determine the seismic capacity of the Vermont Yankee spent fuel pool structure. Failure of the spent fuel pool structure for this study is defined to be a gross, rapid loss of fluid contents providing cooling for the spent fuel rods. Minor leakage is not considered to constitute failure. Investigation was limited to structural components forming the spent fuel pool.

The Vermont Yankee spent fuel pool structure is an integral part of the reactor building, and was designed as a Seismic Category I structure. It is situated at the south side of the reactor building, with the top of the spent fuel pool located at the operating floor which is about 140 feet above the building foundation. The spent fuel pool is twenty six feet wide in the north-south direction and forty feet wide in the east-west direction. It is normally filled with water to a depth of 35.75 feet above the bottom of the pool.

The spent fuel pool structure is built of reinforced concrete. The floor slab is 4′-1" thick with an eleven inch thick grout topping. The walls at the south, east, and west sides are from 4′-6" to 6′-0" thick. The dry well shield wall bounds the spent fuel pool on the north side. The spent fuel pool structure is constructed integral with the reactor building floors at three levels. The interior of the spent fuel pool is lined with stainless steel plates anchored to the walls and slab.

A detailed evaluation of the Vermont Yankee spent fuel pool structure was based on the maximum loading condition when the high density storage racks are filled to their total storage capacity. Of the many potential failure modes of the spent fuel pool structure analyzed, the controlling failure mode with the lowest seismic capacity was out of plane shear failure of the pool slab.

The slab was evaluated for out-of-plane loading resulting from dead load plus seismic load. Sources of dead load are the weights of the slab, grout, water, fuel racks, and attached equipment. Maximum dead load shear at the slab supports due to uniform transverse loadings from the weight of slab, grout, water, and attached equipment was determined by modeling the slab as a one way member.

Seismic response of the slab was derived from the reactor building floor spectra. These floor spectra were reportedly generated from a seismic analysis using the N 69° W component of the 1952 Taft record of the Kern County earthquake normalized to SSE.

For the fragility evaluation, design seismic input to the spent fuel pool were factored to reflect input that would result from the use of median centered seismic response parameters. The factors used vary depending on the response considered as discussed below. Uniform hazard spectra at different annual exceedance frequencies were developed by LLNL [3]. Ten percent structure damping was considered to be a median value based on the recommendations of NUREG/CR-0098 [4] for reinforced concrete structures at or near the yield point. Conservatism in the design basis floor spectra due to broadening and smoothing was also considered in the fragility analysis by inclusion of a median factor of 1.1 for subsystem spectral shape.

The slab fundamental vertical frequency was estimated to be about 25 Hz accounting for potential cracking and continuity at the boundaries. Median slab shears due to vertical response were determined by factoring the dead load shears by the estimated median spectral acceleration of 0.14g. This value was increased by a factor of 1.15 above the SSE spectral acceleration to account for the difference between the median site specific ground spectrum at median structure damping and the SSE ground spectrum at five percent structure damping. The increased factor reflects potential unconservatism of the design ground spectrum at the structure frequency relative to the median ground spectrum.

Seismic response of the pool water in the impulsive and convective modes causes transverse pressures to be exerted on the slab and walls under horizontal excitation. Even accounting for wall flexibility, response of the impulsive mode was determined to be essentially rigid. Fluid response was thus determined following the provisions of TID-7024 [5]. Resulting seismic loads on the slab due to fluid response were found to be small and were therefore neglected.

The new, high density spent fuel storage racks are free standing and not anchored to the structure. In this design, rack loads are transmitted to the slab only by the rack support pads. Seismic response of the racks was determined by dynamic, nonlinear analysis described in Reference [6]. This report contains maximum reactions imposed on the slab by individual support pads as well as maximum total reactions for the rack modules. Inspection of the individual support pad reaction time histories indicates that they are nearly harmonic with long impulse durations relative to the slab natural period. Based upon approximate methods for analysis of structure response to impulse loads described in Biggs [7], the rack loads acting on the slab have a dynamic amplification factor of unity. Maximum slab shears were therefore calculated using maximum total rack module reactions as static loads, with shears from separate modules combined by the square root of the sum of the squares (SRSS) since their phasing is random. Rack module reactions are estimated to have a median factor of safety of about 1.7, accounting for potential conservatism in the input ground motion and the use of bounding base coefficients of friction.

The highest applied slab shear load occurs at the interface with the drywell shield wall. Median slab shear strength at this location was determined from available test data for reinforced concrete beams. From Park and Paulay [8], the ultimate concrete shear stress was estimated to be 2.6 f_c, which represents an increase of about 25% above the ACI 349-80 Code value, not including the strength reduction factor. This shear strength implicitly accounts for moment-shear interaction. Reduction in shear strength due to axial tension imposed by wall reactions is relatively small at seismic levels corresponding to the lower tails of the fragility curves, which dominate the seismic risk and HCLPF capacity. A median ultimate shear strength of 120 kips per foot was calculated with the median concrete compressive strength of 7000 psi. This capacity was based upon one way action for the slab spanning in the short direction between the north and south supports. ASCE [9] recommends a very small increase in shear capacity for this slab accounting for two way action. However, due to the lack of shear reinforcement, shear failure will be nonductile. Because the applied loading is cyclic and the resulting failure mode is nonductile, any load redistribution will be unlikely and was therefore not included in this evaluation.

Following the methodology described above, the slab was found to have the following overall fragility parameters:

$A_m = 1.4g$
$\beta_R = 0.26$
$\beta_U = 0.39$

The median slab fragility curve with 5% and 95% confidence bounds are shown in Figure 2. The HCLPF capacity for slab shear failure is calculated to be 0.5g. This acceleration is about 3.5 times the SSE pga and represents a significant margin of safety. This failure mode is considered to be brittle and it is probable that shear failure will lead to a loss of structural integrity with liner rupture and subsequent rapid loss of spent fuel pool water inventory. Additional redundancy provided by alternative remaining load paths, such as catenary action of the slab, may be possible. However, these load paths were not evaluated since the shear failure capacity is already well in excess of SSE.

The family of structural fragility curves were convolved with the seismic hazard curves to obtain the annual frequency of gross structural failure of SFP due to seismic events.

ROBINSON SPENT FUEL POOL RISK ANALYSIS

The Robinson spent fuel pool structure is a seismic Category I (designed for an SSE of 0.20 g pga) reinforced concrete structure containing 35,000 cubic ft of water and is housed within the Fuel Handling Building. The spent fuel pool is 43 ft wide and 53 ft 6 in. long. It is normally filled with water to a depth of 37 ft above the bottom of the pool which is located at Elevation 236 ft 9 in. The floor slab is 4 ft. 6 in. thick with reinforcement of # 11 bars at 6 in. spacing in the negative moment regions, and # 10 bars at 12 in. spacing in the positive moment regions. A single steel column was installed below the pool floor slab during the plant modification for the spent fuel storage capacity expansion in 1982. The peripheral walls are all 6 ft thick with reinforcement of # 9 bars at 12 in. spacing each way and each face. The interior of the spent fuel pool is lined with stainless steel plate anchored to the walls and slab.

A number of potential failure modes of the spent fuel pool structure were analyzed and the controlling failure mode was determined to be out of plane bending failure of the East wall. The NUREG/CR-0098 median ground response spectrum was assumed as the median spectrum for the SFP fragility evaluation. Using the procedure described for Vermont Yankee analysis, the overall fragility parameters for the spent fuel pool wall at Robinson were estimated as:

$A_m = 2.0g$
$\beta_R = 0.28$
$\beta_U = 0.40$

The HCLPF capacity for pool wall failure was calculated to be 0.65g. This acceleration is about 3.3 times the SSE pga and represents a significant margin of safety.

The seismic fragility of the pool structure was convolved with the site specific seismic hazard curves for Robinson [3] to obtain the annual frequency of gross structural failure of SFP due to seismic events.

RESULTS AND CONCLUSIONS

1. The spent fuel pool structure which is designed to retain large amounts of water and to withstand gravity and lateral loads from the fuel racks has a relatively high seismic capacity (the HCLPF capacity of the pool structure is estimated to be more than 3 times the SSE value); this is true for both the BWR spent fuel pool which is mounted high in the reactor building and the PWR pool which is generally at the ground level. Therefore, the seismic risk contribution from spent fuel pool structural failures is negligibly small.

2. The assessment of potential failure modes of the fuel pool racks and fuel assemblies has indicated that the fuel rack design is such that the assembly cannot be compressed into a critical mass thereby leading to a severe accident.

3. Parts of the cooling and makeup systems for spent fuel pools are not designed as seismic class 1 systems and as such failure of some components might be possible at relatively low seismic levels. However, the failure of cooling and makeup systems would not uncover the spent fuel assemblies for about 3 to 8 days; it is expected that some recovery action could be taken in this time period.

4. This study has shown that the use of plant-specific and site-specific information would reduce the uncertainty bands on the seismic risk estimates; the previous BNL study, using generic information, had estimated the annual frequency of gross structural failure of the pool to vary from 1.6E-10 to 2.6E-04 for PWR; the current study shows this range to be 3.1E-11 to 1.4E-05. Similar results are obtained for the BWR spent fuel pool. Note that the reduction in the uncertainty in the risk estimate on the higher end is more significant. The range of uncertainty in the risk estimate is governed by the range of uncertainty in the seismic hazard at the site. Note that the hazard curves used in this study are preliminary and subject to change following NRC and peer reviews. It is expected that the uncertainty range in hazard curves will be reduced, thereby reducing the uncertainty in the risk estimates.

5. This study used two representative spent fuel pools - a PWR and a BWR. These pools have been designed to meet the seismic design criteria existing in the late 1960s. Their large seismic capacities lead us to the conclusion that the pools designed to current seismic standards should have higher seismic capacities and should not contribute significantly to seismic risk.

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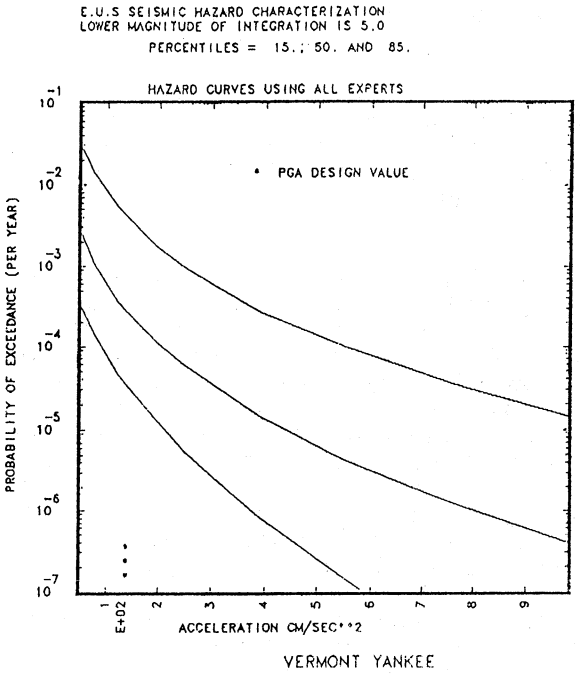

Figure 1: Seismic Hazard Curves for the VYNPS Site (Left)

Figure 2: VYNPS Spent Fuel Pool Structure Fragility (Below)