May 11, 1999

MEMORANDUM TO: John N. Hannon, Branch Chief
Plant Systems Branch, DSSA

FROM: Goutam Bagchi, Senior Level Advisor, DE
Robert Rothman, Senior Geophysicist, DE

SUBJECT: INPUT FOR WORKING GROUP ON DECOMMISSIONING RULE MAKING

Attached is the input for the technical issues paper that the Working Group is developing for an upcoming SECY paper. This input is on seismic issues for Item VII of the Technical Basis Outline. Dr. Robert Rothman has collaborated with me in the preparation of this paper on probabilistic seismic hazard estimates. Any question or comment on the attached paper should be directly addressed to me. Ple ıse note that I shall be away from the office from May 14 to June 1, 1999. During my absence from the office, if there is a need for a clarification on any specific item in the input, Dr. Rothman should be able to help you.

Attachment: as stated

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Spent Fuel Pool Accidents For Decommissioning Plants
Working Group Plan
Structural Integrity Of Pool Structure
Goutam Bagchi and Robert Rothman (DE)

Introduction

As a part of the Generic Issue 82, "Beyond Design Basis Accidents in Spent Fuel Pools," NRC has studied the hypothetical event of an instantaneous loss of spent fuel pool water. The recommendation from a study in support of this generic issue indicates that a key part of a plant specific evaluation for the effect of such an event is the need to obtain a realistic seismic fragility of the spent fuel pool. The failure or the end state of concern in the context of this generic issue is a catastrophic failure of the spent fuel pool which leads to an almost instantaneous loss of all pool water and the pool having no capacity to retain any water even if it were to be reflooded.

Spent fuel pool structures at nuclear power plants are constructed with thick reinforced concrete walls and slabs lined with thin stainless steel liners 1/8 to 1/4 inch thick. The walls vary from 4.5 to 5 feet in thickness and the pool floor slabs are around 4 feet thick. The overall pool dimensions are typically about 50 feet long by 40 feet wide and 55 to 60 feet high. In boiling water reactor (BWR) plants, the pool structures are located in the reactor building at an elevation several stories above the ground. In pressurized water reactor (PWR) plants, the spent fuel pool structures are located outside the containment structure supported on the ground or partially embedded in the ground. The location and supporting arrangement of the pool structures determine their capacity to withstand loads beyond their design basis. The dimensions of the pool structure are generally derived from radiation shielding considerations rather than structural needs. Spent fuel structures at operating nuclear power plants are inherently rugged in terms of being able to withstand loads substantially beyond those for which they were designed. Consequently, they have significant seismic capacity. Because of the ruggedness of the spent fuel pools, licensees have proposed that the continued implementation of the Emergency Plan at a decommissioned plant is burdensome and unnecessary. Also of concern to the licensees are insurance indemnity and safeguards.

The focus of the current effort is to examine the effect of a large seismic event at a plant immediately following decommissioning. The structural assessment of seismic as well as other credible initiating events that can lead to a pool structure failure are addressed in this paper.

Available NRC studies

There are two relevant reports on this issue:
1. NUREG/CR 4982, Severe Accidents in Spent Fuel Pools in Support of Generic Safety Issue 82, Published July, 1987.
2. NUREG/CR 5176, Seismic Failure and Cask Drop Analyses of the Spent Fuel Pools at Two Representative Plants, Published January, 1989.

Subsequent to the completion of work in the above studies, NRC performed a study to review the central and eastern US probabilistic seismic hazard and issued NUREG-1488, Revised Livermore Seismic Hazard Estimates for 69 Nuclear Power Plant Sites East of the Rocky Mountains, Published, October, 1993. It is well recognized that the LLNL seismic hazard curves used prior to the publication of NUREG-1488 were overly conservative. In NUREG/CR 5176 study of the Vermont Yankee plant, the high confidence of low probability of failure (HCLPF) level for the spent fuel pool is 0.5 g and at the H. B. Robinson site the HCLPF value is 0.65 g. A comparison of the 1989 and the 1993 LLNL hazard curves show that the probabilities of exceeding these values are factors of 2 and 1.6, respectively, higher in the 1989 curves.

With respect to the cask drop issue, the first study assumed a conditional failure probability of 0.1, given a cask drop, and in the second study two dimensional finite element models are used but gross structural failure is assumed as a result of the cask drop, even though the maximum deformations are 0.7 and 0.1 inch for the two cases analyzed. The assumption of a conditional failure probability of 1, given a cask drop is very conservative. It appears that for the end state of total loss of water given the cask drop is not likely. Because of the presence of the liner, shear transfer by the concrete aggregate interlock and bending moment resistance under the yield state of reinforcement bars, the walls should have significant capacity to retain water following the impact.

Both the seismically induced and the cask drop induced failure probabilities appear to have been assessed very conservatively rather than realistically.

Risk Perspective of Structural Failure

Based on the available information, the structural failure probabilities or probabilities of reaching the structural end state are as follows:

Cask Drop on the Edge of Pool: 3.5×10^{-7} per ry for structural failure
Seismic Event: mean $1X10^{-6}$ per ry
PWR Range: $2.4X10^{-4}$ to $1.6X10^{-10}$ per ry
BWR Range: $1.4X10^{-5}$ to $1.6X10^{-11}$ per ry
Tornado Missiles: $< 1X10^{-8}$ per ry
Aircraft Crash: $\leq 1X10^{-10}$ per ry

Hazards To consider

From a structural integrity stand point it appears that tornado missiles and aircraft events are not significant hazards and can be eliminated from further scrutiny.

Cask drop accident effect is also different for PWRs and BWRs. However, for a drop at the edge of the pool, the case studied in NUREG /CR 5176, the limiting condition comes from BWR pools and it is noted that the maximum deformation is relatively small and the residual strength of the wall would prevent the pool from failing catastrophically. The case of a drop on the pool floor would require a combined human error and a passive failure of a crane system that is subject to maintenance. This is a low probability event with an upper bound value of about 3.5×10^{-7}. Based on the above discussion, the heavy load drop event can be considered remote and could be eliminated from further consideration.

Seismic vulnerability of spent fuel pool structures is expected at levels of earthquake equal to 2.5 to 3.5 times the plant's safe shutdown earthquake (SSE). These are such large earthquake motions that design basis seismic analyses are not likely to be representative of the behavior of the pool structure under failure level earthquakes. There is considerable difficulty in judging the adequacy of simple analytical models. These large earthquake motions would induce large strain in the foundation medium, the soil structure interaction effect will be modified and if there was not much rocking motion under the SSE, increased rocking motion can be expected for large earthquakes. Impact with adjacent buildings cannot be ruled out for the large seismic event and failure of the pool structure due to the failure of the overhead crane equipment or the failure of the superstructure would have to be taken into account. Uplift of the pool foundation mat and impact on the subgrade would seek out weak links in the pool structure and could lead to local spalling of concrete. Amplification of ground motion up through the reactor building could be substantially higher than the SSE response for BWR pool structures. Also, for BWR pool structures, the pool floor can be subjected to impact forces from free standing rack feet. Thus the design, layout and construction of the pool structures are very important to consider in a realistic fragility assessment.

Heavy Load Drop Accidents

Heavy load drop accidents could be eliminated as a likely event to consider because of its low frequency of occurrence.

Tornado Missiles

Based on the tornado missile frequency and the inherent strength of the spent fuel pool structure, it appears that failure due to tornado missiles is remote and should be eliminated from further consideration.

Safeguards Issues

From safeguards stand point, the ruggedness of the pool structure provides substantial protection. It is possible that additional perimeter hardening, entry point security monitoring and control and consideration of other site specific features could allow the elimination of safeguards issues from evaluation for retaining emergency planning.

Risk Ranking Of Hazards

Seismic hazard ranks high with cask drop events coming second for risk associated with structural failure of spent fuel pools.

Structural Failure Modes

Amongst the various ways a pool structure can fail, the only failure modes that are of concern are those that involve pool floor slab failure, failure of side walls or at the bottom of the pool or at the bottom corners. It is important to ensure that the structural fragility is based on realistic failure modes for catastrophic failure of the structure. This should take into account physical interactions with adjacent structures and equipment.

For PWR spent fuel pools, the pool floor slab is not likely to fail except through the effect of local concrete spalling due to foundation uplift and impact with the subgrade or adjacent structures. Failure of walls in partially embedded pools is not likely. Bending moment capacity of the pool walls is very much dependent on reinforcing patterns and the walls are generally reinforced orthotropically between the horizontal and vertical directions and between one wall and another orthogonal wall . This requires a case by case assessment of the bending capacity of walls.

For BWR spent fuel pools, the floor slab, walls and supporting columns and shear walls need scrutiny to determine the critical failure mode. As in the case of PWR spent fuel pools, the effect of adjacent structures and equipment on structural failure needs to be evaluated.

The stainless steel liner plate is used to assure leak-tightness, cracks in the welded seams are not likely to lead to catastrophic loss of water inventory unless there is a simultaneous massive failure of the concrete structure.

The emphasis here is that spent fuel pool structures not only vary in layout and elevation from PWRs to BWRs, they can also vary within each group. The process of realistic assessment of structural capacity of pool structures begins with a methodical consideration of likely failure modes associated with a catastrophic failure.

The failure mode induced by cask drop accidents may cause local failure, but could also propagate pervasive cracking of concrete and yielding of reenforcement bars . However, even under the cracked condition, significant residual strength may prevent a catastrophic loss of water inventory. Consequently, a realistic assessment of pool capacity must consider residual wall capacity following a cask drop event.

The efforts involved in the assessment of seismic capacity of pool structures typically consist of the following:

- Walk-down the pool structure and its vicinity and note:
    - physical conditions such as cracking, spalling of concrete, signs of leakage or leaching and separation of pool walls from the grade surface,
    - arrangement and layout of supporting columns and shear walls, assessment of other loads from tributary load areas carried by the supporting structure of the pool, as-built dimensions and mapping of any existing structural cracks,
    - adjacent structures that can impact the pool structure both above and below the grade surface, supporting arrangement for superstructure and crane and potential for failure of the superstructure and the crane, the weight of the heaviest object that can drop in the pool structure and the corresponding drop height.
- Seismic capacity calculation of the pool structure typically consist of the following:
    - review existing layout drawings and structural dimensions and reconcile the differences, if any, between the as-built and as designed information and consider the effects of structural degradation as appropriate,
    - from design calculations determine the margin to failure and assess the extrapolated multiple of SSE level that the pool structure should survive, determine whether or not design dynamic response analysis including soil-structure interaction effects are still applicable at the capacity level seismic event, if not, conduct a new analysis using properties of soil at higher strain levels and reduced stiffness of cracked reinforced concrete,

- determine the loads from pool structure foundation uplift and from impact of pool structure with adjacent structures during the capacity level seismic event, determine loads from the impact of spent fuel rack on the pool floor and the side walls and determine the loads from dropping of heavy objects from the collapse of superstructure or the overhead crane,
- determine a list of plausible failure modes; failure of side walls due to the worst loading from the capacity level earthquake in combination with fluid hydrostatic and sloshing head and dynamic earth pressure as appropriate, failure of the pool floor slab in flexure and bending due to loads from the masses of water and the spent fuel and racks, local failure by punching shear due to impact between structures and the spent fuel racks or dropping of heavy objects,
- the calculations to determine the lowest structural capacity can be based on ultimate strength of reinforced concrete structures due to flexure, shear and punching shear. When conducting an yield line analysis, differences in flexural yield capacities in two orthogonal directions and for the negative and positive bending moments influence the crack patterns and several sets of yield lines may have to be investigated to obtain the lowest capacity. For heterogeneous materials, the traditional yield line analysis provides upper bound solutions; consequently, considerable skill is needed to determine the structural capacity based on the yield lines that approximate the lower bound capacity.

Public Meeting of April 13, 1999

Presentations made by NEI relied on the NRC sponsored studies and concluded that structural failure of the spent fuel pool is not likely, based on probability of the initiating events, and should be eliminated from further consideration in the risk informed decommissioning rule making. NEI arguments are risk based and do not take into account uncertainties associated with the seismic risk which range from 2.4×10^{-4} to 3.1×10^{-11} per ry. For this reason, it is important to perform the seismic risk analysis on a case by case basis and establish a risk informed performance goal.

There were also comments related to the potential effects of Kobe and Northridge earthquake related to risk informed considerations for decommissioning. Mr. Paul Gunter's (Nuclear Information Resource Service) comments during the Reactor Decommissioning Public Meeting, Tuesday, April 13, 1999, Rockville, MD are discussed below.

Mr. Gunter's Comments

"I guess I'd like to direct my questions to the seismological review for this risk informed process. And first of all, did any of the NUREGs that you look at take into account new information coming out of the Kobe and Northridge events? I think that what we need to be concerned with is dated information. Particularly as we are learning more about risks associated with those two particular seismological events that were never even considered when plants were sited, particularly though I can't frame it in the seismological language, from a lay understanding, it's clear that new information was gained out of Kobe and Northridge events suggesting that you can have seismological effects of greater consequence farther afield than at the epicenter of the event."

Response to Mr. Gunter's comments

The two NUREGs mentioned by Mr. Gunter were written in the middle and late 1980's and used probabilistic seismic hazard analyses performed for the NRC by Lawrence Livermore National Laboratory (LLNL) for nuclear power plants in the central and eastern U. S. Since then, LLNL has performed additional probabilistic hazard studies for central and eastern U. S. nuclear power plants for the NRC. The results of these newer studies indicated lower seismic hazards for the plants than the earlier studies estimated. Due to the new methods of eliciting information, newer methods of sampling hazard parameters' uncertainties, better information on ground motion attenuation in the U. S. and a more certain understanding of the seismicity of the central and eastern U. S., if the probabilistic hazard studies were to be performed again, the hazard estimates for most sites would probably be reduced still further.

The design bases for each nuclear power plant took into account the effects of earthquake ground motion. The seismic design basis, called the Safe Shutdown Earthquake (SSE), defines the maximum ground motion for which certain structures, systems, and components necessary for safe shutdown were designed to remain functional. The licensees were required to obtain the geologic and seismic information necessary to determine site suitability and provide reasonable assurance that a nuclear power plant can be constructed and operated at a site without undue risk to the health and safety of the public.

The information collected in the investigations was used to determine the earthquake ground motion at the site assuming that the epicenters of the earthquakes are situated at the point on the tectonic structures or in the tectonic provinces nearest to the site. The earthquake which could cause the maximum vibratory ground motion at the site was designated the Safe Shutdown Earthquake (SSE). This ground motion was used in the design and analysis of the plant.

The determination of the SSEs were made following the criteria and procedures required by NRC regulations and using a multiple hypothesis approach in which several different methods were used to determine each parameter and sensitivity studies were performed to account for the uncertainties in the geophysical phenomena. In addition, nuclear power plants have design margins (capability) well beyond the demands of the SSE. The ability of a nuclear power plant to resist the forces generated by the ground motion during an earthquake is thoroughly incorporated in the design and construction. As a result, nuclear power plants are able to resist earthquake ground motions well beyond their design basis and far above the ground motion that would result in severe damage to residential and commercial buildings designed and built to standard building codes.

Following large damaging earthquakes such as the Kobe and Northridge events, the NRC staff reviews the seismological and engineering information obtained from these events to determine if the new information challenges previous design and licensing decisions. The Kobe and Northridge earthquakes were tectonic plate boundary events which occurred in regions of very active tectonics. The operating U. S. nuclear power plants (except for San Onofre and Diablo Canyon) are located in the stable interior portion of the North American tectonic plate. This is a region of relatively low seismicity and seismic hazard. Earthquakes with the characteristics of the Kobe and Northridge events will not occur near central and eastern U. S. nuclear power plant sites

The ground motion from an earthquake at a particular site is a function of the earthquake source characteristics, the magnitude and focal mechanism. It is also a function of the distance of the facility to the fault and the geology along the travel path of the seismic waves and the geology immediately under the facility site. There are two operating nuclear power plant sites in the U. S. which can be considered as having the potential to be subjected to the near field ground motion of moderate to large earthquakes.

These are the San Onofre Nuclear Generating Station (SONGS) near San Clemente and the Diablo Canyon Power Plant (DCPP) near San Luis Obispo. The seismic design of SONGS Units 2 and 3 is based on the assumed occurrence of a magnitude 7 earthquake on the Offshore Zone of Deformation, a fault zone approximately eight kilometers from the site. The design of DCPP has been analyzed for the postulated occurrence of a magnitude 7.5 earthquake on the Hosgri Fault Zone approximately four kilometers from the site. The response spectra used for both the SONGS and the DCPP were evaluated against the actual spectra of near field ground motions of a suite of earthquakes gathered on a world wide basis.

Mr. Gunter stated, "... it's clear that new information was gained out of Kobe and Northridge events suggesting that you can have seismological effects of greater consequence farther afield that at the epicenter of the event." A review of the strong motion data and the damage resulting from these events indicates that this statement is not correct.

We assume that what Mr. Gunter is alluding to is the fact that the amplitudes of the ground motion from the 1994 Northridge earthquake were larger in Santa Monica than those at similar and lesser distances from the earthquake source. The cause of the larger ground motions in the Santa Monica area is believed to be the subsurface geology along the travel path of the waves. One theory (Gao and others, 1996) is that the anomalous ground motion in Santa Monica is explained by focusing due to a deep convex structure (several kilometers beneath the surface) that focuses the ground motion in mid-Santa Monica. Another theory (Graves and Pitarka, 1998) is that the large amplitudes of the ground motions in Santa Monica from the Northridge earthquake are caused by the shallow basin-edge structure (1 kilometer deep) at the northern edge of the Los Angles Basin. This theory suggests that the large amplification results from constructive interference of direct waves with the basin-edge generated surface waves. Earthquake recordings at San Onofre and Diablo Canyon do not indicate anomalous amplification of ground motion. In addition, there have been numerous seismic reflection and refraction studies in the site areas for the evaluations of these sites, and for petroleum exploration and geophysical research. They along with other well proven methods were used to determine the nature of the geologic structure in the site vicinity, to determine the location of any faults, and the nature of the faults. None of these studies have indicated anomalous conditions, like those postulated for Santa Monica, at either SONGS or DCPP. In addition, the empirical ground motion data base used to develop the ground motion attenuation relationships contain events recorded at sites with anomalous as well as typical ground motion amplitudes. The design basis ground motion for both SONGS and DCPP were compared to 84th percentile level of ground motion obtained using the attenuation relationships and the appropriate earthquake magnitude, distance and geology for each site. The geology of the SONGS and DCPP sites do not cause anomalous amplification; therefore, there is no "new information gained from the Kobe and Northridge events" which raise safety concerns for U. S. nuclear power plants.

In summary, earthquakes of the type that occurred in Kobe and Northridge are different than those that can occur near nuclear power plants in the central and eastern U. S.; the higher ground motions recorded in the Santa Monica area from the Northridge earthquake were due to the specific geology through which the waves traveled; improvements in our understanding of central and eastern U. S. geology, seismic wave attenuation, seismicity, and seismic hazard calculation methodology would result in less uncertainty and lower hazard estimates today than those obtained from previous studies.

Notwithstanding the above explanation, there is uncertainty in the seismic risk from spent fuel pool structures is significant enough, to conclude that it is not prudent to base the rule making purely on risk numbers. This is why a risk informed performance goal is recommended for a case by case assessment of seismic vulnerability of spent fuel pool structures.

Deterministic Considerations

NRC sponsored studies have treated the assessment of seismic capacity of spent fuel pools relying on the seismic margins method to determine the high confidence of low probability (less than 5% failure) of failure (HCLPF). The HCLPF value for a structural failure may well be unrealistic and unnecessarily conservative in terms of an instantaneous loss of water inventory. This point needs to be emphasized because the shear and moment capacity of the walls and slabs are determined by using upper limits of allowable stresses. Currently, the guidance provided in EPRI NP-6041-SL, "A Methodology for Assessment of Nuclear Power Plant Seismic Margin (Revision 1)" indicate that an ultimate shear stress value in reinforced concrete structures is a factor of about 2 higher than the value used to determine capacity of the BWR spent fuel pool. In the study which resulted in NUREG/CR 4982, the seismic capacities were based on the Oyster Creek Reactor building and a shear wall from the Zion Auxiliary building. For elevated pool structures, the Oyster Creek estimate may be an acceptable approximation, but the Zion shear wall may be a too highly simplified to substitute for the catastrophic pool failure.

The stainless steel pool liner was not designed to resist any structural load, nevertheless, it can provide substantial water retaining capacity near the bottom half of the pool where structural deformations are likely to be low from seismic loading, except in a highly unlikely failure mode.

For PWR pools that are fully or partially embedded, an earthquake motion that could cause a catastrophic failure, is not likely. However, interaction with adjacent structures and equipment may have to be evaluated to determine the structural capacity on a case by case basis. With respect to cask drop on PWR pools, the residual strength after a drop (see discussion under Available NRC Studies), limitation of structural deformation near the bottom half of the pool, the robustness of the structure all make the catastrophic failure highly unlikely.

For BWR pools, the seismic capacity is likely to be somewhat less than that of a PWR pool and can vary significantly from one plant to another. This is because for BWR pools there is amplification of seismic motion at higher elevation and the pool floor is not supported on the subgrade. Shear failure of the pool floor can occur at a relatively lower level of seismic input for PWR pools. Nevertheless, a combination of the hazard and the spent fuel pool structural capacity can bring down the likelihood of a catastrophic structural failure to a negligible risk. At the same time, plant specific hazard and seismic fragility of spent fuel pools can combine to produce a risk that needs to be examined on a case by case basis.

Using the data from NUREG 1488 (new LLNL data) for currently operating plants in the eastern and central United States, the mean probability of exceedance (POE) of the peak ground acceleration values for the SSE were examined. It was determined that, except for the plants listed below, the POEs are lower than $1X10^{-4}$ per reactor year and for 3 times the SSE, the POEs are below $1X10^{-5}$. For these plants, the likelihood of a catastrophic pool structure failure at a HCLPF value of 3 times the SSE should be less than $5X10^{-7}$. In this approach there is confidence that the seismic hazard is low at the level of 3 time the SSE and there is also a plant specific structural assessment of the HCLPF value is more than or equal to 3 times the SSE. The excepted plants are: H. B. Robinson, McGuire, North Anna, Peach Bottom, Pilgrim, Susquehanna, Three Mile Island, V. C. Summer, Vermont Yankee, Vogtle. At these 10 sites, the POEs are more than $2X10^{-5}$ per reactor year for peak ground accelerations three times the SSE; consequently, the probability of radio active releases following structural failures cannot be considered small without further consideration of zircalloy fire potential given the loss of water inventory and other factors.

Risk Informed Performance Goal

The vulnerability of the structural integrity of spent fuel pools to missiles, aircraft crashes and heavy load drop is negligible. Seismically induced structural failure is also a low frequency event, but there may a combination of hazard and structural failure mode that requires further examination. Realistic seismic fragility evaluations are not available for spent fuel pools for the catastrophic failure state. For robust spent fuel pool structures, it is expected that a catastrophic pool failure is not likely to occur under an earthquake scenario at the level of 3 times the SSE. It is recommended that a risk informed performance goal be set at 3 times the SSE. If a plant meets this goal, emergency planning for seismically induced failure would not be necessary.

Additional Activity

Past evaluation of seismic fragility was based on conservative, rather than realistic assumptions. The failure mode of concern is catastrophic failure of the pool structure such that an instantaneous loss of water will result. Efforts to evaluate the realistic seismic capacity of spent fuel pools should be undertaken by the industry with confirmatory review by the NRC. Through such an effort it is conceivable that a catastrophic failure of pool structures can be eliminated from the risk informed rule making.

Summary

Various scenarios of structural failure of spent fuel pools has been examined and it is recommended that failures induced by aircraft crash, missiles and heavy load drop be eliminated from further consideration under the proposed risk informed rule making for decommissioning. However, for seismically induced failures, a performance goal of 3 times the safe shutdown earthquake as a calculated capacity is recommended.