AGING EFFECTS ON SAFETY MARGINS OF PASSIVE COMPONENTS IN SEISMIC EVENTS

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After the Fukushima accident and the earthquake at North Anna in which the design basis earthquake was exceeded, the results of a review of the adequacy of the design bases for nuclear plants in the central and eastern United States were released with seismic safety receiving increased regulatory attention. Traditionally, seismic probabilistic risk assessment (SPRA) is utilized with best estimate values for material properties of structures, systems, and components (SSCs) without consideration of any aging effects. In order to develop a more realistic evaluation of the seismic safety of a plant, the potential effects of aging of SSCs should be considered, since passive SSCs will degrade over their operational life and this degradation may cause reduction in safety margins. As the lifetime of nuclear plants is extended from 40 years to 60 years, and potentially to 80 years, the effects of aging will increase. Physics-based degradation models are used to examine the change in safety margin as a function of aging based on semi-Markov models for passive SSCs. The methodology is illustrated on the failure of condensate storage tanks (CSTs) in a seismic event. The impact of aging on core damage frequency is assessed within the context of a scenario in a pressurized water reactor involving loss of auxiliary feed-water flow and the failure of safety related equipment as the result of flooding caused by rupture or leakage from the CSTs. The associated impact on seismic risk is assessed over the 60-year lifetime of the plant.

I. INTRODUCTION

The Fukushima Daiichi Nuclear Power Plant, first commissioned in 1971, suffered major damage from the magnitude 9.0 earthquake and tsunami that hit Japan on March 11, 2011 when the plant was 40 years old which is the length of initial operational license given by U.S. Nuclear Regulatory Commission (NRC) for the U.S. plants. When nuclear power plants (NPPs) reach the end of their operating license, they undergo a periodic safety review and an aging assessment of their essential structures, systems and components (SSCs) to extend or renew their license to operate beyond the originally intended service period by conducting an integrated plant assessment. So Fukushima event brings the question into the mind in what degree aging will affect safety margins of the SSCs in case of an earthquake.

Following the Fukushima (and North Anna) events, seismic capacity evaluation has become a crucial issue. In this paper, condensate storage tank (CST) is selected as an example SSC for seismic capacity evaluation since CST is defined as a seismic Class I structure, playing the important role to supply water for the condensate transfer pumps, the control rod drive hydraulic system pumps, the high pressure coolant injection system, reactor core isolation cooling system, core spray system pumps, and the condenser makeup. Failure probability of CSTs should be analyzed in more detail to have realistic seismic margins calculations.

In a previous study[1], dynamic characteristics of a hypothetical seismic scenario in a pressurized water reactor (PWR) involving loss of both auxiliary feed-water trains and the high pressure injection (HPI) system due to a seismically induced CST failure were analyzed. The time-dependent recovery actions of plant personnel to shut down the plant without severe core damage were examined including the implementation of FLEX equipment stored on-site. The potential for delay in recovery actions resulting from the stochastic occurrence of aftershock were modeled and core damage frequency (CDF) was calculated via the traditional seismic probabilistic risk assessment (SPRA) method. In this paper, CDF will be updated with the aging induced failure probability of the CST shell. The probabilistic evolution of the accident sequence is calculated using a semi-Markov approach to model aging of passive component (steam generator tubes and pressurizer surge line pipe) degradation with discrete states and time dependent transition rates[2]. The results indicate that semi-Markov model can accurately represents physics-based characteristics of aging [3].

Section 2 presents the accident scenario being addressed involving failure of CST. Section 3 describes the semi-Markov model, and the fragility curves of the CST at different years. Seismic fragility is defined as the conditional failure probability of SSCs for a given level of peak ground acceleration. Degradation will cause shift in the fragility curve of the CST with subsequent impact on the SPRA. Section 4 presents the conclusions of the study.

II. ACCIDENT SCNEARIO

For this study, potentially significant seismically-induced accident sequences for a generic PWR have been screened and seismically-induced loss of offsite power (LOOP) event has been selected in which CSTs, power operated relief valves (PORVs) and feed and bleed have failed[1]. This sequence also includes flooding of components from the failure of CSTs. Before describing the accident scenario in detail, risk importance of the CSTs will be highlighted in Section II.A.

II.A. Risk Importance of the CSTs

The CST is a flat-bottom cylindrical tank filled with water and under atmospheric pressure. CST volume capacity can vary from plant to plant. Dominant failure modes for CSTs are buckling with anchor bolt yielding[4] and sliding[5]. Reference 4 indicates that CST is one of the high contributors (17.7%) to a seismic core damage of the plant. Studies show that[4] CST failure leads to loss of secondary heat removal. For this reason it is essential that CSTs remains operational when an earthquake occurs.

II.B. Seismic PRA Model and the Assumptions

The generic PWR under consideration has two trains of diverse auxiliary feed-water (AFW) for which water is supplied from redundant CSTs. The CSTs are located in a building adjacent to the auxiliary building. It is assumed that failure mode of the CST is the result of a failure of the bolts fastening the CST to the floor. There are two 8" diameter feed-water lines (suction pipes) exiting the bottom of each CST. The load imposed on the piping associated with motion of the tank results in failure of the one or more of the lines. Equal probability is assigned to the leak size associated with 0.5 *Ap,* 1 *Ap*, 1.5 *Ap* and 2 *Ap*, where *Ap* is the cross sectional area of a pipe. In the previous stuidy[1], the median acceleration (A_m=1.0g) was selected for failure of the CST with lognormal standard deviation (β_c=0.4), and correlation (ρ=0.5) between the failure of the two tanks. Table I shows the spectral accelerations associated with the design basis acceleration and the three return frequencies analyzed, the probability of failure of one of the tanks, Pr(A) and the probability of failure of both tanks, Pr(AB).

TABLE I. Spectral Accelerations and Failure Probabilities for CST Failure by Pipe Rupture
(A_m=1, β_c =0.4, ρ=0.5)[1]

Exceedance Frequency (yr^{-1})	Spectral Acceleration (5 Hz)	Pr (A)	Pr(AB)
1E-4	0.17	4.7E-6	Negligible
3E-5	0.32	2.2E-3	1.6E-4
1E-5	0.6	0.10	3.3E-2

II.C. Accident Scenario and CST in the Seismic PRA Model

Seismically-induced LOOP scenario is selected in which the seismic event leads to failure of one or both of the CSTs. Failure of both CSTs would result in the loss of the water source for AFW and ability to remove heat from the primary system of the PWR.

For the integration of aging CST failure in the PRA, fault trees from NRC's AFW system fault tree Design Class 2[6] are modified to include seismic faults in the front line and support systems in fault trees and also to include failure of passive structures and components such as fire door between the pump rooms which can lead loss of HPI pumps due to flooding. The seismically-induced failures are included in the fault trees as House events which are condition dependent basic events. These "fragility basic events" will then appear in the minimum cutsets and thus indicate which combinations of seismic induced failures would lead to core damage. The CST suction failure (basic event) is modified as the union of random tank failure and seismically-induced CST suction failure (either outlet pipe failure or tank failure) (see Fig. 1)[1]. Core damage frequencies are calculated as 8.9E-8, 5.1E-7 and 6.2E-7 for three return frequencies (3E-5/yr, 1E-5/yr and 1E-6/yr) respectively.

Focus of this paper is the modification of the CST tank failure probabilities in the previously built fault trees of Ref. 1. CST degraded tank shell failure probabilities calculated at 20, 40, 60 years are incorporated into the "CST Tank Failure due to Seismic Event" box in Fig.1 to show sensitivity of the CDF to CST degradation. Comparison of Ref. 1 CDF with the updated failure probabilities will be done only for the 1E-5/yr frequency.

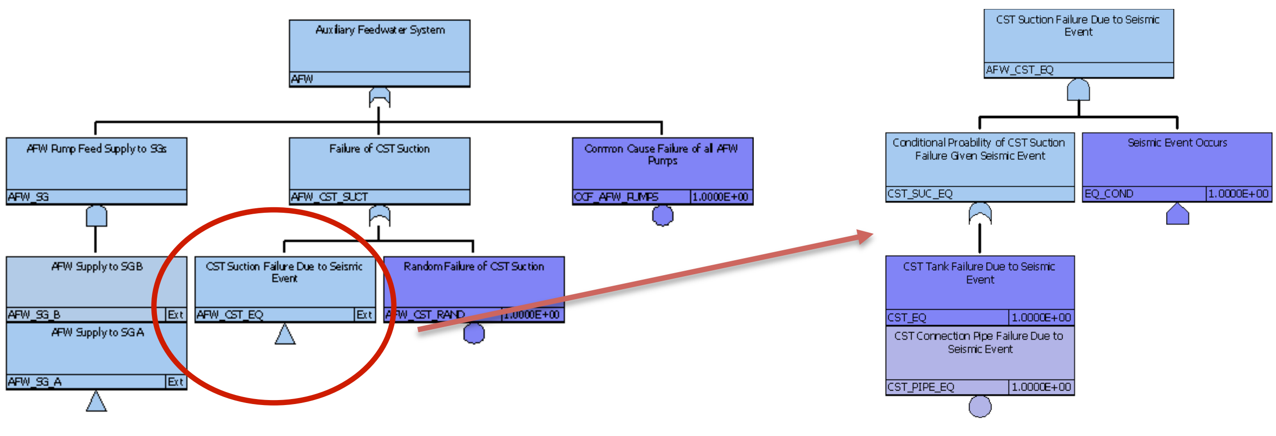

Fig. 1. CST suction failure due to seismic event

III. ANALYSIS

Section III.A describes the semi-Markov model used for the assessment of aging effects. Section III.B describes the seismic analysis using the results obtained from the semi-Markov model.

III.A. Semi-Markov model for the degradation of CST Shell

The failure process of CST tank shell is treated as a stochastic process in this paper. The semi-Markov model is implemented for quantitative degradation modeling and is used to set up a set of first order differential equations whose solution provides the time-dependent probabilities of occupying states of the model. Initial state assumes that both CSTs and HPI pumps have no degradation and pumps are totally dry (See Fig.2).

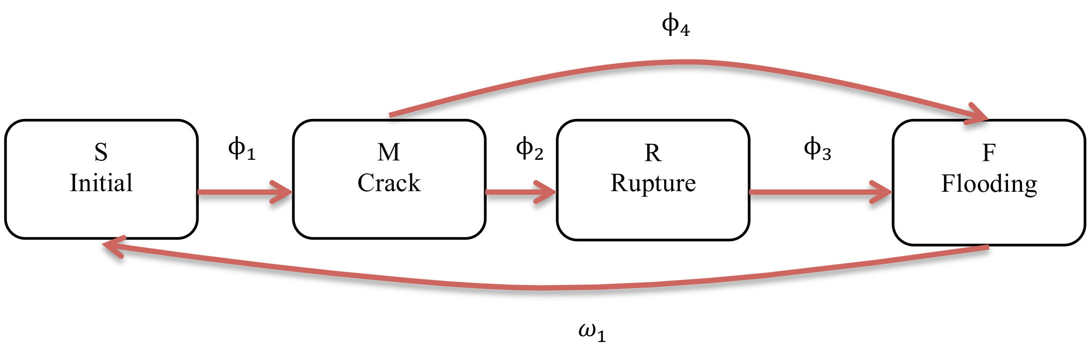

Fig. 2. Markov Model Representation of the Accident Sequence

In Fig.2, The transition rate ϕ_1 from initial state *S* to micro-crack state *M* is represents crack initiation and defined as Weibull distribution. The ϕ_2 represents rack growth and is selected as the numerical model of stress corrosion cracking of CST (304 stainless steel) in 288 C water with the minimum number of parameters is developed by Ref. 8. Tank SCC crack growth rate (m/s) is described as:

$$\frac{da}{dt} = 1.1\times10^{-7}\left[2.5\times10^{10}\exp\left(-\frac{3-0.15(K-9)^{\frac{1}{3}}}{0.0774}\right)\right]^{n} \qquad (1)$$

where $a(t)$ is the crack size at time t and K is the applied stress intensity factor. The exponent n is chosen as 0.87 based on the recommended ranges for parameters[8]. K is calculated as 12,018 MPa$\sqrt{m}$ with the assumption of crack length as the twice of the tank shell thicknesses[9]. These assumptions lead to 0.0075 in/yr growth rate which is the maximum crack growth rate and limit rate for the rupture state. Based on this rate, CST shell thickness will be decreased to 0.175 in from the initial value of 0.625 in at the end of 60 years. Flood propagation data calculated via a seismic flooding model[1] are used to estimate transitions between CST failure, tank rupture (R state in Fig.2), and high pressure injection pumps failure states, flooding (F state in Fig.2). In Fig.2, ω_1 is the repair transition from flooding to initial state, which depends on the timing of failure associated with the flooding of HPI pumps and the subsequent dry out of the HPI pump rooms Flooding probabilities are calculated and used as data for the seismically-induced flooding basic events in Fig.1.

III.B. Seismic Analysis

III.B.1. Hazard Curve

The primary vibrational mode of the CSTs is assessed to be approximately 5 Hz. Figure 3 shows the 5 Hz seismic hazard curve describing the relationship between return period and the peak acceleration at a vibrational frequency of 5 Hz[10].

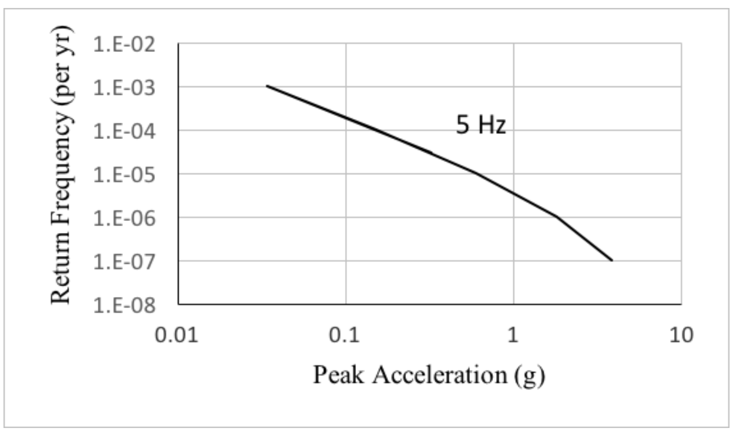

Fig. 3. Peak Acceleration versus Return Frequency at Vibrational Frequency of 5 Hz[4]

III.B.2. Fragility Analysis

Seismic fragility of CST represents resistance capacity of the tank to a ground motion level (peak ground acceleration, peak ground velocity, etc.). This capacity is mostly represented by a median capacity (A_m) and high confidence low probability of failure (HCLPF) capacity with uncertainties.

The seismic fragility of a degraded SSC with the given level of uncertainty and given level of ground acceleration is defined as in Eq. 2.

$$F_{mean}(a,t) = \phi\left[\frac{ln\left(\frac{a}{A_m(t)}\right)}{\beta_c(t)}\right] \quad (2)$$

$$\beta_c(t) = \sqrt{\beta_R(t)^2 + \beta_U(t)^2} \quad (3)$$

where ϕ denotes the cumulative normal distribution with time dependent median A_m and composite logarithmic standard deviation of β_c. In Eq. 3, β_R and β_U are logarithmic standard deviations associated with the aleatory and epistemic uncertainties, respectively. In practice, the values for β_R and β_U are primarily based on expert elicitation and the value of A_m is based on shaker table tests. HCLPF can be expressed as:

$$HCLPF(t) = A_m(\mathrm{t})\exp\left(-1.65\left(\beta_R(t) + \beta_U(t)\right)\right) \quad (4)$$

Degradation will impact fragility of the SSC due to impact on the median capacity (decrease with age) and also impact of uncertainties (uncertainty will increase with age). Fragility curves are calculated at specified time points (0, 20, 40 60 years) and $\beta_c(t)$ is assumed constant. Figure 3 indicates that, with age, CST shell capacity to resist PGA is decreased considerably especially for the low peak ground acceleration (PGA) values. To investigate the effect of the seismic capacity of the CSTs on the frequency of a seismic core damage of the plant, seismic PRA is performed.

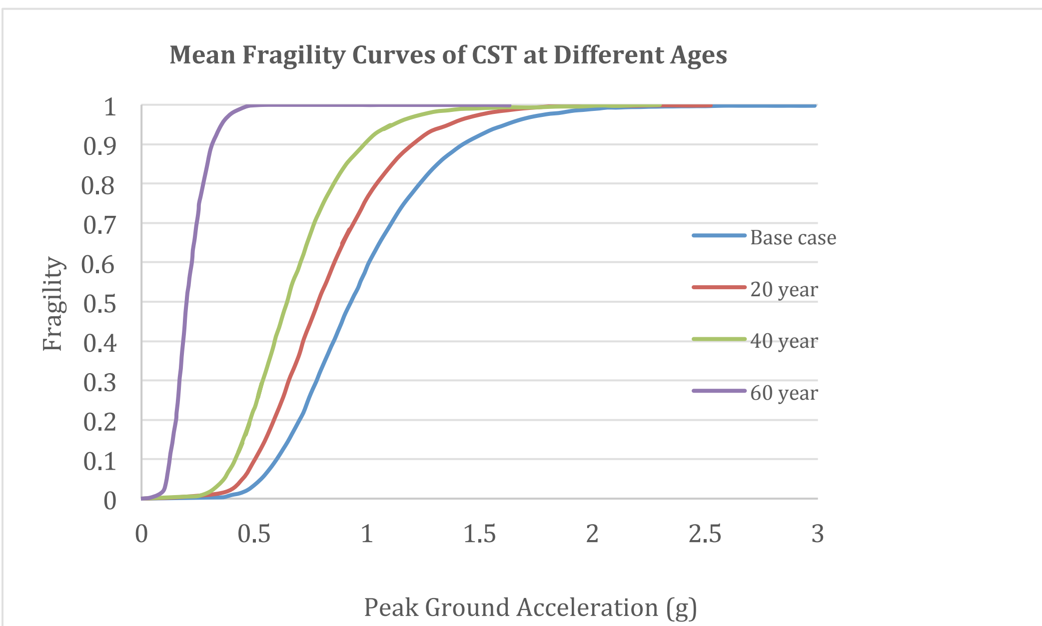

Fig. 3. CST Mean Fragility Curves at 0, 20,40, 60 years

Analysis using the fragilities curves for 20, 40, 60 years to in Fig.3 was performed to evaluate CDFs due to the effects of seismicallly-induced failures or the combined effects of their failures with a LOOP event (CDF_{LOOP}). Table II provides the overall conditional core damage probabilities and the overall frequencies for the return frequency of 1E-5.

TABLE II. Results of Analysis for 1E-5/yr Return Frequency

Year	Conditional Core Damage Probability	CDF_{LOOP} (yr^{-1})	Increase of CDF_{LOOP} (%)
0	0.051	5.1E-7	-
20	0.091	6.3E-7	7.5
40	0.12	1.2E-6	12
60	0.49	4.9.E-6	49

In addition, when the CST seismic capacity decreased, the CDF due to LOOP will increase considerably. In Fig.3 it can be seen that for 60 year fragility is reduced 67.8% since at 1g fragility (conditional failure probability) is around 0.59 or the base case but is approximately 0.99 for the 60 year case. The degradation effects on the other components in the accident scenario such as electrical cabinets on the CDF are not considered.

IV. CONCLUSIONS

Fragility curves represent the probability of structural damage due to various ground motions. In this paper, aging effect on seismic fragility of CSTs was investigated via a semi-Markov model using a generic PWR PRA. Age dependent fragility curves showed remarkable decrease in seismic capacity with aging with subsequent impacts on CDF_{LOOP}.

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