Analysis of Possible Aging Trends in the Estimation of Piping System Failure Rates for Internal Flooding PRA

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Abstract: The Electric Power Research Institute (EPRI) has been sponsoring projects for the development of guidance and tools for the performance of nuclear power plant PRAs including internal flooding PRAs (IFPRAs). The latter requires estimates of internal flood initiating event frequencies. Failures and ruptures in piping systems as well as maintenance induced flooding are key contributors to flood-induced initiating event frequencies. Beginning in 2004, EPRI has published a series of reports on piping system failure rates and rupture frequencies to support IFPRA. Since the completion of the initial work there have been four major revisions that address new operating experience data as well as methodological refinements. An insight from this effort is that there is evidence of aging as manifested by progressively increasing failure rates as more recent experience is incorporated. For the raw water piping systems (e.g. circulating water and service water systems) the analyses imply increasing trends in failure rate estimates from 2004, to 2010, and 2015. The purpose of this paper is to describe the efforts in this EPRI research program to evaluate aging effects in piping systems outside the containment and to enhance the capability to address these aging effects in future internal flooding PRAs.

Keywords: IFPRA, Initiating Event Frequencies, Temporal Trend, Piping System Failure Rates.

1. INTRODUCTION

EPRI has sponsored projects provide guidance and data to support internal flooding PRAs (IFPRAs). Failures and ruptures in piping systems as well as maintenance induced flooding are key contributors to flood-induced initiating event frequencies. Since 2004 a series of reports have been published that provide piping system failure rates and rupture frequencies to support IFPRA; References [1] though [6]. The goal of these reports is to assist nuclear power plant owners in meeting the requirements of the ASME/ANS PRA Standard [7] in the performance of internal flood PRAs (IFPRAs). To date, there have been three major revisions to the pipe failure rate database to cover an increasing scope of piping systems and progressively greater amounts of operating experience. Another report was developed to address corrosion resistant stainless steel piping that is currently being used to replace aging carbon steel pipes in service water systems. This fact alone provides evidence of aging, i.e. service induced degradation that reduces the effective service life of these components.

A fourth revision to the pipe failure database is currently being prepared and is expected to be published in the latter part of 2018. A primary objective of the current project is to address the effects of temporal trends in piping system performance including the effects of plant aging on piping system failure rates. The piping systems of interest are those within the scope of IFPRAs as well as PRAs for high energy line breaks. In each of the successive updates of the failure rate reports (2004 to 2013), the frequency of pipe failures has been observed to increase as the current fleet of operating nuclear power plants in the U.S. continues to age. However to date the only step taken to address temporal trends is to recalculate the average failure rates periodically. This practice was accepted because initially the changes in the average failure rates were small. In the fourth report revision a more direct approach to address aging is pursued.

2. TECHNICAL APPROACH

The technical approach that is being used in the EPRI IFPRA pipe failure rate studies originates from the EPRI methodology for developing risk-informed in-service inspection (RI-ISI) programs. The RI-ISI methodology for pipe failure probability estimation has been modified to specifically support the estimation of flood-induced initiating event frequencies for IFPRAs. The key elements of the approach are summarized as follows:

- A simple model is used to express pipe rupture frequencies as the product of a pipe failure rate and a conditional rupture probability (CRP) which varies with the size of the rupture. Failures are defined as any event that results in the need for repair or replacement of the affected pipe component. These include non-through wall defects, cracks, leaks and major structural failures that are realized as pipe ruptures.
- The model assumes that each pipe failure is a precursor to a pipe rupture.
- A Bayes method is used to characterize uncertainty in the pipe failure rates and in the CRPs; Bayes' prior distributions, based on expert judgment and informed by insights from review of service data, are updated using actual service experience with pipe failures and ruptures.
- The underlying service experience used in the failure rate estimates is documented in a comprehensive pipe operating experience database, known as PIPExp [8].
- Homogenous pipe component populations are defined to analyze the failure and exposure data into to data cells that isolate the key factors that influence pipe failure potential. This provides the capability to address pipe failures in many different systems that have different process fluids, service conditions, pipe sizes, pipe materials, and other factors that influence pipe failure and degradation mechanisms.
- Rupture frequency estimates may be adjusted to account for reliability integrity management (RIM) programs in which surveillance procedures for leak detection and non-destructive examinations are applied to reduce the potential for pipe rupture using a Markov model. This tool enables the user to define risk management strategies to reduce the likelihood of major pipe ruptures that may be found as risk significant in an IFPRA or high-energy line break (HELB) PRA.
- The approach produces a library of pipe failure rate and rupture frequencies for each piping system and pipe size within the scope of an IFPRA as well as PRAs for high energy line breaks. The focus of this effort has been the piping systems outside the containment in operating U.S. pressurized water reactors (PWRs) and boiling water reactors (BWRs), however the resulting generic database has also been useful to support PRAs of advanced reactors and other plants being designed and licensed.

3. EVALUATION OF AGING EFFECTS

The opportunity to identify and evaluate the effects of aging on pipe failure rates has been afforded by two important factors associated with the EPRI project. The first is EPRI's commitment to sponsor the analysis of pipe failure experience over a long period of time. As the fourth major update of the failure rate report is completed it has been twelve years since the first report was issued [1]. The second is the availability of a comprehensive pipe experience database which has been continuously maintained and updated since 1993 and in support of numerous national and international piping reliability analysis projects as well as the EPRI IFPRA reports. With the benefit of using the same methodology and living database to evaluate pipe failure rates over this time period, the opportunity to observe trends in the failure data has presented itself.

As seen in Figure 1 the frequency of service water system pipe failures has exhibited a distinct trend over the lifetime of the operating fleet of PWRs and BWRs in the U.S. For the first 20 years of plant life, the frequency of pipe failures in this system is seemed to be fairly constant. The failure frequency appears to be significantly higher in the next ten years of plant age and in the 4th decade the failure frequency is even higher.

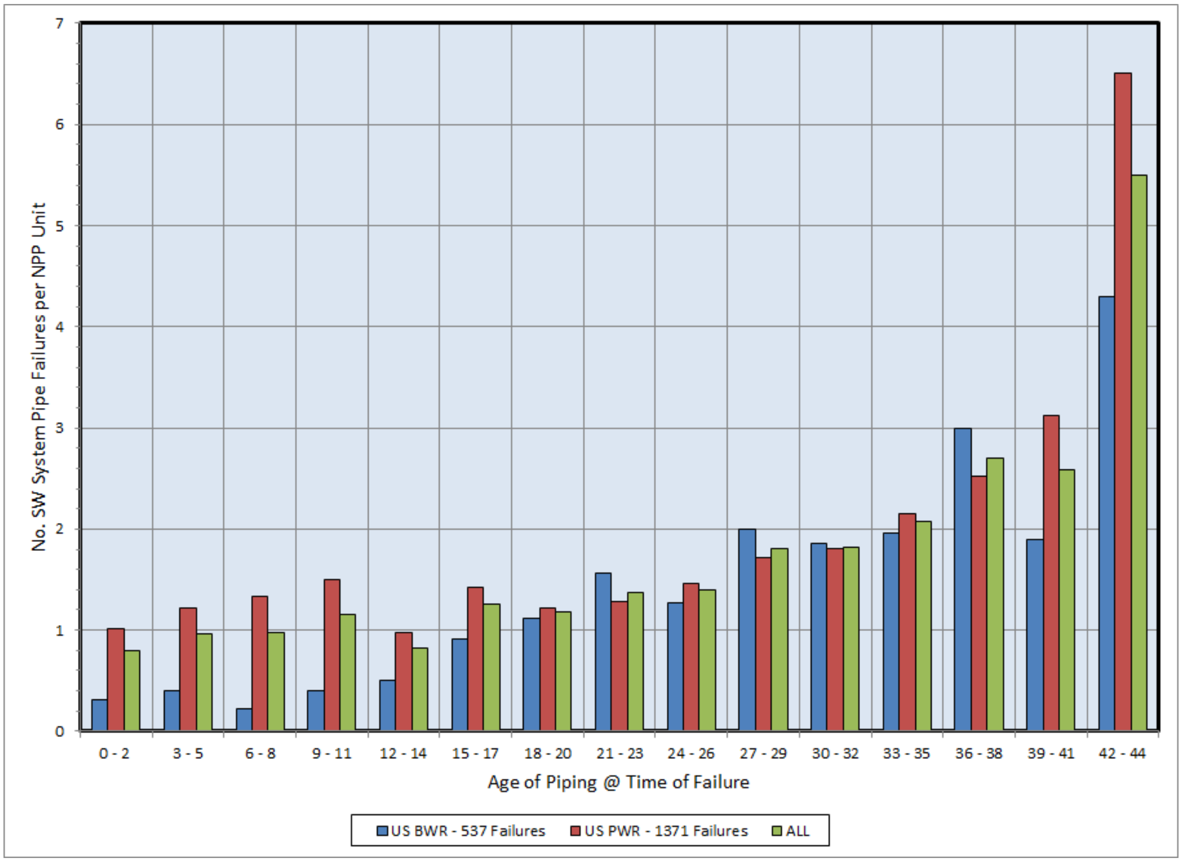

Figure 1: Frequency of Service Water Pipe Failure versus Plant Age

When the current 4th revision to the EPRI IFPRA pipe failure database is published in 2018, an approach to quantifying the effects of plant age on the pipe failure rates will be finalized and implemented that is intended to meet current industry PRA standards [7]. The previous revisions to the database resulted in failure rate estimates that were averaged over various time periods. Currently some preliminary "coarse cut" results are available for review that permits a rough estimate of age dependent failure rates.

4. PRELIMINARY RESULTS FOR AGE DEPENDENT FAILURE RATES

One of the systems with the potential of producing flood sources for flood-induced initiating events in an IFPRA is the essential service water system. As a safety related system outside the containment, this system is normally designed and operated as an ASME Class 3 system. This is of interest in IFPRA because service water system piping is found in many flood areas within the plant, its loss of function can cause the functional unavailability of many front line safety systems as well as a flood induced initiating event, and the system has the potential to deliver large flood rates and flood volumes as a result of a pipe rupture. The EPRI IFPRA failure rate data reports provide 6 sets of failure rate data for ASME Class 3 service water systems. These cover two reactor types, PWR and BWR, and three types of ultimate heat sink fluid: river water, lake water, and sea or brackish water. For each of these 6 sets of data, separate failure rate estimates are provided for four different nominal pipe size (NPS) ranges: less than 2", 2" to 4", 4" to 10", and greater than 10". The last category typically includes 12" and 24" pipe sizes. In the following, the failure rates and rupture frequencies for NPS24 PWR Service Water pipe in a sea water environment is used as an example to examine the effects of aging; Table 1 and Figure 2.

Table 1: NPS 24" Pipe Rupture and Flood Mode Frequencies (1970–2015 Data)

Flow rate[3] [gpm]	EBS (in.)	Cumulative Frequency[2] [1/ROY-ft.]		Flood Rate Interval [gpm]	Interval Frequency [1/ROY-ft.]	
		Mean	RF[1]		Mean	RF[1]
0.25	0.032	4.91E-06	1.7	1-50	1.64E-06	5.0
1	0.063	1.78E-06	2.2	50-100	4.14E-08	5.7
3	0.10	9.12E-07	2.6	100-250	3.63E-08	6.8
25	0.32	1.97E-07	4.3	250-500	1.33E-08	7.4
50	0.45	1.38E-07	5.0	500-1,000	1.04E-08	8.1
100	0.63	9.65E-08	5.7	1,000-2,000	8.06E-09	8.8
200	0.89	6.75E-08	6.5	2,000-10,000	1.40E-08	11.4
250	1.00	6.01E-08	6.8	10,000-100,000	1.06E-08	18.6
500	1.41	4.69E-08	7.4	100,000-288,186	3.88E-09	31.00
1,000	2.00	3.65E-08	8.1			
1,500	2.45	3.16E-08	8.5			
2,000	2.83	2.85E-08	8.8			
2,500	3.16	2.63E-08	9.1			
2,502	3.16	2.62E-08	9.1			
8,005	5.66	1.59E-08	11.0			
10,000	6.32	1.44E-08	11.4			
25,016	10.00	9.72E-09	13.3			
50,000	14.14	6.14E-09	15.8			
72,046	16.97	4.82E-09	17.2			
100,000	19.99	3.88E-09	18.6			
250,161	31.62	2.11E-09	23.3			
288,186	33.94	1.03E-09	31.0			

1. RF = $(95^{th}\text{-tile}/5^{th}\text{-tile})^{0.5}$; these distributions can be approximated as lognormal distributions with the indicated mean and the calculated range factor (RF).
2. Frequency of pipe rupture with EBS equal to or greater than indicated value. The equivalent break size of a double ended guillotine break of a 24" pipe is 33.94 inch.
3. Flow rate calculated for system pressure of 70 psig. The maximum flow rate from a 24" pipe due to a double ended break is approximately 288,186 gpm

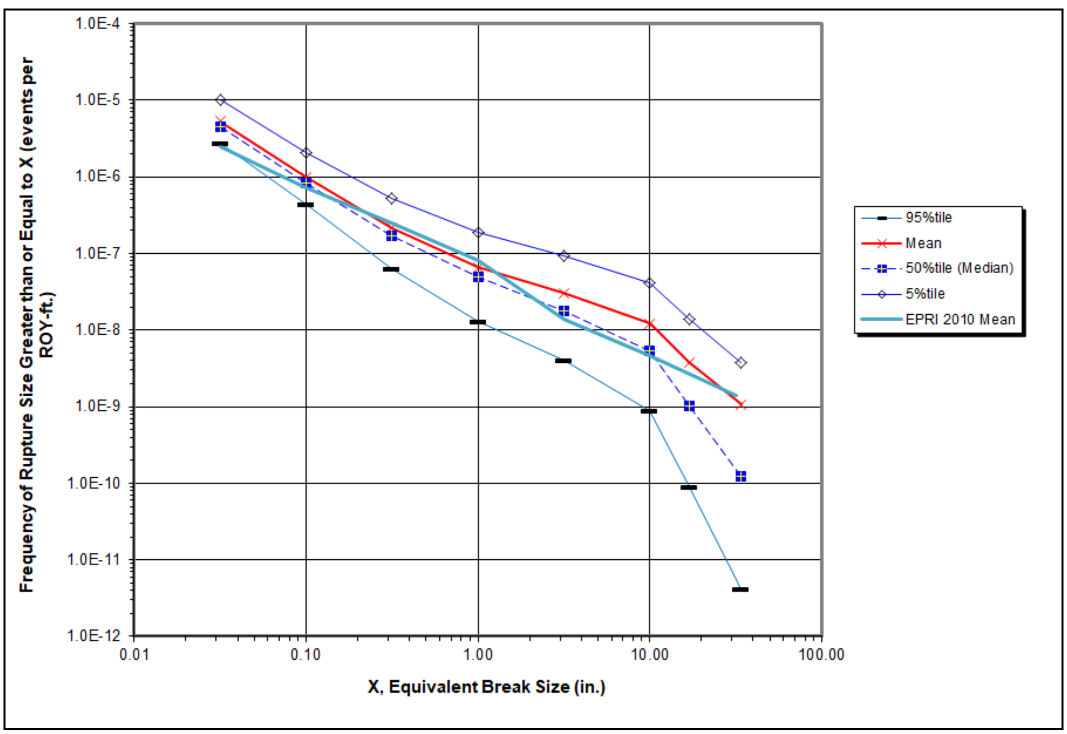

Figure 2: Cumulative Pipe Rupture for NPS24 Service Water Pipe

Revision 4 of the IFPRA pipe failure rate report is based on service data from 1970 through 2015. For the PWR Sea service water case this covers about 2,600 reactor operating years (ROYs) of data with U.S. PWR plants using sea or brackish water for the service water fluid. For use in IFPRA, pipe failure rates are developed on a per-linear-foot-of-piping basis. This data set is supported by more than 4 million feet-years of service experience during which 131 large-diameter pipe failures were observed.

5. TEMPORAL TRENDS IN PIPE FAILURE RATES & RUPTURE FREQUENCIES

Age-dependent pipe failure rate estimation can be performed according to different analysis strategies to obtain piping reliability parameters as function of the age of an affected pipe section at the time of its observed failure, or as a function of the temporal changes in the piping operating experience. An example of the latter analysis strategy is to calculate the pipe failure rate for different time periods that correspond to the different revisions of the EPRI 'pipe rupture frequency' reports. The service data periods covered by the EPRI Report Revisions are as follows:

- Period 1 (P1): 1/1/1970 through 12/31/2004 (Revision 1)
- Period 2a (P2a): 1/1/2005 through 3/31/2009 (Revision 2 for certain systems, refer to Table 2 for details on the scope of the pipe failure rate estimation)
- Period 2b (P2b): 1/1/2005 through 3/31/2010 (Revision 2 for certain systems)
- Period 3a (P3a): 4/1/2009 through 12/31/2015 (Revision 4 for certain systems)
- Period 3b (P3b): 4/1/2010 through 12/31/2015 (Revision 4 for certain systems)
- Period 4 (P4): 1/1/1970 through 12/31/2015 (Revision 4)

Failure rate estimates in Revision 2 were based on the combined Periods 1 and 2a/2b. Therefore, in the previously published estimates (Table 2) the effects of temporal trends in the failure rates were partially obscured by the averaging process.

Table 2: The Scope of the Different EPRI IFPRA Report Revisions (pre-Revision 4)

System	Reactor Type Cases	Type Cases	Safety Class Cases	Nominal Pipe Size [inch] Cases	Operating Experience Data Period
Service Water	BWR, PWR	River, lake, sea	ASME Class 3 & non-safety	2, 4, 10, 24	1/1/70-3/31/09
Fire Protection Water System	All	With & w/o WH protection	NFPA (Class 3)	4, 6, > 6	1/1/70-3/31/09
ECC outside containment	All	N/A	ASME Class 3	4, 10, 24	1/1/70-3/31/10
CCW and CST	All	N/A	Non-safety	24	1/1/70-3/31/10
FWC outside containment	BWR	N/A	Non-safety	10, 24	1/1/88-3/31/09
	PWR	N/A	Non-safety	10, 24	1/1/88-12/31/08
High Pressure Steam in Turbine Building	BWR	N/A	Non-safety	10, 24	1/1/88-3/31/09
	PWR	N/A	Non-safety	10, 24	1/1/88-12/31/08
Low Pressure Steam in Turbine Building	BWR	N/A	Non-safety	10, 24	1/1/88-3/31/09
	PWR	N/A	Non-safety	10, 24	1/1/88-12/31/08
Extraction Steam	BWR	N/A	Non-safety	10, 24	1/1/88-3/31/09
	PWR	N/A	Non-safety	10, 24	1/1/88-12/31/08
Circulating Water	All	Piping	Non-safety	> 30"	1/1/70-3/31/10
		Expansion joints	Non-safety		1/1/70-12/31/04

CCW = Component Cooling
CST = Condensate Storage
ECC = Emergency Core Cooling
WH = Water Hammer
NFPA = National Fire Protection Association

In Revision 4 of the EPRI 'pipe rupture frequency' report the assessment of age-dependent pipe failure rates is preceded by a screening analysis to determine presence of negative or positive aging trends. A 'temporal change factor' (TCF) is calculated as:

$$TCF = \lambda_{(P1+n)} / \lambda_{P1} \quad (1)$$

The temporal change factor accounts for aging, data completeness, and changes in the reporting processes. Some significant plant-to-plant variability exists in the piping operating experience. An interpretation of the screening results is included in Table 3.

Table 3: Temporal Change Screening Guideline

TCF	Period(s)	Interpretation	Impact on Pipe Failure Rates & Rupture Frequency Calculations
< 1	P2, P3, P4	Effective flow-accelerated corrosion (FAC) aging management. No significant trend change anticipated beyond 2015. FAC-free piping performance is achievable.	Applies to FAC-susceptible steam cycle piping systems. Extensive operating experience data available. Most FAC-susceptible piping systems have been replaced with material that is resistant to flow-assisted wall thinning. Simple update; average across chosen time period.
> 1 but < 2	All	No adverse trend in operating experience.	Insufficient data to support aging factor assessments. Alternatively, existing aging management programs sufficiently effective to prevent adverse trends. Simple update; average across chosen time period
> 2	P2 & P3 or All	Indicative of aging of raw water piping systems; CW, FP and SW systems	Results of formal aging factor assessment could be factored into failure rate calculations.

Period 1 is the same data collection period that was used in Revisions 0 and 1 of the failure rate reports. Failure rate estimates in Revisions 2 and 3 were based on the combined Periods 1 and 2, and Revision 4 estimates provided in the previous section based on the combined Periods 1, 2, and 3. Hence in the previously published estimates the effects of temporal trends in the failure rates were partially obscured by the averaging process. In the following the failure rates based on the service data in each of the time periods are examined separately to coarsely identify trends. The service data evaluated in this manner includes the reactor years of exposure as well as the failure counts in each of the applicable pipe size categories. This analysis was done for each of the six Class 3 service water data sets covering two reactor types (PWR and BWR) and three sources of service water (Sea, Lake, and River).

Trends in the failure rates for Class 3 PWR Sea Service Water piping are shown in Figure 3. For each of the applicable 4 pipe sizes, there are clear increasing trends in the estimated failure rates for the three time periods. These time periods are correlated to increases in the average plant ages ranging from about 27 years in Period 1 to 37 years in Period 3. The primary factor responsible for these trends is judged to be aging effects. This is consistent with the fact that plants that are approaching or are have entered into an extended period of operation (> 40 years) have begun to back-fit original carbon steel service water pipe with pipes made of corrosion resistant steels and non-metallic materials.

There are other factors that may contribute to the observed increases besides aging. These include changes in inspection and reporting practices, implementation of the maintenance rule, and the fact that the operating experience database has been undergoing a continual update process. Many of the changes in inspection and reporting practice were confined to Period 1 but changes that occurred over that thirty year period may have indeed tended to suppress the calculated average failure rates during those periods.

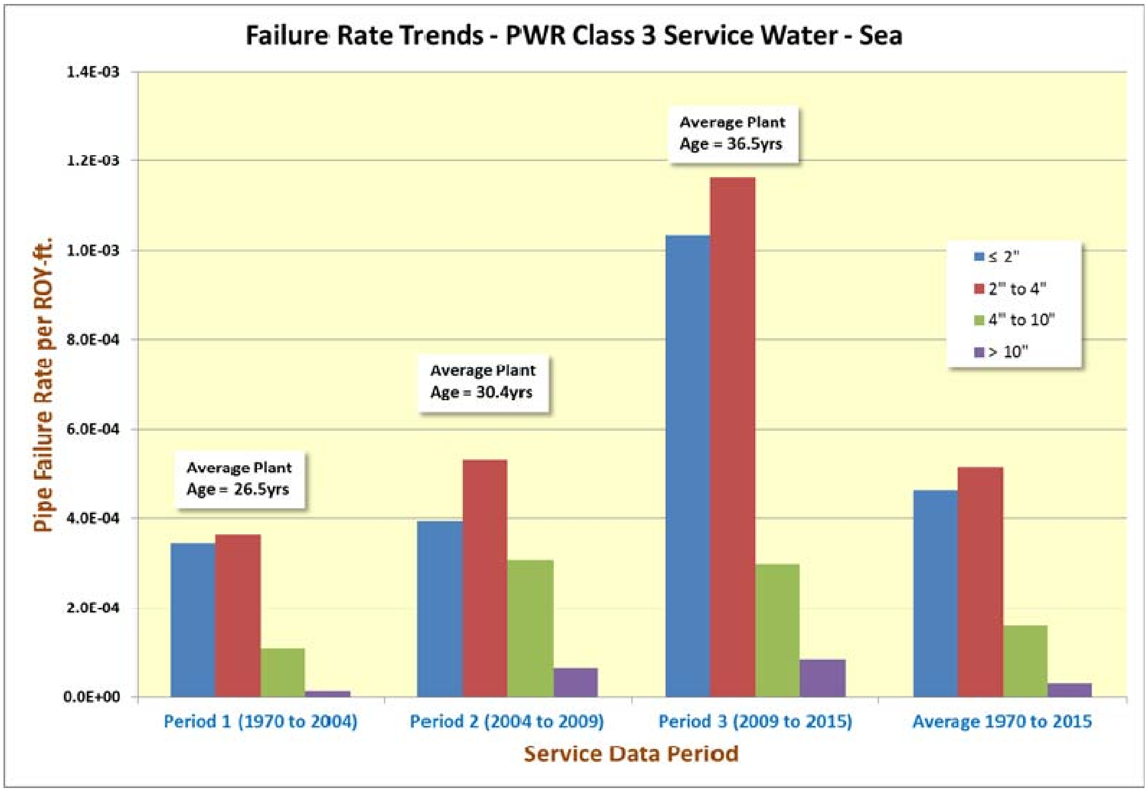

Figure 3: Trends in Pipe Failure Rates over Three Contiguous Time Periods

In order to make a coarse adjustment to the baseline flood frequencies to account for aging effects, the adjustment factors in Table 4 should be applied. These factors are applicable to the baseline flood frequencies presented either as frequency vs. break size, frequency vs. flood rate, or frequency of flood modes. An example application of the factors to the frequency of flood rate intervals for NPS24 Class 3 PWR Sea Water pipe is shown in Table 5.

Table 4: Adjustment Factors for Mean Flood Frequencies

Pipe Size	Plant Age 20 years or less	Plant Age 20 to 30 years	Plant Age more than 30 years
	Use Data Period 1 (1970 to 2004)	Use Data Period 2 (2004 to 2009)	Use Data Period 3 (2009 to 2015)
	Multiply Revision 4 Base Line Mean Flood Frequencies by		
≤ 2"	0.74	0.85	2.23
2" to 4"	0.71	1.03	2.25
4" to 10"	0.67	1.90	1.84
> 10"	0.42	2.14	2.77

Table 5: Age Dependent Mean Flood Frequencies

Flood Rate Interval	Mean Frequency [1/ROY-ft.]				
	Plant Age 20 years or less	Plant Age 20 to 30 years	Plant Age more than 30 years	Baseline Frequencies 1970-2015 Data	
				Mean	RF
1-50	6.92E-07	3.52E-06	4.56E-06	1.64E-06	5.0
50-100	1.74E-08	8.87E-08	1.15E-07	4.14E-08	5.7
100-250	1.53E-08	7.78E-08	1.01E-07	3.63E-08	6.8
250-500	5.59E-09	2.84E-08	3.68E-08	1.33E-08	7.4
500-1,000	4.36E-09	2.22E-08	2.87E-08	1.04E-08	8.1

Flood Rate Interval	Mean Frequency [1/ROY-ft.]				
	Plant Age 20 years or less	Plant Age 20 to 30 years	Plant Age more than 30 years	Baseline Frequencies 1970-2015 Data	
				Mean	RF
1,000-2,000	3.39E-09	1.73E-08	2.24E-08	8.06E-09	8.8
2,000-10,000	5.90E-09	3.00E-08	3.89E-08	1.40E-08	11.4
10,000-100,000	4.44E-09	2.26E-08	2.93E-08	1.06E-08	18.6
100,000-288,186[2]	1.63E-09	8.31E-09	1.08E-08	3.88E-09	31.0

6. CONCLUSION

The opportunity to identify and evaluate temporal trends on pipe failure rates has been afforded by a long term commitment by EPRI to support ongoing IFPRAs in the utility industry and the availability of a comprehensive operating experience database and its continual updating since 1993. Significant increases in pipe failure rates have been identified based on service data in three contiguous time periods from 1970 near the beginning of the US nuclear fleet experience and 2015 as most of the U.S, plants reach the end of their initial design life and as many have entered an extended period of operation. The primary factor contributing to these trends is aging due to service induced degradation mechanisms. The next challenge for the project will be the task of introducing age dependent pipe failure rates into PRA updates and upgrades.

Acknowledgements

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