Sensitivity Analysis of Internal Flooding Probabilistic Risk Assessment Considering Recent Pipe Rupture Frequencies and Aging factors in the Fire Protection and Service Water Systems of an APR1400 Nuclear Power Plant

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1. Introduction

Probabilistic Risk Assessments (PRAs) are used in day-to-day decisions in design, operations, and maintenance and to support risk-informed applications to the Nuclear Regulatory Commission (NRC) for beneficial changes to plant operations[1]. PRAs can be typically categorized into Level 1, Level 2, and Level 3 analyses, as well as into internal and external event assessments. Among these, internal flood events can be a significant contributors to the risk profile at nuclear plants.

Internal flooding probabilistic risk assessment(IFPRA) is conducted to meet ASME/ANS PRA standard(2009)[2], incorporating pipe rupture frequencies for IFPRA(Rev.3)[3] as a part of the PRA in APR1400 nuclear power plant(NPP). Recently, the updated pipe rupture frequencies for IFPRA(Rev.5)[4] was released in 2023.

In this study, a sensitivity analysis of the Core Damage Frequency(CDF) was performed to evaluate the impact of updated pipe rupture frequencies and aging factors in the fire protection system and service water system.

2. Methods and Results

This section presents a summary of the results for the updated mean cumulative pipe rupture frequencies and the aging factors in the fire protection system and the service water systems.

2.1 The Mean cumulative pipe rupture frequencies

The pipe rupture frequencies used for the IFPRA including a summary of the mean cumulative pipe rupture frequencies in the fire protection and service water systems, are presented in the table I and II below.

Table I. Summary of results for fire protection system mean cumulative pipe rupture frequencies versus break size[4]

EBS[1)]	Pipe Diameter(in)		
	0 to 4	>4 to 6	>6 to 24
	CRF[2)] per Reactor Operating Year-Linear Foot		
0.032	1.66E-05	1.21E-05	8.36E-05
0.10	2.69E-06	9.69E-06	1.78E-05
0.316	1.35E-06	5.50E-06	1.67E-06
1.00	3.94E-07	2.16E-07	1.41E-06
3.16	1.56E-07	8.94E-08	7.58E-07
5.66	1.04E-07		

1) Equivalent Break Size(in)
2) Cumulative Rupture Frequency

The fire protection flood mode frequencies generally reduced in this revision, except for small pipe spray, which saw a slight increase[4]

Table II. Summary of results for service water system mean cumulative pipe rupture frequencies versus break size[4]

EBS[1)]	Pipe Diameter(in)			
	0 to 2	>2 to 4	>4 to 10	>10 to 24
	CRF[2)] per Reactor Operating Year-Linear Foot			
0.032	5.24E-05	3.10E-05	1.48E-05	2.53E-06
0.10	9.84E-06	5.72E-06	4.03E-06	1.00E-06
0.45	1.38E-06	1.63E-06	5.95E-07	2.12E-07
0.63	1.18E-06	1.40E-06	5.21E-07	1.20E-07
1.00	7.82E-07	9.73E-07	3.93E-07	2.83E-08

1) Equivalent Break Size(in)
2) Cumulative Rupture Frequency

Service water flood mode frequencies were fairly stable, with maximum decrease of 0.3x and maximum increase of 2.9x, not accounting for aging[4]

2.2 The Aging factor

The updated pipe rupture frequencies for IFPRA(Rev.5) presented the aging factors for only fire protection system and service water system. Aging factor can be used to predict the pipe rupture frequencies according the aging. The aging factors are presented as follow pictures.

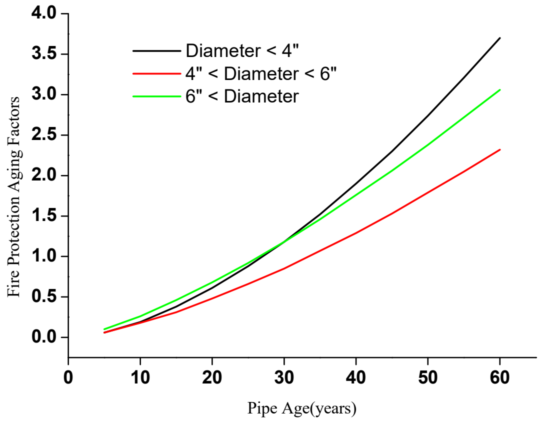

Fig 1. Fire protection aging factors.

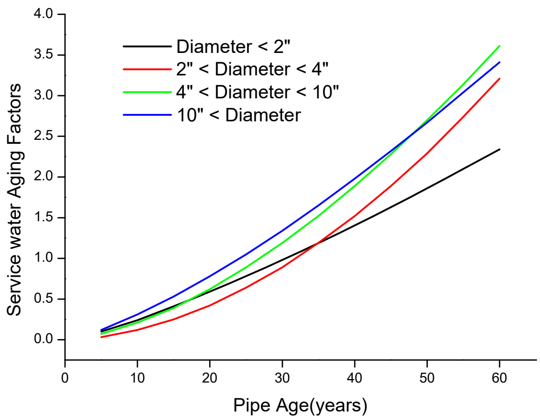

Fig 2. Service water system aging factors.

Aging factors for service water and fire protection were 0.04~0.3x at a pipe system age of 10 years, increasing to 2~4x by 60 years. All other water systems had insufficient data to justify aging factors[4]

2.3 The results of applying the updated pipe rupture frequencies and the aging factors in the fire protection and service water systems

One of the comparison of pipe rupture frequencies is shown in Table III. The results of pipe rupture frequencies according to the aging factor is presented in Table IV.

Table III. Example of the comparison of pipe rupture frequencies

Scenario	Flowrate (gpm)	EPRI TR 3002000079 (Rev.3)	EPRI TR 3002024904 (Rev.5)
D073-T02-FP-1	0~100	5.28E-03/yr	6.86E-03/yr
D073-T02-FP-2	100~6825	1.74E-03/yr	8.17E-03/yr
D100-D01-SX	100~43200	2.97E-04/yr	2.97E-04/yr
D100-D01-FP	100~6825	7.00E-05/yr	3.46E-05/yr

Table IV. Example of Results of pipe rupture frequencies according to the aging factor

	EPRI TR 3002024904 (Rev.5)	Aging factor (5year)	Aging factor (60year)
D073-T02-FP-1	6.86E-03/yr	4.20E-04/yr	2.50E-02/yr
D073-T02-FP-2	8.17E-03/yr	5.29E-04/yr	2.90E-02/yr
D100-D01-SX	2.97E-04/yr	2.44E-05/yr	8.77E-04/yr
D100-D01-FP	3.46E-05/yr	2.07E-06/yr	1.28E-04/yr

The flooding PRA CDF reflecting each pipe rupture frequencies data, based on each flood source and covering accident sequences that contribute over 95% of the total CDF, is summarized in Table V. The results of CDF reflecting aging factor is presented in Table VI.

Table V. The Comparison of IFPRA CDF Results Using Different Pipe Rupture Frequency Data

	EPRI TR 3002000079 (Rev.3)	EPRI TR 3002024904 (Rev.5)
CDF	9.97E-08/yr	9.27E-08/yr

Table VI. Results of CDF reflecting aging factor

	EPRI TR 3002000079 (Rev.3)	Aging factor (5year)	Aging factor (60year)
CDF	9.97E-08/yr	4.61E-08/yr	2.20E-07/yr

In this study, the significant risk contributors in the APR1400 nuclear power plant are re-evaluated using updated pipe rupture frequencies. Accident sequences accounting for more than 95% of the cumulative CDF are analyzed, and the results show a reduction of approximately 7% in CDF compared to the previous assessment based on earlier rupture frequency data.

The impact of aging factors on the fire protection system and service water system is also evaluated. For a newly constructed plant, a realistic 5-year aging factor is applied, resulting in a 54% reduction in CDF. In contrast, when a 60-year aging factor—representing the full design life of the plant—is applied, the CDF increases by more than 120%, highlighting the significant influence of long-term aging on risk.

3. Conclusions

This study re-evaluates the significant risk contributors in the APR1400 nuclear power plant using updated pipe rupture frequencies. Accident sequences contributing over 95% of the cumulative CDF are analyzed, showing an approximate 7% reduction in CDF compared to previous assessments. The application of a 5-year aging factor for the fire protection and service water systems results in a 54% decrease in CDF for new plants. In contrast, using a 60-year aging factor over the plant's design life increases CDF by more than 120%, demonstrating the substantial impact of long-term aging on risk.

REFERENCES

[1] EPRI TR 1019194, Guidelines for Performance of Internal Flooding Probabilistic Risk Assessment, December 2009

[2] ASME/ANS RA-Sa-2009, "Standard for Level 1/Large Early Release Frequency Probabilistic Risk Assessment for Nuclear Power Plant Applications," Addendum A to RA-S-2008, February 2009.

[3] EPRI TR 3002000079, Pipe Rupture Frequencies for Internal Flooding Probabilistic Risk Assessments(Rev.3), April 2013.

[4] EPRI TR 3002024904 Pipe Rupture Frequencies for Internal Flooding Probabilistic Risk Assessments(Rev.5), August 2023.