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An Assessment of the Frequency of Interfacing Loss of Coolant Accident due to Inadvertent Overpressurization of ECCS Piping

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1 INTRODUCTION AND BACKGROUND

The office for Analysis and Evaluation of Operational Data (AEOD) of the U.S. Nuclear Regulatory Commission (NRC) issued a case study report [1] summarizing the analysis of operational events involving actual or potential overpressurization of emergency core cooling systems (ECCS) in boiling water reactors (BWRs) since 1975. The overpressurization results when the ECCS piping and components (designed typically from 150 to 550 psi design pressure) are inadvertently subjected to the nominal reactor pressure of 1050 psi. The operating BWRs reviewed in Reference 1 were product lines BWR/2 through BWR/6. The focus was on overpressurization or potential overpressurization events that occurred in BWRs due to testable isolation check valve failures in ECC systems.

Such an event can be a precursor to an interfacing loss-of-coolant accident (LOCA) between the reactor coolant system and an emergency cooling system. The probability of an interfacing LOCA is the product of overpressurization event frequency and the probability of system rupture given the overpressurization. The AEOD report [1] estimated the overpressurization event frequency as 1.0×10^{-2} per reactor year. The report "judgmentally assigned" probability of ECCS boundary rupture as 1.0×10^{-2} to 1.0×10^{-3} per overpressurization event, resulting in an interfacing LOCA probability of 1.0×10^{-4} to $1.0x^{-5}$ per reactor-year. This "judgmental" probability is two to three orders of magnitude higher than that which had been assessed in previous risk studies (for example, References 2 through 4).

This paper presents the results of a BWR Owners Group funded study [5] to assess a realistic value of probability of ECCS boundary rupture given an overpressurization occurrence.

2 ECCS PIPING AND COMPONENTS AFFECTED BY OVERPRESSURIZATION

The systems potentially subjected to overpressurization are : Core Spray (CS) (BWR/2 through BWR/4); Low Pressure Core Spray (LPCS) (BWR/5 and BWR/6); Residual Heat removal (RHR) (all BWR/4 through BWR/6 and most BWR/3); Low Pressure Coolant Injection and Containment Cooling (LPCI/CC) (some BWR/3); High Pressure Coolant Injection (HPCI) (BWR/3 and BWR/4); and Reactor Core Isolation Cooling (RCIC) (all BWR/4 through BWR/6 and most BWR/3).

Figure 1 shows the typical configuration of RHR, CS and LPCI/CS piping sections subjected to potential overpressurization. The piping and components upstream of the main pump discharge check valve are not subject to overpressurization because, during normal power operation, the systems are required to be aligned with the suction valve and flow path from the suppression pool open. A detailed description of the other systems is given in Reference 5.

3 EVALUATION OF PROBABILITY

3.1 Description of General Approach

In evaluating the piping integrity during the overpressurization event, the following failure modes were considered: (1) burst due to high hoop stress; (2) rupture due to latent axial defects; and (3) rupture due to latent weld defects at circumferential butt welds.

Each of these modes were evaluated as follows: (1) the hoop stress from overpressurization was calculated to compare with a conservative value of pipe burst hoop stress which was based on GE test data for burst hoop stress and a review of technical literature; (2) through-wall flaw lengths that the ECCS low pressure system pipes can tolerate during the overpressurization event were determined (the purpose of this evaluation was to demonstrate that these limiting flaw lengths are large compared to the flaw lengths that are normally detected by in-service inspections); and (3) the probability of a double-ended pipe break (DEPB) during overpressurization resulting from latent defects at circumferential welds was calculated.

The evaluations in (1) and (2) were deterministic and, therefore, were not directly factored into the probabilistic evaluation performed for (3). A piping reliability model [6] developed by Lawrence Livermore National Laboratory (LLNL), with appropriate modifications incorporated by GE for BWR applications, was used to calculate the probability of a DEPB at a circumferential weld.

Potential dynamic loads such as those resulting from earthquakes and safety/relief valve discharges were not included in the analysis because it was concluded that the likelihood of their occurrence simultaneous with an overpressurization event is extremely small. Other potential dynamic loads during the overpressurization event, such as water hammer caused by reactor water filling a partially voided ECCS line downstream of check valve, were also not included in the scope of this evaluation. The probability of partially voided lines is extremely low due to the "keep full" systems. Therefore, it was concluded that there would be no significant dynamic loads being applied to the ECCS system during an overpressurization event.

3.2 Evaluation of Piping

The pipe size, schedule and the material information defining the various BWR ECCS and RCIC piping systems surveyed were reviewed. The conclusions from this review were: (1) the piping is of seamless construction and the material is typically SA 106 Gr. B carbon steel, (2) the pipe diameters range from 6-inches to 24-inches, and (3) the Code of construction was Section III, Class 2 [7] or ANSI B31.1 [8].

The safety margin relative to burst type of failure in ECCS piping systems during an overpressurization event is first evaluated. A review of GE burst test data [9] on pressurized seamless 106 Gr. B pipes showed that the average burst hoop stress is equal to approximately 90% of the ultimate stress. This is consistent with observation by Rodabaugh [10] that for seamless pipes the hoop stress at burst is essentially equal to the ultimate stress of the material. The ASME Code specified minimum value of ultimate stress for SA 106 Gr. B steel is 60 ksi to a temperature of 600°F. Therefore, the expected value of burst hoop stress is (60x0.9) or 54 ksi. Table 1 shows that the burst hoop stress margins range from 3.31 (6-inch) to 1.56 (20-inch). Even the minimum 1.56 margin is greater than the Level D safety margin of 1.4 required by the ASME Code.

A qualitative measure of the assurance of pressure integrity of ECCS piping during an overpressurization event is the length of the axial flaw (latent defect) that can be tolerated without rupture. Since 106 Gr. B carbon steel is expected to behave in essentially a ductile manner in the range of temperatures expected during overpressurization, a limit load approach is appropriate for such an evaluation. A limit load approach is included in the recently proposed flaw acceptance criteria for ferritic piping [11]. A conservative value of flow stress of 47 ksi, based on Reference 12, was used in the evaluation. The allowable axial crack lengths were calculated from the following equation based on Reference 11:

$$\ell = \{ 2.48rt\ [(\sigma_f/\sigma_h)^2 - 1]\}^{0.5}$$

where, σ_f is flow stress, σ_h is hoop stress, and r and t are pipe radius and thickness, respectively. The last column in Table 1 shows the maximum tolerable crack lengths during the overpressurization event for various representative pipe sizes in ECC systems. The allowable crack sizes range from 2.4 inches to 5.8 inches. Since a through wall crack of such length would likely be detected and repaired, it is concluded that the probability of rupture of ECCS piping from unstable crack growth of latent axial defects during overpressurization is negligible.

All of the preceding evaluations of piping integrity are deterministic in nature. An evaluation of failure probability during overpressurization due to a latent defect in a circumferential weld is described next.

Since the ECCS piping is generally seamless, the most likely locations where a latent defect may exist would be the circumferential welds. Probabilistic methodology developed by LLNL [6] and incorporated in their computer code called PRAISE, was used in this evaluation. For this application, the PRAISE code was modified to include a more general limit load based failure criteria. The pipe rupture probabilities were calculated for a typical girth butt weld in the low pressure ECCS piping segments that would be pressurized during an overpressurization event. It was conservatively assumed that the probability of existence of a fabrication defect at a weld is 1.0. Further, no credit was taken for any preservice or inservice inspection.

The axial and bending stresses considered in the evaluation were those due to pressure, weight and thermal expansion. Table 2 summarizes the stress magnitudes used in the failure probability evaluation. A limit load based failure criteria was used with a conservative flow stress of 36 ksi as recommended in Reference 11. The last column in Table 2 shows the calculated values of rupture probabilities for each pipe size considered. The rupture probability for pipes smaller than 6-inch diameter pipes was judged to be no greater than that for the 6-inch diameter pipe. It was conservatively concluded that the rupture probability per weld is bounded at $1x10^{-7}$ for each overpressurization event.

3.3 Evaluation of Valve Integrity

A valve is an assemblage of several subcomponents including a body, stem, disc, bonnet, gland, yoke, and operator. A quantitative analysis to determine the rupture probability would be extremely complex. The conclusions from a qualitative evaluation are the following:

a. The likelihood of rupture of the body of a 150-pound pressure-rated valve during an overpressurization event is less than that of the corresponding diameter standard schedule pipe. In the case of valves rated 300-pounds or greater, the prescribed hydrotest pressure of 1125 psi assures that its probability of rupture during an overpressurization event is negligible.
b. The likelihood of gross rupture at bolted joints in the low pressure side ECCS valves is extremely small. Leakage of fluid through the bolted joints is the more likely consequence during an overpressurization event.
c. The overall rupture probability of a low pressure side ECCS valve was judged to be no greater than that at the circumferential butt weld between the valve and the connecting pipe.

3.4 Evaluation of Heat Exchanger Integrity

Several RHR heat exchanger designs were reviewed with the most limiting one selected for evaluation. The three parts of the heat exchanger that are stressed during RHR overpressurization event are: the shell, the shell-to-tube-sheet flanged joint, and the tubes. The results of the evaluation of these parts lead to the following conclusions:

a. The likelihood of rupture of a RHR heat exchanger shell during an overpressurization event is of the same order of magnitude as the connected piping.
b. The tube sheet-to-shell bolted joint is likely to leak rather than experience a gross rupture.
c. Heat exchanger tubes have an inherent safety margin of three against collapse during an overpressurization event.
d. The overall rupture probability of an RHR heat exchanger was judged to be no greater than that at the circumferential butt weld in the connecting RHR piping.

4 OVERALL SYSTEM RUPTURE PROBABILITY

The overall ECCS low pressure piping system rupture probability during an overpressurization event is approximately equal to the sum of the rupture probabilities of the piping and the piping components such as valves and heat exchangers. The rupture probability in the piping was defined as the product of the per-circumferential butt weld rupture probability (conservatively estimated as $1x10^{-7}$) and the number of circumferential butt welds in the system. The rupture probabilities for valves and heat exchangers was approximated as equal to that at a circumferential butt weld.

The number of welds in the portions of ECCS piping affected by overpressurization depends upon the system configuration. In a limited plant survey, the number of welds in an RHR system were determined as 112 for pipe sizes 3-inches and larger, and the number of valves to be 91. On this basis, the number of equivalent circumferential welds was conservatively assumed as 300. Thus, the ECCS low pressure system piping rupture probability is estimated as $(300)x(1x10^{-7})$ or $3.0x10^{-5}$. This expected probability is at least two orders of magnitude lower than the range of $1x10^{-2}$ to $1x10^{-3}$ stated in Reference 1. Reference 13 calculates the overall interfacing systems LOCA probabilities calculated in this paper and those reported in Reference 1.

When the conditional system rupture probability of $3x10^{-5}$ is combined with a conservatively estimated frequency of 10^{-2} per year for the overpressurization, a frequency of $3x10^{-7}$ per reactor-year is obtained. This value of expected frequency of interfacing LOCA is acceptably low.

5 SUMMARY AND CONCLUSION

Evaluation presented in this paper shows that the conditional probability of of ECCS boundary rupture during and overpressurization event is approximately $3x10^{-5}$ per event which is considerably less than the values reported in Reference 1. The overall calculated frequency of $3x10^{-7}$ per reactor-year for the interfacing LOCA event is acceptably low.

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TABLE 1

Pipe Size (in.)	Circumf. Stress (ksi)	Burst Margin	Critical Axial Crack Length (in.)
6	16.3	3.31	3.3
14	23.9	2.24	3.7
16	27.4	1.97	3.2
20	34.5	1.56	2.4
24	28.9	1.87	5.8

TABLE 2

Pipe Size (in.)	Applied Stress Memb. (ksi)	Applied Stress Bend. (ksi)	Conditional Probability
6	7.9	7.0	9.8×10^{-8}
14	11.7	7.0	9.3×10^{-9}
16	13.5	7.0	6.3×10^{-9}
20	17.0	7.0	2.0×10^{-8}
24	14.5	7.0	5.4×10^{-9}

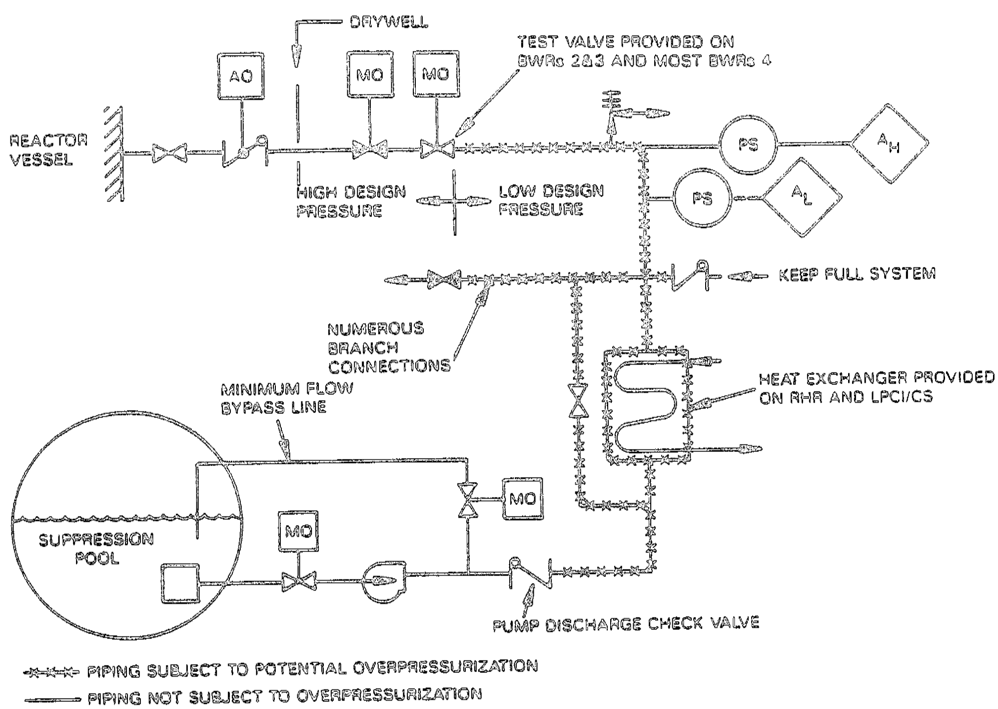

Figure 1 Typical Configuration of RHR, CS and LPCI/CS Piping Sections Subjected to Potential Overpressurization