

A Methodology for ISLOCA Initiating Event Frequency Evaluation Considering Isolation Valve Design Diversity

HyungJun Kim^{a*}, Jin Hee Park^a, Sung-Min Shin^a, Kibeom Son^a, JongWoo Park^a

^aKorea Atomic Energy Research Institute, 111 Daedeok-daero 989beon-gil, Yuseong-gu, Daejeon, 34057, Republic of Korea

*Corresponding author: hjkim3459@kaeri.re.kr

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1. Introduction

Interfacing System Loss of Coolant Accident (ISLOCA) is a high-consequence initiating event in which a failure of isolation barriers between high- and low-pressure systems results in coolant discharge outside containment. Because ISLOCA can directly bypass containment and challenge Level-2 safety functions, ASME PRA guidance requires explicit evaluation of ISLOCA scenarios in probabilistic safety assessment. Traditionally, ISLOCA frequency evaluation has been developed for conventional large PWR configurations, where motor-operated valves (MOVs) are installed in series at high/low pressure interfaces. The Westinghouse WCAP methodology (WCAP-17154-P, Rev.0) provides a systematic derivation of ISLOCA initiating event frequency equations considering:

- Internal leakage (L)
- Transfer open (T)
- External leakage (O)
- Failure to close on demand (d)
- Human failure
- Common cause failure (CCF)
- State of Knowledge Correlation (SOKC)

With the development of small modular reactors (SMRs) and various advanced reactor designs, distinctive design characteristics have emerged compared to conventional large nuclear power plants. Isolation valves may be located either inside or outside containment, piping lengths are often reduced due to compact and integral configurations, and alternative valve types such as ball valves are increasingly adopted. These features represent notable departures from traditional plant designs. Such design changes can influence ISLOCA initiating mechanisms and the contributing failure modes, thereby affecting the overall initiating event frequency. Accordingly, an ISLOCA initiating event frequency evaluation methodology that reflects these design-specific characteristics is required.

In this study, the conventional WCAP-based ISLOCA formulation is extended to develop a design-sensitive ISLOCA initiating event frequency evaluation methodology that explicitly considers valve type and installation location. The evaluation results obtained from the proposed methodology are also presented.

2. Methods and Results

2.1 Base ISLOCA Frequency Formulation

The ISLOCA initiating event frequency was derived based on the WCAP methodology. For two isolation valves in series, the total ISLOCA frequency is expressed as:

$$\lambda_{ISL} = \lambda_{ISL1} + \lambda_{ISL2} + \lambda_{ISL3} + \lambda_{ISL3}$$

Where each term represents combinations of valve failure modes between the isolation valve 1 and isolation valve 2. The failure modes considered are:

- Internal leakage (L)
- Transfer open (T)
- External leakage (O)
- Failure to close on demand (d)

Simultaneous demand failures of both valves are excluded. The formulation adopts a linear failure rate approximation ($\lambda \cdot T$), consistent with the treatment of ISLOCA as a frequency event. The exposure interval is defined as the leak test interval. The base equation accounts for periodic valve operation, human failure, and common cause failure (CCF), consistent with the WCAP framework.

2.2 Treatment of Containment Location

The contribution of external leakage depends on the installation location of the isolation valves.

When isolation valves are installed outside containment, external leakage can directly contribute to an ISLOCA initiating event. In contrast, if the isolation boundary is located inside containment, external leakage of a single valve alone does not result in a containment bypass event. In such configurations, ISLOCA occurs only when internal leakage develops in the valve located inside containment and, simultaneously, external leakage occurs in the valve located outside containment.

In recent small and advanced reactor designs, some isolation valves are increasingly positioned outside containment to improve maintenance accessibility. Therefore, the ISLOCA frequency formulation must distinguish whether external leakage terms are included,

depending on the combination of valve installation locations. In this study, the ISLOCA initiating event equations were selectively applied according to the valve location configuration.

2.3 State of Knowledge Correlation (SOKC)

State of Knowledge Correlation (SOKC) arises when multiple basic events in a cutset share the same failure rate data source. In such cases, statistical correlation in uncertainty leads to a mean cutset frequency that exceeds the simple product of mean probabilities.

Since conventional point-estimate fault tree quantification does not capture this effect, SOKC multipliers were incorporated into the ISLOCA frequency formulation following the WCAP methodology. This ensures compliance with PRA Standard requirements and avoids underestimation of initiating event frequency.

2.4 Ball Valve vs. Gate Valve Modeling

To reflect the diversity of reactor design configurations, both gate valve and ball valve configurations were modeled and compared in this study.

The failure modes considered for both gate valves and ball valves include internal leakage (L), transfer open (T), external leakage (O), and failure to close on demand (d). For gate valves, the failure rate data provided in NUREG/CR-6928 were directly applied.

However, NUREG/CR-6928 does not explicitly provide failure rate data for ball valves. Therefore, reliability data collected from research reactor applications were utilized to compare the failure characteristics of gate valves and ball valves. Based on this comparison, relative failure rate ratios between the two valve types were derived. These ratios were then applied to the NUREG/CR-6928 gate valve failure rates to estimate corresponding failure rates for ball valves.

The valve failure rate data used from the research reactor applications are summarized below..

Table I. Ball and Gate Valve Failure Rate

| Component Type | Failure Mode | Failure Rate (1E-6/h) | 90% CI (5%) | 90% CI (95%) |
|----------------|-------------------------------|-----------------------|-------------|--------------|
| Ball Valve | Spurious function | 4.5 | 0.8 | 10.7 |
| | Leakage | 2.3 | 0.1 | 6.7 |
| Gate Valve | Failure to function | 55.6 | 39 | 94 |
| | Leakage | 7.9 | 2.2 | 23.8 |
| | Failure to remain in position | 7.1 | 2.2 | 21.1 |

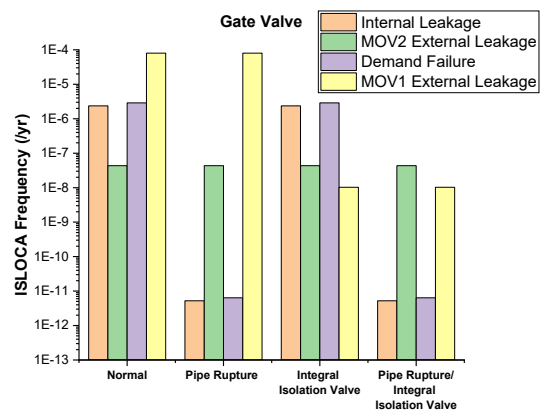
3. Conclusions

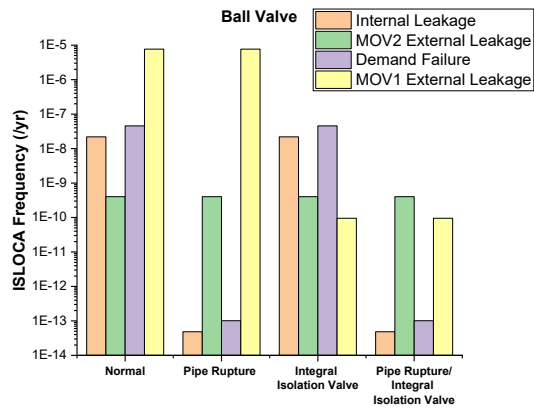
In this study, the ISLOCA initiating event frequency was evaluated under the condition that both isolation valves are installed outside containment (CV), and a comparative analysis was performed between gate valve and ball valve configurations.

For the gate valve configuration, the total ISLOCA frequency was estimated to be approximately 8.0E-05 to 8.5E-05 per year. The dominant contributor was external leakage of the upstream valve (MOV1). Failure mode contribution analysis indicated that, under normal conditions, more than 94% of the total ISLOCA frequency was governed by MOV1 external leakage. This result confirms that when both isolation valves are located outside containment, external leakage becomes the primary driver of ISLOCA frequency.

In contrast, for the ball valve configuration, the total ISLOCA frequency was estimated to be approximately 1.7E-06 per year, representing a reduction of approximately one to two orders of magnitude compared to the gate valve configuration. Although MOV1 external leakage remained the dominant contributor, the contributions from internal leakage and demand failure were significantly reduced relative to the gate valve case. The lower internal leakage and transfer-open failure rates of the ball valve resulted in a smaller contribution from non-external leakage failure modes.

Overall, when both isolation valves are located outside containment, external leakage is the dominant contributor to ISLOCA frequency. The ball valve configuration demonstrated a substantially lower ISLOCA frequency compared to the gate valve configuration, primarily due to its improved sealing characteristics and lower failure rates. Therefore, in high- and low-pressure interface applications where valves are installed outside containment, valve type selection can be an important design factor for ISLOCA risk reduction..





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