

A Study on the Mass Release Mechanism and Its Implications for Energy Release according to Break Size during Main Steam Line Break Accident of APR1000

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1. Introduction

A Main Steam Line Break (MSLB) results in the most limiting consequences among secondary side pipe breaks. Alongside Loss of Coolant Accidents (LOCA), MSLB mass and energy (M/E) release analyses provide essential data for evaluating containment pressure and temperature. These evaluations are critical for ensuring structural integrity during accidents involving the release of high-energy steam and liquid.

In particular, the MSLB M/E analysis requires a break-size spectrum analysis to identify the true limiting conditions for containment integrity. This is because smaller breaks can paradoxically induce higher peak temperatures due to superheated steam and delayed safety actuation. Indeed, recent MSLB studies for the APR1000 and APR1400 demonstrated that the maximum peak containment pressure occurs at intermediate break sizes, ranging from 30% to 40% of the maximum break area [1,2].

To mitigate the time and resource burdens of performing these repetitive spectrum analyses, this study explores M/E release behaviors across different break sizes by leveraging previous findings and plant-specific characteristics.

Specifically, this study investigates and compares the break flow rates from both the affected steam generator (SG) and the turbine sides. Furthermore, it evaluates the flow restrictor (FR) upstream pressure (i.e., SG pressure) calculated during the MSLB M/E release analysis for each break area fraction (AF) of the APR1000. All M/E release calculations in this study were performed using the SPACE-ME methodology [1,3].

2. Modeling and Methods

The SPACE-ME code calculated the thermal-hydraulic behavior of the Nuclear Steam Supply System (NSSS) during the MSLB accident of the APR1000 [3]. To identify the MSLB M/E release mechanism according to break size, a spectrum analysis was performed for 10 cases with break sizes ranging from AF 0.1 to AF 1.0 at 102% initial core power.

A double-ended guillotine break was assumed to occur and the containment was modeled with the SPACE-ME code reflecting the actual design data, followed by the

calculation of the backpressure behavior resulting from real-time M/E releases.

The break location is selected upstream of the Main Steam Line Isolation Valve (MSIV) to simulate a main steam line break inside the reactor containment. The initial conditions and assumptions for a conservative analysis are described in Table I and Table II.

Table I. Initial Conditions for the MSLB M/E Release Analysis

Parameter	Value
Core power [%]	100 + instrumental error
Pressurizer pressure [%]	103 (normalized value to the nominal value)
Pressurizer level [%]	120 (normalized value to the nominal value)
Core inlet temperature [%]	101 (normalized value to the nominal value)
Reactor coolant system flow rate [%]	95 (normalized value to the nominal value)
SG water level	Nominal value + instrumental error

Table II. Assumptions for the MSLB M/E Release Analysis

Parameter	Assumption
Break type	Double-ended guillotine break
Break size	AF 1.0, 0.9, 0.8, 0.7, 0.6, 0.5, 0.4, 0.3, 0.2 and 0.1
Turbine trip	At the break initiation
Feedwater flow	Maximum only to the affected SG with maximum enthalpy
MSIV and MFIV* closure	Maximum delay time after HCP-MSIS** signal
Offsite power	Available

*Main feedwater isolation valve

**High containment pressure Main steam isolation signal

3. Results of Analysis

The M/E release is characterized by a large initial discharge within the first few seconds, which triggers the reactor trip and subsequent MSIV closure (occurring between approximately 10 and 30 seconds depending on AF). Prior to closure, the intact SG inventory is also released, contributing to a significant early discharge; afterward, only the affected SG inventory is released, with behavior varying according to where critical flow conditions are established.

The accident was assumed to initiate at 0.0 seconds. Fig. 1 illustrates the break mass flow rate discharged from the affected SG side over time. Fig. 2 shows the mass flow rate released from the turbine side, which includes contributions from the main steam header and intact SG. Fig. 3 depicts the transient pressure of the affected SG dome.

As shown in Figs. 1 and 2, before MSIV closure, mass flow rates from both the affected SG and turbine sides increase nearly in proportion to AF. High-pressure, high-enthalpy fluid is released into the containment from both sides. Fig. 3 confirms that the affected SG dome depressurization rate is also roughly proportional to break size greater than AF 0.3, reflecting typical critical-flow behavior where the break area governs flow resistance. Since the released fluid is near-saturated and high-enthalpy, larger mass flow implies proportionally greater energy transfer to the containment.

After MSIV closure, the turbine-side flow drops to zero, leaving the affected SG flow as the sole release path. Fig. 3 shows a clear distinction in the depressurization slope of the affected SG dome (upstream of the flow FR) immediately after closure. For larger breaks (AF 0.5–1.0), the more rapid pre-closure release leaves lower dome pressure at closure compared to AF 0.3 and 0.4, reducing the driving pressure for subsequent critical flow through the FR. Lower dome pressure also corresponds to lower saturation temperature and enthalpy, so the energy content of post-closure fluid is reduced for larger breaks.

The analysis shows that for AF 0.3–1.0, the flow ranking reverses to $AF\ 0.3 > 0.4 > \dots > 1.0$ after MSIV closure. This reversal is attributed to three combined mechanisms: (1) the FR becomes the limiting section for larger breaks, with the release rate governed by upstream dome pressure and thermodynamic state under choked-flow conditions, while for smaller breaks (AF 0.1–0.2) the break remains dominant; (2) case-dependent dome pressure history—larger breaks exhibit steeper pre-closure pressure drops, leaving lower driving pressure, whereas AF 0.3 and 0.4 retain higher dome pressure and thus sustain higher mass flow and enthalpy through the FR; and (3) for breaks larger than the effective FR flow area, increasing break size does not necessarily increase post-closure release because the FR governs, and larger breaks undergo greater pre-closure depressurization, resulting in lower post-closure pressure and enthalpy.

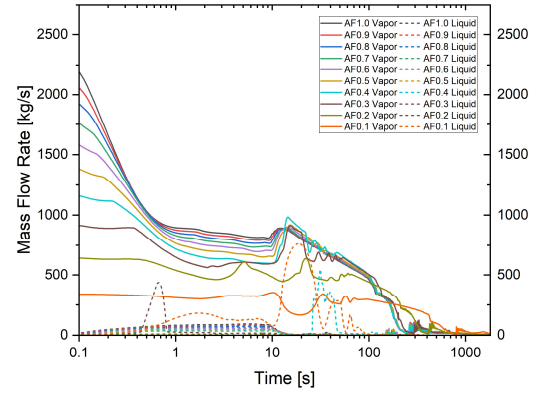


Fig.1 Affected SG-side Break Mass Flow

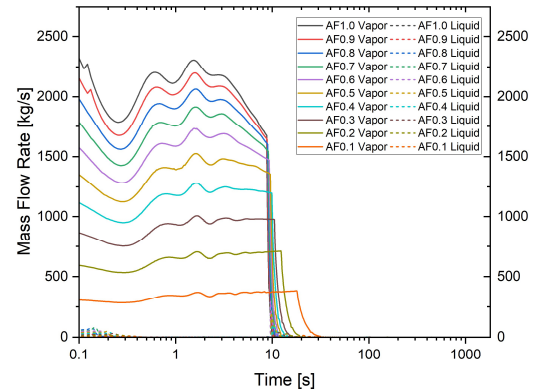


Fig.2 Turbine-side Break Mass Flow Rate

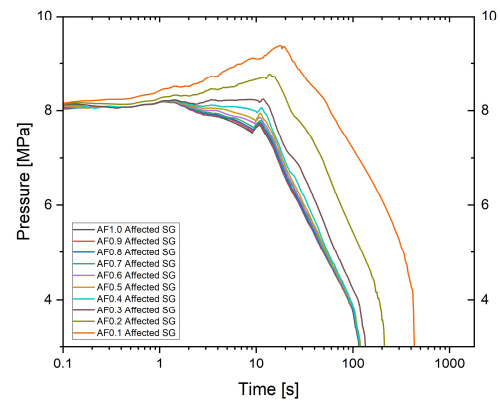


Fig.3 Pressure of Affected SG Dome

Overall, the release behavior is non-monotonic across the AF range. For smaller breaks (AF 0.1-0.2), the release rate increases with break size because the break remains the dominant restriction. For larger breaks, post-closure release is governed primarily by the affected SG conditions at MSIV closure and the FR-limited flow path.

The AF 0.3 case represents a balance between pre-closure release and the thermodynamic conditions retained in the affected SG after closure. Larger breaks release more fluid early but experience greater pre-closure depressurization, so post-closure release occurs under lower pressure and enthalpy. Smaller breaks retain higher dome pressure but have smaller pre-closure flow capacity. Therefore, the highest containment peak pressure at AF 0.3 is interpreted as the combined effect of pre-closure release and subsequent release characteristics, rather than break size alone, consistent with previously reported results.

4. Conclusions

This study evaluated the MSLB mass-release detailed behavior from the affected SG side and turbine-side break for break AFs ranging from 0.1 to 1.0. Through this study, it was identified that the M/E release behavior of the APR1000 MSLB according to the break area depends on the change in the critical flow choking location due to the FR and the pressure of the SG after MSIV isolation. Furthermore, this study suggests that when performing break area spectrum analyses in future MSLB M/E release analyses, the peak pressure is expected to be derived near the break area corresponding to the FR area, without the need to analyze many cases.

The AF 0.3 and 0.4 cases can therefore be understood as a case in which the pre-closure and post-closure release characteristics combine to produce the highest previously reported containment peak pressure. The results indicate that the relationship between break size and containment pressurization is not necessarily monotonic in systems with an FR.

As future work, a comprehensive parametric sensitivity analysis will be conducted to evaluate the influence of key design and transient parameters on the limiting break size. Specifically, the effects of MSIV closure delay times, High Containment Pressure setpoints, and variations in the effective flow area of the FR will be investigated. Because the peak-pressure-inducing break size is determined by the balance between pre-closure blowdown and the choked-flow transition at the FR, varying isolation delays and FR flow area designs could shift the limiting break size. This follow-up study will help establish a more generalized design-basis framework for containment pressure mitigation and safety system optimization in the APR1000.

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