

# Analysis of Source Term Releases in TI-SGTR induced by ADV-based Secondary-Side Heat Removal

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## 1. Introduction

In general, the probability of Thermally-induced steam generator tube rupture (TI-SGTR) is considered to be very low. However, according to the RASP Handbook Volume 5, CE-type steam generators have a TI-SGTR occurrence probability of up to 20% under HDL (High RCS pressure/Dry steam generator/Low secondary side pressure) conditions, where steam generator tubes are subjected to extreme stress[3]. Furthermore, if loop seal clearing accompanies such conditions, the occurrence of TI-SGTR becomes unavoidable.

Among initiating events, station blackout (SBO) and total loss of component cooling water (TLOCCW) have a high likelihood of creating HDL conditions. As initial mitigation strategies, both events rely on secondary-side heat removal. In this process, steam is discharged either through the atmospheric dump valves (ADV) or the main steam safety valves (MSSV); however, the use of ADV tends to promote HDL conditions by rapidly reducing the secondary-side pressure. If auxiliary feedwater injection is interrupted during mitigation, or if the auxiliary feedwater storage tank (AFWST) is depleted and water source switching fails, the reactor heat is re-accumulated in the RCS, leading to HDL conditions. TLOCCW and SBO (without successful power recovery) lack any further mitigation strategies, leaving them directly exposed to TI-SGTR risk. Moreover, both initiating events may be accompanied by loop seal clearing, which further increases the probability of TI-SGTR. Therefore, it is necessary to analyze the behavior of radioactive source terms in the event of TI-SGTR following TLOCCW or SBO.

In this study, the severe accident analysis code MELCOR was employed to calculate source term releases. The source term releases from TI-SGTR accidents after the implementation of secondary-side heat removal strategies with ADV were analyzed, and the severity was evaluated by comparing the results with those of an accident scenario in which no mitigation measures were performed, resulting in containment damage.

## 2. Methods

### 2.1 MELCOR Inputs

MELCOR is an integrated severe accident analysis code developed for light water reactor nuclear power plants. It simulates a wide range of physical phenomena, including core degradation, thermal-hydraulic responses, and radionuclide transport during accident progression. The nodalization of the reference plant MELCOR input used in this study is shown in Figure 1.

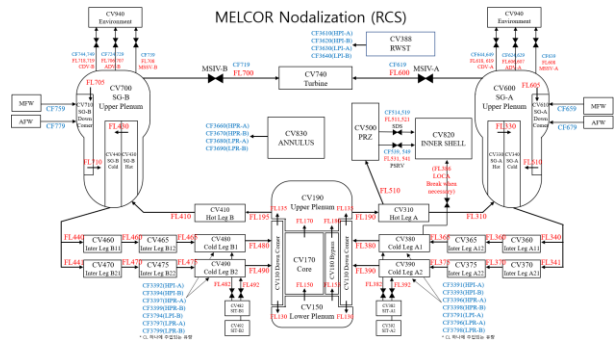


Figure 1. MELCOR input nodalization for the reference plant

The design specifications of the reference plant used in this study are summarized in Table 1.

Table 1. Design specifications of the reference plant

| Plant Parameters           | Value                    |
|----------------------------|--------------------------|
| RCS Pressure (Pressurizer) | 15.50 (MPa)              |
| SG Pressure                | 7.488 (MPa)              |
| RCS Hot Leg Temperature    | 603.3 (K)                |
| RCS Cold Leg Temperature   | 574.5 (K)                |
| RCS Mass Flow Rate         | 13704 (kg/s)             |
| AFWST Water Volume         | 1261.8 (m <sup>3</sup> ) |

### 2.2 Accident Scenario Selection

To establish accident scenarios for analyzing source term behavior under TI-SGTR conditions, a preliminary scenario was first used to identify the HDL time window. For both TLOCCW and SBO, the reactor and reactor coolant pumps trip immediately after the initiating event, and the main feedwater (MFW) pumps stop. Since both initiating events show identical behavior in MELCOR if their mitigation strategies are the same, the analysis was carried out without distinguishing between them.

Table 2. Preliminary analysis scenario

| Event               | IE (TLOCCW) | ADV opening | AFW injection |
|---------------------|-------------|-------------|---------------|
| Occurrence time (h) | 0           | 0.5         | 0.5           |

The time-dependent responses of RCS pressure, SG water level, and secondary-side pressure for the preliminary scenario is shown in Figures 2, 3, and 4.

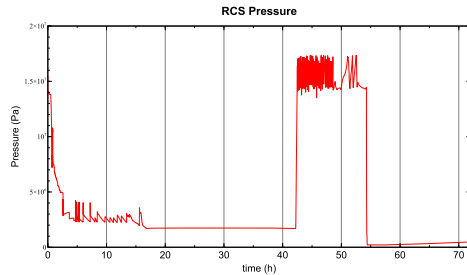


Figure 2. RCS pressure in the preliminary scenario

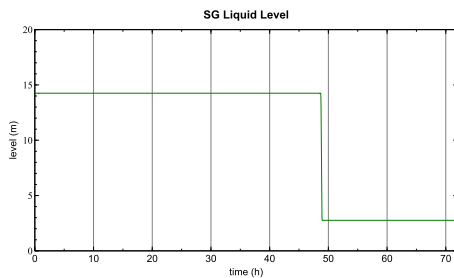


Figure 3. SG water level in the preliminary scenario

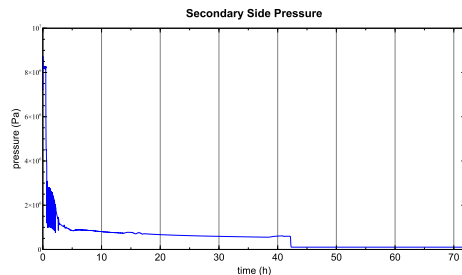


Figure 4. Secondary-side pressure in the preliminary scenario

The AFWST was depleted at 38 hours 26 minutes. After auxiliary feedwater injection, the RCS pressure dropped but rose sharply again at 42 hours 15 minutes, maintaining high pressure until vessel failure at 54 hours 16 minutes. The steam generators dried out at 49 hours, while the secondary-side pressure remained low after ADV opening. Thus, the HDL window was identified between 49 hours and 54 hours 16 minutes.

The TI-SGTR occurrence time was chosen within this HDL period, and ADV re-closure was assumed either after AFWST depletion or after TI-SGTR occurrence. Based on this, six analysis scenarios were constructed as shown in Table 3.

Table 3. Accident Scenarios for analysis

| Unit: hours        | A | B   | C   | D   | E   | F    |
|--------------------|---|-----|-----|-----|-----|------|
| ADV Opening        | - | -   | 0.5 | 0.5 | 0.5 | 0.5  |
| AFW Injection      | - | 0.5 | 0.5 | 0.5 | 0.5 | 0.5  |
| TI-SGTR Occurrence | - | -   | -   | 50  | 50  | 50   |
| ADV Closure        | - | -   | -   | -   | 40  | 50.5 |

### 3. Results

The initial inventory of source terms in the reference plant MELCOR model is shown in Table 4.

Table 4. Initial source term inventory of the reference plant

| Source Term            | Xe    | Cs    | Be    | I <sub>2</sub> | Te    | Ru     | Mo     | Ce     | La    | UO <sub>2</sub> | Cd      | Ag |
|------------------------|-------|-------|-------|----------------|-------|--------|--------|--------|-------|-----------------|---------|----|
| Initial Inventory (kg) | 282.3 | 157.4 | 123.9 | 12.16          | 24.77 | 174.22 | 205.53 | 362.63 | 36.47 | 4560.82         | 284.673 |    |

The release fractions of radionuclides after 72 hours for each scenario are presented in Table 5.

Table 5. Radionuclide release fractions after 72h

| 72h (%) | Xe   | Cs   | Ba   | I <sub>2</sub> | Te   | Ru  | Mo  | Ce  | La  | UO <sub>2</sub> | Cd   | Ag   |
|---------|------|------|------|----------------|------|-----|-----|-----|-----|-----------------|------|------|
| A       | 97.1 | 12.5 | 0.49 | 95.9           | 15.4 | 0.0 | 0.0 | 0.0 | 0.0 | 0.5             | 0.4  | 0.9  |
| B       | 0.0  | 0.0  | 0.0  | 0.0            | 0.0  | 0.0 | 0.0 | 0.0 | 0.0 | 0.0             | 0.0  | 0.0  |
| C       | 0.0  | 0.0  | 0.0  | 0.0            | 0.0  | 0.0 | 0.0 | 0.0 | 0.0 | 0.0             | 0.0  | 0.0  |
| D       | 98.0 | 4.5  | 0.3  | 96.3           | 51.6 | 0.2 | 0.8 | 0.0 | 0.0 | 0.6             | 15.5 | 12.4 |
| E       | 86.7 | 1.8  | 0.1  | 82.5           | 19.3 | 0.0 | 0.0 | 0.0 | 0.0 | 0.2             | 9.6  | 6.8  |
| F       | 97.7 | 4.3  | 0.3  | 94.8           | 46.8 | 0.2 | 0.6 | 0.0 | 0.0 | 0.6             | 25.5 | 16.6 |

The time-dependent release fractions of radionuclides for each scenario are illustrated in Figure 5.

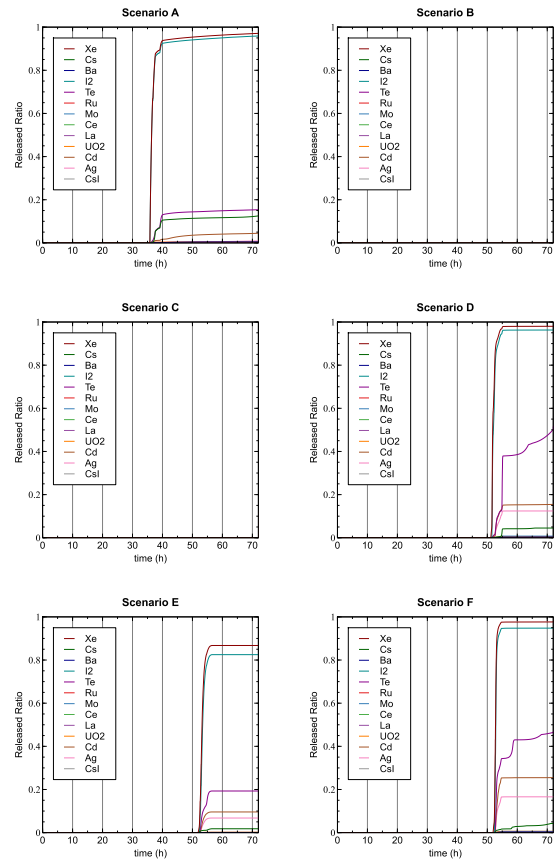


Figure 5. Time-dependent release fractions of radionuclides

Scenario A, in which no mitigation strategy was applied, resulted in containment failure at 35 hours and

48 minutes, leading to the onset of radionuclide release. In contrast, Scenarios B and C, where secondary-side heat removal was performed and no TI-SGTR occurred, maintained containment integrity for the full 72 hours, with no radionuclide release observed. Scenarios D, E, and F experienced TI-SGTR at 50 hours, with source term releases beginning at 51 hours 5 minutes, 51 hours 43 minutes, and 51 hours 50 minutes, respectively. In all scenarios involving containment or steam generator failure (A, D, E, F), radionuclide release occurred rapidly following the structural degradation.

When comparing the accident sequences involving TI-SGTR, Scenarios D and F exhibited similar release fractions: xenon (Xe) at 98.0% and 97.7%, cesium (Cs) at 4.5% and 4.3%, barium (Ba) at 0.3% for both, and molecular iodine (I<sub>2</sub>) at 96.3% and 94.8%, respectively. The tellurium (Te) release fraction was somewhat higher in Scenario D (51.6%) compared to Scenario F (46.8%). Conversely, cadmium (Cd) and silver (Ag) releases were higher in Scenario F (25.5% and 16.6%) than in Scenario D (15.5% and 12.4%). These results indicate that re-closing the ADV after TI-SGTR does not significantly reduce radionuclide release.

Scenario E, where the ADV was closed before TI-SGTR occurred, showed lower release fractions compared to Scenarios D and F: Xe at 86.7%, Cs at 1.8%, I<sub>2</sub> at 82.5%, and Te at 19.3%. In some cases, the release reduction was over 30% compared to the other TI-SGTR cases. However, the absolute quantities released were still substantial, suggesting that this measure alone is insufficient as a practical mitigation strategy against source term release.

A comparison of Scenario A (no mitigation) with Scenarios D, E, and F (TI-SGTR cases) revealed that cesium release was higher in Scenario A, reaching 12.5%, more than twice the level of the TI-SGTR accident sequences. For most other radionuclides, however, including Xe (97.1%), I<sub>2</sub> (95.9%), Te (15.4%), Cd (0.4%), and Ag (0.9%), the releases were either similar to or even lower than those in the TI-SGTR cases. This outcome suggests that, excluding cesium, even with secondary heat removal until the AFWST is depleted the occurrence of TI-SGTR may actually lead to more radionuclide releases.

#### 4. Conclusion

While TI-SGTR has generally been regarded as a low-probability event, its likelihood increases sharply under HDL conditions. SBO and TLOCCW are initiating events that rely almost exclusively on secondary-side heat removal as a mitigation strategy. If continuous auxiliary feedwater injection cannot be sustained, HDL conditions are highly likely.

In this study, TI-SGTR scenarios initiated by TLOCCW were analyzed using the severe accident code MELCOR to investigate radionuclide release behavior. The scenarios considered included (1) no mitigation, (2) secondary-side heat removal with no TI-SGTR, (3) TI-

SGTR occurrence, and (4) TI-SGTR occurrence followed by re-closure of the ADV.

The analysis showed that Cs release was more than twice as high in the no-mitigation scenario compared with the TI-SGTR cases. However, for most other radionuclides, including Xe, I<sub>2</sub>, and Te, the accident sequences involving TI-SGTR exhibited similar or even greater releases. Even if secondary-side heat removal is performed until the depletion of the AFWST, once TI-SGTR occurs, the overall source term releases are not significantly different from those of the no-mitigation case, except for cesium. Furthermore, re-closing the ADV prior to the TI-SGTR resulted in only limited reductions in release fractions, whereas closing the ADV after the TI-SGTR had virtually no effect.

#### Acknowledgments

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