Effects of the Number of Ruptured U-tubes During mSGTR Transient in CANDU-6 Plants

Seon Oh YU [a*] and Kyung Won LEE [a]
[a]*Safety Research Division, Korea Institute of Nuclear Safety, 62 Gwahak-ro, Yuseong-gu, DAEJEON 34142*
[*]*Corresponding author: k378yso@kins.re.kr*

1. Introduction

A steam generator tube rupture (SGTR) is a reactor building bypass event that leads to a release of fission products into the environment. SG u-tubes can rupture in all SGs rather than in a particular single SG, and a rupture of the u-tubes in an SG not directly connected to a pressurizer can accelerate the coolant inventory reduction in the broken loop. In other words, even if the total number of u-tubes ruptured in the SGs of CANDU-6 plants is the same, thermal-hydraulic behaviors, such as channel flow rate of the primary coolant and pressure of the reactor header, are expected to differ depending on the connection state with major components. It can also affect when nuclear fuel channel integrity is lost, thus requiring a quantitative analysis.

For this purpose, we performed a sensitivity analysis for the number of ruptured u-tubes to compare the plant responses against the hypothetical multiple events of multiple SGTR (mSGTR) followed by an unmitigated station blackout (SBO).

2. Methods and Results

Figure 1 shows a schematic nodalization for the detailed analytical modelling of Wolsong units 3 and 4, which are typical 600-MW class CANDU-6 plants, indicating the ruptured location of SG u-tubes. The primary heat transport system (PHTS) consists of a reactor inlet/outlet header (RIH/ROH), feeder, PHT pump, SG, pressurizer, D_2O feed tank, and the connection pipes among them.

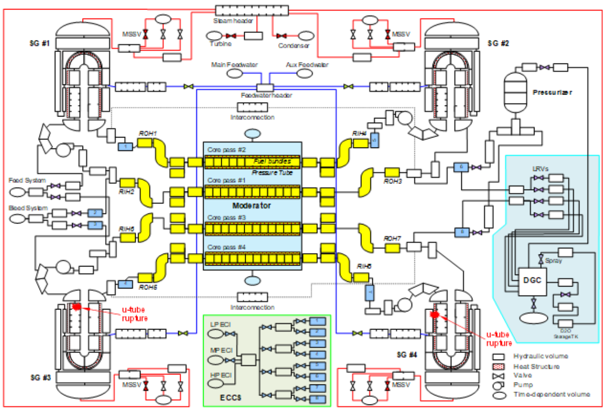

Fig. 1 MARS-KS nodalization of a CANDU-6 plant.

The analysis model developed by the MARS-KS code [1] includes the logic for controlling the PHTS pressure and the inventory decreasing due to the rupture of the u-tubes. It also includes the main features of PHTS with a simplified model for the horizontal fuel channels, the secondary heat transport system including the shell side of SGs, the feedwater and main-steam lines, and the moderator system.

The base scenario of this study is when 10 u-tubes of SG#4 are ruptured and there are no operators' actions for recovering the essential safety functions after the simultaneous occurrence of an SBO and a turbine trip [2]. To conduct the sensitivity calculation for the number of ruptured u-tubes, as shown in Table I, the following assumptions were considered:

- The event begins when a total of 10 u-tubes rupture from 2 SGs in the same pass at 0.0 s.
- The pressurizer heaters and the feed system for controlling the PHTS pressure and inventory are available until the SBO occurrence.
- The reactor trips due to the low-level signal and low-pressure signal of the pressurizer and reactor header, respectively, and the turbine stops due to the low pressure of the steam [3].
- The SBO occurrence causes all electric-powered pumps, such as the PHT pumps, main feedwater pump, moderator circulation pump, and D_2O feed pump, to trip. The PHT pump seal leakage is allowed [4].
- The accumulator of high-pressure emergency cooling injection (ECI) is on standby, but the ECCS pumps of the mid-pressure/low-pressure ECI are unavailable.
- Atmospheric steam discharge valves are unavailable and remain closed over the transient. The main steam safety valves for over-pressure protection are repeatedly opened and closed around the set-point to relieve pressure; however, SG crash cooling by the operators is not credited.

Table I: Calculation matrix for sensitivity analysis

	Base	Case1	Case2	Case3	Case4	Case5
SG#3	0	1	3	5	7	9
SG#4	10	9	7	5	3	1
Total	10	10	10	10	10	10

3. Results and Discussion

During the transient period, the behavior of major thermal-hydraulic parameters such as coolant discharge flow rate through the ruptured u-tubes, header pressure, coolant flow rate, void fraction, and peak cladding temperature (PCT) in PHTS, was similar to the base case where 10 u-tubes were broken in a single SG#4. In addition, the two loops were isolated from each other by the LOCA signal, and residual heat removal was degraded due to the rapid reduction of the coolant flow and the rapid soar-up of the void fraction in the broken loop. Eventually, PCT exceeded the limit in all cases and the integrity of the nuclear fuel was expected to be lost.

However, even if the total number of the ruptured u-tubes was the same, there was a difference in the occurrence times of the pressurizer low-level and the reactor header low-pressure signals. Because a pressurizer is connected between ROH and SG#4, when more u-tubes are broken in SG#4 (Base, Cases 1~3), not only the coolant in the fuel channels but also the coolant in the pressurizer are discharged to the SG#4 shell, causing the pressurizer low-level signal to occur faster than the reactor header low-pressure signal. Conversely, when more u-tubes are ruptured in SG#3, not directly connected to the pressurizer (Cases 4~5), more coolant in the fuel channels discharges into the SG#3 shell causing the reactor header pressure to decrease faster to the set value. Hence, depending on the number of ruptured u-tubes for each SG, the time to reach the set value of the pressurizer low-level and the reactor header low-pressure signals were each predicted differently. As shown in Fig. 2, the time ratios of the reactor trip and the PCT limit reach were reduced to 0.86 and 0.71, respectively, compared to the base case.

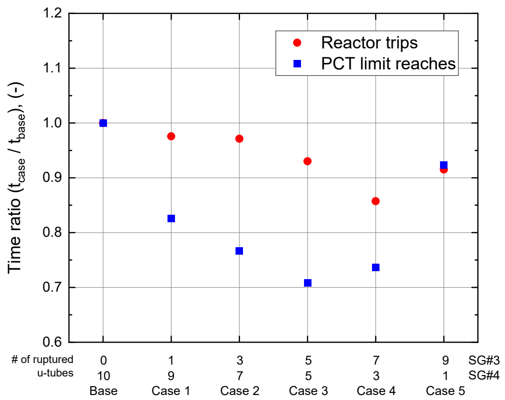

Fig. 2 Comparison of times of reactor trip and PCT limit reach by case.

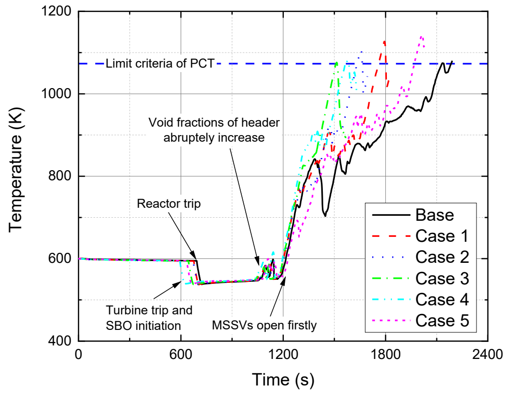

Fig. 3 Comparison of peak cladding temperatures by case.

Through the present sensitivity analysis, it was confirmed that even if the total number of ruptured u-tubes is the same, the time to reach the PCT limit can significantly shorten compared to the base case depending on the number of ruptured u-tubes for each SG, as shown in Fig. 3.

4. Conclusions

A sensitivity analysis with the analysis model for an mSGTR followed by an unmitigated SBO was performed to compare plant responses under the assumption of 10 ruptured u-tubes.

In all calculation cases, the transient behavior of major thermal-hydraulic parameters, such as discharge flowrate through the ruptured u-tubes, reactor header pressure, and void fraction in the fuel channels, was generally similar to that of the base case having a single SG with 10 u-tubes ruptured. Additionally, as the conditions of low-flow coolant and high void fraction in the broken loop persisted, leading to the degradation of decay heat removal, PCT was expected to exceed the limit criteria. However, because of the different connection states between the SG and pressurizer, there was a difference in time between the pressurizer low-level signal and reactor header low-pressure signal, affecting the time to trip the reactor and to reach the PCT limit.

Therefore, when conservative accident analysis is performed with up to 10 u-tubes ruptured, it is necessary to consider the effect of the number of ruptured u-tubes for each SG as well as the u-tube rupture in a single SG.

Acknowledgments

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