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Sensitivity Analysis of Tube and Pipe Rupture Time during Thermally-Induced Steam Generator Tube Rupture (TI-SGTR)

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1. Introduction

Thermally-induced steam generator tube rupture (TI-SGTR) or consequential SGTR (C-SGTR) is the event that the initiating event such as station blackout (SBO) causes the heat-up of the core and then causes a creep rupture of steam generator (SG) tube. The TI-SGTR causes the fission products from the core to be released to the environment via the secondary side of SG, therefore is one of the containment-bypass accidents. Although the probability of occurrence is very low, the TI-SGTR has a high radiological influence to the public, collecting interests in terms of public health risk.

The typical TI-SGTR is initiated by a complete loss of cooling such as station blackout (SBO). When the reactor cooling pumps (RCPs) are stopped operating and the additional cooling measures are lost, the reactor core is cooled by the natural convection via the SG tubes. Absent of external cooling for a long time, the core and the entire primary system is heated up, and then a piping of primary system such as the SG tube, the hot leg and the surge line ruptures by creep failure.

Among the potential location, the rupture at the hot leg and the surge line has relatively less important because the containment-bypass of fission products does not occur when the rupture occurs at these locations. However, the initial location of the creep rupture among those positions are highly uncertain and are believed to be the function of the natural convection behavior via the SG tubes.

In this article, the sensitivity analysis of the creep rupture at primary side of APR1400 was performed with respect to the variables including the parameters related to the natural convection via the SG tubes. The order of rupture between the SG tubes and the hot leg/surge line was statistically shown along with the variables.

2. Modeling and Analysis

2.1 Modeling of TI-SGTR

Figure 2 shows the nodalization of APR1400, including the primary side and the secondary side of SG [1]. The reactor has two main cooling loop with two SGs, and the secondary side of the SGs has the paths to the environment via multiple atmospheric dump valves (ADVs) and main steam safety valves (MSSVs). When the SGTR occurs, the secondary side of SG is pressurized by the hot steam, and then the steam is ejected through those ADVs and MSSVs upon opening. Since the design pressure of the SG secondary side (typically 70 bar) is set much lower than that of the primary side (higher than 150 bar), it is probable that the steam is ejected through the MSSVs when the SGTR occurs and the pressure of the primary side is transferred to the SG secondary side.

Figure 2 shows the modeling of SG to simulate the natural convection via the SG tubes. When the accident such as SBO occurs, the natural convection through the primary cooling loop is blocked by the loop seal at the cold leg. Instead, the natural convection occurs such that the hot steam enters to the portion of SG tubes, and then returns through the remaining SG tubes. To simulates this phenomena, the hot leg and the SG tubes are divided into two separate paths respectively. With this nodalization, the steam flows out from the core through the upper volume of hot leg (CV310), and then flows to the hot tubes (CV330), and returns through the cold tubes (CV345) via the SG outlet plenum (CV350). Meantime, a portion of the hot steam from the CV310 is mixed with returning cold steam to the CV311, because the SG inlet plenum is a single volume in reality. To simulate the mixing in the SG inlet plenum, the inlet plenum is divided virtually into three separate volumes, hot volume (CV320), mixing volume (CV322) and the cold volume (CV321). The flowrate to the mixing volume determines the mixing ratio in the inlet plenum.

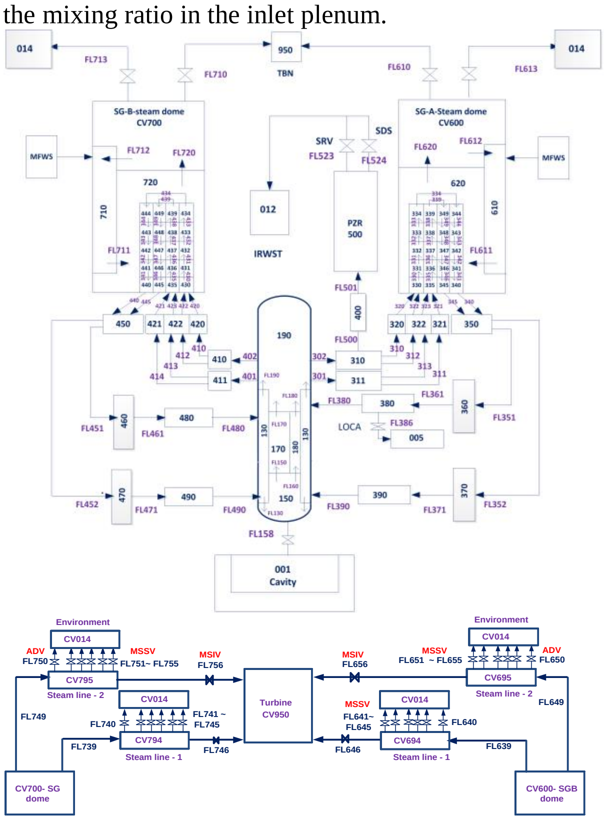

Fig. 1 Nodalization of APR1400 system (top), and SG secondary side (bottom)

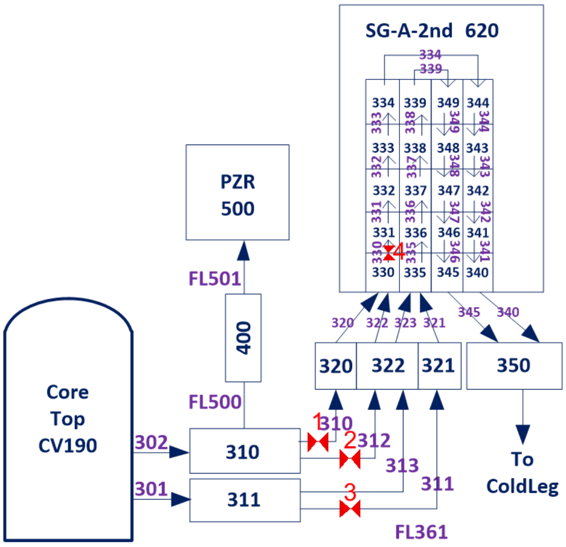

Fig. 2 Model for Natural Convection via SG tubes

Table 1 shows the variables for the sensitivity analyses, and three of them are the variables related to the natural convection via the SG tubes. The discharge coefficients, C_d, determines the mass flow rate of natural convection through the hot leg. The mass flow rate of natural convection is the function of fluid density, ρ, the density difference, Δρ, the pipe diameter, D, and the gravitational acceleration, g. The mixing fraction means the portion of the mixed mass flow versus the total mass flow of the fluid from the hot leg to the SG inlet plenum. If the f=1, the hot and cold steam in the SG inlet plenum are mixed perfectly. The recirculation ratio is the ratio of the steam mass flow to the hot SG tube over the mass flow rate through the hot leg which is determined by the discharge coefficient above. These three variables determine the overall natural convection behavior via the hot leg and the SG tubes.

The ADV delay means the delay time of operator action to open the ADV after the procedure following the severe accident management guideline (SAMG) starts. When the core exit temperature (CET) reaches 650°C, the operator should start to follow the SAMG, and one of the procedure in SAMG is to depressurize the primary side by depressurizing the secondary side by opening the ADVs manually.

Table 1 Sensitivity variables used for the analyses

Variable	Symbol	Equation
Discharge coefficients	C_d	$m=\rho C_d(gD^5\Delta\rho/\rho)^{1/2}$
Mixing fraction	f	$f=m_{mixed}/m$
Recirculation ratio	r	$r=m_h/m$
ADV delay	ADV	Delay from CET=650°C to ADV open
Relative area of rupture	A	Relative rupture area of hot leg/surge line to SGT

The rupture area of the SG tube is assumed to be the twice of the cross-sectional area of the tube because the rupture is assumed as a guillotine break. The rupture area at the hot leg and the surge line is expressed as the relative value divided by the rupture area of the SG tubes. When the rupture area is large, the primary side depressurizes fast, therefore, an additional rupture at another location is less probable.

Table 2 shows the range and the probability density function (PDF) of the sensitivity variables. The variables related to the natural convection behaviors are determined considering the value suggested in the previous report [2]. Some of the variable ranges are little expanded from the original values from the report, to see the effect of the variables more clearly.

Table 3 shows the figure of merits (FOMs) for the analyses. The first is the rupture time of SG tubes, and the other is the delay time from the SG tube rupture to the hot leg or to the surge line rupture. If the dt_HLSL_SG is positive, the SG tube ruptures earlier than hot leg or the surge line. If the value is negative, the SG tube ruptures later than the others.

Table 2 Sensitivity parameters used for the analyses

Variable	Base case	Range	PDF
C_d	0.13	0.12-0.14	Uniform
f	0.75	0.6-0.9	Uniform
r	1.1	1.0-2.0	Uniform
ADV delay	1800s	0-1800 s	Uniform
Rel. A	1	0.5~2.0	Uniform

Table 3 Figure of Merits (FOMs)

FOM	Definition
SG_rup	SG rupture time (s)
dt_HLSL_SG	Delay from SG tube rupture to hot leg/surge line rupture

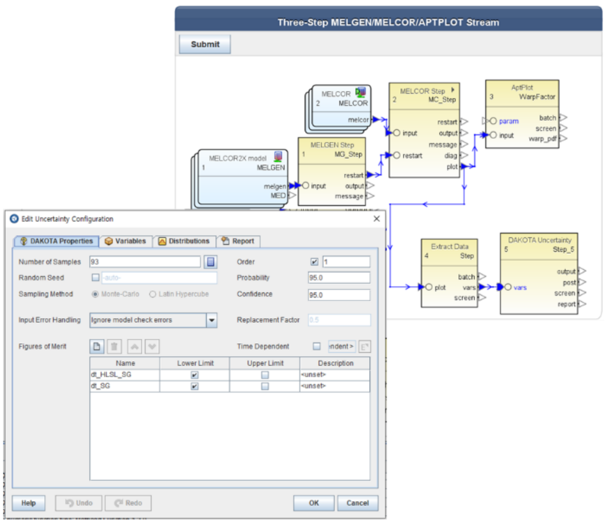

Fig. 3 SNAP/DAKOTA model

2.2 Analysis Method

Figure 3 shows the interface of DAKOTA analysis model in SNAP. The SNAP is the tool facilitating the system code analysis with graphical user interface, and enabling the post process or uncertainty quantification using the additional software plug-in. The DAKOTA is the uncertainty quantification plug-in, which provides the automatic sampling and the summary reports [3]. The sensitivity analyses in this report were performed using the SNAP with DAKOTA plug-in, with MELCOR 2.2 for the accident analyses.

The sensitivity variables in Table 1 were assigned to the coefficients of control functions for the valves used for controlling the natural convection flows in Fig. 2. Total 93 sample sets were generated and the same number of code runs were performed following by the Wilk's formula with 95 % probability and 95% confidence level. The calculation time were set to 60000s. The rupture of SG tube or hot leg or surge line occurred within the calculation time, however, the core degradation and the corresponding fission product releases are not shown in this time scale.

3. Analysis Results

3.1 Base Case Analysis

Table 4 shows the event sequences of the base case analysis. When a station blackout (SBO) occurs, the reactor is tripped by dropping of the control rods, and also the RCP and main feedwater stop by the loss of electric power. Then, auxiliary feed water (AFW) is supplied for 8 hours, delaying the accident progress. After the AFW supply is stopped, the primary system of the reactor is heated and pressurized. The SG A and B are dried out by the transferred heat from the primary side, and then the pressure-operated safety relief valve (POSRV) is open to relieve the system pressure. The primary coolant inventory decreases by the ejected steam through the POSRV, and then the fuel uncover starts. The core temperature increases and the core exit pressure reaches 650°C, the SAMG entry condition, and then the SAMG procedures start by the operator.

Among the SAMG procedure, the operator did not perform the direct depressurization of primary side. Instead, the operator depressurized the primary pressure by reducing the secondary pressure using ADVs. When ADVs are opened, the pressure of the SG secondary side decreases, resulting in a creep rupture of SG tubes by the pressure difference across the tube wall. In the base case analysis, the SG A and SG B tubes ruptured almost simultaneously, and then the hot leg ruptured. No surge-line rupture occurred in the case because the primary pressure decreased by the ruptures of the SG tubes and the hot leg.

In the base case, the delay of the ADV open by the operator was assumed to 1800s from the SAMG entry condition, conservatively. However, the delay time was included in the analyses considering a real operation.

Table 4 Event sequences for base case.

Events	**Time(s(hr))**
SBO occurs. Rx trips and MFW/RCP stops. AFW supply on	0
AFW depleted	28,800 (8.0)
SG A dryout	39,392 (10.9)
SG B dryout	39,500 (11.0)
POSRV(PRZ) open first	41,731 (11.6)
Core uncover start	47,901 (13.3)
Core Exit Temp = 650°C SAMG procedure starts	49,300 (13.7)
Gap release starts	49,606 (13.8)
ADV open by operator	51,100 (14.2)
Creep rupture of SG B tube	56,391 (15.7)
Creep rupture of SG A tube	56,393 (15.7)
Creep rupture of hot leg	56,501 (15.7)
Safety injection starts	58,813 (16.3)
Calculation termination	60,000 (16.7)

3.2 Results of Sensitivity Analyses

Table 5 and Table 6 shows the Pearson and Spearmann correlation coefficients between the sensitivity variables and the FOMs. The Pearson correlation coefficient is defined as the covariance of the two variables divided by the product of their standard deviation as

$$PCC = \frac{Cov(X,Y)}{\sigma_X \sigma_Y}$$

The Spearmann correlation coefficient is defined as the PCC between the rank of the variables, not the variables themselves. The PCC is the measure of linear correlation between variables, whereas the Spearmann's is the measure of monotonic functional relationship.

Table 5 Pearson correlation coefficients of variables

Variable	SG_rup	dt_HLSL_SG
C_d	-0.012	0.061
f	-0.297	**0.662**
r	0.460	**-0.328**
ADV	-0.005	0.079
A	-0.188	0.178

Table 6 Spearmann correlation coefficients of variables

Variable	SG_rup	dt_HLSL_SG
C_d	-0.039	0.075
f	-0.317	**0.679**
r	0.444	**-0.417**
ADV	-0.017	0.097
A	-0.215	0.189

Among the sensitivity variables, the mixing fraction, f, has a strong positive relationship with the dt_HLSL_SG, and the recirculation ratio has a weak negative relationship with the dt_HLSL_SG. This results shows that the higher mixing fraction results in the early SG tube rupture, therefore it is more probable that the SG rupture occurs earlier than the hot leg/surge line rupture. On the contrary, the high recirculation ratio delays the SG rupture, resulting in the higher probability of later rupture of SG tubes than the other piping rupture. The other variables, the discharge coefficient, the ADV delay, the relative area of the hot leg and the surge line rupture, have very week or negligible influence to the SG rupture time or the delay between SG tube rupture and the other piping ruptures.

Figure 4 shows the two influential variables, the mixing fraction and the recirculation ratio with respect to the dt_HLSL_SG. Although scattered, they show the increasing and decreasing trends versus the dt_HLSL_SG, respectively.

The high bound value having 95% probability and 95% confidence level of dt_HLSL_SG was 852 s. Because an earlier rupture of the SG tube is expected to induce a larger release of fission product to the environment,

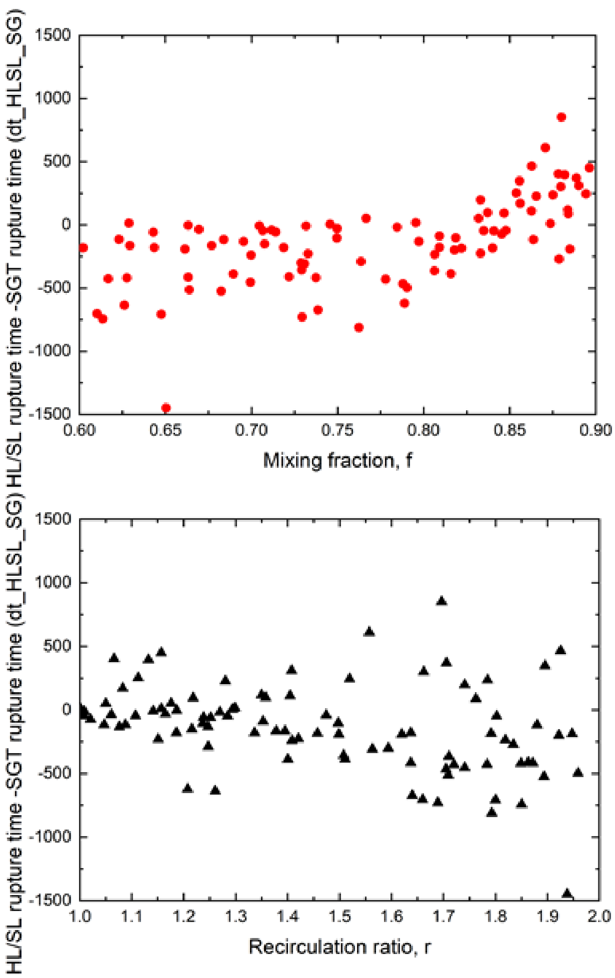

Fig. 4 Delay from SG rupture to hot leg/surge line rupture to sensitivity parameters; mixing fraction (top) and recirculation ratio (bottom)

this high bound value can be used for the analysis of the fission product behavior during TI-SGTR.

5. Summary

The sensitivity analysis for the creep rupture of the SG tubes, the hot leg and the surge line of APR1400 was performed using SNAP/DAKOTA package with MELCOR 2.2. The rupture sequence of the SG tubes and the hot leg/surge line were calculated with respect to the 5 variables, and the correlation coefficients were estimated for the 93 random sample sets.

The three sensitivity variables among the five were the variables related to the natural convection via the SG, and the remaining two were the ADV opening delay by operator and the relative rupture area of the hot leg/surge line versus the SG rupture area.

The two FOMs were set; one is the SG rupture time and the other is the delay from the SG rupture to the other piping rupture.

Among the sensitivity variables, the mixing fraction had the strongest relation with the FOMs, and the second was the recirculation ratio. The other three variables showed weak or negligible relationship to the FOMs.

With the high mixing fraction and with the low recirculation ratio, the SG tube is more probable to be ruptured earlier than the other piping, resulting in more fission product to the environment. The 95/95 value of the high bound was 852 s, which means the SG tube ruptures 852 s earlier than the other piping rupture. The values are planned to be used for the fission product behavior by TI-SGTR.

Acknowledgement

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