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

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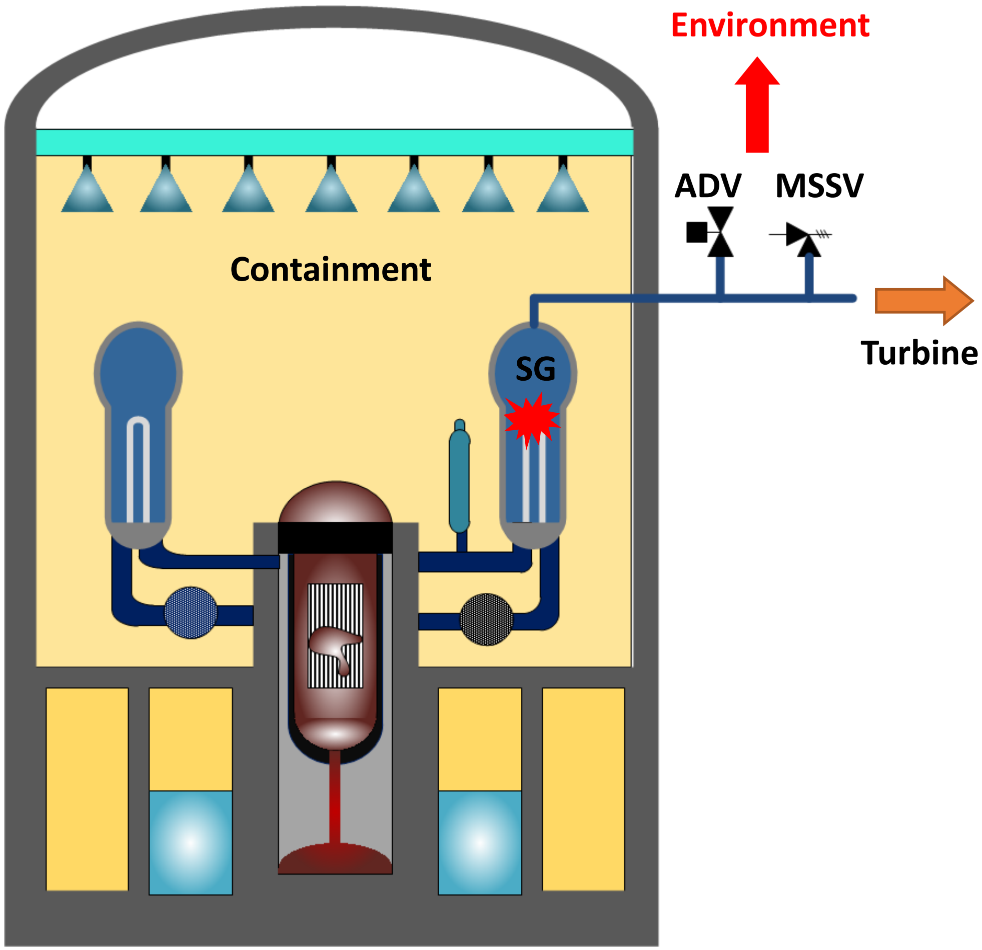
1 SGTR with Severe Accident

» One of Containment Bypass Accidents

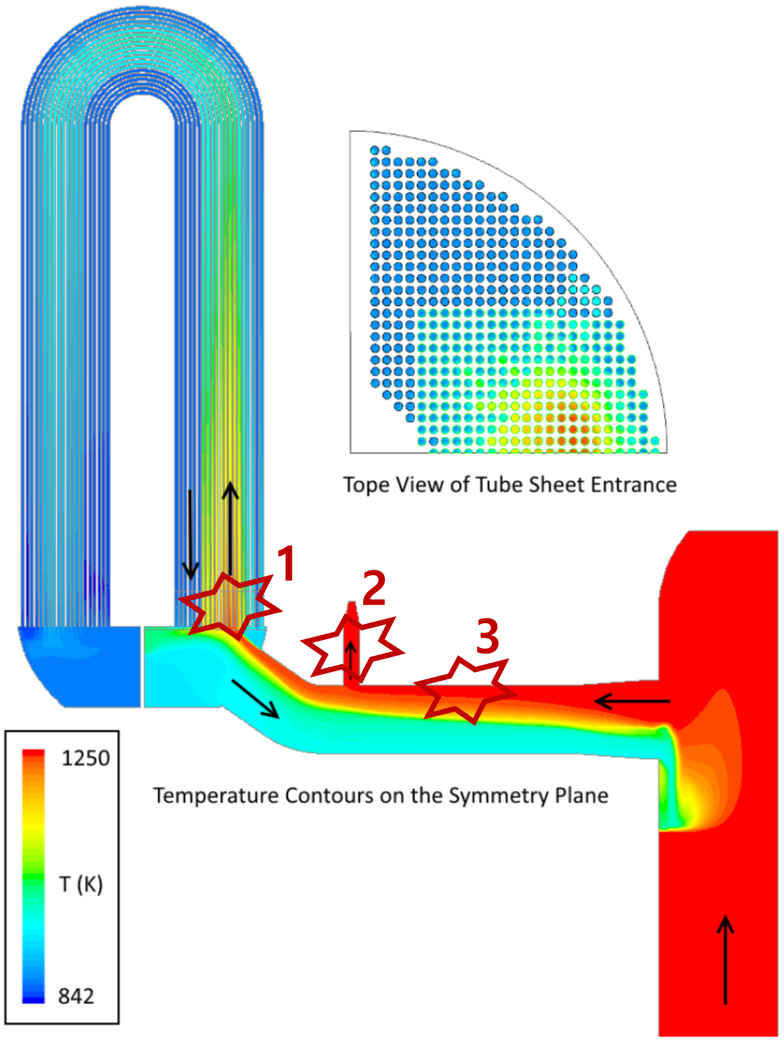
- Steam generator tube rupture with core damage
- Very low event frequency, however, dealt in SOARCA project by USNRC (NUREG-2195 etc.)
- TI-SGTR(C-SGTR) vs. S-SGTR
- Fission products from core releases to environment via ADV or MSSV
- Hard to achieve severe accident goal (Cs 137 more than 100 TBq <10^{-6}/RY)



1 TI-SGTR (Consequential-SGTR, C-SGTR)

» Thermally-Induced SGTR

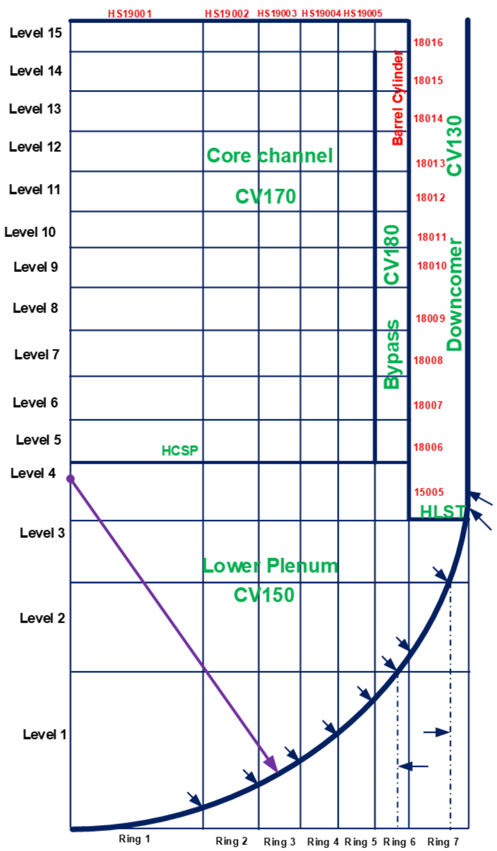
- Starts from other event (SBO, etc)
- Pumps stop: Coolant flow is lost.
- The core is then cooled by natural circulation via SG tubes
- High temperature in the SG tube with high pressure condition.
- Creep rupture of
  1. SG tube
  2. Hot leg
  3. Surge line
- Depending on the rupture position, the following radiological consequences to environment varies



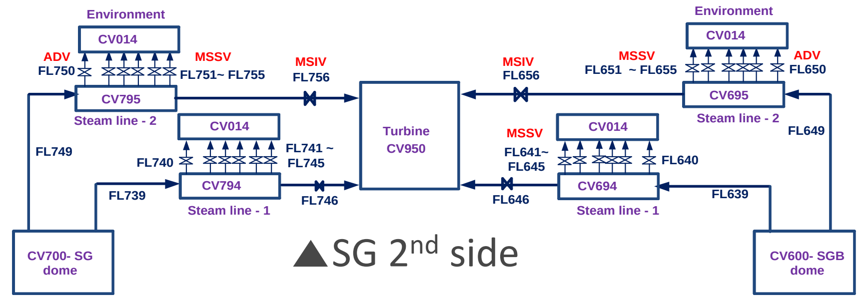
2 Modeling of Reactor

Model Plant : APR1400

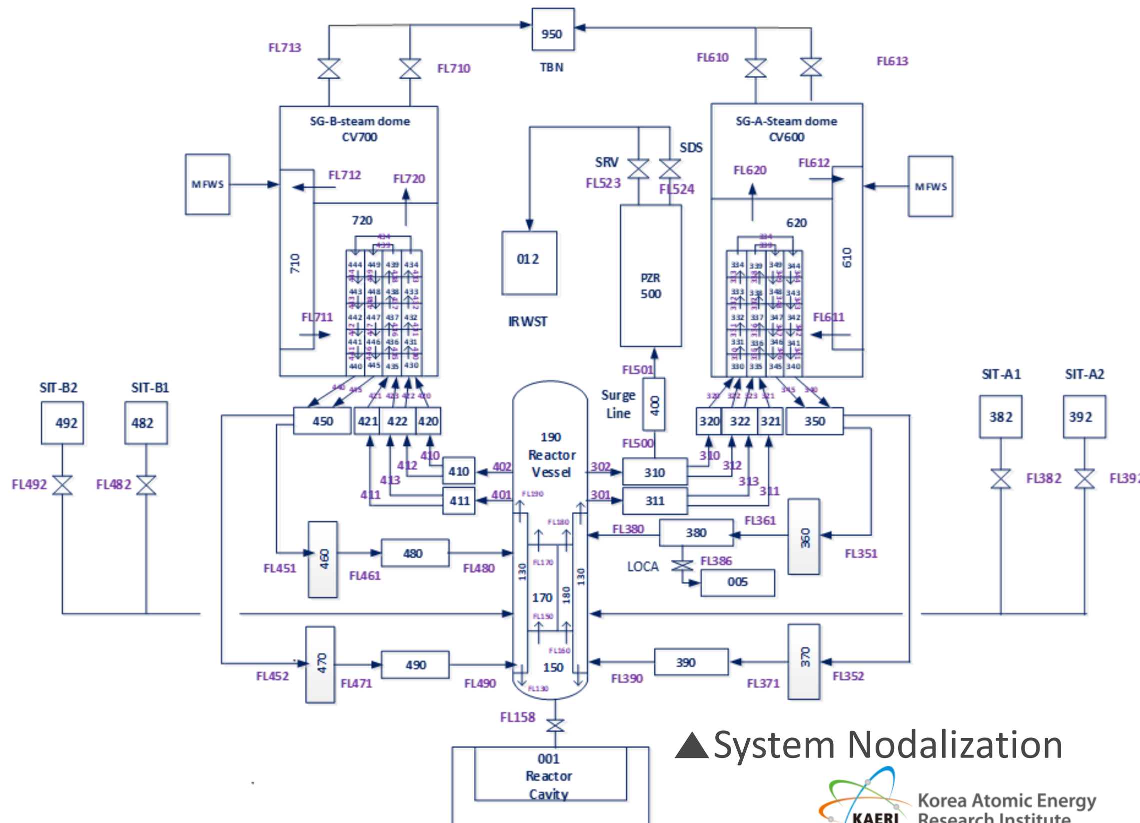
- MELCOR 2.2, SKN3,4



▲Core model



▲SG 2nd side



▲System Nodalization

2 Modeling for TI-SGTR

» Larson Miller Creep model

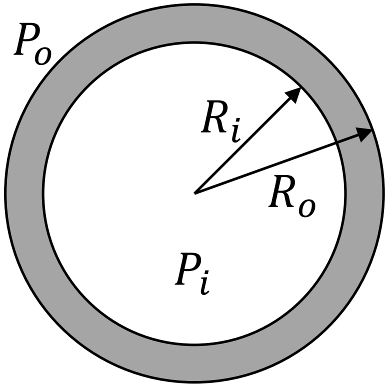
- Built in MELCOR 2.2
- Integration of LM parameter over time, and creep occur when LM-CREEP(t)=1
- LM parameter is the function of pipe stress over the wall

$$\mathrm{LM-CREEP\ (t)} = \int \frac{dt}{t_R(t)} \approx \sum \frac{\Delta t_i}{t_R(t_i)}$$

$$t_R = 10^{\left(\frac{P_{LM}}{T} - C\right)}$$

$$P_{LM} = \min[a_1 log_{10}(\sigma_e) + b_1, a_2 log_{10}(\sigma_e) + b_2]$$

$$\sigma_e = \frac{(R_o^2 + R_i^2)P_i - 2R_o^2 P_o}{R_o^2 - R_i^2}$$



	a_1	b_1	C	in Model
A-508	-5335	62291.3	16.44	Hot Leg
SS-316	-7400	81088.4	16.44	Surge Line
INC-690	-3973.7	48627.9	11.26	SG tube

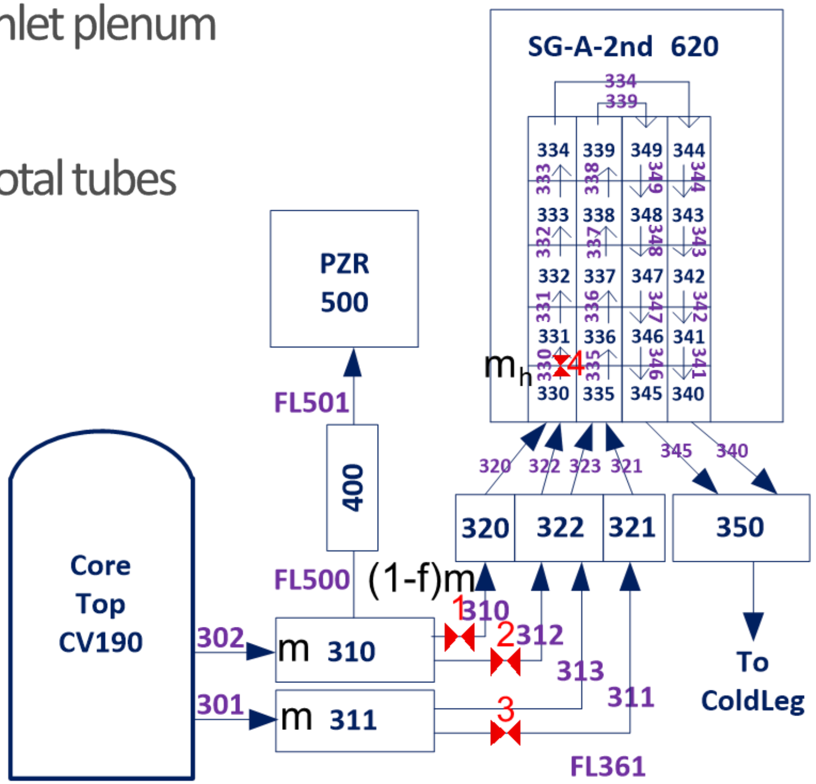
2 Modeling for TI-SGTR

» Control of natural circulation

- Parameters related to natural convection
  1. Discharge Coeff. (Cd) : $m=\rho C_d(gD^5\Delta\rho/\rho)^{1/2}$
  2. Mixing fraction (f) : fraction mixed in SG inlet plenum
  3. Recirculation ratio (r) : m_h/m
  4. Hot tube fraction = volume of hot tube/total tubes
- Control method
  1. Controlling valve 1 to valve 4
  2. To match Cd, f, r to the set value

Ref. NUREG 2195

Parameter	Average from NUREG-1922 Westinghouse SG	Predicted range Combustion Engineering SG
Cd, discharge coefficient	0.12	0.13–0.14
f, mixing fraction	0.96	0.65–0.85
r, recirculation ratio	2.4	1.05–1.20
hot tube fraction	41%	20–25%
Tn, normalized (hottest tube)	0.43	0.9–0.99



2 Modeling for TI-SGTR

Mitigation actions in SAMG

- Injection to SG cools down the core by cooling SG secondary side with **auxiliary feed water (AFW)**. The water injected into SG 2nd side flows out through condenser/MSSV/ADV
- RCS depressurization is achieved by direct/indirect depressurization. The latter is depressurizing 2nd side using turbine bypass valve or ADV
- Injection into RCS from outside water source requires depressurization of RCS first (note: This is not the RCS injection by safety injection systems.)

Mitigation Procedure	APR1400/OPR1000
1	Injection into SG
2	Depressurize RCS
3	Injection into RCS
4	Injection into CNT
5	Mitigate fission product release
6	Control CNT condition
7	Control CNT hydrogen
8	Control SFP condition

3 Uncertainty Analyses

Uncertainty parameters

- Parameter 1,2,3 are related to the natural convection via SG tubes
- Parameter 4: Operator action delay after SAMG entry condition (CET=650°C)
- Parameter 5: Rupture area. Relative value to the SG tube rupture area

#	Variable	Description	Base Case	Variation Range	PDF	Notes
1	Cd	Discharge Coefficient	0.13	0.12-0.14	Uniform	Expanded from NUREG-2195 (CE type)
2	F	Mixing fraction	0.75	0.6-0.9	Uniform	
3	R	Recirculation ratio	1.1	1.0-2.0	Uniform	
4	ADV	ADV open delay after SAMG entry condition	1800s	0-1800s	Uniform	Maximum delay: 1800s for conservative analyses.
5	A	Creep rupture area of hot leg and surge line	1**	0.5~2.0	Uniform	Guillotine break area of SG (2x Cross section of SGT)

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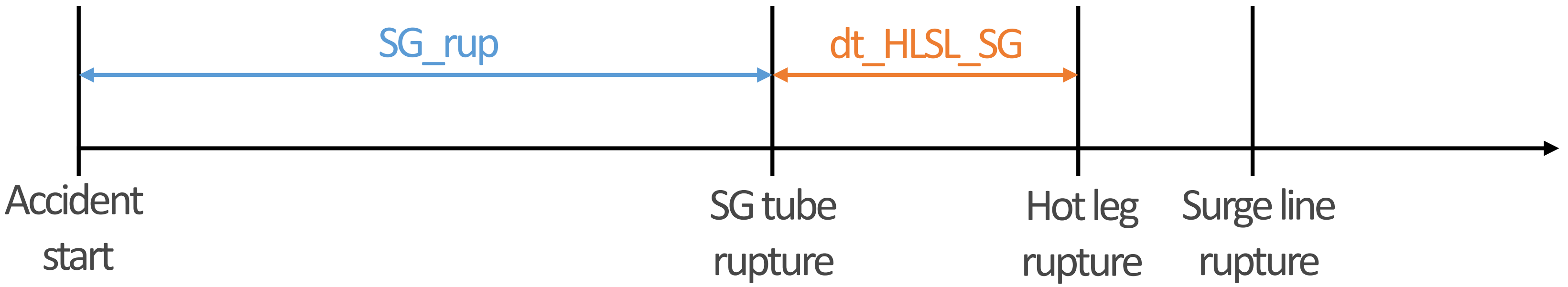
3 Uncertainty Analyses

FOM (Figure of Merit)

- The order of rupture among SG tube/Hot leg/Surge line
- If SG rupture occurs first, more fission products are expected to be released to environment via SG 2ndary side
- If hot leg or surge line ruptures before SG tube, the fission products are expected to be released to containment.



#	Parameters	Explanation
1	SG_rup	SG tube rupture time (earlier one between SGA and SGB)
2	dt_HLSL_SG	Delay from SG tube rupture to hot leg or surge line rupture

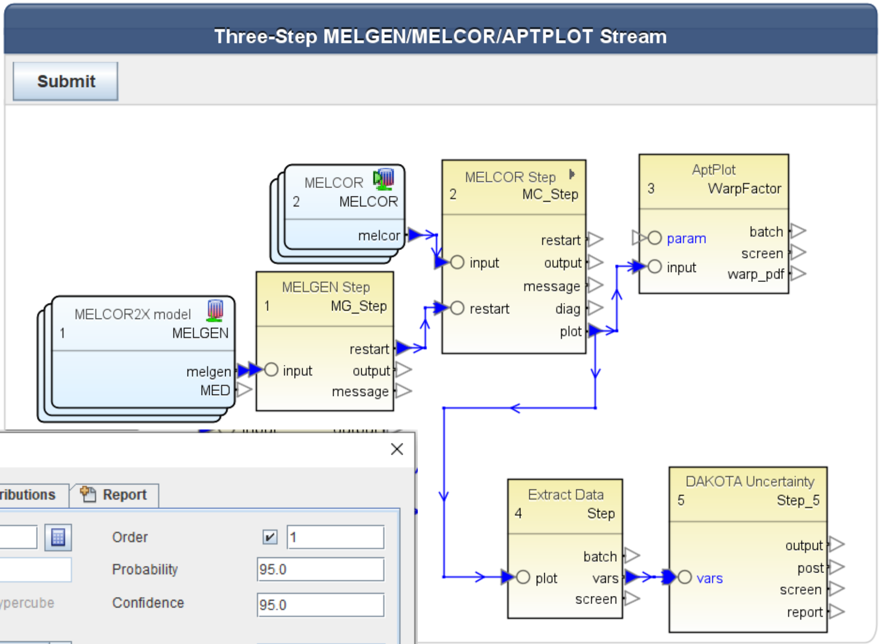
3 Uncertainty Analyses

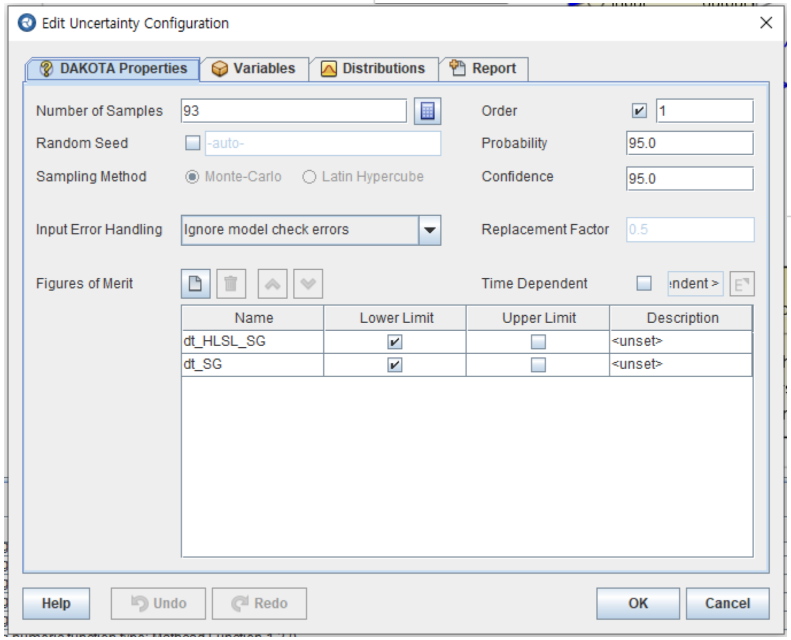
» DAKOTA UQ analysis (SNAP with MELCOR)

- An automated tool managing UQ analyses
- Automatic sampling, analyses, report
- Interface tool : SNAP 3.1.1
- Analysis : MELCOR 2.2
- Similar UQ tools

  -SUSA (GRS)

  -MOSAIQUE (KAERI)





Details of analyses

	Description
Uncertainty Methodology	Non-parametric
Number of Code run	93 (1^{st} order Wilk's formula, One sided)
Sampling methods	Monte-Carlo
Probability & confidence levels	95% probability, 95% confidence level
Sensitivity analyses	Pearson, Spearman

4 Base Case Results

Sequence of events

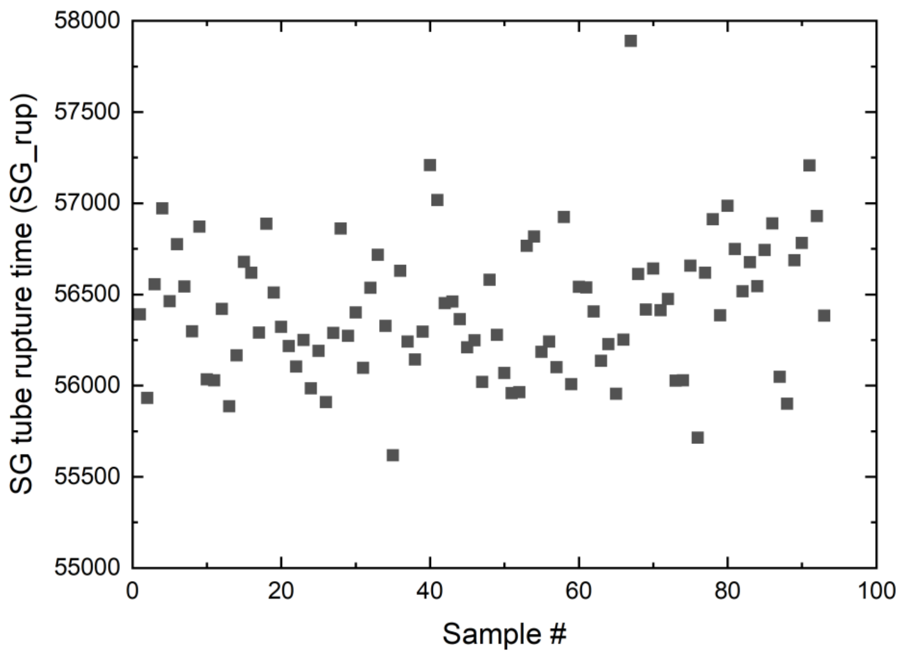
- AFW supplied for 8 hours
- When the CET reaches 650ºC, SAMG procedure starts.
- Operator opens the ADVs after 1800s from the start of SAMG procedure.
- When the ADVs open, the SG tubes ruptures by creep failure.
- Calculation terminated after the hot leg and the SG tubes are ruptured.

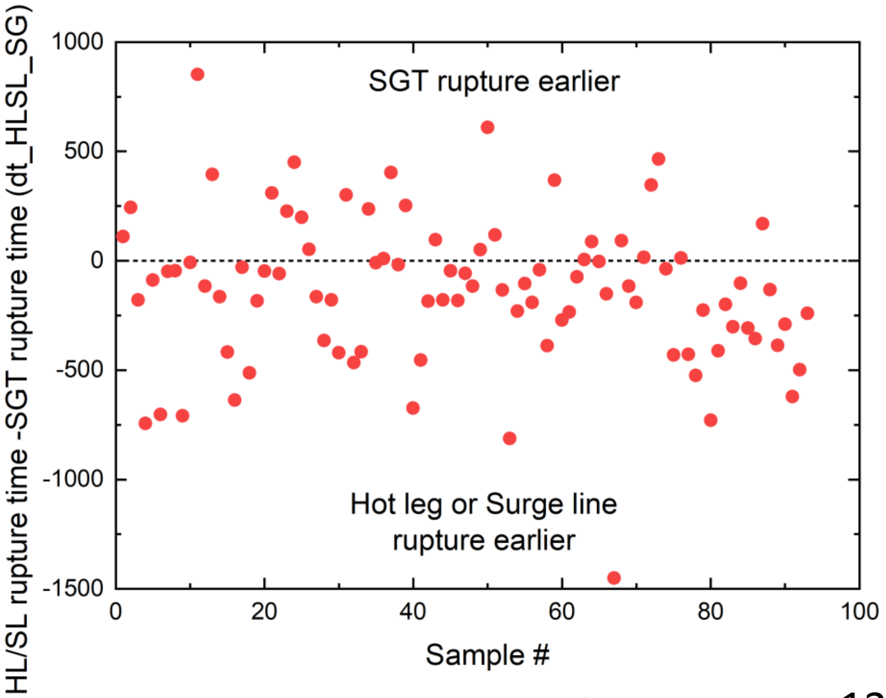
Events	Time(s(hr))
SBO occurs. Rx trips and MFW/RCP stops. AFW supply on	0
AFW depleted	28,800 (8.0)
SG A dryout	39,392 (10.9)
SG B dryout	39,500 (11.0)
POSRV(PRZ) open first	41,731 (11.6)
Core uncover start	47,901 (13.3)
Core Exit Temp = 650ºC SAMG procedure starts	49,300 (13.7)
Gap release starts	49,606 (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)

4 Results of UQ Analysis

» Major observation

- SG tube ruptures about 55,000 ~ 58,000 s from event initiation
- In 66/93 cases (about 71 %), the hot leg or the surge line ruptures earlier than SG tubes
- 95/95 level value : 851.9 sec (SG tube rupture occurs 851.9 sec earlier than HL/SL rupture)



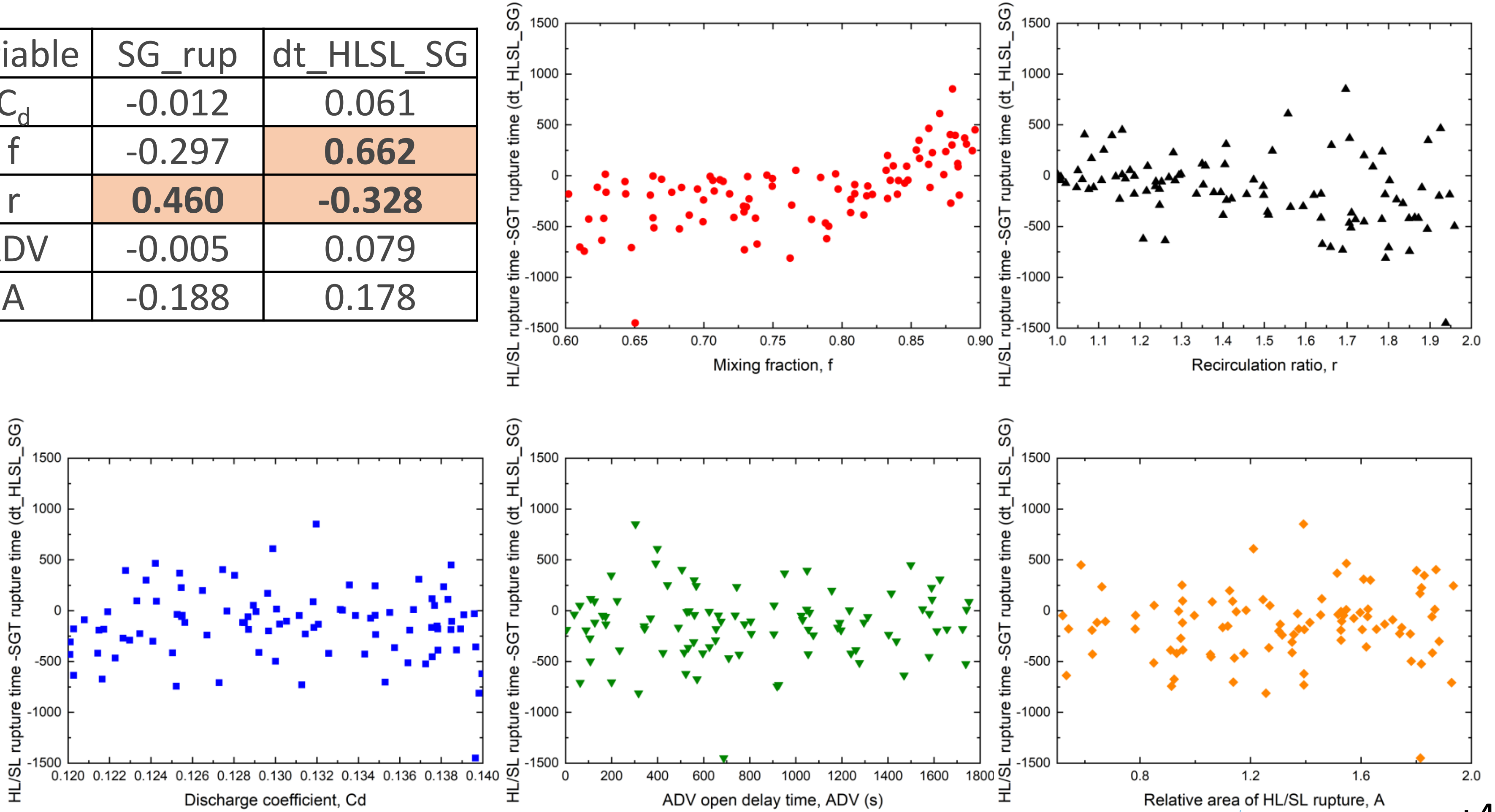


Pearson Correlation Coefficients

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

- Mixing fraction (f) and recirculation ratio (r) are relevant

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



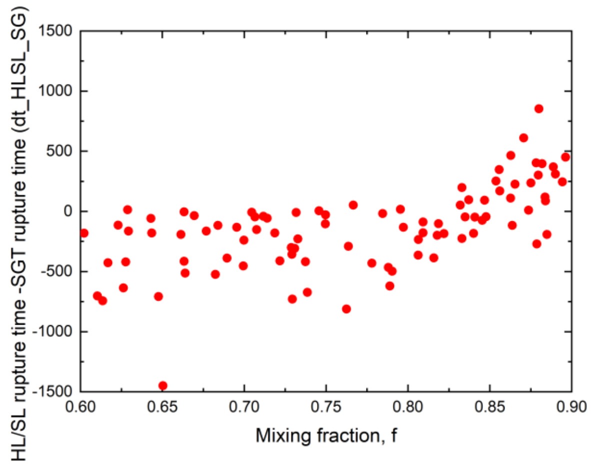
4 Sensitivity Analysis

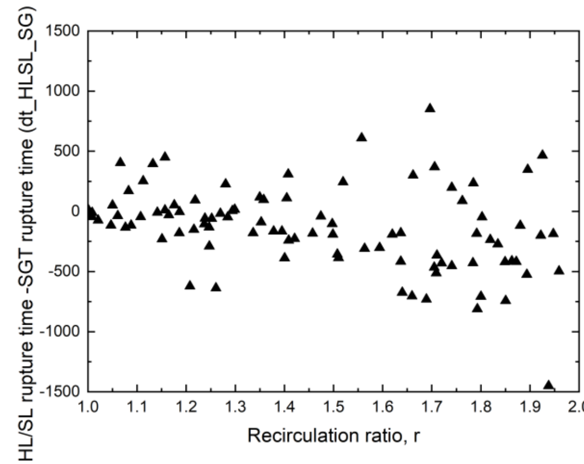
» Spearmann Correlation Coefficients

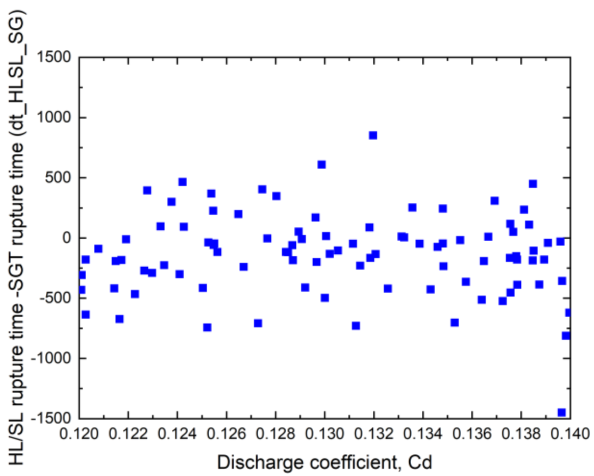
$$SCC = \frac{Cov(rank(X), rank(Y))}{\sigma_{rank(X)} \sigma_{rank(Y}}$$

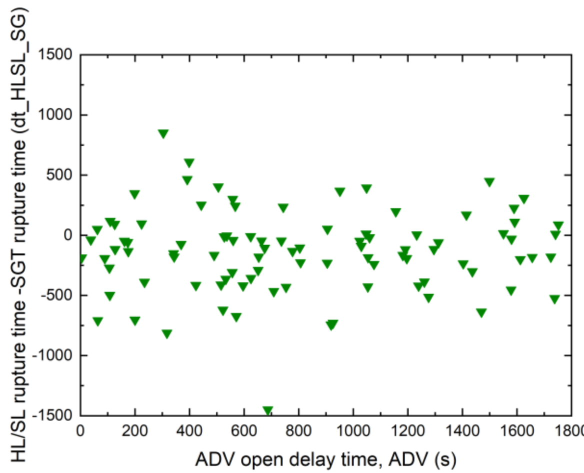
- Mixing fraction (f) and recirculation ratio (r) are relevant

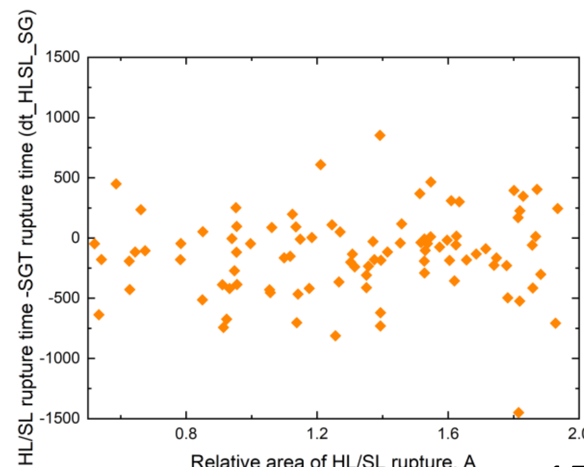
Variable	SG_rup	dt_HLSL_SG
C_d	-0.039	0.075
f	-0.317	**0.679**
r	**0.444**	**-0.417**
ADV	-0.017	0.097
A	-0.215	0.189











5 Summary

Uncertainty Analysis for SG tube rupture for C-SGTR

- For a given condition in APR1400 type reactor, SG tube ruptures about 55,000 ~ 58,000 s from event initiation from SBO scenario.
- In 66/93 cases (about 71 %), the hot leg or the surge line ruptures earlier than SG tubes
- 95/95 level value : 851.9 sec (SG tube rupture occurs 851.9 sec earlier than HL/SL rupture)
- Among the selected input variables, the mixing fraction & the recirculation ratio are relevant to the results

Next plan

- Determines the parameters of natural convection coefficients.
- UQ for fission product : FOM as fission product release to environment.

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THANK YOU