Analytical Study of Joule-Thomson Effect on Aerosol Retention during SGTR accident

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CONTENTS

01 Introduction

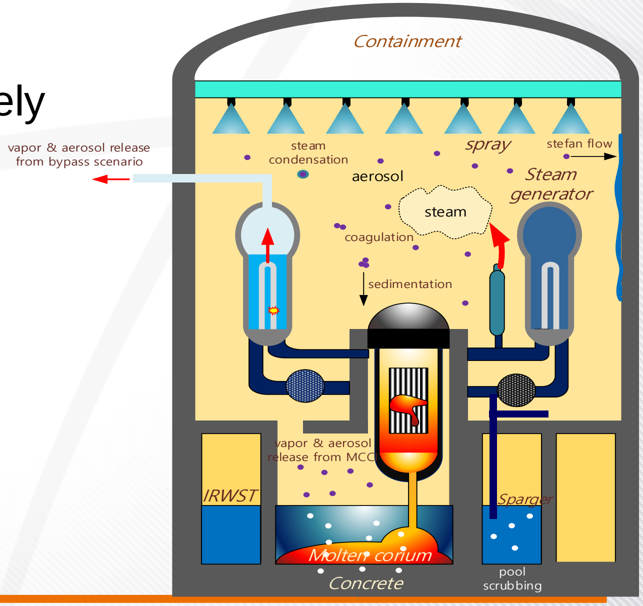
❖ Containment bypass accident

- Low probability, serious consequence

- Steam generator tube rupture (SGTR) accident is a representative accident

- Evaluation of the amount of radionuclides in the environment has become important
  - Severe Accident in Fukushima
  - Nuclear Safety Act amendment
    - ✓ Dose rate at site boundary < 250 mSv
    - ✓ Frequency of accident with Cs-137 release of more than 100 TBq < 10^{-6}/ry

- It is necessary to evaluate the amount of radionuclides released to environment during the SGTR accident accurately
  - Accident scenario/analysis
  - Fission product retention inside steam generator
  - Fission product retention in the pipes
  - Accident management strategy: pool scrubbing

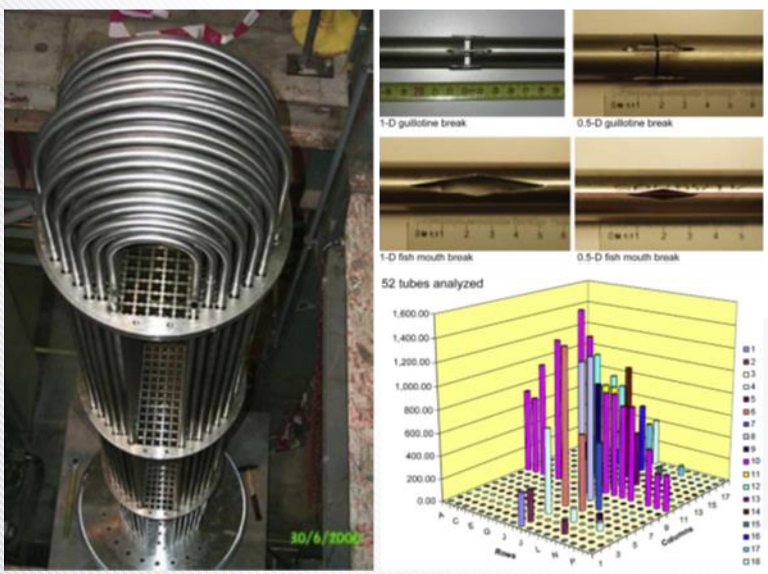


01 Introduction

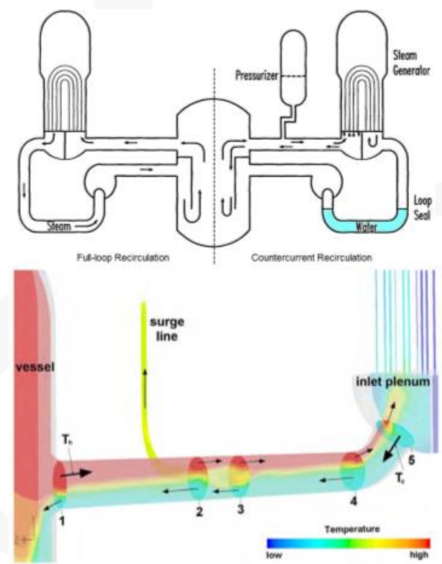
❖ Previous Researches on SGTR accident

2000 | 2010 | 2020

- 198x-200x: SGTR research by USNRC
- 1988-2010: PHEBUS FP programme
- 2000-2002: EU 5th Framework
- 2003-2011: ARTIST
- 2011: FK accident
- 2015-2018: BSAF2
- 2016-2019: STEM2
- 2017-2021: SGTR research in KAERI
- 2019: AMP submit
- 2019-2021: ARC-F
- 2019-2023: MUSA
- 2020-2024: THEMIS



<ARTIST project in PSI>



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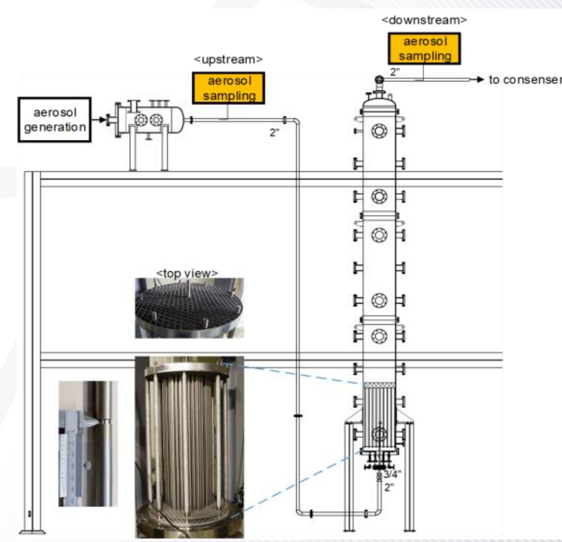
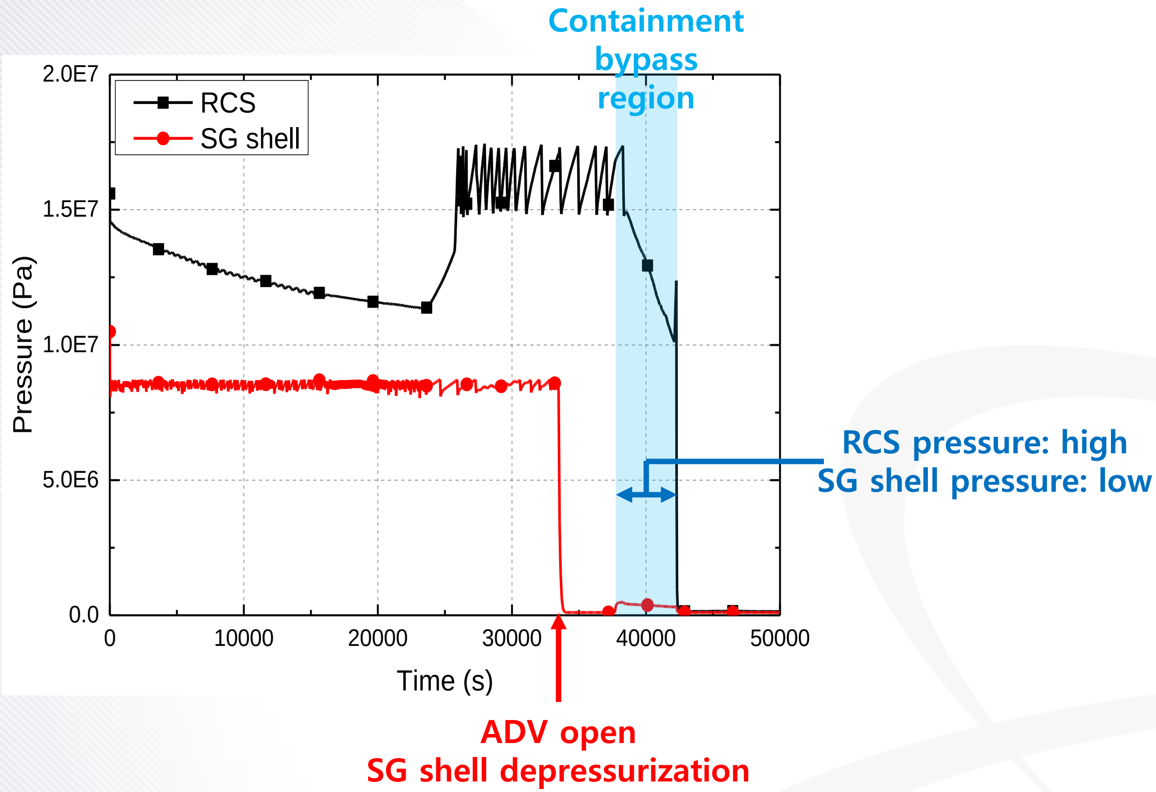
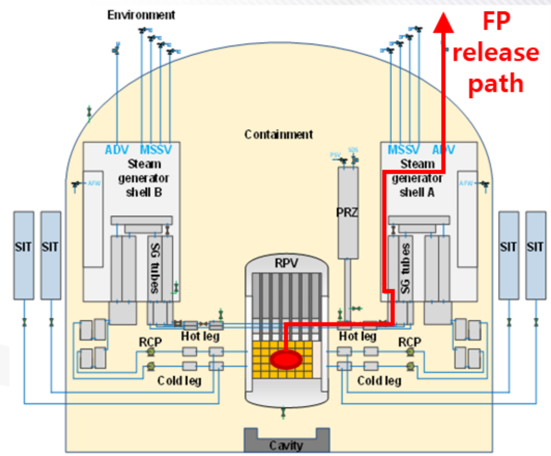


<SGTR experiment in KAERI>

02 Accident scenario





Event	Time (s)
SBO accident	0.0
RCP trip	0.94
AFW start / stop	1897.0 / 16297.0
Water mass in both SGs< 700 kg	27491.8
SAMG entry condition	31690.0
ADV open in both SGs	33490.2
Fuel gap release start	34553.7
SGTR accident occurrence	37692.3
Fuel candling begin	39217.0
Lower head failure	42265.8
SIT operation start / stop	42283.4 / 42581.0
Calculation end	50000.0

❖ Containment bypass region

- Large pressure difference between RCS and SG shell
- Small size hole with SG tube rupture (1 tube rupture)
- Throttling effect can occur during the period
- Gas temperature can be changed and it can affect the fraction of aerosol type fission products
- More fission products can be removed inside SG with aerosol type

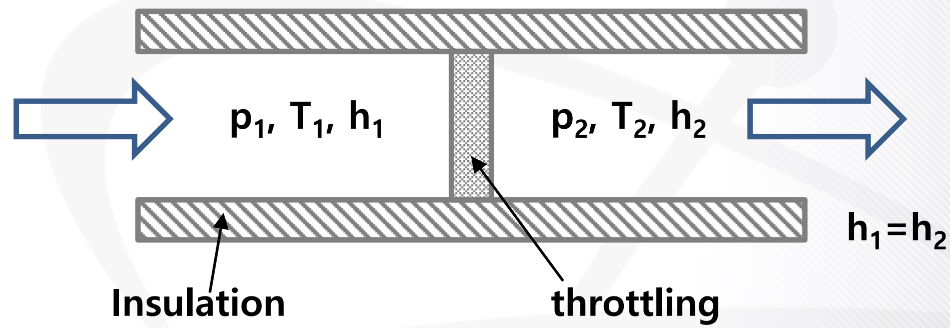
02 Throttling effect (Joule-Thomson effect)

❖ Throttling effect (Joule-Thomson effect)

- When a compressed gas releases occurred through a small hole, it then expands to a low pressure and the gas temperature falls on account of the performance by the gas of internal work in expanding against the forces of attraction between the molecules
- In such an expansion process, there is no change in kinetic energy of the gas, and the enthalpy of the gas before and after expansion remains constant since the process takes place adiabatically.
- When the pressure of a gas changes by an amount dp on passing a throttle or expansion valve, the temperature is changed by an amount of dT

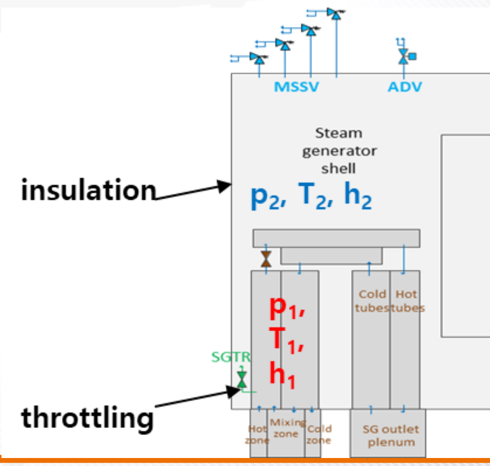
Joule-Thomson coefficient

$$\mu_{JT} = \left(\frac{\partial T}{\partial P}\right)_h = \frac{v}{C_p}(\alpha T - 1)$$



❖ SGTR accident condition

- High pressure gases inside SG tubes are released to SG shell
- Pressure difference is high enough to consider the Joule-Thomson effect
- Gas composition could be different with time due to hydrogen generation (different J-T coefficient)
- Gas temperature can be changed with considering the J-T effect



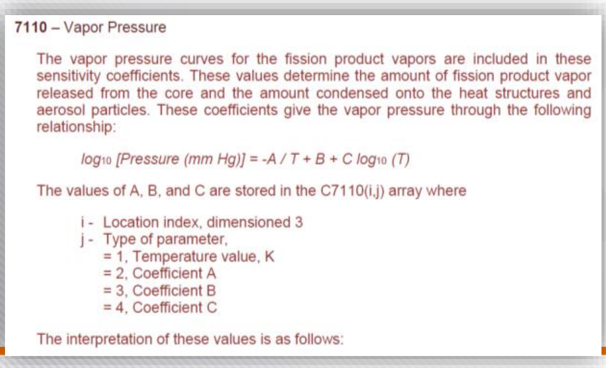
02 Vapor pressure of radionuclides

- Although the amount of temperature variation can be lower than 100 K, it could be important in a point of view of fission product release to environment
  - the effect could be increased as the gas temperature increases

- The gas temperature can affect the amount of aerosol type fission products because the vapor pressure of radionuclides is increased with temperature

- The quantity of aerosol type radionuclides can affect the total amount of released fission products to environment, because of aerosol retention inside steam generator
  - Aerosol type radionuclides have a certain range of decontamination factor (DF) passing the SG
    - ✓ Impaction to SG tubes
    - ✓ Turbulent deposition
  - on the other hand, there is no DF in case of gas phase fission product

- Vapor pressure data in MELCOR 2.2 user's manual was employed in this study
  - sensitivity coefficient 7110



7110 – Vapor Pressure

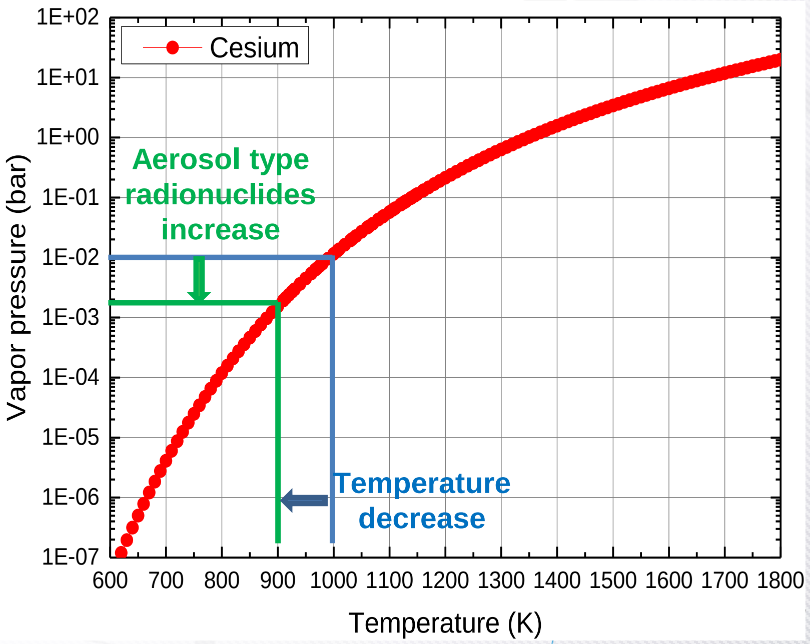
The vapor pressure curves for the fission product vapors are included in these sensitivity coefficients. These values determine the amount of fission product vapor released from the core and the amount condensed onto the heat structures and aerosol particles. These coefficients give the vapor pressure through the following relationship:

$\log_{10}$ [Pressure (mm Hg)] = -A / T + B + C $\log_{10}$ (T)

The values of A, B, and C are stored in the C7110(i,j) array where

i - Location index, dimensioned 3
j - Type of parameter,
= 1, Temperature value, K
= 2, Coefficient A
= 3, Coefficient B
= 4, Coefficient C

The interpretation of these values is as follows:

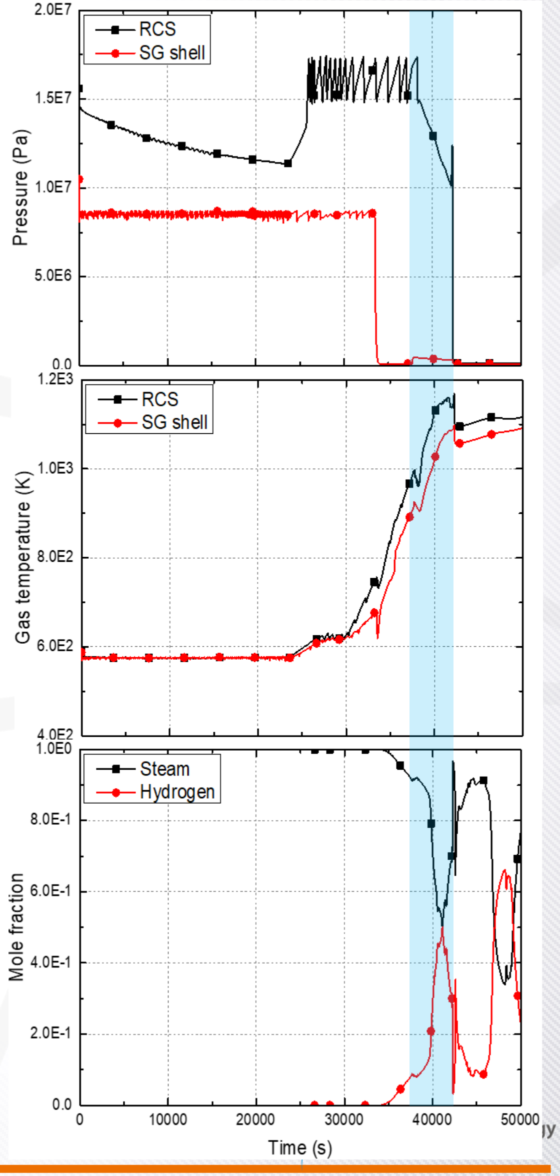


03 Results

- Thermal hydraulic data(pressures, temperatures, gas mole fraction) were summarized in every thousand seconds after the SGTR accident and before the lower head failure

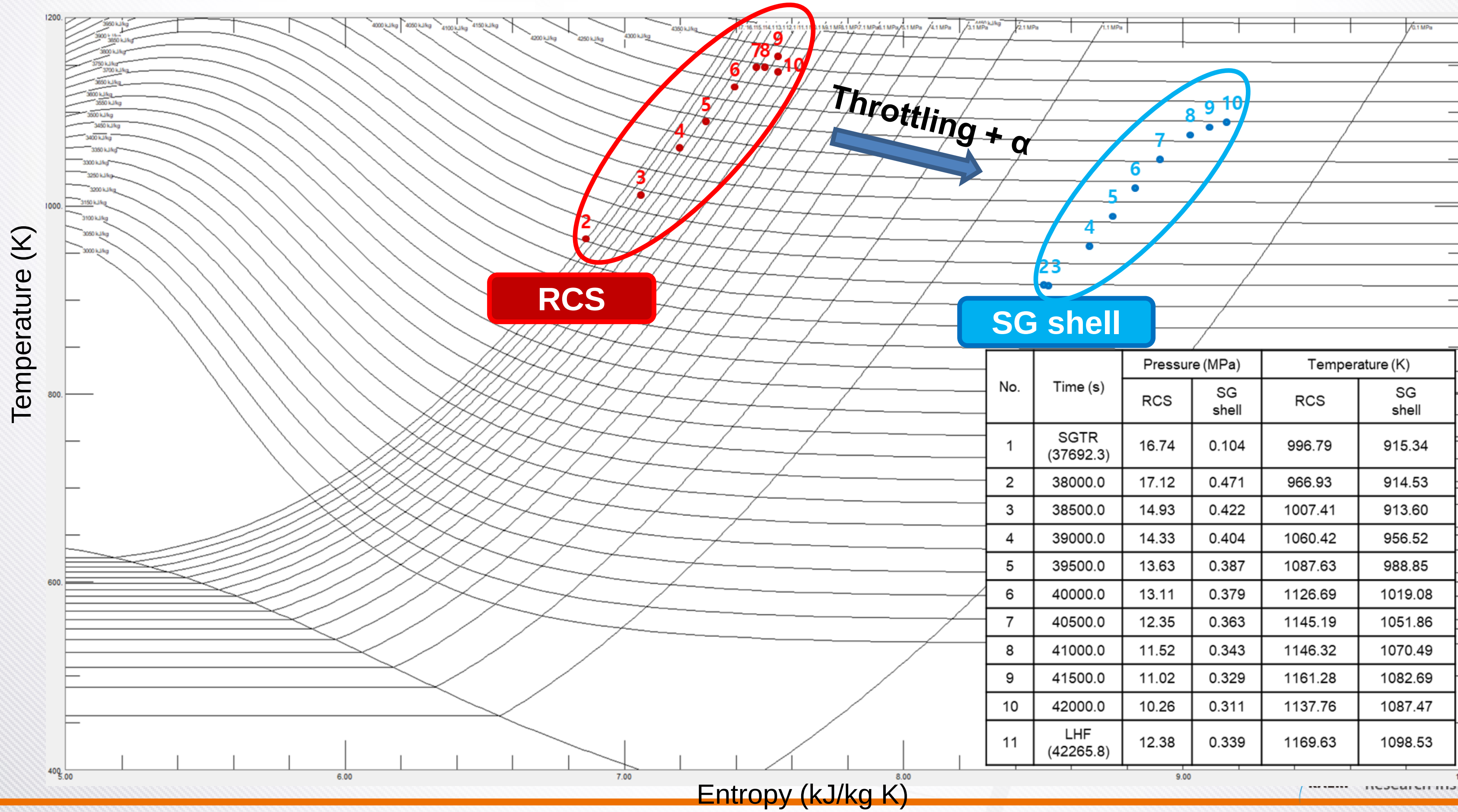
- Gas pressure in the primary and SG shell at the SGTR occurrence were 16.74 and 0.104 MPa, and it was decreased to 12.38 and 0.339 MPa, respectively
  - large pressure difference over than 10 MPa

No.	Time (s)	Pressure (MPa)		Temperature (K)	
		RCS	SG shell	RCS	SG shell
1	SGTR (37692.3)	16.74	0.104	996.79	915.34
2	38000.0	17.12	0.471	966.93	914.53
3	38500.0	14.93	0.422	1007.41	913.60
4	39000.0	14.33	0.404	1060.42	956.52
5	39500.0	13.63	0.387	1087.63	988.85
6	40000.0	13.11	0.379	1126.69	1019.08
7	40500.0	12.35	0.363	1145.19	1051.86
8	41000.0	11.52	0.343	1146.32	1070.49
9	41500.0	11.02	0.329	1161.28	1082.69
10	42000.0	10.26	0.311	1137.76	1087.47
11	LHF (42265.8)	12.38	0.339	1169.63	1098.53



03 Results

- The states of the RCS and SG shell were indicated in Temperature-Entropy (T-s) diagram of steam
  - ✓ Mole fraction of steam during the SGTR duration was varied with hydrogen generation, but only 100% steam was assumed in this analysis for simplicity
  - ✓ Steam and hydrogen have different Joule-Thomson coefficients, so it can affect the temperature behavior with throttling process



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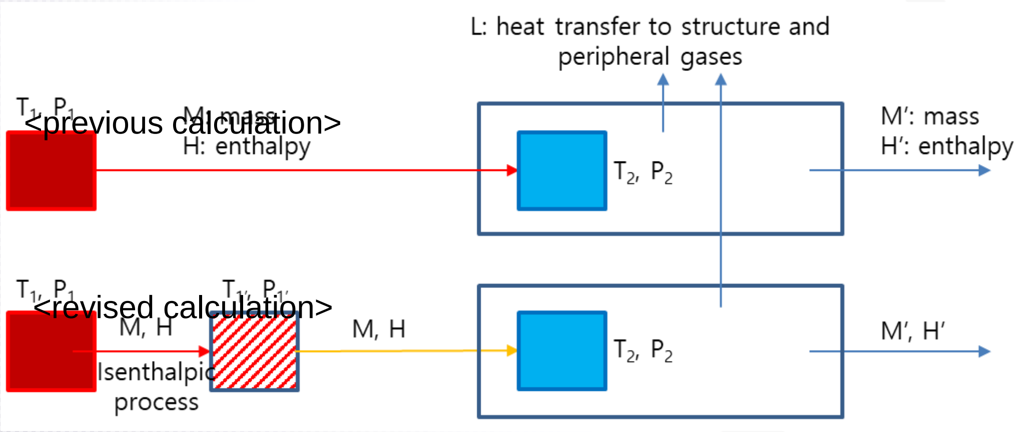
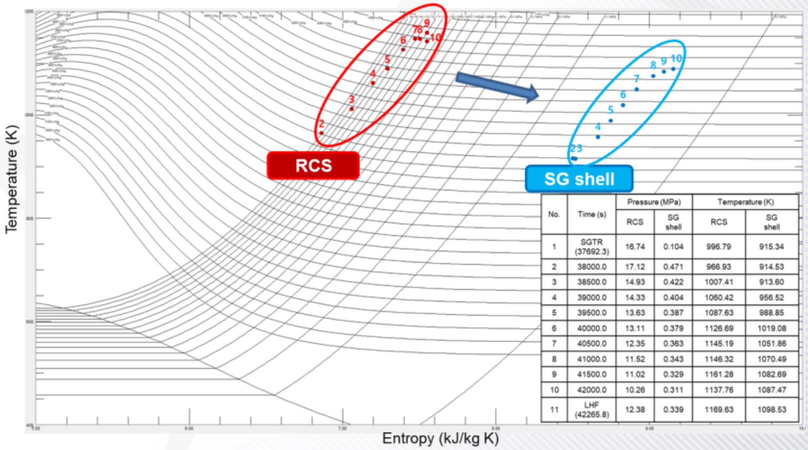
03 Results

- Comparison of paths from the RCS region to SG shell region
  - Previous calculation in the system code, such as MELCOR, only considered mass and energy conservation equations
  - In the revised calculation, isenthalpic process is added in the calculation
    - ✓ It is not affect the thermal hydraulic results of the analysis, but may affect the fission product behavior results





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03 Results

- Aerosol type fission product mass increase
  - Cs is chosen as a representative radionuclide in this analysis (molecular weight was assumed to 133)

$$P_a V = n_a RT \qquad \Delta m_a = (n_{initial} - n_{final}) M_a$$

  - Gas temperature was obtained with considering J-T coefficient in the isentropic process
  - Increased aerosol mass was calculated with ideal gas state equation
  - To estimate the removed aerosol mass in the SG, previous study results were referred
    - ✓ PSI and KAERI experimental data

No.	Time (s)	mole number (mole)			Temperature (K)		J-T Coefficient (K/Mpa)	ΔT with and without J-T effect (K)	Increased the number of aerosol mole (mol)	Increased aerosol mass (g)	Removed aerosol mass (g) (DF=4)
		RCS	J-T effect	SG shell	J-T effect	SG shell					
1	SGTR (37692.3)	0.570805	5.622218	5.888904	958.7584	915.34	2.2861	38.03156	0.2667	35.4692	26.6019
2	38000	0.337295	5.722044	5.791154	925.5755	914.53	2.4839	41.35445	0.0691	9.1916	6.8937
3	38500	0.682399	5.323082	5.680689	974.9759	913.6	2.2356	32.43408	0.3576	47.5616	35.6712
4	39000	1.565648	12.24001	13.22427	1033.437	956.52	1.9376	26.98302	0.9843	130.9066	98.1800
5	39500	2.313108	21.99912	23.66453	1063.709	988.85	1.8063	23.92083	1.6654	221.4989	166.1242
6	40000	3.899715	36.17938	39.26123	1105.888	1019.08	1.634	20.80245	3.0818	409.8850	307.4137
7	40500	4.922811	61.14307	65.47997	1126.469	1051.86	1.5618	18.7213	4.3369	576.8069	432.6052
8	41000	4.991948	81.72488	86.18193	1128.872	1070.49	1.5611	17.44841	4.4571	592.7877	444.5908
9	41500	5.986315	96.96438	102.5618	1145.19	1082.69	1.505	16.08995	5.5974	744.4578	558.3433
10	42000	4.487846	106.3047	109.6631	1121.826	1087.47	1.6016	15.93432	3.3584	446.6684	335.0013
11	LHF (42265.8)	6.609468	121.7836	127.7065	1151.956	1098.53	1.4678	17.67378	5.9229	787.7401	590.8051

04 Conclusions and Plans

❖ Conclusions

- It was found that the quantity of removed aerosol inside the steam generator during the SGTR accident duration can be increased with considering Joule-Thomson effect

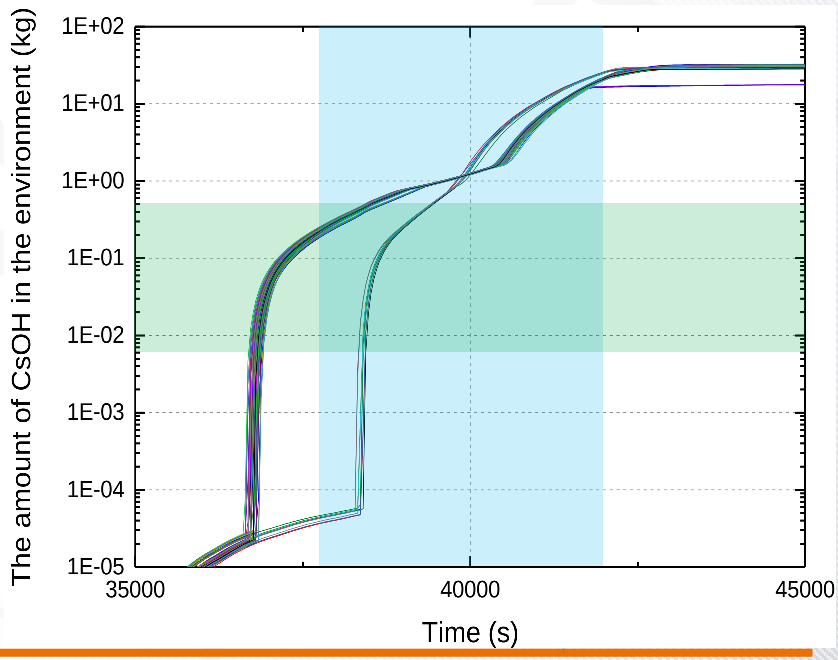
- The increased Cesium(Cs) masses in this analysis is located in the range of 6~558 g

- It can be seen that the J-T effect is noticeable at the beginning of the radionuclides release

❖ Plans

- Effect of gases mole fraction was not considered in this study. Hydrogen has a negative J-T coefficient and it is expected that the gas temperature would behave unlike in the only steam case

- The number of ruptured tube also could affect the temperature behavior. It will be also analyzed.



THANK YOU

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