2021 KNS Spring Meeting

Development of MELCOR Analysis for a TI-SGTR Accident in the OPR1000

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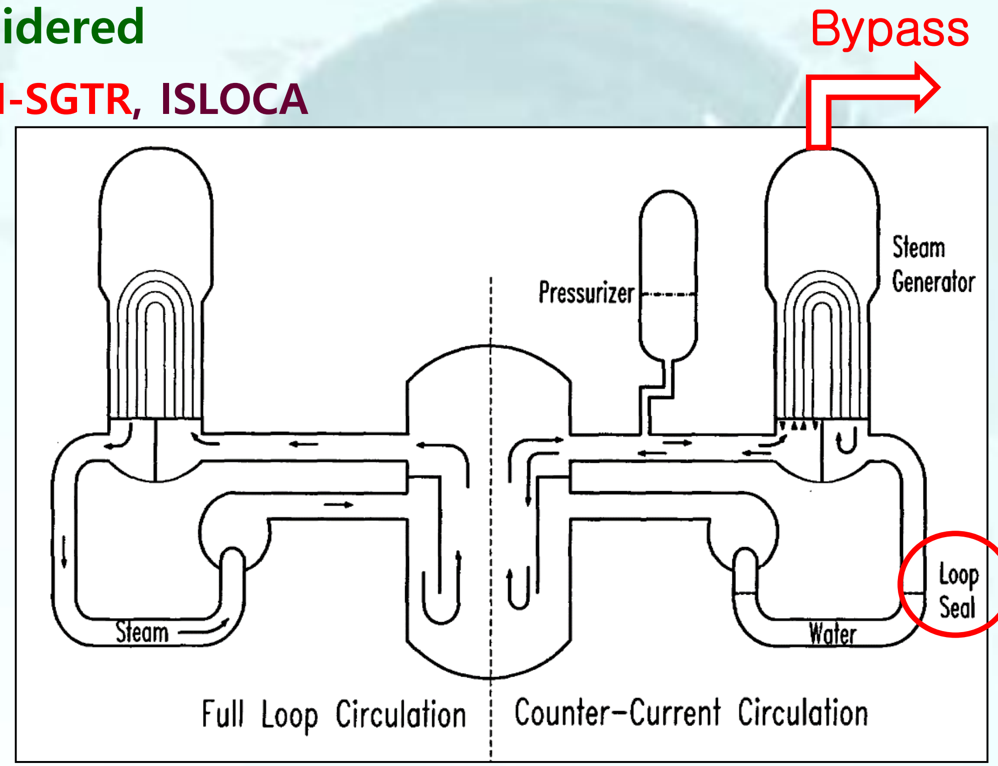
❑ Amendment of Nuclear Safety Action(2015)

- Accident Management Program(AMP) – Effective date: 23 June 2016
- Safety Target
  - Site boundary dose < 250 mSv
  - Release to environment : Cs-137, 100 TBq < 10^{-6}/ry
- Accidents should be considered
  - Containment bypass : TI-SGTR, ISLOCA

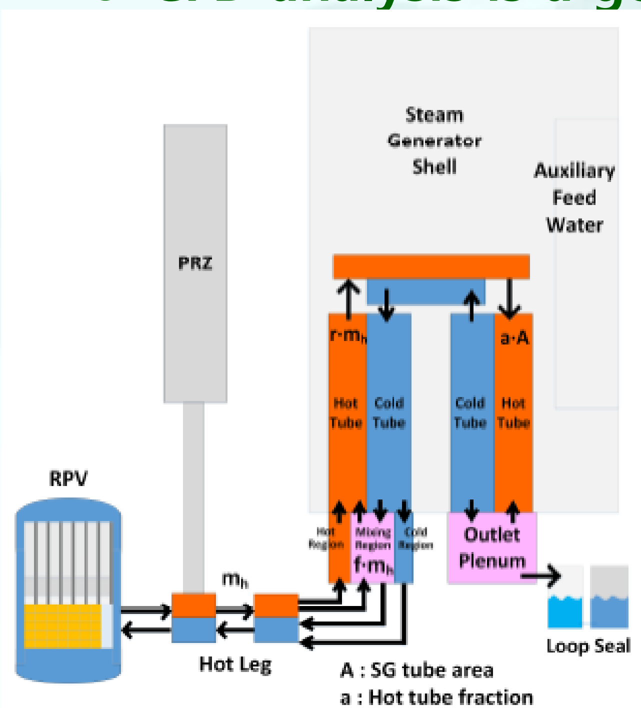
Fukushima accident (2011.3.)

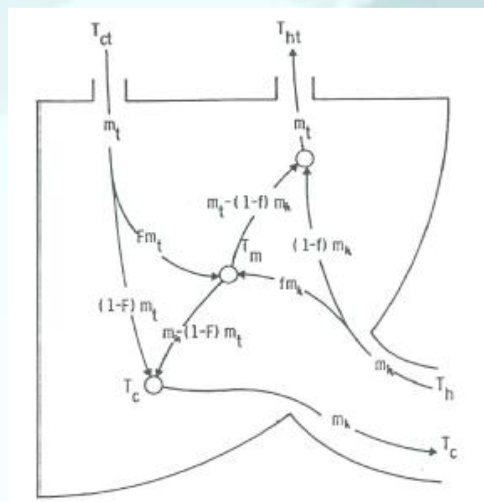


MELCOR Analysis

❑ Nodalization and Input Parameters for RPV & SG

- MELCOR is a lumped parameter code
- We need input parameters to simulate the counter-current flow in the hot-leg between the RPV and the SG
- CFD analysis is a good way to produce the input parameters





$$r = \frac{m_t}{m_h}$$

$$f = 1 - r\left(\frac{T_{ht} - T_m}{T_h - T_m}\right)$$

$$T_m = \frac{1}{1+r}\left[T_h + rT_{ct}\right]$$

$$m_h = C_d\left[g\bar{\rho}(\rho_c - \rho_h)D^5\right]^{1/2}$$

Analysis Methodology for Natural Circulation Flow

- **CFD Analysis Methodology using WH 1/7 Test Results**
  - We established CFD analysis methodology to produce the lumped parameter code's input parameters with an error range of about 10% compared to test data except the hot tube number. This methodology may be efficient when compared to the methods proposed by other institutes.
  - Transient calculation results used as the initial condition for the steady state calculation. This method can greatly reduce the computational time in the calculation of OPR1000 TI-SGTR

- **Development of the SG Model using OPR1000 Design Data**
  - Pressure drop data during the normal operation condition

WH 1/7 Test Facility

- WH 4 loop Plant(Indian Point II-1040 MWe) 참조
  - EPRI Report (TR-102815)

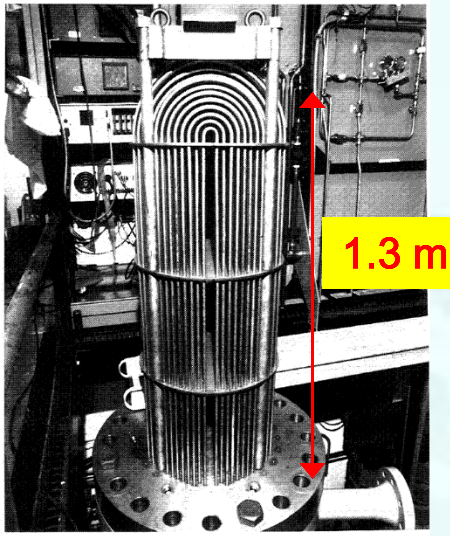
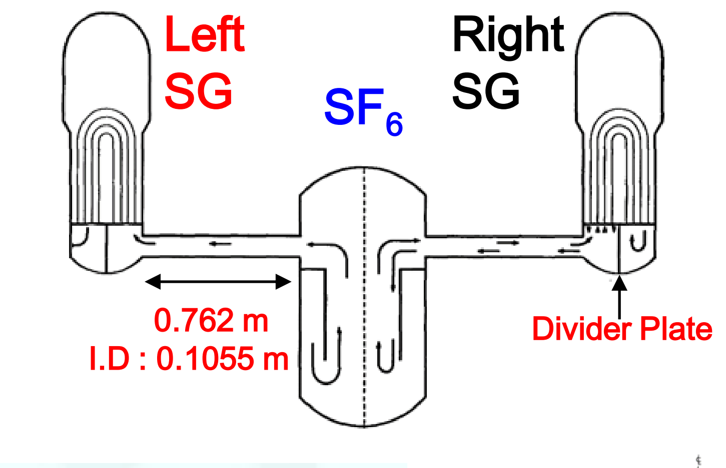
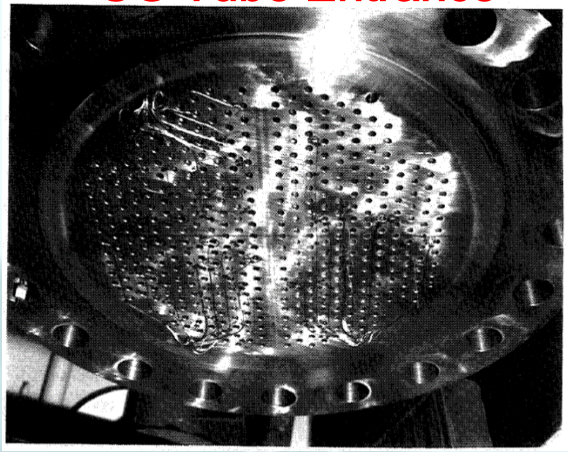


Figure 3-10. Left Side Steam Generator Without Shell Assembled.



SG Tube Entrance



SG tube # : 216

Tube I.D. : 7.75 mm

Axial / Cross Flow

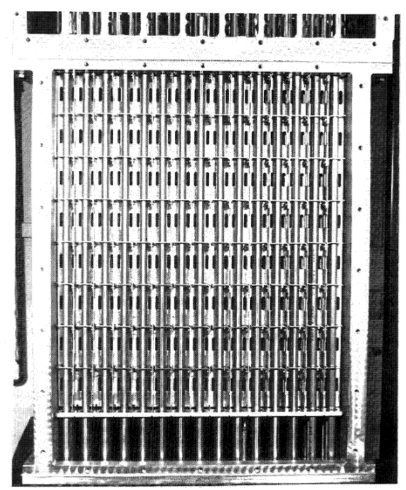
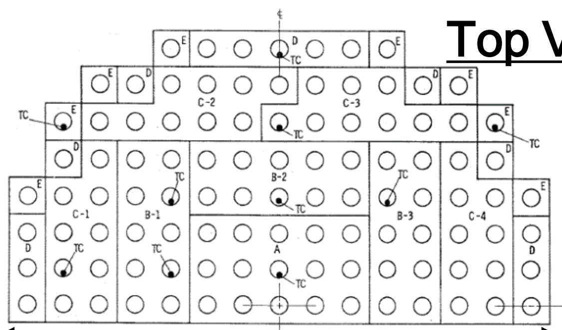


Figure 3-2. View of the Model Core Region With Its Fuel Assembly Models.

Top View



Section	P/P	Volts	Amps	kW
A	1.14	[illegible]	41.6	5.74
B-1	1.12	136	27.8	3.78
B-2	"	"	27.9	3.80
B-3	"	"	27.6	3.74
C-1	1.02	130	23.7	3.08
C-2	"	"	23.8	3.10
C-3	"	"	24.0	3.12
C-4	"	"	23.5	3.03
D	0.80	116	35.0	4.07
E	0.55	96	15.5	1.49
			TOTAL	34.95

Figure 3-3. Core Fuel Assembly Heater Sections and Power Distribution.

WH 1/7 Test Condition & Results

Left SG

Table 4-13

SUMMARY OF MODEL STEAM GENERATOR TESTS

S : Steady   T : Transient

Test Number	SG-S1	SG-S2	SG-S3	SG-S4	SG-T1	SG-T2	SG-T3	SG-T4
SF_6 Pressure (psia)	300	400	300	400	300	400	300	400
Core Power (kW)	22	22	30	30	22	22	30	30
Number of Hot Tubes	75	62	75	62	119	110	132	101
Number of Cold Tubes	141	154	141	154	97	106	84	115
Bundle Mass Flow (lb_m/s)	0.251	0.321	0.264	0.302	0.083	0.183	0.223	0.300
Hot Leg Mass Flow (lb_m/s)	0.115	0.180	0.132	0.178	0.044	0.080	0.098	0.132
m_t (bundle)/m (hot leg)	2.18	1.78	2.01	1.69	1.88	2.39	2.28	2.10
Mixing Fraction, f	0.87	0.89	0.85	0.85	0.78	0.83	0.76	0.86
$(T_{ht}-T_m)/(T_h-T_m)$	0.06	0.06	0.07	0.09	0.12	0.07	0.10	0.06
$(T_{ht,max}-T_m)/(T_h-T_m)$	0.18	0.14	0.16	0.15	0.28	0.26	0.27	0.27
$(T_{ht,max}-T_{ht})/(T_h-T_{ht})$	0.13	0.09	0.10	0.07	0.18	0.20	0.18	0.23
$\Delta T_{ht,tubesheet}/(T_h-T_{ht})$					-0.15	-0.05	-0.08	-0.06
Flanges Heater Power (kW)	-	-	-	-	2.06	2.93	2.60	3.36
Flanges Power/Flanges Heating	-	-	-	-	0.81	0.93	0.70	0.80

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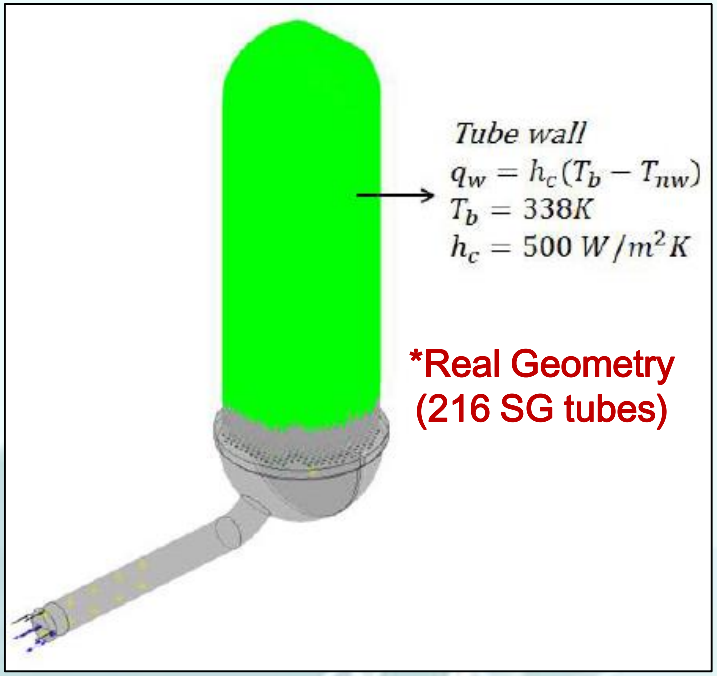
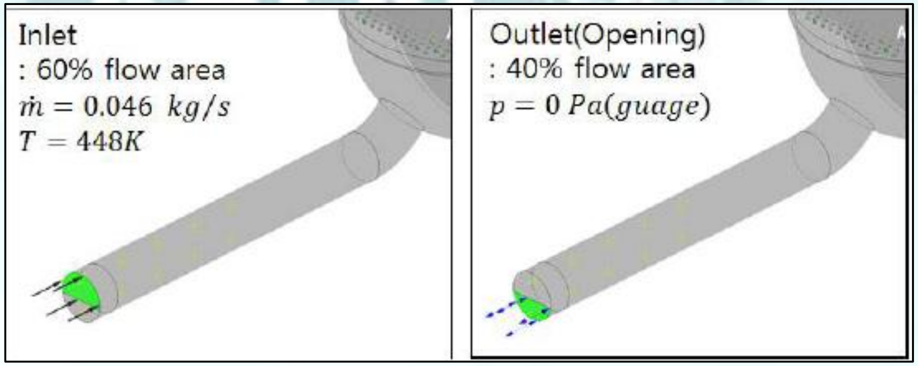
$$m = q_{SG}/\bar{C}_p\,(\bar{T}_{h,out} - \bar{T}_{c,in})$$

CFD Analysis for WH 1/7 Test (1)

❑ Analysis Methodology

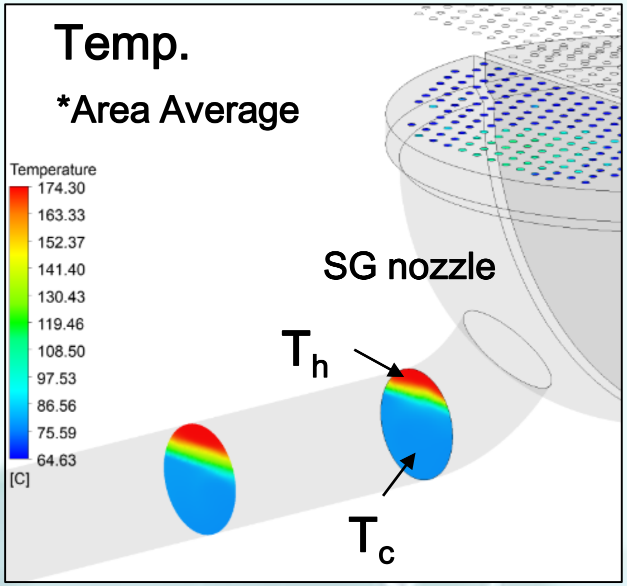
- NUREG-1781, PSI 논문 참조
- Numerical model
  - N-S momentum eq.
  - SST turbulent model
    - Buoyancy turbulence generation
  - Energy eq.
    - Heat transfer coeff. at tube walls
  - Steady state calculation
    - Initial condition from transient calculation of 200 sec
  - Convergence criteria
    - Residual < 2.5×10^{-4}
- Grid Model
  - 29,025,136 elements (base)

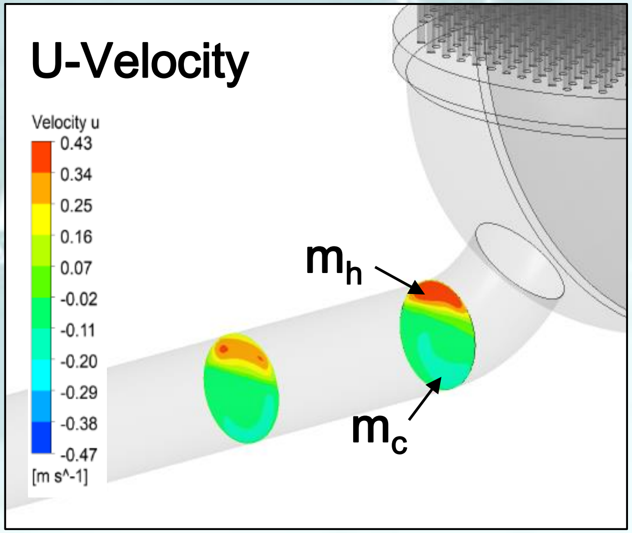




❑ MELCOR Input Parameters

Parameters	Test	CFD			
		Case-1		Case-2	Case-3
		P_{kb}	No P_{kb}		
SG Heat Loss (kW)	3.56	3.55	2.10	3.43	3.59
T_h (℃)	159.3	151.3	116.2	149.9	154.7
T_c (℃)	86.8	78.7	81.7	79.8	80.6
T_{ht} (℃)	100.8	100.3	91.2	98.4	99.8
T_{ct} (℃)	64.7	64.7	64.7	64.8	64.7
T_m (℃)	96.2	94.0	83.8	93.5	94.5
m_h (kg/s)	**0.059**	**0.055**	**0.054**	0.058	0.058
m_t (kg/s)	**0.119**	**0.107**	**0.092**	0.113	0.117
r	2.01	1.95	1.70	1.95	2.01
f	0.85	0.78	0.60	0.83	0.82
C_d	0.110	0.107	0.115	0.113	0.110
# Hot Tubes	75	56	57	61	63
# Cold Tubes	141	160	159	155	153





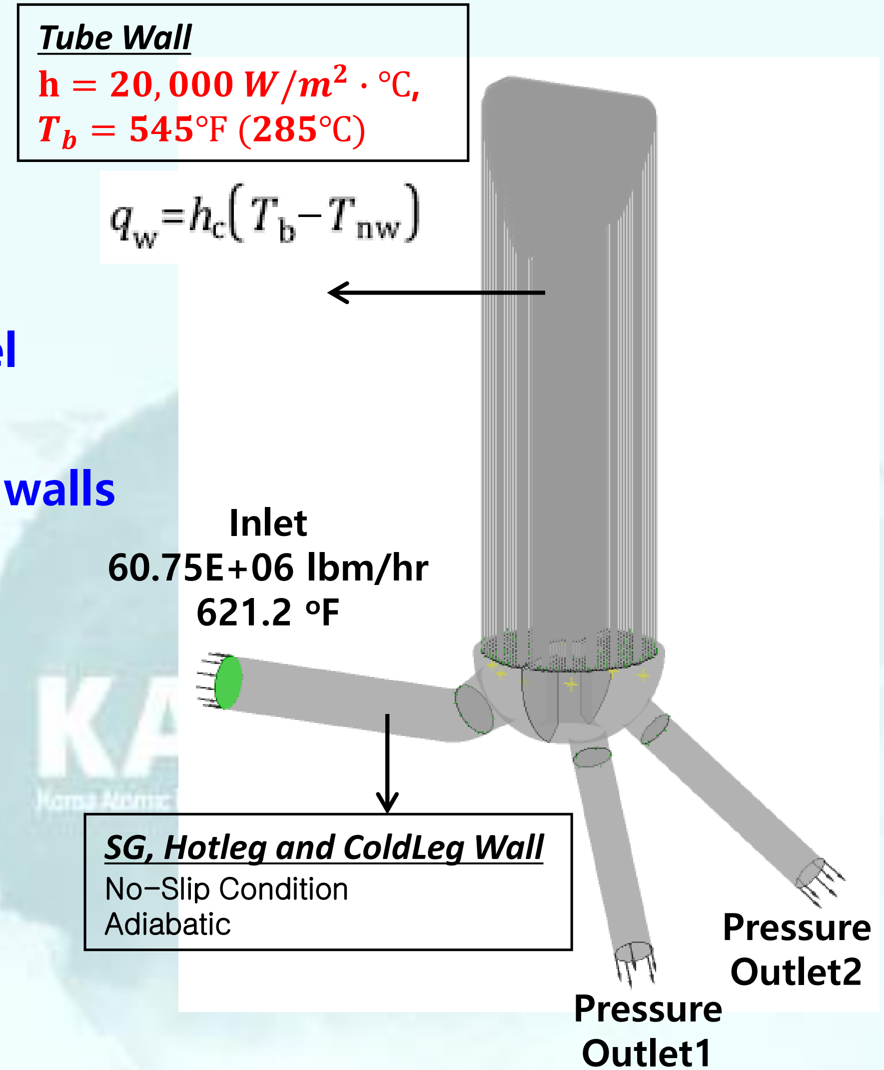
Steady : m_h[kg/s] = m_c[kg/s]

CFD Analysis for OPR1000 SG Model (1)

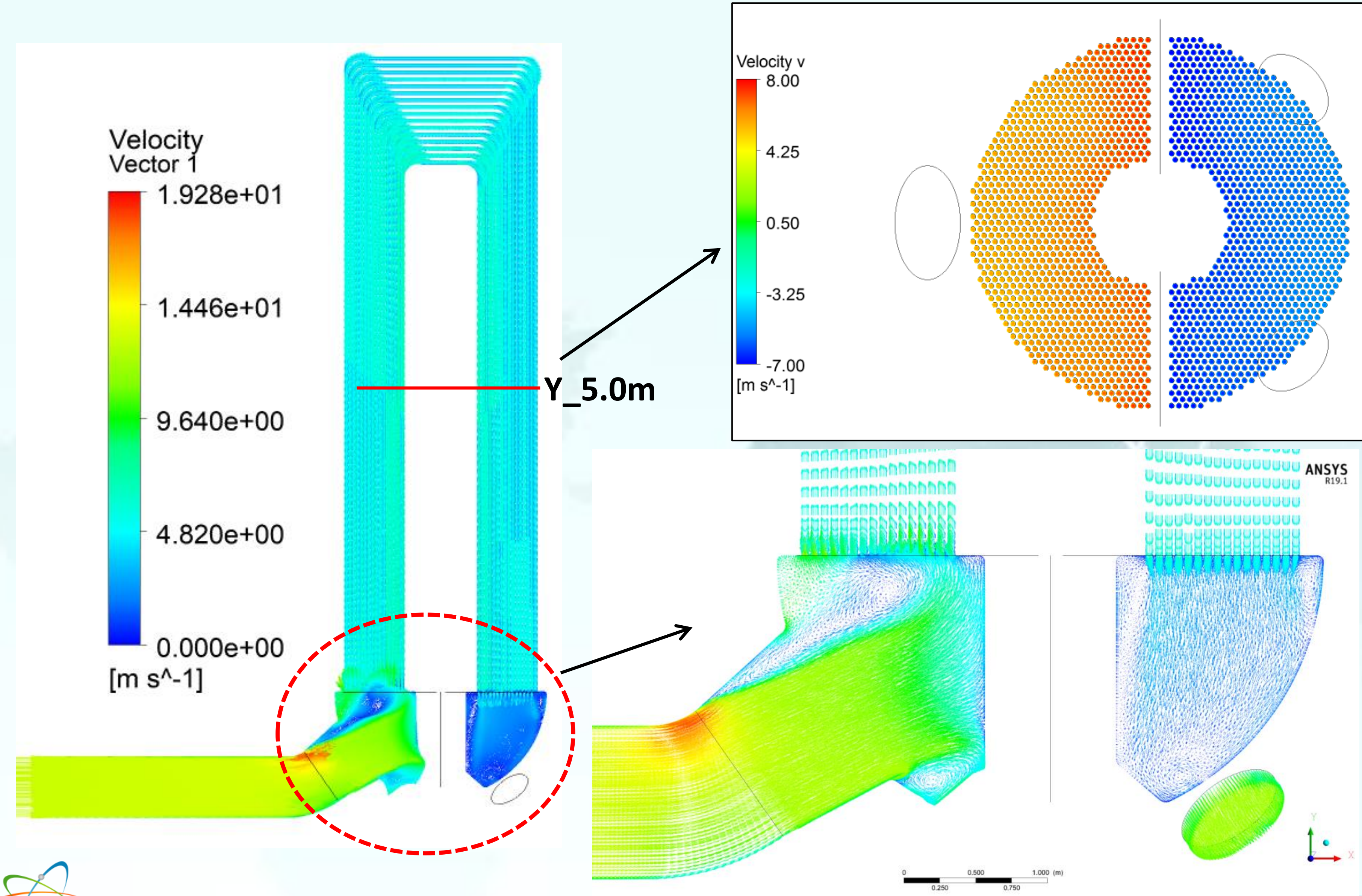
❑ OPR1000 SG Model

❍ CFD Analysis Model

- N-S momentum eq.
- Standard k-ε turbulent model
  - Scalable wall function model
- Energy eq.
  - Heat transfer coeff. at tube walls
- Inlet condition : Mass flow
  - Normal operation
- Outlet condition : Pressure
- Steady state calculation
  - Parallel computation
  - 100 CPUs
- Convergence criteria
  - Residual < 10^{-4}



CFD Analysis for OPR1000 SG Model (2)



CFD Analysis for OPR1000 SG Model (3)

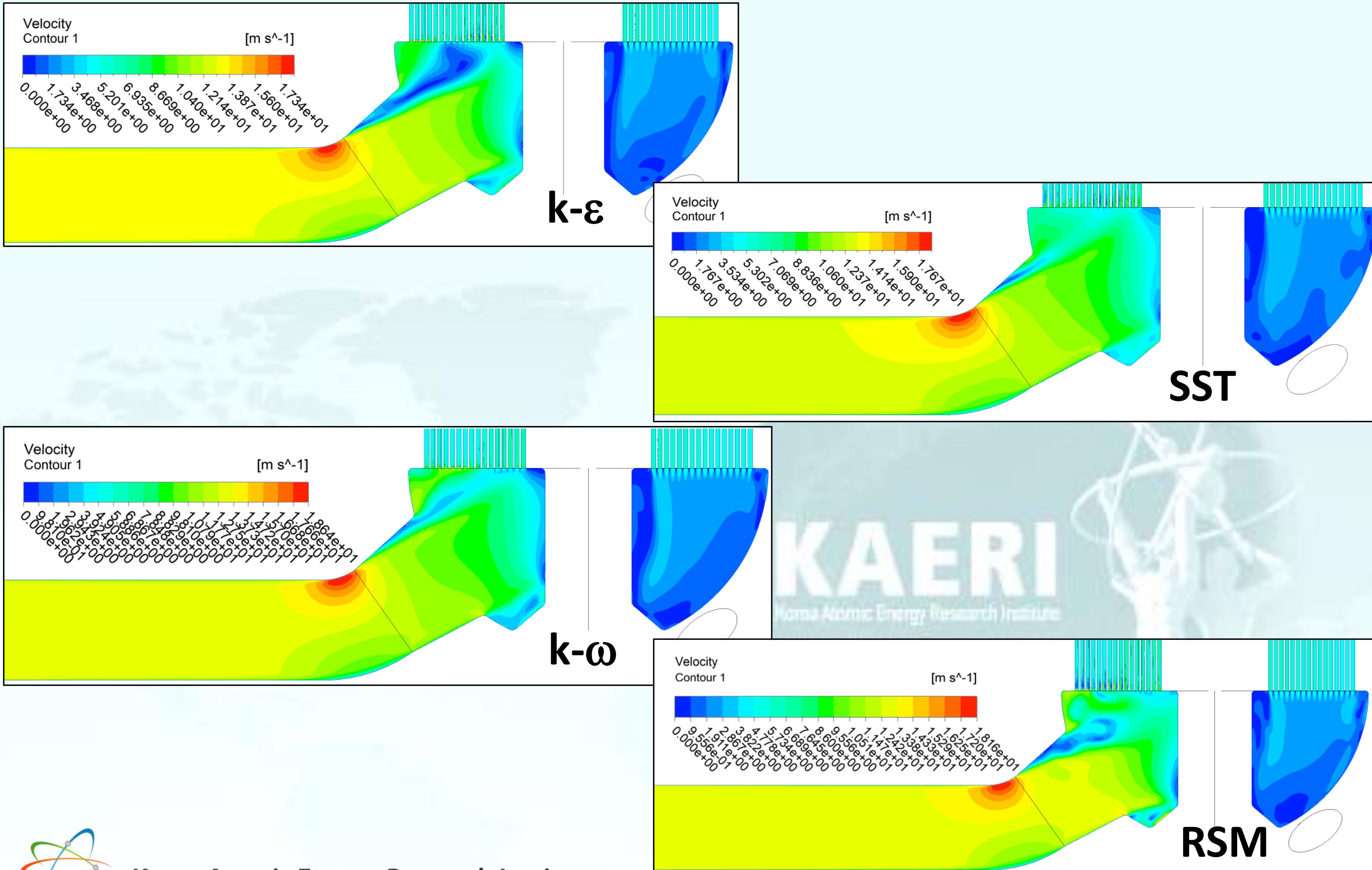
❑ Turbulent Model Sensitivity Calculation Results

*Unit : psi, 1 psi = 6895 Pa, 100% Flow Condition (60.75 × 10^6 lbm/hr)

OPR1000	SST	Standard k-ε	k-ω	RSM
SG ΔP Total	**30.01**	**31.56**	**30.97**	30.66
ΔP ①(Inlet Plenum)	1.65	3.28	2.34	1.51
ΔP ②(Tube)	27.54	27.16	27.72	28.41
ΔP ③(Outlet Plenum)	0.82	1.12	0.91	0.74

OPR1000	SST	Standard k-ε	k-ω	RSM
Temperature (Outlet, Cold Leg)	**564.3** ℉	**564.8 ℉**	**564.40 ℉**	**564.82 ℉**
Temperature (Inlet, Hot Leg)	**621.2 ℉**	**621.2 ℉**	**621.2 ℉**	**621.2 ℉**

CFD Analysis for OPR1000 SG Model (4)

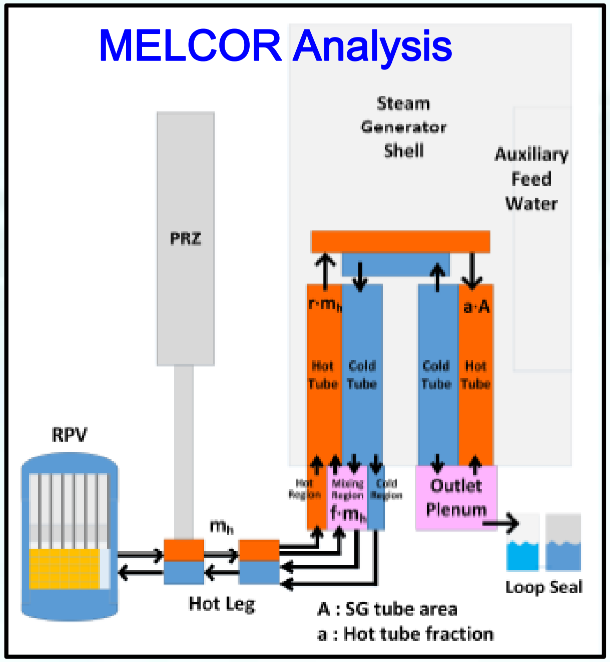


CFD Analysis for OPR1000 TI-SGTR (1)

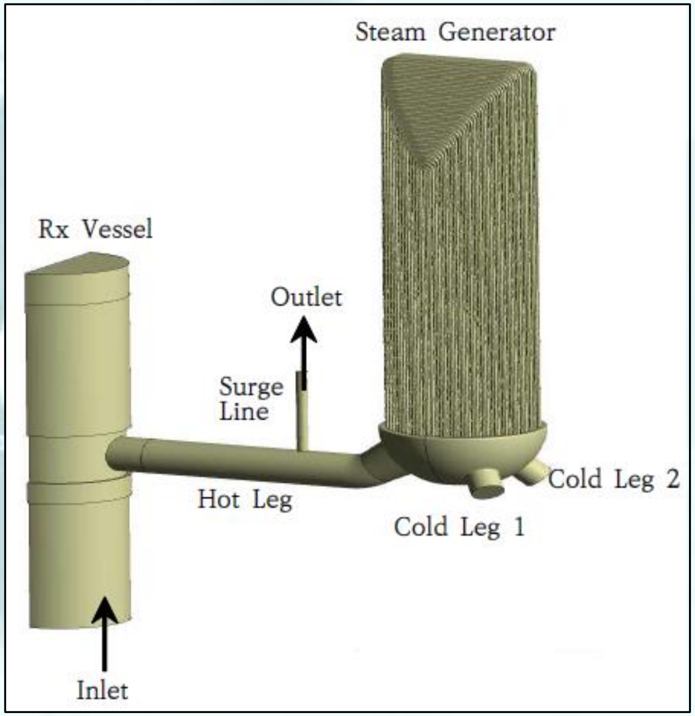
❑ Boundary Conditions in the OPR1000 TI-SGTR Analysis

❍ Reference : NUREG-1922 Analysis Methodology

- MELCOR results : Boundary Condition

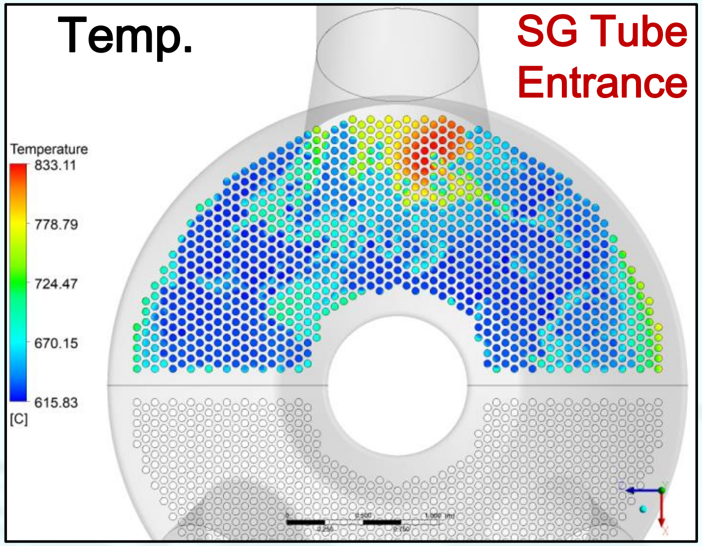


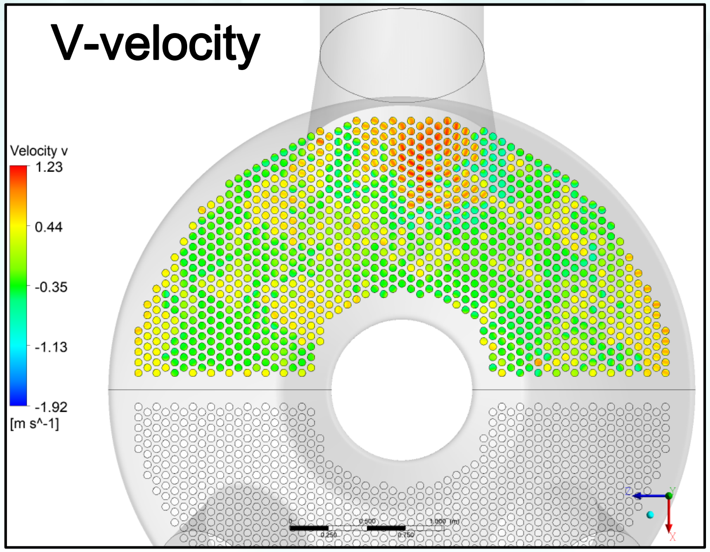
Inlet	Steam-H_2 gas : 13.24 kg/s, 929.18 ℃
Outlet	Zero reference pressure
Wall at SG Tubes	Heat transfer coeff. : 20.37 W/m[2]℃' Ambient temp. : 613.75 ℃

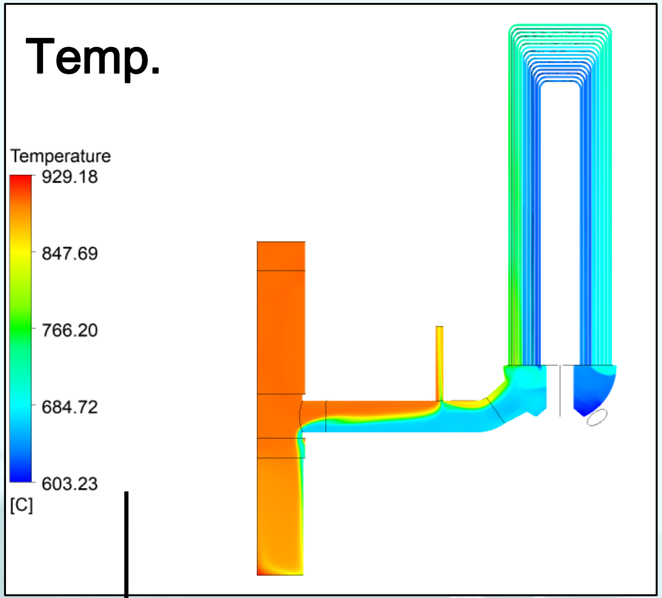


Parameter	WH SG	CE SG	OPR1000 SG
Recirculation ratio (r)	2.4	1.05	1.44
Mixing fraction (f)	0.96	0.65	0.84
Hot tube fraction (a)	41%	22%	25.7%
Discharge coeff. (C_d)	0.12	0.13-0.14	0.16

CFD Analysis for OPR1000 TI-SGTR (2)







Parameter	Value
Recirculation ratio (r) $r = m_t / m_h$	1.44
Mixing fraction (f) $f = 1\text{-}r(T_{ht}\text{-}T_m)/(T_h\text{-}T_m)$	0.84
Hot tube fraction (a) *based on the areas of hot tube & cold tube	25.7%
Discharge coefficient (C_d) $Q = C_d\,(g \times D^5 \times \triangle\rho/\rho\,)^{1/2}$	0.16
T_h : gas temp. flowing to SG inlet plenum	744.8 ℃
T_{ht} : gas temp. flowing to upper region of SG tubes	684.2 ℃
T_{ct} : gas temp. returned from SG tubes	629.1 ℃
T_m : avg. temp. of the mixing zone	676.5 ℃
m_h : gas flow rate to SG inlet plenum	7.89 kg/s
m_t : gas flow rate to upper region of SG tubes	11.42 kg/s

Conclusion and Further Work

❑ Conclusion

- We produced the input parameters of the MELCOR analysis for the OPR1000 TI-SGTR through the CFD analysis using the established CFD analysis methodology developed from the validation of the WH 1/7 test results and the OPR1000 design data
- The accuracy of the produced MELCOR input parameters through the CFD analysis is approximately 10% except the hot tube number which has an error range of approximately 25%

❑ Further Work

- Additional CFD analysis is recommended for another accident sequence in the OPR1000 TI-SGTR such as no flow to the pressurizer