Korean Nuclear Society Spring Meeting
May 13-14, 2021

Analysis of IVR-ERVC Evaluation Characteristics for Small Reactor

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IVR-ERVC

- IVR-ERVC(In-Vessel corium Retention through External Reactor Vessel Cooling)의 원전 적용 현황
  - **중대사고 대처설비**: **APR1000 & SMART in Korea, AP600 & 1000 in USA, KERENA(BWR, SWR1000의 새 노형) in Germany & France(AREVA), Loviisa in Finland, CAP1000 & 1400 in China, SMART, and so on**
  - **중대사고 관리방안: 가동 원전(국내 OPR1000 등), APR1400, APR+ 등**

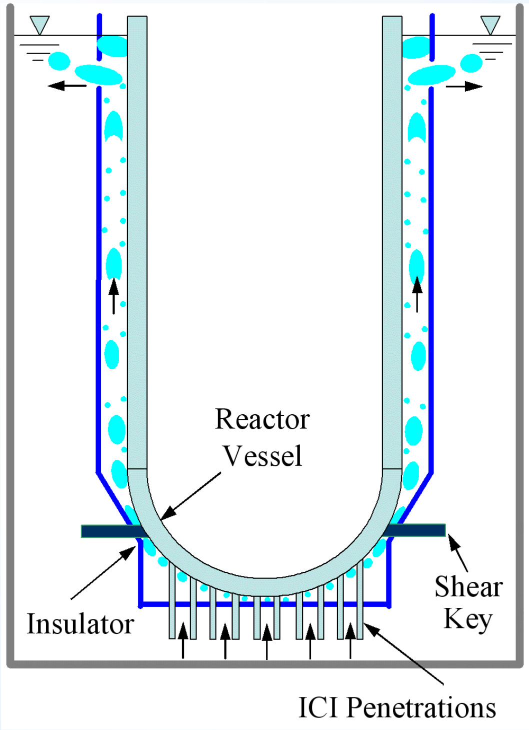
- IVR-ERVC의 인허가
  - **중대사고 대처설비 : DC (Design Certification) 때부터 SSAR 19.2 절에 기술, PSA와 SAMG에 적용**
  - **중대사고 관리방안 : DC 때는 기술하지 않고 OL(Operating License)시 SAMG(Severe Accident Management Guidance)에 반영 (가용성 및 최소한 유로 확보는 필요)**

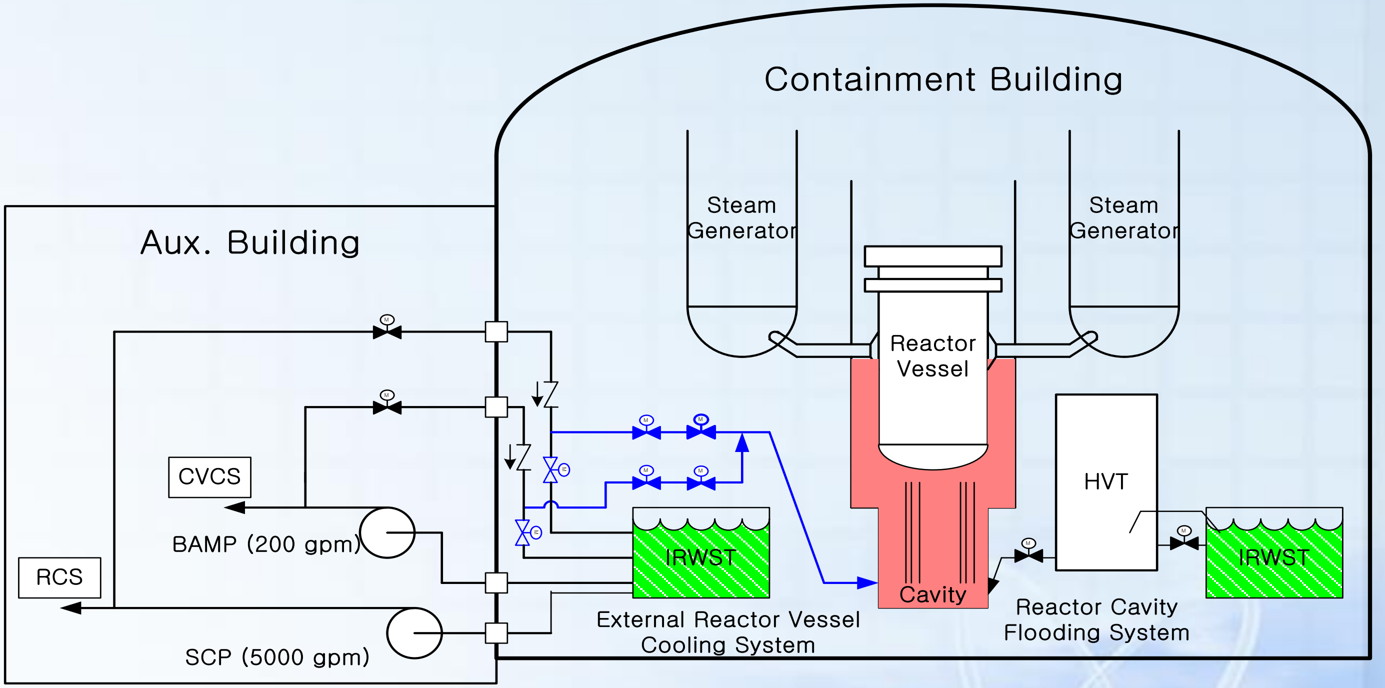
연구 목적

- Aanalysis of the IVR-ERVC evaluation characteristics of small power reactor of SMART to compare with high power reactor, such as APR1400

APR1400 IVR-ERVC

❖ 원자로공동(Reactor Cavity)에 펌프 사용 냉각수 능동 주입

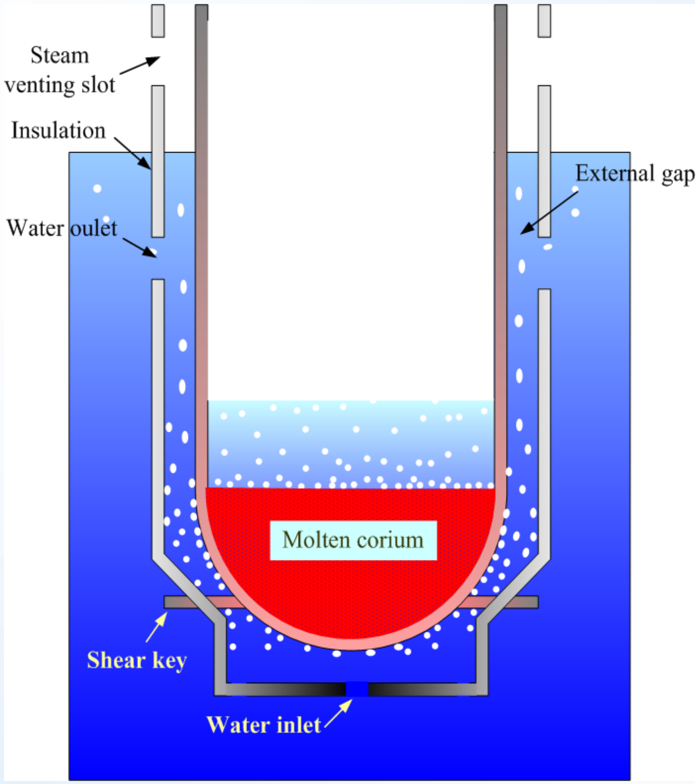


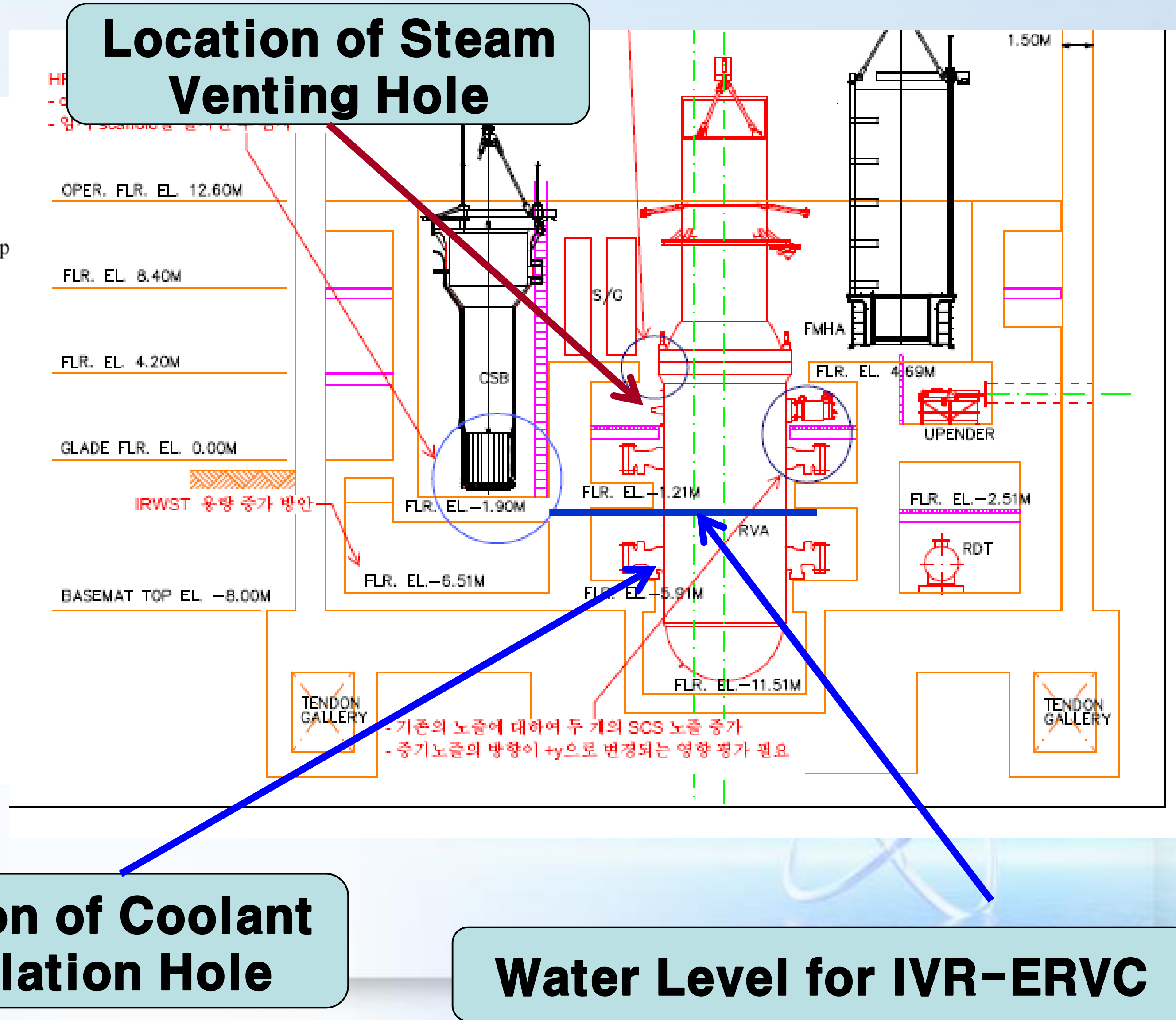


❖ **APR 1400: The cavity is flooded by the SCP and the BAMP (to the Hot Leg Penetration Bottom Elevation).**

SMART IVR-ERVC

❖ **원자로공동에 냉각수 피동 주입: 밸브 개방**





IVR-ERVC Analysis Method

❑ Required System for IVR-ERVC

- Safety Depressurization System: POSRV in APR1400, ADS in SMART
- CFS(Cavity Flooding System) with IRWST(In-containment Refueling Storage Tank)
- Reactor Vessel Insulation and Steam Venting System

❑ IVR-ERVC Analysis Method Development

- Thermal Load Analysis from corium pool to RPV using severe accident analysis computer code, such as CINEMA-SMART
- Analysis of Coolant Natural Circulation Between Outer Vessel Wall and Insulation using thermal hydraulic analysis computer code, such as MARS, SPACE
- Analysis for Maximum Heat Removal Rate (CHF) on Outer Vessel Wall based on the Coolant Natural Circulation Mass Flow Rate
- To evaluate the thermal margin by comparison of the thermal load with the CHF
  - IVR-ERVC Success Criteria: CHF > Thermal Load
- Structure Integrity Analysis for Reactor Vessel Wall using structure analysis computer code, such as ANSYS

Design Parameters

Design Parameters	APR1400	SMART100
Core Thermal Power (MW)	3983	365
Fuel(UO_2) Mass (ton)	120.0	16.8
Mass for Active Core Zircaloy-4 (ton)	33.6	4.7
Bottom Head Inner Diameter (m)	4.7	5.3
Bottom Head Thickness (cm)	16.5	20.0
Number of ICI Nozzle in the Lower Head	61	None

❖ **Low thermal Power than High Reactor Vessel Size & No ICI Nozzle lead to increase in thermal margin for SMART IVR-ERVC.**

Natural Convection Correlation for Thermal Load

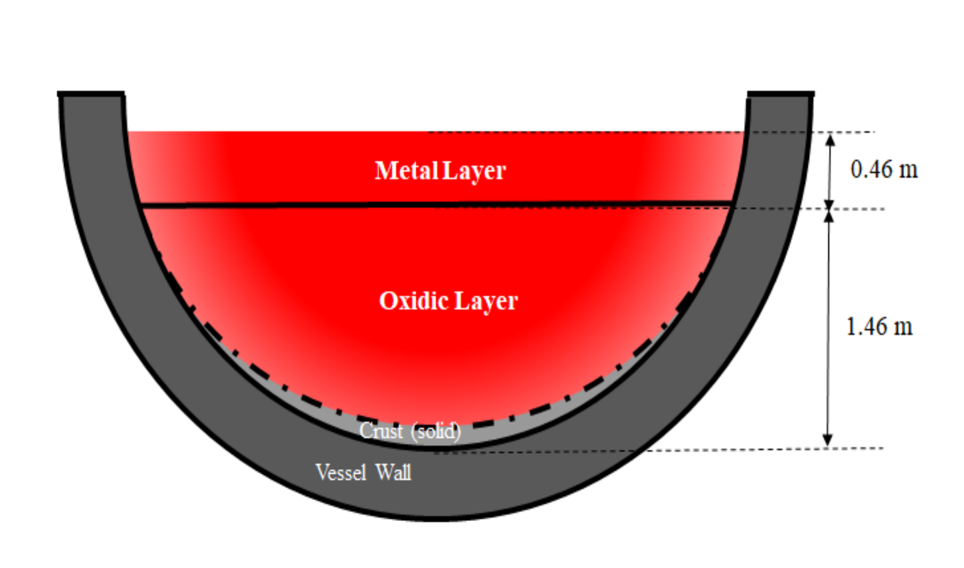
Model	Upper Part	Lower Part
Metallic Layer	**Globe-Dropkin** $Nu_l = 0.069\, Ra_l^{0.333}\, Pr_l^{0.074}$ Churchill and Chu correlation for side wall heat transfer (focusing effect)	**Globe-Dropkin** $Nu_l = 0.069\, Ra_l^{0.333}\, Pr_l^{0.074}$ $Nu = 1 + \frac{0.15\,(Ra \cdot \sin\theta)^{1/3}}{\left(1+\left(\frac{0.492}{Pr}\right)^{9/16}\right)^{16/27}}$
Oxidic Layer	**Kulacki-Emara** $Nu_d = 0.345\left(Ra_{q\mu}\right)^{0.226}$	**Mini-ACOPO** $\frac{Nu_d}{\overline{Nu}_d} = 0.1 + 1.08\left(\frac{\theta}{\theta_{tot}}\right) - 4.5\left(\frac{\theta}{\theta_{tot}}\right)^2 + 8.6\left(\frac{\theta}{\theta_{tot}}\right)^3$ $for\ \ 0.1 \le \left(\frac{\theta}{\theta_{tot}}\right) \le 0.6$ *and* $\frac{Nu_d}{\overline{Nu}_d} = 0.41 + 0.35\left(\frac{\theta}{\theta_{tot}}\right) + \left(\frac{\theta}{\theta_{tot}}\right)^2$ $for\ \ 0.6 \le \left(\frac{\theta}{\theta_{tot}}\right) \le 1.0$

주요 상관식 적용범위

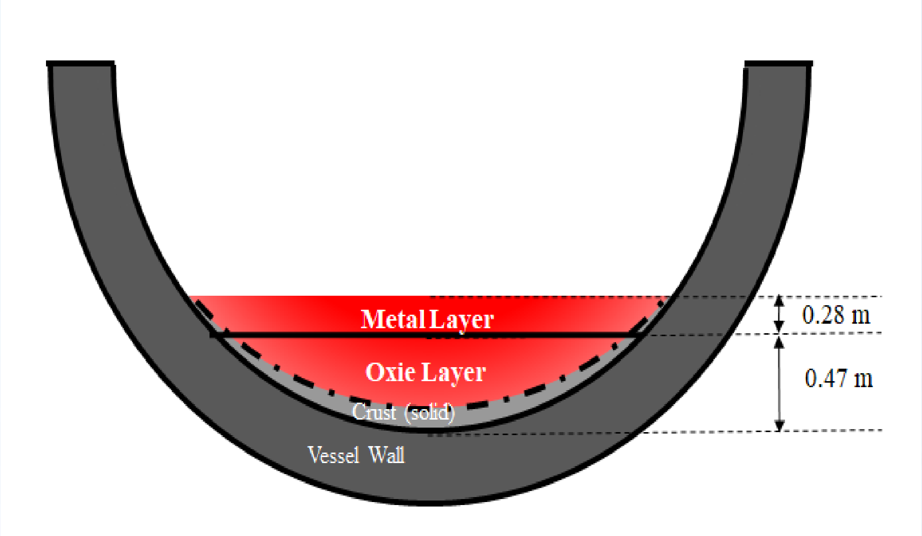
Model		Heat Transfer Correlation	Range of applicability	
			Ra	Pr
ERI	Ceramic Pool	Mayinger	$7x10^{6}$ - $5x10^{14}$	0.5
		Kulacki-Emara	$2x10^{4}$ - $4.4x10^{12}$	7
	Top Metal Layer	Globe-Dropkin	$3x10^{5}$ - $7x10^{9}$	0.02-8750
		Churchill-Chu	0.1 - 10^{12}	Any
DOE	Ceramic Pool	Mini-ACOPO	10^{12} - $7x10^{14}$	2.6-10.8
	Top Metal Layer	Globe-Dropkin "Specialized"	$3x10^{5}$ - $7x10^{9}$	0.02-8750
		Churchill-Chu	0.1 - 10^{12}	Any
INL	Ceramic Pool	ACOPO	10^{12} - $2x10^{16}$	4-7
	Top Metal Layer	Globe-Dropkin	$3x10^{5}$ - $7x10^{9}$	0.02-8750
		Churchill-Chu	0.1 - 10^{12}	Any

Thermal Load Analysis

❑ Corium Relocation to the Lower Plenum



APR1400



SMART

Non-Dimensional Number	APR1400	SMART100
Ra Number in Metal Layer	10^{10}	10^{8}
Ra Number in Oxide Layer	10^{16}	10^{13}

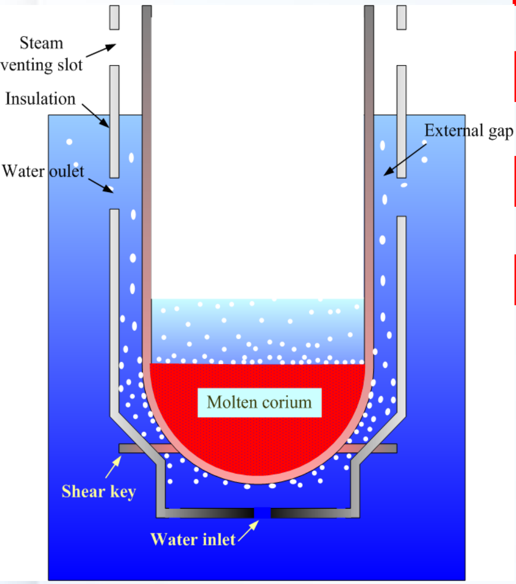
최대열제거량 평가방법

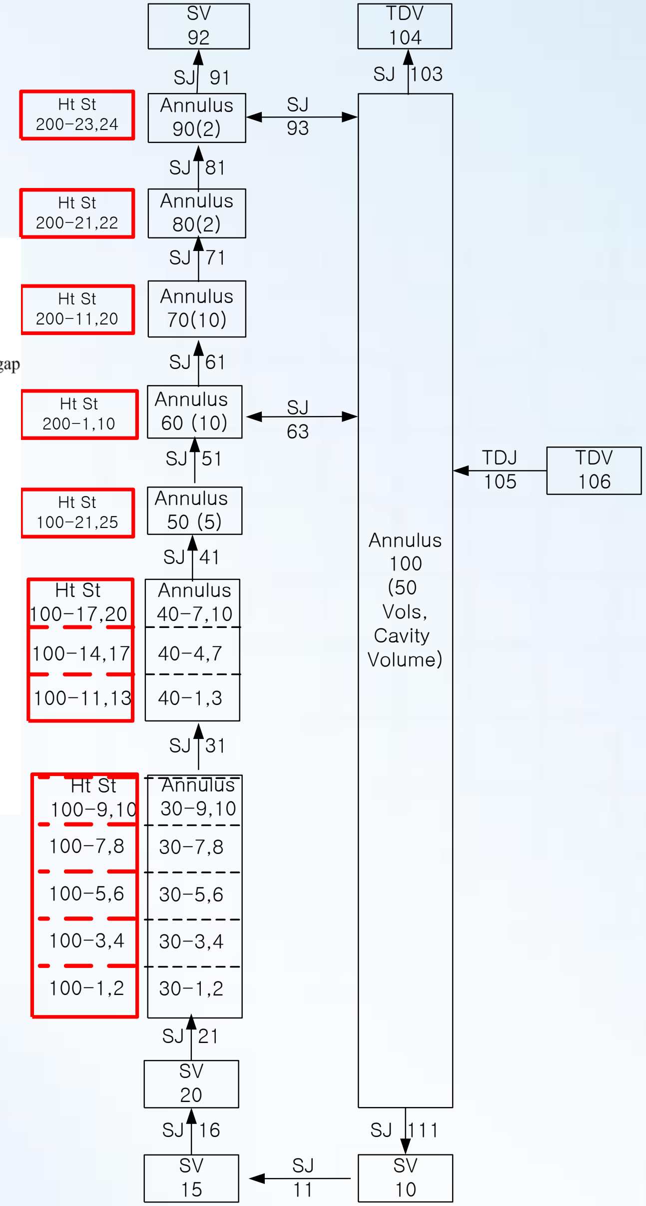
- CHF: as a function coolant circulation mass flow rate between RPV wall and RV insulator

- To determine the coolant circulation mass flow rate using MARS or SPACE computer codes

- To determine the maximum heat removal rate of CHF using the experimental data at CEA and KAIST

MARS or SPACE Input Model

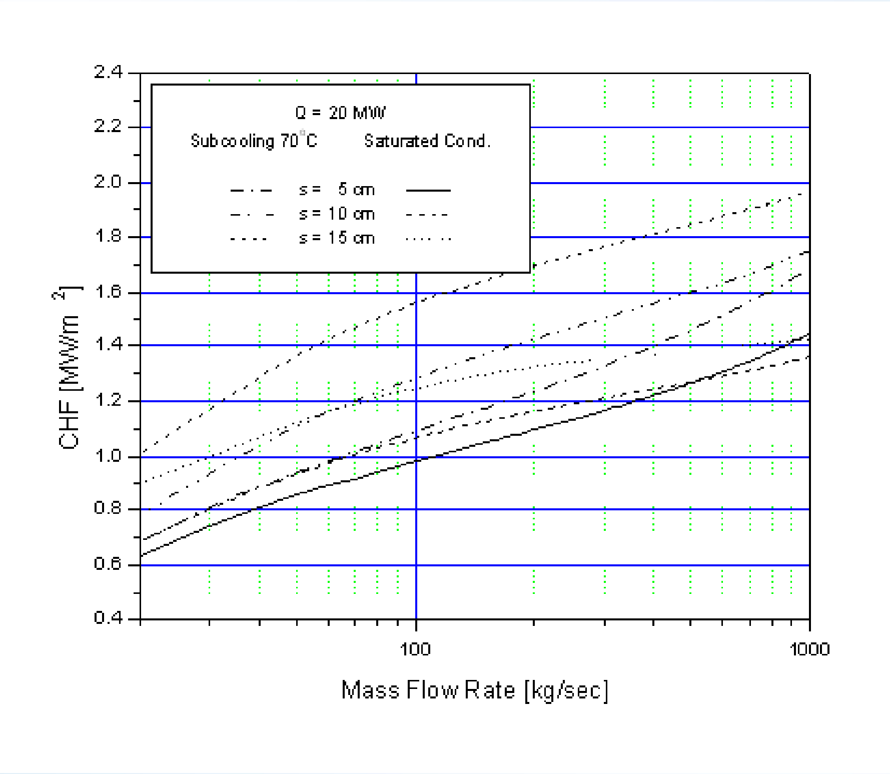




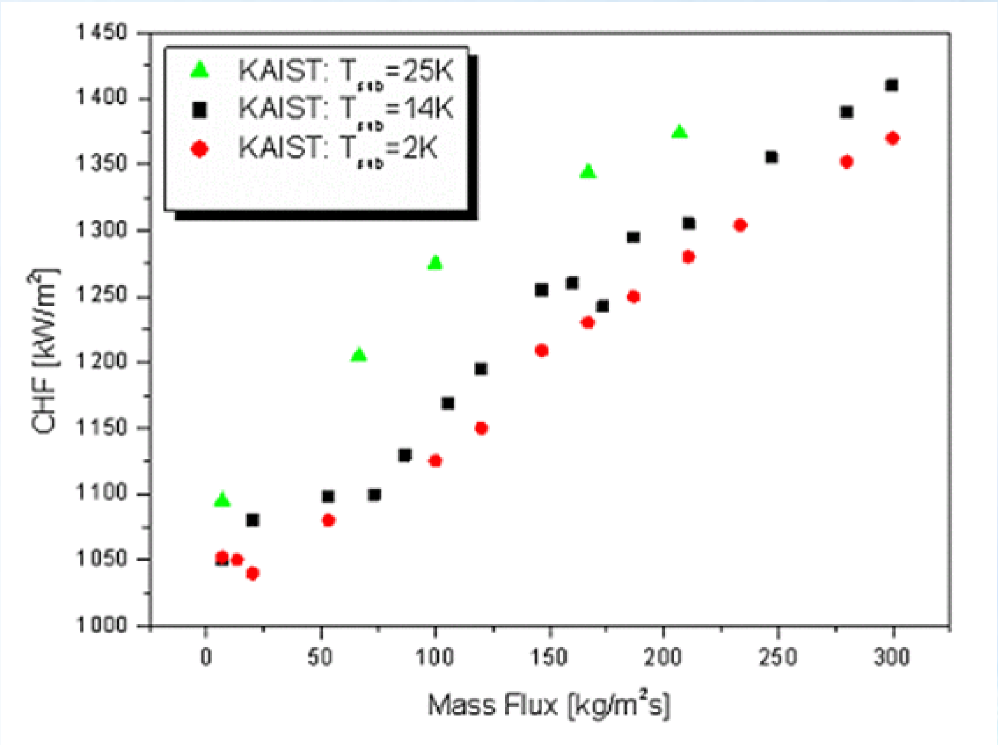
No.	Description
Heat Structure 100	Spherical Reactor Vessel
Heat Structure 200	Cylindrical Reactor Vessel
Single Volume 20	Volume Between the Reactor Vessel Bottom and the Insulation
Annulus 30, 40 ,50	Volume Between the Spherical Reactor Vessel and Insulation
Annulus 60,70, 80, 90 Single Volume 92	Volume Between the Cylindrical Reactor Vessel and Insulation
Annulus 100	Reactor Vessel Outside Cavity Volume
Single Volume 10	Bottom Side Cavity Volume
Single Volume 15	Bottom Cavity Volume under the Reactor Vessel
Time Dep. Volume 104	Containment Atmosphere
Time Dep. Volume 106	Water Source (IRWST)
Single Junction 16	Water Inlet
Single Junction 63	Water Outlet
Single Junction 93	Steam Outlet

Experimental Data for CHF

Coolant Circulation Mass Flow Rate in APR1400 = Approx. 900-1200 kg/m².sec
Coolant Circulation Mass Flow Rate in SMART = Approx. 250-590 kg/m².sec



SULTAN in CEA



KAIST in Korea

CHF Value

- CHF Value (Gap size= 10 cm, Saturated Water) in APR1400
  : **1.4 - 1.9 MW/m^2**

- CHF Value (Gap size= 10 cm, Saturated Water) in SMART
  : **1.3 - 1.4 MW/m^2**

Mean Heat Flux to Lower Hemisphere of Reactor Vessel (MW/m^2)	Mean Coolant Recirculation Mass Flow Rate (kg/s)	Coolant Mass Flux (kg/m^2.s)	Estimated CHF (MW/m^2)	
			Results of SULTAN Test	Results of KAIST Test
0.401	405	253 - 506	About 1.3	About 1.3
0.489	460	287 - 575	About 1.3	About 1.4
0.536	470	293 - 587	About 1.4	About 1.4

Conclusions (1)

- There is no difference between the high and small power reactors in IVR-ERVC evaluation method in general.
- However, main difference for IVR-ERVC evaluation is in scale, which affects heat transfer in molten pool and natural convection outside reactor vessel wall.
- In heat transfer evaluation for molten pool, non-dimensional Rayleigh number for used correlations are used.
- For this reason, the difference between the high and small power reactors is that these values, namely, a large value in the APR1400 and a small value in the SMART, which affects the used correlation value.
- In natural convection outside reactor vessel wall, the difference between the high and small power reactors is value of the natural coolant circulation mass flow rate, which depends on the geometry scale and heat flux from the corium pool to the coolant in the outer reactor vessel wall.

Conclusions (2)

- The difference between two reactors of SMART and APR1400 is a large value in high power reactor and a small value in small power reactor. This affects the CHF on the outer reactor vessel wall.

- If experimental data on the CHF, such as SULTAN and KAIST experiment are used, the maximum heat removal depends on the coolant circulation mass flow rate. The large value in this mass flow rate leads to large value of the CHF, but a small value leads to a small value.

- For this reason, it is concluded that. there is no difference on the IVR-ERVC evaluation method between the SMART and APR1400, because non dimensional Rayleigh number and experimental data are used, which depends on the reactor scale

Thank You!

중대사고 · 중수로안전연구부

SEVERE ACCIDENT AND PHWR SAFETY RESEARCH DIVISION