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Preliminary Study on Thermal Margin of External Reactor Vessel Cooling Using MARS-KS1.4 Code with Newly Implemented CHF Correlations

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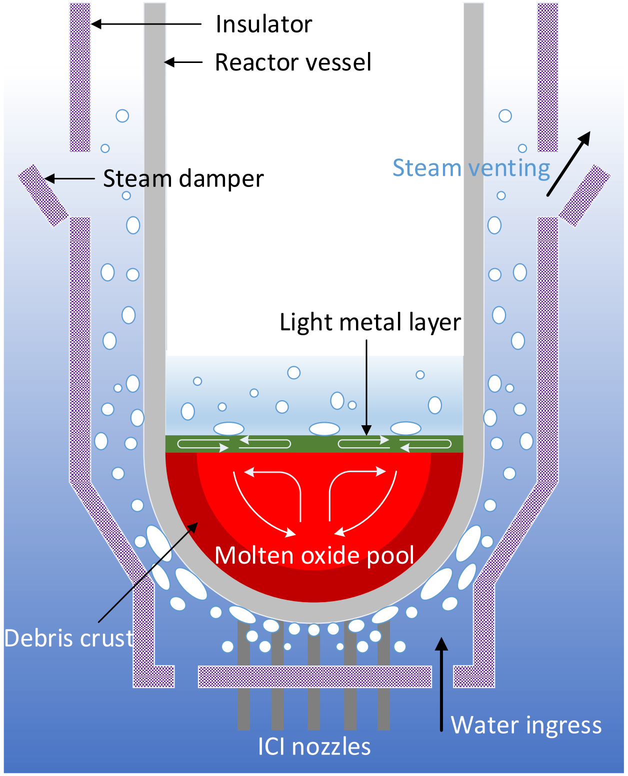
External reactor vessel cooling (ERVC)

- Severe accident management strategy adopted by APR1400 to arrest the molten core debris by flooding the reactor cavity and submerging the reactor vessel
  - Specific insulation design to promote natural circulation and heat removal
  - Principal failure mechanism
    : occurrence of boiling crisis

ERVC analysis via T/H system codes

→ High-fidelity prediction of two-phase natural circulation flows, but

→ **No CHF model for downward-facing hemispheres** (lower CHF than that predicted by the default model)

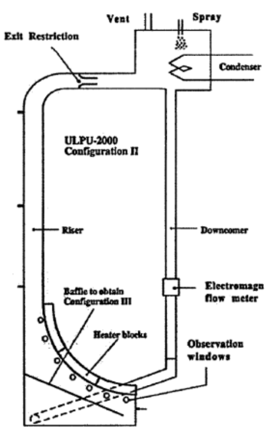
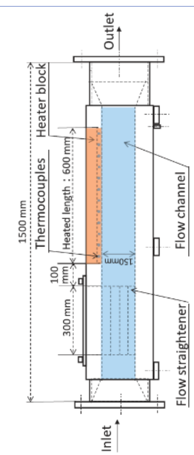
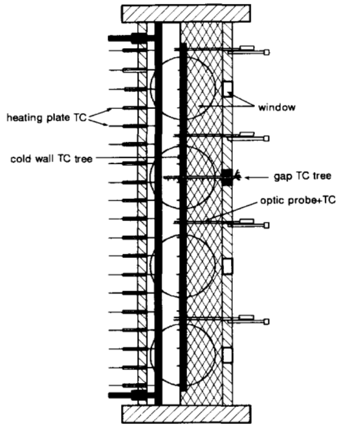


External reactor vessel cooling

❖ Research objectives

To implement CHF correlations proper for the downward-facing hemisphere into the MARS-KS 1.4 code to better predict the thermal margin of ERVC w/ APR1400 as the reference plant

Reviewed experimental studies on CHF for ERVC

Test	ULPU-III test	Toshiba's test	SULTAN test
Organization	University of California, Santa Barbara	Toshiba Energy Systems & Solutions Corporation	CEA
Geometry	Hemisphere	Flat plate	Flat plate
Test Facility			

Selected correlations for downward-facing hemisphere

Name	Correlations	Ranges
ULPU-III correlation[1]	$q''_{CHF} = 490 + 30.2\theta - 8.88 \cdot 10^{-1}\theta^2 + 1.35 \cdot 10^{-3}\theta^3 - 6.65 \cdot 10^{-5}\theta^4$	$0° < \theta < 90°$
Toshiba correlation[2]	$q''_{CHF} = -3626.79P^2 - 2.45025 \cdot 10^{-4}G^2 - 434757x^2 + 0.0610736\theta^2 + 2263.69P + 0.914268G - 14657.4x + 0.300264\theta + 35.5521P\theta - 2.30392 \cdot 10^{-3}G\theta + 136.071x\theta + 0.0152043PG - 1993.24Px - 6.65384Gx - 88.0463$	$50° < \theta < 90°$ $0.1 < P < 0.6$ MPa $360 < G < 1900$ kg/m²s $-2.6e-2 < x < 3.1e-3$
SULTAN correlation[3]	$q''_{CHF} = A0(E,P,G) + A1(E,G) \cdot x + A2(E) \cdot x^2 + A3(E,P,G,X) \cdot \theta + A4(E,P,G,X) \cdot \theta^2$	θ = 10°, 45°, 90° $0.1 < P < 0.5$ MPa $10 < G < 5000$ kg/m²s 0< Subcooling < 50 K

P: pressure, G: mass flux , x: quality,
E: channel gap

Flow effect on CHF reflected

1) T.G. Theofanous et al., Nuclear Engineering and Design 169 (1997)
2) C. Iwaki et al., Journal of Nuclear Science and Technology 57 (2020)
3) S. Rouge et al., Workshop on in-vessel core debris retention and coolability (1998)

CHF Correlations

❖ Implementation into MARS-KS1.4

Three subroutines for the selected CHF correlations were added to source files of the MARS-KS 1.4 code → convective boundary condition types in 'heat structure'

Modified convection boundary type in heat transfer package

<table>
<tr><th>Index</th><th colspan="2">Geometry type</th></tr>
<tr><td>1, 100, 101</td><td colspan="2">Default</td></tr>
<tr><td>102</td><td colspan="2">Parallel plates</td></tr>
<tr><td>…</td><td colspan="2">…</td></tr>
<tr><td>135</td><td colspan="2">Helical S/G shell side</td></tr>
<tr><td>190</td><td rowspan="3">Downward -facing hemisphere</td><td>ULPU-III correlation</td></tr>
<tr><td>191</td><td>Toshiba correlation</td></tr>
<tr><td>192</td><td>SULTAN correlation</td></tr>
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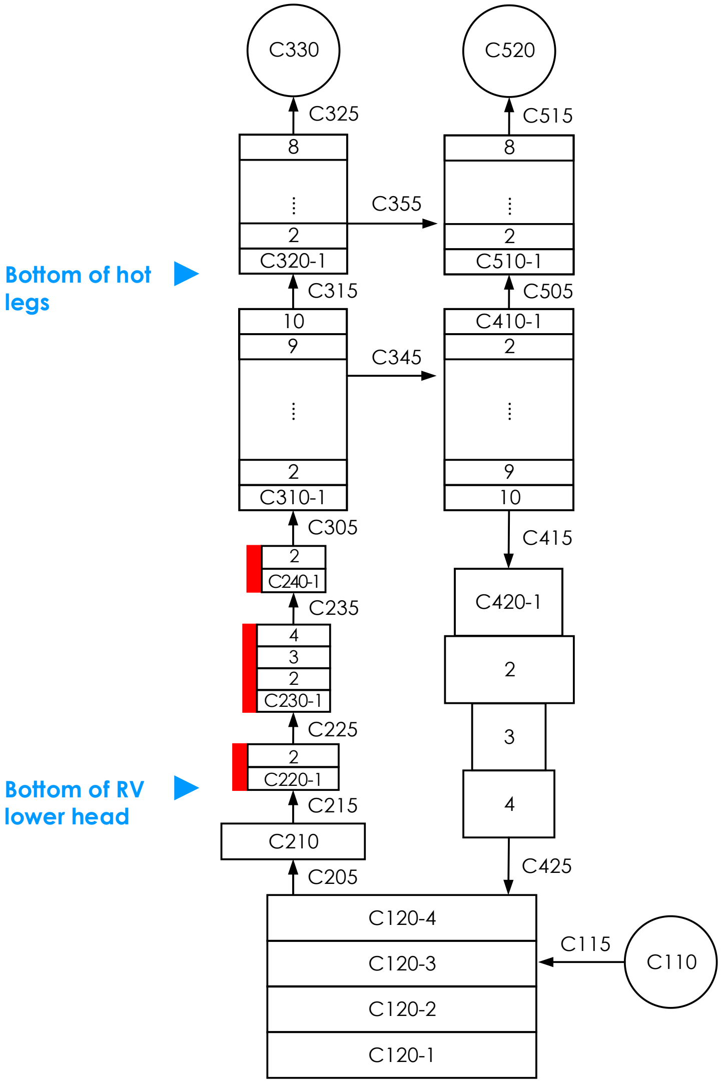
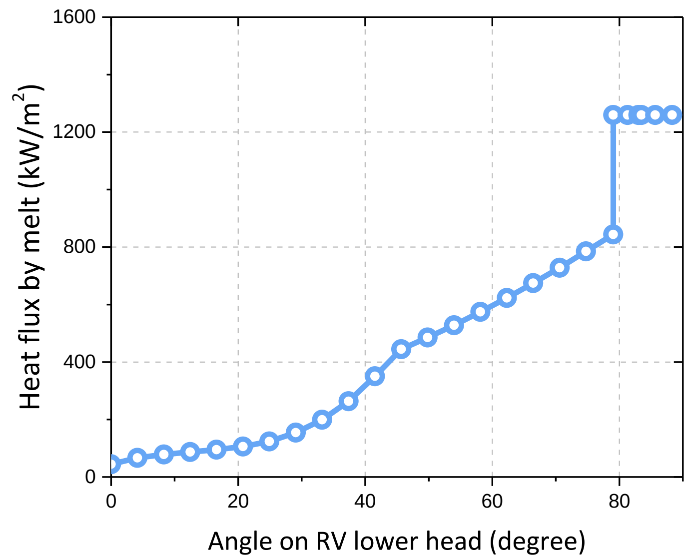
MARS-KS Simulation



Nodalization of the natural circulation flow channels during ERVC

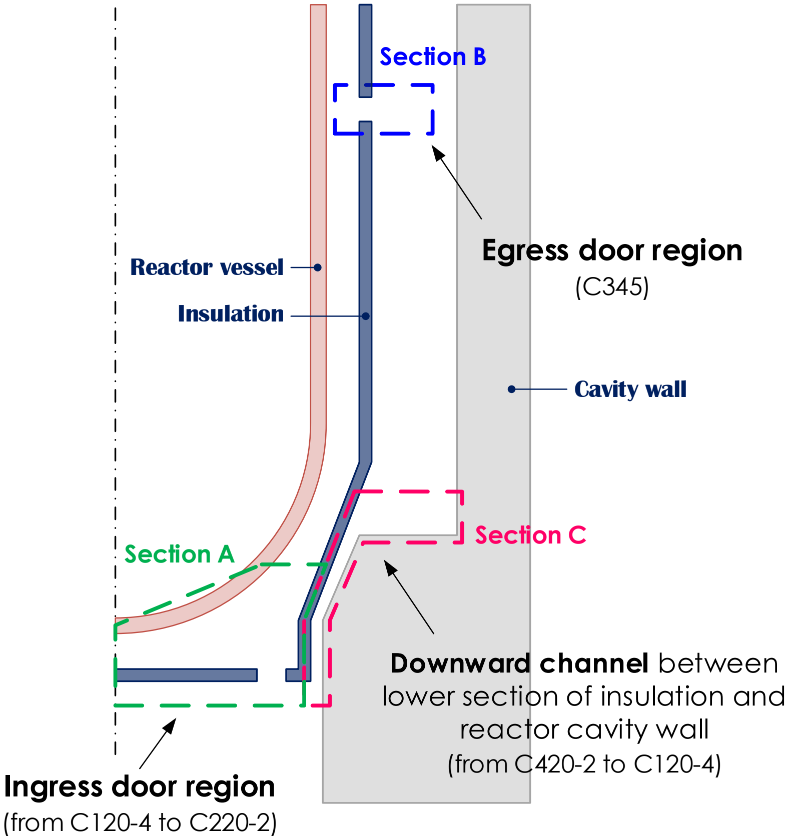


Heat flux profile by relocated core melt

Boundary & initial conditions

Parameters	Value
Containment Pressure	2.5 bar
Total heat load	23.3 MW
Initial water temperature	48.9 °C
Initial water level	Bottom of CL
BAMP makeup rate	170 GPM

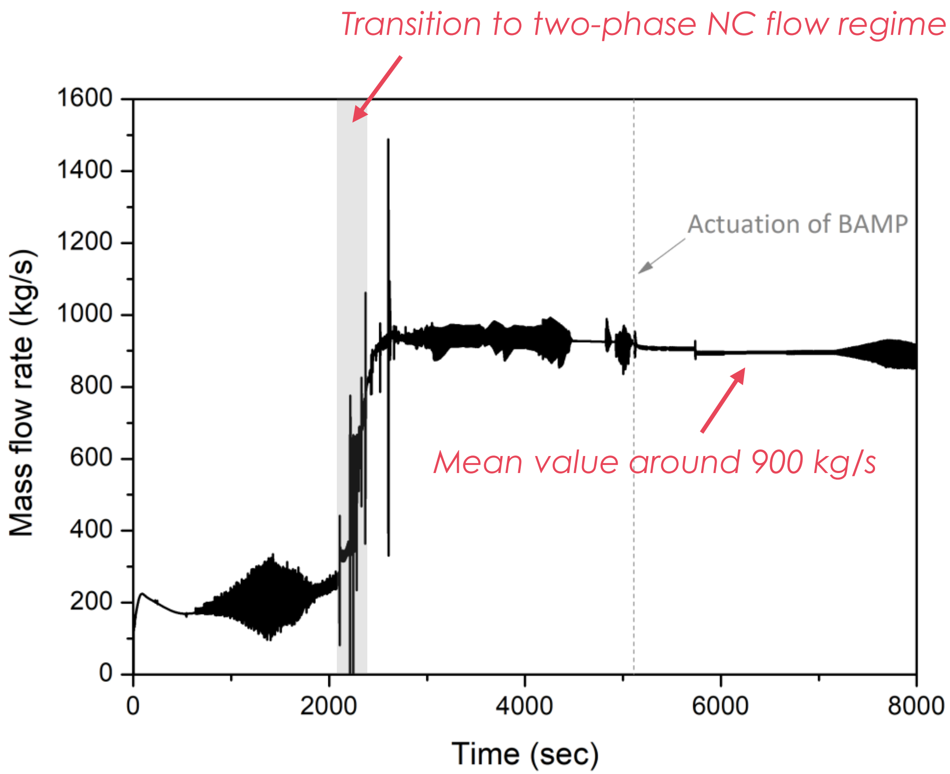
❖ Natural circulation flow rate



Locations of significant minor pressure drops

Loss coefficient at dominant minor loss points

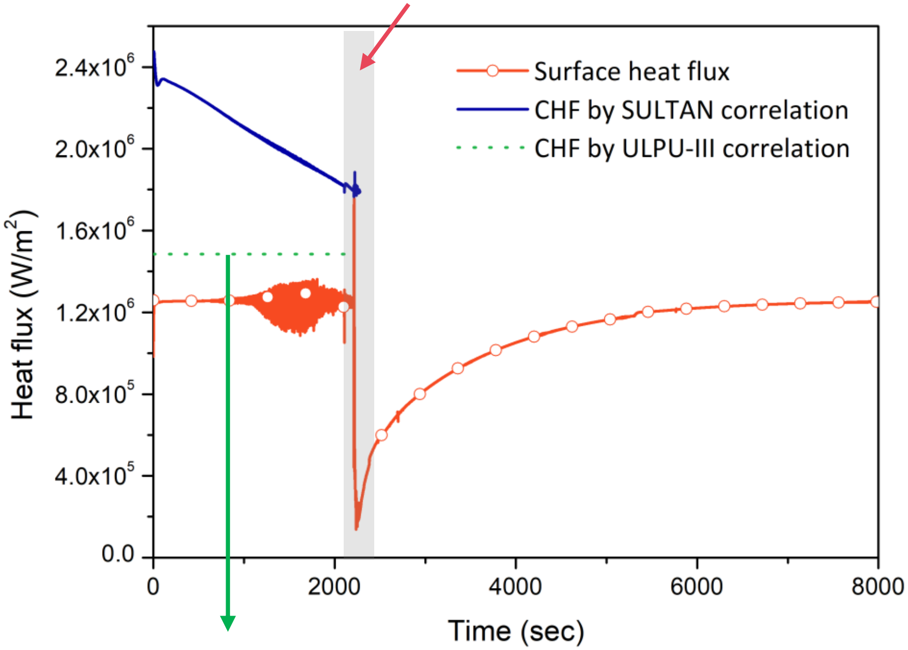
→ estimated based on CFD analysis at the single-phase liquid state before significant void generation

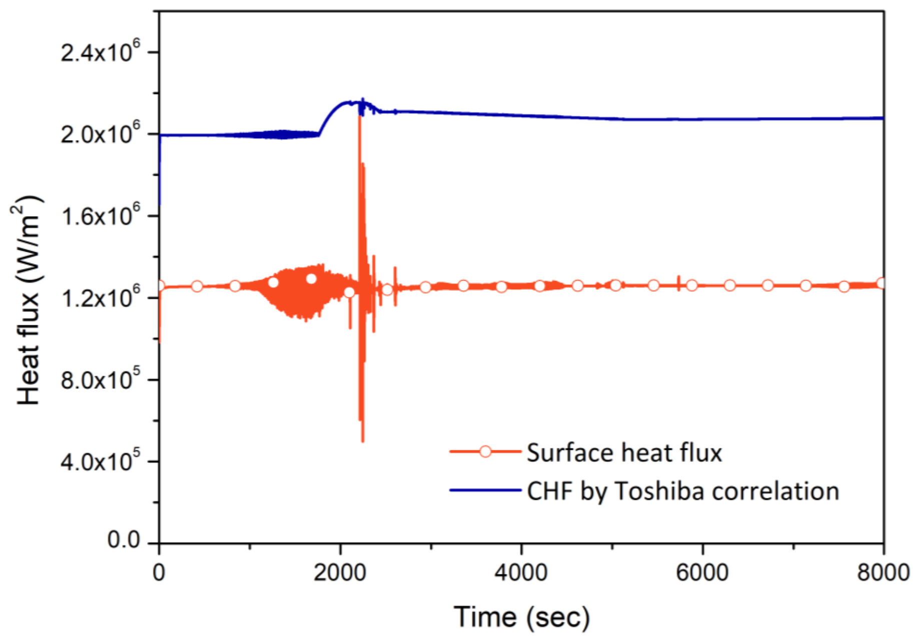


Surface heat flux & CHF per applied correlation

- ULPU-III or SULTAN correlation: boiling regime transition to the **post-DNB** region
- Toshiba's correlation: subcooled nucleate boiling regime sustained

Significant flow oscillations due to transition to two-phase regime

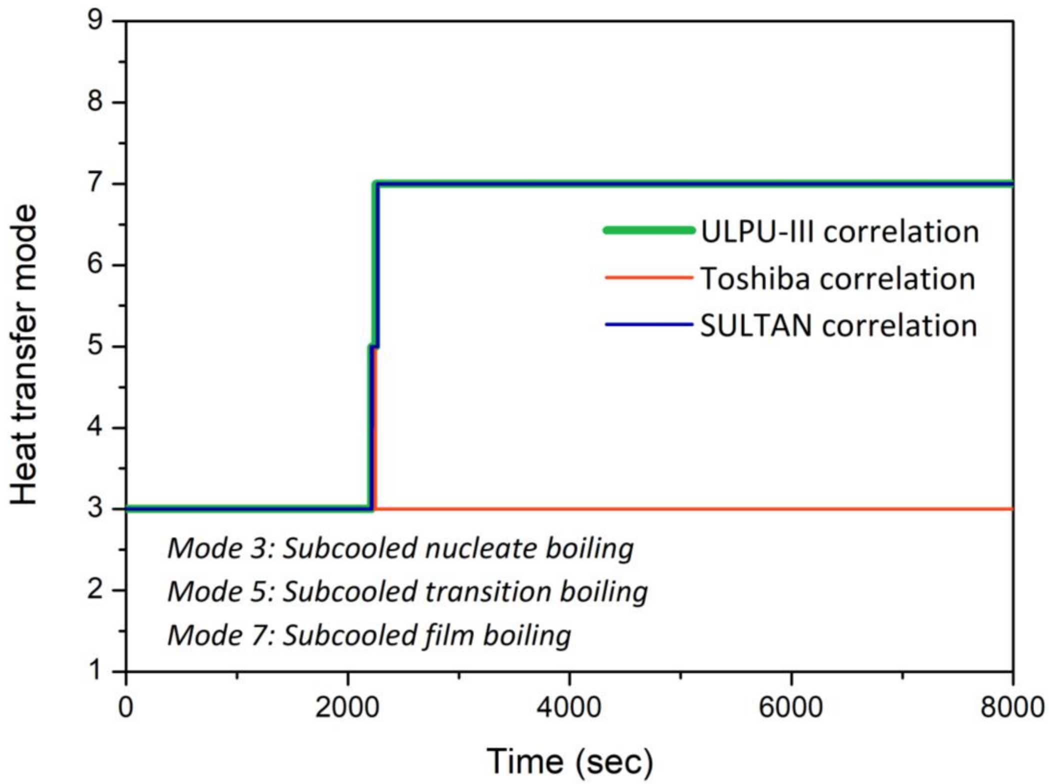




No flow effect considered ← only a function of polar angle

Natural circulation flow rate

Different conclusions about the thermal margin of ERVC relying upon the selected CHF model for downward-facing hemisphere



- Three CHF correlations for the lower head of the reactor vessel was newly implemented into MARS-KS1.4 code to better predict the thermal margin of ERVC of the APR1400. Predicted boiling regimes were different per the selected correlation.

- Future works

  In-depth review of CHF tests for user recommendations for ERVC simulation

  Coupling with the smoothed-particle hydrodynamics code, named SOPHIA[4], to propose a new analysis method for in-vessel retention

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4) S. H. Park et al, the Korean Nuclear Society Virtual Spring Meeting, July 9-10, 2020

Thank you for your interest!

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