Uncertainty Analysis of In-vessel Retention of a High Power Nuclear Power Plant during Severe Accident

Seokwon Whang, Kiyofumi Moriyama, Hyun Sun Park

Presenter: Seokwon Whang (Ph.D. student)

POSTECH(Republic of Korea), Division of Advanced Nuclear Engineering

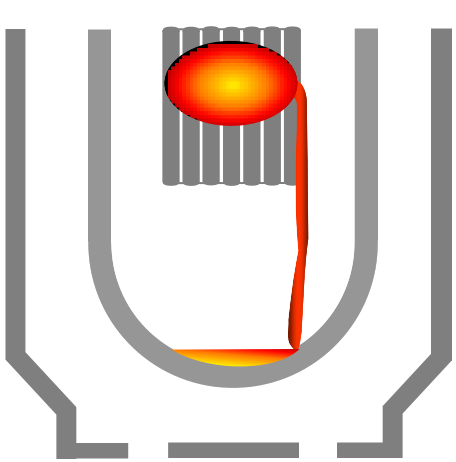
ERMSAR 2015, Marseille March 24 – 26, 2015

Contents

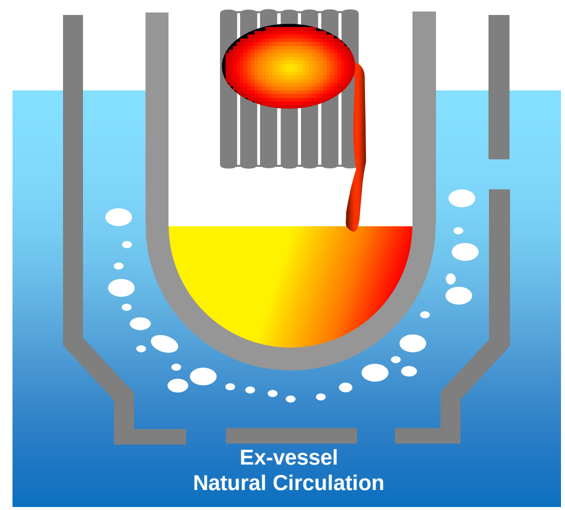
- Introduction
- Methodology
- Verification
- APR1400 analysis
- Conclusion

Introduction: SA and NPPs

- Severe Accident Management Strategy
  - In-Vessel Retention by External Reactor Vessel Cooling (IVR-ERVC)

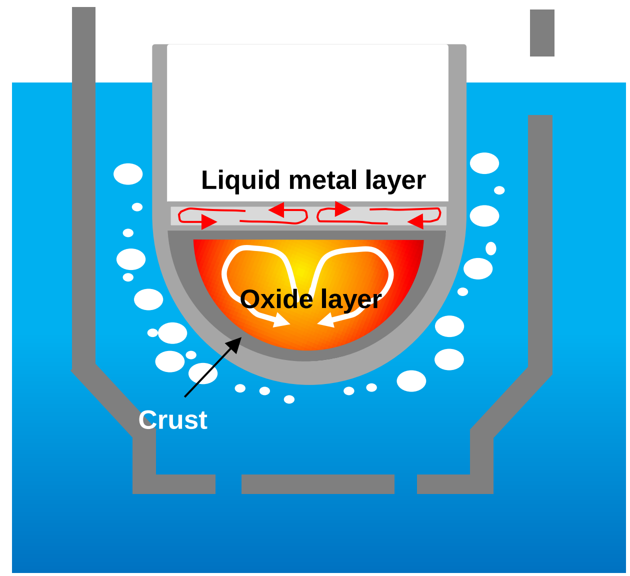


Core degradation



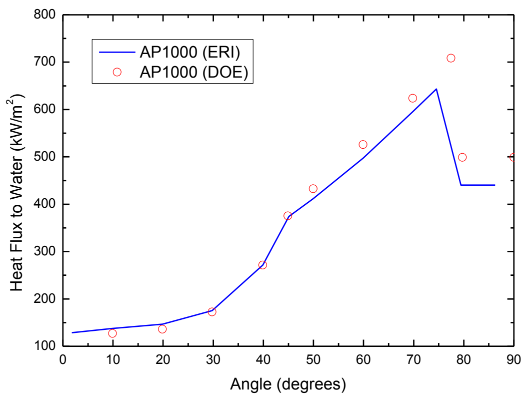
Introduction: Phenomena of IVR-ERVC

- n-layered system
  - Metal layer: Fe-Zr
  - Oxide layer: UO_2-ZrO_2
- Internal heat generation, Q'''
- Highly turbulent natural convection
- Crust formation
- Natural circulation of external coolant

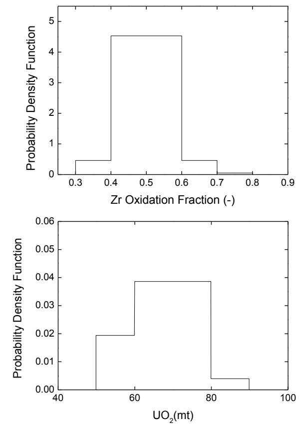


Introduction: Previous work

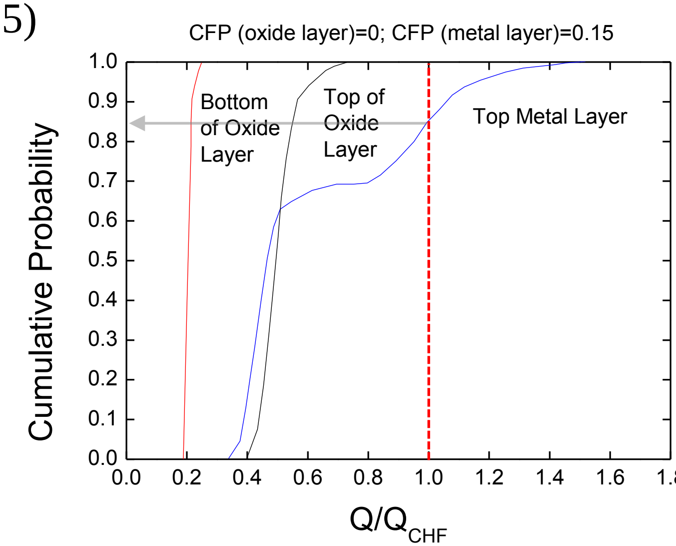
- AP600, AP1000 (H. Esmaili and Khatib-Rahbar, 2004, 2005)



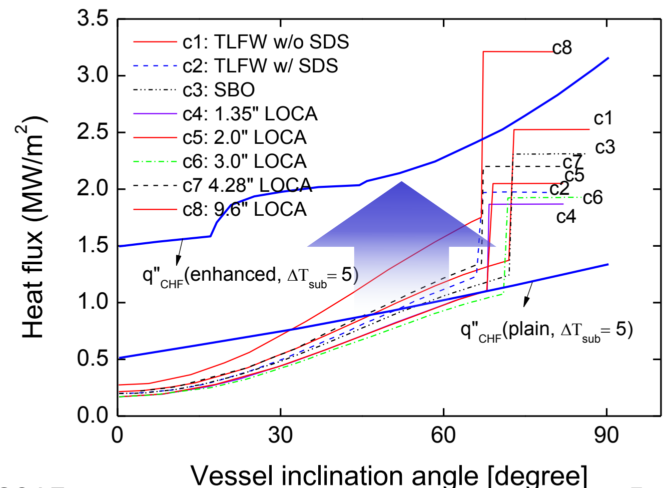
Lumped parameter (LP) model



PDF



- APR1400 (J.L. Rempe et al., 2005)
  - 8 SA conditions (SCDAP/RELAP5)
  - Evaluation of IVR feasibility with CHF enhancement by porous coating
    - Most cases are safe (one of their result)

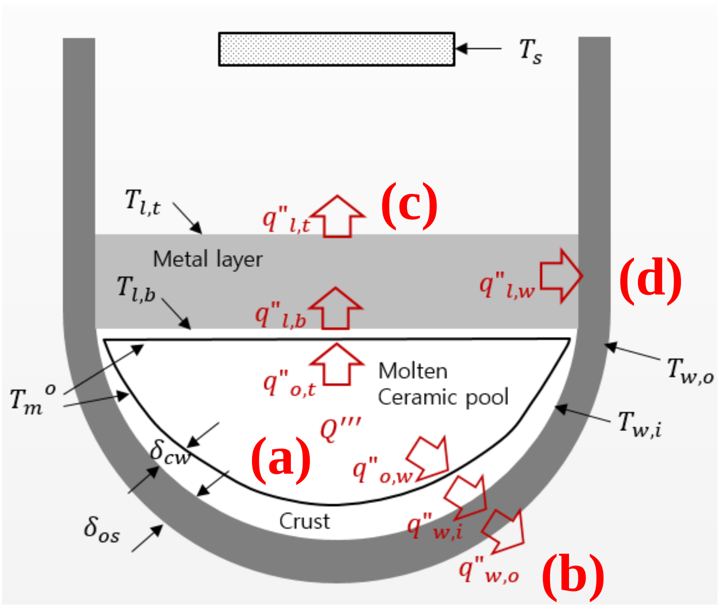


Introduction: This work

- LP code was developed to evaluate APR1400
- Probabilistic assessment for 8 SA conditions
- Uncertainty study
  - Importance analysis for the selected uncertainty parameters
  - Influence of probability density function profile
  - Influence of heat transfer coefficient

Methodology: Lumped-Parameter Method (LPM)

- Energy balance equation



m : melt	w : wall
o : oxide	t : top
l : light metal	i : inside
cw : crust wall	o : outside
v: vessel	b : bottom
s : structure	

- Oxide layer

$$Q_o'''V_o \text{ (a)} = q_{o,t}''A_{o,t} + q_{o,w}''A_{o,w}$$

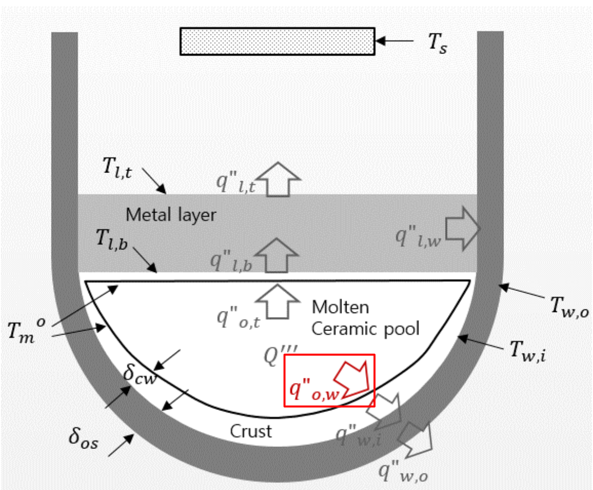
$$q_{w,i}''A_{w,i} = Q_c'''V_c + q_{o,w}''A_{o,w} = q_{w,o}''A_{w,o} \text{ (b)}$$

- Top metal layer

$$q_{l,b}''A_{l,b} = q_{l,t}''A_{l,t}\text{(c)} + q_{l,w}''A_{l,w} \text{ (d)}$$

Methodology: Lumped-Parameter Method (LPM)

- Heat transfer correlations (experiments)



m : melt	w : wall
o : oxide	t : top
l : light metal	i : inside
c : crust	o : outside
v : vessel	b : bottom
s : structure	

i) Determine the energy partitioning

$$q''_{o,w} = h_{o,w}(T^o_{max} - T^o_m) \qquad Nu_d = 0.55(Ra_{q,d})^{0.2}$$

Mayinger

ii) Determine the angular distribution

$$q''_{o,w}(\theta) = h_{o,w}(\theta)(T^o_{max} - T^o_m)$$

$$\frac{Nu_d}{\overline{Nu}_d} = 0.1 + 1.08\left(\frac{\theta}{\theta_{tot}}\right) - 4.5\left(\frac{\theta}{\theta_{tot}}\right)^2 + 8.6\left(\frac{\theta}{\theta_{tot}}\right)^3$$
$$\text{for } 0.1 \le \frac{\theta}{\theta_{tot}} \le 0.6$$

$$\frac{Nu_d}{\overline{Nu}_d} = 0.41 + 0.35\left(\frac{\theta}{\theta_{tot}}\right) + \left(\frac{\theta}{\theta_{tot}}\right)^2$$
$$\text{for } 0.6 \le \frac{\theta}{\theta_{tot}} \le 1.0$$

mini-ACOPO

Methodology: Uncertainty analysis

LP code

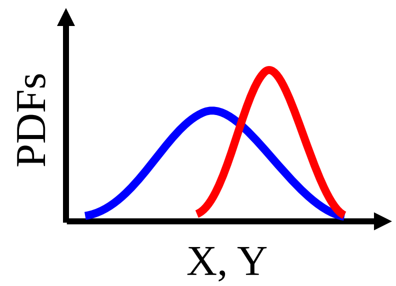
Input (X, Y)

↓

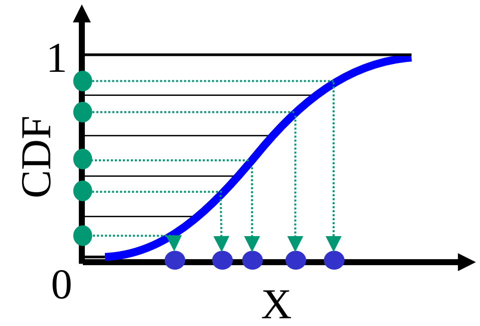
Model F(X, Y)

↓

Result (Z)



Input PDFs



Latin hypercube sampling (LHS)
: Stratified random sampling

Input: $(X_1, Y_1), \ldots, (X_n, Y_n)$

↓

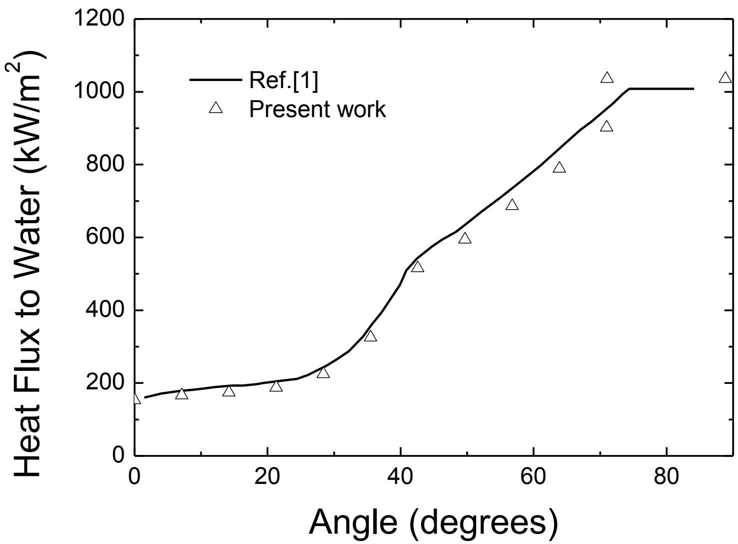
Model
$F_1(X_1, Y_1), F_2(X_2, Y_2), \ldots, F_n(X_n, Y_n)$

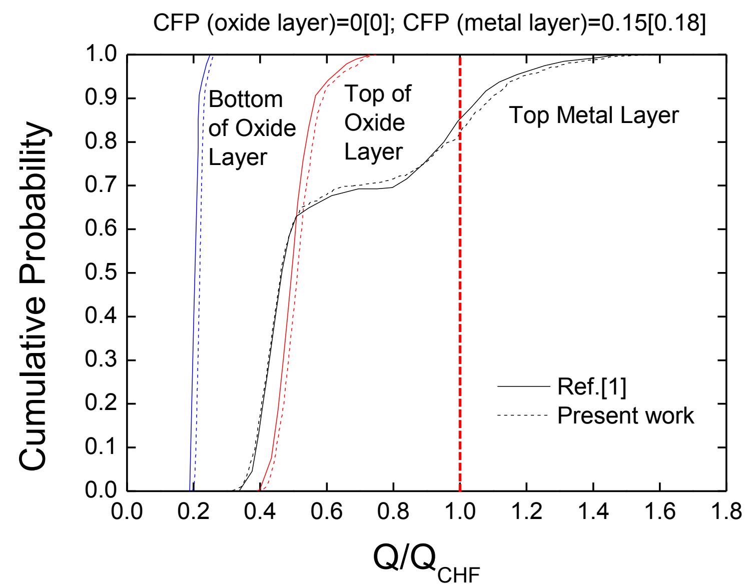
↓

Result: $(Z_1), \ldots, (Z_n)$

Verification of the model with previous work on AP1000

- Uncertainty parameters:
  Quantity of each layer and volumetric heat generation rate
  - Mass of UO2 (kg), Zr oxidation fraction (-)
  - Decay power (MW) or decay heat (MW/m^3)
  - etc.





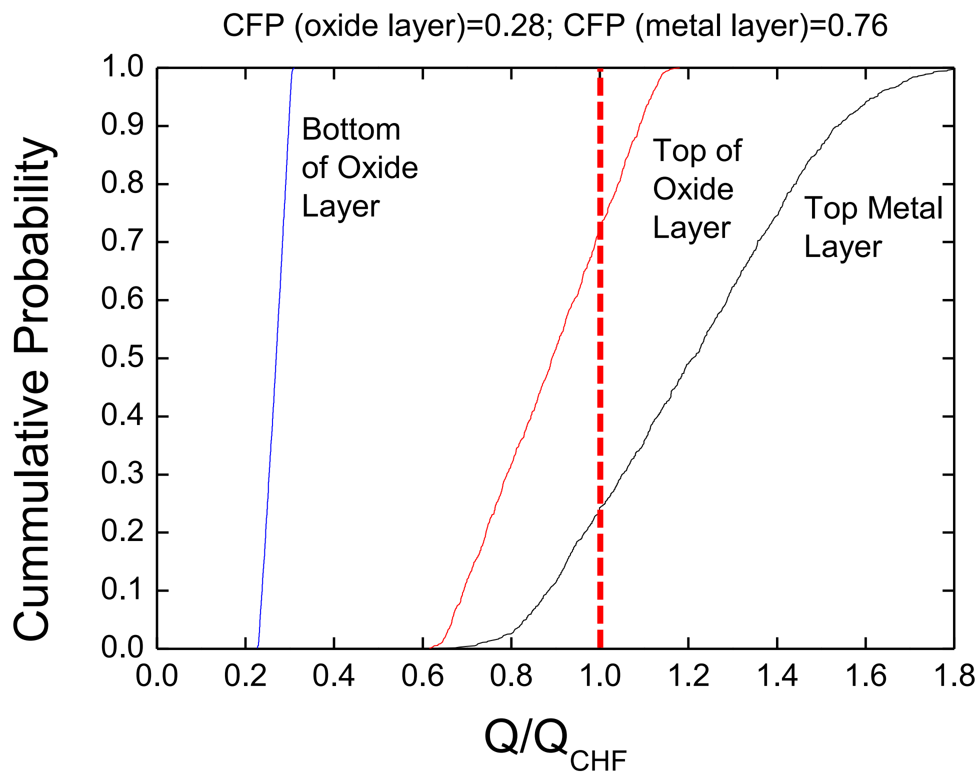
APR1400 analysis: Input conditions (base case)

- LP code (AP1000) is modified to evaluate APR1400
- Initial PDFs
  - Result of SCDAP/RELAP5 for various SA scenarios
  - Parameters: m_{UO2}, m_{ZrO2}, m_{Zr} and Q'''
  - Type: Uniform distribution between min ~ max value

Parameter	Minimum value	Maximum Value
m_{UO2} (ton)	94.7	113.2
m_{ZrO2} (ton)	2.8	19
m_{Zr} (ton)	4.7	17.7
Q''' (MW/m^3)	2.32	4.15

APR1400 analysis: Base case

- CFP increases
  - 0 to 0.28 (oxide layer)
  - 0.15 to 0.76 (metal layer)

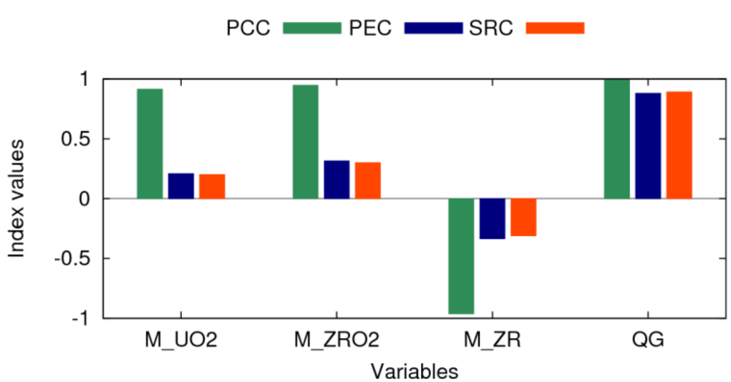


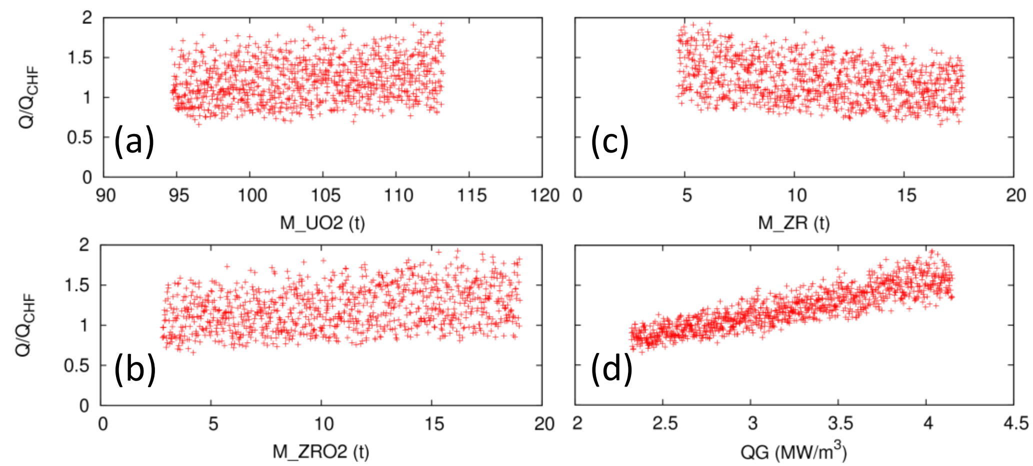
- Mean value
  m_{UO2} and Q''' increase by 40%
  - Total heat energy increases

APR1400 analysis: Importance analysis

- Relative importance of the uncertainty input variables
  - Decay heat (QG) showed the largest correlation coefficient

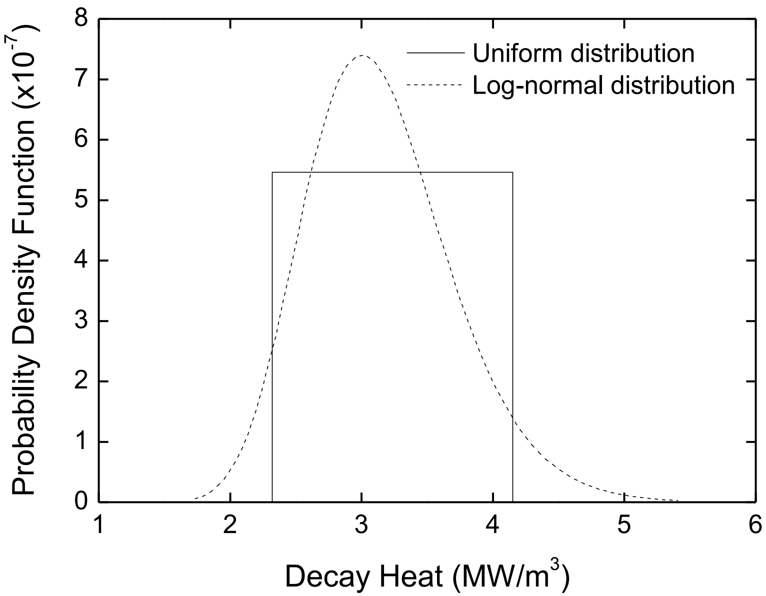
    → primarily determines Q/Q_{CHF}
  - Other 3 also showed large PCC (partial corr. coeff.)
  - Zirconium metal mass → Thicker metal layer moderates the focusing effect

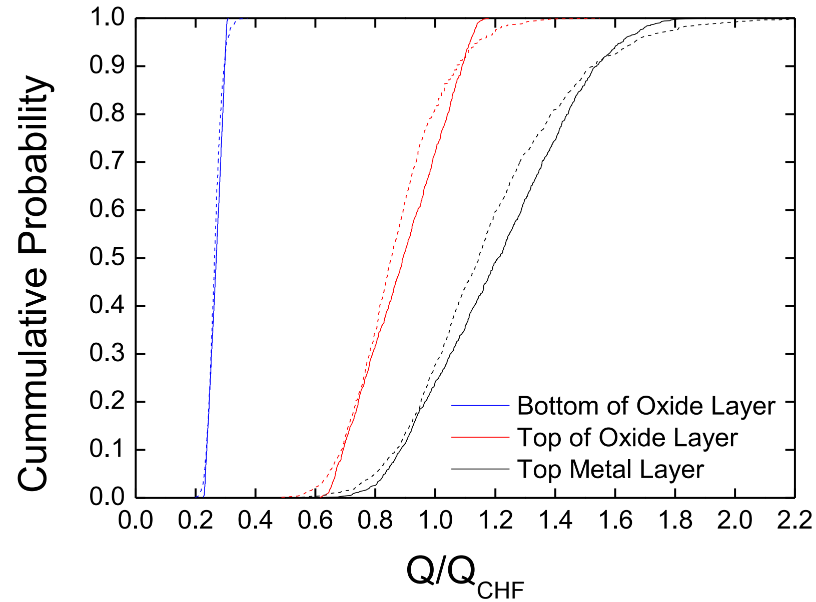




APR1400 analysis: Influence of the distribution profile

- Uniform → Log-normal distribution
  - $Error\ Factor(EF) = \sqrt{\frac{x_{95\%}}{x_{05\%}}}$
  - $x_{50\%} = x_{05\%} \times EF$ (or $x_{50\%} = x_{95\%}/EF$)





APR1400 analysis: Influence of the distribution profile

- Specific probability profile should be defined for some parameters

Case	Description			Conditional failure property	
	Parameter	Log-median	Error factor	Oxide layer	Metal layer
1	Base case			0.28	0.76
2	m_{UO2}	103.54	1.09	0.28	0.75
3	m_{ZrO2}	7.29	2.60	0.26	**0.71**
4	m_{Zr}	9.12	1.94	0.28	0.79
5	Q'''	3.10	1.34	**0.19**	0.72
6	Case 2~5 combined			0.17	0.71

APR1400 analysis: Influence of the heat transfer coefficients

- CFP is largely influenced by heat transfer characteristic
  - Case 2, 3, 5: HTC in oxide layer
  - Case 4: CHF

Case	Description	Conditional failure property	
		Oxide layer	Metal layer
1	Base case	0.28	0.76
2	Heat transfer correlations of ACOPO	0.18	0.84
3	Heat transfer correlations of mini-ACOPO	0.30	0.78
4	Assumed ±10% uncertainty in CHF (ULPU-V)	0.08~0.48	0.64~0.89
5	25% increase in HTC (oxide to metal layer)	0.03	0.89

Conclusion

- LP code was developed as previous work to evaluate the coolability of high power NPPs (APR1400)
- Uncertainty study was conducted for several SAs
  - Base case: CFP = 0.28 (oxide layer), 0.76 (metal layer)
  - Importance analysis
  - Influence of PDF, HTC
- Before we assess the APR1400, it is necessary to reduce the uncertainty by using plant-specific information
  - Initial condition (PDF)
  - CHF correlation
  - Thermal behavior (HTC) in oxide layer by CFD analysis

Thank you for your attention

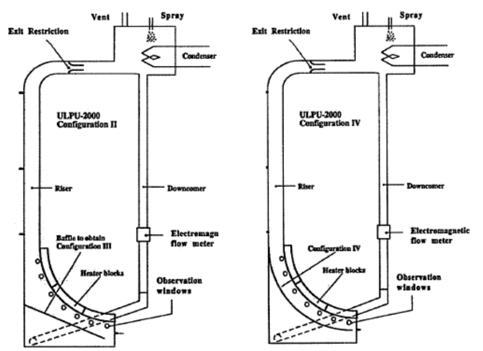
Appendix

- CHF (20)
- Heat flux (21)
- SCDAP/RELAP5 (22-23)
- Correlation (24-26)
- etc. (27)

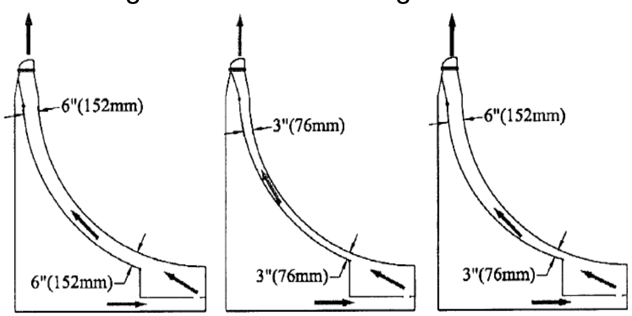
Critical heat flux (CHF)

- Cooling limitation

ULPU experiment [1]



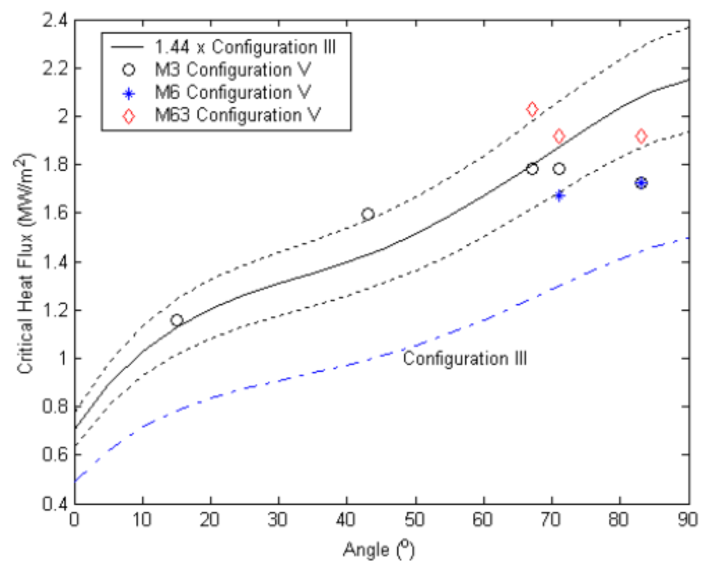
Configuration III Configuration IV



Configuration V

Coefficient	Config. III	Config. V
A_{CHF}	4.9 x 10^5	Config. III x 1.44
B_{CHF}	3.02 x 10^4	“
C_{CHF}	-8.88 x 10^2	“
D_{CHF}	13.5	“
E_{CHF}	-6.65 x 10^{-2}	“

$$q''_{CHF} = A_{CHF} + B_{CHF}\theta + C_{CHF}\theta^2 + D_{CHF}\theta^3 + E_{CHF}\theta^4$$



- $q"_{w,i} = \frac{k_c}{\delta_{c,w}} \left(T_m^o - T_{w,i}\right) + \frac{Q_c'''\delta_{c,w}}{2}$

- $q"_{w,o} = C_{boil}(T_{w,o} - T_{sat})^3$

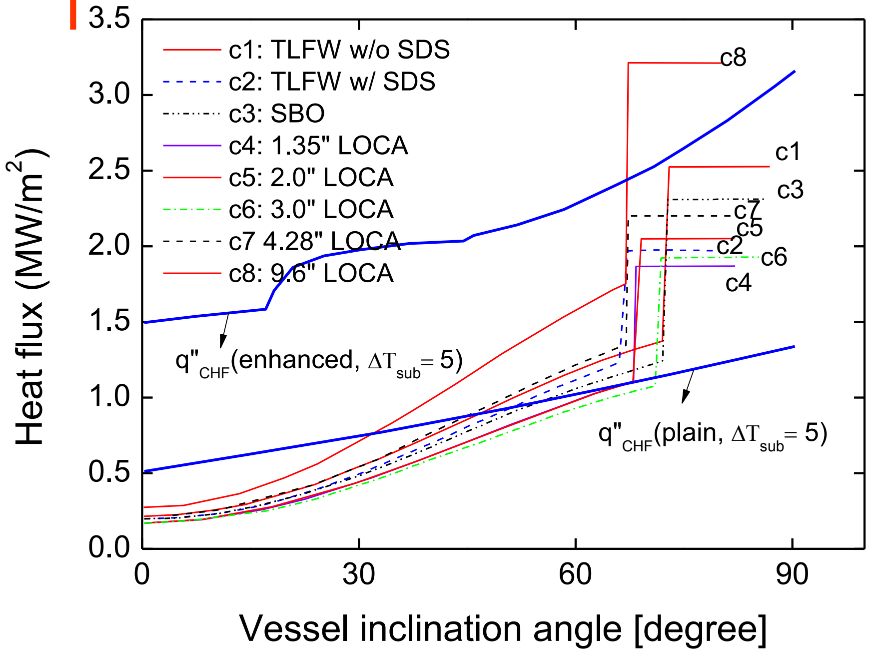
- $C_{boil} = \left(\frac{g[\rho_l - \rho_v]}{\sigma_l}\right)^{\frac{1}{2}} \left(\frac{c_{p,l}}{h_{fg} C_{sf} Pr_l}\right)^3 (\mu_l h_{fg})$

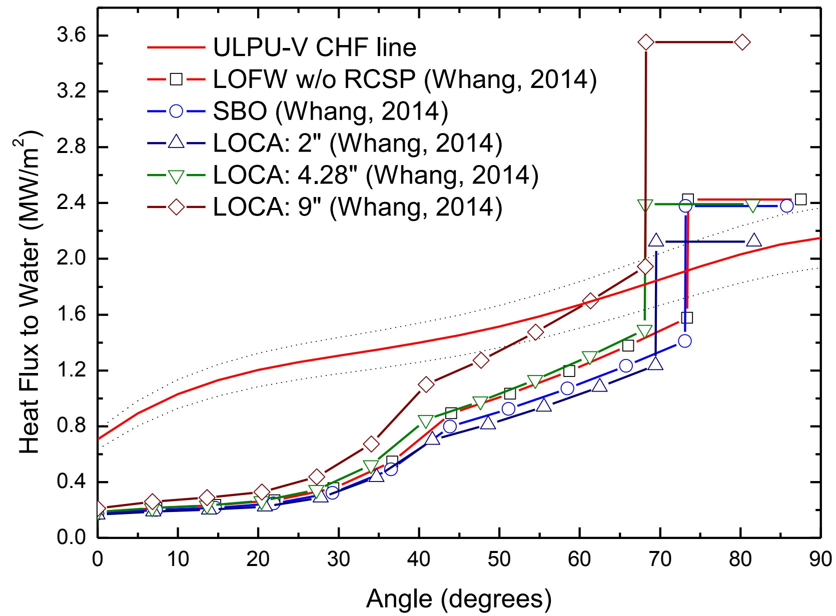
Scenario analysis with SCDAP/RELAP5 (S. B. Kim et al, 2004)

Scenarios			Q‴(MW/m^3)	Pool deg. (°)	δ_{METAL} (m)
HP	LOFW	w/o RCSP	2.91	72.9	0.59
		w/ RCSP	2.95	66.9	0.63
	SBO		2.62	72.7	0.58
LP	LOCA	1.35″	2.32	71.9	0.6
		2″	2.54	69	0.55
		3″	2.53	68.3	0.59
		4.28″	3.19	67.3	0.61
		9.6″	4.15	67.2	0.54

HP: High Pressure
LP: Low Pressure
LOFW: Loss of Feed Water
RCSP: Radiation Control and Safety Program
SBO: Station Black Out
LOCA: Loss Of Coolant Accident, number″: LOCA rupture size (inch)

Scenario analysis with SCDAP/RELAP5 (S. B. Kim et al, 2004)





Base correlation set

	Top surface	Bottom surface	Side wall
Metal layer	Globe-Dropkin (1959) $Nu_l = 0.069Ra_l^{0.333}Pr_l^{0.074}$		Churchill-Chu(1975)
Oxide layer	Kulacki-Emara(1975) $Nu_u = 0.345(Ra_{q,u})^{0.226}$	Mayinger(1976) $Nu_d = 0.55(Ra_{q,d})^{0.2}$	Mini-ACOPO

Churchill-Chu(1975)

$$Nu_{l,w} = [0.825 + \frac{0.387Ra_l^{1/6}}{[1 + (^{0.492}/_{Pr_l})^{9/16}]^{8/27}}]^2$$

Mini-ACOPO

$$\frac{Nu_d}{\overline{\overline{Nu}}_d} = 0.1 + 1.08\left(\frac{\theta}{\theta_{tot}}\right) - 4.5\left(\frac{\theta}{\theta_{tot}}\right)^2 + 8.6(\frac{\theta}{\theta_{tot}})^3$$

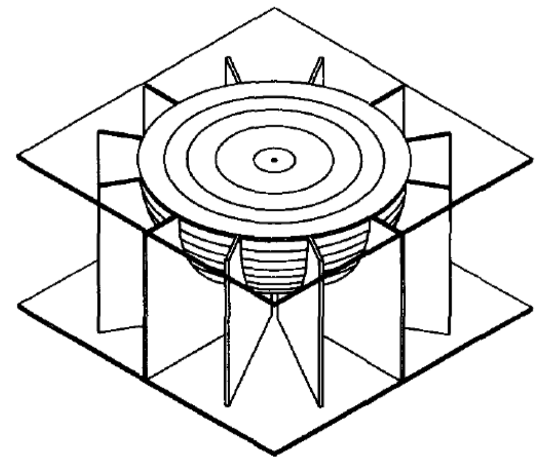
for $0.1 \leq \frac{\theta}{\theta_{tot}} \leq 0.6$

$$\frac{Nu_d}{\overline{\overline{Nu}}_d} = 0.41 + 0.35\left(\frac{\theta}{\theta_{tot}}\right) + \left(\frac{\theta}{\theta_{tot}}\right)^2$$

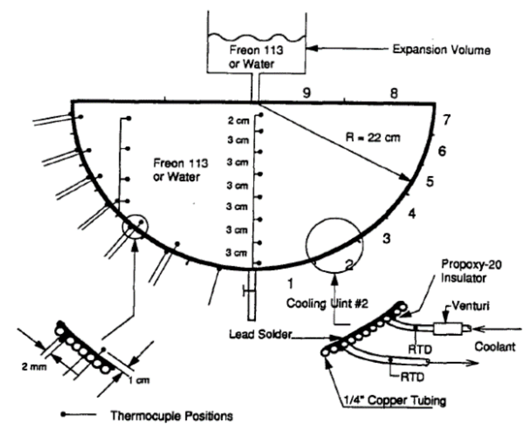
for $0.6 \leq \frac{\theta}{\theta_{tot}} \leq 1.0$

Correlation for oxide layer

Top surface	Bottom surface
Mini-ACOPO $Nu_u = 0.345(Ra_q)^{0.233}$	Mini-ACOPO $Nu_d = 0.0038Ra^{0.35}(\frac{H}{R})^{0.25}$
Kulacki-Emara $Nu_u = 0.345(Ra_{q,u})^{0.226}$	Mayinger $Nu_d = 0.55(Ra_{q,d})^{0.2}$
ACOPO $Nu_u = 2.4415(Ra'_p)^{0.1772}$	ACOPO $Nu_d = 0.1857Ra'^{0.2304}_p(\frac{H}{R})^{0.25}$



Schematic of the ACOPO test vessel showing the individual cooling units and the vessel support



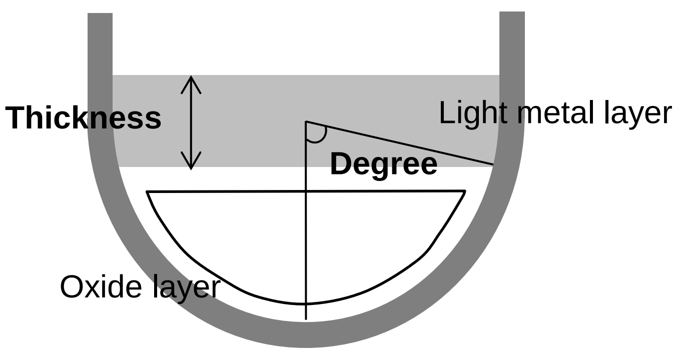
Mini-ACOPO

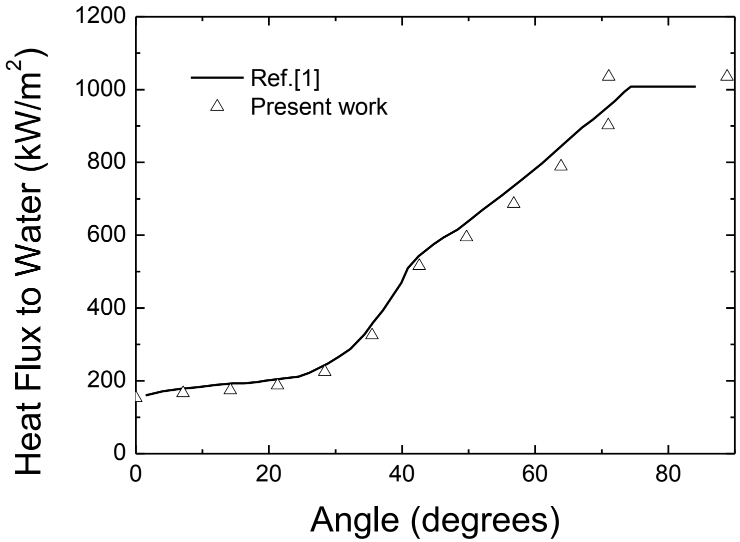
Range of applicability

Table 2.2 Ranges of applicability of the correlations listed in Table 2.1

Model		Heat Transfer Correlation	Range of applicability	
			Ra	Pr
ERI [1-2]	Ceramic Pool	Mayinger [24]	$7x10^{6} – 5x10^{14}$	0.5
		Kulacki-Emara [31]	$2x10^{4} – 4.4x10^{12}$	7
	Top Metal Layer	Globe-Dropkin [29]	$3x10^{5} – 7x10^{9}$	0.02-8750
		Churchill-Chu [30]	$0.1 – 10^{12}$	Any
DOE [18]	Ceramic Pool	Mini-ACOPO [32]	$10^{12} – 7x10^{14}$	2.6-10.8
	Top Metal Layer	Globe-Dropkin "Specialized"	$3x10^{5} – 7x10^{9}$	0.02-8750
		Churchill-Chu	$0.1 – 10^{12}$	Any
INEEL 19]	Ceramic Pool	ACOPO	$10^{12} – 2x10^{16}$	
	Top Metal Layer	Globe-Dropkin	$3x10^{5} – 7x10^{9}$	0.02-8750
		Churchill-Chu	$0.1 – 10^{12}$	Any

etc.


Thickness
Light metal layer
Degree
Oxide layer


Ref.[1]
Present work
Heat Flux to Water (kW/m²)
Angle (degrees)
0
200
400
600
800
1000
1200
0
20
40
60
80