Evaluation of Two Phase Natural Circulation Flow in the Reactor Cavity under IVR-ERVC for Different Thermal Power Reactors

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  - IVR-ERVC Concept
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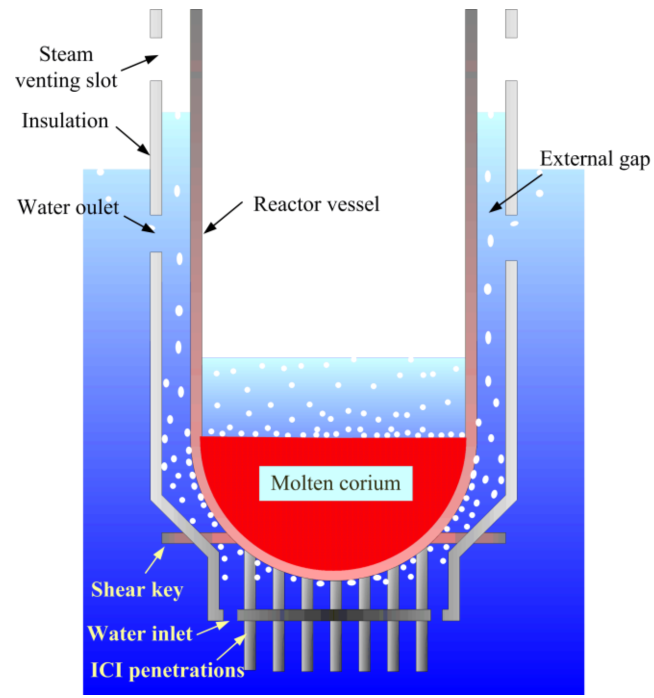
Introduction (1)

- In-Vessel corium Retention through External Reactor Vessel Cooling
  - Design Feature for SA Mitigation
    - AP600 & AP1000 in USA
    - Loviisa in Finland
    - KERENA in Germany, and so on
  - As a part of SAMG Strategies
    - APR1400 & OPR1000 in Korea
    - Current Operating Plants, and so on

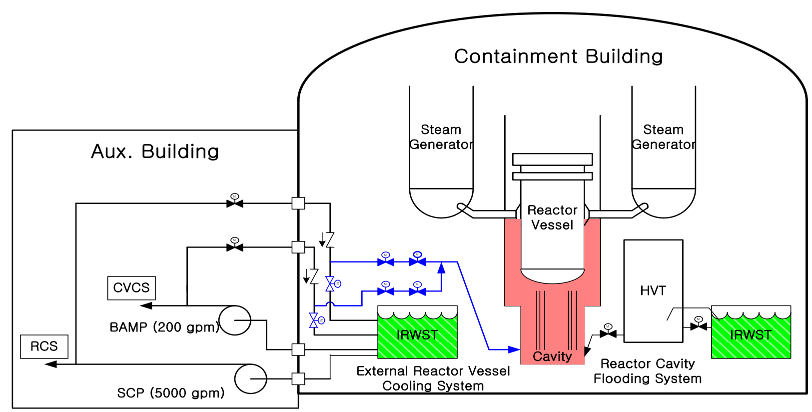


Schematic Diagram of IVR-ERVC

Introduction (2)

- IVR-ERVC
  - The strategy of the APR1400 for severe accident mitigation aims at retaining molten core in-vessel first and ex-vessel cooling of corium second in case the reactor vessel fails, reinforcing the principle of defense-in-depth.
  - IVR-ERVC was adopted as one of severe accident management strategies. In IVR-ERVC condition, the cavity will be flooded from IRWST by the SCP and the BAMP to the hot leg penetration bottom level.

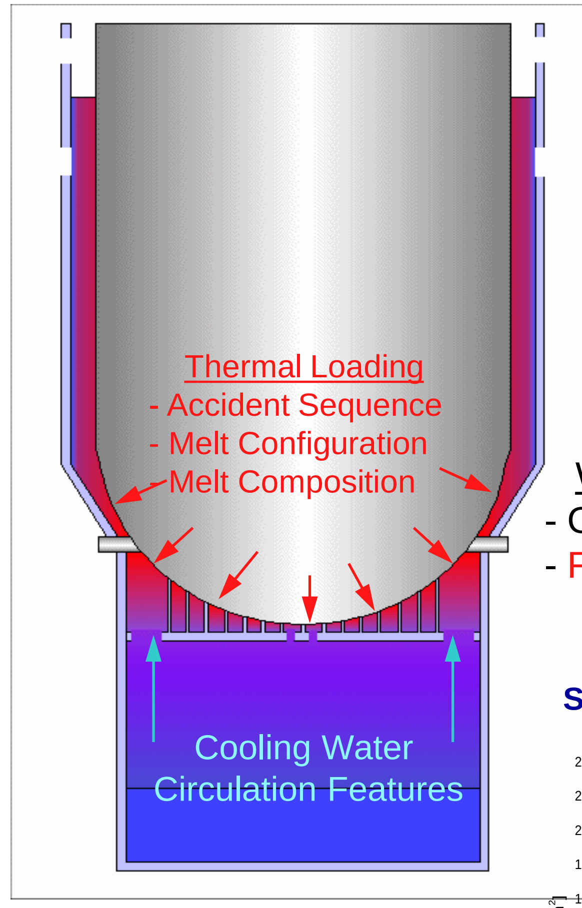
IVR-ERVC in the APR1400 : Active system (Not passive) & non severe accident design feature



Schematic Diagram of the APR1400(Advanced Power Reactor)

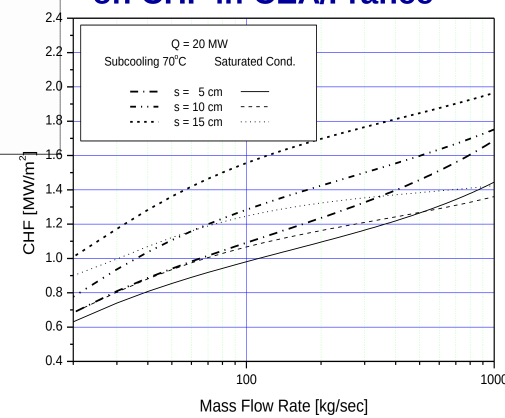
Introduction (3)

- To evaluate IVR-ERVC
  - Thermal load
  - Heat removal rate (CHF)
  - Success Criteria
    - CHF > Thermal Load
- In general, an increase in natural circulation coolant mass flow rate in cooling channel leads to increase in the heat removal rate at the reactor vessel wall.
- To Increase natural circulation flow rate
  - Gap configuration to form streamline flow
  - Optimal coolant inlet/outlet design
  - Steam venting to prevent pressure build-up in annular gap between reactor vessel and insulation



Wall CHF
- Geometry
- Flow Condition

SULTAN Experimental Results on CHF in CEA/France



Natural circulation flow feature should be evaluated.

Introduction (4)

- Design features of OPR1000 and APR1400

Design Parameters	OPR1000	APR1400
Core Thermal Power (MW)	2815	3983
Fuel(UO_2) Mass (ton)	85.6	120.0
Mass for Active Core Zircaloy-4 (ton)	23.9	33.6
Bottom Head Inner Diameter (m)	4.2	4.7
Bottom Head Thickness (cm)	15.2	16.5
Number of ICI Nozzle in the Lower Head	45	61

- To enhance heat removal rate(increase natural circulation flow)
  - APR1400 : Optimal insulation design
  - OPR1000: Not yet

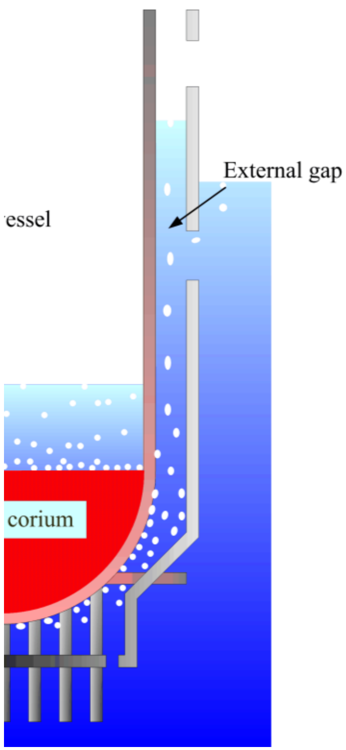
Introduction (5)

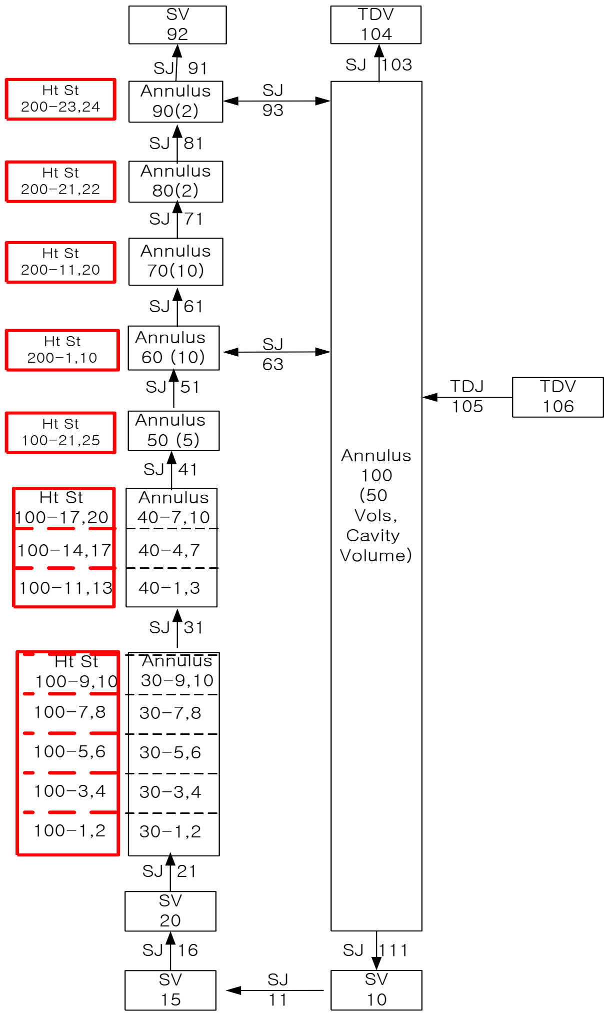
- Objective:
  - Analysis of two phase natural circulation mass flow rate in the annular gap between the outer reactor vessel wall and the insulation using the RELAP5/MOD3
- Contents
  - To analyze the coolant circulation coolant mass flow rate in APR1400 & OPR1000
  - To analyze the effects of the coolant injection temperature and water level on the coolant mass flow rate

RELAP5 Input Model (1)

- RELAP5/MOD3
  - This system thermal hydraulic computer code was developed at the INL(Idaho National Laboratory) for the USNRC.
  - This 1-D best estimate transient simulation computer code uses six equations on mass, momentum, and energy equations.
  - This computer code includes analyses required to support rulemaking, licensing audit calculations, evaluations of accident mitigation strategies, evaluations of operator guidelines, and experiment planning analyses.
  - This computer code can be used for the simulation of a wide variety of hydraulic and thermal transients in both nuclear and non-nuclear systems involving mixtures of steam, water, non-condensable, and solute.

RELAP5 Input Model (2)





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 (CFST)
Single Junction 16	Water Inlet
Single Junction 63	Water Outlet
Single Junction 93	Steam Outlet

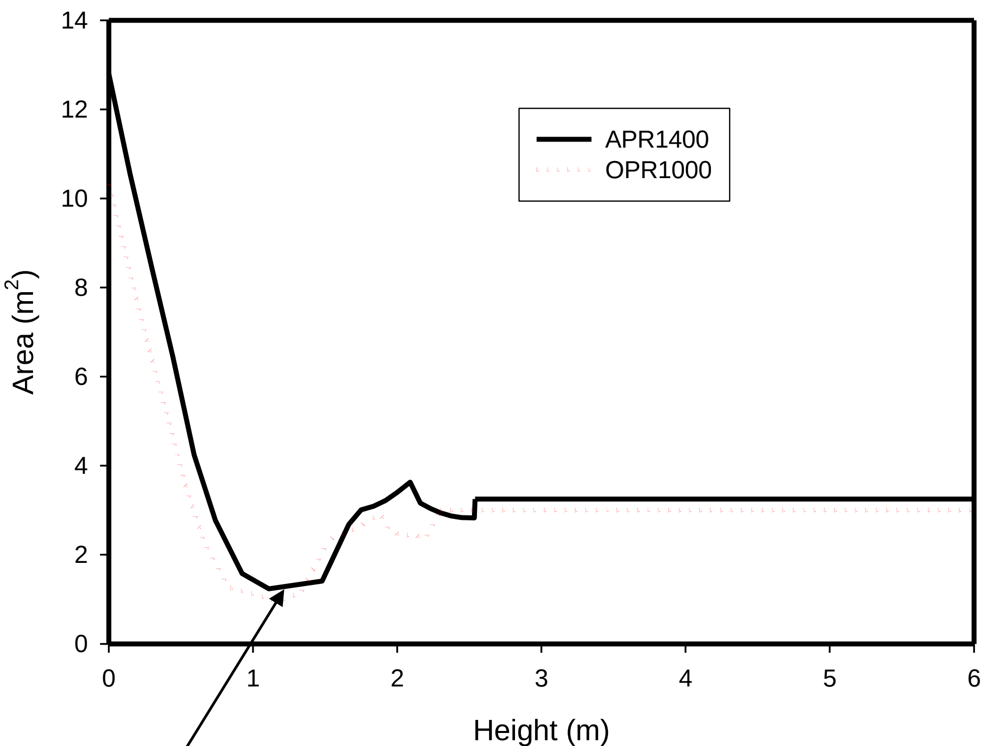
RELAP5 Input Model (3)

- Insulation design for natural circulation flow

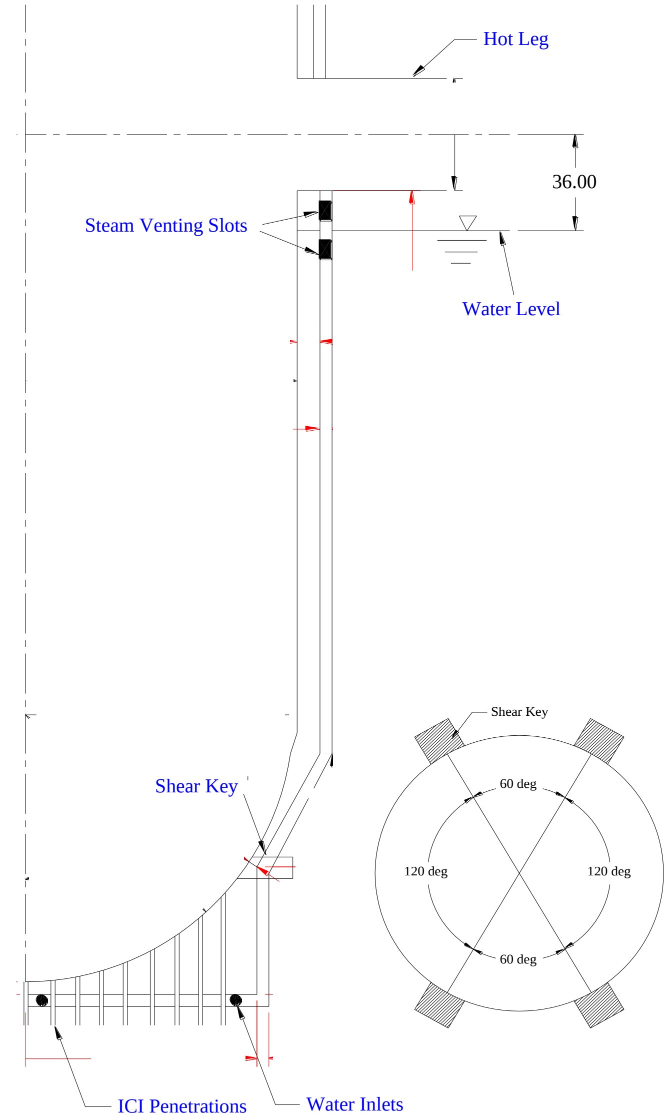
Input Conditions	OPR1000 (Assumed)	APR1400
Water Inlet Area (m^2)	1.765	1.765
Water Outlet Area (m^2)	1.486	1.672
Steam Outlet Area (m^2)	0.372	0.372
Water Outlet Position from the Reactor Vessel Bottom (m)	5.69	6.14
Steam Outlet Position from the Reactor Vessel Bottom (m)	8.13	8.60
Distance Between Insulation and Reactor Vessel Bottom (m)	0.05	0.12

RELAP5 Input Model (4)

- Annular gap area

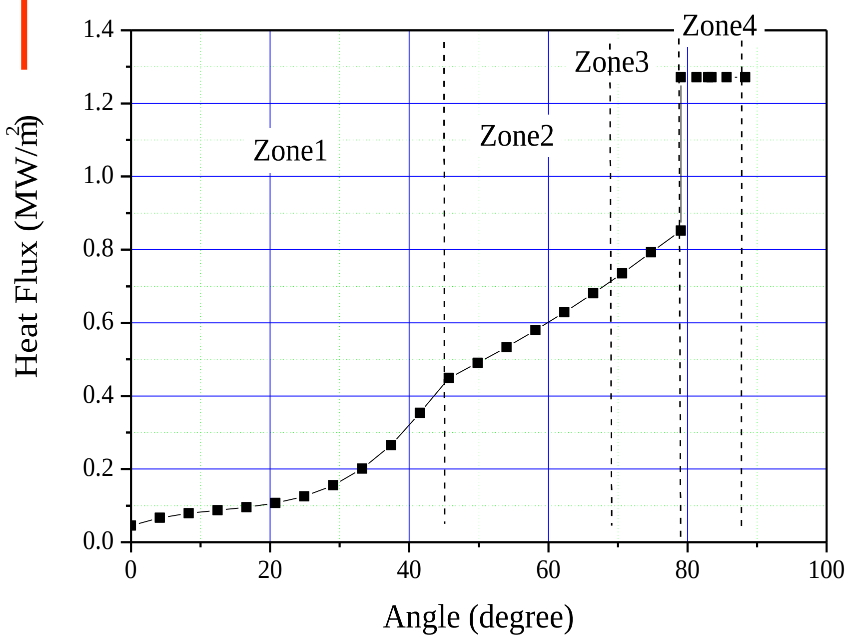


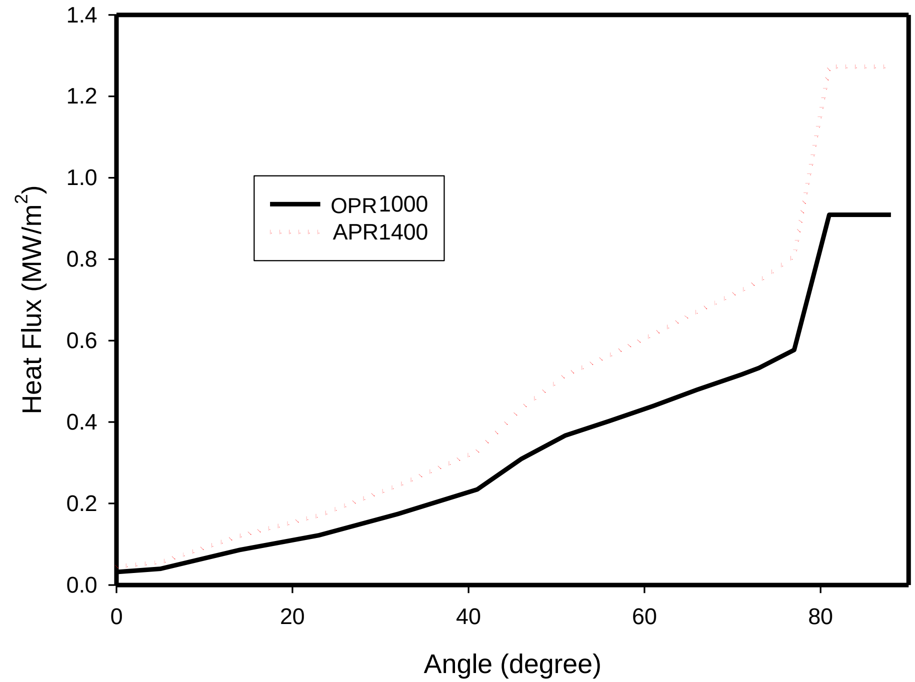
Minimum Gap Area



RELAP5 Input Model (5)

- Thermal load



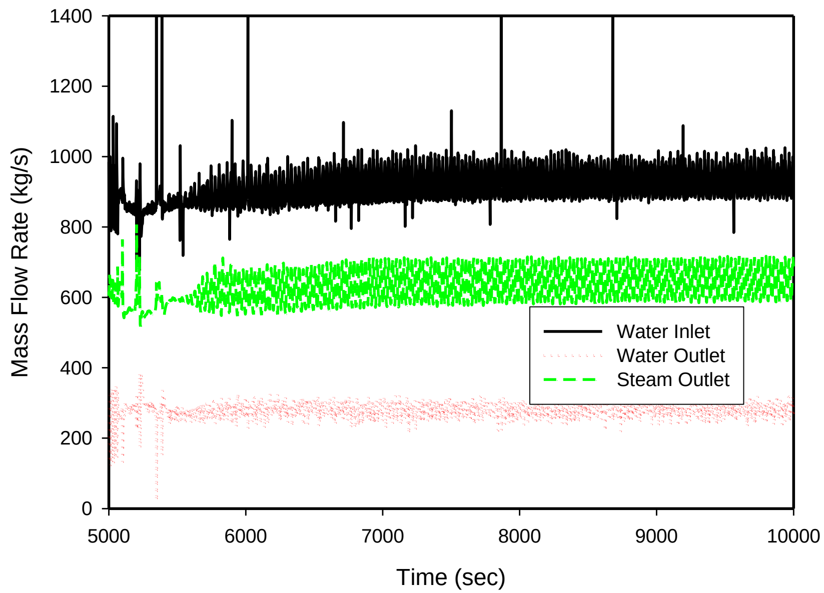


MAAP4 Results for the APR1400 (from KHNP)

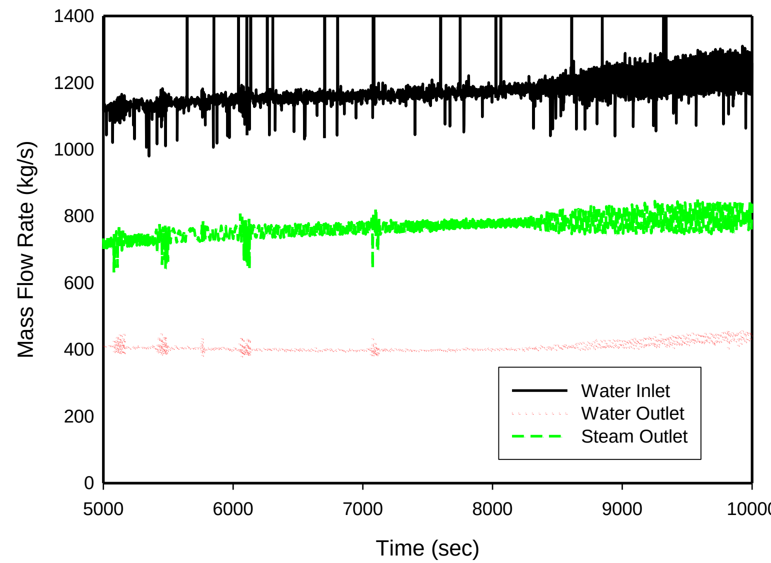
Reduced Results for the OPR1000

RELAP5 Results & Discussion (1)

- Temporal coolant circulation mass flow rate



OPR1000

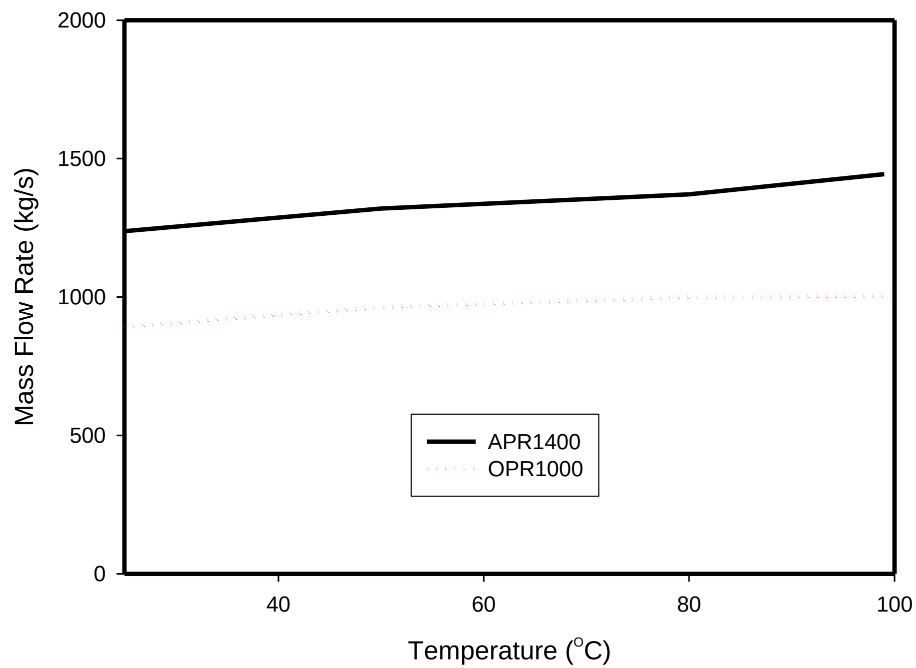


APR1400

- Oscillatory Flow, APR1400 > OPR1000(Annular Gap Area, Thermal Load)
- Some water circulates through the steam outlet because two phase water level increases in the annular gap

RELAP5 Results & Discussion (2)

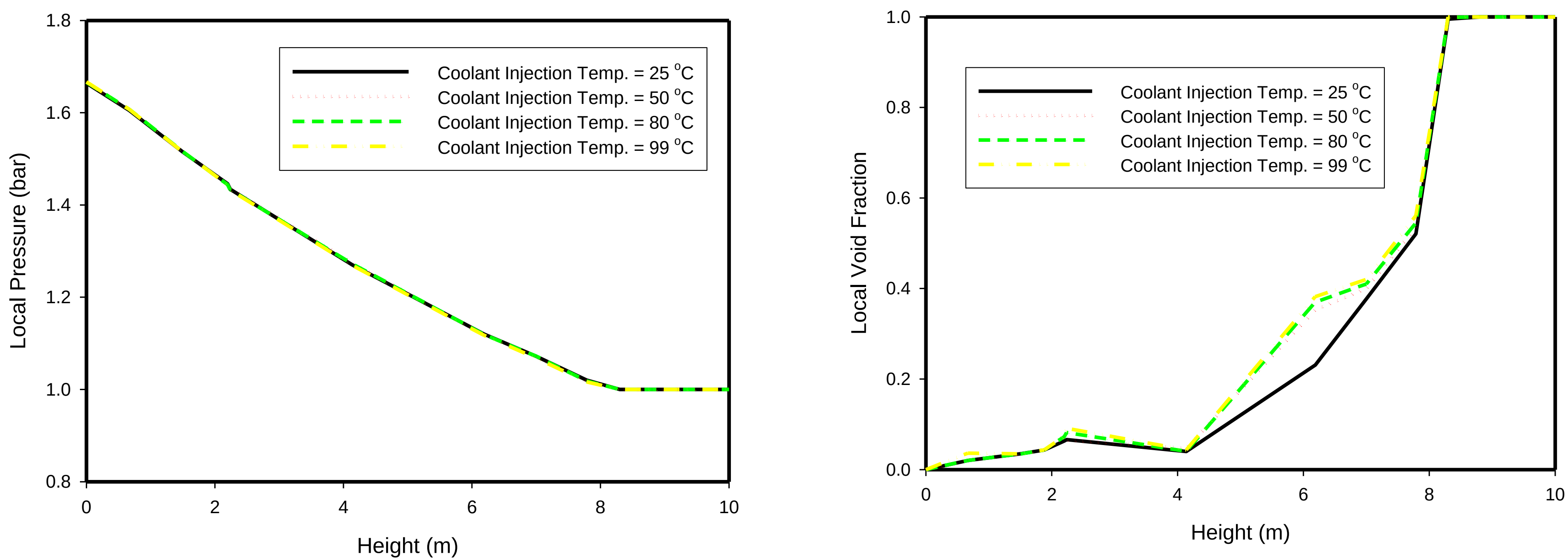
- Coolant injection temperature effect



  – An increase in coolant injection temperature leads to an increase in the coolant circulation mass flow rate.

RELAP5 Results & Discussion (3)

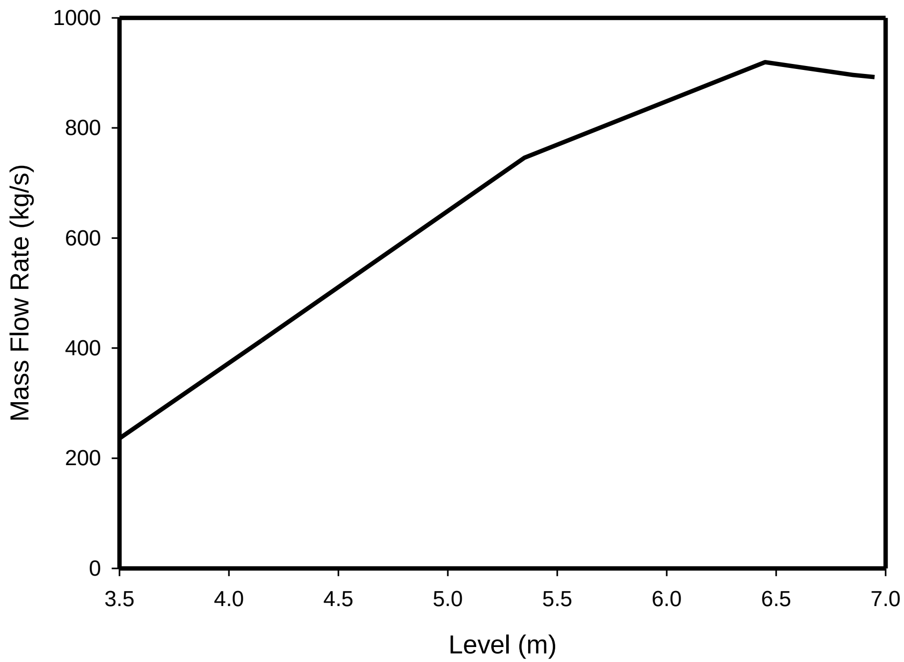
- Local pressure and averaged void fraction (OPR1000)

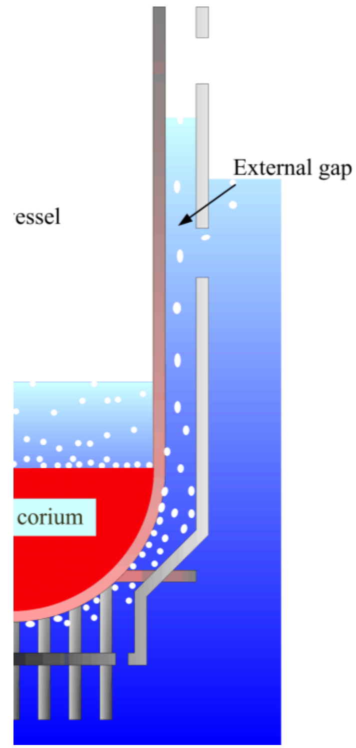


  – Coolant Injection Temp ↑ ⇨ Bubble Generation ↑ ⇨ Coolant Circulation Mass Flow Rate ↑

RELAP5 Results & Discussion (4)

- Water level effect in the reactor cavity (OPR1000)

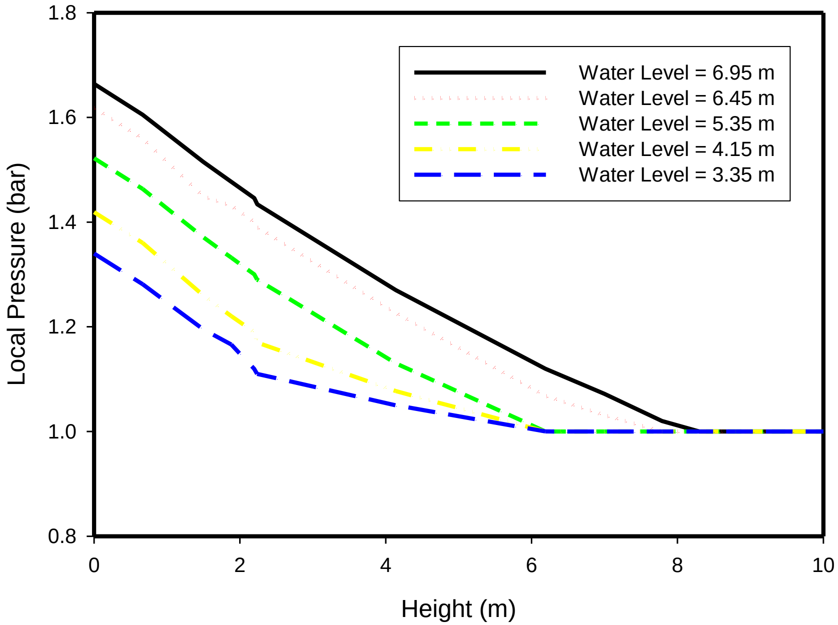


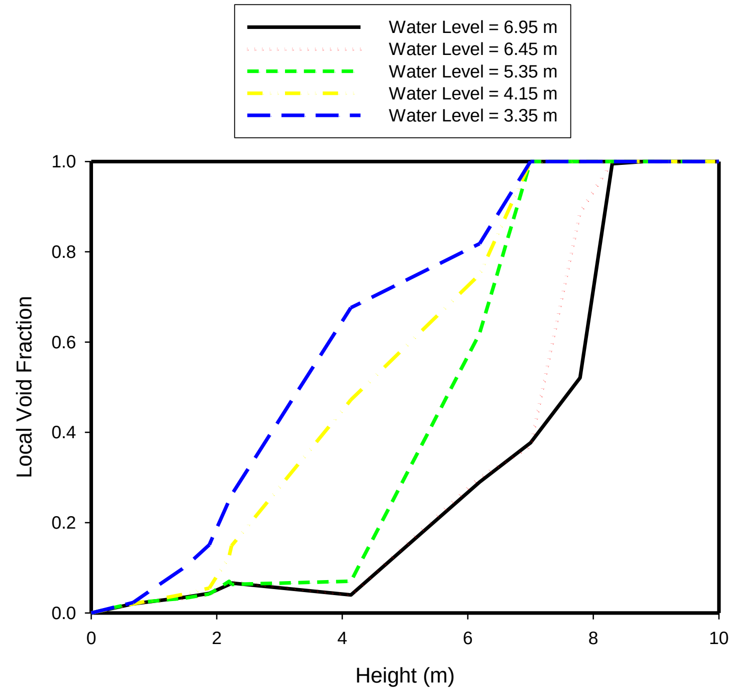


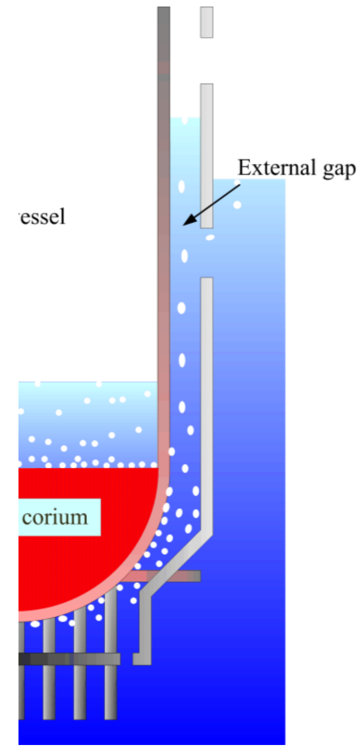
  - If water level is lower than the outlet, an decrease in water level leads to an rapid decrease in the coolant circulation mass flow rate.

RELAP5 Results & Discussion (5)

- Local pressure and averaged void fraction (OPR1000)



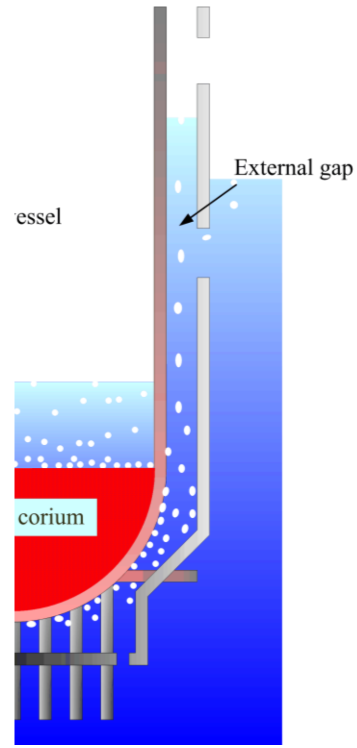




– If water level is lower than water outlet,
  - Water level ↓ ⇨ Local pressure ↓ ⇨ Challenging distance in gap to flow out ↑ ⇨ Circulation Mass Flow Rate ↓

RELAP5 Results & Discussion (6)

- Driving mechanism of circulation flow
  - Circulation flow = driving force – pressure loss
  - Driving force = pressure difference in gap and pool
    - To increase driving force (higher void fraction)
      - higher wall heat flux
      - Higher coolant temperature
  - Pressure loss = gap pressure, form & friction loss
    - To decrease pressure loss
      - Lower two-phase level in gap
      - Larger gap size (minimum gap region)
      - Uniform gap (reductions of form loss)



Conclusions (1)

- Natural circulation flow features of APR1400 and OPR1000 were examined by RELAP5 code.
  - The coolant circulation mass flow rate at high power of the APR1400 is higher than that at low power of the OPR1000.
  - The increase of the coolant injection temperature leads to an increase in the steam generation rate, which leads to an increase in the coolant circulation mass flow rate.
  - The coolant injection temperature is not effective on the local pressure, but is effective on the local average void fraction.
  - A decrease in the water level in the reactor cavity leads to a decrease in the local pressure at the lower region and an increase in the challenging distance in gap, which leads to a decrease in the coolant circulation mass flow rate.

Conclusions (2)

- It is concluded from the RELAP5 results that the present design of the reactor vessel insulation in the APR1400 and the OPR1000 is suitable for the IVR-ERVC.
- Verification experiments and a more detailed analysis are necessary to evaluate the IVR-ERVC in OPR1000.

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