Effectiveness of External Reactor Vessel Cooling (ERVC) Strategy for APR1400 and Issues of Phenomenological Uncertainties

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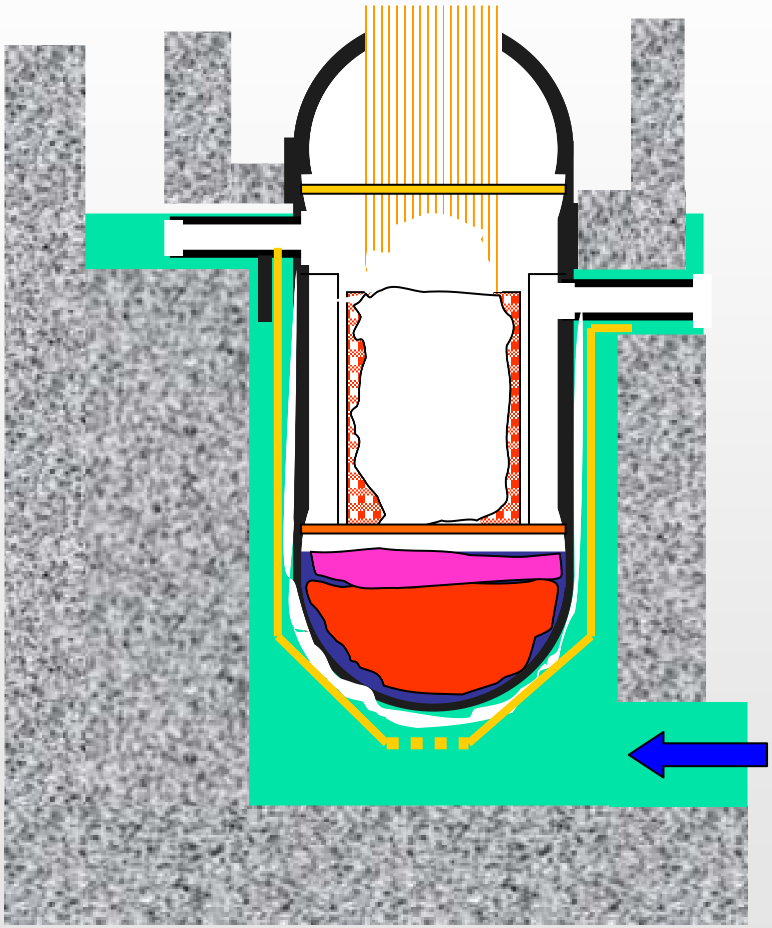
Nov. 8th, 2005

Contents

In-Vessel Melt Retention (IVR) as Severe Accident Management

- External Reactor Vessel Cooling (ERVC) Strategy
  - Evolved since mid. 80's
  - One of high level candidate strategy to mitigate severe accident for operating plants (EPRI SAMG Technical Basis Report)
  - With the application to AP600, systematic evaluation has been performed
  - Submerged water will help remove the decay heat and maintain vessel's integrity

In-Vessel Melt Retention (IVR) as Severe Accident Management



Loviisa VVER-440

Westinghouse AP600

IVR History

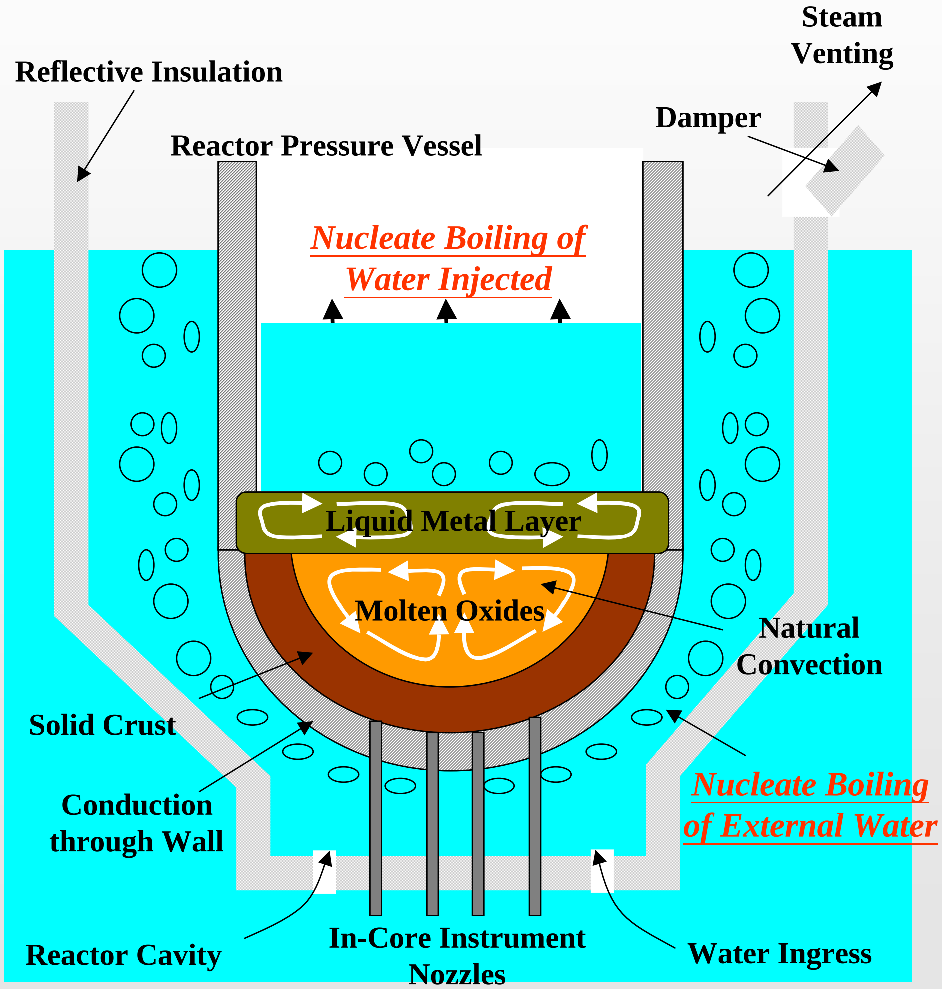
In-Vessel Retention as SAM Strategy	IVR was developed for AP600. The AP600 technology offers too narrow a thermal margin for IVR in high-power reactors.
AP600 Implementation and Base Technology R&D (UCSB, W)	IVR implementation to AP600. Develop a basic understanding of governing phenomena (NC inside and CHF outside). Effectiveness examined using ROAAM process
AP1000 Implementation of IVR (W, UCSB)	Streamlined insulation design, lower support structure optimization to enhance the thermal margin
APR1400 Implementation of IVR (KHNP/KAIST/PSU)	APR1400 plant-specific natural circulation tests for the insulation design. CHF tests to support the effectiveness evaluation. Systematic evaluation to support the IVR implementation to APR1400

IVR Technology and Implementation in APR1400

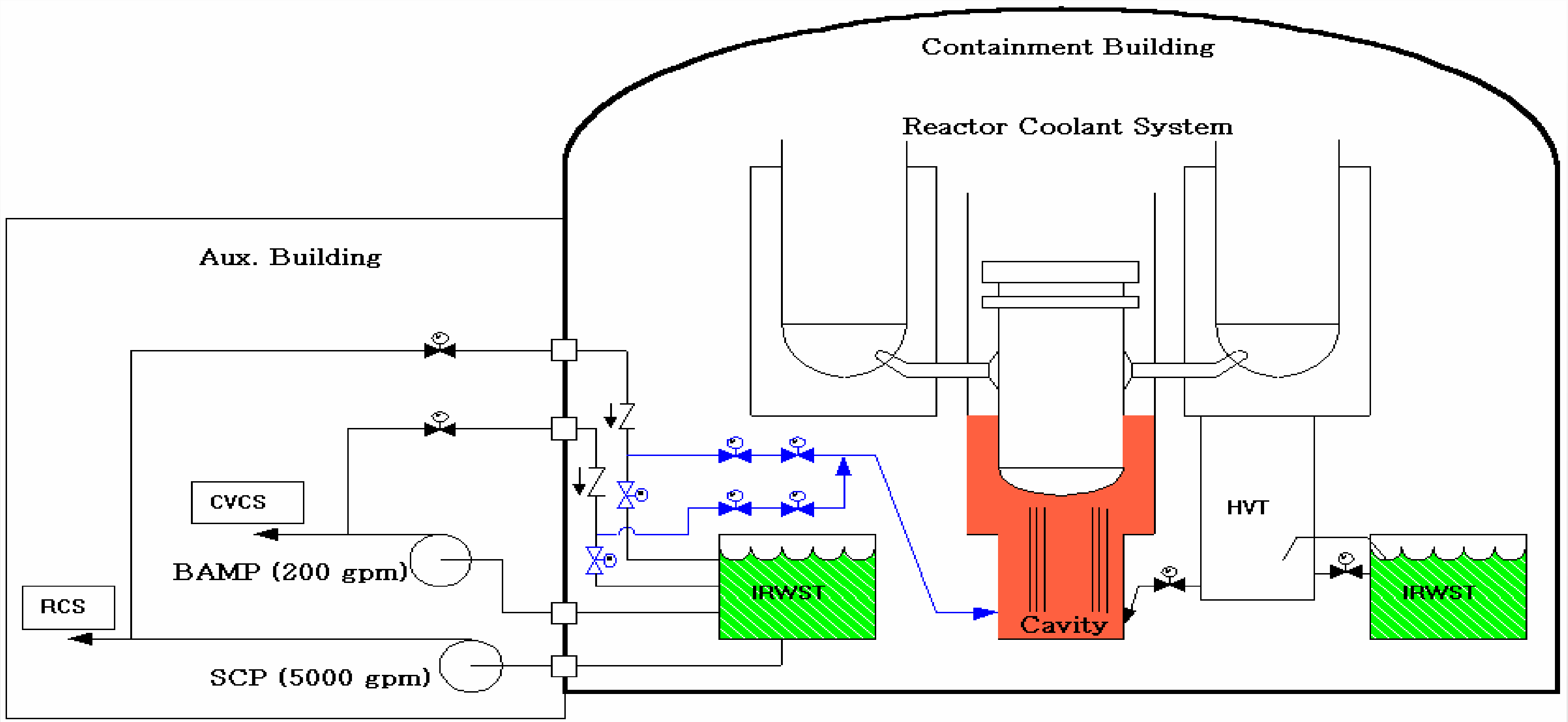
- External Reactor Vessel Cooling (ERVC)
  - Primary severe accident management (SAM) strategy for APR1400
  - In-vessel retention (IVR) strategy
    - Submerging the reactor vessel exterior using SCP and BAMP
    - Inject into the vessel to arrest core melt if possible
    - APR1400 –specific insulation design to promote heat removal and natural circulation
  - Implementation as a part of Severe Accident Management Guidance (SAMG) in Korea

- Examine the effectiveness of ERVC and its implementation in APR1400
  - Risk-oriented accident analysis methodology (ROAAM) by Theofanous is adopted for the systematic evaluation
  - Supporting material for level 2 PSA quantification
  - Do not try to claim ‘vessel breach is physically unreasonable’

IVR Technology and Implementation in APR1400



Basic Design of ERVCS for IVR and Cavity Flooding System (CFS) of APR1400



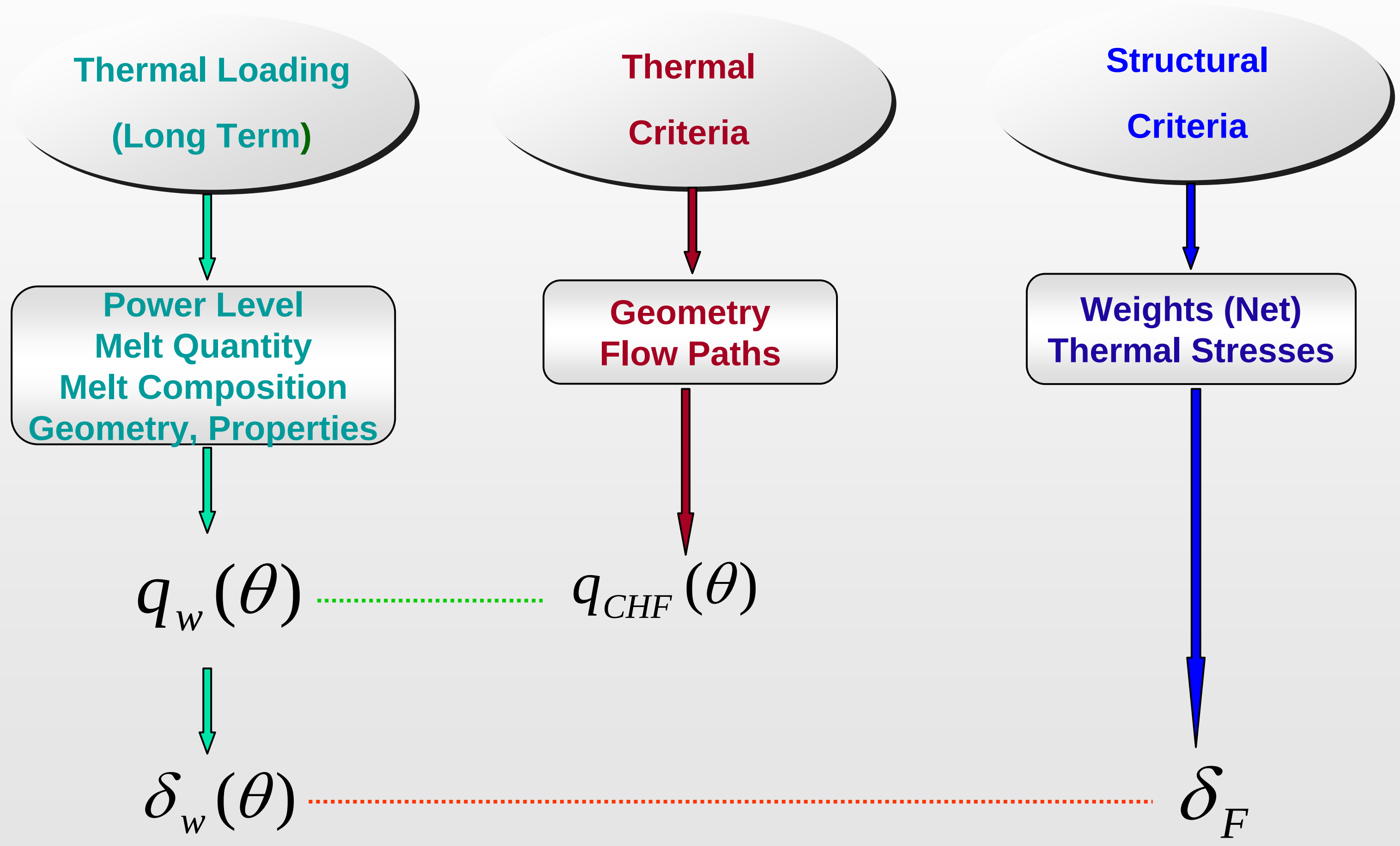
ROAAM Approach

- In general, the effectiveness of severe accident mitigation features have been examined as a part of Level 2 PSA
  - As a part of NUREG1150, expert elicitation process was used
  - Inherent difficulty: rare event with incomplete evidence (diverging expert opinion)
- Risk-oriented accident analysis methodology (ROAAM)
  - To overcome the difficulty of quantifying under uncertainty, Prof. Theofanous proposed to ‘resolve’ uncertainty using a structured evaluation with bounding scenarios
  - Examine the critical issues based on the physically-based decomposition with bounding assumption
  - Similar to expert elicitation, independent reviews by experts will be conducted.
  - Prof. Theofanous proposed that the issue is closed once experts agree on the result

ROAAM Approach

- Proposed numerical value as a part of ROAAM
  - P=0.1: Behavior is within known trends but obtainable only at the edge of spectrum parameters
  - P=0.01: Behavior cannot be positively excluded, but is outside the spectrum of reason
  - P=0.001: Behavior is physically unreasonable and violates well-known reality
  - Question: Are these reasonable value?
- Application of ROAAM to AP600 IVR study by Theofanous
  - Identify the key issues of vessel integrity
  - Thermal failure criterion is the limiting one
    - Wall heat flux vs. CHF heat flux
    - Wall thickness vs. Min thickness required for structural integrity
  - Sensitivity study to find out the thermal margin with the known CHF limit and thermal load
  - Peer Review with documented response
    - Key issue seems to be the melt configuration in view of complex physico-chemistry effect

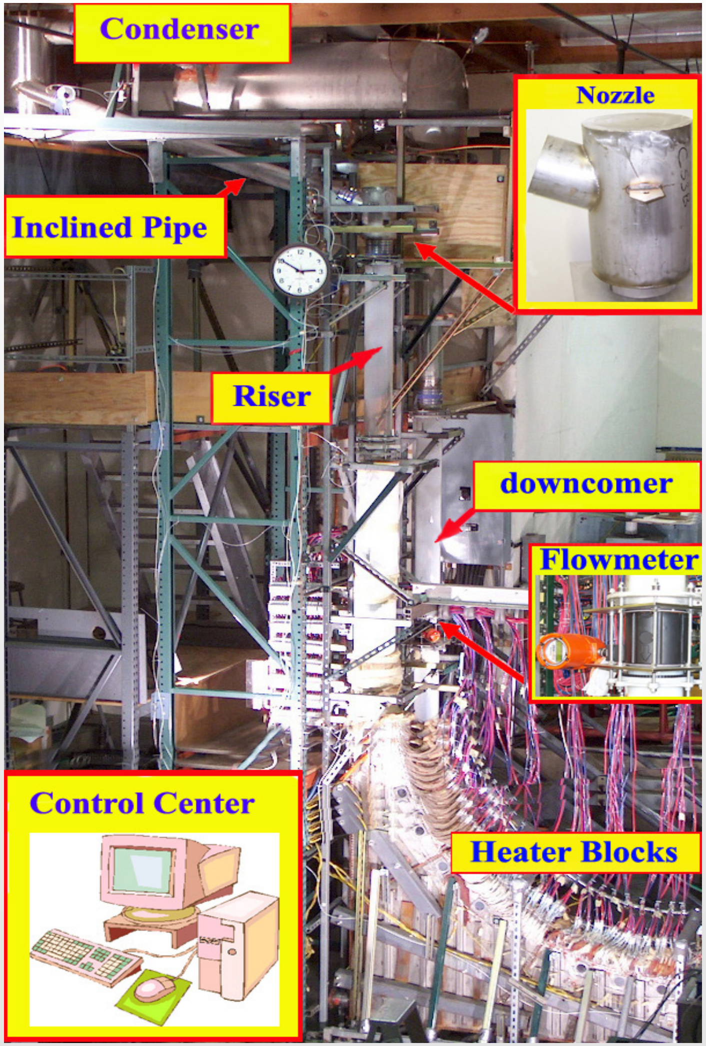
Overall view of in-vessel retention issues



UCSB ULPU Test Series

- ULPU-III: extension of CHF tests performed for AP600
- ULPU-V series: full-height 1/84 slice geometry representation of AP1000
  - 36 tests
  - Series M: streamlined geometry
  - Series C and P: effect of surface condition and power shape
- Key findings
  - With streamlined insulation design, CHF limit would be increased to 1.8 -2.0 MW/m^2
  - Microlayer scale phenomena are important for CHF
  - Surface effect and water chemistry are important

Experimental Setup of ULPU-2400 Configuration V



1152 heaters (power control)

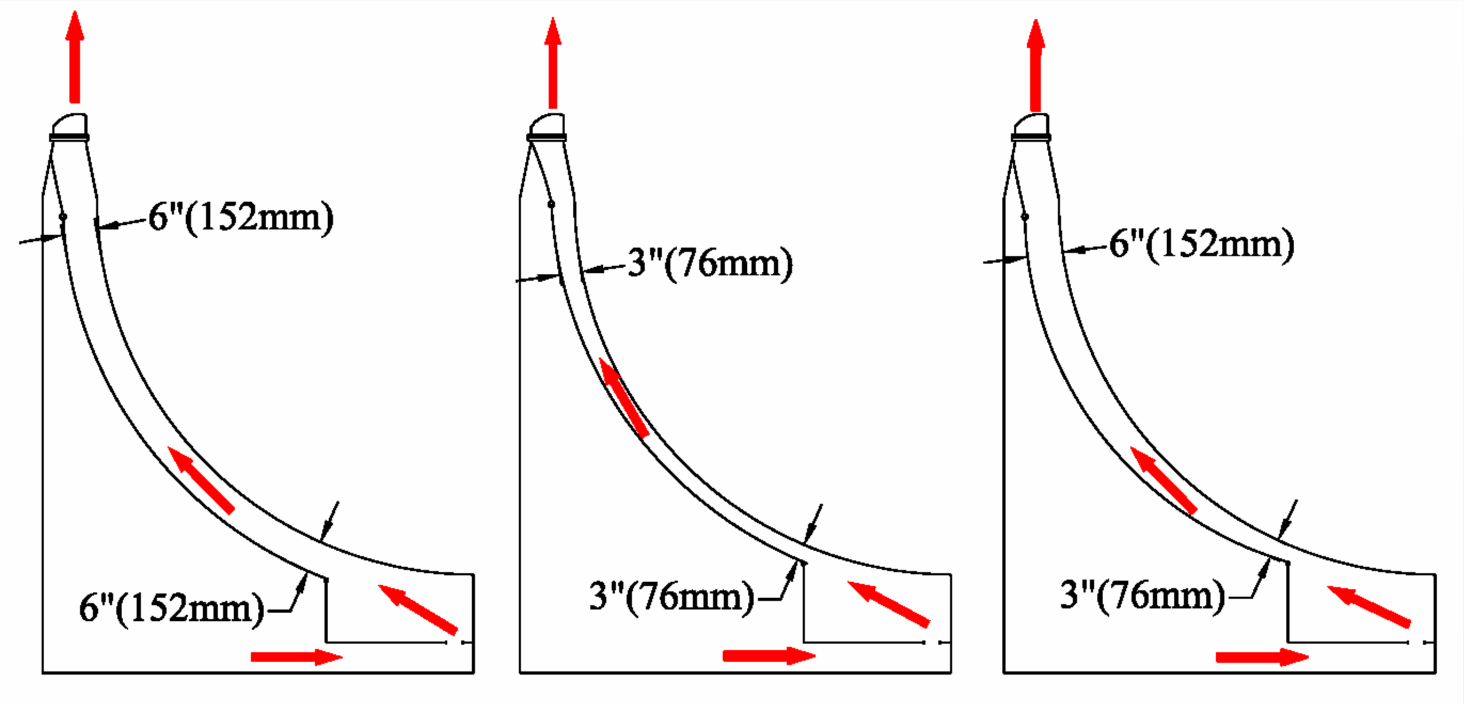
Magnetic Flowmeter

72 thermocouples

7 pressure transducers

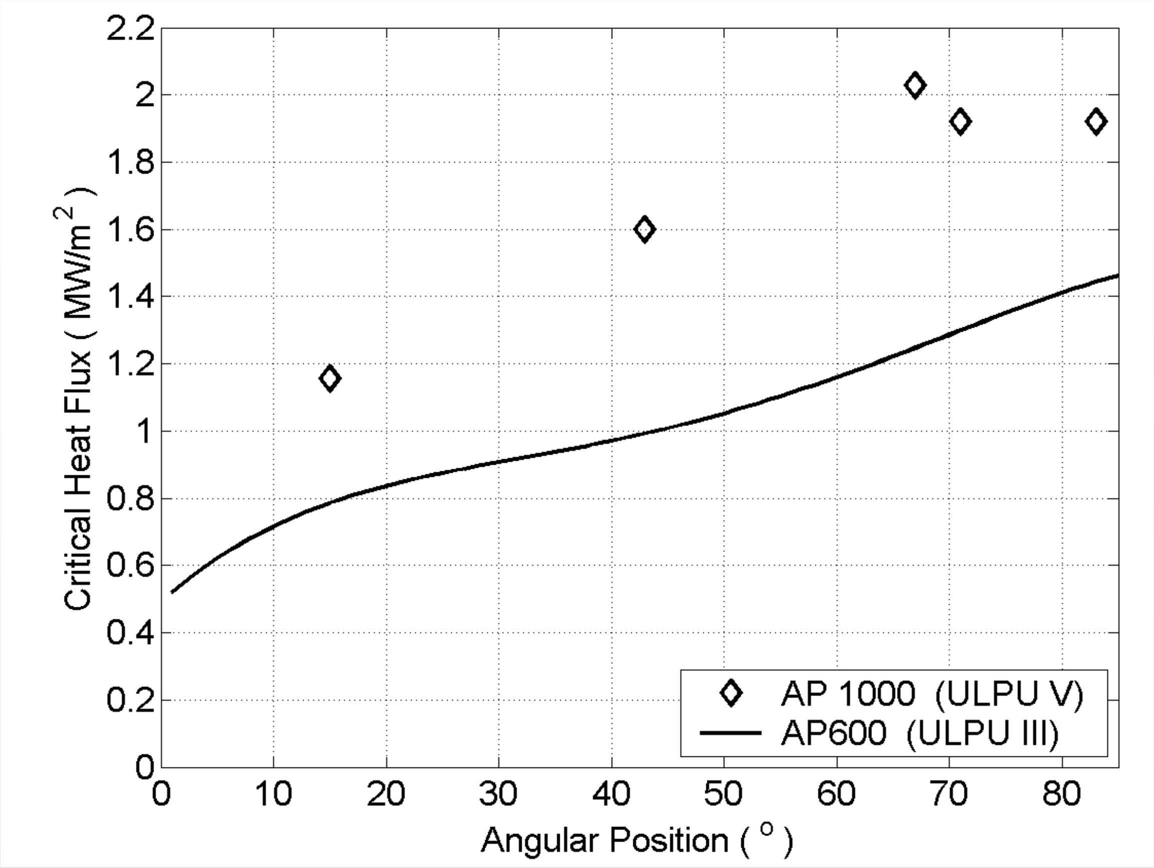
Flow visualization

Experimental Setup of ULPU-2400 Configuration V



Three Baffle Configurations

Results of ULPU-2400 Configuration V



Effectiveness of IVR Strategy for APR1400

- Effectiveness Examination Procedures
  - Choose representative scenarios from Level 1 PSA results
  - Examine the BC for ERVC strategy using MAAP4 code
  - Structured examination using ROAAM framework

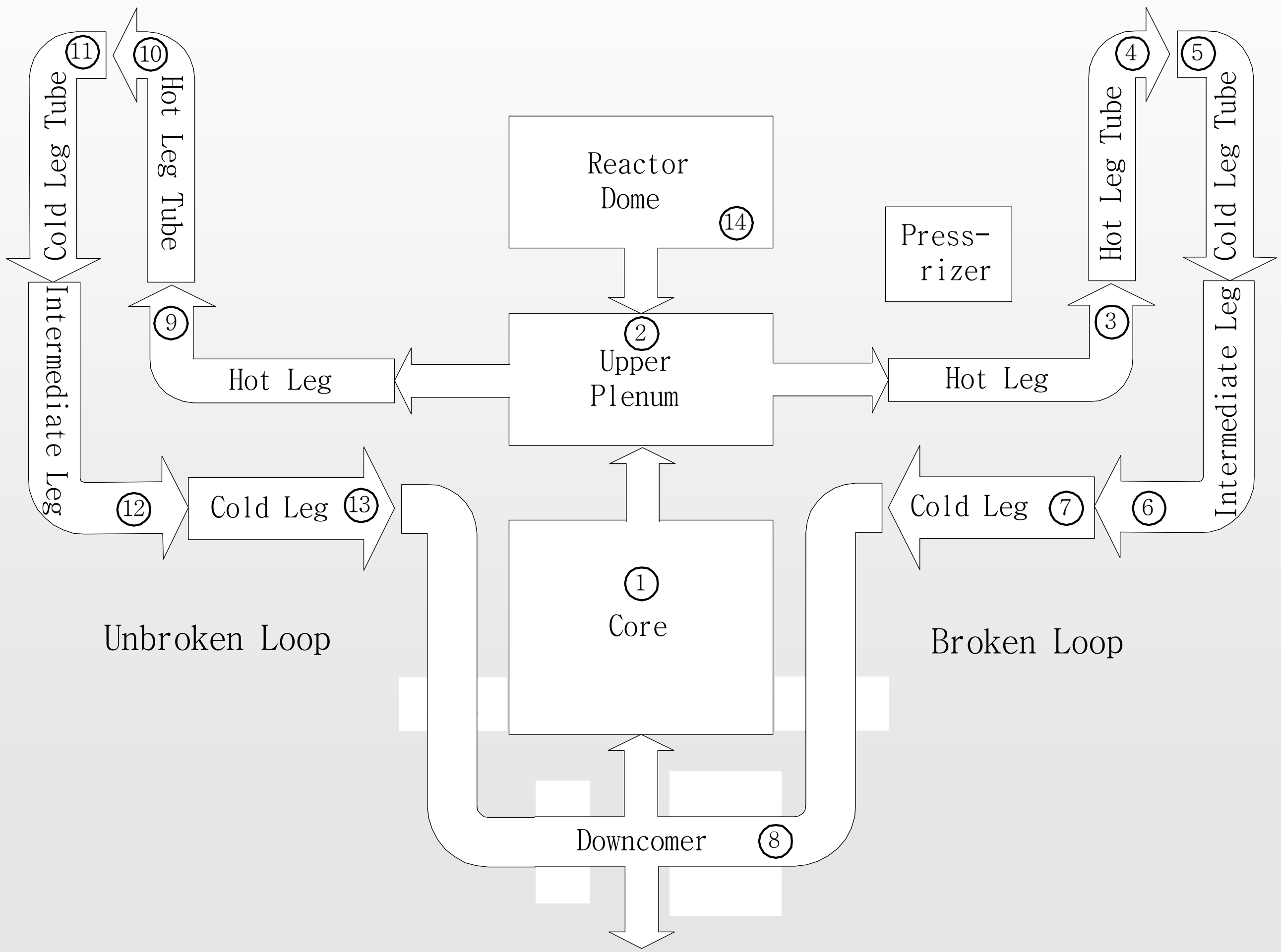
APR1400 IVR Performance

- Effectiveness of IVR strategy is evaluated using the structured approach developed for AP600
  - Four representative scenarios are selected from Level 1 PSA
  - Using MAAP4 code, the boundary condition at the time of vessel failure is determined
  - Based on the method developed for AP600 study, thermal margin is examined
  - A limiting scenario is developed from LLOCA scenario at the recommendation of the peer review
    - full core melt in 3.72 hrs from shutdown.
    - Steel mass is estimated to be 30 tons.
  - The two layer melt pool configuration (metallic layer above oxidic layer) is assumed in the study

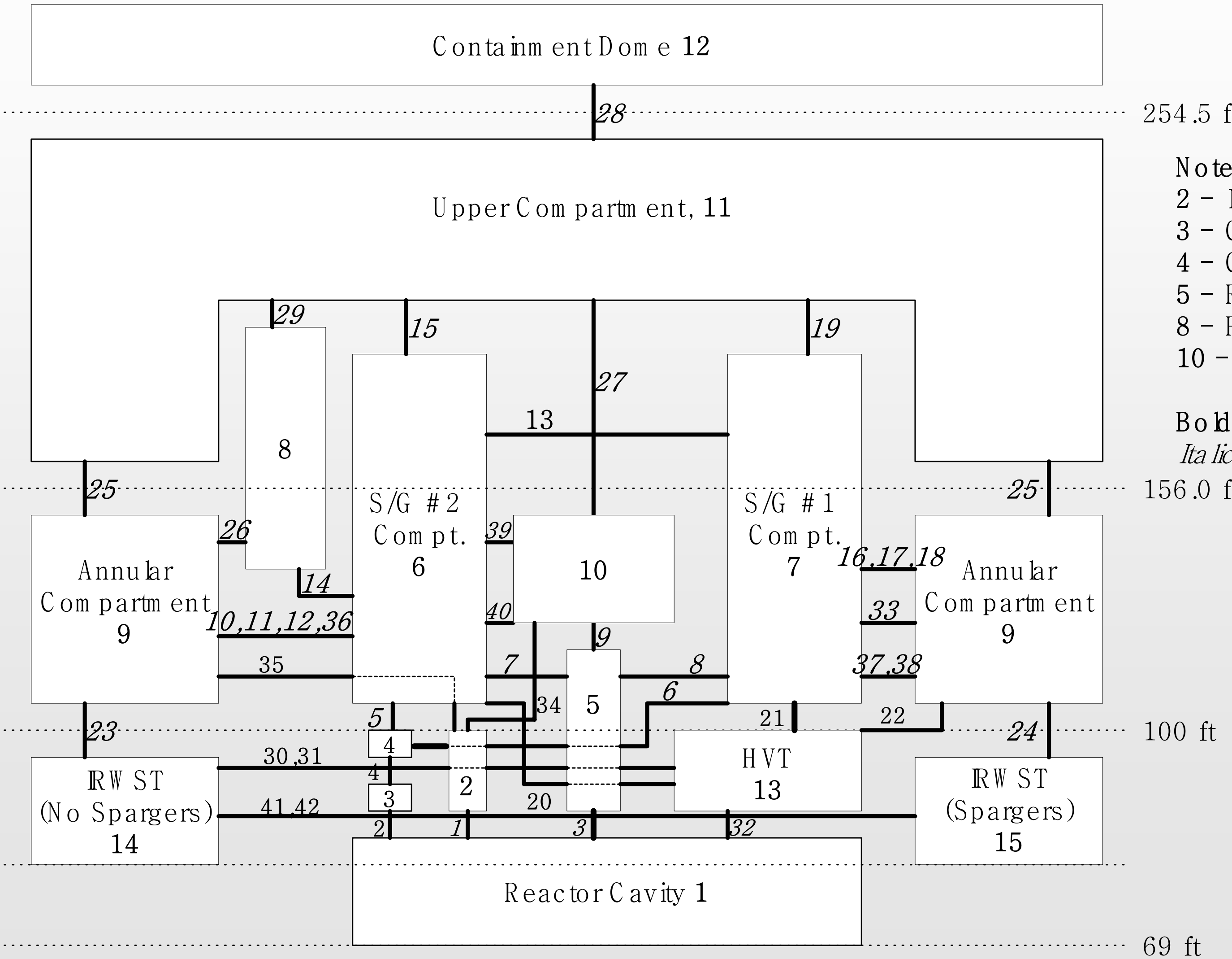
APR1400 Dominant Scenarios

Category	Sequences	Bounding Sequence	Percentage of Total CDF (%)	Steel mass molten (M_{steel}), (tons)	Zirconium oxidation fraction (f_{ox})	Core melt fraction (f_{U02})	Time to Full Core Melt (hr)	MHFR
LOFW	LOFW-17 GTRN-17 LOFW-6	LOFW-17	35.2	32	0.38	0.85	10.14	0.50
SLOCA	SLOCA-23 WGTR-28 SLOCA-22	SLOCA-23	26.7	28.4	0.42	0.78	9.5	0.51
MLOCA	MLOCA-3 MLOCA-4 MLOCA-2	MLOCA-4	9.6	32.7	0.44	0.88	5.6	0.62
LLOCA	LLOCA-4	LLOCA-4	2.3	25.2	0.34	0.82	3.72	0.74

RCS Nodalization of MAAP4 in APR1400



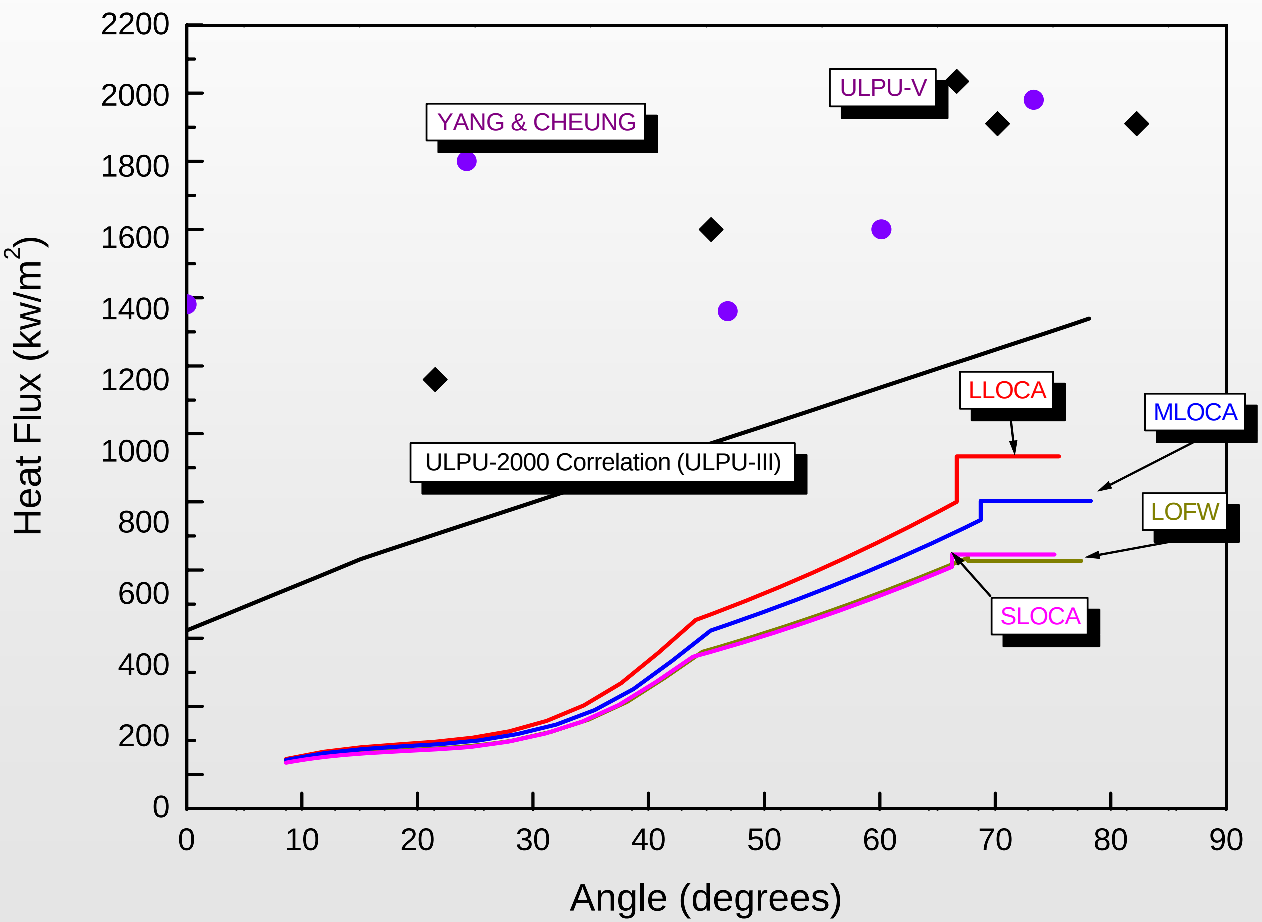
Containment Nodalization of MAAP4 in APR1400



Note
2 - In-Core Instru. Chase
3 - Corium Chamber Room
4 - Cavity Access Area
5 - Reactor Vessel Annulus
8 - PZR Compt.
10 - Refueling Pool

Bold : compartment no.
Italic : junction no.

APR1400 IVR Assessment



Summary

- IVR is an effective SAM strategy for APR1400
  - Except LLOCA limiting case, there are enough thermal margin with ULPU-III CHF data
  - With the adoption of streamlined insulation, there are enough thermal margin even for the limiting LLOCA case

- There are still ongoing discussion about plausible melt configuration in-vessel
  - With proper SAM action (inject into vessel with IVR), severe accident will be arrested in-vessel before full core melt and the melt configuration issue would be less of importance
  - However, study similar to that by Seiler et al would be useful

- The structured approach of ROAAM is useful in evaluating effectiveness. If there is no consensus, one needs to resort back to expert elicitation process
  - Experience shows that, in this case, there is a strong bias toward failure by participating experts due to the bounding assumptions and the worst case scenario focused during the ROAAM process

Collaboration Works

- Close coordination with SNU
  - SNU provides an input to the streamlined thermal insulation design using CFX
- Base Technology R&D with Center for Risk Studies and Safety, UCSB
  - Robust quantification and enhancement of IVR margins
- APR1400 melt progression information exchange with INEEL (MAAP, SCDAP)
- Close coordination with PSU on insulation design
  - PSU will generate CHF data from 3-D scaled geometry of APR1400