Idaho National Engineering and Environmental Laboratory

SCDAP/RELAP5-3D© Analyses Supporting Improved In-Vessel Retention Margins for High Power Reactors

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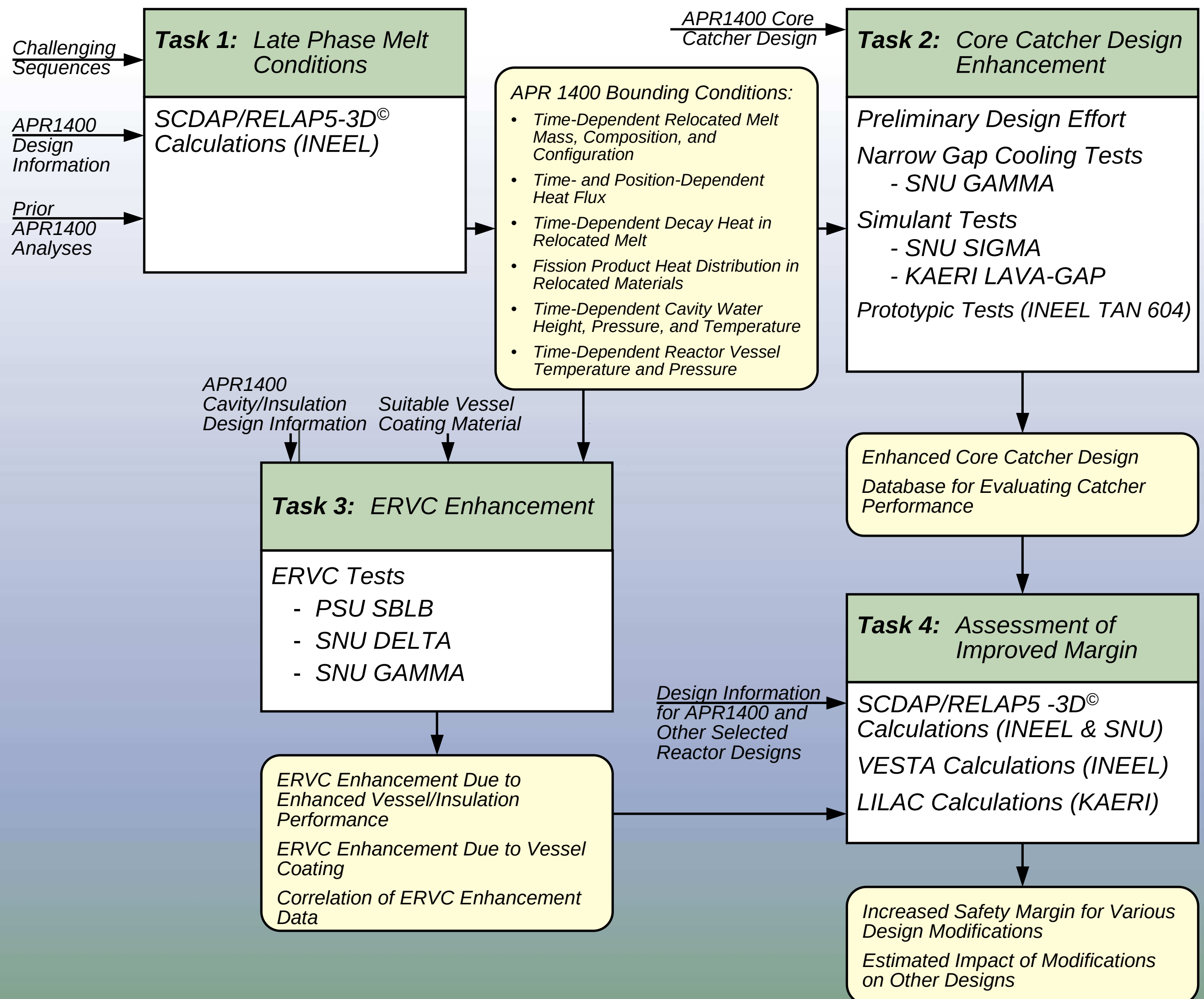
Outline

- *International Nuclear Energy Research Initiative (I-NERI) overview*
- *Objectives*
- *External reactor vessel cooling (ERVC)*
- *In-vessel core catcher (IVCC)*
- *Late-phase melt conditions using SCDAP/RELAP5-3D©*
  - *Code description*
  - *Analytical approach*
  - *Model description*
  - *Transient selection and results*
- *Summary*

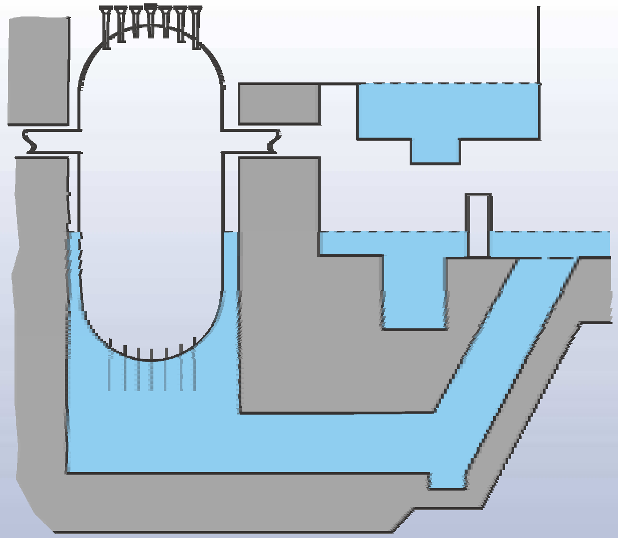
I-NERI Research Divided into Four Tasks



Objectives

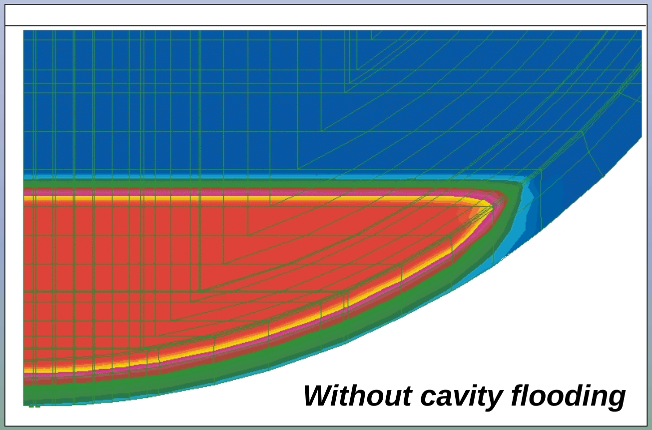
- *I-NERI*
  - *Use systematic approach to develop specific recommendations to improve the margin for In-Vessel Retention (IVR) of relocated materials during severe accidents in high-power reactors (> 1000 MWe)*
  - *Combine state-of-the-art analytical tools and key U.S. and Korean experimental facilities*
  - *Focus on modifications to enhance ERVC and IVCC performance*
  - *Focus on APR1400, but develop strategies easily applied to other designs*
- *Presentation*
  - *Outline ERVC and IVCC efforts and current status*
  - *Describe SCDAP/RELAP5-3D© efforts to quantify late phase melt conditions affecting potential for APR1400 IVR of corium*
    - *Providing input for ERVC enhancement and IVCC design efforts*
    - *Providing base values for estimating improved IVR margins*

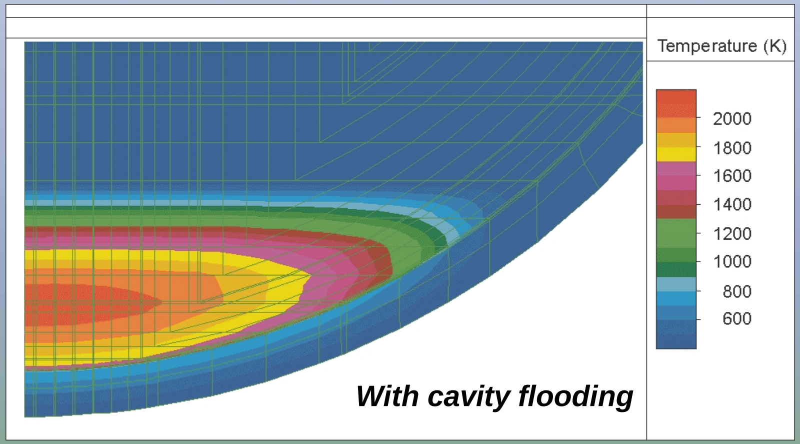
ERVC Via Cavity Flooding Provides Mechanism to Delay And/or Prevent Vessel Failure



Cavity flooding to enhance heat removal from the reactor vessel

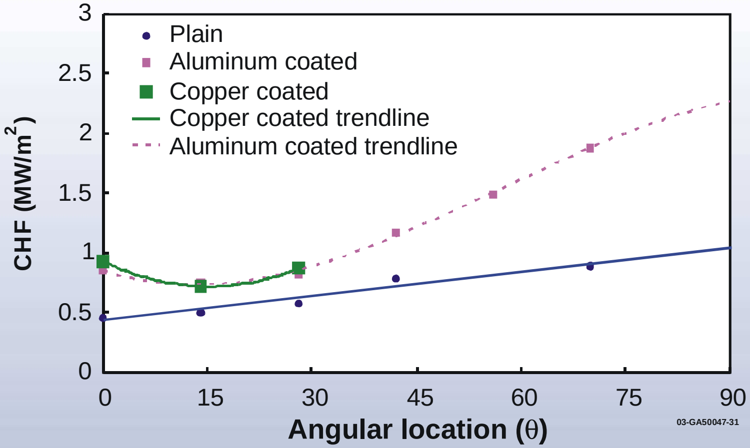
SCDAP/RELAP5-3D© analyses of vessel response





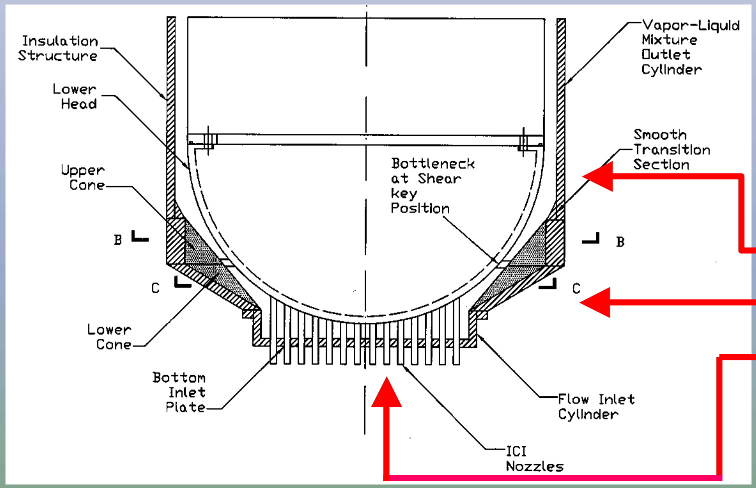
SBLB Used to Evaluate Proposed Coatings and Insulation/Vessel Configuration

Proposed coatings significantly increase CHF



Subscale Boundary Layer Boiling Facility

Insulation modified to enhance ERVC flow

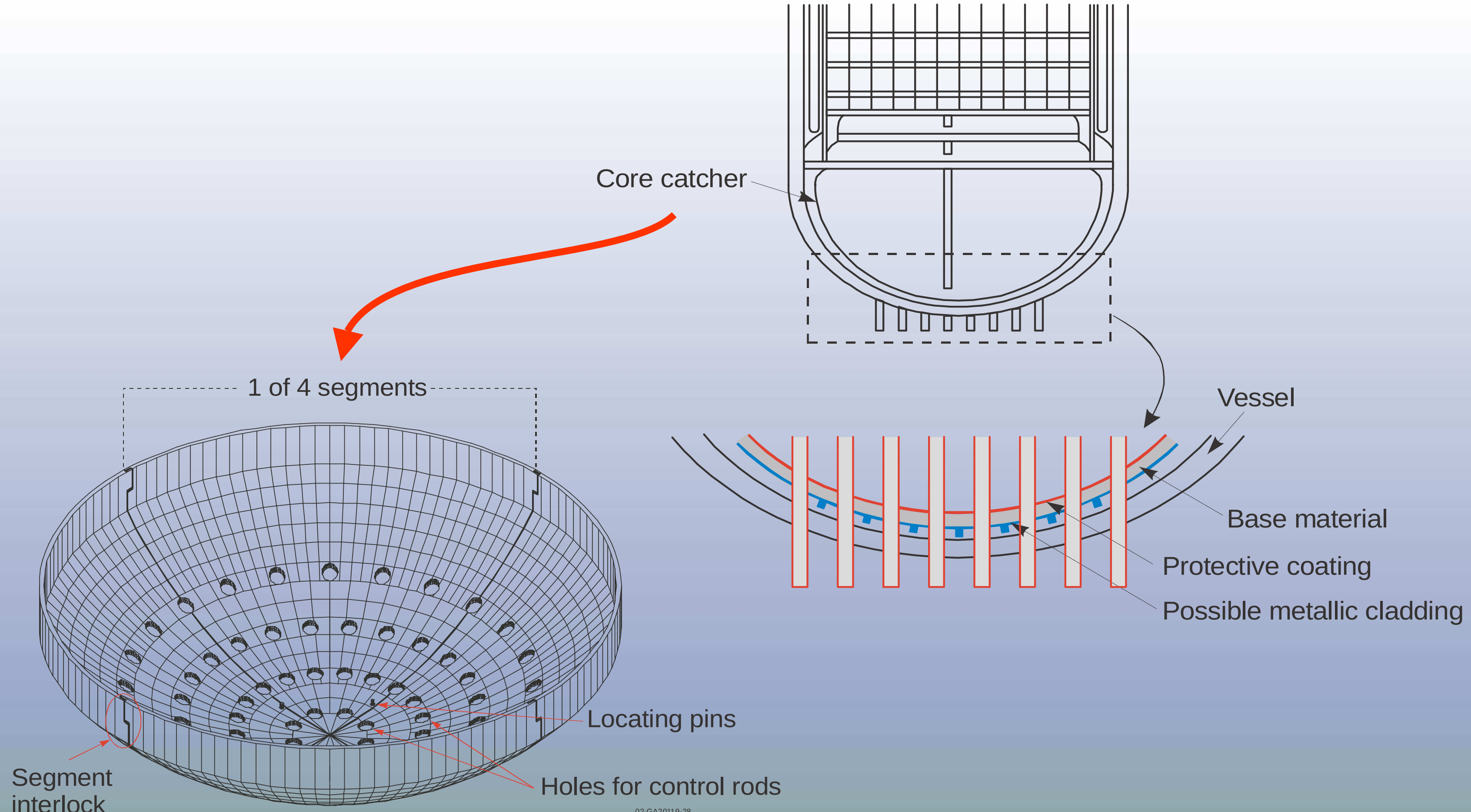


Upper flow outlet section.

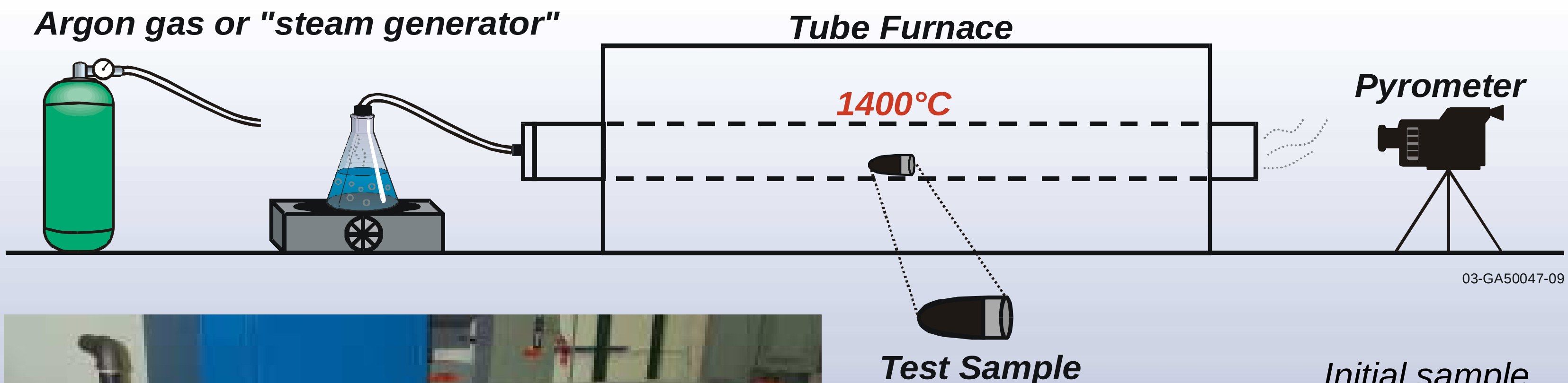
Conical section.

Lower flow inlet section.

Unique In-Vessel Layered Design Proposed and Evaluated



Materials Interaction Tests with Plasma Sprayed Samples Used to Select Core Catcher Materials

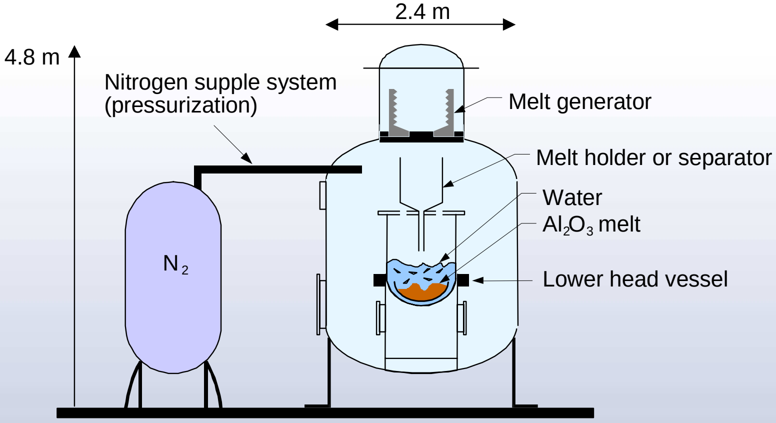


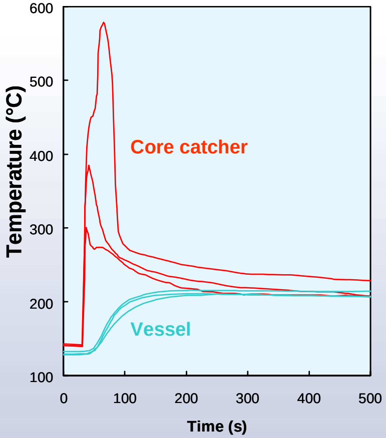
Initial sample

ZrO_2 coated endstate

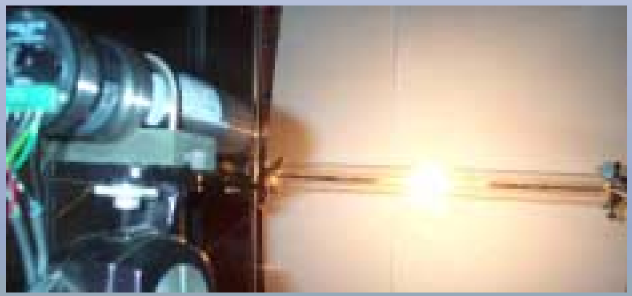
MgO coated endstate

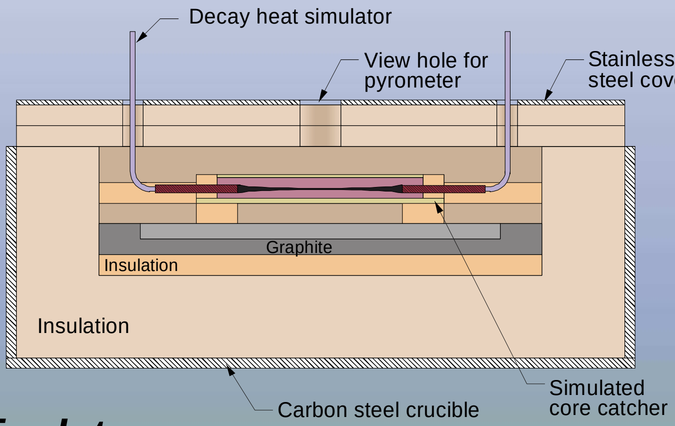
KAERI and INEEL Facilities Provide Integral Data for Assessing Core Catcher Performance Using Simulant and Prototypic Materials





KAERI LAVA-GAP results suggest IVCC reduces vessel heat loads



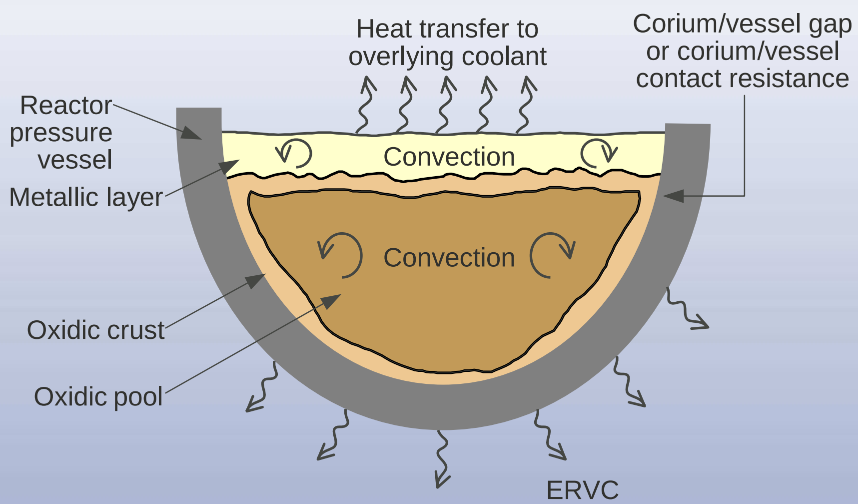


INEEL high temperature test facility provides prototypic data

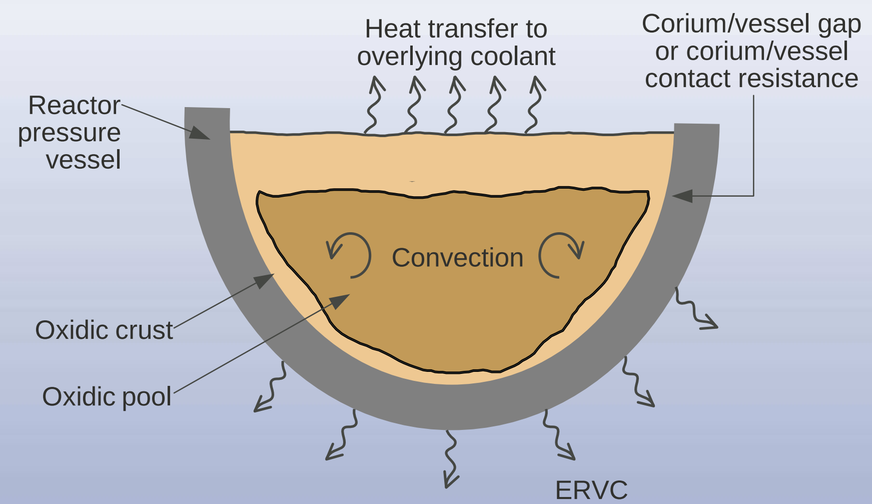
SCDAP/RELAP5-3D© Best-Estimate Tool for Simulating Severe Accidents

- *Detailed mechanistic models for thermal hydraulics, core damage, and structural response*
- *Modular architecture*
  - *RELAP5: multi-dimensional thermal hydraulics and kinetics*
  - *SCDAP: core damage progression*
  - *COUPLE: heat transfer and structural response*
  - *MATPRO: material properties*
- *PVM links possible for mechanistic integration of fission product transport, containment response, etc.*

SCDAP/RELAP5-3D© Represents All Major Processes Affecting IVR of Corium



Stratified Configuration

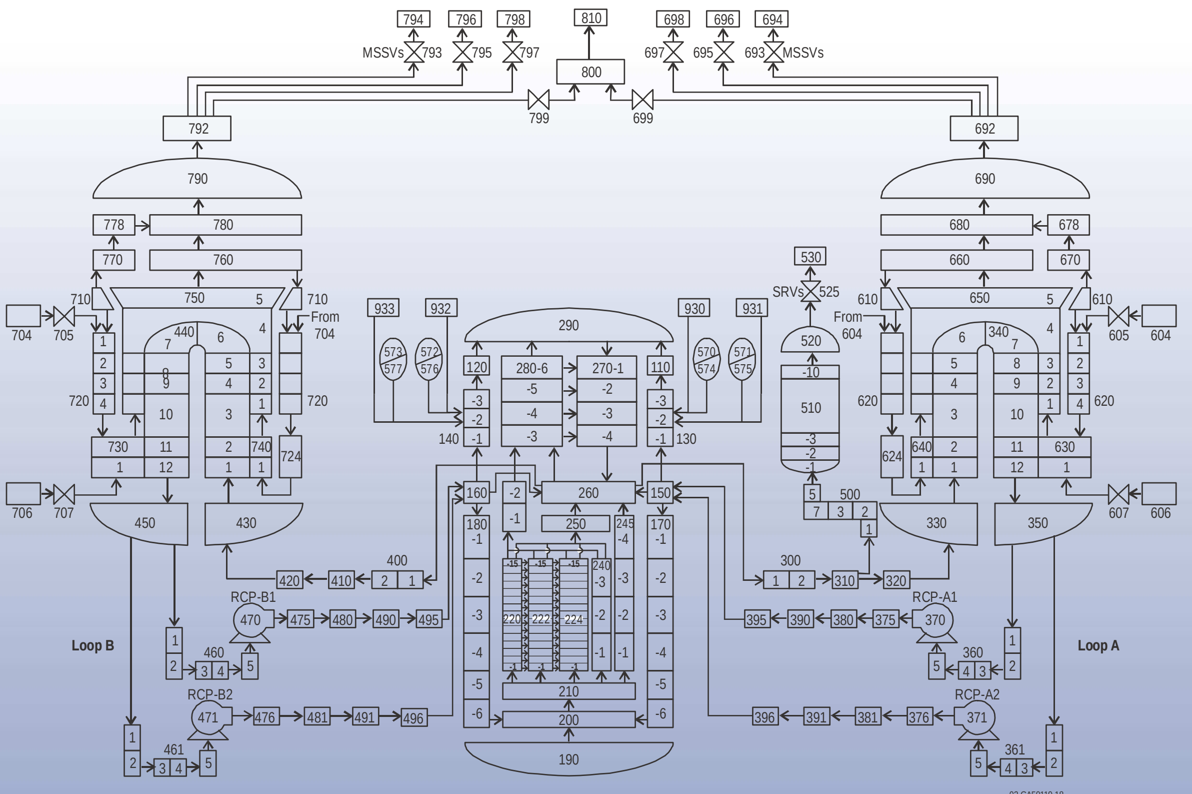


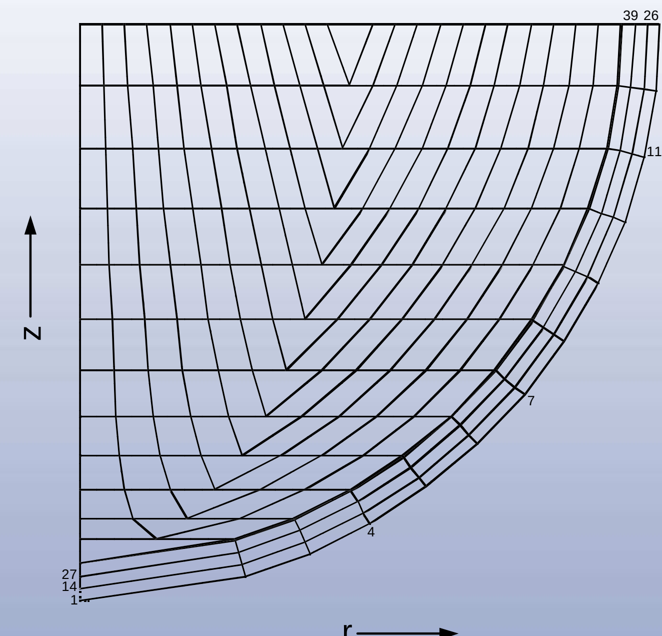
Homogeneous Configuration

Analytical Approach

- *Develop SCDAP/RELAP5-3D© model of APR1400*
- *Use model to establish steady state conditions*
- *Identify bounding transients relative to IVR*
  - *May or may not align with dominant CDF transients*
- *Simulate identified transients using SCDAP/RELAP5-3D©*
- *Compile results to meet analysis objective*
  - *Consisting of corium mass, temperature, composition, power, etc.*

SCDAP/RELAP5-3D© Model Includes Latest RELAP5 Nodalization with Refined SCDAP Core and COUPLE Lower Head





RELAP5 (250 volumes, 316 junctions, 284 heat structures)

SCDAP (3 channels, 15 axial nodes, with radial crossflows)

COUPLE (234 nodes, 204 elements, with adiabatic outer surface)

Transients Selected in Attempt to Bound APR1400 Late Phase Melt Conditions

- *Selecting bounding transients non-trivial*
- *Three major IVR scenarios identified*
  - *LOCA*
  - *SBO*
  - *LOFW*
- *Two transients selected*
  - *Cold leg LOCA to represent LOCA scenario*
  - *SBO with LOFW to represent remaining IVR scenarios*

SCDAP/RELAP5-3D© Transient Assumptions Yield Conservative Late Phase Melt Conditions

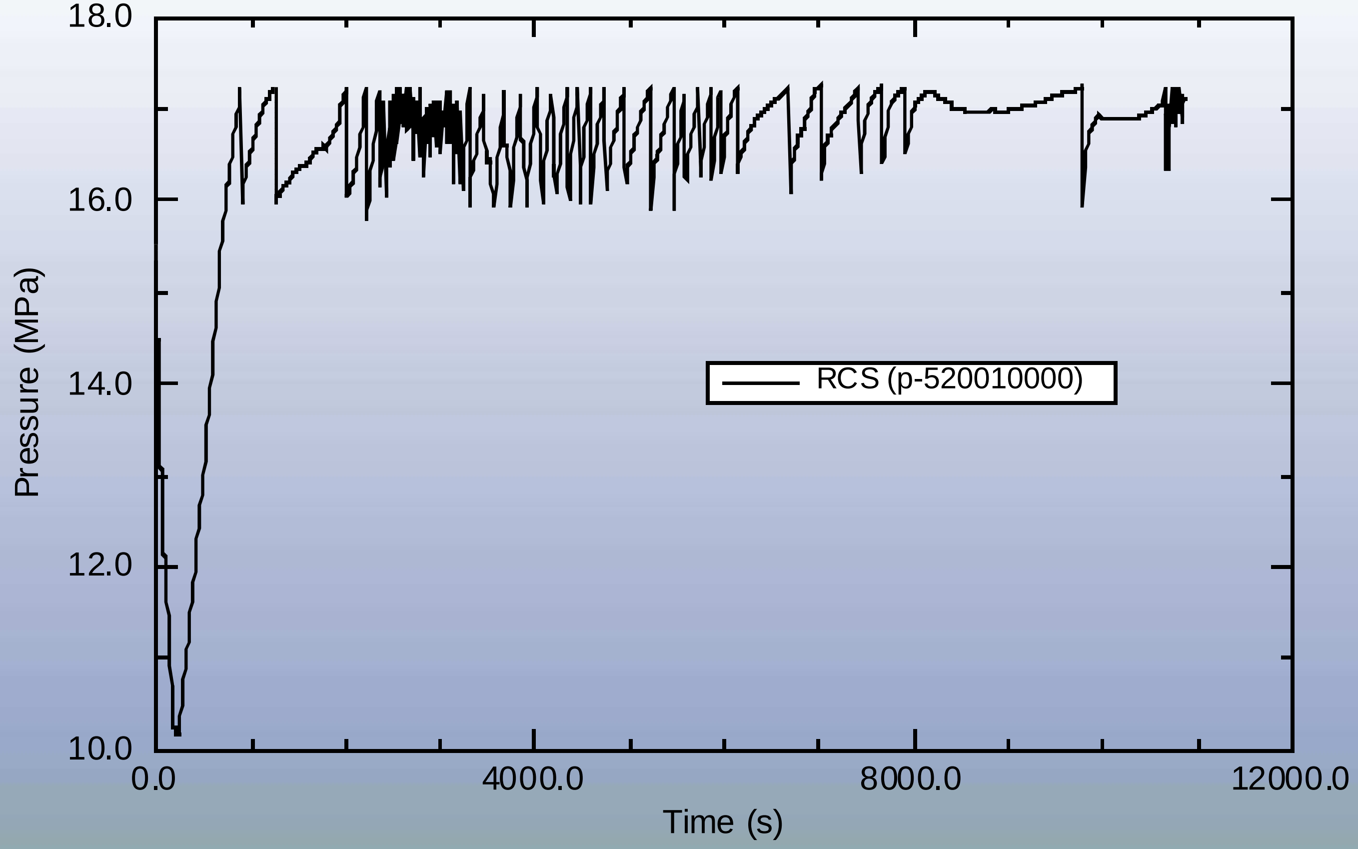
Transient	Description
SBO	- *Loss of all AC power (w/ failure of backup power, w/o recovery)* - *Reactor and RCP trip on loss of power w/o automatic RCS depressurization* - *Loss of all SG feedwater with SGA depressurization via stuck open SVs* - *All safety injection systems fail* - *No IRWST flow* - *Normal SIT operation*
LOCA	- *Break in cold leg A (area = 0.0465 m^2)* - *Reactor and RCP trip on break* - *All safety injection systems fail* - *No IRWST flow* - *Normal SIT operation*

Lower Head Fails Shortly After Relocation Without Benefit of ERVC or IVCC

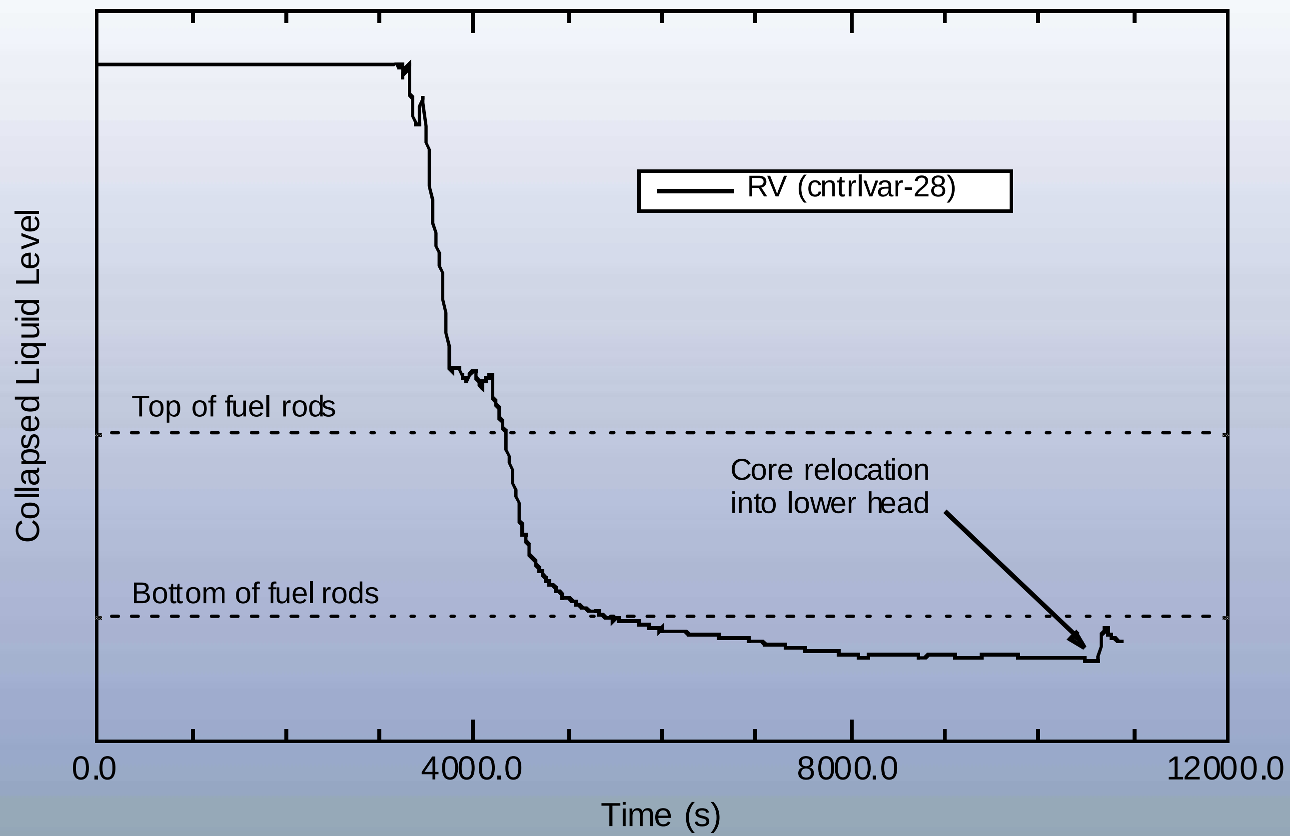
Event	Time (in seconds)			
	SBO-1[1]	SBO-2[1]	SBO-3[1]	LOCA-1
Transient initiation	*0*	*0*	*0*	*0*
SGA / SGB dryout	*970 / 2,370*	*979 / 2,370*	*1,090 / 2,380*	*np / np*
Liquid full loop natural circulation ends	*3,530*	*3,530*	*3,530*	*np*
Onset of SIT injection	*np*[2]	*np*	*np*	*212*
SITs empty	*np*	*np*	*np*	*876*
Onset of fuel rod oxidation	*4,980*	*4,980*	*4,960*	*2,190*
Collapsed liquid level falls below bottom of fuel	*5,440*	*5,420*	*5,440*	*2,090*
Onset of fuel melting	*5,900*	*5,810*	*5,810*	*3,660*
Pressurizer surge line creep failure	*7,680*	*7,370*	*7,650*	*np*
First relocation into lower head	*8,950*	*5,810*	*8,800*	*3,280*
First relocation of molten fuel into lower head	*11,100*	*8,630*	*10,600*	*4,990*
Lower head creep failure and end of calculation	*11,300*	*8,910*	*10,900*	*np*

1. *Addressing absorber and core roughness sensitivities*
2. *np = not predicted*

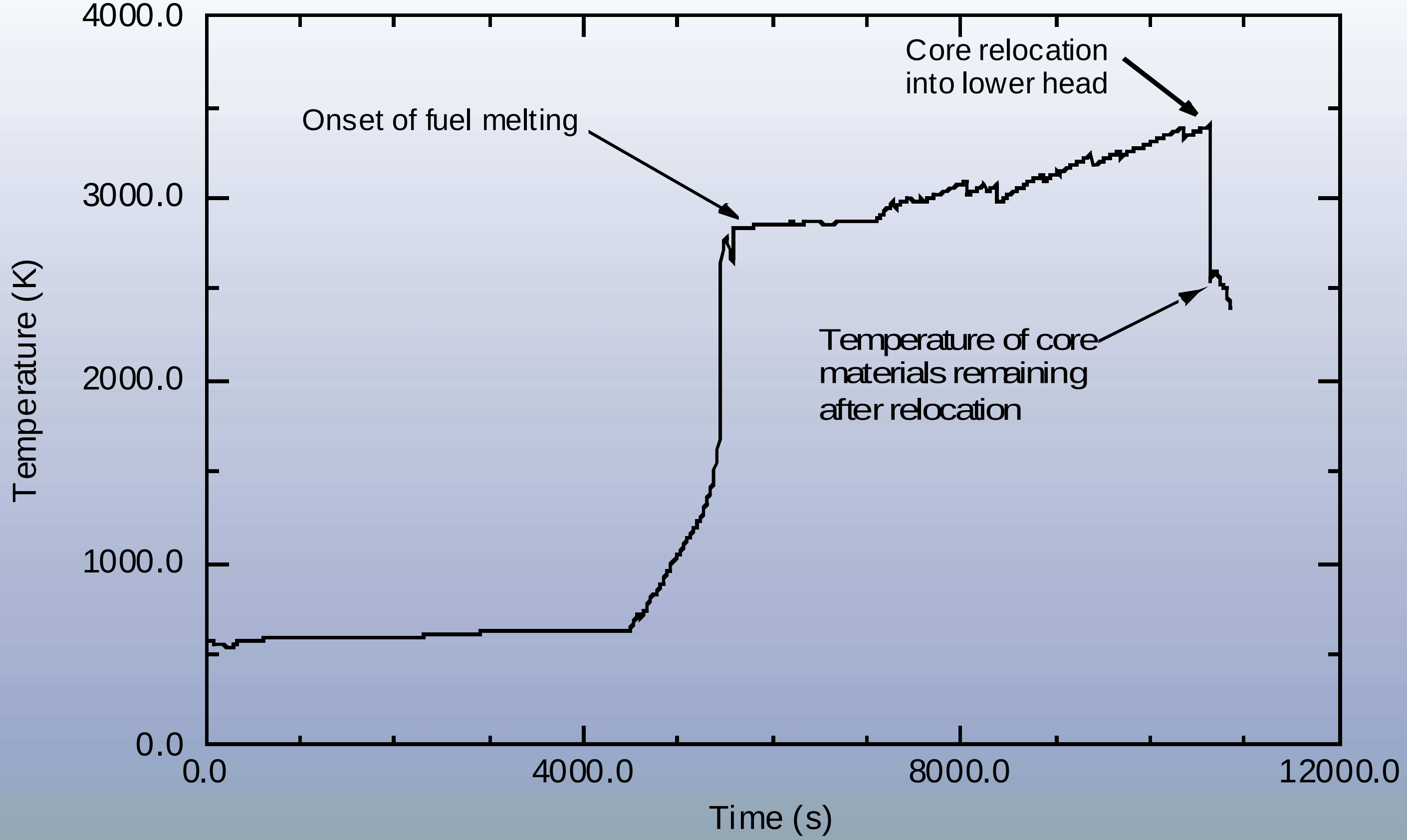
Pressurizer SRVs Control RCS Pressure by Venting Inventory



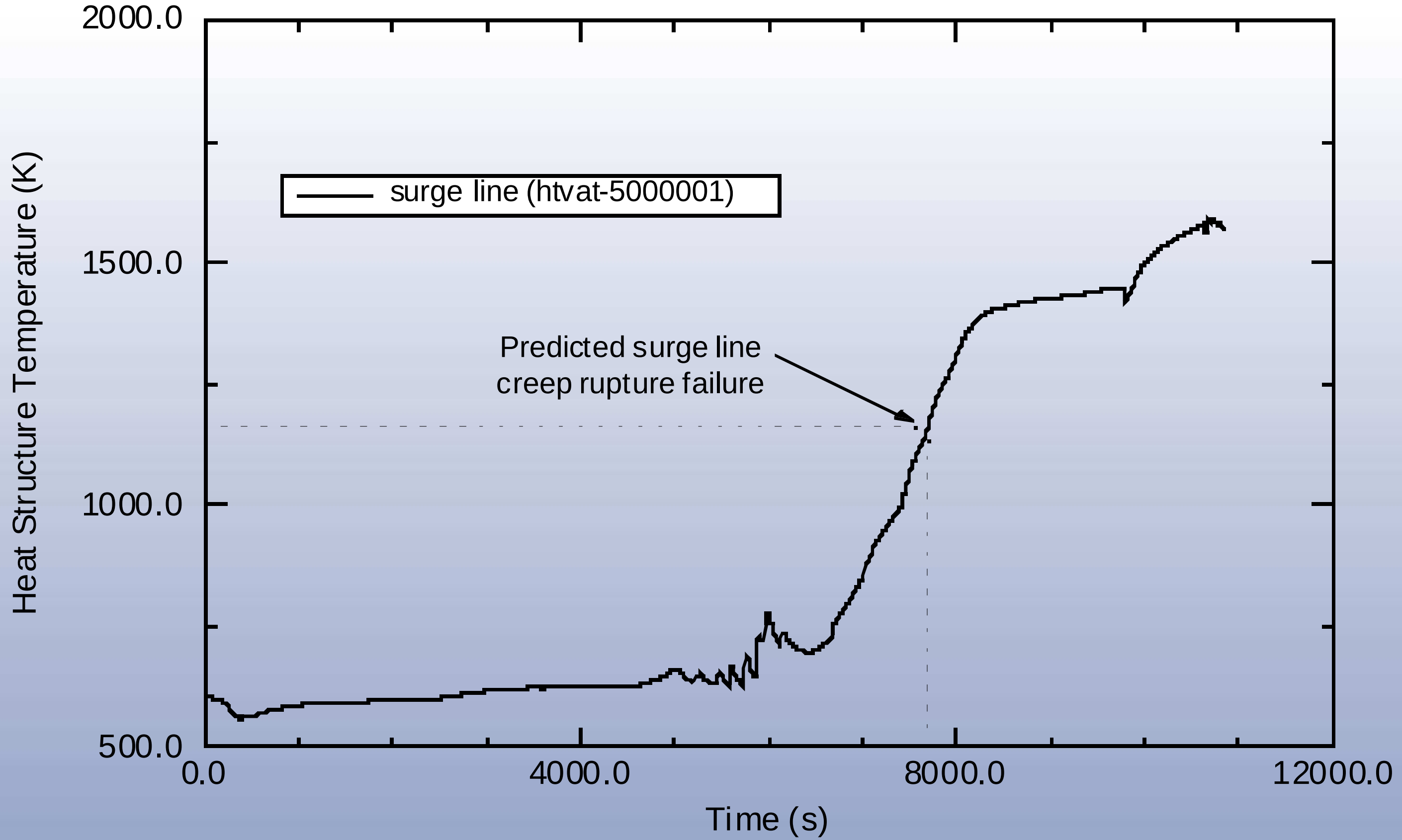
RCS Inventory Loss Leads to Core Uncovery



Core Heatup and Relocation Follow Core Uncovery

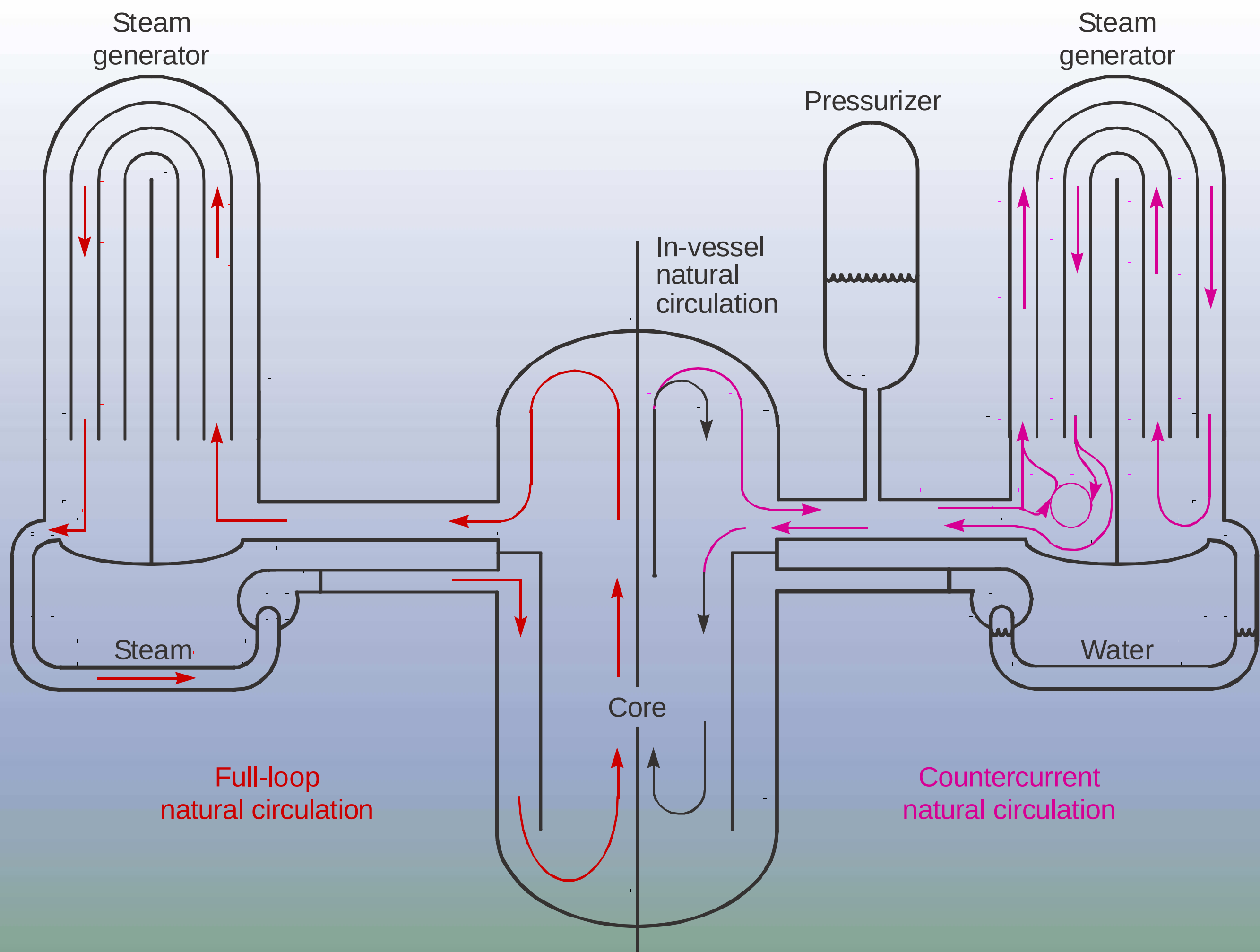


Surge Line Failure Induced by Core Heatup

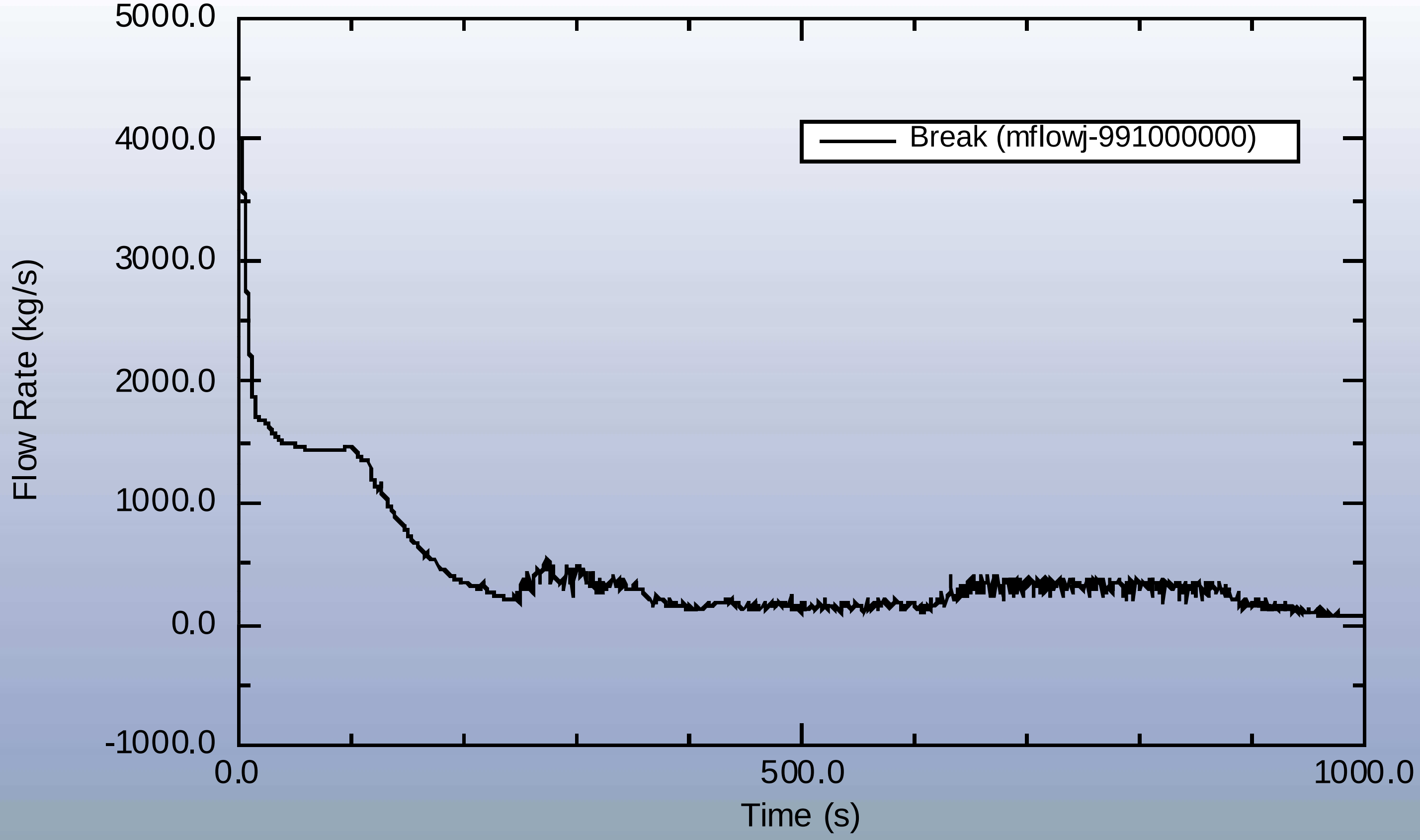


Consistent with conservative approach, RCS depressurization following surge line failure was not modeled..

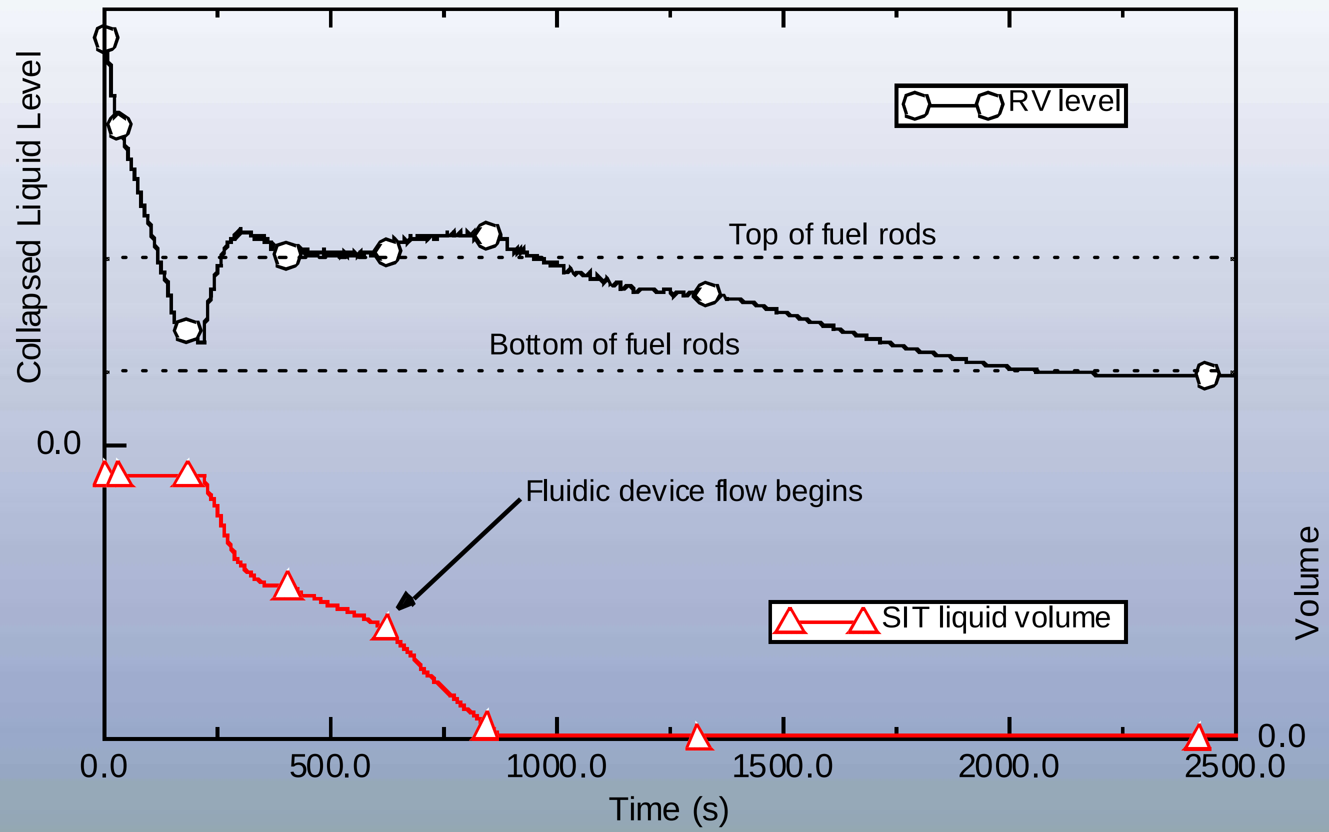
Modeling All Natural Circulation Flows Could Lead to Other RCS Piping Failures



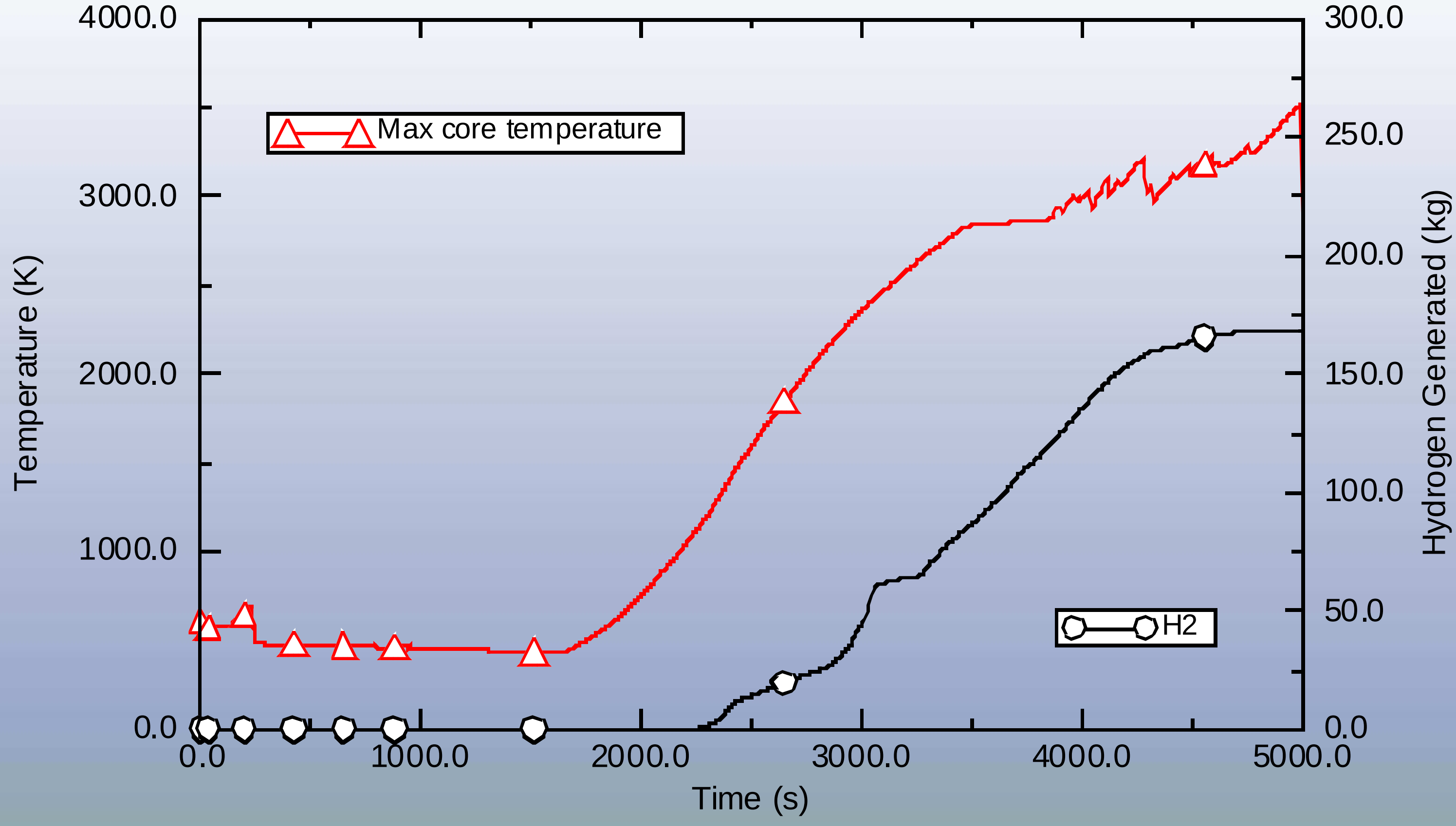
RCS Blowdown Complete by ~200 s



SITs Delay Core Uncovery



Core Heatup and Relocation after SITs Empty

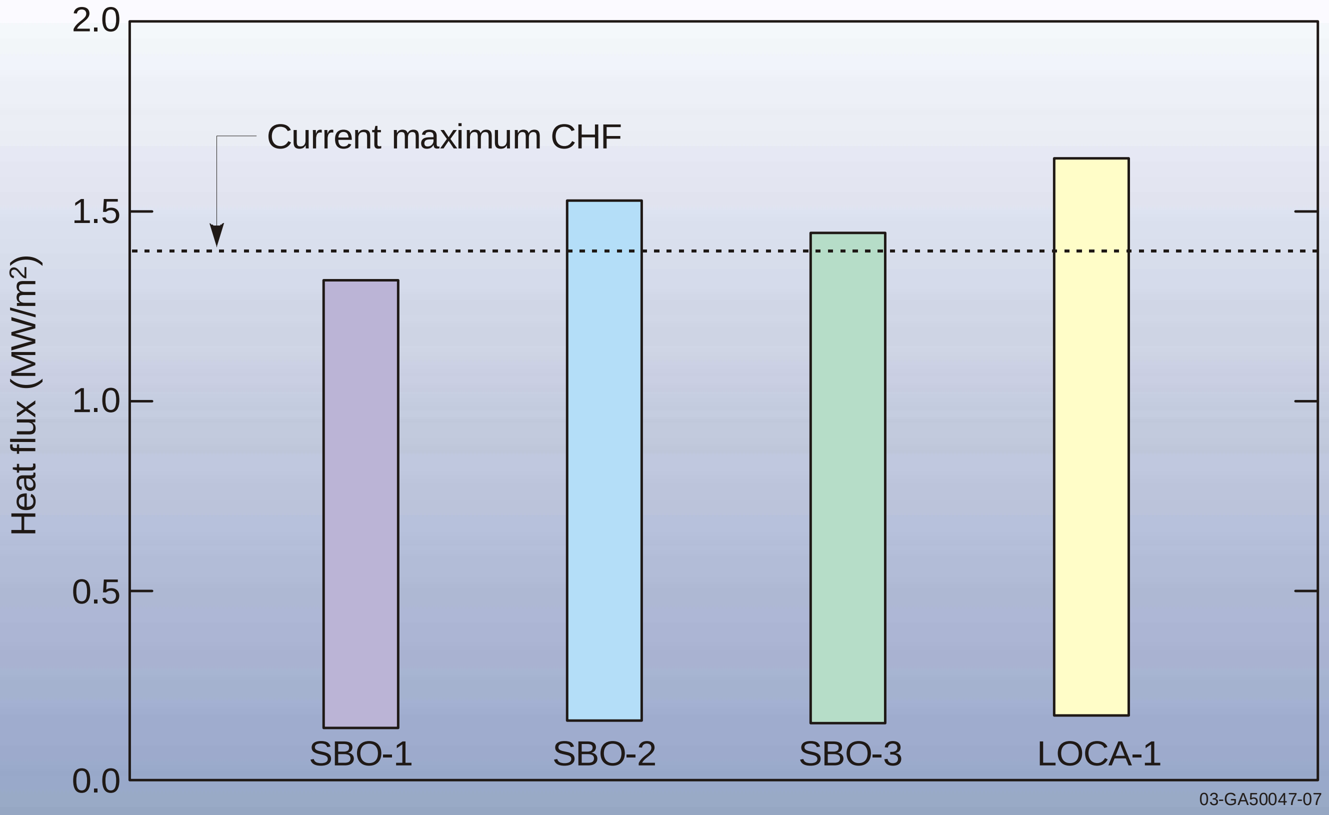


SCDAP/RELAP5-3D© Results Indicate an IVR Challenge for APR1400

Transient	Time of relocation (s)	Relocated constituents (kg)				Corium characteristics at relocation		
		UO_2	ZrO_2	Zr	Total	Temp (K)	Power Density (MW/m^3)	Est avg vessel heat flux (MW/m^2)[a]
SBO-1	*11,100*	*111,000*	*24,200*	*6,440*	*145,000*	*3,300*	*2.49*	*0.147 to 1.32*
SBO-2	*8,630*	*99,600*	*18,500*	*6,940*	*125,000*	*3,010*	*3.28*	*0.170 to 1.53*
SBO-3	*10,600*	*111,000*	*21,200*	*8,300*	*144,000*	*3,390*	*2.72*	*0.161 to 1.45*
LOCA-1	*4,990*	*108,000*	*5,180*	*3,520*	*119,000*	*3,460*	*3.48*	*0.182 to 1.64*

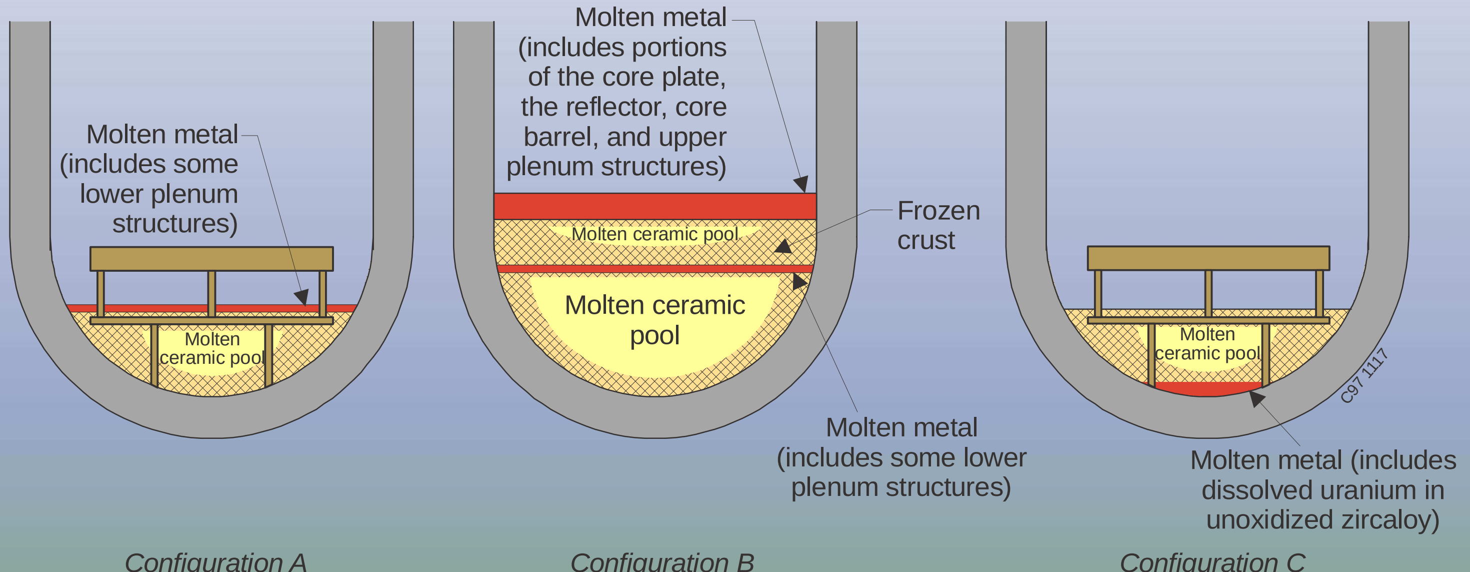
a. Assuming hemispherical configuration, without sensible heat effects, for quasi-steady conditions, with estimated heat loss from upper corium surface at 10 and 90% of total.

APR1400 Estimated Average Heat Flux Exceeds Current Maximum CHF



Issues Affecting IVR Viability to be Addressed in Detailed Lower Head Analyses

- _RCS depressurization_
- _Corium dilution_
- _Heat transfer to and from lower head_
- _Lower head corium configurations_



Summary

- *Increased ERVC heat removal viable with enhanced vessel/insulation configuration and vessel coatings*
- *Proposed IVCC promising avenue for decreasing vessel heat loads*
- *Late-phase melt conditions for APR1400 established*
  - *SCDAP/RELAP5-3D© APR1400 model developed*
  - *Two "bounding" transients identified*
  - *Four transient calculations completed*
  - *Results indicate an APR1400 IVR challenge*
  - *Detailed lower head analyses, based on late phase melt conditions and consideration of other issues, needed to determine viability of IVR for APR1400*