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Modeling of Thermal Stratification in Sodium Fast Reactor Outlet Plenums During Loss of Flow Transients

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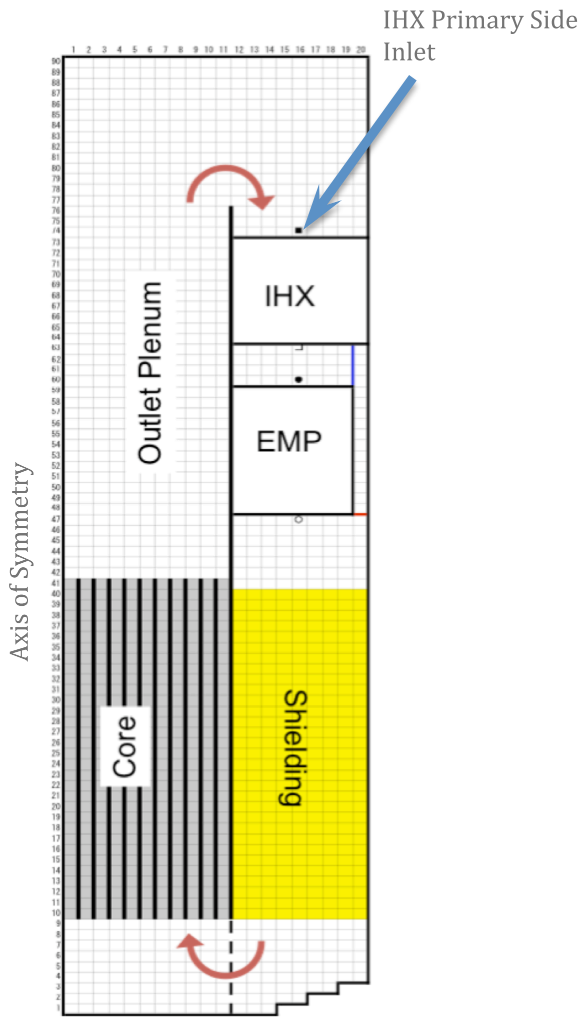
International Conference on Fast Reactors and Related Fuel Cycles (FR09)
Kyoto, Japan
December 6 – 11, 2009

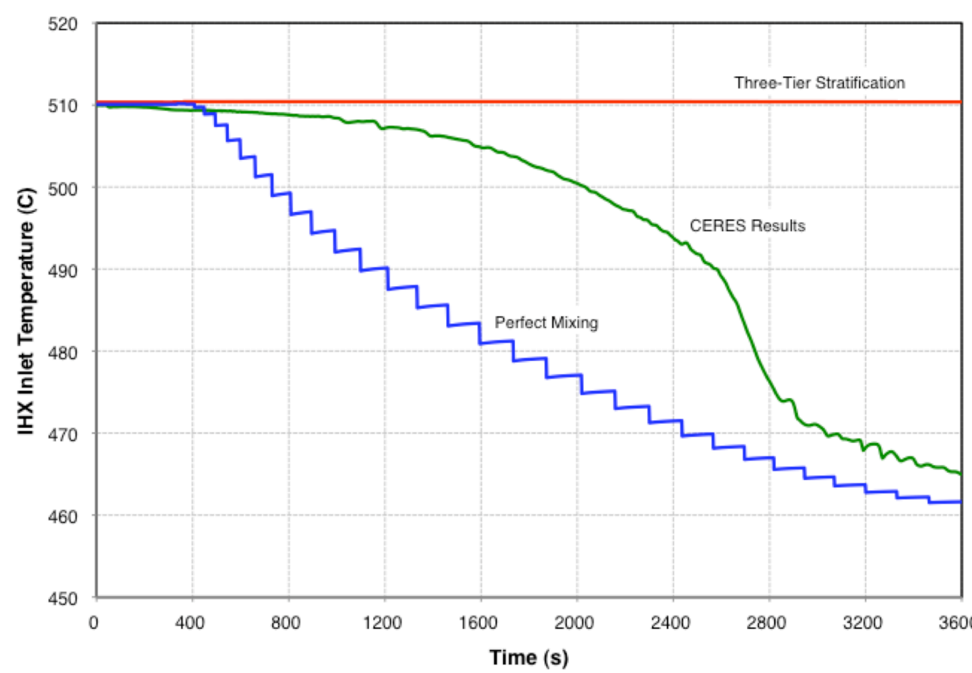
Overview and Motivation

- Potential for sodium-cooled fast reactors to survive severe accident initiators with no damage has been demonstrated through whole-plant testing in EBR-II
  - Natural reactivity feedback mechanisms were sufficient to reduce core power
  - Natural convection cooling was sufficient to remove heat during the transients
- Accurate, whole-plant dynamics safety simulations will be required to demonstrate the degree to which new, advanced designs will possess these desired safety features.
- Current transient safety capabilities in SAS4A/SASSYS-1 are limited to perfect mixing or coarse, 1-D treatment of plenums.
  - 1-D treatment is currently limited to three, discrete, stratified layers.
  - Correlations are used for incoming jet flow and entrainment.
  - Thermal stratification impacts natural circulation driving forces, reactor vessel expansion, control-rod driveline expansion, IHX performance, pump inlet conditions, RVACS heat rejection, etc.
- Thermal stratification was evaluated by coupling SAS4A/SASSYS-1 with the high-fidelity CFD thermal-hydraulics analysis capabilities of STAR-CD.
  - Applied to the multidimensional simulation of a reactor outlet plenum.
  - Provides much better resolution of multidimensional temperature and flow fields, especially during low flow conditions that result in thermal stratification.

4S Outlet Plenum Stratification

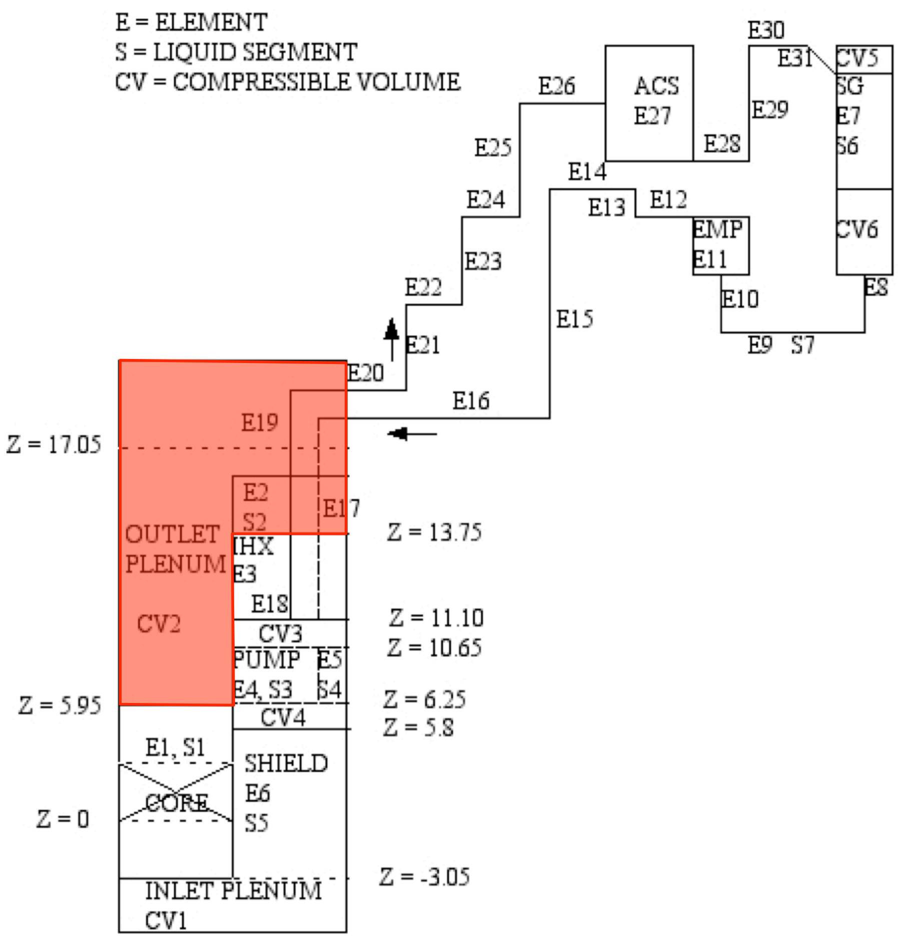


- Previous work with CRIEPI compared system-wide results from PLOF and ULOF accident sequences.
- Plenum results from the 2-D treatment (CERES) fall between SAS4A/SASSYS-1 stratified model (blue) and a perfect mixing model (red) during a PLOF.
- More detailed treatment may reveal better mixing than CERES results predict.



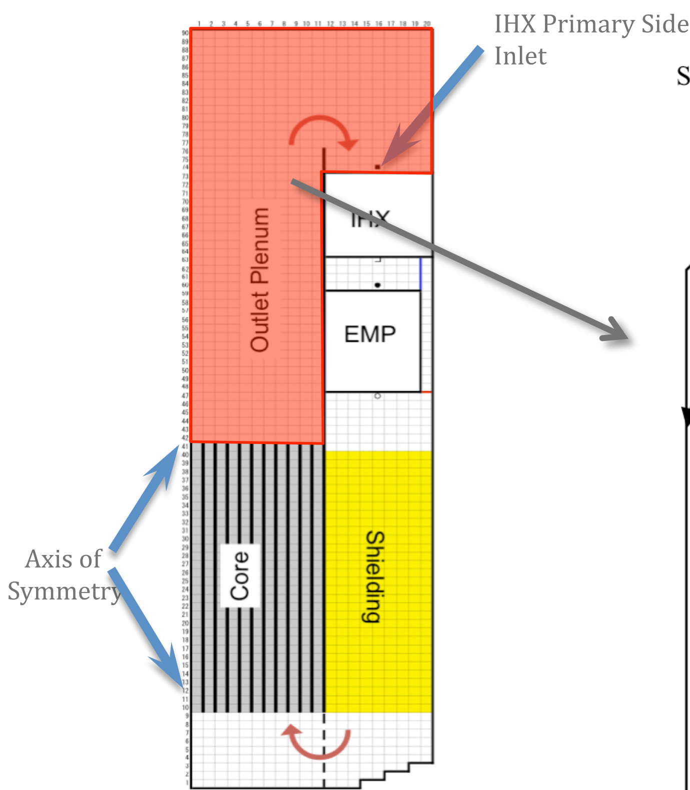
Impact of Stratification on IHX Inlet Temperatures

SAS4A/SASSYS-1 Model Represents the Whole-Plant

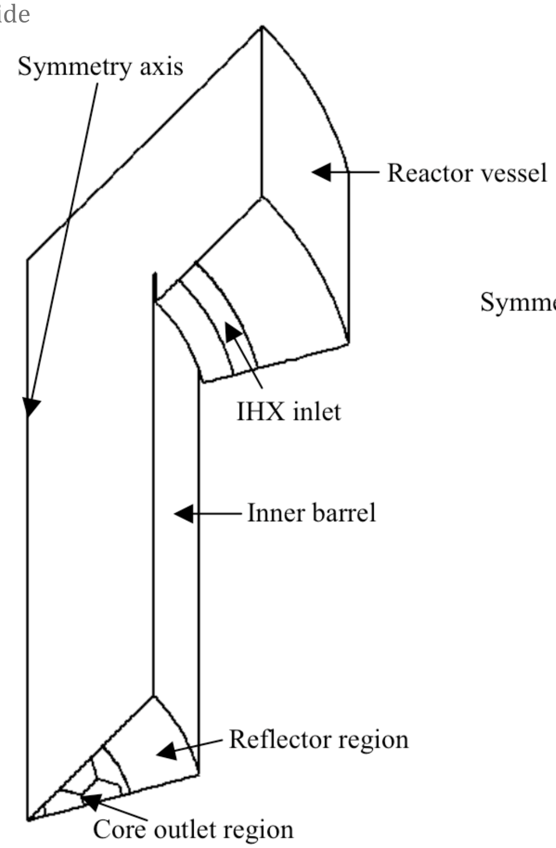


- Whole-plant discretization by CFD is beyond current computing capabilities.
- Core channel model represents central shutdown assembly; inner, middle, and outer core assemblies; and radial reflector.
- PRIMAR-4 employs a modular network of compressible volumes connected by liquid flow segments.
  - Inlet and outlet plenums.
  - IHX, EMP, SG, RVACS, IRACS, piping, shields, etc.
- Compressible Volumes:
  - Quasi one-dimensional.
  - Single temperature (perfectly mixed).
  - Single pressure at reference elevation.
  - Gravity head adjustments for inlet and outlet elevations.
  - Include dV/dT_w and dV/dP effects.

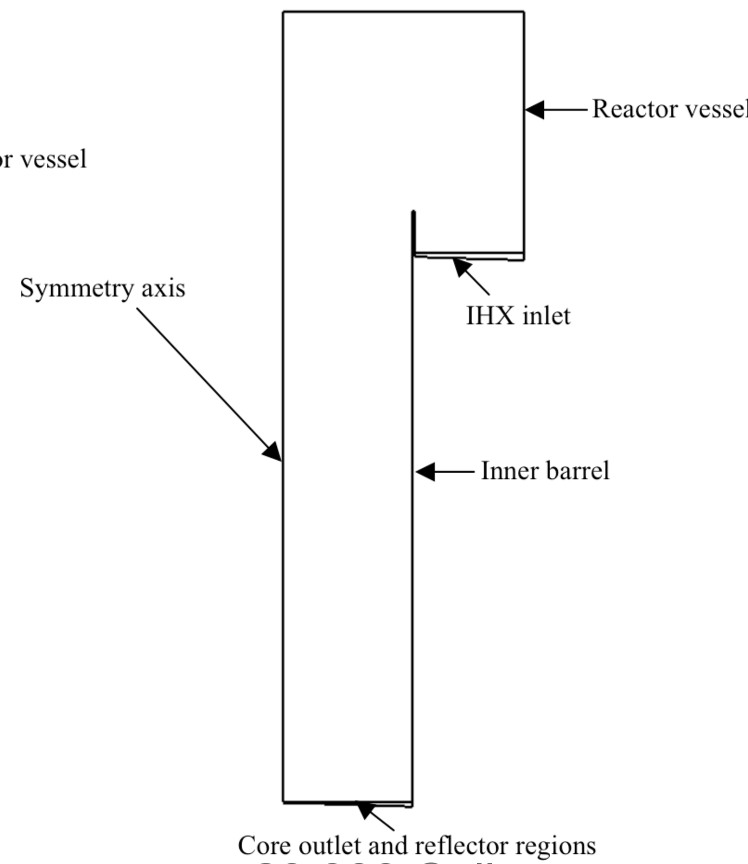
Outlet Plenum Replaced by 3-D or 2-D CFD Model



~700 Cells

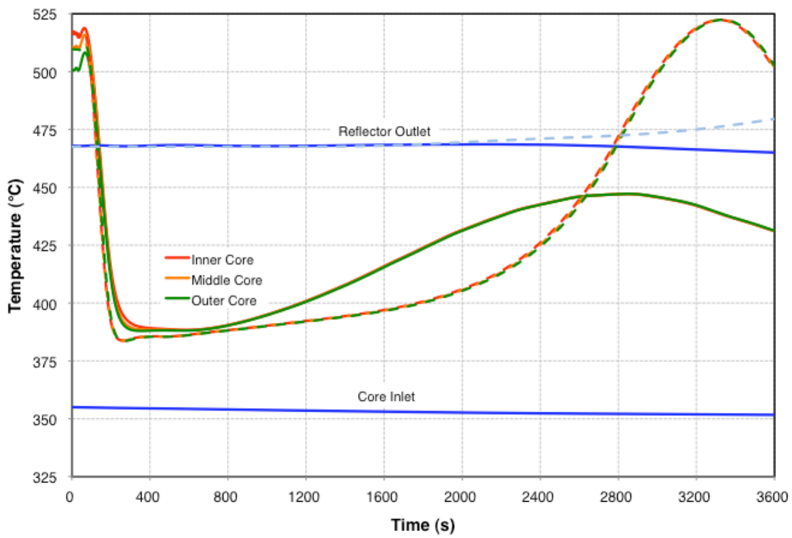


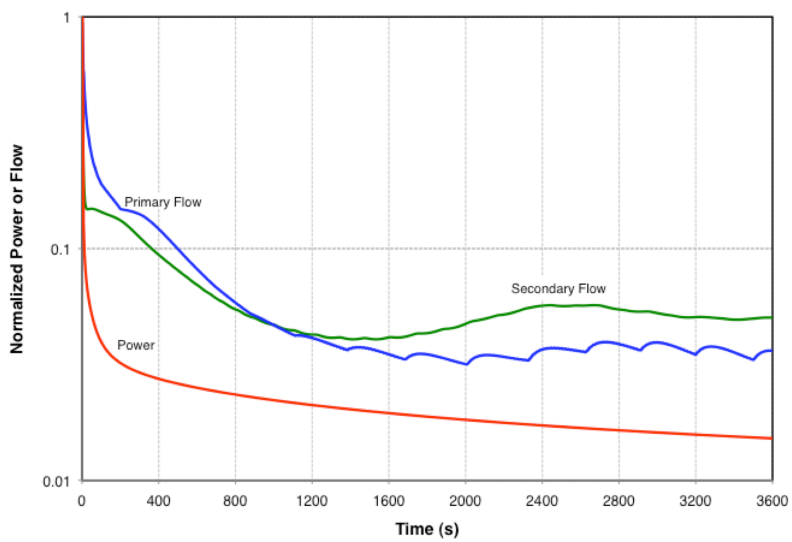
191,000 Cells



29,000 Cells

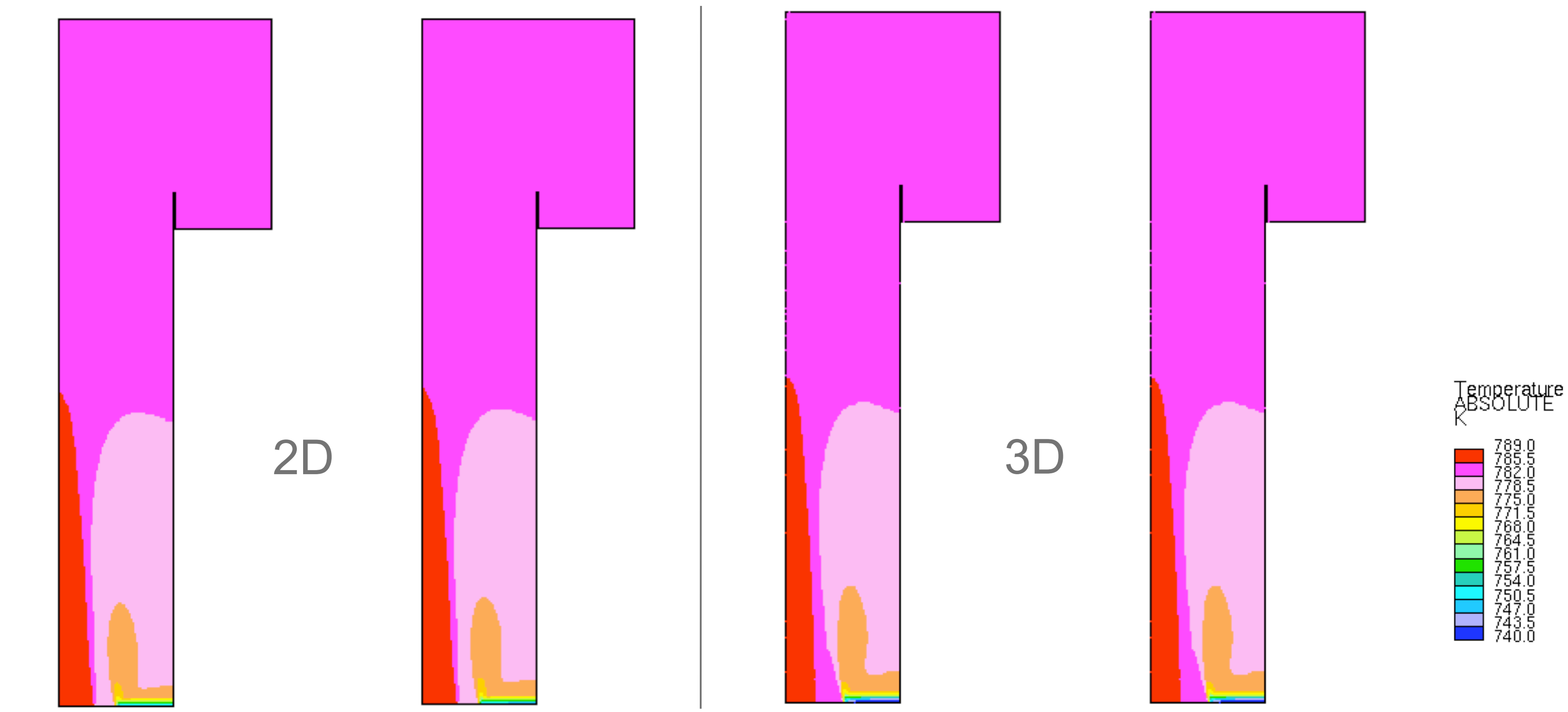
Treatment of Boundary Conditions





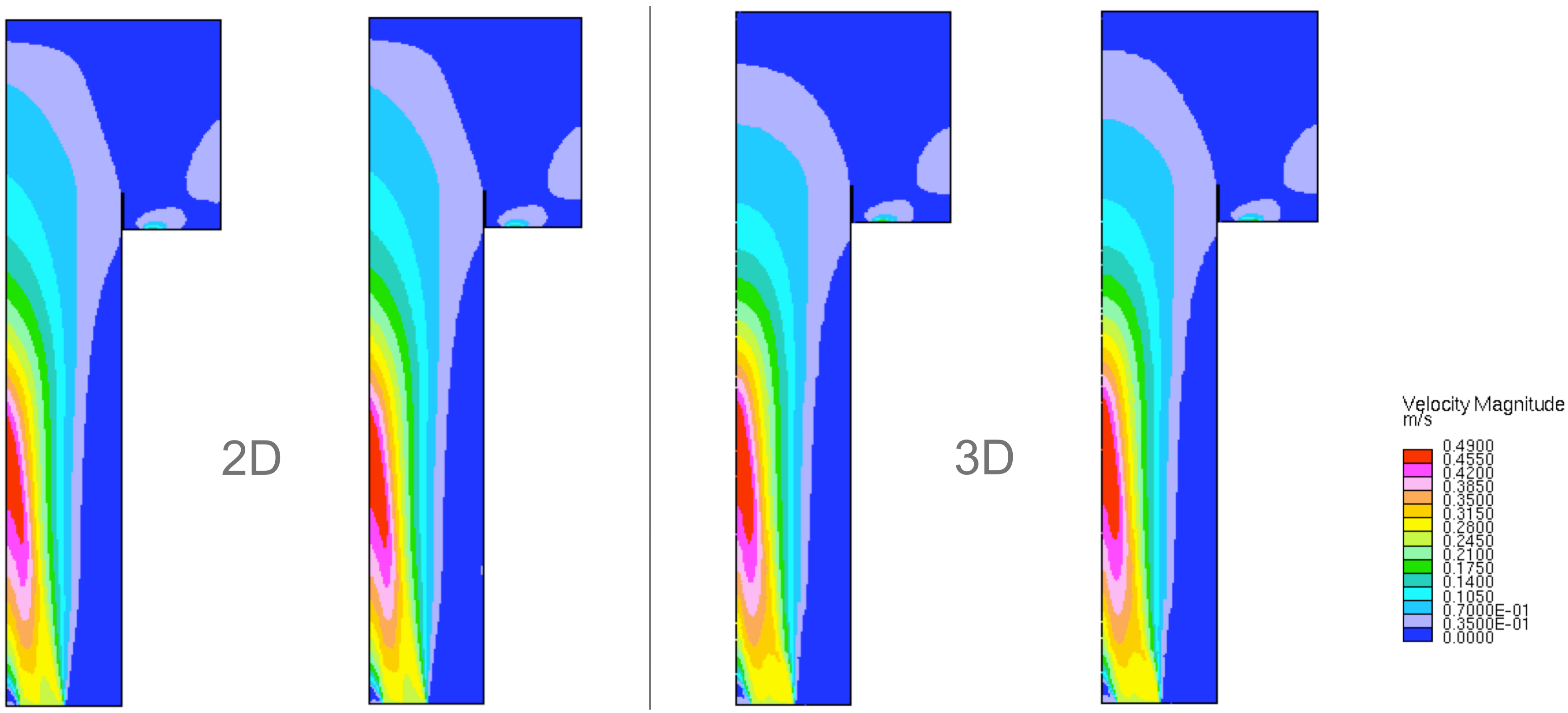
- Initial coupling is one way:
  - SAS4A/SASSYS-1 → STAR-CD
  - Valid during steady-state (well mixed)
  - Valid during initial pump coast-down (not buoyancy driven)
  - Not valid at later times
- Used to evaluate the effects of model assumptions and fidelity on thermal stratification, flow distributions, and primary-side IHX inlet temperatures.
- Thermal feedback will be added in future developments.
- Individual core assembly flow rates and temperatures are used as boundary conditions for the STAR-CD CFD simulation.
- For the free surface simulation, outflows to the IHX provide an additional boundary condition.

Steady State Temperature Distributions



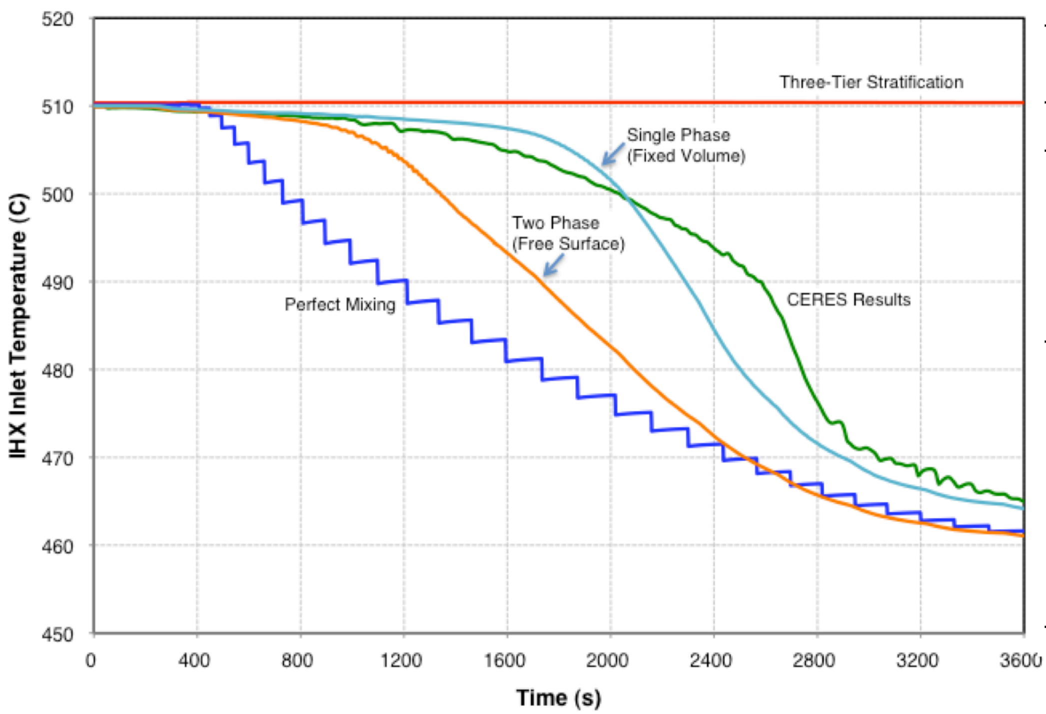
Two-Phase (Free Surface) | Single-Phase (Fixed Volume) | Two-Phase (Free Surface) | Single-Phase (Fixed Volume)

Steady State Velocity Magnitude



Two-Phase (Free Surface) | Single-Phase (Fixed Volume) | Two-Phase (Free Surface) | Single-Phase (Fixed Volume)

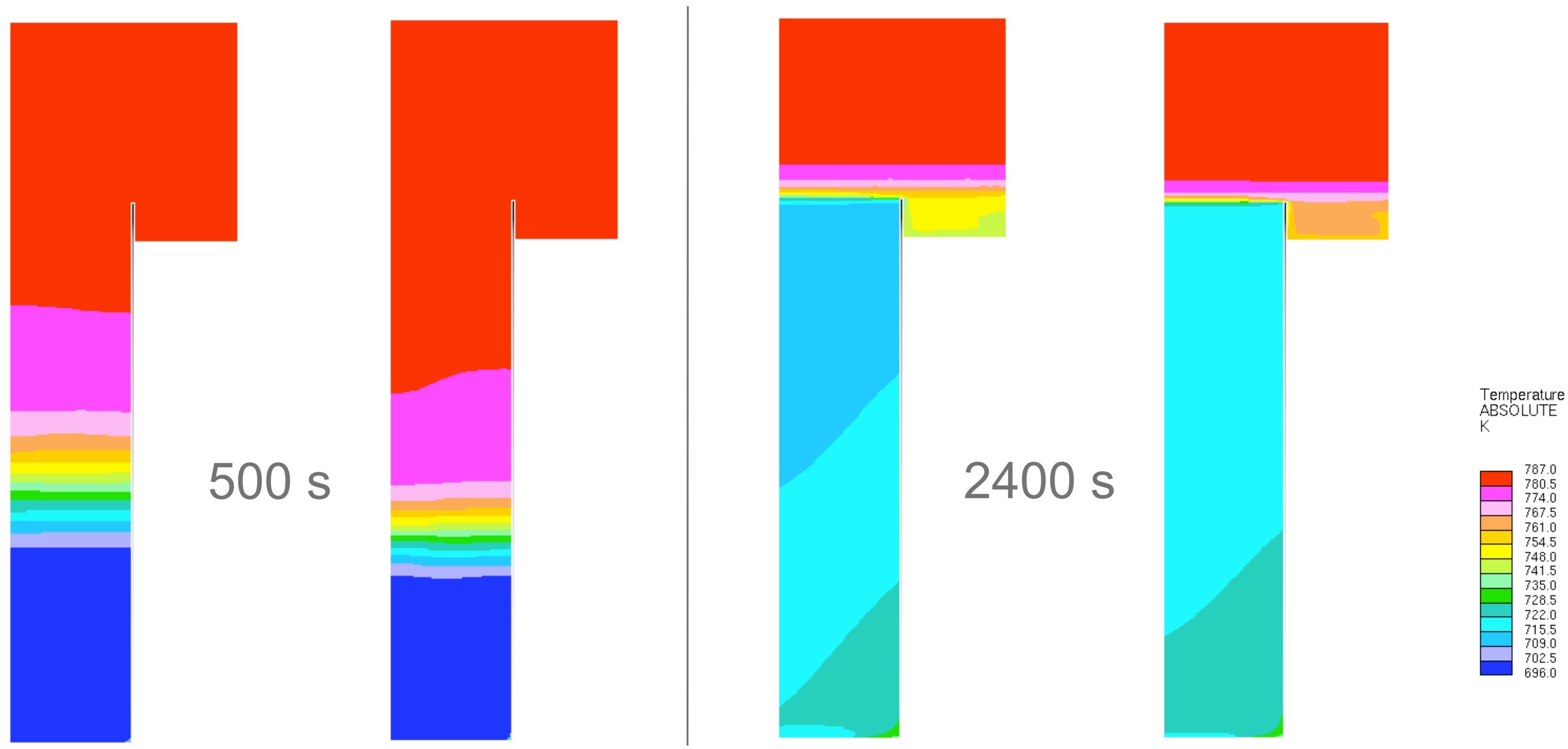
Transient Primary-Side IHX Inlet Temperatures



Model	Number of Processors	CPU Time (hours)	Total Time (hours)
SAS4A/SASSYS-1 (0 – 3600 s)	1	< 1 min	< 1 min
2-D Axisymmetric, VoF (cover gas)			
Stage 1 (0 – 1535 s)	8	187.4	239.3
Stage 2 (1535 – 3600 s)	12	90.3	137.4
Total		277.7	376.7
2-D Axisymmetric, Single Phase			
Stage 1 (0 – 1000 s)	12	84.3	86.2
Stage 2 (1000 – 2000 s)	12	23.8	25.3
Stage 3 (2000 – 3000 s)	12	21.0	22.4
Stage 4 (3000 – 3600 s)	12	5.3	5.4
Total		134.4	139.3

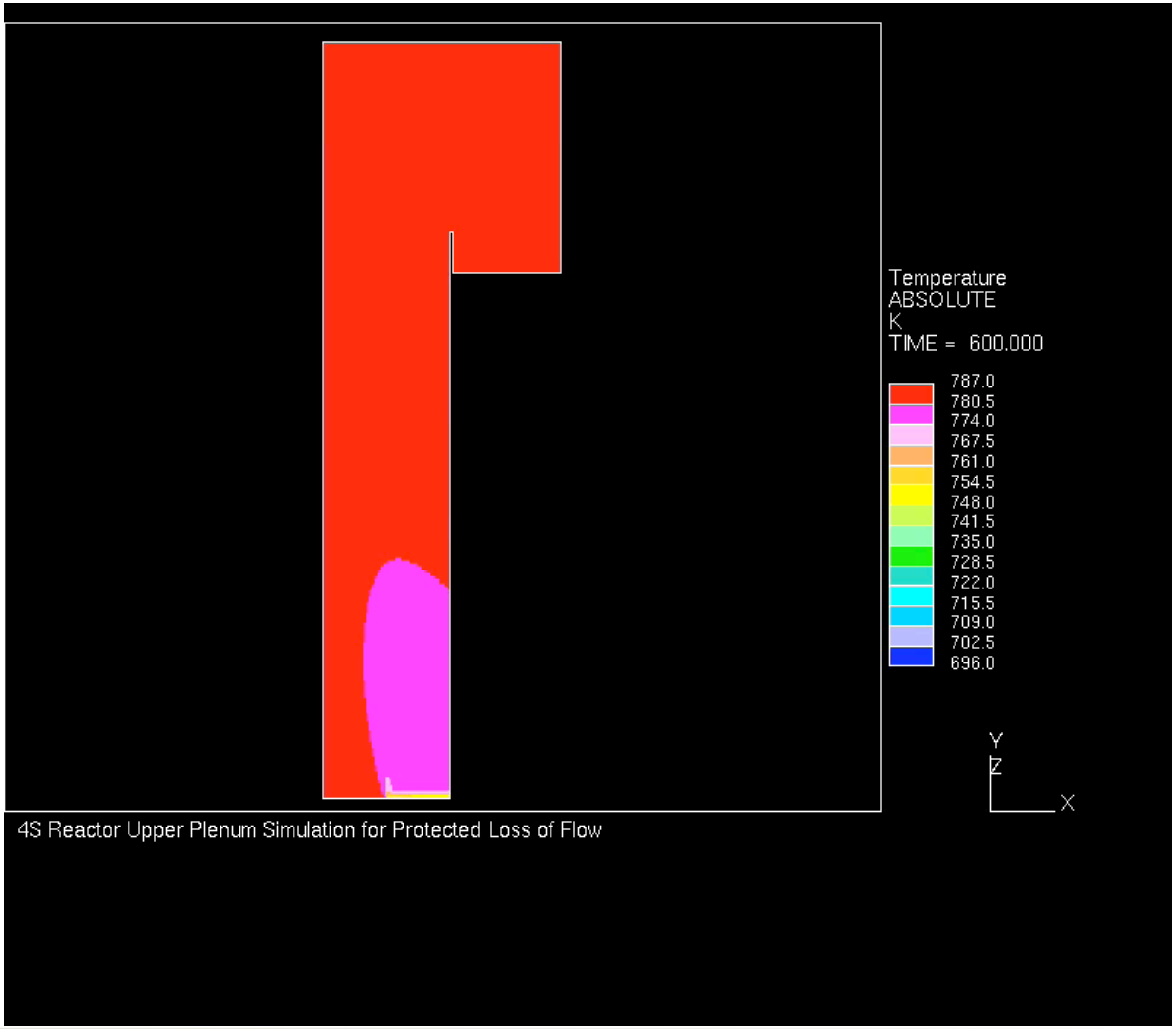
- Only the 2-D models were used to compute the full transient.
- Calculation of initial flow coast down dominates computing time.
- Treatment of free-surface motion appears to result in significant increase in thermal mixing throughout the plenum.
  - Converges to perfect mixing results by 2400 seconds.
- Single phase model is generally consistent with the results from CERES.

Transient Temperature Profiles



Two-Phase (Free Surface) | Single-Phase (Fixed Volume) | Two-Phase (Free Surface) | Single-Phase (Fixed Volume)

Transient Temperature Profiles



Summary

- Coupling between an existing, whole-plant systems code and a high-fidelity CFD code has been carried out.
  - Evaluate the conditions of outlet plenum thermal stratification during a long-term PLOF.
  - Four models were created to evaluate the effects of model assumptions and fidelity on thermal stratification, flow distributions, and primary-side IHX inlet temperatures.
    - 3-D (steady-state) and 2-D (steady-state and transient)
    - Single phase (no cover gas) and two-phase (with cover gas)
- Modeling treatment (free surface vs. single phase) has a considerable impact on thermal mixing.
- Future work will include thermal feedback in the SAS4A/SASSYS-1/STAR-CD coupling.
  - Assess the impact of thermal stratification on natural circulation flow rates in the PLOF and ULOF transient for 4S.
  - Compare with CERES results.