Thermal Stratification Modeling for Sodium-Cooled Fast Reactors: A Status Update

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July 25th, 2018

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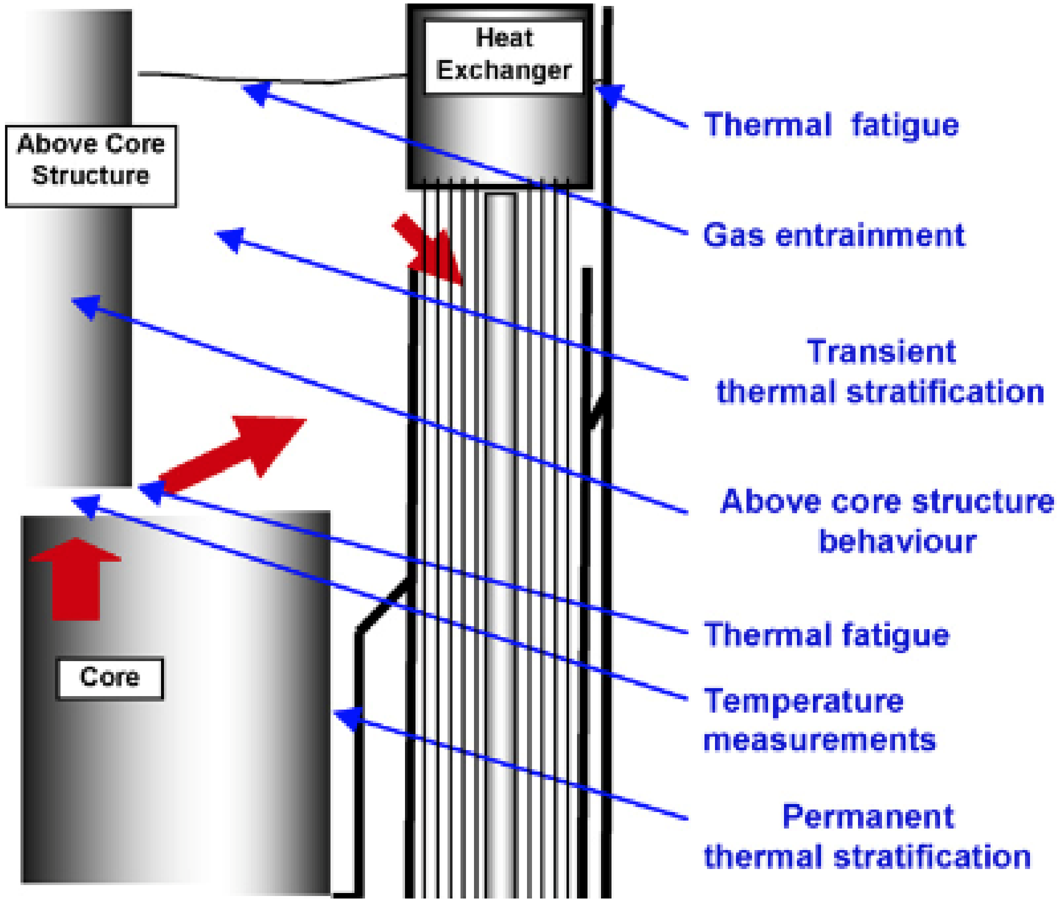
Background

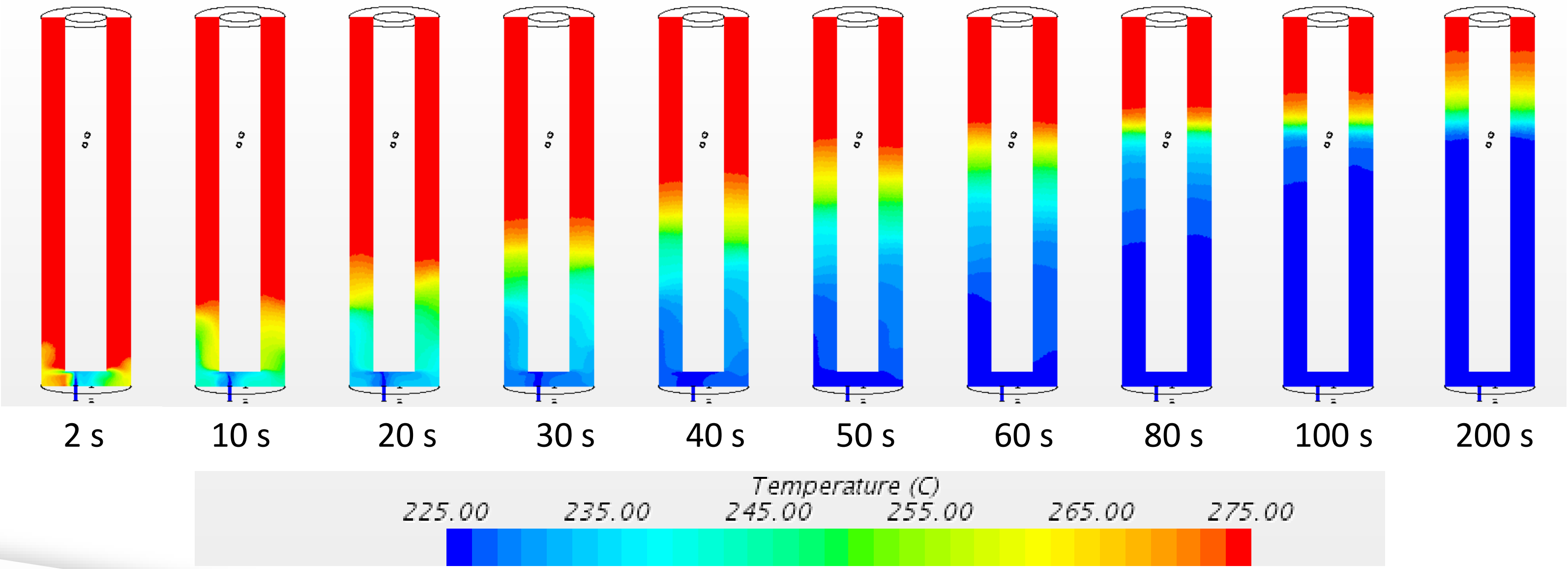
- Sodium fast reactor (SFR) is currently a leading candidate for the next phase of advanced nuclear reactor commercial deployment
- Thermal hydraulics in upper plenum of SFR designs is a major concern – refined modeling of the region is still needed
- Key technology gaps are still present
  - Thermal mixing
  - Thermal stratification
  - Thermal striping



Thermal hydraulic challenges identified in the upper plenum of SFRs (Tenchine).

Thermal Stratification (1/2)

- 3D phenomenon most commonly observed in loss of flow scenarios
  - Such case involves a large pool (upper plenum) with colder fluid entering beneath warmer fluid and the momentum of the flow is not large enough to overcome buoyant forces
- Differences in fluid densities result in colder more dense fluid flowing in lower region while upper region remains hot



Thermal stratification in a protected loss of of scenario (Baglietto et al. 2017).

Thermal Stratification (2/2)

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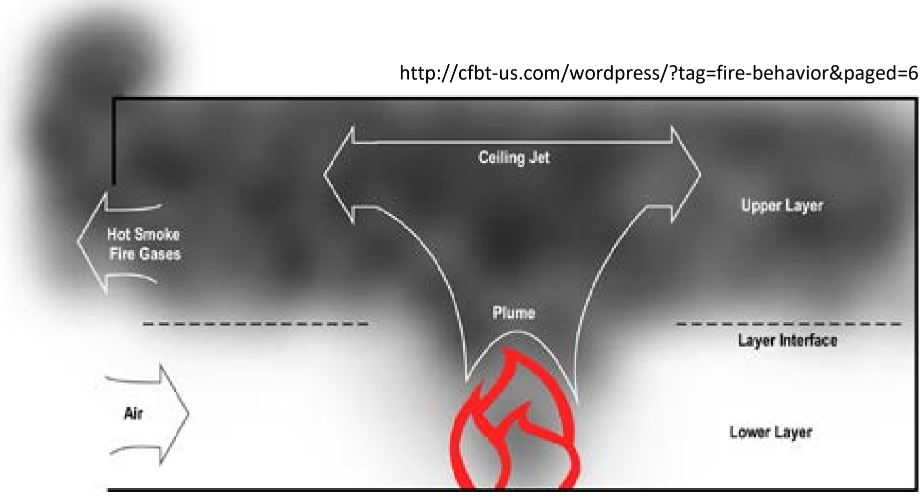
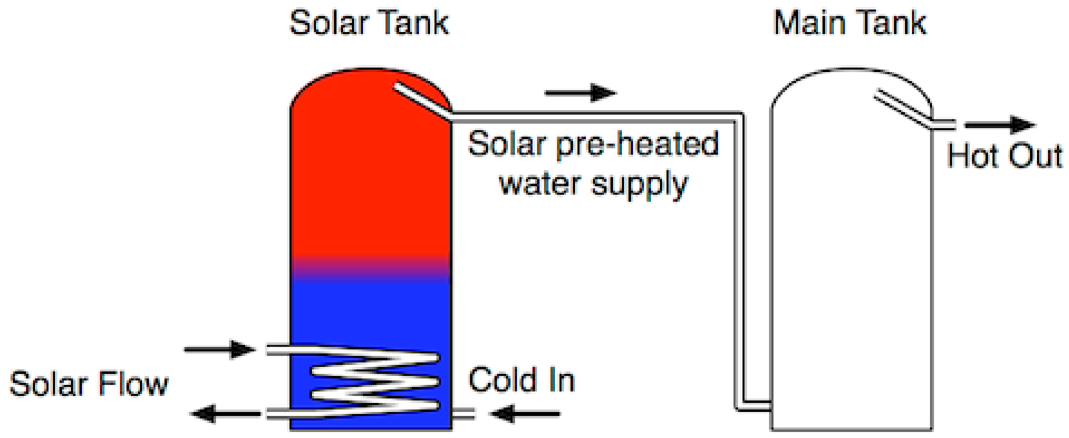


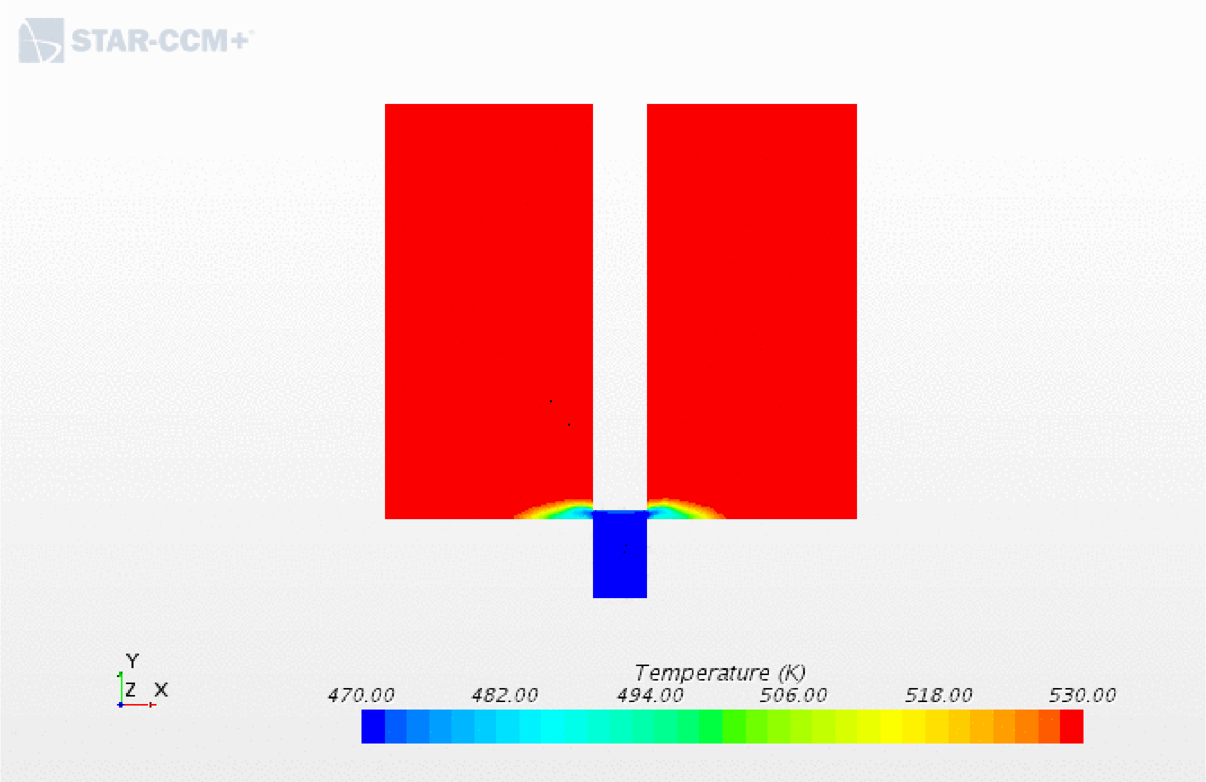


http://www.apricus.com/html/solar_hot_water_basics.htm#.WrlO8_nwZhE

- Thermal stratification has been studied for many applications
  - Solar industry
  - Biological sciences
    - Oceans and lakes
    - Pollutant discharge
  - Zone mixing models for enclosure fires
- Thermal stratification has been studied in many designs in the nuclear industry
  - BWR – GE ESBWR
  - PWR – Westinghouse AP1000
  - HTGR & AHTR

Current Modeling of Thermal Stratification (1/3)

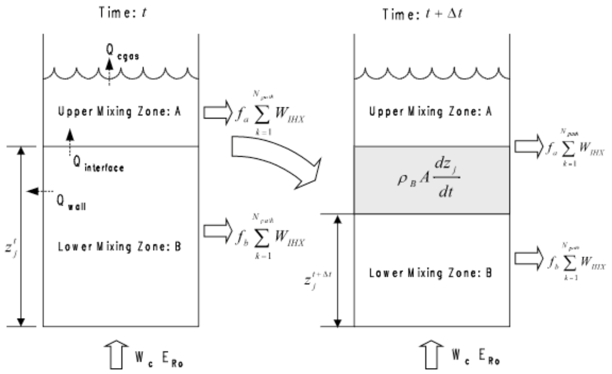
- 3D Methods – CFD
  - Difficulties accurately predicting rise time
  - High computational cost
  - Relatively limited geometries



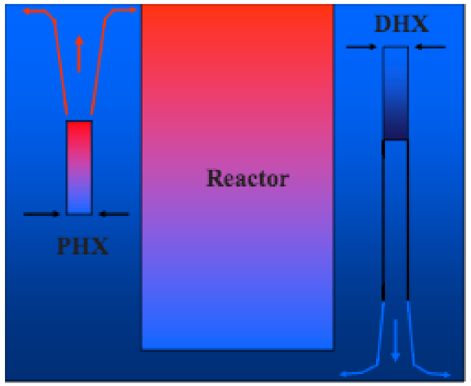
Thermal stratification simulation for proposed experiment setup (Baglietto et al. 2017).

Current Modeling of Thermal Stratification (2/3)

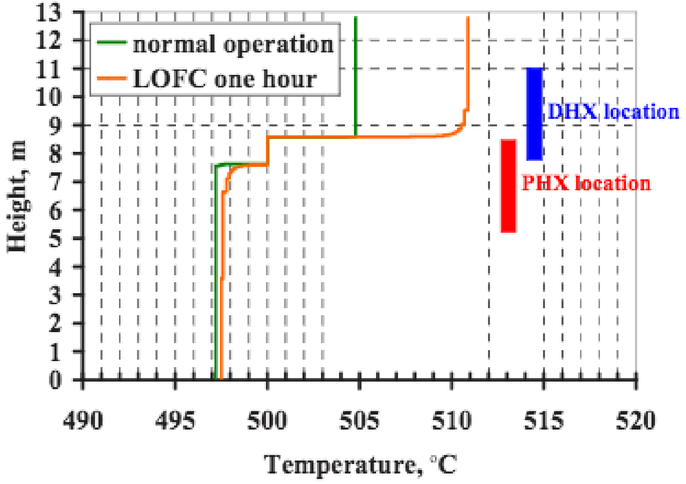
- Most system level codes, such at SAS4A/SASSYS-1, currently employ 0D models (lumped parameter)
  - Approximate results and can only handle simple cases
  - Fast computational time
- Other approaches
  - Japanese Super-COPD – 1D model
  - Korea’s SSC-K code has an optional 2D model
  - Berkeley’s BMIX++ uses 1D governing equations with Lagrangian approach and has been validated but can only handle stably stratified conditions



Two mixing zone model for the hot pool in SSC-K (Chang et. All, 2002).



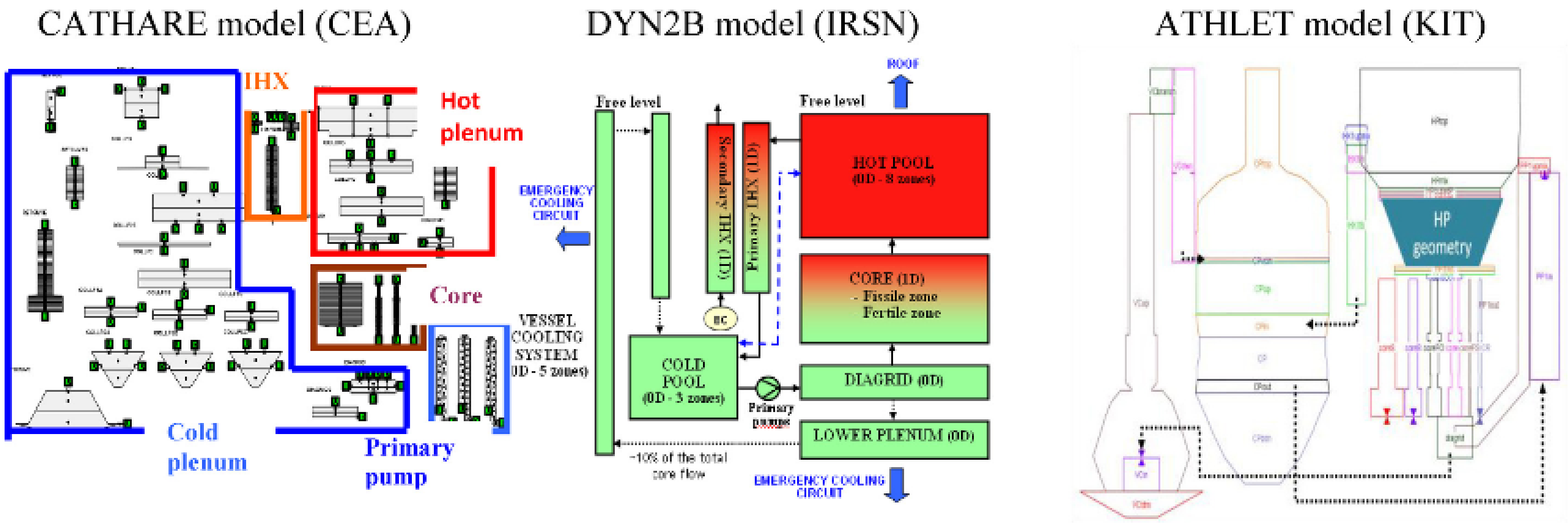
Mixing in the AHTR buffer pool system



Temperature profiles in AHTR Buffer Salt Tank, using BMIX++ (Zhao & Peterson, 2010).

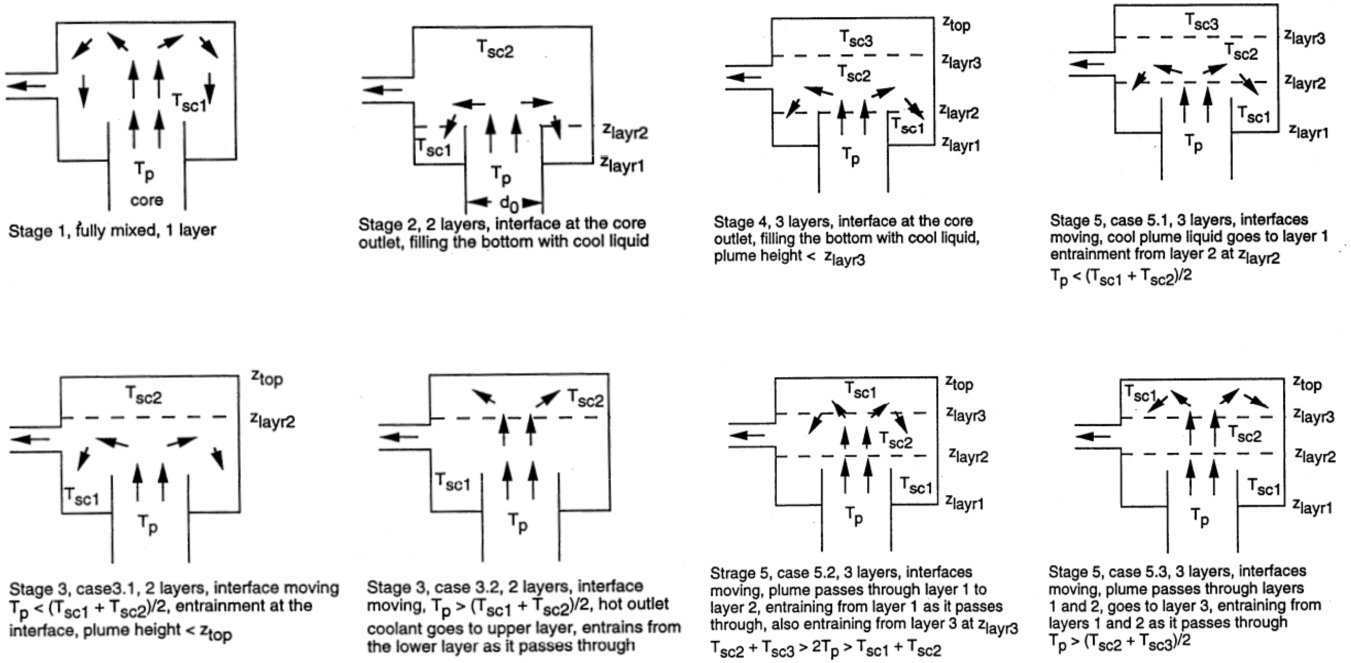
Current Modeling of Thermal Stratification (3/3)

- Coupling system level codes to CFD
  - THINS Project of the 7th Framework EU Program
  - Still relatively computationally expensive
  - Coupling only the relevant geometrical zones



System code model for a PHENIX benchmark test in THINS project (Bandini).

SAS4A/SASSYS-1 Stratified Volume Model (1/2)



Stratified volume stages from SAS4A/SASSYS-1 User's Manual (Fanning).

T_p = plume temperature = core outlet temperature
T_{sci} = temperature in layer i
z_{top} = elevation at top of plenum
z_{layri} = interface elevation at bottom of layer i

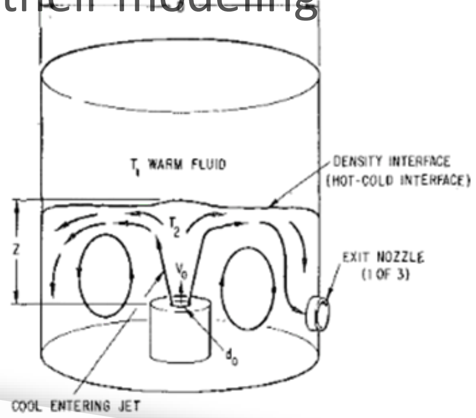
- Stage 1: fluid is fully mixed
- Stage 2: temperature and velocity drop – a boundary layer is formed at the outlet of the core
- Stage 3: liquid fills a quarter of the volume of the layer formed in Stage 2, causing the interface to rise while the plume entrains liquid from the interface into the first layer
  - Case 3.1: liquid entering the region is cooler than the bulk temperature
  - Case 3.2: liquid entering the plenum is hotter than the bulk temperature
- In stage 4 and 5 three layers are developed- these stages occur later in the transient and only if the core outlet temperature starts out rising and later falls, or vice versa
- If the coolant inlet into the volume is horizontal (as in the case with the discharge from the IHX into the cold pool) only stages 1, 3, and 5 are used.

SAS4A/SASSYS-1 Stratified Volume Model (2/2)

Lorenz and Howard's Model

- Modified Baine's correlated entrainment data for jets and plume
  - $\frac{\varepsilon}{V_j}\left(\frac{D}{d_j}\right)^2 = a\left(Ri_j\right)^{-b}$
- Currently used in PRIMAR-4
- Pointed out possible dependency of the Peclet number not used in their modeling

Density interface in a thermally stratified cylindrical vessel (Lorenz and Howard, 1979).

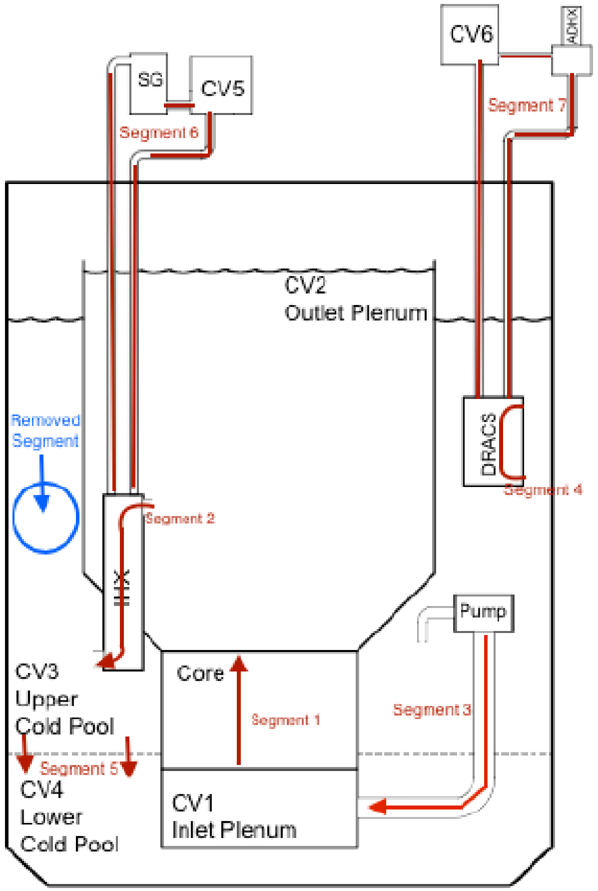


Yang's Jet Penetration Distance

- Correlates penetration distance as a function of the Froude number
- States simplified one-dimensional approach provides satisfactory prediction and is currently used in SAS4A/SASSYS-1
  - $z_m = 1.0484 Fr_0^{0.785}$
- Mentions several theories for prediction of vertically discharge buoyant jets – many based on the integral form of equations of motion

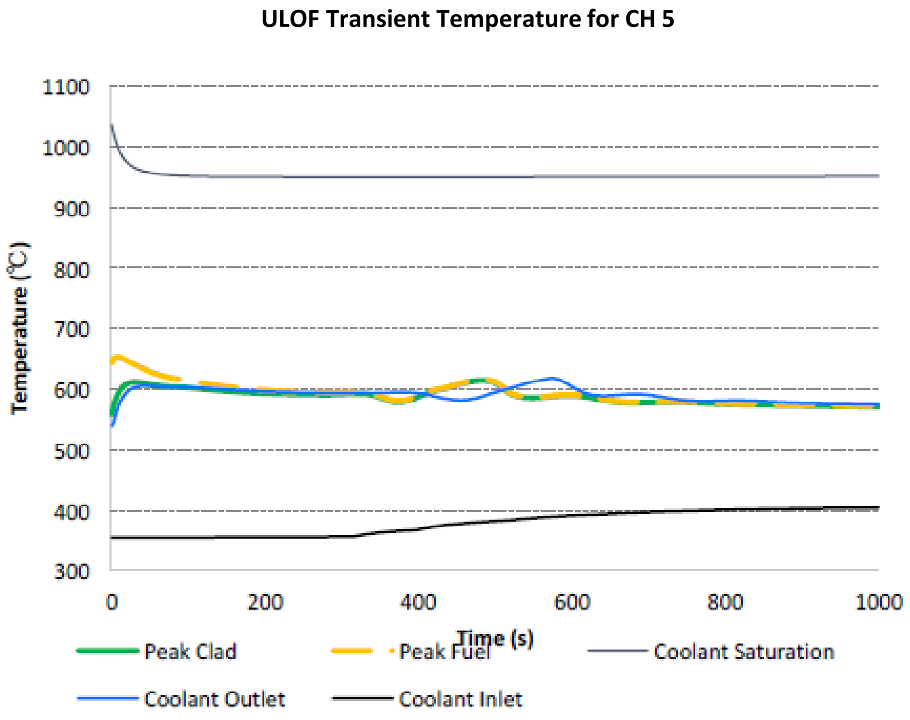
SAS4A/SASSYS-1 ABTR Example and Shortcomings

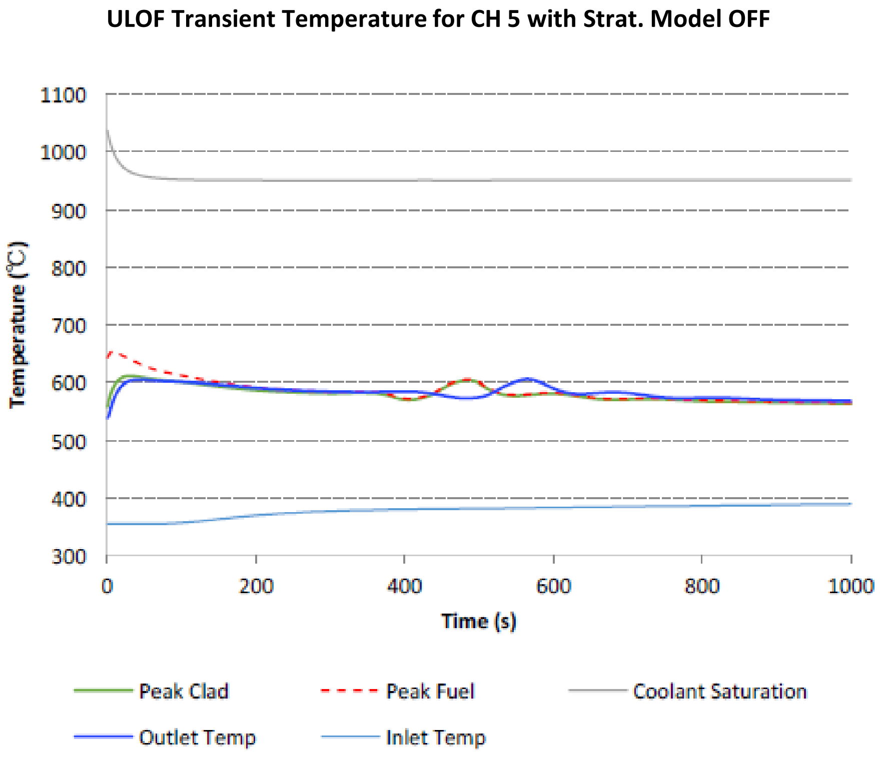
- This project is examining the ABTR design which has previously been modeled in SAS4A/SASSYS-1 using the existing stratified volume model
- Channel Region:
  1. Inner Core
  2. Middle Core
  3. **Outer Core**
  4. Reflectors and Test Assemblies
  5. **Peak Inner Core Channel**
- In order to change the ULOF input deck to a PLOF scenario, 23.87 $ was inserted into the core at one second and left inserted for the remainder of the calculations (from ABTR report as control rod worth)



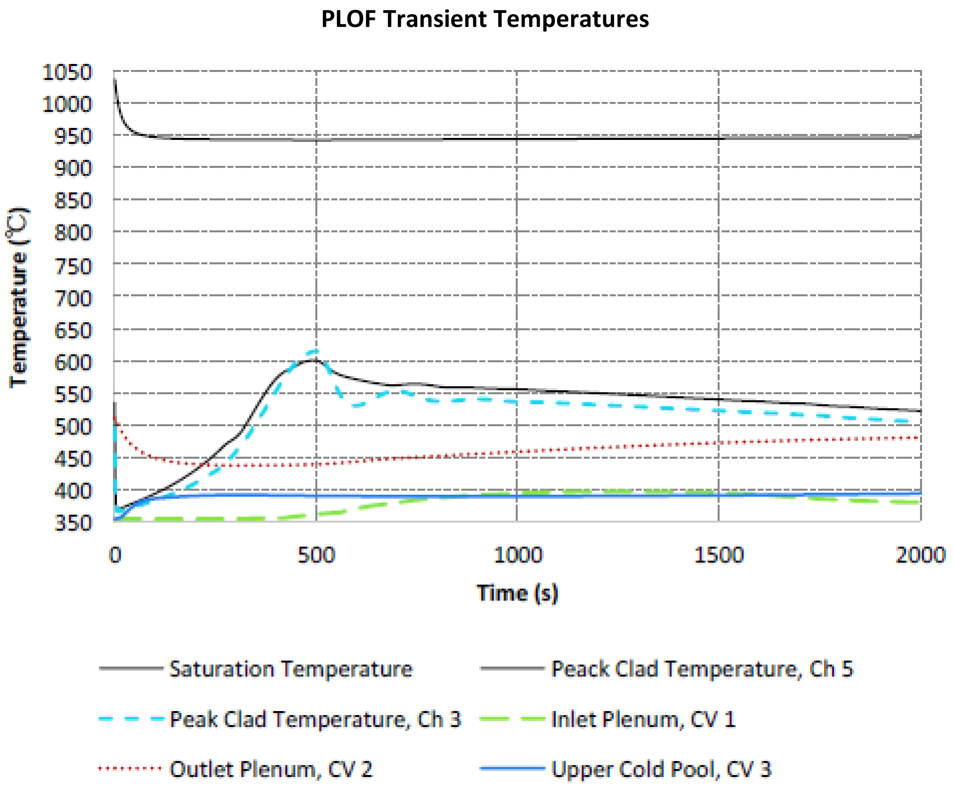
Model for input deck used, showing the segment that was removed from the model used in the ABTR Conceptual Design Report.

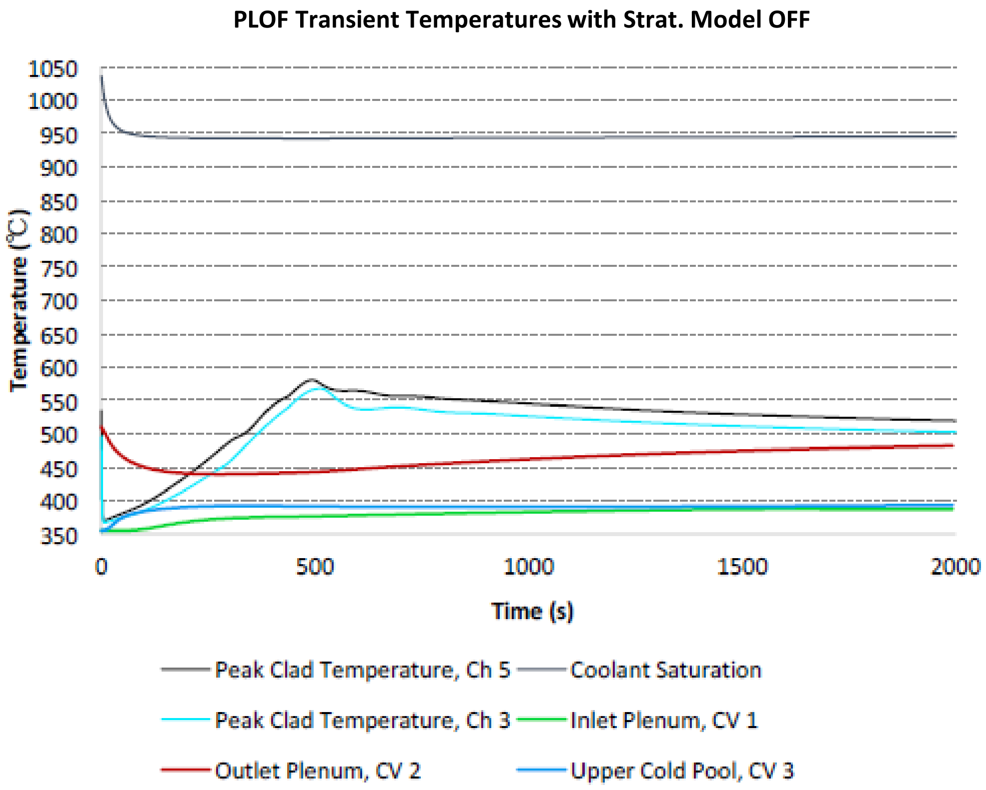
SAS4A/SASSYS-1 ABTR Example and Shortcomings – Unprotected Loss of Flow





SAS4A/SASSYS-1 ABTR Example and Shortcomings – Protected Loss of Flow



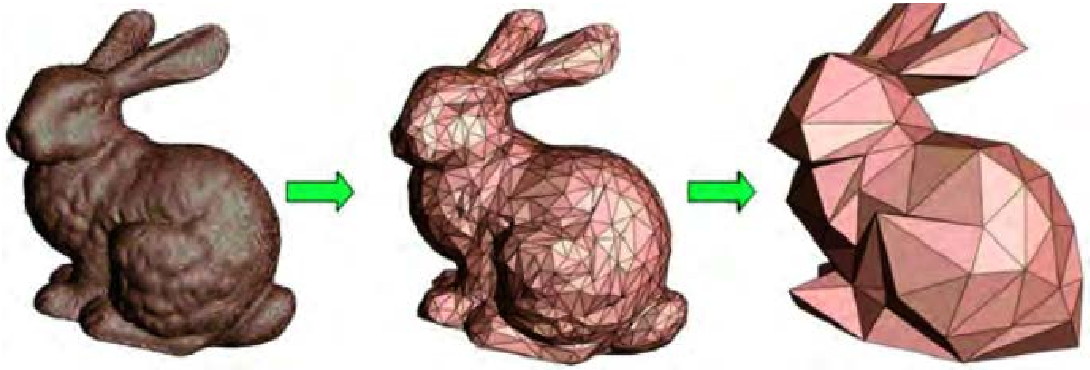


Other Modeling Efforts

- Nuclear Energy’s Advanced Modeling and Simulation (NEAMS) is developing System Analysis Module (SAM) out of Argonne National Laboratory
  - SAM utilizes reduced-order three-dimensional modeling techniques to address thermal mixing
- Machine learning techniques can be very useful to develop reduced order models (ROMs) to alleviate computational expense in modeling and simulation of complex 3D phenomenon such as thermal stratification
  - Currently used often to improve computational cost of CFD
  - Could be combined with ROM methods to improve system level codes

NEAMS
NUCLEAR ENERGY ADVANCED MODELING & SIMULATION PROGRAM

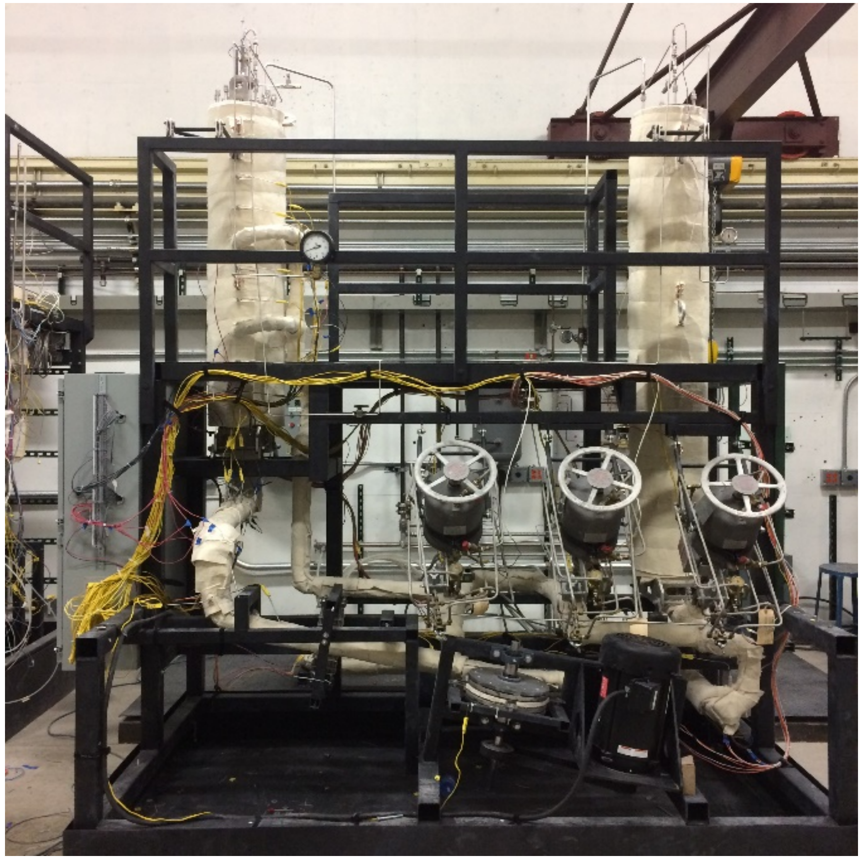
MOOSE



Graphical illustration of model order reduction (Schilders).

Future Work of This Project

- Goal of this project is to couple system code model, CFD results, and experimental results to define a way to accurately predict thermal stratification
- Experimental results will be compared with both CFD simulations and the model developed by our team. If the model is successful it will be implemented into SAS4A/SASSYS-1, or other system codes requiring improved models…



Conclusions

- Computational modeling is an indispensable tool however prohibitively high computational costs make it not feasible for all applications
- A 0D/1D approach seems like a sensible approach and will be further explored
  - A 2D approach will not be completely eliminated at this point, and further research into this option will be done
  - ROM methods will be further
- Over the next year,
  - Begin developing model
  - Work on code construct
  - Inform developed model based on experimental and CFD results

Acknowledgements

This work was performed with support from the Department of Energy, Nuclear Energy University Programs, Grant 16-10268

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Thoughts?

Questions?

Thank You!