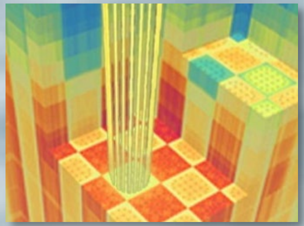
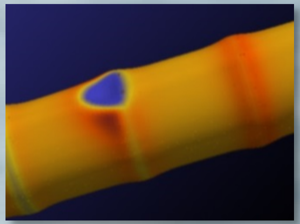
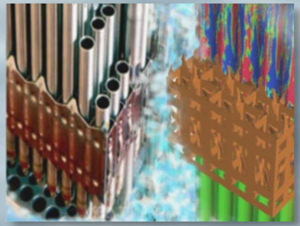
CTF
A thermal-hydraulic subchannel tool for standalone and coupled simulation of LWRs







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Oak Ridge National Laboratory

February 11, 2019

VERA Workshop

CASL
The Consortium for Advanced Simulation of LWRs
A DOE Energy Innovation Hub

U.S. DEPARTMENT OF ENERGY

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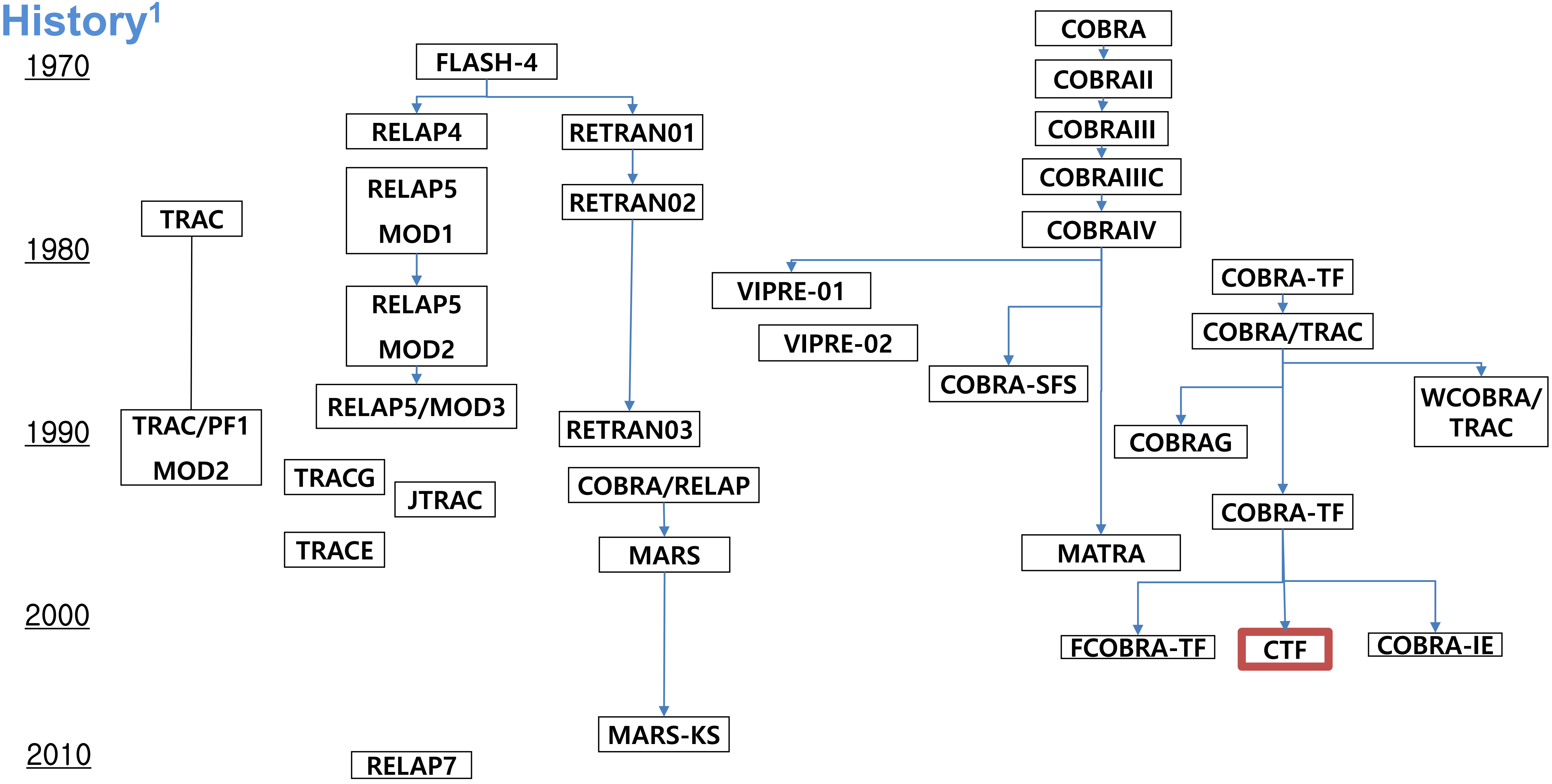
History[1]



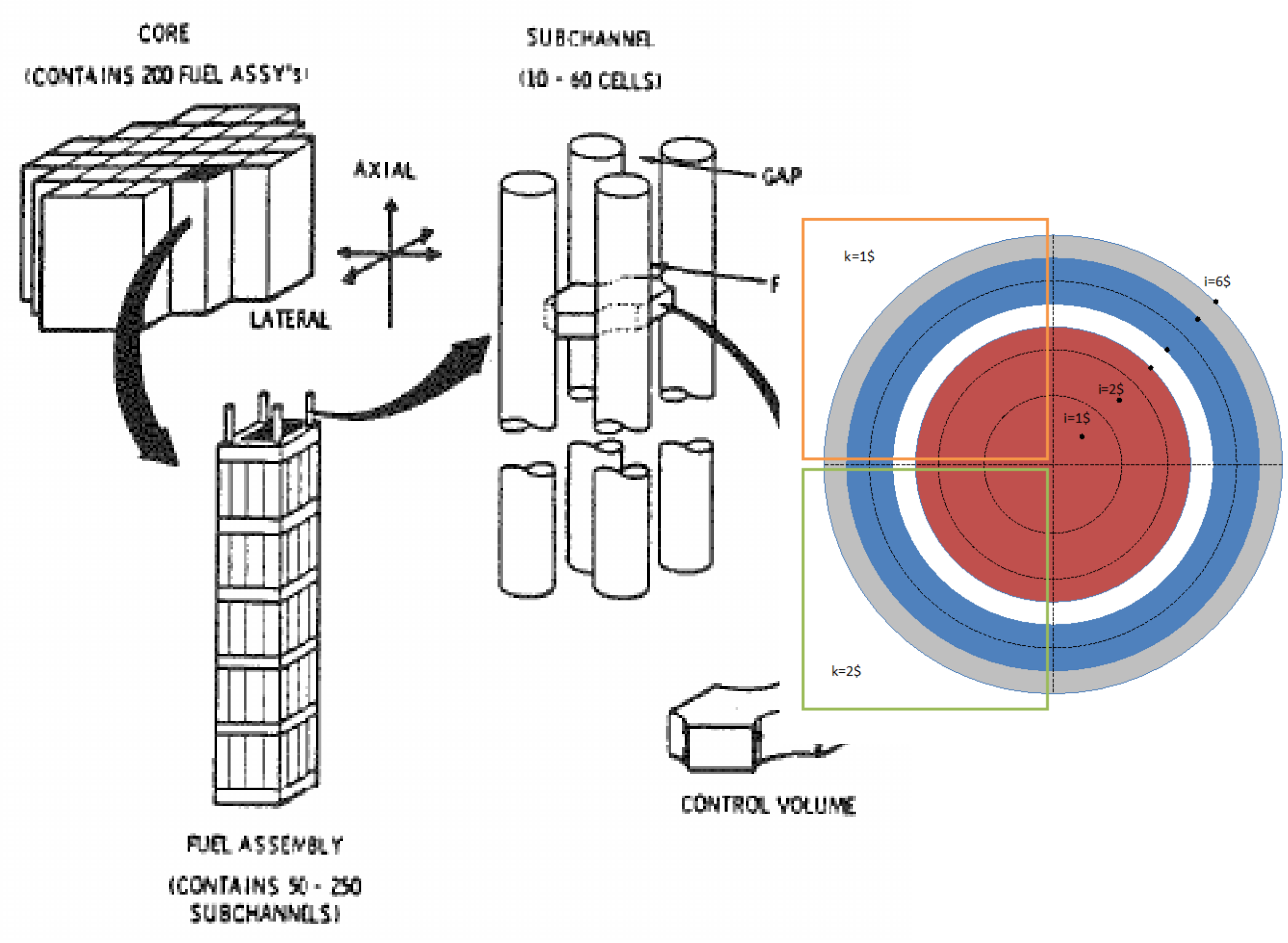
1. S. Sim, "Plans for COBRA-TF in MARS-KS", CTF-3 Presentation, Villigen, Switzerland, 2016

Introduction
CTF User Group

- Network of CTF users
- Organized by North Carolina State University
- Forum for sharing development, research, and applications related to a common version of CTF
- Distributes the standalone version of CTF and provides user support
- Annual meeting held in May/June

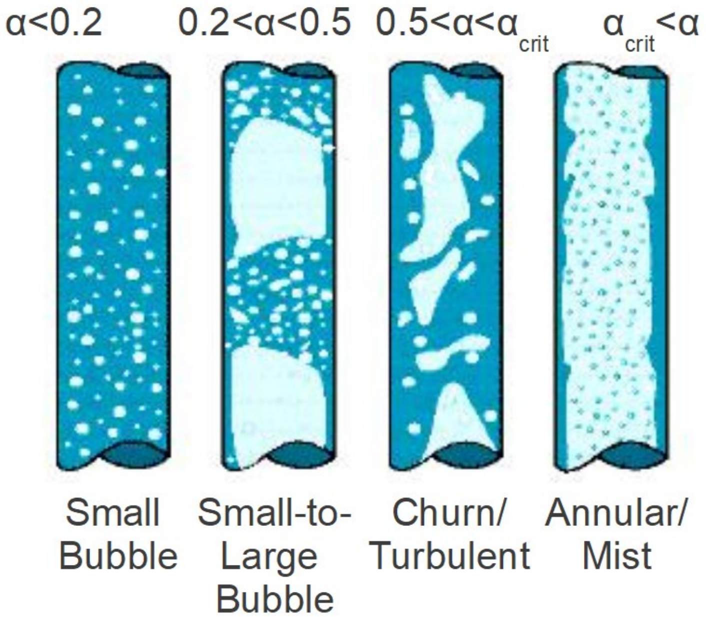
Introduction
Solution Approach

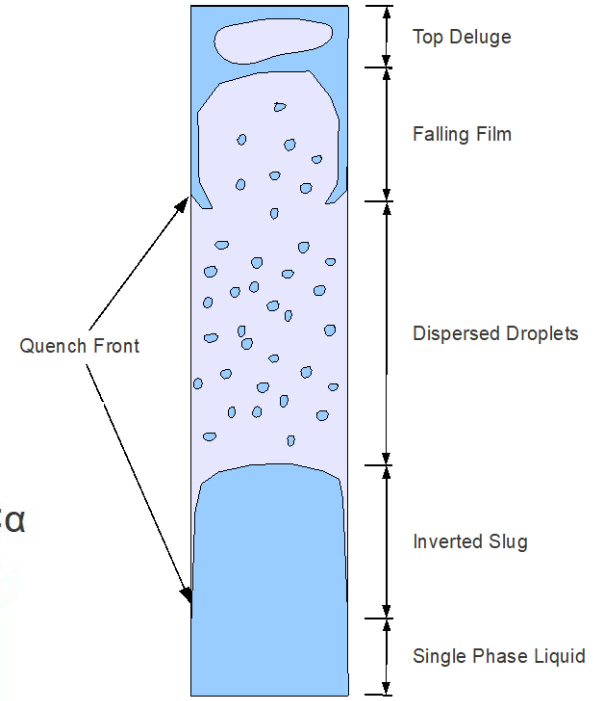
- In-core thermal-hydraulics modeling of LWRs using sub-channel approach
- Transient solution
- Models both solids and fluids
- Two-fluid, three-field (liquid,vapor, and droplets)
- Coarse mesh used with closure models to resolve smaller scale physics



Introduction
Solution Approach

- Range of flow-regime dependent closure relationships
- Rod-to-fluid heat transfer
- Wall friction and form losses
- Inter-phase heat/mass transfer
- Inter-phase friction
- Turbulent-mixing and void drift
- Grid-enhancement of heat transfer
- Fluid and rod property lookups
- Non-condensable gas model
- Geometry distortion (rod bow, blockages)

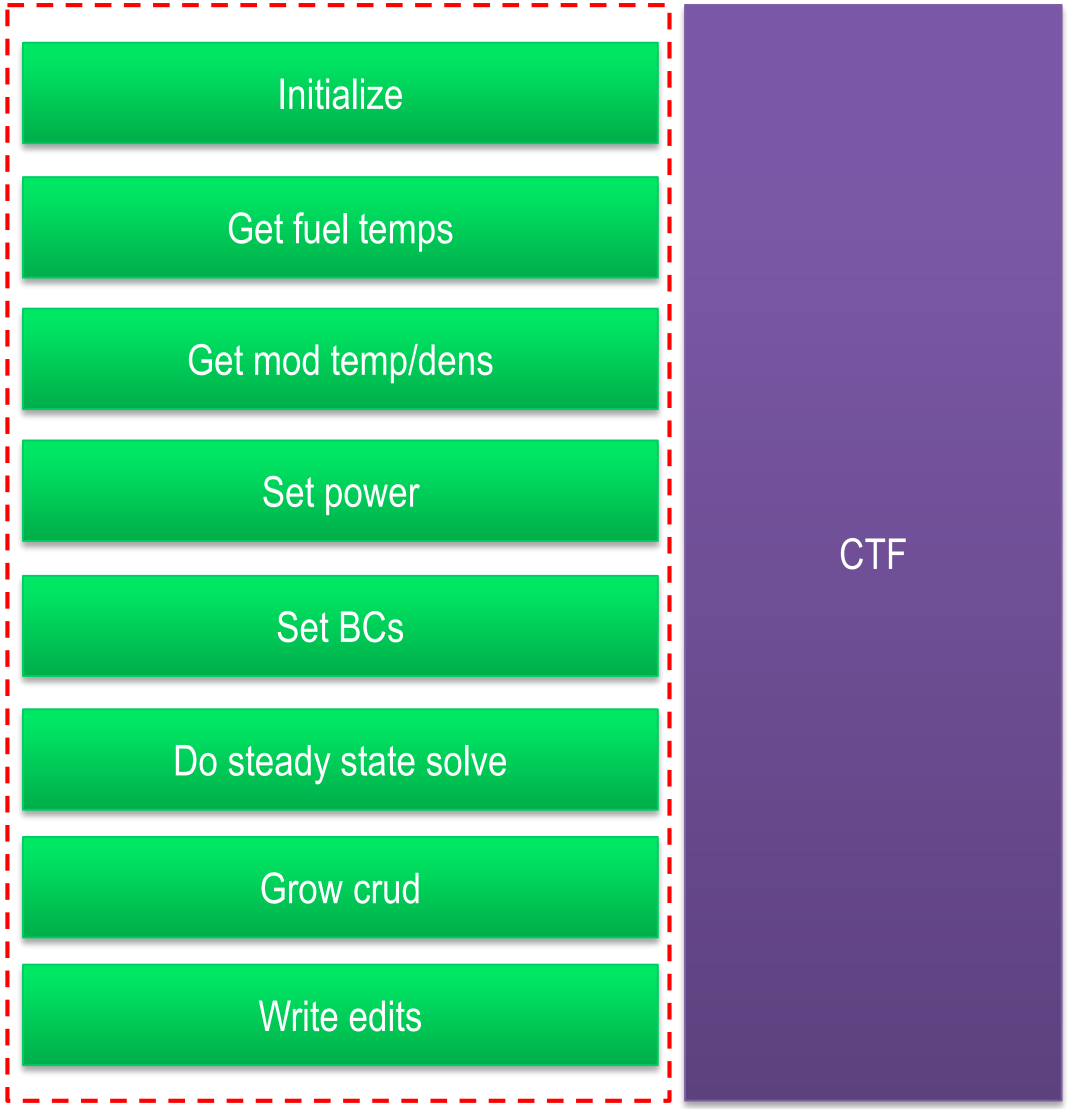




Code Features
Application Interface

- Code refactored and API added for coupling to neutronics and fuel performance codes

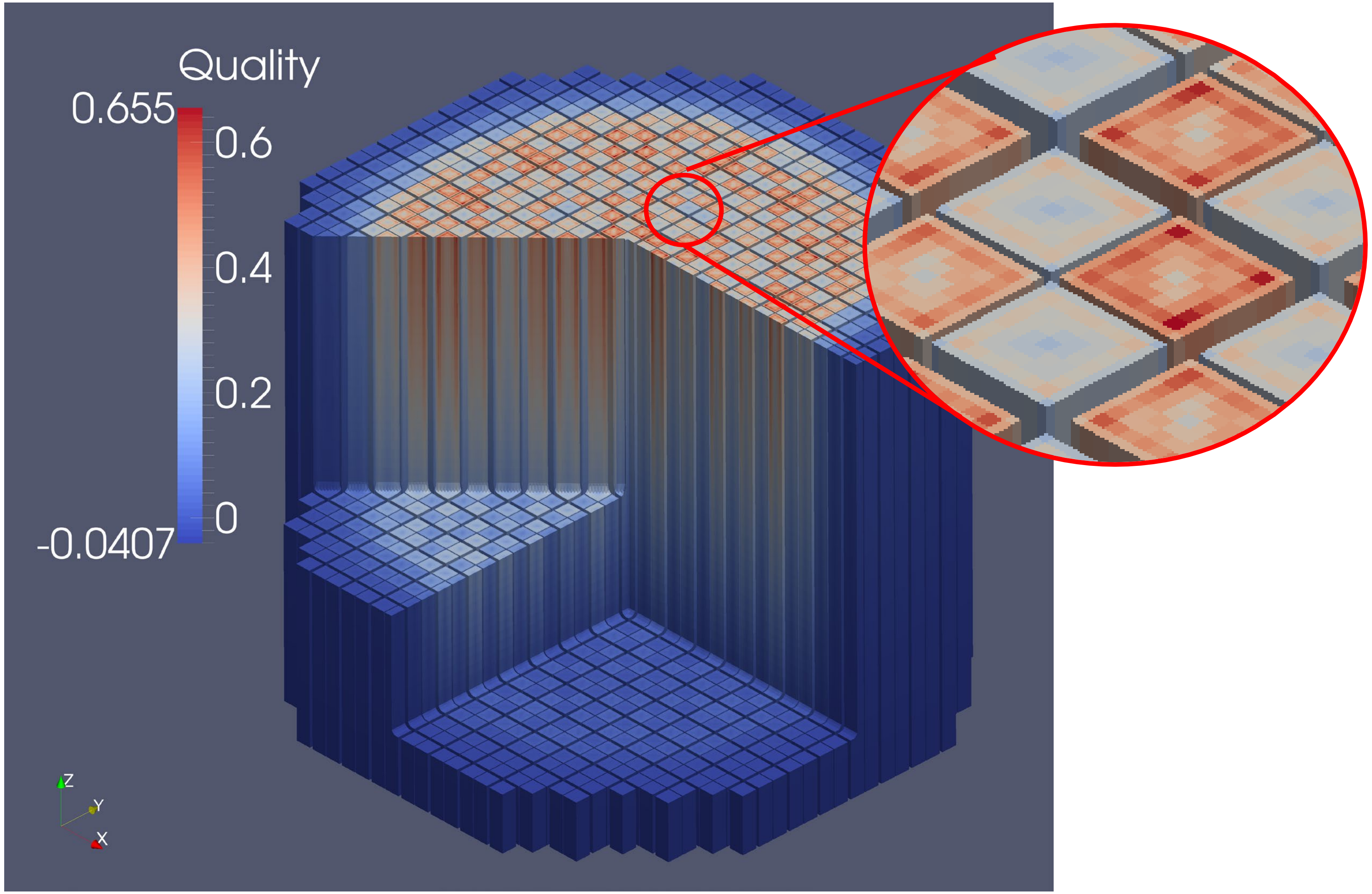
Code	Physics
MPACT	neutronics
MAMBA	chemistry/crud
Bison	fuel performance
Dyn3D	neutronics
nTracer	neutronics
Athlet	system
PARCS	neutronics
RELAP5-3D	system



Coupling Interface

Code Features
Preprocessor Utility

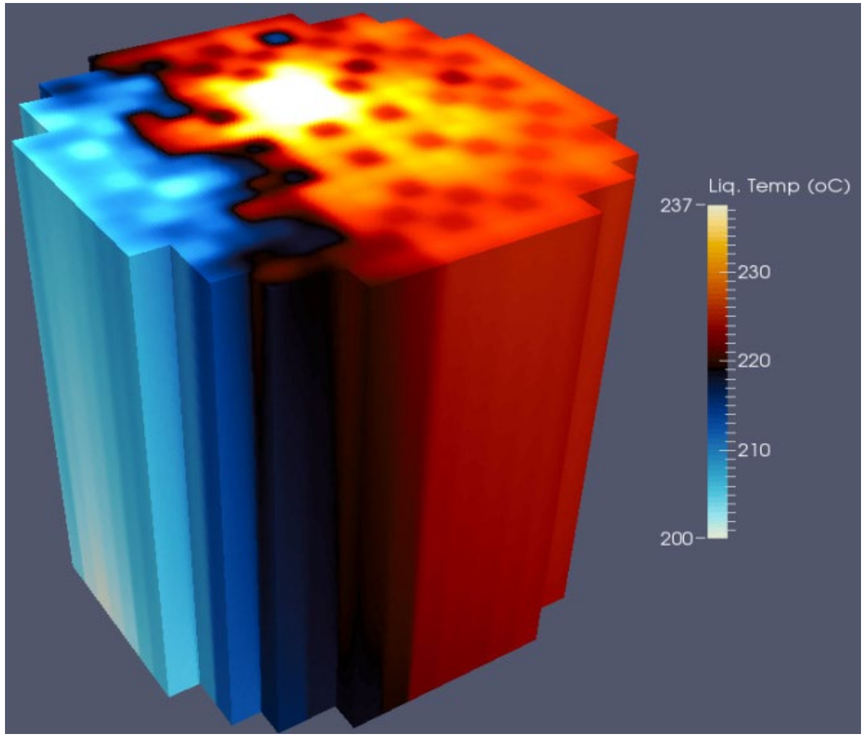
- Code front-end for reading the VERAIn common input file
- Generates pin-resolved models
- Handles all geometry connection information
- Defaults closure models to reduce user-effect
- Applicable to PWR and BWR geometries



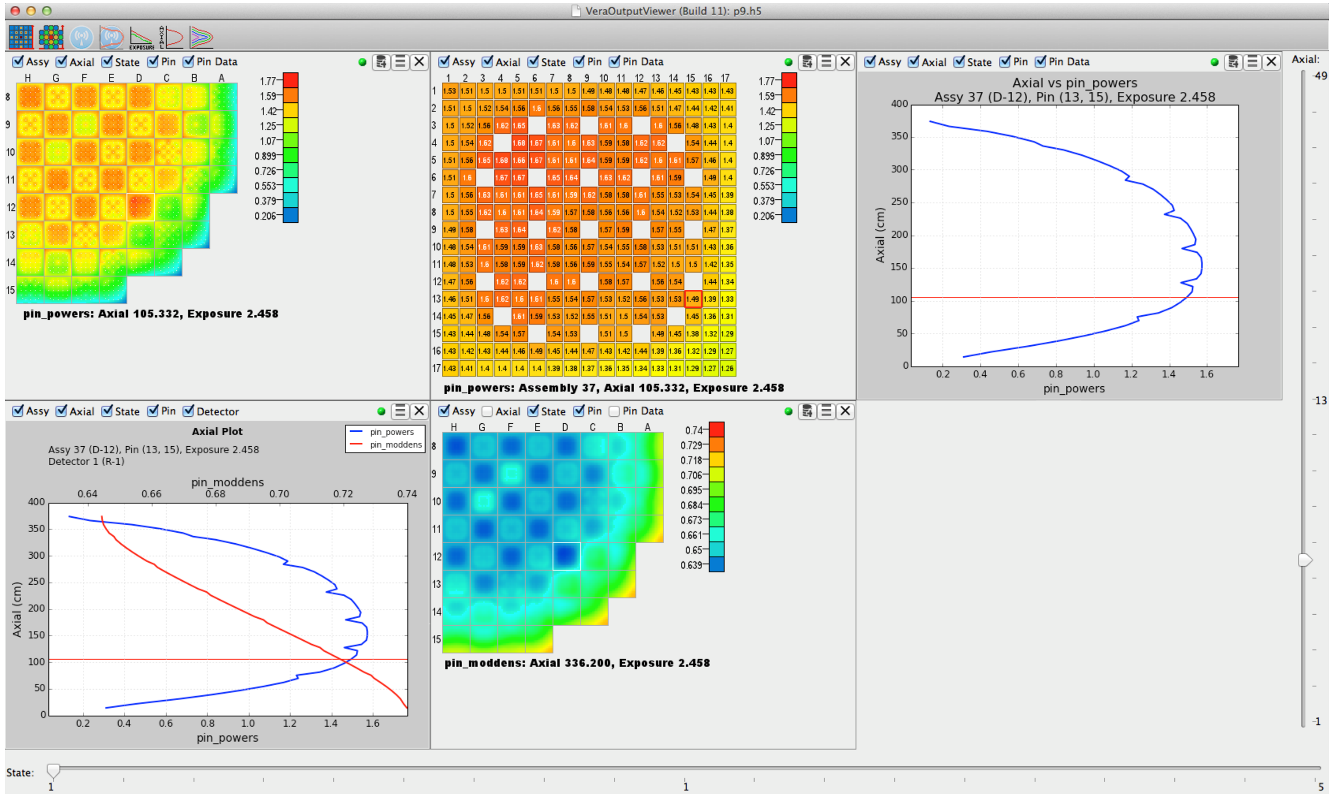
Pin-resolved BWR simulation using standalone CTF

Code Features
Output Visualization

- Produces HDF5 file for visualizing in VERAView
- Produces VTK file for all model types



VTK file visualized in Paraview for steamline break simulation



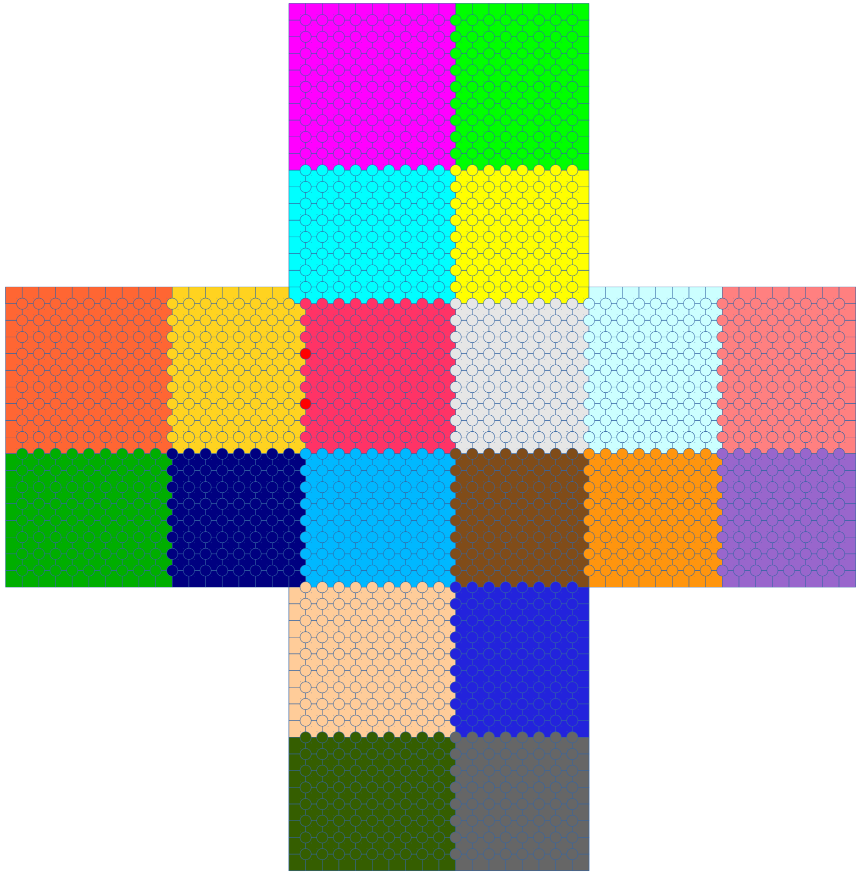
Screenshot of VERAView tool used for visualizing HDF5 file

Code Features
Parallelization

- Domain decomposition approach used to add parallel solution capabilities to CTF
- Can use up to 16 processors per assembly

Walltime of Problem 7 (~700k fluid cell model) using different numbers of processors

Number of processors	Walltime [s]	Speedup over serial
1	18565	---
56	347	53.5
193	116	160.0
457	99	187.5
776	101	183.8



Example of domain decomposition approach using 4 processors per physical assembly

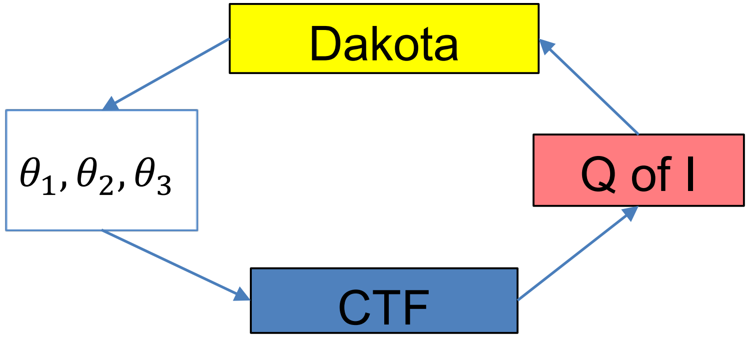
Code Features
CTFFuel

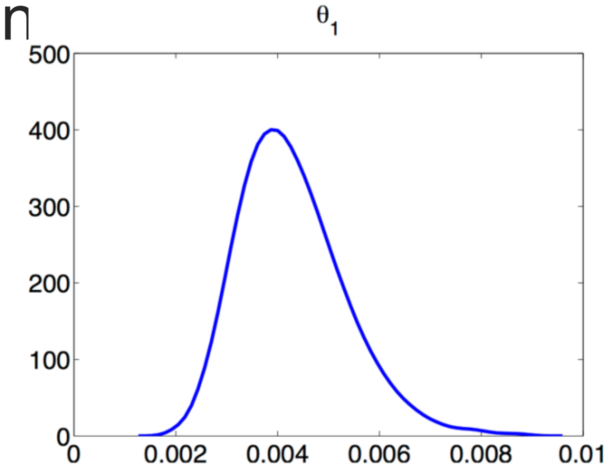
- Fuel rod modeling capability in CTF includes
  - 3D conduction
  - Temperature and burnup dependent fuel pellet thermal conductivity
  - Radial power and burnup distribution
  - Fuel pellet densification, swelling, and relocation
  - Dynamic gap conductance model, which includes:
    - Pellet and clad thermal expansion
    - Irradiation dependent clad creepdown
    - Pressure driven clad expansion
    - Composition dependent gas thermal conductivity
    - Pellet clad contact and radiative heat transfer effects
  - Benchmarked against Bison 1.5D for nominal PWR operating conditions

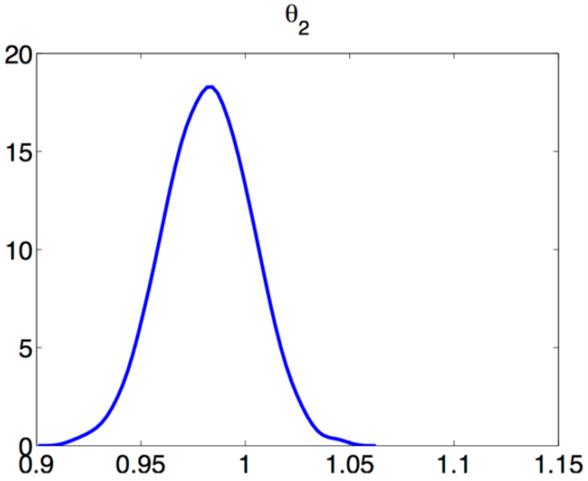
Code Features
Parameter Exposure Input File

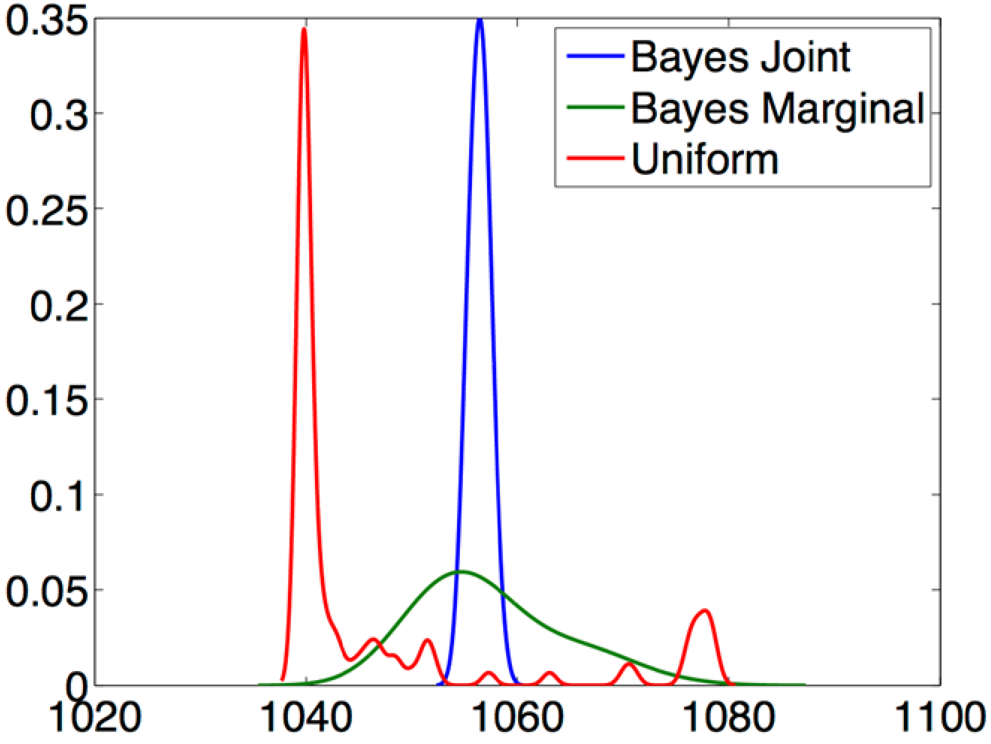
$$Nu = 0.023\,\mathrm{Re}^{0.8}\,\mathrm{Pr}^{0.4} = \theta_1\,\mathrm{Re}^{\theta_2}\,\mathrm{Pr}^{\theta_3}$$

- Exposure of many equation source terms and closure model coefficients for performing
  - Code verification
  - Sensitivity studies
  - Uncertainty quantification
- Used for UQ on heat transfer model[1]









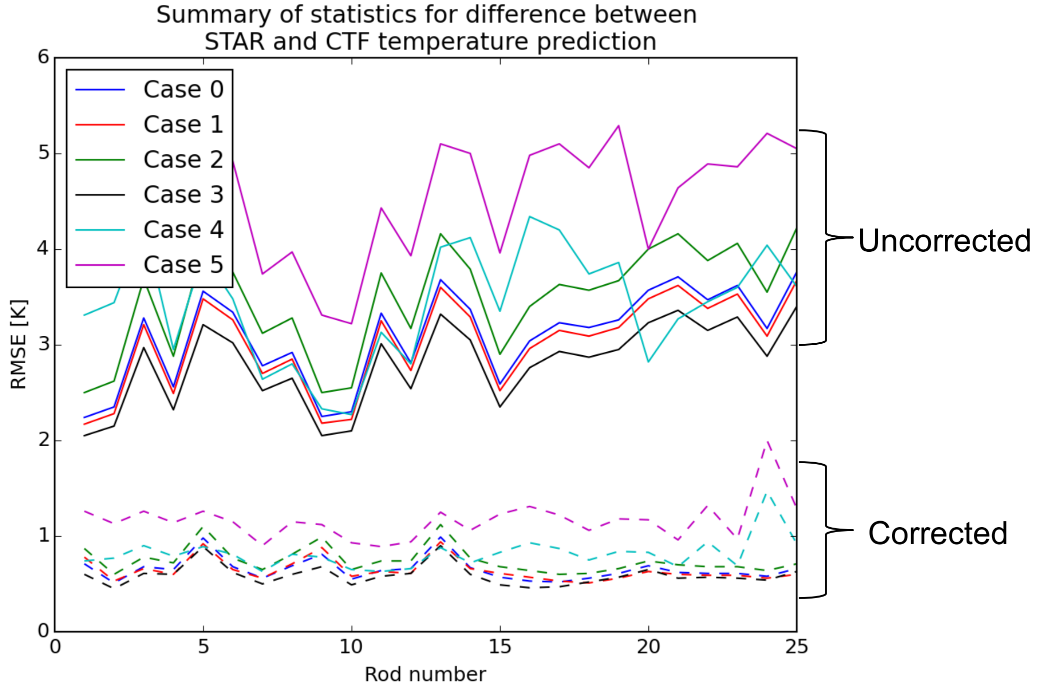
Comparison of Dittus-Boelter uncertainty

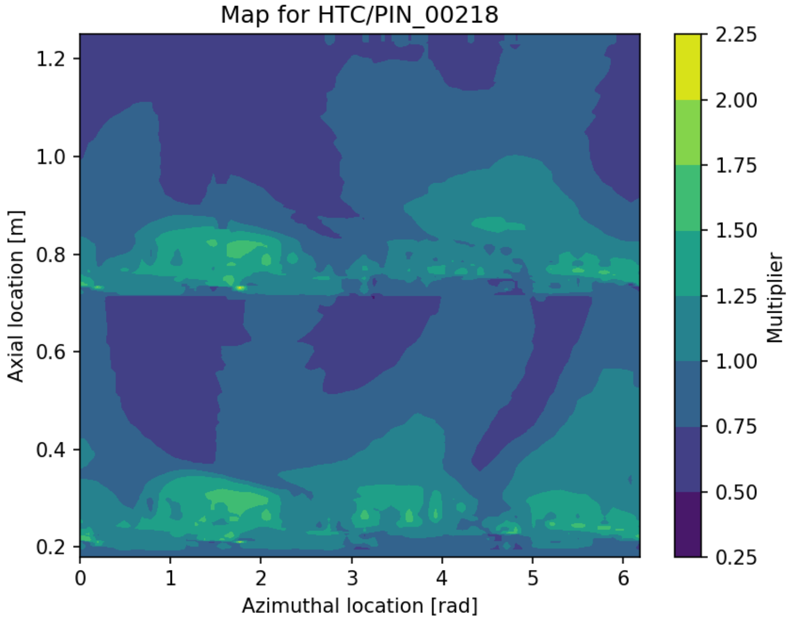
1. R. Ganhem et al., "Handbook of Uncertainty Quantification", Springer International Publishing, 2015

Code Features

Rod thermal hydraulic reconstruction (ROTHCON)

- Uses CFD data to develop grid-dependent, non-dimensional rod surface maps used by CTF
- Add capability in CTF to create a refined coupling mesh for MAMBA coupling





$$M(z - z_g, \theta) = \frac{Nu_{grid}(z - z_g, \theta)}{Nu_{bare}(z - z_g)}$$

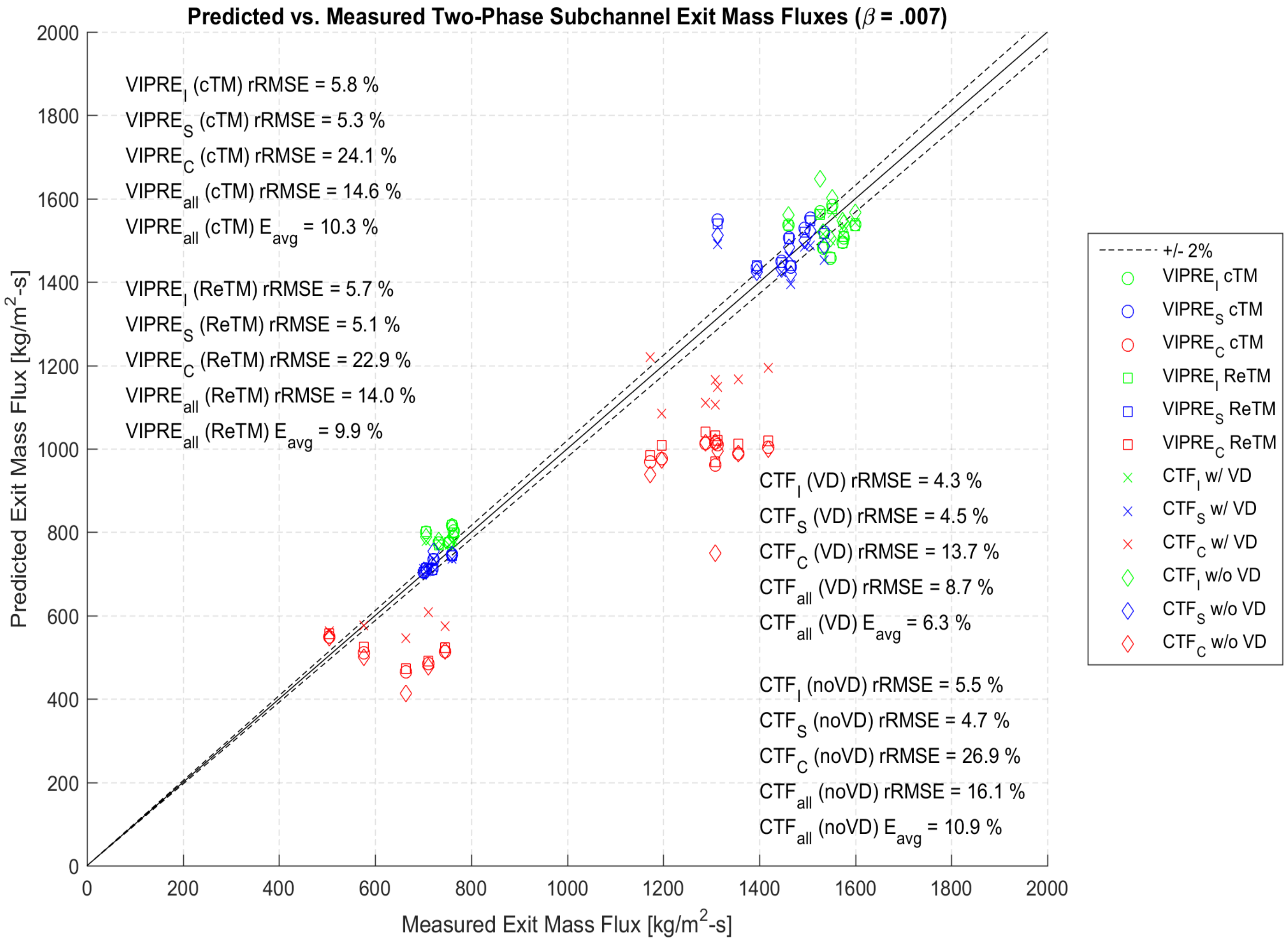
Code SQA and Testing
Code Maintenance

- Currently working on making development and maintenance program NQA-1 compliant
- Software quality assurance (SQA) plan defined by CASL SQA plan
- Version control implemented using Git
- Automated continuous build and test system using CMake/TriBITs with code requirements traceability
- Suite of regression tests aimed at LWR simulations and include validation and verification (V&V) tests
- Full suite of documentation including user, theory, V&V manuals, software requirements, and software management plan

Code SQA and Testing

Two-Phase Validation Work

- V&V plan supports the CASL challenge problems:
  - Nominal PWR
  - Nominal BWR
  - DNB
  - CIPS
  - RIA
- Single- and two-phase V&V problems
  - BFBT
  - PSBT
  - GE 3x3
  - Riso



1. X. Zhao, "Validation and Benchmarking of CTF for Two-Phase Flow using VIPRE-01", CASL Technical Report, CASL-U-2016-1184-000, 2016

Applications

Simulation of Main Steamline Break (MSLB) Transient

- MSLB of 4-loop, 193-assembly core analyzed at HZP, with and without coolant pumps using VERA[1]
- Assume most reactive RCCA stuck withdrawn
- Analysis steps:
  - Determine most limiting point in transient using RETRAN-02
  - Determine core inlet flow distribution using STAR-CCM+
  - Run steady-state simulation using VERA

B				484	484	483	483	481	480	479				C
Avg		485	484	483	483	482	481	480	479	478	477	476		
T (K)	486	485	484	483	483	482	481	479	478	477	476	476	476	
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A				486	487	487	487	487	487	486				D

Inlet temperature distribution (low-flow)

Core operating conditions

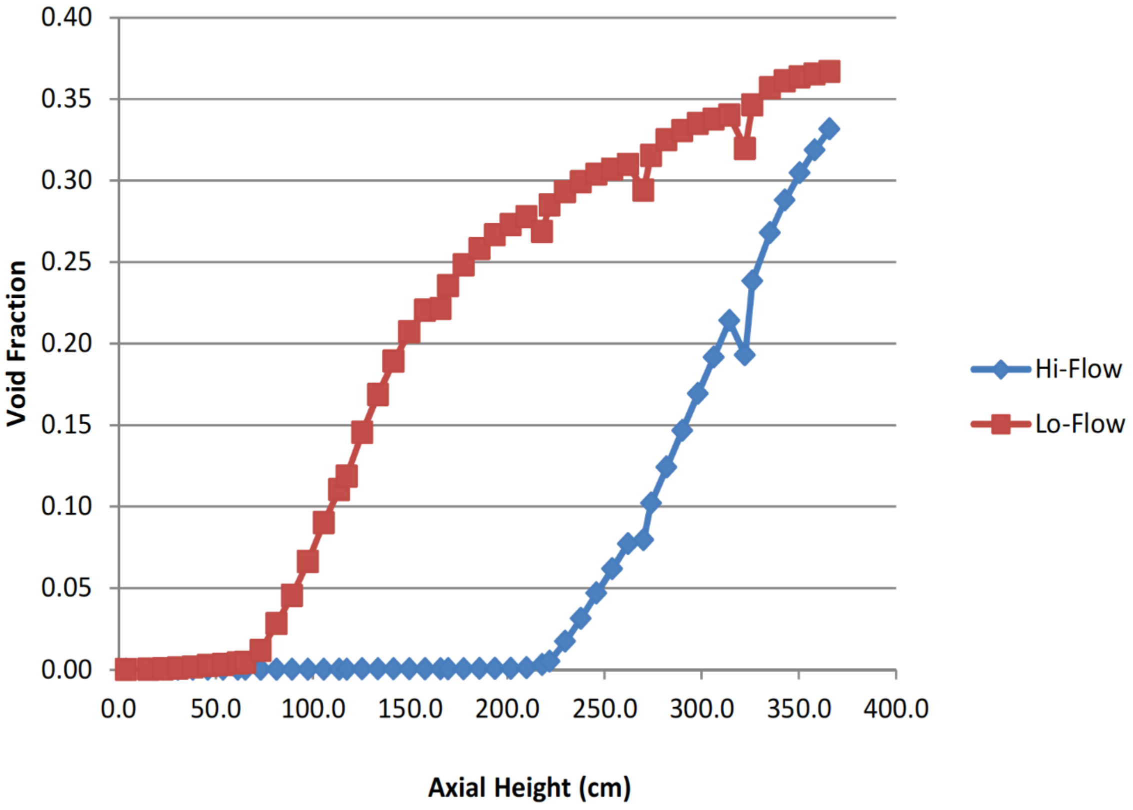
High Flow	Low Flow
22.9% of rated power	11.9% of rated power
100% of nominal flow rate	10.7% of nominal flow rate
426.3°F (219.1°C) inlet average temperature	410.6°F (210.3°C) inlet average temperature
489 psi (3.37 MPa) system pressure	853.1 psi (5.9MPa) system pressure

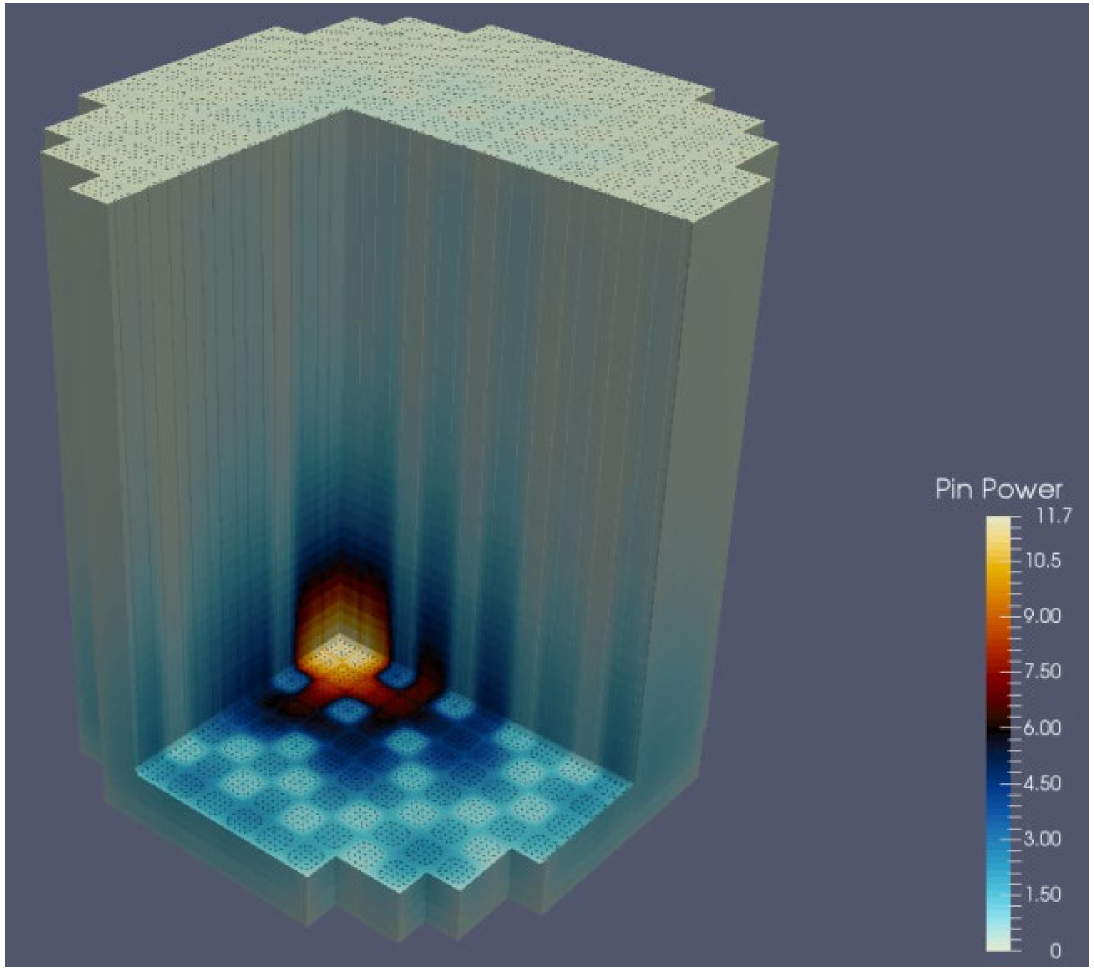
1. V. Kucukboyaci et al., "VERA-CS Modeling and Simulation of PWR Main Steam Line Break Core Response to DNB", Proceedings of the 24th International Conference on Nuclear Engineering, 2016

Applications

Simulation of Main Steamline Break (MSLB) Transient

- High-flow case more limiting
- Both high- and low-flow cases well within safety limits



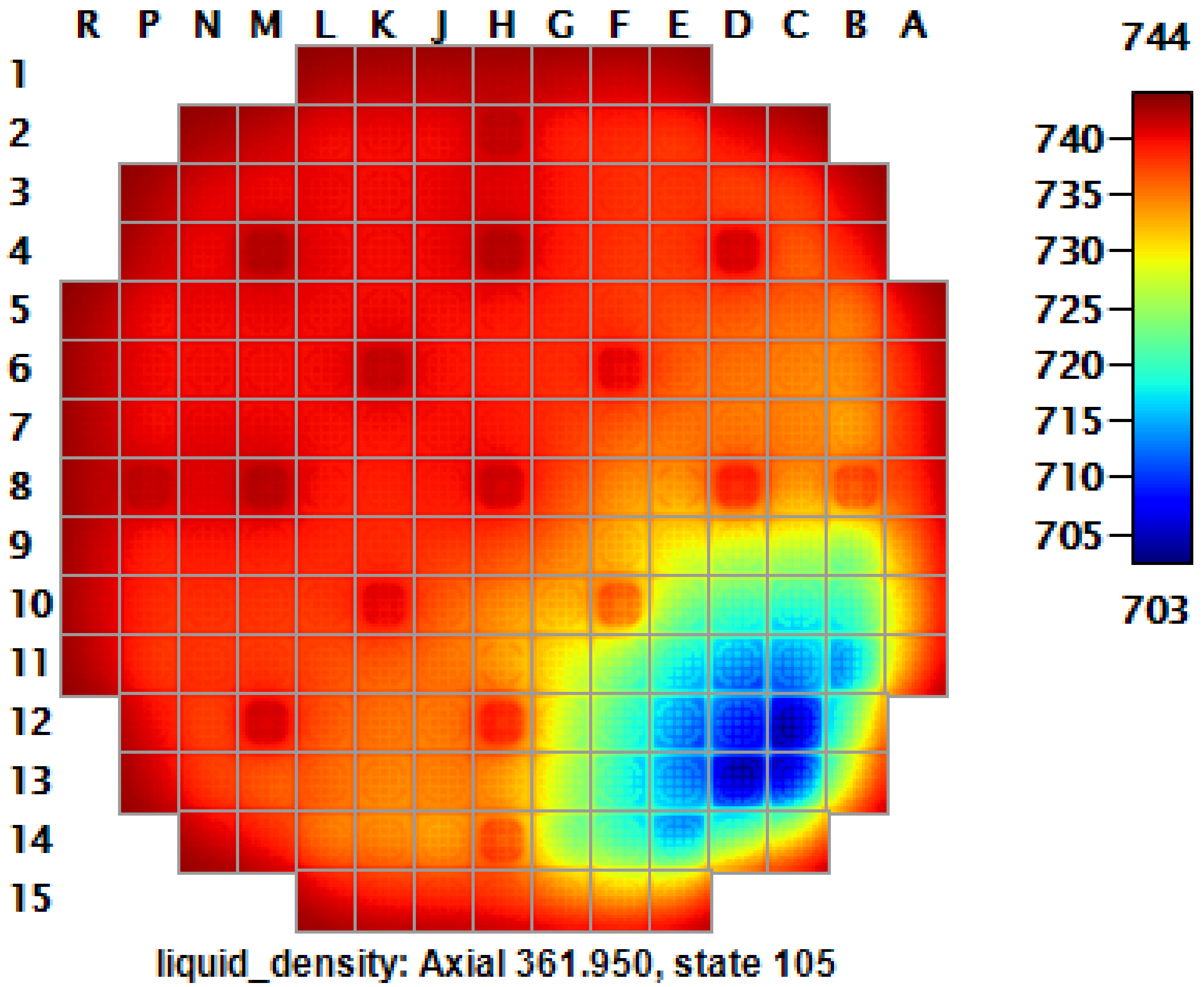


Low-flow case power distribution

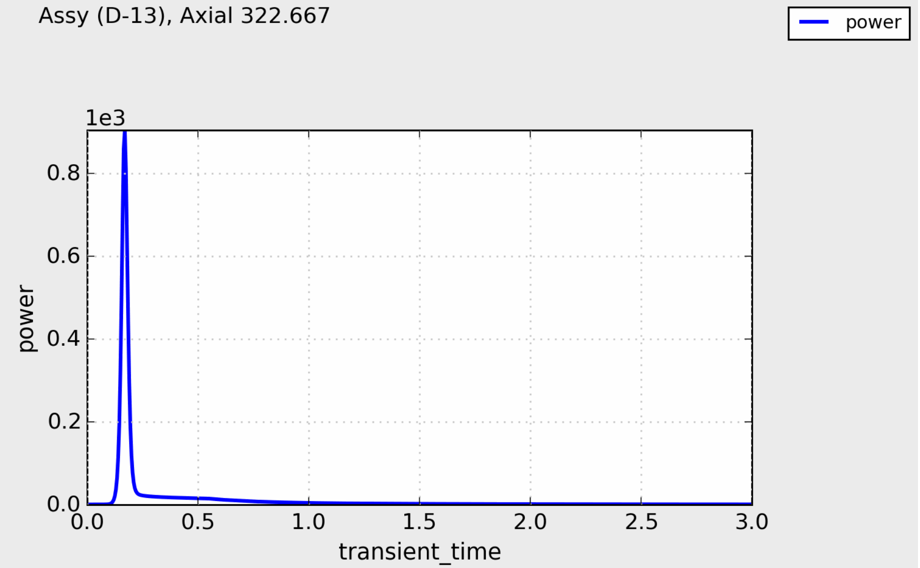
Applications

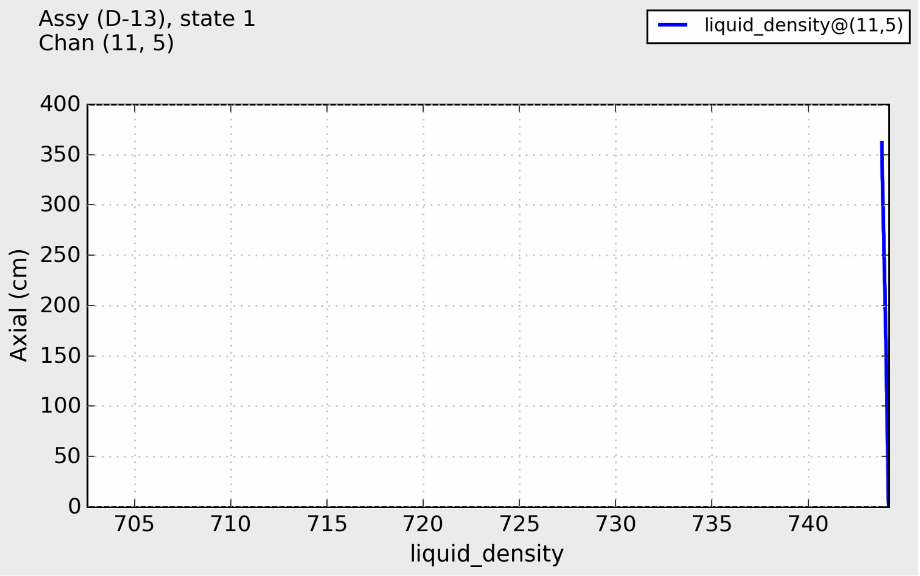
Reactivity insertion accident (RIA)

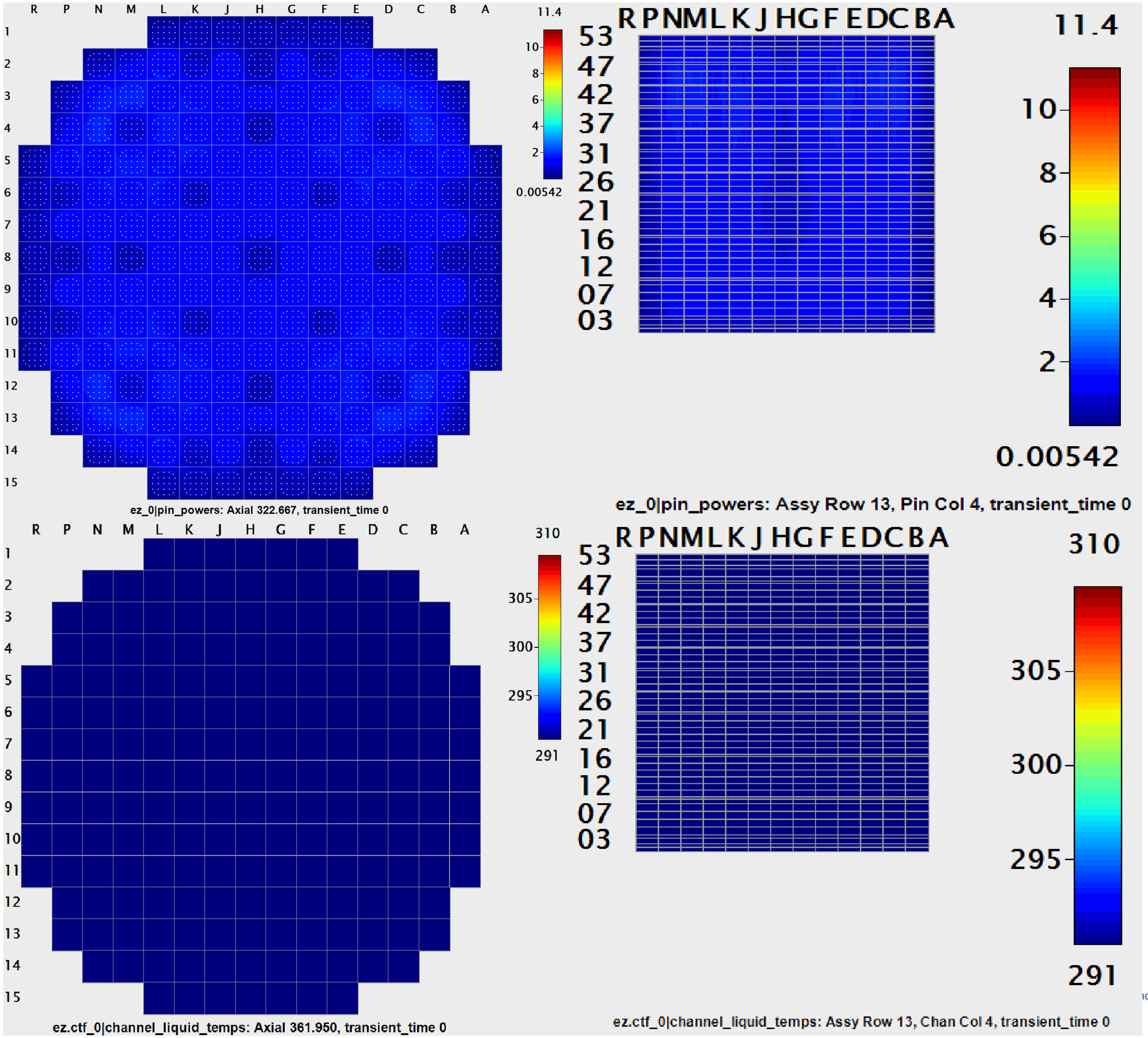
- Fully coupled neutronics/ thermal-hydraulics transient solution
- Internal simplified fuel rod model with dynamic gap
- Existing commercial Westinghouse 4-loop core design at End-of-Cycle
- Can apply conservatism on Beta and other parameters
- Initiated from HZP conditions – core power reached 904% FP with $1.5 ejected rod worth
- 6480 cores in 36 hours



Applications
RIA







Conclusion

- CTF is a thermal-hydraulic simulation tool designed for LWR analysis using the subchannel approach
- Adoption of CTF by CASL has led to a large investment in the code, resulting in numerous new features and capabilities including
  - Implementation of comprehensive SQA plan
  - Integration into VERA
  - Implementation of new closure models and user features
  - Validation and verification testing
- Code is distributed to nuclear community through CTF User Group and available to ORNL
- CTF has been used for numerous applications in and out of CASL

Questions?

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