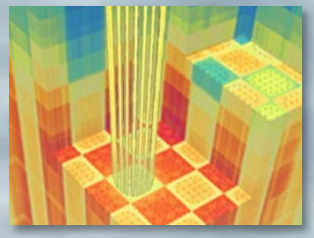
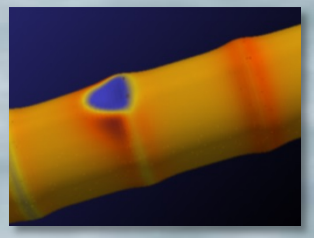
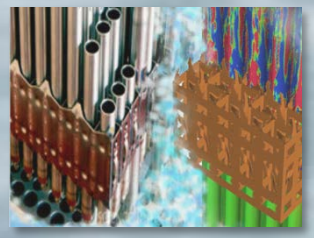
DNB Challenge Problem Progress - Steamline Break Analysis

Industry Council Meeting

April 12, 2016







The Consortium for Advanced Simulation of LWRs
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U.S. DEPARTMENT OF ENERGY

Outline

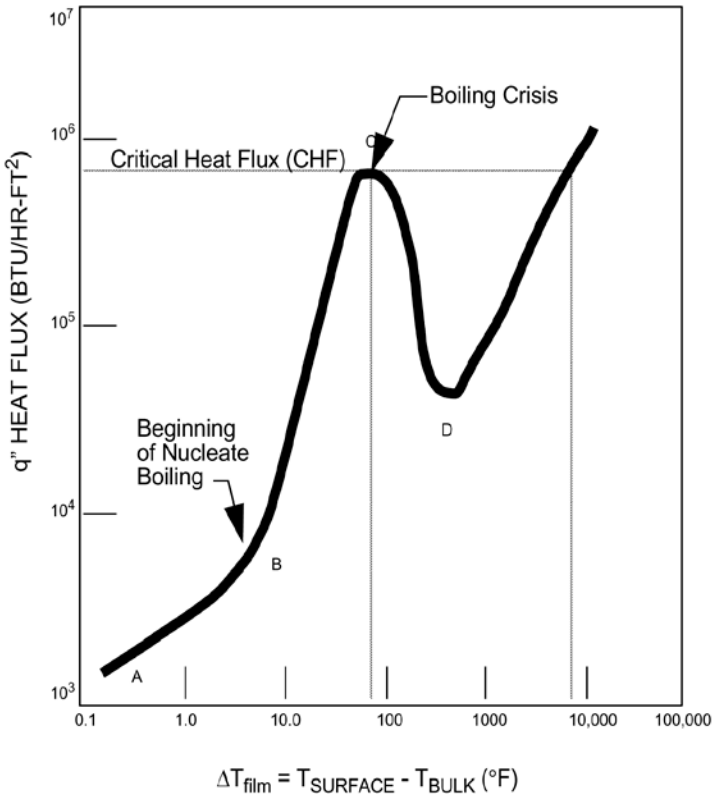
- DNB CP to Meet Industry's Needs
- PWR Steamline Break (SLB) Analysis Overview
- Ongoing FY16 Activities on SLB Analysis

Departure from Nucleate Boiling (DNB)

- DNB also referred to as Critical Heat Flux (CHF)
  - Local clad surface dryout causes dramatic reduction in heat transfer during transients
  - One of safety and regulatory acceptance criteria for PWR (DNB) and BWR (dryout)

- CASL DNB CP objectives support industry initiatives for cost reduction and safe operations
  - Fuel hardware thermal performance improvements
  - Margin quantification and effort reduction in safety analysis

Boiling Curve



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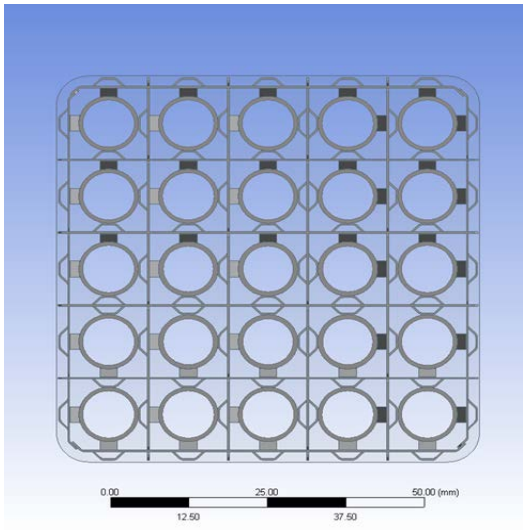
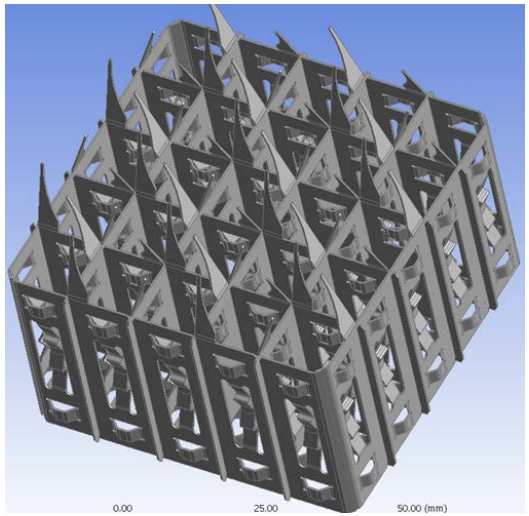
CASL Focus on DNB Modeling & Simulation (M&S) Needs for Industry

- Fuel design improvement (STAR-CCM+ CFD)
  - Higher fidelity of multi-phase M&S capabilities
  - Control and optimization of fuel cladding surface morphology

- WEC proprietary data provided to CASL partners supporting code and model development and validation
  - Turbulent mixing and DNB tests from 5x5 rod bundles containing non-mixing vane and mixing vane grid spacers
  - Detailed information and drawings on bundle geometry and grid spacer designs for CFD modeling



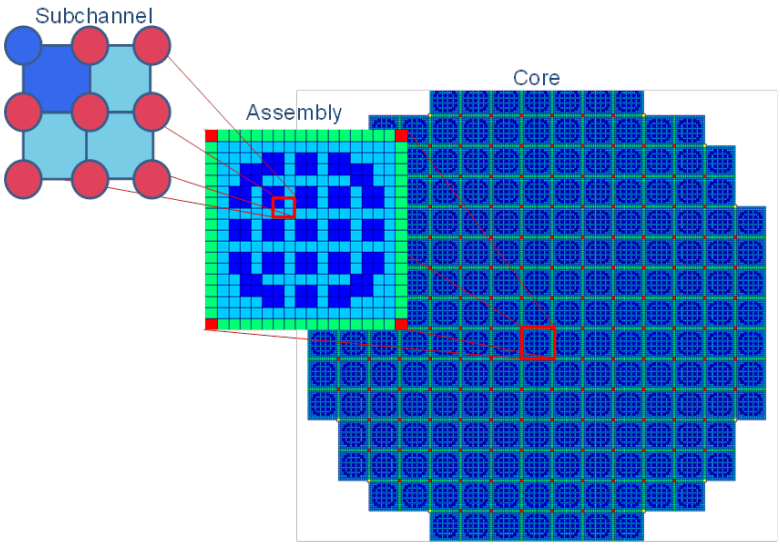


CASL Focus on DNB Modeling & Simulation (M&S) Needs for Industry (continued)

- Margin quantification in accident analysis (VERA-CS)
  - High resolution multi-scale and multi-physics M&S capabilities
  - *Coupled neutronic and subchannel T/H code system*

VERA-CS 4-Loop Core Model
- 56,288 channels
- 112,064 gaps
- 50,952 fuel rods, 4,825 GT/IT
- ~60 axial nodes

- *VERA-CS application to Hot Zero Power (HZP) main Steamline Break (SLB) case study*
  - *Quasi-steady state core response*
  - *Detailed full core pin-by-pin and subchannel modeling*



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HZP SLB Analysis Overview

- HZP SLB is a cooldown event that challenges fuel thermal limit (e.g. DNB)
  - Increased steamflow → Reduced RCS temperature and pressure → Positive reactivity insertion → Reactor core power and peaking factor increase → DNB challenge
  - Condition 4 event analyzed to meet Condition 2 acceptance criteria

- Reactor core response affected by reload fuel management
  - Location of most reactive RCCA stuck out of core
  - Reactor shutdown margin requirement

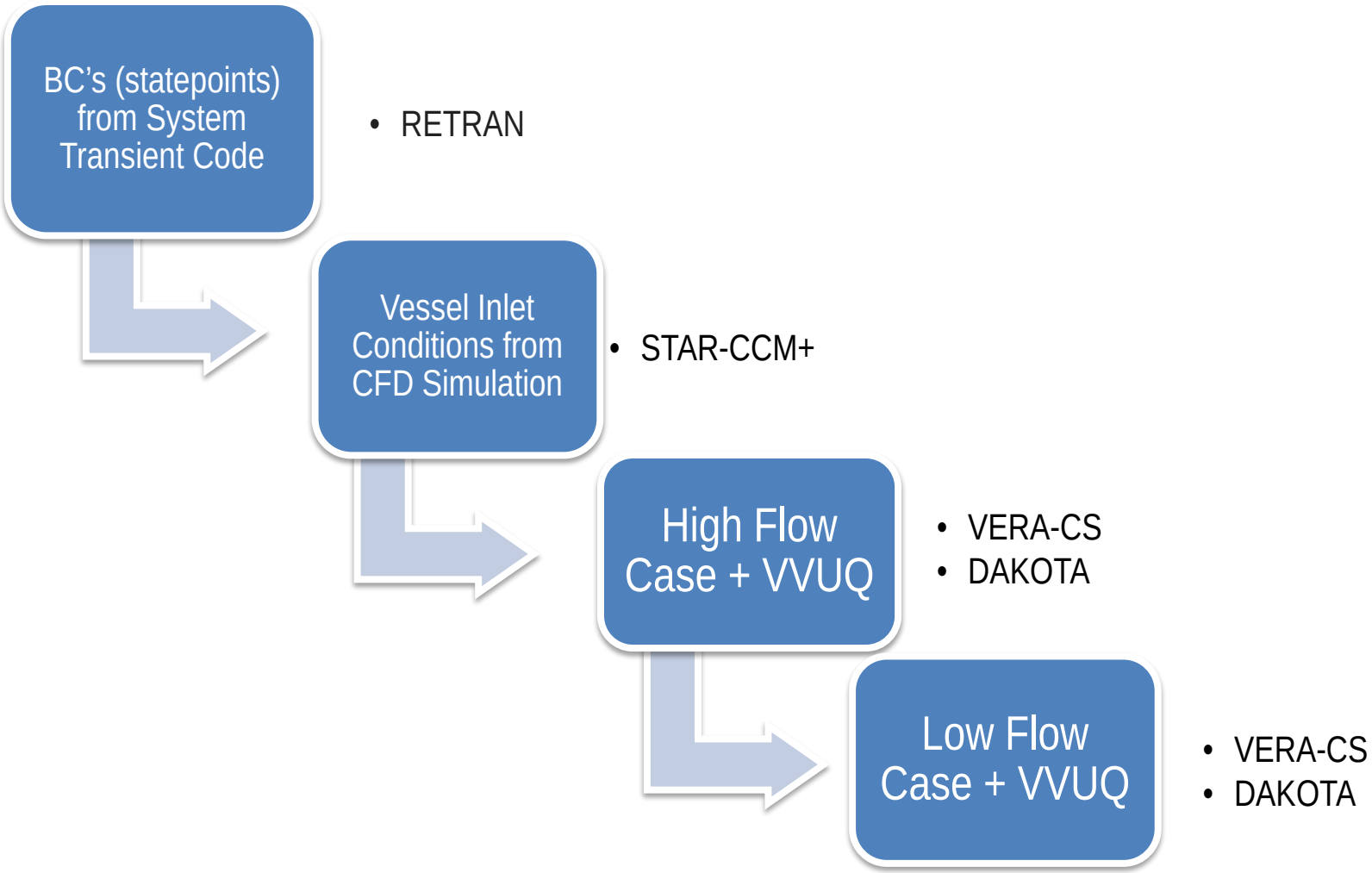
HZP SLB Analysis Overview (continued)

- HZP SLB cases considered in plant safety analysis
  - With offsite power available and RCPs in operation (high flow)
  - Without offsite power and natural circulation (low flow)

- Reactor core modeling and simulation affect determination of DNB limiting case

- VERA-CS case study based on 4-loop Cycle 1 core
  - Input of system statepoint (core boundary condition) from a system transient code RETRAN
  - Input of reactor core inlet flow and temperature distributions from STAR-CCM+ CFD vessel simulation

VERA-CS SLB Case Study – Work Flow



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HZP SLB Statepoints from System Code

Parameter	Units	High Flow Case	Low Flow Case
Transient Time	Seconds	82.75	75.50
Core Outlet Pressure	Psia	489.00	837.54
Core Heat Flux	FON	0.229	0.107
Cold Leg Temperature Loop 1 (faulted loop) Loop 2 Loop 3 Loop 4	°F	386.5 439.0 439.0 440.7	363.3 425.6 425.6 428.6
Volumetric Flow Rate Loop 1 (faulted loop) Loop 2 Loop 3 Loop 4	FON	1.005 1.002 1.002 1.002	0.103 0.101 0.101 0.099
Core Boron Concentration	ppm	0.00	0.00
Core Reactivity	%Δk/k	0.037	0.051
Core Density	gm/cc	0.841	0.815

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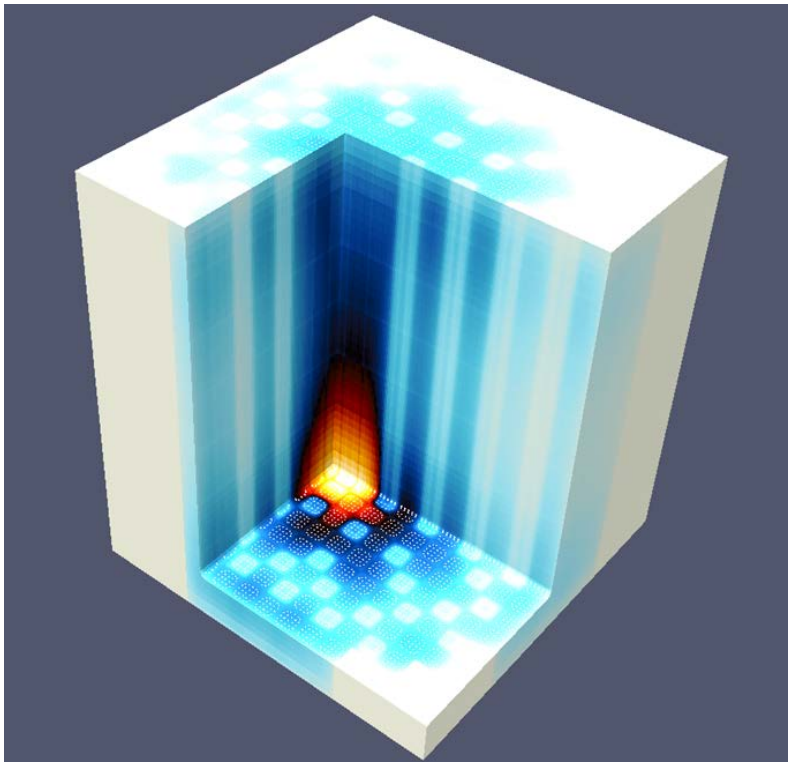
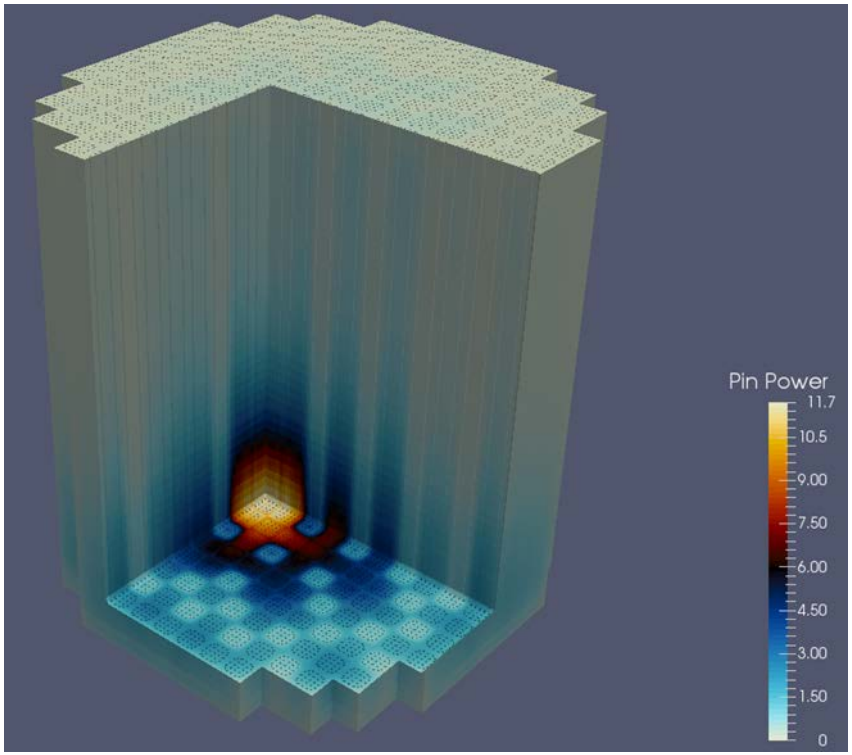
DNB CP HZP SLB Case Study



High Flow Case

VERA-CS Results from ORNL Titan Run

Low Flow Case



Core Pin Power Distributions

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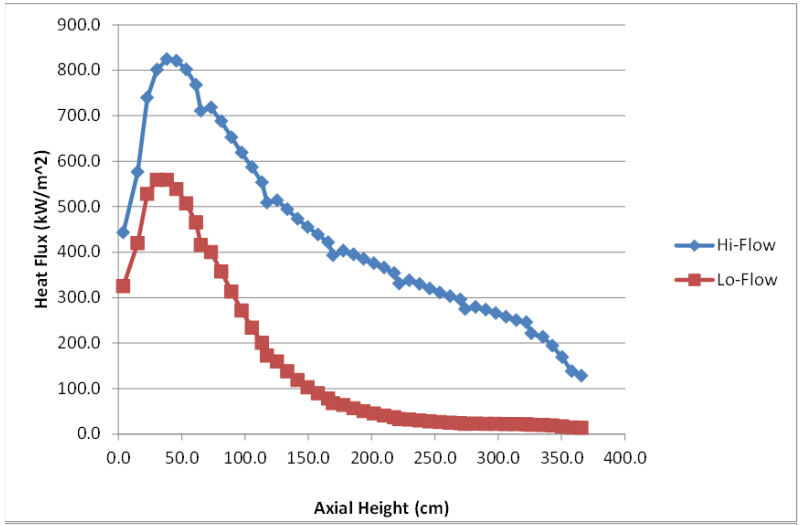
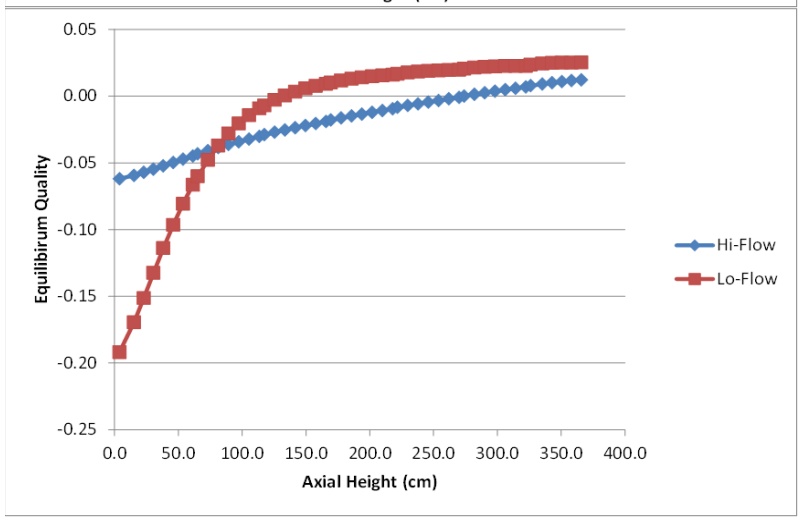
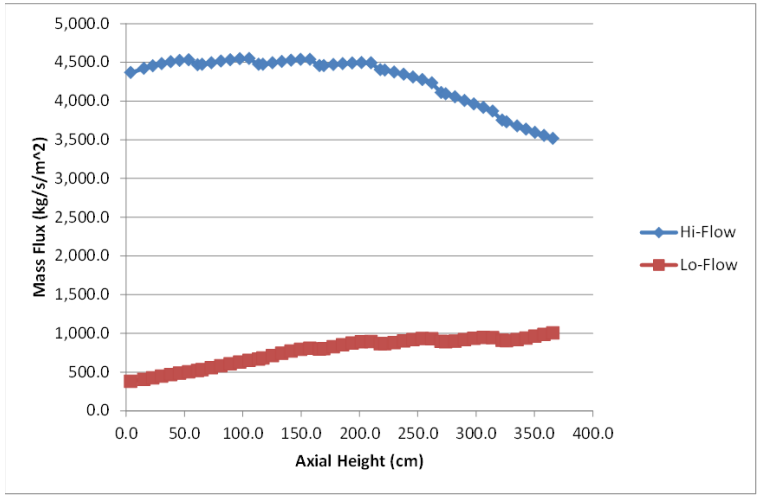
DNB CP HZP SLB Case Study



High flow case is more DNB limiting than low flow case due to higher heat flux

Parameter	High-Flow	Low-Flow
DNB Limiting Elevation (cm)	45.9	30.5
Max. Pin Linear Power (W/cm)	264.3	178.5
Heat Flux (W/m^2)	801.4	558.7
Equilibrium Quality	-0.047	-0.114
Mass Flux (kg/m^2/s)	4529.1	466.9



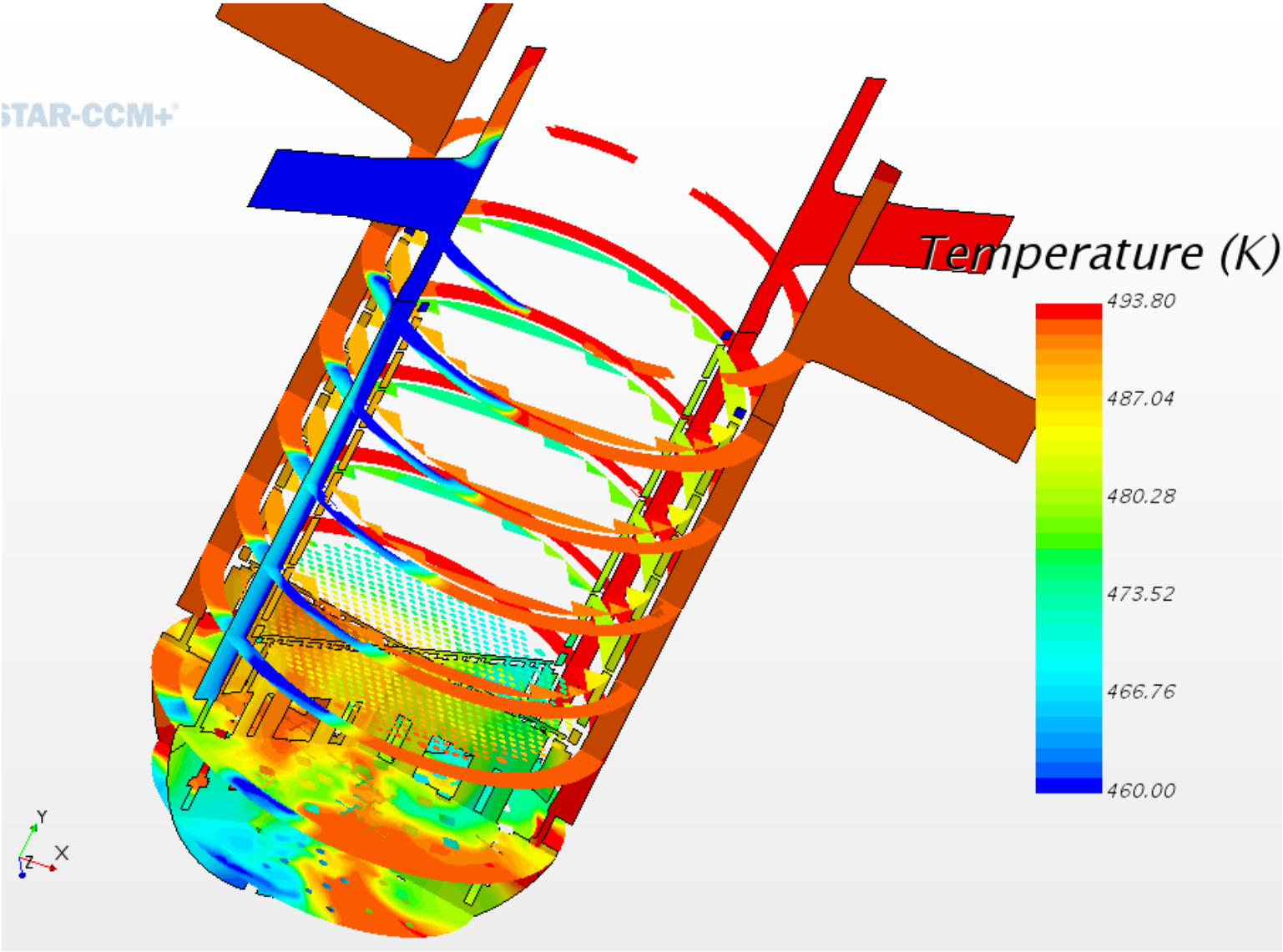


Hot Channel Parameter Comparisons

FY16 Work in Progress

- New VERA-CS runs on INL HPC platform
  - High flow case (~ 5 hours on 4408 computational cores)
- New statepoints being iterated
  - VERA-CS core response & RETRAN system transient
  - WEC ANC9 and RETRAN results for comparison
- Model and parametric sensitivity study and UQ study
  - Full core VERA-CS model and 2x2 fuel assembly model
  - To be linked with DAKOTA
- CFD simulation improvement for inlet input to VERA-CS
  - Mesh and model sensitivity study
  - Vessel inlet flow and temperature distributions

CFD Result Update – Low Flow SLB Case



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CFD Result Update – Low Flow SLB Case

Core inlet Temperature Distribution (in K)

D	T (K)			490.71	491.28	490.94	491.63	490.92	490.34	489.22			Low T	A
		488.98	489.73	487.70	489.33	489.65	489.54	490.08	486.45	482.30	483.18	487.63		
	487.79	485.53	483.05	482.86	483.54	487.26	489.05	487.36	483.51	480.88	481.54	484.55	487.21	
	482.78	478.13	477.79	479.12	481.40	486.51	488.16	485.94	483.53	483.08	485.48	486.54	486.87	
480.38	477.11	477.21	477.85	479.56	483.10	486.99	489.09	484.71	484.91	485.05	487.55	489.07	488.97	487.35
476.13	476.28	478.67	482.55	482.54	484.53	486.84	486.09	485.71	486.99	486.73	489.02	490.55	489.79	487.84
475.03	477.07	483.76	485.87	483.97	484.16	485.72	485.95	487.39	487.74	488.56	491.04	491.21	490.68	489.12
473.62	475.85	483.48	485.11	484.15	483.95	486.25	487.50	488.60	489.27	490.51	491.65	491.66	491.30	490.39
472.43	473.39	480.87	481.88	482.00	482.01	486.06	487.79	488.72	490.19	491.23	492.26	491.88	491.67	491.22
471.80	471.09	473.40	475.55	475.83	480.36	483.30	486.32	486.22	487.40	488.71	491.18	491.23	490.85	490.95
471.87	470.74	469.95	470.30	475.25	478.50	479.02	480.66	483.92	484.17	483.82	485.77	487.71	488.74	489.21
	470.37	469.60	469.68	473.10	476.15	474.51	476.19	478.01	478.82	479.52	479.72	483.63	486.29	
	469.59	469.50	469.37	470.73	472.24	472.44	473.42	474.91	473.82	475.19	475.68	476.78	483.60	
		469.67	470.14	471.08	471.19	471.38	472.31	472.78	472.77	472.85	473.92	479.26		
C				471.68	471.93	471.52	471.73	471.87	472.15	472.96				B

D				1.04	1.05	0.99	1.16	1.02	1.02	0.96			Low T	A
		1.14	1.05	1.07	1.00	1.08	0.95	1.07	0.95	0.94	0.96	0.96		
	1.13	1.00	1.01	0.95	0.99	0.98	1.09	0.99	0.87	0.99	0.96	0.97	0.93	
	1.03	0.97	0.96	0.93	0.93	1.04	1.00	1.05	0.95	0.95	1.03	1.04	0.96	
1.07	0.99	0.98	0.98	0.96	0.94	0.96	1.20	0.95	0.93	0.98	1.10	0.99	0.98	0.93
1.05	0.98	0.99	1.01	0.95	1.02	1.07	0.91	1.00	1.00	1.11	1.00	0.97	1.02	0.90
1.03	0.97	1.03	1.16	0.99	1.02	1.00	1.00	0.90	1.24	0.94	1.05	1.05	0.94	0.91
1.04	0.96	1.03	1.04	1.13	0.90	1.17	1.07	0.92	0.96	1.20	0.98	0.94	1.00	0.92
1.02	0.98	1.06	1.16	0.99	0.95	1.02	1.17	1.01	1.16	0.99	1.12	1.00	1.00	0.94
1.06	1.01	0.95	0.97	1.02	0.96	0.96	0.92	0.98	1.02	1.02	1.00	1.11	0.95	0.93
1.01	1.03	0.97	0.97	1.01	1.00	1.02	1.00	1.04	0.96	0.98	0.94	1.00	1.10	0.90
	1.01	0.98	0.98	0.99	1.02	0.99	1.01	0.97	0.98	0.94	0.96	1.01	0.97	
	1.08	0.99	1.00	1.01	0.99	0.98	0.99	0.97	0.98	0.96	0.95	0.94	0.88	
		1.04	0.98	0.99	0.98	0.99	0.99	1.05	0.99	1.00	0.95	0.93		
C				0.99	1.01	0.95	0.96	0.97	0.97	0.91				B

Core Inlet Mass Flow Distribution (Normalized)

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Initial Sensitivity Study – High Flow Case

Parameter	Original Statepoint	New Statepoint	High Hgap	No Void Drift
DNB Correlation	W3	W3	W3	W3
Max Pin Linear Power (W/cm)	242.0	254.2	294.3	254.2
k-eff	0.9468	0.9461	0.9472	0.9461
Maximum Outer Clad Surface Temp (C)	243.9	247.2	246.8	247.2
Maximum Center-Line Fuel Temp (C)	955.9	1010.7	882.0	1010.7
MDNBR	Base	-3%	-16%	-3%
CHF (W/m^2)	4660958	4838274.5	4813860.4	4838274.9
Heat Flux (W/m^2)	756977	807318.9	932940.2	807316.0
Eq. Quality	-0.054	-0.062	-0.06	-0.062
Mass Flux ($kg/m^2/s$)	6064.9	6238.3	6236.5	6238.3
Computational Cores	4408	4408	4408	4408
Wall Clock Time	05:44	05:12	05:47	06:33

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Summary

- CASL addresses industry's need through development and application of advanced VERA modeling and simulation capabilities to DNB Challenge Problem
  - Single-phase and multi-phase CFD
  - VERA-CS coupled neutronic and subchannel T/H code system
  - DAKOTA for VVUQ
- HZP SLB DNB limiting case study helps industry to quantify margin and reduce cost for reload fuel management and regulatory compliance
  - Current plant analysis of record is conservative and margins are available for improvement
  - FY16 work results to be documented in a CASL report by September 2016

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