CIPS Simulation Progress and Path Forward

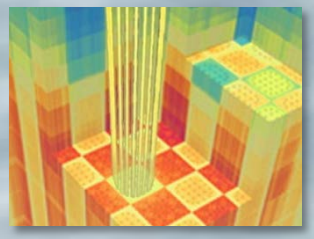
CASL Industry Council Meeting

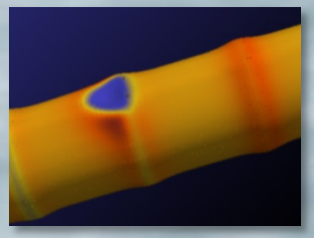
April 12-13, 2016

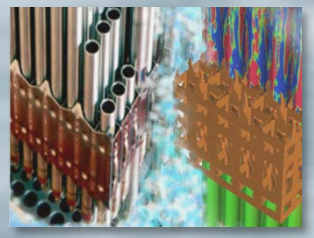
Greenville, SC

Brian Kendrick

Los Alamos National Laboratory







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

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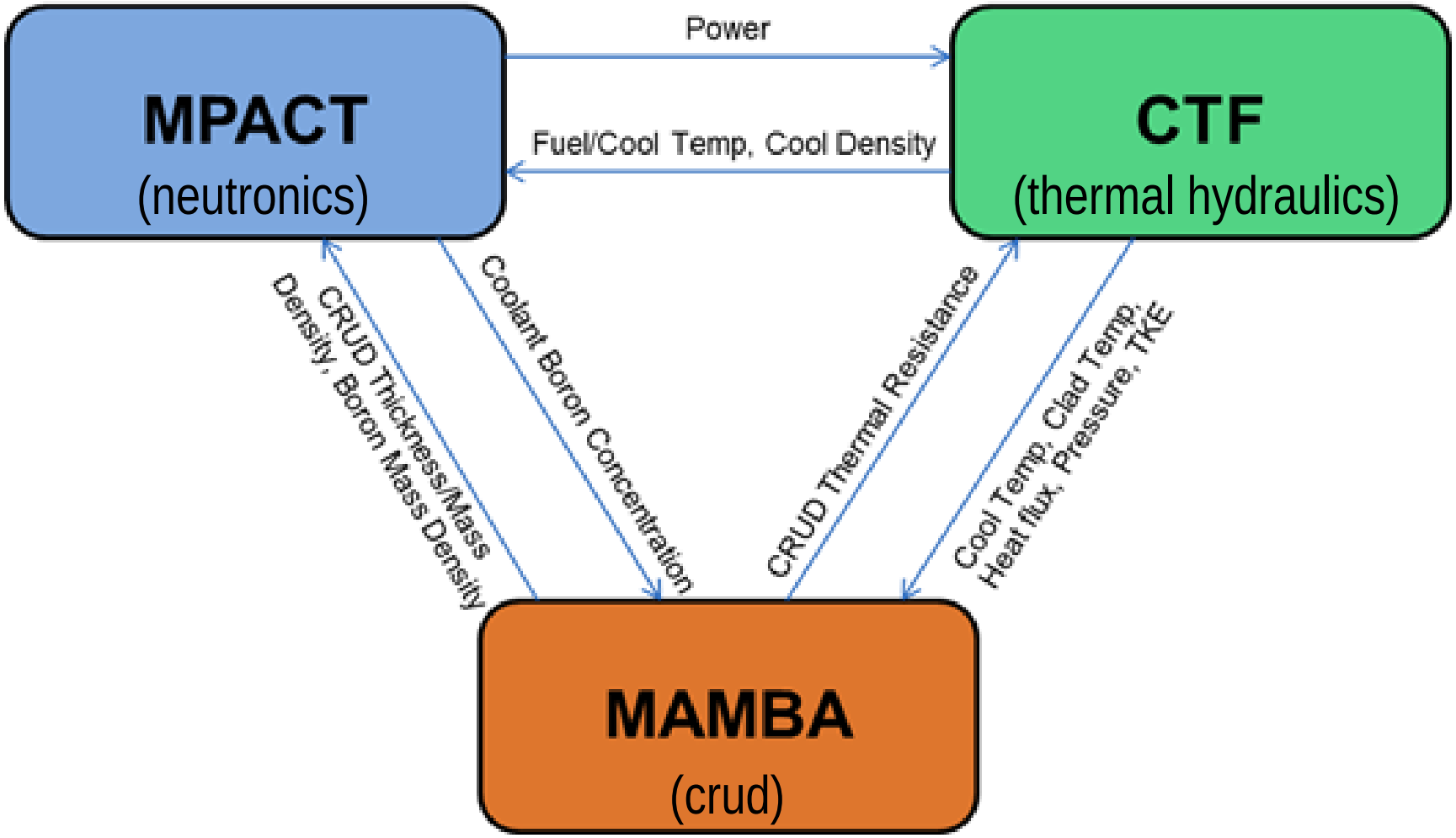
U.S. DEPARTMENT OF ENERGY

Crud Risk Analysis

- Since the occurrences of severe CIPS in the 1980's/1990's the industry has developed tools to predict the risk of CIPS occurring for a given reload design and core loading pattern (Westinghouse BOB code which became the EPRI BOA code)
- If CIPS risk appears excessive, then steps can be taken to reduce the risk of thick crud deposits and boron deposition in the crud that can lead to CIPS or CILC
- High risk may require altering the proposed core loading pattern to decrease risk
  - Add more fuel assemblies
  - Reduce peak assembly powers, increase neutron leakage
  - Initiate Ultrasonic Fuel Cleaning to remove crud from fuel
- All of these approaches can increase the operating costs of operations for nuclear plants
- Improved, more accurate methods, such as those being developed by CASL to simulate crud deposition and it's effects, can help to avoid the cost increases that are implemented to reduce the risk of crud deposition (CIPS/CILC)

CASL multi-physics tools for crud modeling to assess/mitigate risk for CIPS/CILC



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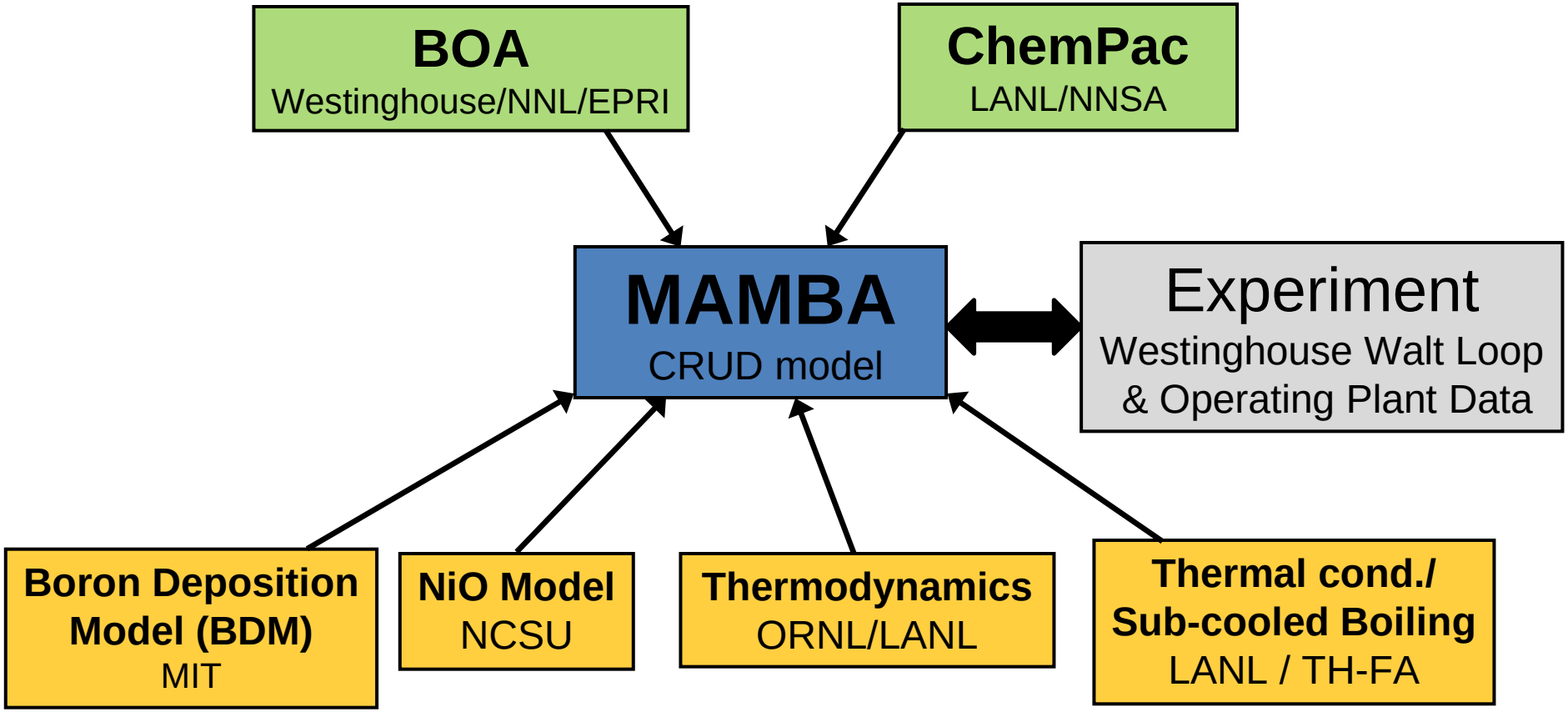
MAMBA crud modeling development framework within CASL



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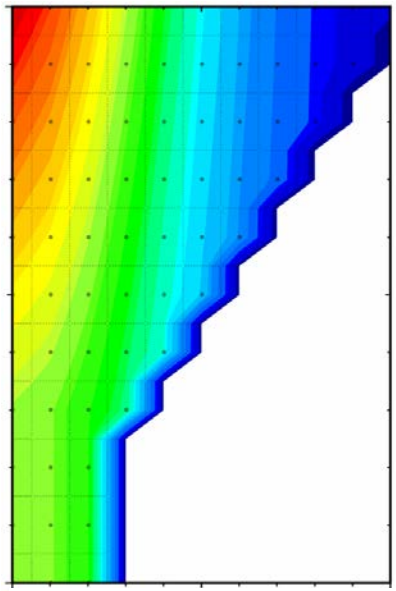
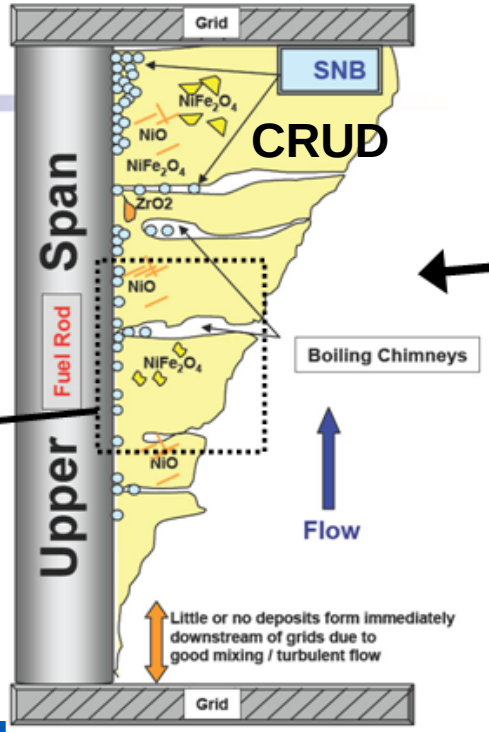
MAMBA is a high-resolution 3D crud simulation code

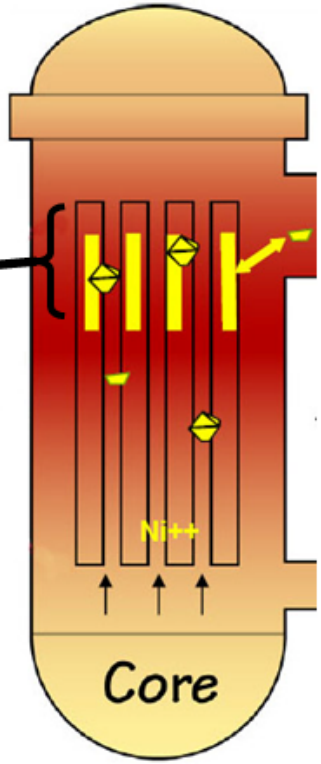
MAMBA 2D crud profile



1 – 400 cm

50 – 150 microns





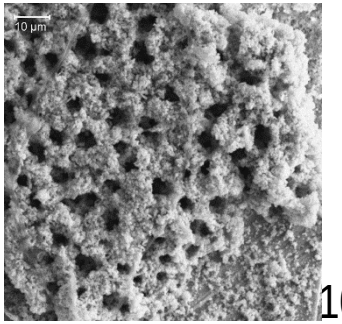
CRUD
(Chalk River Unidentified Deposit)

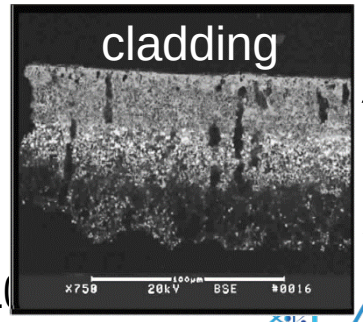
Industrial relevant issues:

1) Crud Induced Power Shift (**CIPS**)
2) Crud Induced Localized Corrosion (**CILC**)

CRUD

top view

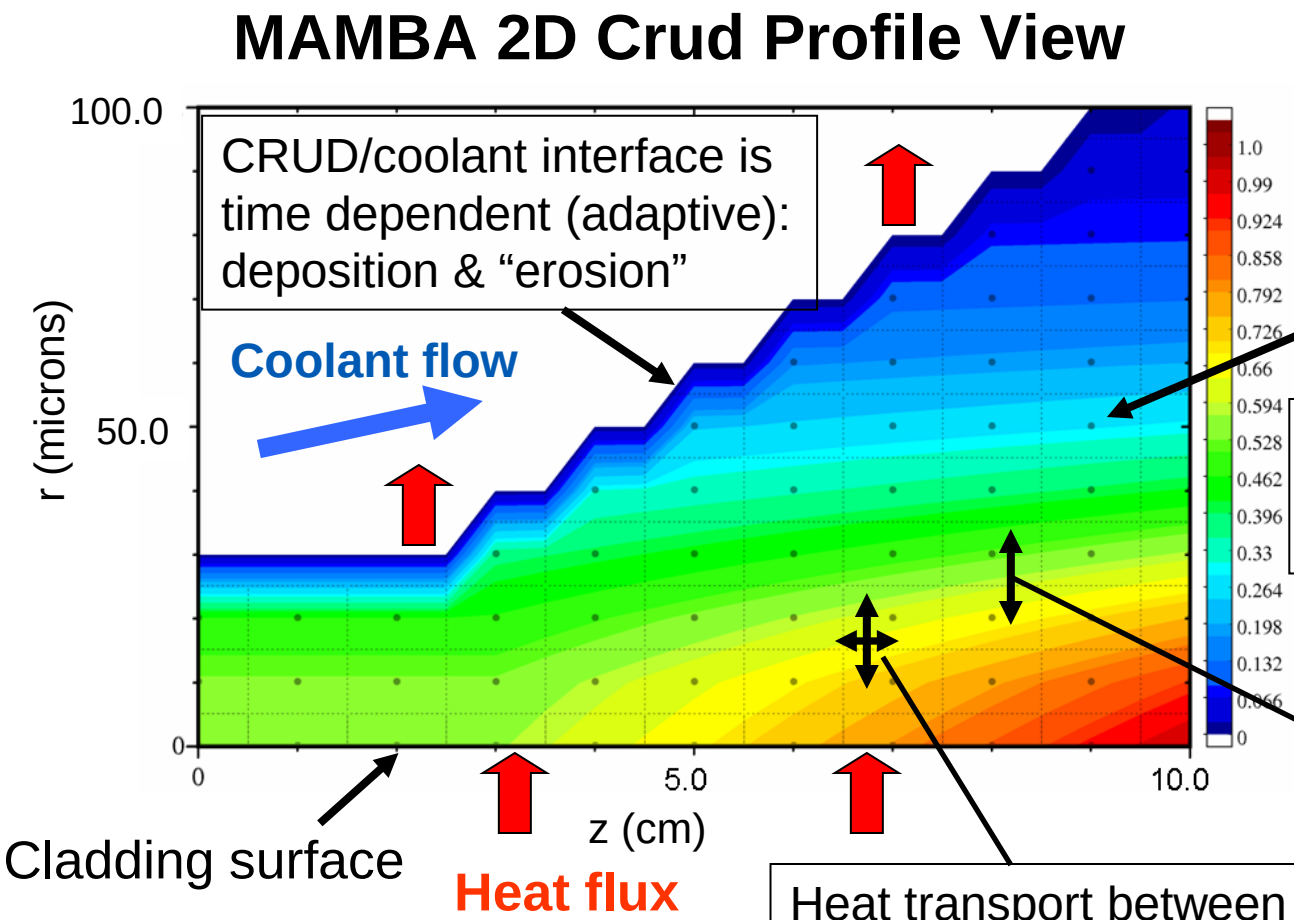




side view

80 microns

Modeling CRUD is a coupled multi-scale and multi-physics problem



Colored contours: normalized boron concentration

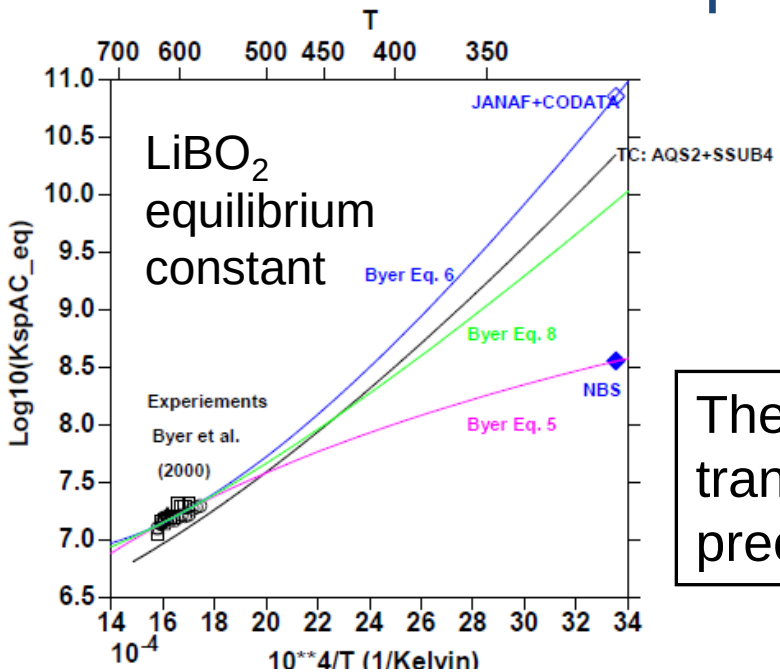
Compute node and volume element

Thermodynamics and chemical kinetics computed at each node and time step

Boiling induced convective & diffusive transport between nodes and coolant

Heat transport between nodes:
3D non-linear, iterative, numerical solution
at each time step, with local "sinks" due to boiling

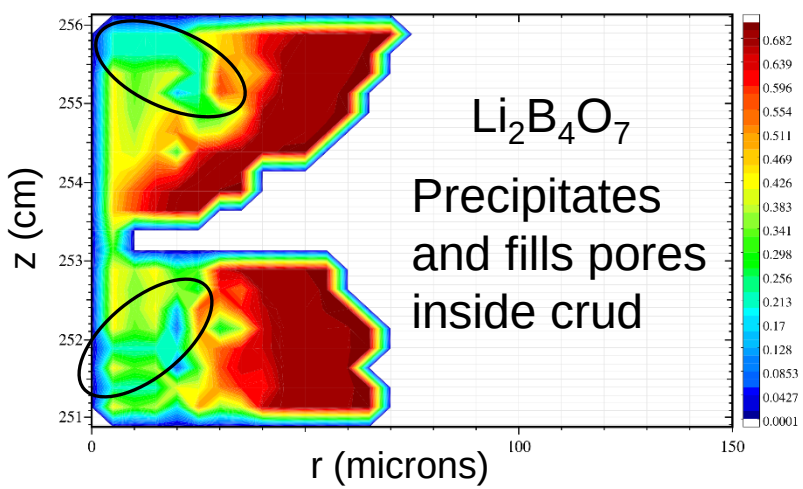
Fundamental DFT-Based Free Energies and Thermodynamic Correlations Have Been Incorporated into MAMBA

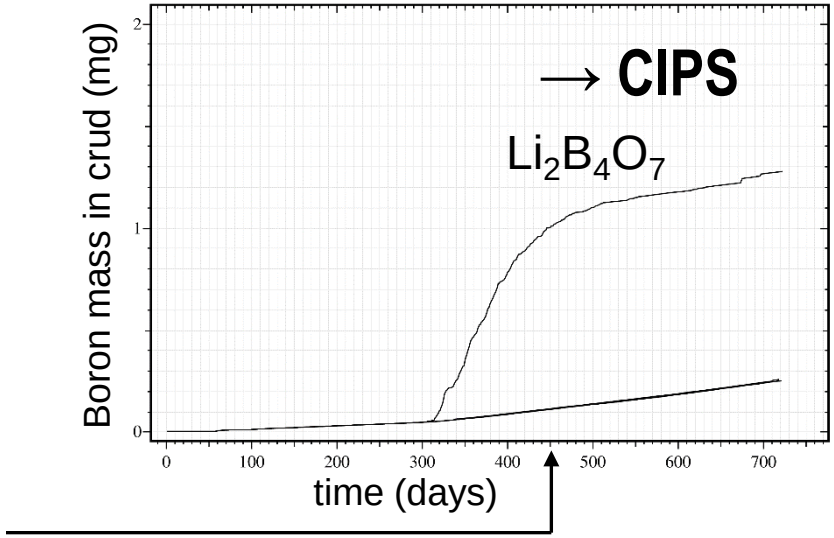


Solubility correlations also developed for $Li_2B_4O_7$ and Ni_2FeBO_5 (bonaccordite)

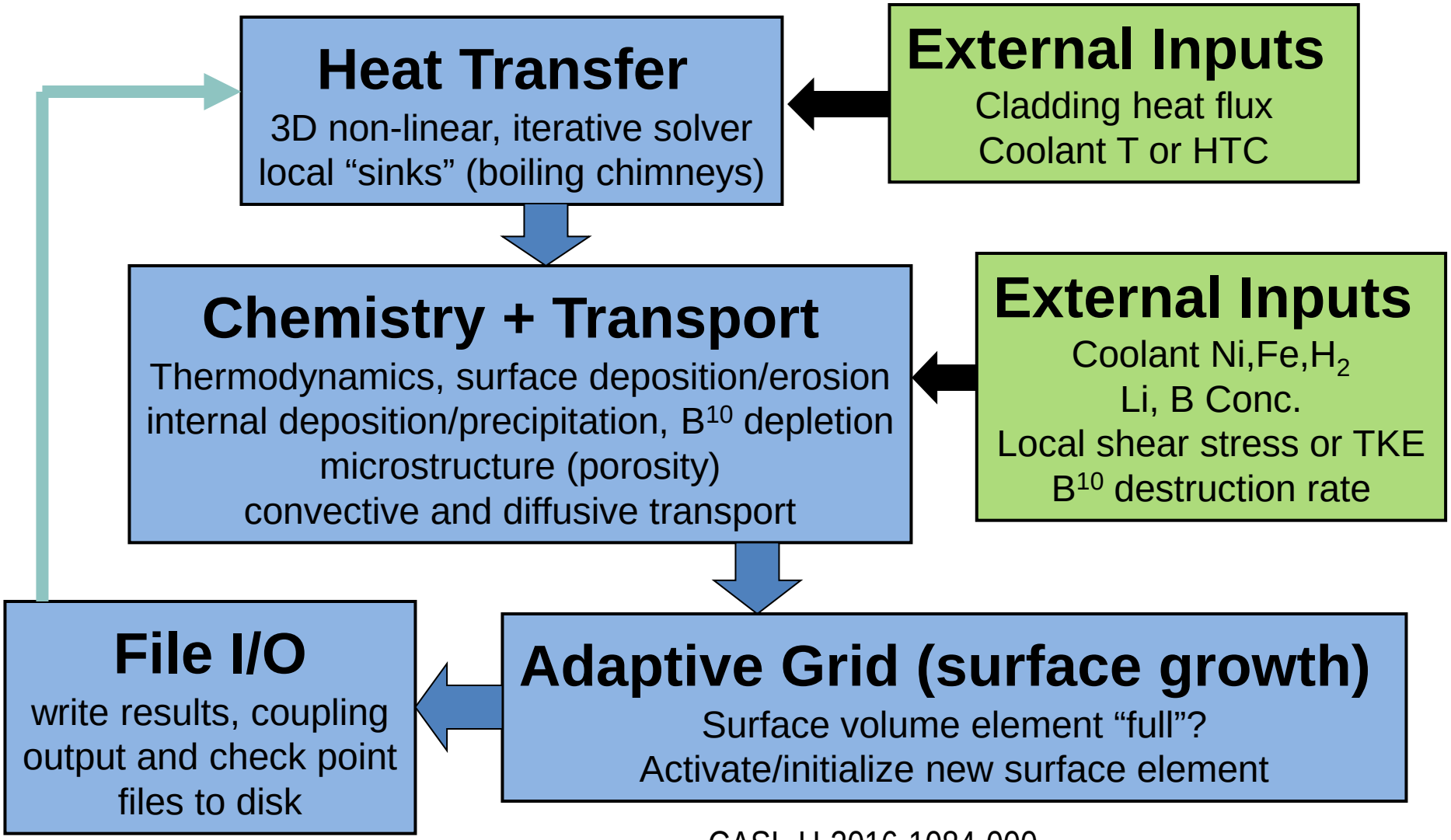
Thermodynamic correlations + MAMBA transport / boiling models determine precipitation threshold and boron uptake

Crud porosity at 450 days





The physics and chemistry of CRUD: MAMBA flow diagram



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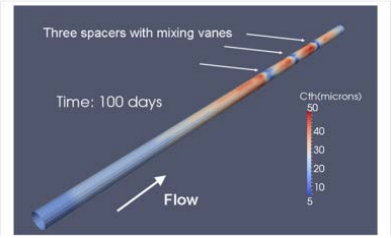
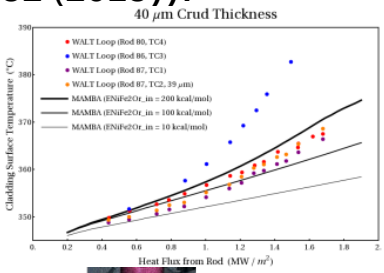
MAMBA Development, Applications, and Validation (Highlights)

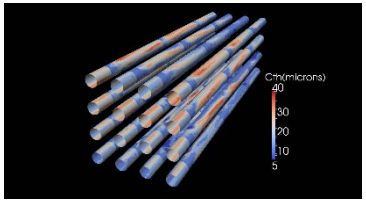
- 2D MAMBA v1.0 source code released to CASL (12/ 7/11)
- 3D MAMBA v2.0 source code released to CASL (2/28/12)
- 1D MAMBA v3.0 source code released to CASL (2/2/15)



- Coupled MAMBA / STAR-CCM$^+$ / DeCART initial demonstration simulation for a 3D single pin cell geometry (CASL DOE reportable L1, 2012, Annals of Nuclear Energy **85**, 1152 (2015)).

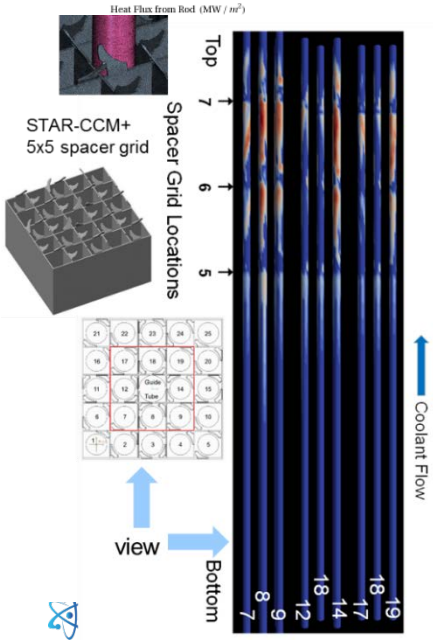


- Initial Validation and Benchmark Study of 3D MAMBA v2.0 against the Walt Loop Experiment and BOA v3.0 Lead to improved boiling models in industry's BOA v3.1 code (CASL milestone report 2012).



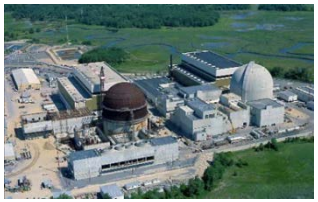
- Coupled MAMBA/STAR-CCM$^+$/DeCART simulations for 4x4 subassembly (CASL milestone report 2013).

- Coupled MAMBA/STAR-CCM$^+$/ANC simulations for 5x5 subassembly for Seabrook Unit 1 cycle 5 (CASL L2 report 2014, Nuclear Engineering & Design **299**, 95 (2016)).



- Coupled MAMBA/MPACT/CTF quarter core CIPS simulation Watts Bar Unit 1 cycle 7 (CASL DOE reportable L1, 2015)

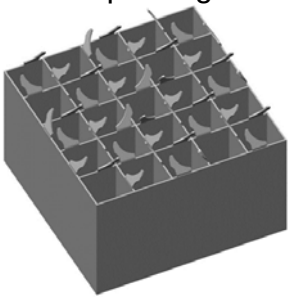
MAMBA has been applied to operating PWR coupled with STAR-CCM+

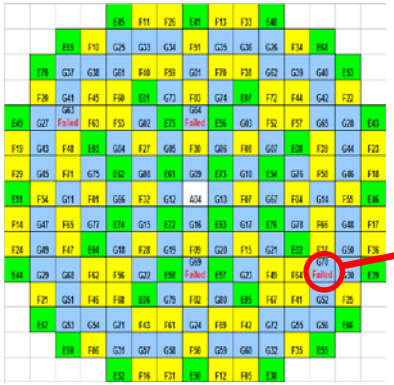


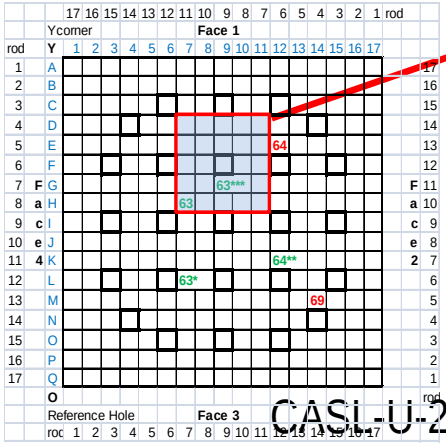
Seabrook Unit 1 Cycle 5

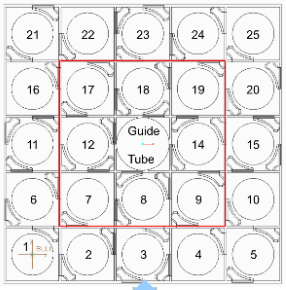
- 5-rod by 5-rod array for which qualitative and quantitative plant data is available was selected for analysis
- First high-fidelity, two-way coupled CFD/CRUD simulation of an industrial relevant plant cycle
- Input power provided by industry simulations (ANC)
- Showed that <u>both</u> axial and azimuthal thermal hydrauli effects dramatically affect CRUD deposition patterns
- Axial and azimuthal CRUD deposition patterns were consistent with plant data

STAR-CCM+
5x5 spacer grid

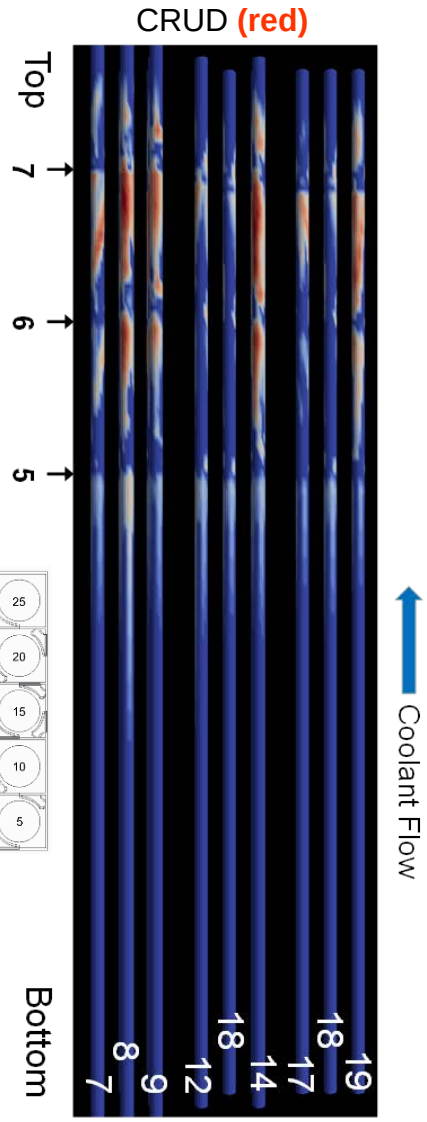








side view



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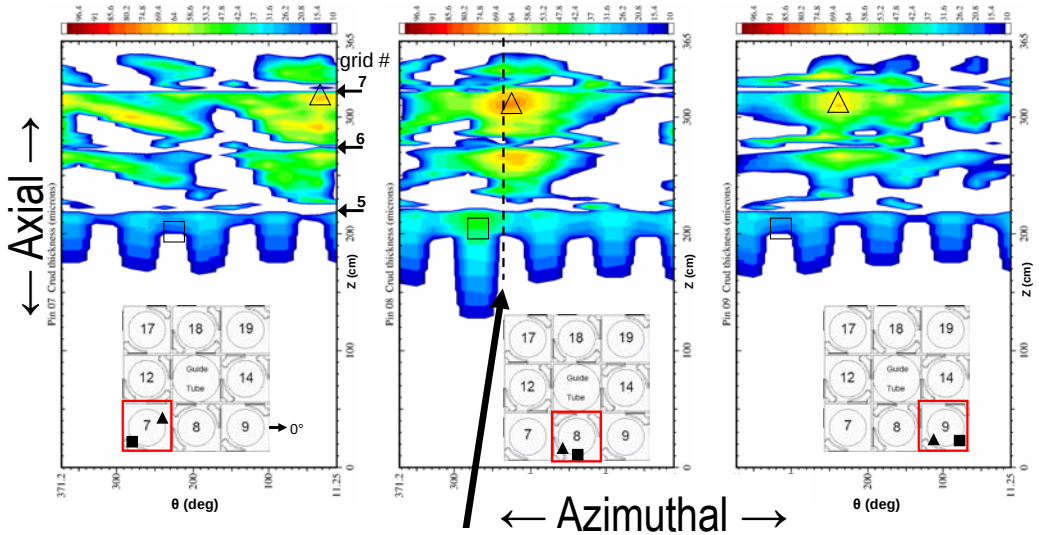
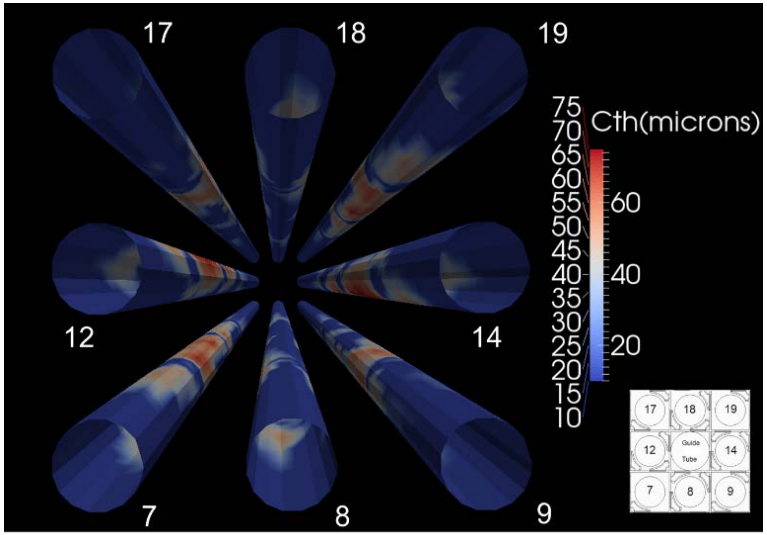
See Nuclear Engineering & Design 299, 95 (2016)

MAMBA Computed CRUD distributions for Seabrook 5x5 subassembly

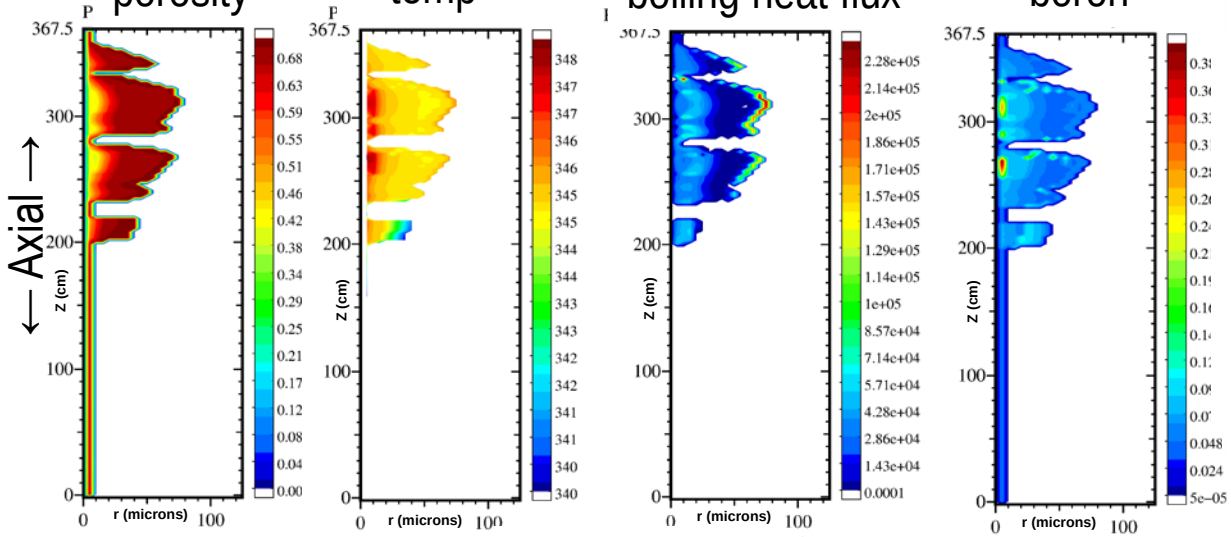
Pin #7 Pin #8 Pin #9



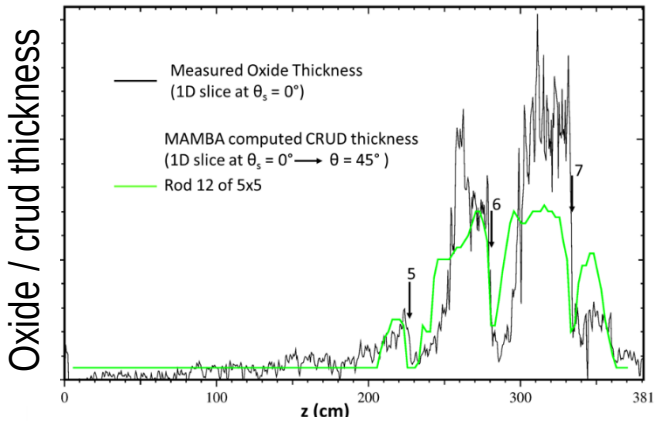
CRUD (red) 3D Top view



porosity temp boiling heat flux boron



Measured Oxide Thickness for FA G63 Rod G09



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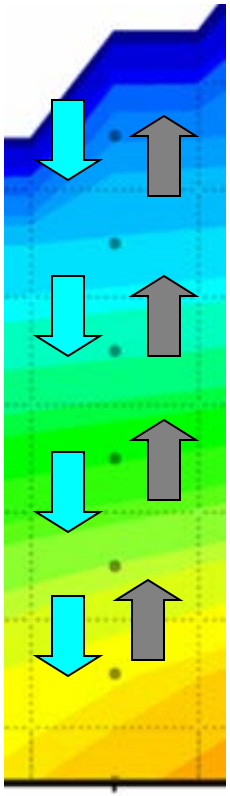
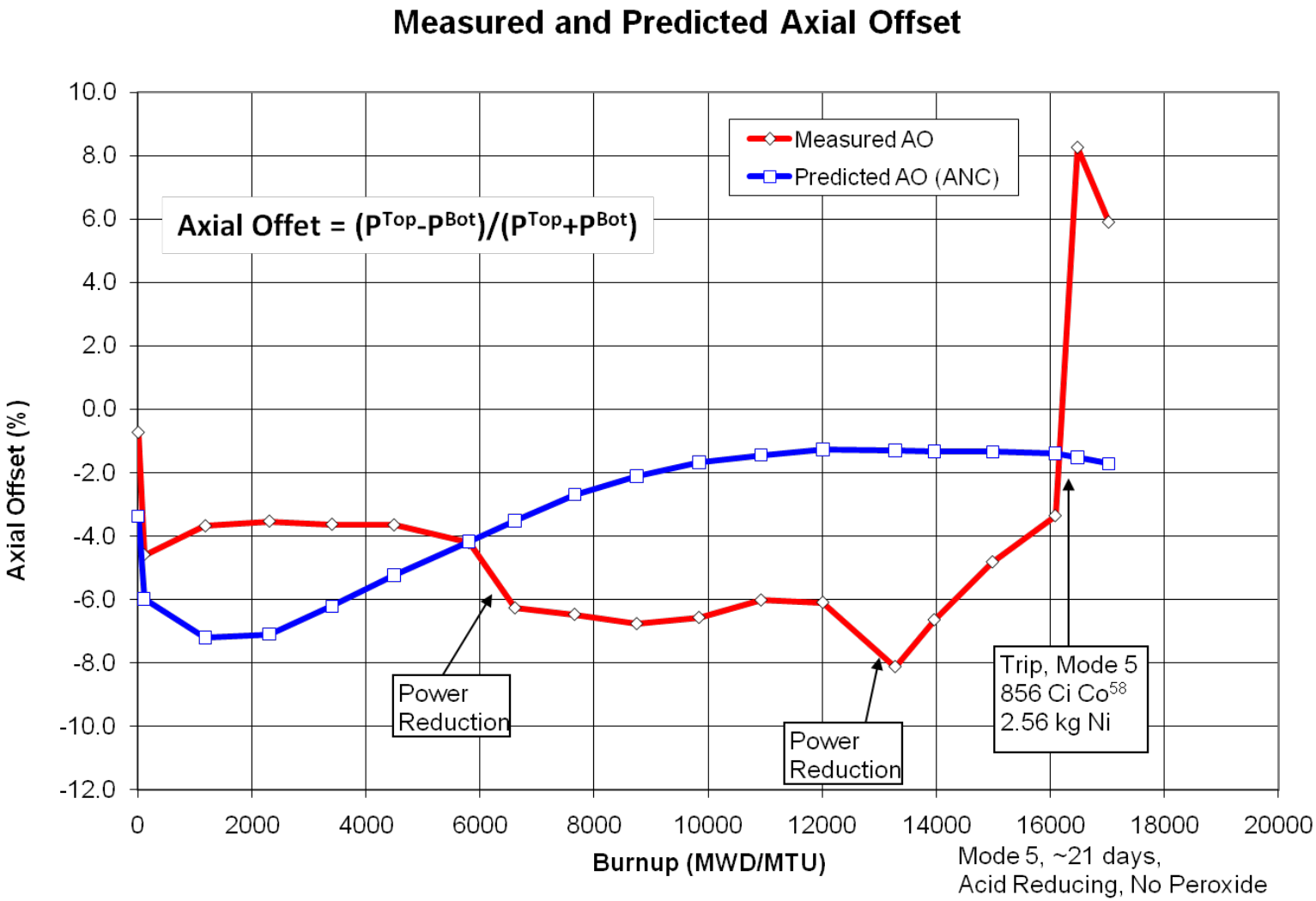
Subgrid (1D) version of MAMBA was developed to enable full core crud simulations (CIPS)

- Uses parameterized models to avoid expensive computational steps (reduces cpu & memory)
  - Heat transfer
  - Thermodynamics
- Avoids additional mesh mapping requirements
- Crud is simulated at the same resolution as the thermal hydraulics code (sub-channel or CFD)
- Isolates critical parameters for boron uptake
  - Precipitation threshold → when CIPS appears in cycle
  - Max. boron layer thickness → magnitude of CIPS
- Crud growth & transport models are same as in MAMBA 3D
- Parameterized models verifed against MAMBA 3D coupled with STAR-CCM+
- Successful preliminary application to Watts Bar CIPS

Radial (1D) transport dominates

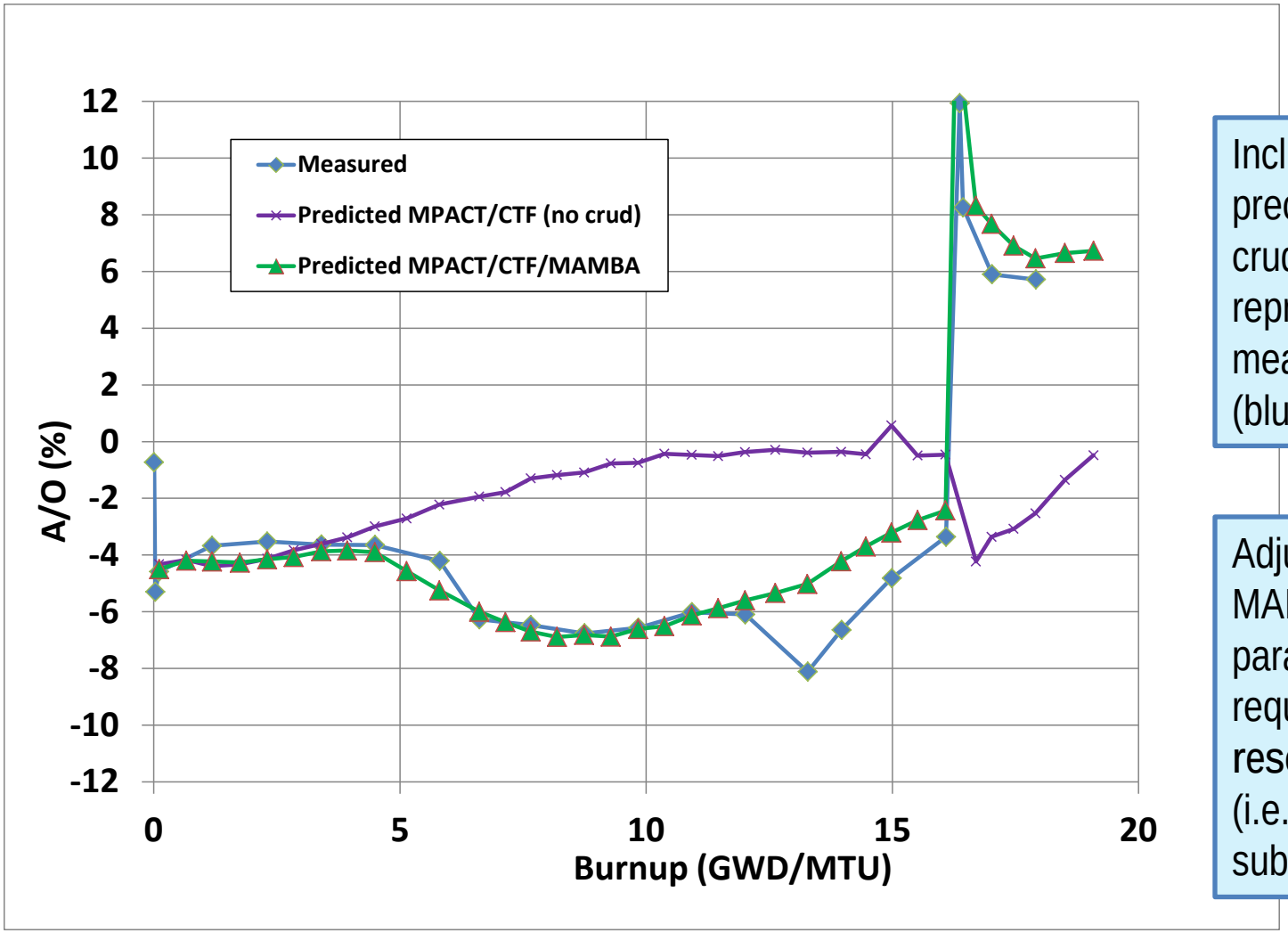


Watts Bar Unit 1 Cycle 7 CIPS



Cycle 7 Experienced CIPS

MPACT/CTF/MAMBA Simulations: Watts Bar Unit 1 Cycle 7 CIPS



Including boron precipitation in crud layer (green) reproduces measured AO (blue)

Adjustments to MAMBA's boron parameters were required due to **resolution** effects (i.e. CFD vs subchannel)

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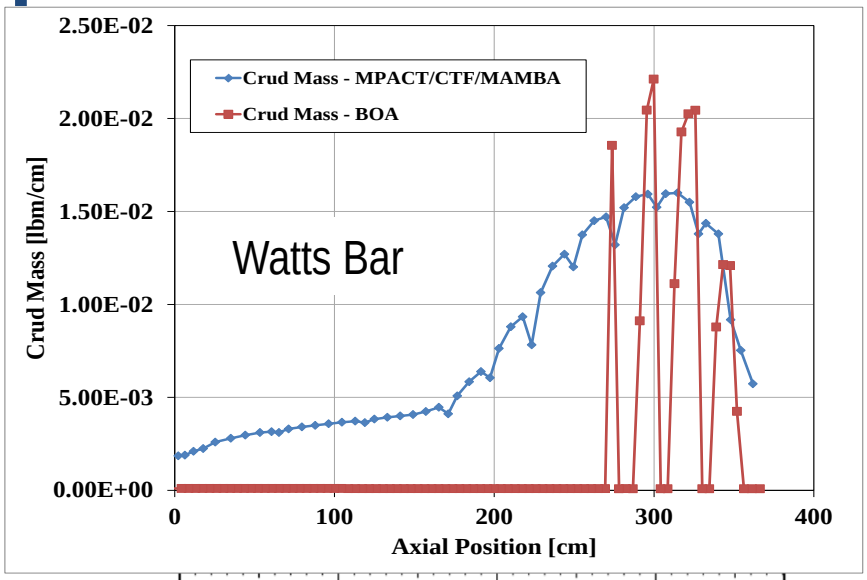
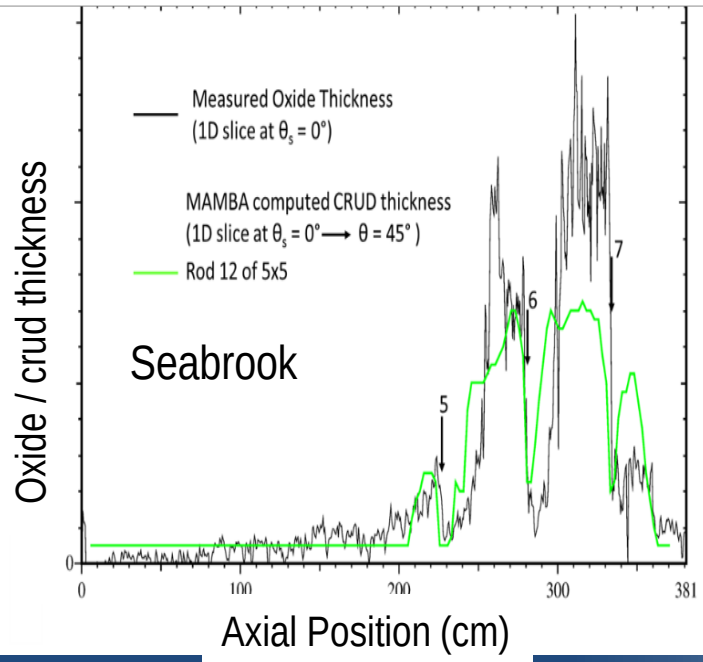
Thermal hydraulic resolution affects crud predictions



Low resolution subchannel thermal hydraulics code (CTF) does not capture **localized** thermal and erosion effects due to spacer grids → too much crud & broad distribution (blue)

Note: BOA simulations include a spacer grid erosion model.



High resolution CFD thermal hydraulics code (STAR-CCM+) captures **localized** thermal and erosion effects due to spacer grids → less crud & localized distribution (green)

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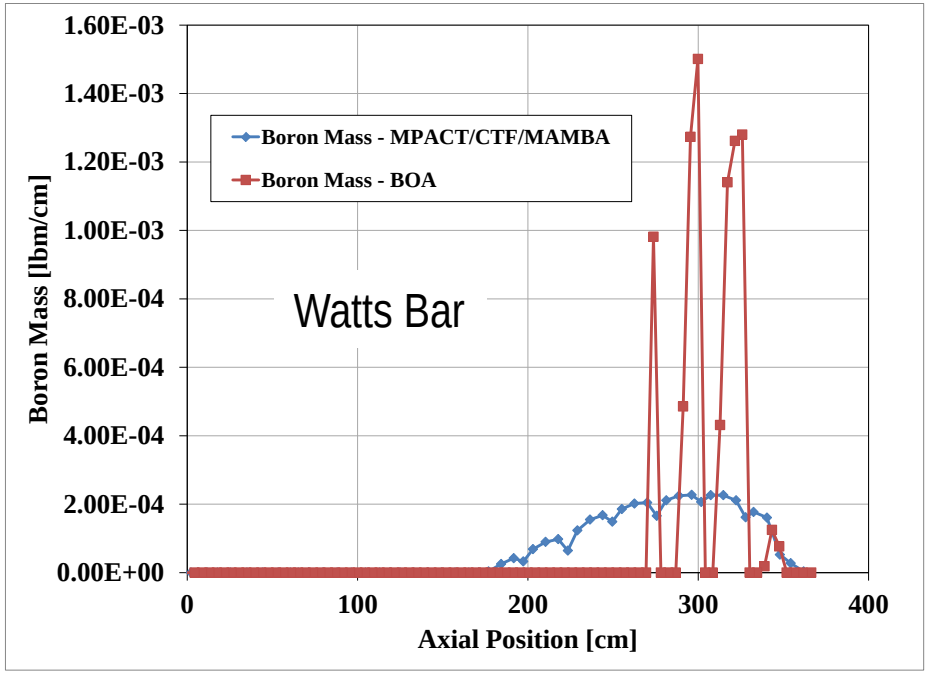
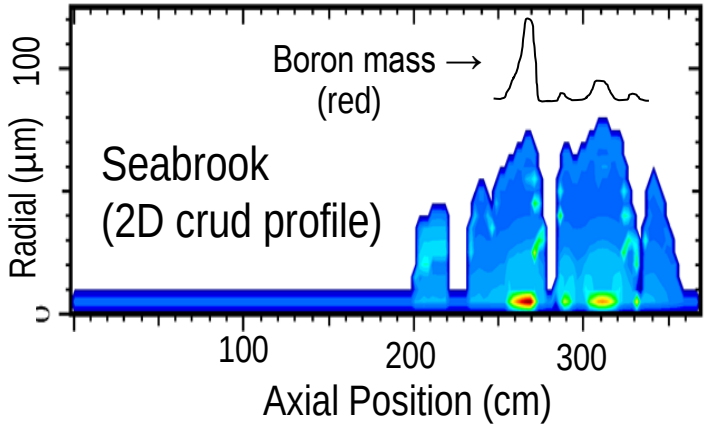
Thermal hydraulic resolution affects boron predictions



Low resolution subchannel thermal hydraulics code (CTF) does not capture **localized** thermal and erosion effects due to spacer grids → broad boron distribution (blue)

Note: BOA simulations include a spacer grid erosion model.



High resolution CFD thermal hydraulics code (STAR-CCM+) captures **localized** thermal and erosion effects due to spacer grids → highly localized boron distribution (red)

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Capturing thermal hydraulic resolution

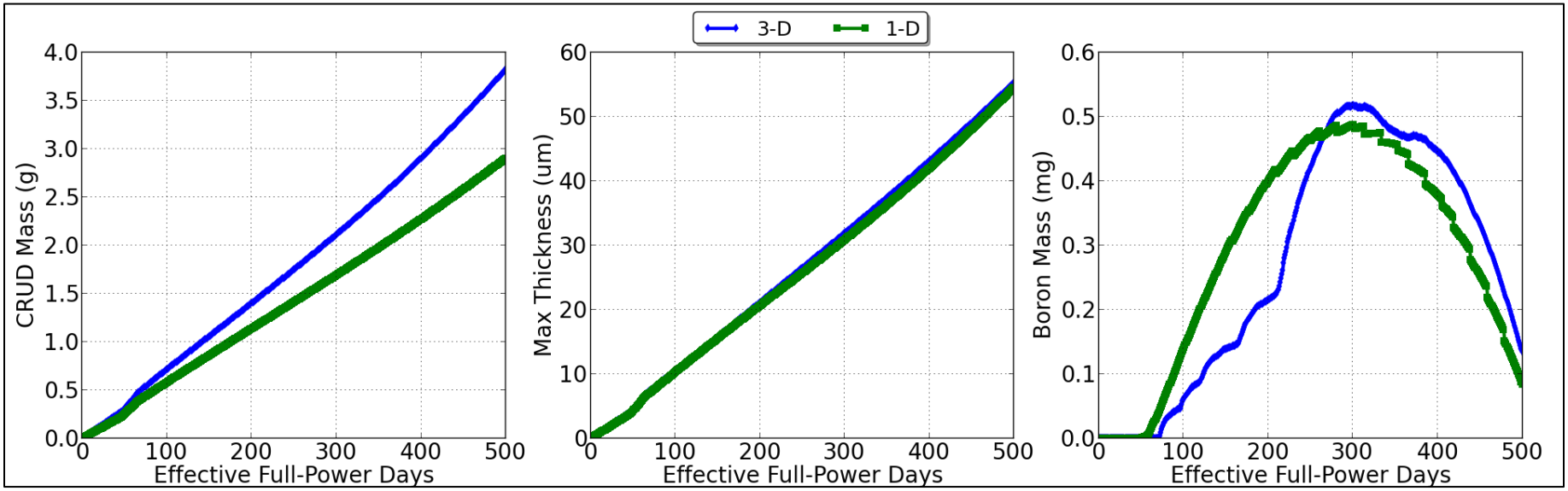
- Localized thermal hydraulic effects require high resolution treatment
  - Temperature
  - Turbulent kinetic energy
- Include subgrid models for these effects in CTF
- Adjust MAMBA's boron precipitation and crud growth/erosion parameters to compensate
- Current on going efforts within CASL to benchmark MAMBA/CTF against MAMBA/CFD to:
  - Develop appropriate subgrid thermal hydraulic models for CTF
  - Develop appropriate parameter sets for using MAMBA with CTF
- Current on going efforts within CASL to benchmark MAMBA 1D vs 3D

Benchmarking MAMBA 1D against MAMBA 3D using STAR-CCM+

No spacer grids and no erosion

Single pin model one-way coupling only

Preliminary analysis by
Dr. Dan Walter, U. Mich



Good overall agreement

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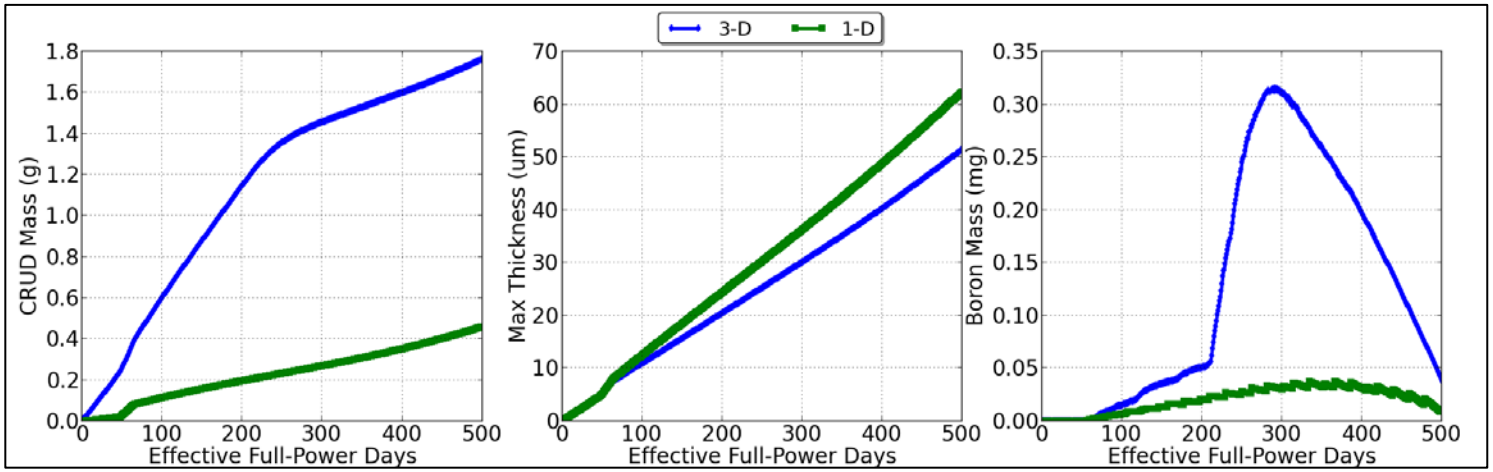
Benchmarking MAMBA 1D against MAMBA 3D using STAR-CCM+

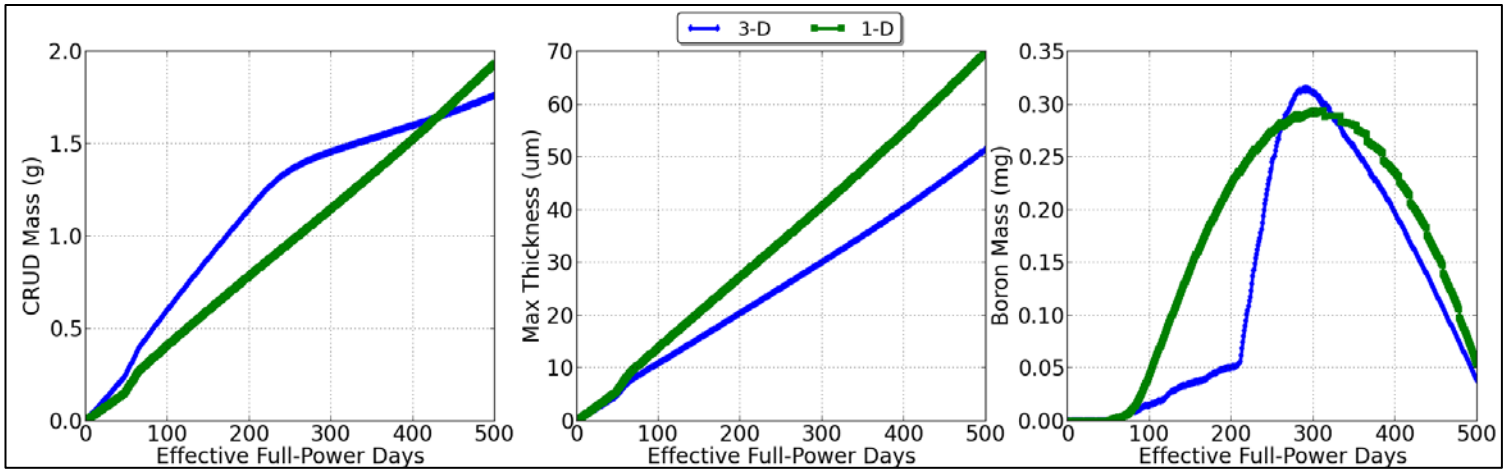
Preliminary analysis by
Dr. Dan Walter, U. Mich

With spacer grids and with erosion

Single pin model one-way coupling only



Some adjustment needed to erosion rate



Decreased erosion rate parameter by 3X to improve overall response

Additonal analysis in progress

Crud Related CASL Milestones for FY16

- L1 CASL.P13.04 Jeff Secker "Qualify CFD-based PWR Crud Induced Localized Corrosion (CILC) Capability"
  - Couple MAMBA 1D with STAR-CCM+ and apply to Seabrook unit 1 cycle 5
  - Verify against previous 5x5 MAMBA 3D /STAR-CCM+ simulation results
- L2:FMC.P13.04 Brian Kendrick "MAMBA work supporting L1 CILC Milestone" + several other milestones: theory manual, 1D vs 3D validation
- L3 THM.CFD.P12.02 Annalisa Manera "Status STAR-CCM+/MAMBA Coupling"
- L2:VMA.P13.01 Jeff Secker "VERA-CS with MAMBA Model of Seabrook"
- L3 VMA.AMA.P13.01 Andre Godfrey "Updated Watts Bar Cycle 7 CIPS Analysis"
- L2:VMA.P13.03 Jeff Sector/Vince Mousseau "Initial UQ Analysis for CIPS and Define UQ approach for CILC"
- L3:PHI.CMD.P13.02 Stuart Slattery "Support for CILC L1 milestone using STAR-CCM+"
- L3:PHI.CTF.P13.04 Aaron Wysocki "CTF support for CIPS challenge problem"
- L3:FMC.CRUD: Andersson, Brenner, Shin, Short, Was, several milestones supporting thermodynamic & oxide model development for MAMBA.

Summary and Future Plans

- MAMBA is a high resolution crud simulation code
  - Validated against WEC WALT Loop experiment, BOA code, and plant data
- MAMBA has been coupled to both neutronics and thermal hydraulics and successfully applied to operating PWRs
  - Seabrook unit 1 cycle 5: MAMBA/STAR-CCM+ (CILC) computed high resolution crud distrubition and validated against plant measured oxide thickness data
  - Watt Bar unit 1 cycle 7: MAMBA/CTF/MPACT (CIPS) computed AO which reproduced measured plant AO data
- Localized thermal hydraulic effects have been identified which greatly affect crud and boron predictions
- Future work will develop subgrid models and parameter sets needed to inform lower resolution codes CTF and MAMBA 1D
- Future work will also extend thermodynamic models to include zinc
- Additional validation studies against plant data needed to develop and verify a fully predictive CIPS/CILC capability
- CASL crud simulations tools will enable more reliable CIPS/CILC risk assessment with cost savings to industry

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