VERA Deployment at Westinghouse

Vefa Kucukboyaci
Westinghouse Electric Company LLC

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Introduction

- CASL’s mission: Provide coupled, higher-fidelity modeling and simulation capabilities needed to address Light Water Reactor (LWR) operational and safety performance-defining phenomena.
- VERA has advanced the state-of-the-art for commercial reactor simulations.
- Strong Westinghouse engagement with CASL
  - Application to several different problems
  - User feedback to developers
- Evaluate and adopt available and mature CASL technology for Westinghouse product development
- Through test-stand development and resolution of the challenge problems in multi-disciplines.
- **Expectation**: Matured CASL technology will be adopted for Westinghouse PWR applications.

**CASL Technology adaptation will improve multiphysics capabilities**
Main focus in the performance-based components (e.g., MPACT, CTF, etc…) for solving large, realistic problems

Tools outside the blue box provide the necessary accuracy on small scale problems to improve the accuracy from “production” tools
Computer Platforms

- **INL’s Flagship System *Falcon***, an SGI ICE-X system
  - A distributed memory system
  - 34,992 cores,
  - 121 TB of memory
  - A LINPACK rating of 1,088 TFlops.

- **OLCF Titan and EOS**
  - *Titan*: Cray Cluster
  - 18,688 nodes w/ 16 cores/node, 32GB RAM
  - 299,008 cores total
  - 598 TB Memory
  - > 20 Petaflops
  - GPU acceleration emphasized

  - *EOS*: Cray Cluster
  - 736 nodes
  - 11,776 cores (23,552 logical cores with Intel Hyper-Threading enabled)
  - 47.104 TB of memory
Computer Platforms

- **Westinghouse’s Binford**
  - 48 compute nodes
  - 576 cores
  - 4.6TB memory

- **Westinghouse’s HPC Cluster**
  - 15 HP C7000 blade chassis totaling over 3700 cores
  - Chassis interconnected via InfiniBand
  - Typically 8 GB/core memory
  - Some nodes with larger memory

- Binford will be merged with the Westinghouse HPC Cluster
- VERA being deployed on the larger HPC Cluster
- Plans to expand the cluster
- Cloud HPC considered in WEC mix of engineering computing options
Advanced Core design
- Heterogeneous core
- 5 Fuel Regions
- IFBA and part-length WABA inserts

```
 3.20 ^{235}U  
 8-in Solid blanket

 3.20 ^{235}U  
 8-in Annular blanket

No ^{10}B  
43-in

No ^{10}B  
8-in

Reg. D,E
No BA
Fuel Rod
Reg. D,E
IFBA
Fuel Rod
Reg. D
Short Waba (SW)
Reg. D
Long Waba (LW)

Zr-spacer 15-in

Fully Enriched with FBA (1.96 mg 10 B/in)

Short WABA 102 in (15.3 mg 10 B/in)

Long WABA 152 inches (15.3 mg 10 B/in)
```

Zr-spacer 15-in

Reg. D,E
No BA
Fuel Rod
Reg. D,E
IFBA
Fuel Rod
Reg. D
Short Waba (SW)
Reg. D
Long Waba (LW)
**HZP calculations**

Comparison of global and local parameters indicated excellent numerical agreement between VERA-CS, Monte Carlo predictions, and ANC/PARAGON, reinforcing confidence in the startup predictions.

**HFP calculations**

Lattice depletion simulations at HFP conditions with VERA-CS, PARAGON2, and Serpent showed excellent agreement.
Core depletion simulations performed with VERA-CS and ANC/PARAGON demonstrate excellent agreement, confirming the Westinghouse design values for the AP1000 PWR first core.
**AP1000® PWR Analysis**

**AP1000 plants Cycle 1**

**Measured - Predicted HZP Critical Boron (ppm)**

<table>
<thead>
<tr>
<th>Plant</th>
<th>VERA-CS</th>
<th>ANC9</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>12</td>
<td>15</td>
</tr>
<tr>
<td>B</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>C</td>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td>D</td>
<td>1</td>
<td>8</td>
</tr>
</tbody>
</table>

**AP1000 plants Cycle 1**

**Measured - Predicted ITC (pcm/°F)**

<table>
<thead>
<tr>
<th>Plant</th>
<th>MPACT</th>
<th>ANC9</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.58</td>
<td>0.54</td>
</tr>
<tr>
<td>B</td>
<td>0.53</td>
<td>0.51</td>
</tr>
<tr>
<td>C</td>
<td>0.43</td>
<td>0.33</td>
</tr>
<tr>
<td>D</td>
<td>0.55</td>
<td>0.49</td>
</tr>
</tbody>
</table>

Very good agreement between VERA, ANC9, and measurements for CBC and ITC.
Watts Bar Unit 2 Startup Simulations

M-P Soluble Boron during Power Ascension Testing

- Watts Bar Unit 2 startup presented a unique opportunity to apply
- A thorough comparison of ANC9 and VERA models
- Compare ANC9 and VERA-CS startup predictions
  - Boron Endpoint
  - Isothermal Temperature
  - Bank Worth
  - Differential Boron Worth
  - Power Distribution
- Several sensitivity studies to understand the cause of differences
- Opportunity to improve our modeling approach
  - Reactivity Predictions
    - Cross-section data (ENDF/B-VI vs ENDF/B-VII)
    - PARAGON2
  - Power Distribution and Axial Offset
    - WABA modeling
    - Reflector Data

VERA was utilized to follow the entire initial power ascension procedure, through all power ramps, load reductions, and shutdowns, with comparisons of measured core reactivity and in-core power distributions.

With the help of VERA results, Westinghouse was able to refine its in-house models (e.g., detailed explicit WABA, reflector constants, cross-section library based on ENDF/B-VII.1 data, etc.)
AP1000 Reactor Core Rod Ejection Analysis (REA)

Cycle 1 Depletion Calculations

- Quarter-core model for depletion calculations
- 56 axial meshes, 4 in the bottom reflector, 3 in the top, 49 in the middle
- Quadrature set of 16 angles
- 51-group cross-section library with TCP0 scattering
- Spatial decomposition for MPACT using 896 cores
- CTF model included 11471 channels, 22813 gaps, and 11471 rods
- Spatial decomposition for CTF based on 4 cores per assembly

pin_powers: Axial 252.800, exposure 0
AP1000 Reactor Core Rod Ejection Analysis (REA)

Initial Conditions and Accident Assumptions

- Ejection at HZP, 5%, 15%, 25%, 50%, 75%, and HFP
- AO bank, ejected rod at their corresponding rod insertion limits
- Full reactor coolant flow to maximize heat transfer
- Constant core inlet temperature and outlet pressure at nominal values
- Transient initiated with full core model at EOC
- 0.75 $\beta_{eff}$ multiplier to maximize $\$ reactivity insertion
- Ejection velocity 2640 steps/second
- Trip simulated by dropping in the partially or fully withdrawn rod banks using conservative control rod acceleration and terminal velocity.

<table>
<thead>
<tr>
<th>Time Period</th>
<th>Time Step Size</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0-5.5E-02</td>
<td>0.005</td>
<td>Rod Ejection</td>
</tr>
<tr>
<td>5.5E-02-1.2</td>
<td>0.010</td>
<td>No rod movement</td>
</tr>
<tr>
<td>1.2-2.0</td>
<td>0.025</td>
<td>Reactor trip</td>
</tr>
<tr>
<td>2.0-3.7</td>
<td>0.100</td>
<td>Reactor trip continues</td>
</tr>
<tr>
<td>3.7-5.0</td>
<td>0.100</td>
<td>No Rod Movement</td>
</tr>
</tbody>
</table>

- Variable time step size for different periods
- 193 steps to complete 5 s transient

Reactor Trips at 1.2 seconds with 0.5 s delay

Rod ejected from RIL position

Stuck Rod

Ejected Rod

Ejected Rod
AP1000 PWR Rod Ejection Analysis (REA)

REA at HZP: Highly asymmetric power distribution

Peak power reaches ~970% of the initial power at 0.155 seconds.

At the peak, the total reactivity insertion is $1.80 (or 744 pcm with $\beta_{eff} = 0.00409$)
- CTF calculations provide T/H data for each sub-channel for both Doppler feedback and also for safety parameters (temperatures, DNB, etc.)
- No DNB occurrence, coolant remains subcooled
Main Steam Line Break Analysis (MSLB)

• Departure from Nucleate Boiling (DNB) response at the limiting time step of a 4-loop PWR postulated MSLB initiated at HZP

Two MSLB scenarios:
• **High Flow Case**: Offsite power available and all coolant pumps remained in operation
• **Low Flow Case**: Without offsite power and the reactor core is cooled through natural circulation
Main Steam Line Break Analysis (MSLB)

- Reactor system state-points generated as the core boundary condition at the DNB limiting time step from the HZP MSLB transient calculation using RETRAN-02
- Core inlet temperature and flow distributions using the STAR-CCM+ at the DNB limiting time step
- Full core models to capture the asymmetric power distribution due to the broken steam pipe in one loop and the stuck RCCA

<table>
<thead>
<tr>
<th>High Flow</th>
<th>Low Flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>22.9% of rated power</td>
<td>11.9% of rated power</td>
</tr>
<tr>
<td>100% of nominal flow rate</td>
<td>10.7% of nominal flow rate</td>
</tr>
<tr>
<td>426.3°F (219.1°C) inlet average temperature</td>
<td>410.6°F (210.3°C) inlet average temperature</td>
</tr>
<tr>
<td>489 psi (3.37 MPa) system pressure</td>
<td>853.1 psi (5.9MPa) system pressure</td>
</tr>
<tr>
<td>0 ppm soluble boron</td>
<td>0 ppm soluble boron</td>
</tr>
</tbody>
</table>

- All rods in; RCCA at (8,6) or in assembly 67 stuck out

![Table of data](image)
Main Steam Line Break Analysis (MSLB)

HZP MSLB case with offsite power available (the high-flow case) is more limiting with respect to the DNB acceptance criterion, consistent with the limiting case analyzed in a 4-loop plant Safety Analysis Report.

<table>
<thead>
<tr>
<th>Case</th>
<th>$P$ (psia)</th>
<th>$h_{inlet}$ (BTU/lbm)</th>
<th>$m_{inlet}$ (Mblbm/hr-ft$^2$)</th>
<th>$q'$ (BTU/s-ft)</th>
<th>MDBNR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low-flow</td>
<td>808.2</td>
<td>377.70</td>
<td>0.275</td>
<td>0.489</td>
<td>9.616  (W3)</td>
</tr>
<tr>
<td>High-flow</td>
<td>460.1</td>
<td>398.90</td>
<td>3.000</td>
<td>1.069</td>
<td>3.624  (W3)</td>
</tr>
</tbody>
</table>
Thermal-Hydraulics – CTF

• CTF offers the following technical advantages:
  – Advanced two-phase flow two-fluid model
  – Potential for DNBR margin recovery in the annular flow regime
  – Setting up and performing full core subchannel analysis
  – Analyzing fast transient, flexible time step sizes
  – In-house CTF expertise for developing CTF into a production code

• To be completed before CTF can be used as a Quality Assurance (QA) and licensed production code:
  – Work with CASL to complete CTF software Verification & Validation (V&V) and Uncertainty Quantification (UQ)
  – Seek partnership with North Caroline State University and others to continue Research & Development (R&D) beyond CASL
  – Apply CTF as a supplement code to support or substantiate current Westinghouse T/H technology based on the VIPRE-W code

• Ongoing Work:
  – CTF Validation for RIA
  – CTF Development and Qualification

CTF has the potential to be the next-generation subchannel code
Thermal-Hydraulics – CTF

Margin Assessment of OTΔT Reactor Trip Setpoints

- Utilizing VERA in steady-state, to provide more realistic predictions of the core power distributions, followed by a transient.
- Guide input to the “Over-Temperature Delta-T (OTΔT)” trip protection system
- Enable utilities to reallocate design margins to both enhance reactor safety and reduce fuel reload cost

Preliminary results indicate significant increases in safety margins
Thermal-Hydraulics – CTF

Study of Two-Phase Flow Modeling Capability – PSBT Void Data Analysis

• 5x5 rod bundle test simulating PWR fuel design with mixing vane grid spacers
• Steady state and transient void test data collected

CTF predictions are in good agreement with data
Thermal-Hydraulics - CFD

• WEC is actively working with the CASL to develop improved models and methodologies for CFD prediction of DNB
• These activities complement the ongoing work in the ATHM innovation program.
• The resulting methodologies will ultimately be developed into a computational tool to complement existing analytical methods (VIPRE, CTF), and testing.
• Extensive validation needed: establish the range of validity of the physical models, as well as quantifying mesh sensitivity and developing modeling best practices.
Thermal-Hydraulics - CFD

STAR-CCM+ Applications

• Current DNB predictions rely on empirically-derived parameters or correlations to model the spacer grid effects
• CFD has potential to eliminate these limitations

Significant step in advancing to a mechanistic approach to DNB

• Hi2Lo approach uses detailed information from CFD and faster run times of CTF, coupled with DAKOTA for calibration
• Calibrated $\beta$ (two-phase turbulent mixing coefficient)
• Optimal value of $\beta=0.037$ determined using Hi2Lo
Westinghouse ATF FRD Methods Development

- Fuel performance code development (PAD-ATF) is well progressed to support ATF test rod and lead test rod (LTR) design
- Advanced modeling and simulation supports method development and licensing
  - Main objective is determination of physical properties of irradiated materials
  - Based on first principles rather than being totally empirical
- Westinghouse involvement on industry programs
  - NEAMS – DOE program on basic property prediction
  - CASL – Virtual reactor design

Westinghouse has a comprehensive development plan for EnCore® FRD methods
BISON Application to EnCore Accident Tolerant Fuel (ATF)

- BISON used to assess impact of eccentricity in postulated double encapsulated U$_3$Si$_2$ lead test rod design
  - Focused on fuel and cladding temperature distribution

BISON provides an important tool for evaluating ATF concepts where empirically based codes are limited in scope because of the limited availability of measured data.
BISON Application to EnCore Accident Tolerant Fuel (ATF)

• Fuel temperatures calculated with BISON for UO₂ and U₃Si₂

Advanced models and higher order methods in BISON confirm expected behaviors

Westinghouse has an integrated approach for development of advanced ATF fuel performance models using the PAD code supplemented by the results of multi-scale modeling of materials properties and higher fidelity analyses with the BISON code.
ATF Assessment of In-Core Implementation: Objectives

• Evaluate transition cycles from current UO₂/Zirlo/18-mo cycles to U₃Si₂/Coated Cladding/24-mo cycles
• Assess Westinghouse in-house core vs. VERA to confirm adequacy
• Perform selected safety analysis
  – DNB
  – RIA
  – SLB
  – FRD
  – CIPS

VERA can enable high-fidelity ATF analysis
ATF Assessment of In-Core Implementation: Approach

• Rationale: Westinghouse ATF fuel concepts have higher U density than UO₂ fuel
  • Higher U density enables economically viable (e.g. fuel utilization efficient) 24-mo operational cycles with U-235<5%

• Implementation:
  • Starting point is a state-of-the-art uprated 4-loop UO₂/Zirlo/18-mo cycle
  • Introduce ATF regions at each reload until equilibrium cycle is reached
  • Transition cycles are key for assessing viability (challenges to peak pin burnup, power distribution while maintaining high fuel efficiency for best economics)
  • Transition performed for both U₃Si₂ and U¹⁵N with dopants, aiming at improving high-temperature water corrosion resistance

• Goal: evaluate reactor physics behavior, fuel cost potential and perform selected safety analysis

Westinghouse ATF aims at higher safety as well as better fuel efficiency compared to current UO₂
Current Status

- Reactor physics benchmark of ATF under progress with good preliminary results
- UO₂ and ATF core models set-up in VERA and executed showing good agreement with Westinghouse in-house tools
- Economic appeal of 24-mo ATF transition demonstrated
- Safety analysis to be performed next

VERA suitability for ATF analysis being demonstrated
Sample Results – $\text{U}_3\text{Si}_2$ Transition Cycle 1

**BOC Assembly Burnup**

**EOC Assembly Burnup**

**BOC Pin Power**

**EOC Pin Burnup**
Advanced Analyses of CRUD

- Performed for each iteration until convergence between all three is achieved
- Repeated for each depletion step in simulation of plant operation

- The CASL crud tools remain under development and are not yet as robust and functional as the EPRI BOA code used for crud risk analysis in Westinghouse.
- MPACT coupled with CTF has been a large step forward in multi-physics coupling of neutronics/T-H/crud-chemistry tools when MAMBA is included with the coupling.
- WEC is closely following MAMBA testing/evaluation/calibration in progress
- Actively participating in CRUD related milestones
  - VERA Benchmark for Seabrook Cycle 5 CIPS
  - VERA Benchmark for Callaway Cycles 4-12 CIPS
  - Analysis of Seabrook Cycle 5 CILC Failure with Cicada

**VERA-MAMBA calculations demonstrated that more aggressive core designs may be acceptable, leading to potential cost savings**
Summary & Conclusions

• Specific industry applications of the CASL technology
  • Neutronics (VERA)
    • Predictive nuclear design methodology, such as reactivity and power distributions
  • Thermal-Hydraulics (CTF, STAR-CCM+)
    • More realistic prediction of limiting reactor constraints such as DNB
  • Fuel Rod Performance (BISON)
    • Recent modelling advances needed for predicting ATF behavior.
  • Crud Applications (MAMBA)
    • Prediction of the CIPS phenomena

With the help of the CASL tools, it is recognized that advanced M&S techniques can inform decisions for the next generation of advanced fuel designs and new generation reactors, as well as help in the resolution of any anomalous core behavior in existing LWRs.
Way Forward

Particular areas for further work:

• Crud Predictive Capability
  • Source term development; calibration based on plant data; CFD informed sub-channel for mixing grid effects; validation & uncertainty quantification

• DNB Predictive Capability
  • Mechanistic DNB model based on CFD; ATF applications; validation

• Fuel Rod Performance
  • PCMI assessments for load-follow and reduced power operations; fission gas release; missing pellet surfaces; advanced reactor/fuel designs; ATF applications.

• Nuclear Capability
  • Validation and assessment; run-time performance improvements; ATF applications

Significant progress to date to advance the M&S state of the art; however, further work needed to improve confidence in robustness of the software (physics, geometry, and numerical solvers) and fully benefit the industry.
Acknowledgments

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