CASL Applications and Validation

Andrew Godfrey, ORNL
AMA Deputy Lead

VERA Workshop
February 11, 2019
From the VERA beginning, CASL has maintained a subset of staff devoted to meaningful applications and testing of VERA.

“AMA will work closely with the nuclear industry and provide compelling demonstrations of VERA capabilities and workflows.”

– Jess Gehin, former Director
Advanced Modeling Applications

Objectives and Strategies

- Apply VERA to relevant industry problems and demonstrate compelling value for the commercial nuclear power industry
- Provide requirements, priorities, user testing, validation, and benchmarking for VERA from nuclear industry perspective
- Staff composed of industry analysts

Requirements Drivers

- Reactor Benchmarking
- Challenge Problems
- Test Stand Support
- Industry Engagement
- Code testing and feedback

Requirements Drivers

Outcomes and Impact

- Significant value demonstrations
- Collaboration with the nuclear industry
- Obtain data, develop models, generate customer base, facilitate VERA deployment
- Successful testing of Challenge Problem capabilities (CRUD, RIA, PCI, Excore)
AMA in 2019

- $5M funding
- 30 staff members
  - 57% industry
  - 30% laboratory
  - 3% university
  - 10% consultants
- ~80 milestones
- Maintaining 21 reactor models
  - >150 fuel cycles

CASL is investing heavily in industry now to ensure long-term success of VERA
VERA Validation Plan

• Power Plant Benchmarking
  – Next slide
• Critical Experiments
  – B&W, Kritz, Dimple, SPERT
• Fuel Rod PIE
  – TMI Cycle 10
  – Catawba MOX LTAs
  – CRUD Scrapes
• Comparisons with CE Monte Carlo Codes
  – MCNP, KENO, Serpent, MC21, etc.
# Power Plant Models

<table>
<thead>
<tr>
<th>Plants</th>
<th>Cycles</th>
<th>Reactor and Fuel Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>AP1000</td>
<td>1-5</td>
<td>W Gen III+ 2-loop 17x17 XL</td>
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<tr>
<td>Byron 1</td>
<td>17-21</td>
<td>W 4-loop 17x17</td>
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<td>Callaway</td>
<td>1-12</td>
<td>W 4-loop 17x17</td>
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<tr>
<td>Catawba 1</td>
<td>1-9</td>
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<tr>
<td>Catawba 2</td>
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<td>Davis-Besse</td>
<td>12-15</td>
<td>B&amp;W 15x15</td>
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<tr>
<td>Farley</td>
<td>23-27</td>
<td>W 3-loop 17x17</td>
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<tr>
<td>Haiyang</td>
<td>1</td>
<td>W Gen III+ 2-loop 17x17 XL</td>
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<tr>
<td>Krško</td>
<td>1-3,24-28</td>
<td>W 2-loop 16x16</td>
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<tr>
<td>NuScale</td>
<td>1-8</td>
<td>SMR</td>
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<tr>
<td>Oconee 3</td>
<td>25-30</td>
<td>B&amp;W 15x15</td>
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<tr>
<td>Palo Verde 2</td>
<td>1-16</td>
<td>CE System 80 16x16</td>
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<tr>
<td>Sanmen</td>
<td>1</td>
<td>W Gen III+ 2-loop 17x17 XL</td>
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<td>Seabrook</td>
<td>1-5</td>
<td>W 4-loop 17x17</td>
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<td>Shearon Harris</td>
<td>Surrogates</td>
<td>W 3-loop 17x17</td>
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<tr>
<td>South Texas 2</td>
<td>1-8</td>
<td>W 4-loop 17x17</td>
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<tr>
<td>TMI</td>
<td>1-10</td>
<td>B&amp;W 15x15</td>
</tr>
<tr>
<td>V.C. Summer</td>
<td>17-24</td>
<td>W 3-loop 17x17</td>
</tr>
<tr>
<td>Vogtle 1</td>
<td>7-15</td>
<td>W 4-loop 17x17</td>
</tr>
<tr>
<td>Watts Bar 1</td>
<td>1-18</td>
<td>W 4-loop 17x17</td>
</tr>
<tr>
<td>Watts Bar 2</td>
<td>1-2</td>
<td>W 4-loop 17x17</td>
</tr>
</tbody>
</table>
Watts Bar Unit 1 Cycles 1-15 Benchmark

- RCCA bank worths = -0.2 ± 2.0%
- Isothermal temperature coeffs = -1.4 ± 0.7 pcm/F
- Critical boron concentrations = -9 ± 17 ppm
- In-core power distributions = 1.6% radial, 3.4% total, 0.2% AO

960 processors
~22 statepoints/cycle
~21 hours per cycle
20,600 core-hours

Critical Boron Difference (ppm) vs. Cycle Burnup (EFPD)

Critical Boron Comparison Graph

Bank Worths Graph

945 in-core flux maps
• MAMBA not-predictive at the time but potential benefits are clear
  – ~50% improvement in power distribution comparisons
  – Cycle 7 flux map results are as good as non-CIPS cycles
  – Up to 40% improvement in 1st half of Cycle 8 as well
CIPS Risk Assessment for Catawba 2

- VERA analysis of 3 candidate core designs which had already been screened for CIPS with industrial methods
- Duke selected most conservative design
- VERA results showed increased risk of power shift and loss shutdown margin was likely insignificant
- Most cost effective pattern was:
  - 0.3% difference in axial offset
  - 51 pcm in shutdown margin loss
  - $250,000 in fuel savings ($125K-$425K)
- In FY18, performing CILC risk assessment for Oconee 3

VERA advanced capabilities have potential to reduce the fuel costs of the nuclear industry

“If we would have had this information for cycle 22 we may have chosen differently”

Scott Thomas
Manager Safety Applications
Duke Energy
Watts Bar Unit 2 Startup Analysis

- 4,130 hourly statepoints
- 13.5 days of runtime on 2,784 cores
- 892,837 core-hours
- 16,605 fully-coupled neutronics/TH iterations

Measured Power Distribution Differences

Vanadium Wire Currents = 0.7 ± 2.4%

<table>
<thead>
<tr>
<th>Measured Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial Critical Boron Concentration Difference</td>
<td>-2</td>
</tr>
<tr>
<td>Isothermal Temperature Coefficient Difference</td>
<td>-0.8</td>
</tr>
<tr>
<td>Average Control Bank Worth Error (%)</td>
<td>0.7</td>
</tr>
</tbody>
</table>

WBN2 VERA vs. Online Monitor

**VERA**

All Wire Currents = 0.7 ± 2.4%
Long Wire Currents = 0.3 ± 2.3%

**Online Core Monitor**

All Wire Currents = -0.1 ± 3.4%
Long Wire Currents = 0.4 ± 3.1%
AP1000® PWR Advanced First Core

• Extensive applications by Westinghouse to confirm current predictions for the startup of Sanmen and Haiyang Nuclear Plants
• Measurements from these startups will be available later this year
B&W 1810 Critical Experiments

- Critical Experiments Run in early 1980’s
- Main purpose was to test Gadolinia, but also tested other absorbers and two different enrichments
- Limited pin-by-pin measurements
B&W 1810 Results

<table>
<thead>
<tr>
<th>Core</th>
<th>CASMO</th>
<th>47g</th>
<th>51g</th>
<th>51g P2</th>
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<tbody>
<tr>
<td>1</td>
<td>83.0</td>
<td>-358.3</td>
<td>39.1</td>
<td>205.8</td>
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<tr>
<td>2</td>
<td>27.0</td>
<td>-340.3</td>
<td>39.5</td>
<td>193.0</td>
</tr>
<tr>
<td>3</td>
<td>47.0</td>
<td>-377.6</td>
<td>-7.3</td>
<td>142.4</td>
</tr>
<tr>
<td>4</td>
<td>106.0</td>
<td>-265.1</td>
<td>93.9</td>
<td>238.5</td>
</tr>
<tr>
<td>5</td>
<td>18.0</td>
<td>-402.1</td>
<td>-41.2</td>
<td>103.1</td>
</tr>
<tr>
<td>5A</td>
<td>8.0</td>
<td>-410.3</td>
<td>-53.1</td>
<td>89.7</td>
</tr>
<tr>
<td>5B</td>
<td>25.0</td>
<td>-396.6</td>
<td>-35.5</td>
<td>109.2</td>
</tr>
<tr>
<td>6</td>
<td>37.0</td>
<td>-340.3</td>
<td>13.0</td>
<td>155.2</td>
</tr>
<tr>
<td>6A</td>
<td>31.0</td>
<td>-341.7</td>
<td>6.7</td>
<td>146.8</td>
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<tr>
<td>7</td>
<td>19.0</td>
<td>-398.7</td>
<td>-38.0</td>
<td>106.5</td>
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<tr>
<td>8</td>
<td>28.0</td>
<td>-385.2</td>
<td>-33.5</td>
<td>108.1</td>
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<tr>
<td>9</td>
<td>15.0</td>
<td>-362.8</td>
<td>-16.4</td>
<td>125.0</td>
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<tr>
<td>10</td>
<td>10.0</td>
<td>-404.2</td>
<td>-52.9</td>
<td>87.5</td>
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<td>12</td>
<td>114.0</td>
<td>-313.2</td>
<td>50.5</td>
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<tr>
<td>13</td>
<td>156.0</td>
<td>-273.0</td>
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<td>228.9</td>
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<td>14</td>
<td>84.0</td>
<td>-324.9</td>
<td>11.9</td>
<td>178.8</td>
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<td>15</td>
<td>140.0</td>
<td>-275.9</td>
<td>59.5</td>
<td>195.3</td>
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<tr>
<td>16</td>
<td>81.0</td>
<td>-322.5</td>
<td>7.9</td>
<td>168.2</td>
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<tr>
<td>17</td>
<td>98.0</td>
<td>-312.0</td>
<td>19.4</td>
<td>154.2</td>
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<tr>
<td>18</td>
<td>268.0</td>
<td>-170.2</td>
<td>181.7</td>
<td>371.0</td>
</tr>
<tr>
<td>19</td>
<td>235.0</td>
<td>-188.1</td>
<td>148.9</td>
<td>318.7</td>
</tr>
<tr>
<td>20</td>
<td>214.0</td>
<td>-197.9</td>
<td>127.8</td>
<td>283.6</td>
</tr>
<tr>
<td>Average</td>
<td>83.8</td>
<td>-325.5</td>
<td>27.4</td>
<td>180.1</td>
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<tr>
<td>Stdev</td>
<td>76.9</td>
<td>71.6</td>
<td>66.1</td>
<td>76.8</td>
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<tr>
<td>Minimum</td>
<td>8.0</td>
<td>-410.3</td>
<td>-53.1</td>
<td>87.5</td>
</tr>
<tr>
<td>Maximum</td>
<td>268.0</td>
<td>-170.2</td>
<td>181.7</td>
<td>371.0</td>
</tr>
</tbody>
</table>

\[ \Delta k = (k_{\text{eff}} - 1) \times 10^5 \text{ pcm} \]

- Very good agreement
- Compare well to industry standard codes
- Within +/- 200 pcm target

Pin Power RMS (%)

<table>
<thead>
<tr>
<th>Core</th>
<th>MPACT (%)</th>
<th>CASMO (%)</th>
<th>KARMA (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.48</td>
<td>0.51</td>
<td>0.60</td>
</tr>
<tr>
<td>5</td>
<td>0.50</td>
<td>0.57</td>
<td>0.68</td>
</tr>
<tr>
<td>12</td>
<td>0.69</td>
<td>0.69</td>
<td>0.71</td>
</tr>
<tr>
<td>14</td>
<td>0.79</td>
<td>0.79</td>
<td>0.82</td>
</tr>
<tr>
<td>18</td>
<td>1.09</td>
<td>0.86</td>
<td>0.96</td>
</tr>
<tr>
<td>20</td>
<td>1.23</td>
<td>n/a</td>
<td>1.12</td>
</tr>
</tbody>
</table>
Krško Radial Core Power Distribution

2D Core Comparison of VERA to CE Monte Carlo results at BOC HZP

\[ \Delta k = 15 \text{ pcm} \]

RMS = 0.22%

Max = -0.86%
Radial Reflector Modeling

W 4-loop truncated geometry

W 2-loop truncated geometry

AP1000 full geometry
NNL Benchmark against MC21

- Single assembly at BOC HFP (Problem 6)
- Reference solution is KAPL’s MC21 coupled with COBRA-IE and COBRA-TF

\[ \Delta k = -63 \text{ pcm} \]
\[ \text{RMS} = 0.09\% \]
\[ \text{Max} = -0.19\% \]

## NNL HFP Quarter Core Benchmark

- **BOC HFP** with eq. Xenon and boron search (Problem 7)
- **Reference solution** is KAPL's MC21 coupled with CTF

### MC21/CTF Differences

<table>
<thead>
<tr>
<th>Δk</th>
<th>RMS</th>
<th>Max</th>
<th>ΔAO</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;1 ppmB</td>
<td>0.22%</td>
<td>-0.47%</td>
<td>0.03%</td>
</tr>
</tbody>
</table>

### Radial Assembly Powers

- $\Delta k = <1 \text{ ppmB}$
- $\text{RMS} = 0.22\%$
- $\text{Max} = -0.47\%$
- $\Delta \text{AO} = 0.03\%$

### Exit Coolant Temperatures

- $\text{RMS} = 0.13 \degree \text{C}$
- $\text{Max} = \pm 0.2 \degree \text{C}$

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NuScale Test Stand

• NuScale Test Stand completed first phase
  – 8 fuel cycles simulated with VERA
  – Comparisons to licensed industry methods
  – Validation of effects of steel reflector block
  – In-house build of VERA completed in Corvallis
  – VERA training completed in June 2018
• Initial MAMBA-1D application successful in demonstrating multi-physics feedback effects on CRUD generation and boron deposition
• Proprietary report completed and public version available soon

VERA Pin Powers

NuScale SMR with reflector block
• 37 +/- 23 pcm for 900K over 6 fuel and burnable absorber types
• Good agreement with both Serpent continuous-energy Monte Carlo depletion code
• Good agreement with Westinghouse latest lattice physics methods Paragon-2
**WB1 Excore Transport Demonstrations**

- **Power range detector responses for core surveillance and accident simulations.**
- **Source range detector responses for core loading sequences and approach to criticality simulations.**
- **Coupon irradiation for fluence validation.**
- **Activation and dose in reactor building materials.**
- **Simulation of fluence in the reactor vessel over the full life of Watts Bar Unit 1.**

**Surveillance coupons (Co, Cu, Fe) in the single surveillance capsule.**

**Average Fluence Rate By Cycle**

-14% to +11%
Shearon Harris Downcomer Attenuation
Smith, Davidson – RPSD 2018

- VERA proven capable of direct excore detector response calculations consistent with industry-grade applications
**Initial Neutron Fluence and Iron dpa Results**

Cumulative neutron fluence and total iron dpa in the iron coupon located at the center of the surveillance capsule from cycles 1 to 3

<table>
<thead>
<tr>
<th>Parameter (Accumulated from Cycles 1 to 3)</th>
<th>VERA – CADIS (1σ %RE)</th>
<th>*REFERENCE</th>
<th>%Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neutron Fluence (E &gt; 1.0 MeV) n/cm³</td>
<td>9.78 × 10¹⁸ (0.8%)</td>
<td>1.072 × 10¹⁹</td>
<td>-8.79%</td>
</tr>
<tr>
<td>Neutron Fluence (E &gt; 0.1 MeV) n/cm³</td>
<td>4.68 × 10¹⁹ (0.2%)</td>
<td>5.224 × 10¹¹</td>
<td>-10.34%</td>
</tr>
<tr>
<td>Iron dpa</td>
<td>1.96 × 10⁻² (0.3%)</td>
<td>2.205 × 10⁻²</td>
<td>-10.99%</td>
</tr>
</tbody>
</table>

Computational Performance

- 50 million particles per state point in Shift with CADIS
- Weight windows generated at first state point and the same VR parameters are used for all the state points
- Neutron-only transport

<table>
<thead>
<tr>
<th></th>
<th>MPACT / CTF [min, max, avg]</th>
<th>MPACT / CTF [cores]</th>
<th>Shift [min, max, avg]</th>
<th>Shift [cores]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cycle 1 run time per state point (minutes)</td>
<td>22.3, 147.3, 68.3</td>
<td>840</td>
<td>1.1, 1.6, 1.2</td>
<td>400</td>
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<tr>
<td>Cycle 2 run time per state point (minutes)</td>
<td>42.6, 195.1, 89.1</td>
<td>915</td>
<td>1.2, 4.4, 1.5</td>
<td>400</td>
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<tr>
<td>Cycle 3 run time per state point (minutes)</td>
<td>21.8, 204.6, 60.3</td>
<td>992</td>
<td>1.2, 1.5, 1.3</td>
<td>400</td>
</tr>
</tbody>
</table>
Development of Public Reactor Benchmark Specifications

• Public benchmark specs for Cycle 1 released in 2014
• Based on data from Watts Bar and publicly available fuel design data
• Updating in 2019 for:
  – Cycle 2 startup tests and depletion
  – Cycle 3 shuffle and depletion
  – Measured flux maps
• NCSU is developing draft NEA/OECD benchmark specification to be released in 2019

Study of HZP SLB DNB Limiting Case

<table>
<thead>
<tr>
<th>Parameter</th>
<th>High-Flow</th>
<th>Low-Flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>DNB Limiting Elevation (cm)</td>
<td>45.9</td>
<td>30.5</td>
</tr>
<tr>
<td>Max. Pin Linear Power (W/cm)</td>
<td>264.3</td>
<td>178.5</td>
</tr>
<tr>
<td>Heat Flux (W/m²)</td>
<td>801.4</td>
<td>558.7</td>
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<tr>
<td>Equilibrium Quality</td>
<td>-0.047</td>
<td>-0.114</td>
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<tr>
<td>Mass Flux (kg/m³/s)</td>
<td>4529.1</td>
<td>466.9</td>
</tr>
</tbody>
</table>

VERA-CS 4-Loop Core Model
- 56,288 channels
- 112,064 gaps
- 50,952 fuel rods, 4,825 GT/IT
- ~60 axial nodes
### AP1000 Rod Ejection at HFP

<table>
<thead>
<tr>
<th>R</th>
<th>P</th>
<th>N</th>
<th>M</th>
<th>L</th>
<th>K</th>
<th>J</th>
<th>H</th>
<th>G</th>
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<td>11</td>
<td>12</td>
<td>13</td>
<td>14</td>
<td>15</td>
</tr>
</tbody>
</table>

- **Highly asymmetric power distribution**
- **High power clustered in and around the ejected rod, and tapers off away from the ejected rod.**
- **The max. power peaking factor of ~17.3 at the peak of the pulse.**

![Highly skewed axial power initially with partially inserted rod](image)
AP1000 Rod Ejection at Part-Power

Additional simulations starting at 5%, 15%, 25%, 50%, and 75% power

- 5% power case appears to be most limiting in VERA results
Reactivity Insertion Accident with VERA

- 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
- Conservatism on Beta
- Initiated from HZP conditions – core power reached 904% FP with $1.5 ejected rod worth
- 6480 cores in 36 hours
Subcritical, Source-Driven Application

- Subcritical, source-driven problem to simulate excore detector response during core refueling
- Neutron sources from burned fuel (ORIGEN) and activated secondary source rods (Sb-Be)
  - Photoneutron reaction correlation developed with ORIGEN and MCNP
- MPACT pin-wise diffusion used for sub-critical multiplication
- Shift hybrid MC transport used for source-range detector response

Subcritical thermal neutron flux in WB1C8 when fully loaded, including secondary neutron sources (log scale)
Ex-Core Detector Response Benchmark

- VERA used to predict detector response outside of the pressure vessel in Watts Bar Unit 1
- Relative comparisons to measured source range detector signals
- Excellent agreement between calculations and measurements: -0.3±3.9% over ~17,000 measured points averaged over 140 total intervals (8 fuel cycles)
- Report available soon for public release

State-of-the-Art Capability for Coupled In-Core and Ex-Core Neutron Transport Analyses
www.casl.gov