EPRI VERA Experience

Usage, Strategy, and Concerns

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Overview

- EPRI VERA Usage
  - Initial test stand
  - Current AMA applications
    - CIPS/CILC
    - PCI
    - Ex-core
  - How EPRI will be using VERA

- Concerns for industry adoption of VERA
  - Documentation
  - Debugging
  - Procedures
VERA Usage at EPRI
CASL Test Stands

- The first real tests of VERA came by way of the first batch of Test Stands, which started back around 2013.
  - Westinghouse – AP1000 analysis of a 1\textsuperscript{st} cycle core
  - EPRI – pellet-cladding interaction (PCI) analysis
  - TVA – evaluation of lower plenum flow anomaly (LPFA)
2D FEM plot of the hoop stress for a full-length PWR fuel rod using aspect ratios of 1:1 (left), 20:1 (center), and 400:1 (right).

- Usage Statistics
  - 400+ individual simulations
  - 15,000+ core hours

Inside cladding surface hoop stress predicted by BISON during second-cycle restart.
1/4-Core Fuel Performance Analysis Demo Performed (2015)

Max Inside Cladding Hoop Stress During 3rd Cycle Startup

<table>
<thead>
<tr>
<th>Module</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aggregation</td>
<td>15 seconds</td>
</tr>
<tr>
<td>Model Development</td>
<td>10 minutes</td>
</tr>
<tr>
<td>Execution</td>
<td>14 hours</td>
</tr>
<tr>
<td>Postprocessing</td>
<td>10 minutes</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>15 hours</strong></td>
</tr>
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</table>

Capability exists in VERA
2019 EPRI Projects Using VERA

- EPRI has 5 projects on-going that will use VERA:
  1. VERA Code Application to Modeling Fluence Distributions in the Reactor Vessel Extended Beltline Region
  2. RIA ATF Evaluation
  3. Byron Cycle 20 Load Follow PCI Screening Analysis
  4. High Resolution Crud Analyses
  5. CIPS/CILC analysis of TMI-1 cycle 10
VERA Code Application to Modeling Fluence Distributions in the Reactor Vessel Extended Beltline Region (1/3)

- **Project Description:**
  - VERA will be used to compare and calibrate fluence analyses for extended beltline regions of reactor vessels (RVs), which attenuate and accumulate fluence differently than vessel regions directly adjacent to the nuclear core.

- **Project Objectives:**
  1. Evaluate fluence and fluence gradient for the RV extended beltline region above and below the core.
  2. Benchmark VERA ex-core results against available ex-vessel dosimetry, and compare the VERA results to industry and/or NRC/ORNL results.
  3. Perform sensitivity analyses on uranium loading and other parameters.
  4. Build support for VERA’s ex-core capabilities to provide motivation for wider use of the tools.
The heights of the beltline and extended beltline regions are usually defined by a fluence limit. Note that they usually indicate the maximum distance of the fluence limit above or below the active fuel (because the fluence profile around the circumference of the RPV is not flat).
VERA Code Application to Modeling Fluence Distributions in the Reactor Vessel Extended Beltline Region (3/3)

- How VERA will be used:
  - A pre-constructed VERA ex-core model will be adapted to a target plant where an industry comparison is available
  - The results of the VERA calculation will be compared to available ex-vessel dosimetry measurements for the target plant and the results of the industry fluence evaluation
  - Sensitivity analyses will be performed for uranium loading and up to three additional parameters

- VERA Advantages:
  - High fidelity source term
  - Significant ex-core modeling versatility

- Project Value:
  - The results of this project can be used to independently evaluate Nuclear Regulatory Commission (NRC) research for calculating fluence in the extended RV beltline region
    - NRC is performing this research to develop technical bases for improving the guidance contained in Regulatory Guide 1.190, and to extend this guidance to RV locations above and below the core and for RV internal components
Byron Cycle 20 Load Follow PCI Screening Analysis (1/2)

VERA’s versatility provides a capability to mitigate PCI
- Narrows PCI risk to rods considered most limiting
- Local effects analysis on limiting rods to predict fail/non-fail

Project Goal: conduct a core wide load follow PCI screening analysis
- Determine which rods are limiting by assessing:
  - Burnup, ΔPower, pellet-cladding gap thickness, and cladding hoop stress

Results provide value directly to the utilities
- Confidence that fuel rods are less susceptible to failure
- Option to have more aggressive operating strategies
Byron Cycle 20 Load Follow PCI Screening Analysis (2/2)

Load Follow PCI Screening Methodology

- When did the LF event occur?
- How great is ΔPower?
- How long was the rod at reduced power?

Assess Reactor Operation

Screen for PCI Risk
- Evaluate gap thickness prior to return to power
- Evaluate cladding hoop stress at peak power and/or during Xe swing

Predict PCI failure
- Conduct local effects analyses for “limiting rods”
- Compare results to predetermined failure threshold
RIA ATF Evaluation (1/2)

- Draft RIA regulatory guidance is being reviewed for implementation
  - Proposed limits are much lower relative to existing limits

- Most of the plants with existing methodologies are unlikely to meet the new criteria
  - High fidelity 3D methods is expected to provide margin
RIA ATF Evaluation (2/2)

- Goal of the project is to use the high fidelity capability of the VERA code to evaluate the RIA performance of two plants
  - Limiting Westinghouse 3-loop design (expected to be limiting)
  - A Combusting Engineering plant
  - EPRI and CASL programs already evaluated Westinghouse 4-loop designs

- The results will provide insights on benefits of 3D methods
  - Ability of the nuclear fleet to meet the proposed RIA limits
  - Performance of ATF concepts
High Resolution Crud Analyses (1/2)

- CTF input from the last converged MPACT/CTF iteration step is used for composing the VIPRE input
- VIPRE can be run at every time step or at selected timesteps

Iterative coupling between MPACT and CTF, and one way coupling between CTF and VIPRE
High Resolution Crud Analyses (2/2)

- **The methodology:**
  - Aims at harnessing VERA high resolution analytical capability for VIPRE+BOA
  - May enable the use of VERA with VIPRE, preserving user licensing bases
  - Establishes a common basis for comparing MAMBA and BOA crud performance

- **The approach:**
  - Uses the existing CTF ↔ VIPRE thermal-hydraulic benchmarking
  - Minimizes or eliminates the need for coding changes in VIPRE, BOA, and VERA

- **The product:**
  - Provides a method to perform core thermal-hydraulic analyses at an elevated level of accuracy
  - A common basis to compare VERA and BOA crud predictions
TMI-1 CIPS/CILC Analysis (1/2)

- Project: Run VERA to analyze TMI-1 cycle 10, which had both crud-induced power shift (CIPS) and crud-induced localized corrosion (CILC), the latter of which resulted in fuel failures
- Purpose: compare VERA results to plethora of data available in EPRI reports
- Challenges
  - Old data (TMI-1 is 22 years older than Watts Bar-1)
  - Old models (derived from SIMULATE-3 models from the 90s)
  - Many fuel design changes early in life
  - Different operating procedures (e.g. APSRs)
TMI-1 CIPS/CILC Analysis (2/2)

- **V&V opportunity**
  - Neutronics
    - Power distribution
    - Boron concentration
    - Rod-level burnup
    - Nuclide activities
  - Chemistry
    - pH
    - Oxide thickness
    - Crud thickness
    - Crud composition
  - Fuel
    - Diameter
    - Pressure
    - Void volume
    - FGR
Past Ideas / Future Topics

- PWRs
  - Control rod
    - Absorber depletion calculations
  - Margin estimates
  - Performance improvement evaluations
  - Reconstitution economics
- Depending on BWR capabilities
  - Control blades
    - Depletion calculations
    - Calculations to assess blade leakage
  - PCI
    - VERA would provide significantly higher fidelity in terms of coolant flow characteristics compared to current methods
EPRI Strategy Moving Forward

- EPRI, as a CASL partner, is committed to demonstrating the value of VERA in 2019 for multiple different applications
- EPRI’s Fuel Reliability Program (FRP) is standing up a new Project Area in 2019-2020 dedicated to VERA and other M&S tools
- VERA will be available as an R&D tool for the commercial nuclear power industry
  - Results published to broader EPRI membership, and in some cases directly to the public
- Adoption of tools alongside current industry tools
  - BISON / Falcon
  - CTF / VIPRE
  - MAMBA / BOA
- VERA capable of providing power history information that represents a key input in many M&S evaluations
Objectives

1. Identify issues and share experiences to aid other users (traditional user group objective)
2. Emphasize a need to shift additional resources to issues that affect VERA usability
3. Identify opportunities for the User Group to support objective #2

Prepare for transition from “developmental code” to “production code”
EPRI Expectations

- **CASL**
  - Support
  - Documentation
  - Model library
  - License and version lifecycle
  - Quality control
  - Tools, best practices, and analysis procedures

- **User Group**
  - Forum/FAQ/Wiki
  - Test/production HPC platform
  - Ability to influence development activity
  - Shared user experiences
  - Tools, best practices, and analysis procedures
VERA Not Yet Ready for Wide-Scale Industry Application

- Three key issues associated with VERA deployment and usage by the industry:
  1. Documentation
  2. Errors and Error Messages
  3. Analysis Procedures

- The majority of VERA users:
  - Are either a part of CASL, a developer, or a test stand participant
  - Have direct access to the developers in some way
  - Have significant experience with Linux

- These attributes will not remain true moving forward
  - How can we (the User Group) help?

User Group should try and support these issues
How much developer's like documentation...

- I love my job
- My job is okay
- I hate my job
- I hate my life
- I quit
Documentation

- VERA documentation explains core functionality well
  - Does not necessarily help will teaching you how to use the code
  - Documentation updates not as frequent as releases
    - Major documentation produced in 2015
    - VERA is still a development code, so this is somewhat expected for now
      - To most developers, it is the least fun part of the job and the last item on their “to-do” list

- Good user manuals exist...for codes that are 20+ years old

- **Developers aren’t users**
  - Differences in terminology
  - You don’t know what information is missing until you give it to someone with a drastically different knowledge base

- **Users aren’t developers**
  - Users will try and do things the developers never intended or even dreamed of

- Can Users Group help close this gap?
  - Wiki?
  - Git repo with write access?
  - Ticket tracking system?
Quality Control of the Technology (not the methods)

- VERA installation is one of the most complex installs you will ever see
  - The complexity being hidden from the user is immense and impressive
- EPRI has not been able to build a version of VERA since VERA 3.6 without running into build failures that required developer debugging
  - Developers are quick to aid in debugging, but it still takes significant time and resources
  - There used to be another Focus Area directed at deployment and encompassing quality control for releases. Now there is just (to my knowledge) one person, and one person can only do so much.
  - As usage by non-CASL individuals increases, the support workload may become overwhelming
  - Assessing the quality assurance procedure surrounding the release process is something the User Group can support and provide feedback on
    - Many will want to regardless when they integrate VERA into procedure
- Future concerns:
  - What happens when I can’t install VERA 4.0 on my new machine in 2022 in the post-CASL era?
    - Such issues have the potential to significantly hamper VERA adoption
      - Failed installs get frustrating quickly
      - General user knowledge of Linux compiling/installing likely less than most current users (who are mostly a part of CASL)
    - User group members will not have the knowledge to tackle such issues
Debugging Errors

- VERA is still a development code
  - Error messages make sense to developers
  - Error messages often do **not** make sense to the users

- VERA User Group would be an ideal group of people to aid in this endeavor
  - Ideal scenario: Document the error you observed, work with developers to fix, how you fixed it, and provide non-proprietary models to reproduce if possible
    - Non-proprietary models take time to build
    - Error could be caused by many, many things, including system-dependent issues
    - Debugging difficult for HPC code with non-instantaneous runtimes
  - Realistic scenario: find a pathway to enable developers and support personnel to view actual (potentially proprietary) models
    - On actual systems (probably not as realistic, but it is worth the overhead in some cases)
    - Utilizing the User Group machine Lemhi is an advantageous pathway
This error plagued me for a long time

19:17.68 Calculating Equivalence XS...
   Solving Subgroup FSP...
   Running Batch   1/5 (1-53)
Fatal error in PMPI_Waitall: Other MPI error, error stack:
PMPI_Waitall(323)...............: MPI_Waitall(count=3840, req_array=0x390bde40, status_array=0x1) failed
MPIRD_Waitall_impl(166).........:
MPIDI_CH3I_Progress(393).......:
pkt_CTS_handler(321)............:
MPID_nem_lmt_shm_start_send(270):
MPID_nem_delete_shm_region(923):
MPIU_SHMW_Seg_detach(707).......: unable to remove shared memory - unlink No such file or directory

- Solution: Add the following to your MPACT block

```
moc_mg_data_passing false
```

- Issues:
  - MPI errors are tough to catch and prevent under the hood, and especially tough to debug (often have some system dependence).
  - Issue had been identified and fixed on all tested platforms, but the EPRI machine was not one of these platforms
Other Error Message Examples

#### EXCEPTION_ERROR ####
MODULARMESH::graphOrderingInit - For graph decomposition the number of processors must be a multiple of nz or less than nz!

What is nz?

#### EXCEPTION_ERROR ####
STATETYPES::setVar_StateType - Data is not within min/max range!

Which data? What range?

#### EXCEPTION_ERROR ####
Incorrect input to AssemblyGeom::addgrid_AssemGeomRec - the grid starting position cannot be less than or equal to zero!

What does 0 mean?

#### EXCEPTION_ERROR ####
MODULARMESH::graphOrderingInit - For graph decomposition the number of processors must be a multiple of nz or less than nz!

What are material type 5 and insert type 12?

#### EXCEPTION_ERROR ####
STATETYPES::setVar_StateType - Data is not within min/max range!

Which data? What range?

#### EXCEPTION_ERROR ####
ControlRodMovement::init_bank - Control Rod Bank 8, Name 8 has a material id specified for rod 9 that is less than 0 and does not exist!

What are control rod bank 8, name 8, and rod 9?

#### EXCEPTION_ERROR ####
Incorrect input to INSERTTYPES::init_InsertType - material type ID=5 is not associated for insert type ID=12!

application called MPI_Abort(MPI_COMM_WORLD, 666) - process 15

What are material type 5 and insert type 12?

Looks like something isn’t defined, but what?

Will document these issue in 2019 report
Meshing, Meshing, Meshing...

- If you are creating a custom mesh, it can often be the source of your issues

```
### EXCEPTION_ERROR ###
COREMESH::init_CoreRec - Assembly ID=2 has modular geometry dimensions that do not mesh properly with other assembly types!
application called MPI_Abort(MPI_COMM_WORLD, 666) - process 46

### EXCEPTION_ERROR ###
PINTYPES::PinManager_MeshGeom - Grid strap is too thick in x-direction and intersects fuel pin!

### EXCEPTION_ERROR ###
Incorrect Input to LATTICETYPES::LatticeManager_MeshGeom - Lattice Geometry ID=-3 is uninitialized! Lattice Mesh will not be set up!
application called MPI_Abort(MPI_COMM_WORLD, 666) - process 332
```

```plaintext
<table>
<thead>
<tr>
<th>ERROR</th>
<th>ERROR</th>
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<th>ERROR</th>
<th>ERROR</th>
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<th>ERROR</th>
<th>ERROR</th>
<th>ERROR</th>
<th>ERROR</th>
</tr>
</thead>
<tbody>
<tr>
<td>VERAInCTF::Convert_z_to_j</td>
<td></td>
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<tr>
<td>Passed axial location: 1.591E+02</td>
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<tr>
<td>does not correspond to any scalar cell boundary in the axial mesh.</td>
<td></td>
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<tr>
<td>within a tolerance of 0.0001 cm.</td>
<td></td>
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</tr>
</tbody>
</table>
```
Spacer Grid Difficulties with Changing Fuel Designs

- Several different grid types/locations in a given cycle
  - Grids must be bound by axial planes
  - Axial planes cannot dissect grids
  - Results in very thin axial regions which can cause the solvers issues

- Top and bottom of active fuel are different among different batches
  - Results in very thin axial regions which can cause the solvers issues

- Constant movement of control rods and black and grey APSRs during the cycle
  - Mesh studies needed to identify significance of not having mesh boundaries where the APSR and control rod absorber materials end
Best Practices

- Use include files to separate information that may be used across multiple cycles
- Don’t use file symbolic links
  - Folders are okay, but files can cause issues
- Limit the number of significant figures in your dimensions (all planes must line up exactly, so more significant figures means more unpleasant bookkeeping)
  - Use consistent rounding
- List restart_read/restart_shuffle files in order of newest to oldest
- Make sure your thermal expansion parameters are consistent from cycle to cycle
- The total core fuel mass may be the most important parameter when it comes to model accuracy

```plaintext
[CASEID]
  title 'TMI-1 Cycle 2'

[STATE]
  include includes/c02.boc.inp
  include includes/c02.states.inp

[CORE]
  include includes/materials.inp
  include includes/core.inp
  include includes/cycle2.inp

[ASSEMBLY] include includes/batch2.inp
[ASSEMBLY] include includes/batch3.inp
[ASSEMBLY] include includes/batch4.inp

[CONTROL]
  include includes/controls.inp

[EDITS]
  include includes/edits.inp
  include includes/c02.edits.inp

[MPACT]
  include includes/mpact.inp
  include includes/c02.mpact.inp

[COBRATF]
  include includes/ctf.inp
```

Cycle-specific  Batch-specific
Analysis Procedures

Development and Upkeep of a Model Library

- Test Library
  - Series of non-proprietary models with increasing complexity for testing and debugging
    - Progressions problems should be a perfect fit

- Model Library
  - Have baseline non-proprietary models for various NSSS designs
    - Include references so the information can be verified
  - Could possibly be hosted on Gitlab and contributed to by users
Analysis Procedures

How to use VERA

- **Procedure library**
  - One procedure and example for each completed challenge problem
    - Most work is likely documented in a CASL report somewhere
    - May simply need to repeat with non-proprietary model
    - Results should be tied to VERA value statements (e.g. identifying margin)
  - Additional procedures/examples for other applications (e.g. ex-core)

- **Series of examples to investigate other less complex phenomena**
  - Reactivity coefficients
  - Control rod worth calculations
  - Compare peaking factors for different core designs
Analysis Procedures

PCI Analysis Procedure – a high level example

1. Run VERA-CS through the cycle to be assessed
2. Run full core (R-Z) BISON calculations
3. Determine peak stress time(s) and axial location(s)
4. Develop (R-\(\theta\)) local effects BISON inputs from R-Z results
   - This needs some level of automation or a procedure of its own. Otherwise the task is too complicated for the general user.
5. Run local effects (R-\(\theta\)) BISON calculations
   - VERA needs meshing capability to do (R-\(\theta\)). Cubit only available to government employees.
6. Analyze R-\(\theta\) results in VERA and determine limiting assemblies/rods
7. Compare against PCI threshold to determine fail/no fail for limiting rods

Both needs are being actively investigated by CASL
Summary

- EPRI is excited to be at the value demonstration stage of VERA development
  - There is a significant amount of potential value VERA can deliver to the industry
  - EPRI has several CASL milestones in 2019 alone to serve as value demonstration for the industry
- There are some usability concerns that must be addressed for VERA usage to be sustainable post-CASL and/or with a larger user base
  - Working installs
  - Documentation
  - Error messages
  - Analysis procedures

What can the User Group do to help?
Together...Shaping the Future of Electricity