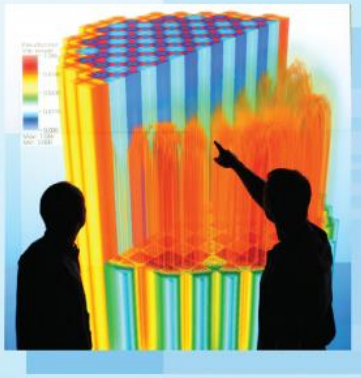
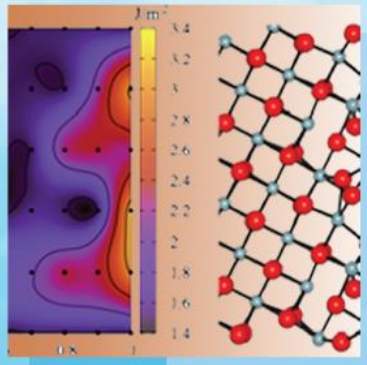
CASL-U-2013-0117-000-a

Power uprates
and plant life extension



Engineering design
and analysis

Science-enabling
high performance
computing



Fundamental science

Plant operational data

Consortium for Advanced Simulation of LWRs

L1:PAC.P6.04
Westinghouse Test Stand Technical Readiness Review

Andrew Godfrey
ORNL

Completed: June 25, 2013

U.S. DEPARTMENT OF ENERGY | Nuclear Energy

Consortium for Advanced Simulation of LWRs

Consortium for Advanced Simulation of Light Water Reactors
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Email: casl-info@ornl.gov

Date: 6/25/2013

To: Jess Gehin

c: Erik Walker, Mark Baird,

From: Andrew Godfrey

Subject: Westinghouse Test Stand Technical Readiness Review

Jess,

I have completed a thorough technical review of VERA capabilities which are relevant to the goals of the upcoming test stand delivery at Westinghouse, based on the requirements provided by Bob Oelrich and others in Reference 1 below. This memo provides documentation of the readiness of VERA to support the test stand at this time. Attached is the completed review checklist discussed at the Test Stand Readiness Review Meeting held at ORNL on June 12, 2013. Included are eigenvalue and pin power comparisons to CE KENO-VI for over fifty cases used to assess VERA for its neutronics capability and accuracy.

The assessment of VERA's ability to support the relevant AP1000® calculations in Reference 1 was performed using a controlled version of the software components. The testing was performed by myself and Erik Walker on the following computers using the builds from Mark Baird at the following locations:

natasha.ornl.gov: /projects/vera/VERA_062413_final
titan.ccs.ornl.gov: /tmp/proj/nfi007/mbaird/VERA_062413_final

The source for these builds and supporting files (cross section libraries and material composition files) have been included in the appropriate repositories and tagged in source control.

The attached checklist contains the details of the assessment of VERA to support HZP BOL AP1000® neutronics analyses. At this time, the VERA components and capabilities which are believed to be ready to support this work are the following:

Insilico – Insilico (XSProc + Denovo) has been used for AMA Core Physics Problem 5 calculations (Ref. 2) to support the completion of the CASL Level 1 Milestone CASL.003 on June 7, 2013 (Ref. 3). The methods used in Insilico for these calculations were the SP_N transport approach with unit-cell generated homogenized cross sections. While it was shown to produce acceptable results for the start-up physics parameters in this milestone report, the Insilico methods are still under development and have known issues for the prediction of power distributions for 2D core and 3D cases. Cases ranging from 2D assembly lattices to 3D full and

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quarter core AP1000® calculations would be expected to run on the WEC computing resources using pin-homogenized cross sections and the SP_N neutron transport approach.

MPACT – MPACT has been tested for 2D single assembly configurations using the ORNL 60 group subgroup cross section library. The results are accurate and consistent with those found in Reference 4. However, while initial calculations have been performed, MPACT has not been fully evaluated and tested for 2D core and 3D calculations of eigenvalue and power distributions. MPACT could be expected to be applied to 2D lattices, as indicated in the checklist below, for AP1000® applications at this time. Development is continuing on the 2D core and 3D problems with the expectation that this capability can be used in a testing mode at the current time.

VERAIN – The common ASCII input current supports all the relevant Insilico and assessed MPACT configurations as documented in the checklist. This input is the only input supported or tested for this VERA application.

Please review the assessment in the attached checklist and feel free to let me know if you have any questions.

Regards,

Andrew T. Godfrey

References:

1. Test Stand Requirements Reference: R. Oelrich, F. Franceschini, K. Drudy, Memo: "Definition of Westinghouse Initial Test Stand Simulation Topic", Westinghouse, May 6, 2013.
2. A.T. Godfrey, "VERA Core Physics Benchmark Progression Problem Specifications", Revision 2, CASL-U-2012-0131-002, CASL, March 29, 2013.
3. J. C. Gehin, et. al., "Operational Reactor Model Demonstration with VERA: Watts Bar Unit 1 Cycle 1 Zero Power Physics Tests", CASL-U-2013-0105-000, CASL, June 7, 2013.
4. A.T. Godfrey, F. Franceschini, et. al, "Analysis of Two Dimensional Lattice Physics Verification Problems with MPACT", CASL-U-2012-0172-000, CASL, December 21, 2012.

Attachment: Readiness Review Checklist

Westinghouse Test Stand Readiness Review Checklist – Completed 6/25/2013

Test Stand Requirements Reference: R. Oelrich, F. Franceschini, K. Drudy, Memo: "Definition of Westinghouse Initial Test Stand Simulation Topic", Westinghouse, May 6, 2013.

High Level Capability Requirements (3Q2013)

1. Core physics analysis of AP1000® initial startup at HZP conditions
2. Core Physics Benchmark Progression Problems 1-5 (pertaining to AP1000®)

VERA Components Being Considered

1. MPACT with 60g ORNL sub-group library
   a. Evaluated for Core Physics problems 1 and 2 only. Not ready for 3D problems or 2D cores.
   b. Evaluated using 60g cross sections without Tungsten
2. Insilico (Pin homogenized SP_N only – S_N not being considered for Test Stand) with 252g IR library
   a. Evaluated only with SP3 and only with 2x2 mesh per pin
   b. 252 groups collapsed to 23 groups for the transport calculation

3. VERAIN – Assumed implicitly with the application of Insilico and MPACT.

1. Core Physics Problems Checklist†

"Ready" requires execution of all problems independently by AMA and confirmation of acceptable performance. Documentation of the results of any AMA testing to support the test stand release is preferred, and software performance can be included in the comments as appropriate, or attached at the end of this checklist. Additional information may be provided to provide an assessment of capabilities in addition to those requested in the table below.

Capability	Description	Comments	Ready
a. Problem 1	Predict reactivity for single solid fuel pin cells	Problems 1a-1e executed with both codes and compared to CE KENO-VI results. Insilico: Avg. eigenvalue difference = -252 pcm MPACT: Avg. eigenvalue difference = -255 pcm These cases execute in seconds on a single compute core.	☑

<table>
<tr>
<td>b. Problem 2</td>
<td>Predict reactivity and pin power distributions for 2D lattices - excluding gadolinia cases, which aren't required for the AP1000® test stand.</td>
<td>Problems 2a-2q executed for both codes and compared to CE KENO-VI results. The pin power (fission rate only) comparisons are provided in absolute percent $(P_2-P_1)\times100$.
<table>
<tr><th>Insilico</th><th>Eigenvalue (pcm)</th><th>RMS (%)</th><th>Max (%)</th></tr>
<tr><td>Average</td><td>-101</td><td>0.29</td><td>0.64</td></tr>
<tr><td>St. Dev.</td><td>90</td><td>0.23</td><td>0.50</td></tr>
<tr><td>Max</td><td>-264</td><td>1.02</td><td>2.23</td></tr>
</table>
<table>
<tr><th>MPACT</th><th>Eigenvalue (pcm)</th><th>RMS (%)</th><th>Max (%)</th></tr>
<tr><td>Average</td><td>-101</td><td>0.19</td><td>0.56</td></tr>
<tr><td>St. Dev.</td><td>188</td><td>0.12</td><td>0.82</td></tr>
<tr><td>Max</td><td>346</td><td>0.53</td><td>3.48</td></tr>
</table>
MPACT performs well for all cases except for 2J (appears to be a bug). Insilico pin power accuracy decreases for the control lattices.

These cases run in less than 1 minute on 8-16 compute cores for both codes. For MPACT, the IFBA lattices require ~6 minutes due to the decreased ray spacing required.</td>
<td>☑</td>
</tr>
<tr>
<td>c. Problem 3</td>
<td>Predict reactivity and pin power distributions for 3D assemblies – including spacer grids, Pyrex, and axial structure geometries</td>
<td>Problems 3a and 3b executed with Insilico and compared to CE KENO-VI.
<table>
<tr><th>Insilico</th><th>Eigenvalue (pcm)</th><th>RMS (%)</th><th>Max (%)</th></tr>
<tr><td>Average</td><td>-46</td><td>1.07</td><td>3.10</td></tr>
<tr><td>Max</td><td>-47</td><td>1.19</td><td>3.48</td></tr>
</table>
Insilico exhibits larger than expected axial power deviations at spacer grid locations and at the top and</td>
<td>☑</td>
</tr>
</table>

<table>
<tr><td></td><td></td><td>bottom regions of the fuel. These cases we run with 16 cores in ~8 minutes (32 GB).

MPACT 3D capability was not ready for testing at time of evaluation. Issues exist for the output pin powers and the inserted pyrex for Problem 3b.</td><td></td></tr>
<tr><td>d. Problem 4</td><td>Predict reactivity, pin powers, and control rod worth for a 3D 3x3 assembly configuration – including Pyrex and hybrid control rods</td><td>Problem 4 (12 cases) was executed with Insilico only with the following results:
Average eigenvalue difference of 18 pcm (64 pcm maximum difference)
3D pin power comparisons of 1.3% RMS and 4.7% maximum difference
3D assembly power comparisons of 1.2% RMS and 2.8% maximum difference
Average Differential Rod Worth difference of 10 pcm (21 pcm maximum difference)
Integral Rod Worth error of -3.2%
Insilico results are very good for reactivity but power distribution differences are larger than desired and requires additional methods development and testing. Each of the cases ran on 144 cores in under a minute (288 GB).</td><td>☑</td></tr>
<tr><td>e. Problem 5</td><td>Predict the criticality, control bank worths, boron worth, and temperature coefficient for a startup core (WBN1)</td><td>The ten critical configurations for Watts Bar Nuclear 1 (WBN1) were executed with Insilico and compared to CE KENO-VI and measured data.
<table>
<tr><th>Insilico</th><th>KENO-VI Difference (pcm)</th><th>WBN1 Difference (pcm)</th></tr>
<tr><td>Average</td><td>190</td><td>102</td></tr>
<tr><td>St. Dev.</td><td>53</td><td>30</td></tr>
<tr><td>Max</td><td>253</td><td>169</td></tr>
</table></td><td>☑</td></tr>
</table>

		The Insilico cases were executed using 720 cores (1.4 TB) and about 30 minutes walltime each. However, further testing revealed that the calculations could be run on as few as 80 cores if each core was allocated 8 GB (requires about 1 hour or walltime) The axial mesh size used for these calculations was increased to ~3" between spacer grids. These affected the core reactivity by less than 2 pcm. Axial power distribution convergence is reached at ~0.5", which requires ~4 TB of memory and perhaps ~500 compute cores. Power distribution was not evaluated for this test since a reference solution is not currently available.	
f. Extension of Pb. 5	Predict the pin power distribution for a 2D core (problem 5-2D)	Problem 5-2D was executed with Insilico on 144 cores (288 GB) in approximately 3 minutes with the following results: • Eigenvalue differences of 86 pcm and 111 pcm • 2D pin power comparisons of 2.5% RMS and 6.2% maximum difference • 2D assembly power comparisons of 2.2% RMS and 4.5% maximum difference • AIC Rod Worth error of -4.1% Insilico exhibits a clear radial power distribution tilt compared to CE KENO-VI, with assembly powers underpredicted in the core center by >4%, and assemblies adjacent to peripheral locations overpredicted by ~2.5%. This radial power distribution error requires further investigation and testing.	☑

†reactivity and worth calculations require only system eigenvalue (k-effective). Pin power distributions require appropriate normalization of fission rates (at a minimum) or energy deposition (preferable).

2. Additional AP1000® Requirements

"Ready" requires AMA confirmation and execution of suitable test problems to confirm acceptable performance.

Capability	Description	Comments	Ready
a. IFBA	Predict the neutronics effects of IFBA on problems of all scales, up to whole-core analyses	Insilico handles IFBA explicitly in the 1D cross section solution for energy collapse from 252g and for cross section homogenization. This results in a small increase in run time for the cross section generation but no effect on the transport time. The IFBA lattices for problem 2 are accurately predicted and, due to the homogenization, the full core model is expected to have similar issues as cores without IFBA. MPACT treats IFBA explicitly in the transport calculation and requires a ~5-10x increase in computation requirements to resolve the thin layer. This approach works well for the Problem 2 lattices, but it has not been evaluated for full core problems and is expected to significantly increase computing requirements.	☑
b. Grey control rods #1	Accurately model Tungsten control rods and their effects	2D lattice calculations were performed with Insilico and CE KENO-VI using a publicly available model for tungsten control rods. These results agreed well with a 34 pcm difference in reactivity and 0.15% pin power RMS (0.44% max difference). MPACT was not tested for Tungsten because the 60g subgroup library does not yet support it. A 64g development library does have Tungsten and will be evaluated for future release.	☑
c. Grey control rods #2	Support composite CRs (e.g. two concentric rings of tungsten and	This capability was tested with the 2D tungsten lattice from the previous item.	☑

	inconel)		
d. Grey control rods #3	Support composite RCCAs (e.g. 20 stainless steel rodlets plus 4 rodlets of Ag-In-Cd)	This capability is supported. A simple test case was executed successfully with Insilico, and there are no differences expected with MPACT that will cause a problem.	☑
e. Axial heterogeneity: fuel #1	Support modeling of axially heterogeneous fuel rods with blankets and "cutback" regions	This capability is supported by allowing an arbitrary number of stacked lattices to be defined for each unique assembly type. A simple test case was executed successfully with Insilico, and there are no differences expected with MPACT that will cause a problem. Note that with MPACT, the use of model definitions that lead to thin planes has not been fully evaluated and tested for solution stability, so complex axial geometries may need to be approximated.	☑
f. Axial heterogeneity: inserts	Support modeling of axially heterogeneous inserts (e.g. B-10 poisoned with Zr blanket)	This capability is supported by allowing an arbitrary number of stacked lattices to be defined for each unique insert type. A simple test case was executed successfully with Insilico, and there are no differences expected with MPACT that will cause a problem. Note that with MPACT, the use of model definitions that lead to thin planes has not been fully evaluated and tested for solution stability, so complex axial geometries may need to be approximated.	☑
g. Annular fuel pellets	Accurately model annular fuel in the axial blanket region of the fuel assemblies	2D lattice calculations were performed with Insilico and CE KENO-VI using an approximate specification for annular blanket pellets (50% volume fraction). The lattice arrangement for these annular pellets was consistent with the pattern for 128 IFBA (Problem 2m). These results agreed well with a -64 pcm difference in reactivity and 0.28% pin power RMS (0.71% max	☑

		difference). The use of annular fuel does not impact Insilico due to the pin homogenization approach. However, MPACT is currently limited in modeling annular fuel simply due to limitations in defining the fuel pin mesh with the common ASCII input.	
h. Radial lattice heterogeneity	Model configurations of annular and solid rods in an axial slice	This capability was demonstrated with the previous item, with the MPACT meshing caveats as described.	☑
i. Axial heterogeneity: fuel #2	Support modeling of axially heterogeneous fuel rods with annular blankets and solid central portions	A sample 3D assembly problem was successfully executed with Insilico using 6" axial blankets with approximately half of the blanket being annular pellets (using the 128 IFBA pattern). Because of the 1D homogenized cross section approach with Insilico, this is not expected to be a problem. With MPACT, the current application could be limited by the ability to input appropriate meshing parameters.	☑
j. IFM Spacer Grids	Account for effects of IFMs on neutronics	Three sample IFM grids were added to a single 3D assembly model (Problem 3A) and successfully executed with Insilico. The grid depressions in the axial power distribution were as expected, in that they occur in the correct axial location and visually have a reasonable magnitude. Though MPACT has not been tested for a 3D assembly problem, it is expected that the IFM grids my need to be smeared in such a way to avoid an axial plane thickness that could lead to instability.	☑
k. 14-ft active fuel	Support modeling of 14-ft fuel	There is no expected impediments to modeling fuel stacks shorter or taller than 12-ft. The core height is entered by the user and all other axial	☑

		parameters are provided based on or relative to that quantity.	
I. Radial and axial heterogeneous reflector regions	Simulate axially and radially heterogeneous reflector regions (as needed)	Reflector regions are only supported consistent with the models used for WBN1. These are, specifically: • Specific definition of axial reflector regions for nozzles and core plates • Generic definition of axial reflector regions of arbitrary thickness, material, and volume fraction (consistent with 1D reflector models used with nodal methods) • Specific definition of a thin stainless steel baffle for the radial reflector Therefore, there are several restrictions currently for reflector treatments: • Cannot create "lattices" of arbitrary mixed materials to be used as reflectors • Cannot model core barrel, neutron pads, vessel, etc. • Cannot change radial reflector material (must be moderator) • Cannot model thick radial shroud-type reflectors While these capabilities appear to be sufficient for WBN1, it is not known if it will be acceptable for AP1000®. Insilico and MPACT support the same types of reflector modeling and have the same limitations.	☑

3. Additional Requirements

"Ready" requires AMA confirmation and execution of suitable test problems to confirm acceptable performance.

Capability	Description	Comments	Ready
a. Custom fuel enrichments	Support user specific enrichment or user defined fuel isotopics	A simple case was successfully executed with Insilico with a custom enrichment vector as: `u-235=20.0 u-234=0.0 u-236=0.0` Currently, this feature is not supported by MPACT, and only the U-235 enrichment may be input (the others are calculated by the code).	☑
b. Custom materials	Support materials and mixing, especially for those materials contained in AP1000®	Any material in the composition file (casl_comp_r2.sh5) may be mixed and used in the common input. Other materials are not supported. Materials included in the composition file are: AIC, Al2O3, B-10, B-11, B2O3, B4C, Boron, CS (carbon steel), Gad (Gd2O3), He, Inc (Inconel), O, Pyrex, SiO2, SS (stainless steel), Tungsten, Water, Zirc2, Zirc4, and Zr (pure zirconium). Currently, for Insilico, a single material must be declared on a mat card before it can be used in a mixture. Tungsten is not supported by the 60g subgroup library for MPACT. Note that MPACT does not use the composition file directly.	☑
c. Material input by atomic number density	Support specification of materials by atomic number density rather than weight fraction and density	This feature is not supported through VERAIN. MPACT can support this but through its own input structure.	☐

4. Expected Computational Requirements of VERA Components

"Ready" requires AMA confirmation that problems related to requirements can be executed with available resources.

Component	Description	Comments	Ready
a. MPACT	CPU, memory, and runtime requirements are expected to be within the availability for Westinghouse (approx. 256 cores with 8 GB memory per core) or other arrangements for sufficient computing resources has been made.	MPACT has only been evaluated up to problem 2, which can be run on almost any computer.	☑
b. Insilico		Insilico can run all the previously described neutronics problems on <= 80 cores. However, it is limited by the available memory. A quarter core AP1000® model is expected to require at least 80 cores and around 650 GB of memory. Note that the quarter core problems use a 3" axial mesh rather than a 0.5" axial mesh, which doesn't appear to affect reactivity significantly but will affect power distribution.	☑
c. VERAIN		The VERA input processor is not computationally limiting	☑

5. Available Documentation of VERA Components

"Ready" requires some level of user level documentation to assist test stand users in application of the software.

Component	Description	Comments	Ready
a. MPACT	Users and/or theory manuals are available to test stand users to assist them in model setup, execution, and post processing.	Not assessed here	☐
b. Insilico		Not assessed here	☐
c. VERAIN		Not assessed here	☐

6. Acceptance of Known Software Bugs or Issues

"Ready" requires AMA confirmation that any outstanding issues with the components will not inhibit performance for test stand application.

Component	Description	Comments	Ready
a. MPACT	Known bugs or activities to address current issues are not expected to negatively impact the	1. Combinations of Pyrex inserts and detector thimbles (Problem 2J) do not produce the correct	☑

	test stand activity. List issues by component with justification of acceptability.	power distribution. This is not expected to be a critical requirement of the test stand.	
b. Insilico		1. For full core 3D geometry (such as WBN1 Bank SC insertion), Insilico calculates the eigenvalue but crashes when writing its SILO file. However, the silo file is not likely to be used or needed for the test stand.	☑
c. VERAIN		N/A	☑

7. Review of Intellectual Property, Licensing, and Export Control Issues

"Ready" requires confirmation that there are no limits or restrictions to release of the VERA components or data to the test stand users.

Component	Description	Comments	Ready
a. MPACT	Software and data components have been reviewed and evaluated with respect to IP and EC issues and are deemed acceptable for release to the test stand.	Not assessed here	☐
b. Insilico		Not assessed here	☐
c. VERAIN		Not assessed here	☐

8. Summary Readiness of VERA Components

"Ready" requires successful evaluation of all items in the checklist and listing of any exceptions in the subsequent section. These exceptions must be deemed by AMA and potentially test stand users to be acceptable and not completely detrimental to the goals of the test stand.

Component	Description	Comments	Ready
a. MPACT	Reasonable confidence that the component can meet the test stand requirements to model Core Physics Problems 1-5 and the Westinghouse AP1000® initial startup at HZP conditions	MPACT has been tested and qualified for 2D lattice physics calculations consistent with Core Physics Benchmark Problem 2. The current version has not been confirmed to function for annular fuel or tungsten controlled lattices. Other caveats and bugs are included in Sections 6 and 9 of this checklist.	☑

		MPACT is not deemed ready for 3D physics problems or 2D core problems at this time but can be used for these problems for testing purposes.	
b. Insilico		Insilico has been tested for all of problems in this checklist and the results are deemed acceptable for preliminary eigenvalue calculations only. This assessment concludes that more research, development, and testing is needed before the accuracy in pin power distribution is reliable.	☑
c. VERAIN		The common ASCII input is implicitly used to support the evaluation of each of the included cases for both Insilico and MPACT.	☑

9. Summary of Exclusions and Caveats

a. MPACT not assessed for problems 3-5 or 2D core at this time until further development and testing is completed
b. MPACT does not support IFBA blanket lattices or tungsten control rods at this time.
c. MPACT does not support custom fuel isotopics
d. MPACT power distributions for 2D lattices are acceptable, but for 2D core and 3D problems these have not been assessed.
e. Insilico methods are still under development and from the results documented for these assessment problems, the power distribution accuracy for 3D problems, controlled lattices, and 2D cores is not as good as desired. Given deviations in power distributions, caution should also be exercised in relying on eigenvalue predictions
f. The Insilico results for WBN1 calculations are based on a 3” maximum axial mesh size rather than the converged mesh size of 0.5”.
g. Radial reflector modeling is limited to WBN1-type structures.
h. Gadolinia fuel rods not supported
i. All pin power distributions are “fission rate only” distributions

Items a-d are expected to be improved or eliminated in the coming weeks or months as MPACT development continues.