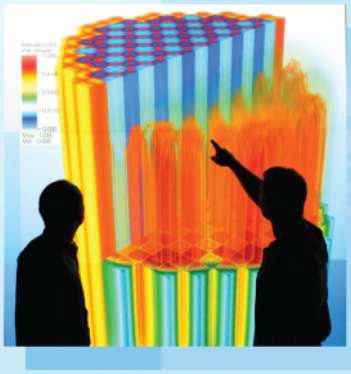
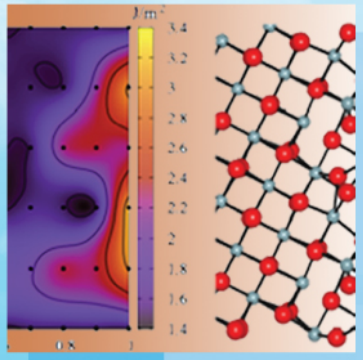
CASL-U-2014-0187-000

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

L2:AMA.P9.01 Update to Industry Test Stand Experience Using VERA

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ACRONYMS

AMA	Advanced Modeling Applications
CASL	Consortium for Advanced Simulation of Light Water Reactors
CE	Combustion Engineering
CFD	Computational Fluid Dynamics
CP	Challenge Problem
CRUD	Chalk River Unidentified Deposits (industry acronym for all issues related to deposition of impurities on the fuel and reactor internals)
CS	Core Simulator
DNBR	Departure from Nucleate Boiling Ratio
DoE	Department of Energy
EPRI	Electric Power Research Institute
FA	Focus Area
FY	Fiscal Year
HPC	High Performance Computing
HZP	Hot Zero Power
IFBA	Integral Fuel Burnable Absorber
ITC	Isothermal Temperature Coefficient
LPFA	Lower Plenum Flow Anomaly
NPP	Nuclear Power Plant
M&S	Modeling and Simulation
OD	Outside Diameter
PCI	Pellet Clad Interaction
PI	Principal Investigator
PoR	Plan of Record
PWR	Pressurized Water Reactor
QA	Quality Assurance
RCP	Reactor Coolant Pump
SCC	Stress Corrosion Cracking
SLT	Senior Leadership Team
SMT	Small Modular Reactor
TVA	Tennessee Valley Authority
VERA	Virtual Environment for Reactor Applications
WABA	Wet Annular Burnable Absorber
WBN	Watts Bar Nuclear
ZPPT	Zero Power Physics Test

1. INTRODUCTION

A critical focus of the Advanced Modeling Applications (AMA) Focus Area (FA) is to support the transfer and use of technology developed by the Consortium for Advanced Simulation of Light Water Reactors (CASL). A key element of this strategy is to deploy these technologies in Test Stand applications. During fiscal year (FY) 2014 a major AMA objective was to execute a Test Stand application at each of the founding industry partners in the consortium and to apply insights and feedback from these Test Stands to support an extensive and more effective technology transfer to the broader nuclear energy community. As a result of this focus, during Plan of Record (PoR) 8, AMA conducted a Level 2 Department of Energy (DoE) reportable milestone to describe experience with use of VERA in industry Test Stand applications (L2.AMA.P8.01). This milestone was successfully completed on 28 March 2014 and documented in CASL Report CASL-U-2014-0036-000 [1].

In this initial report, the purpose and objectives of this initial implementation of CASL Test Stands was summarized as follows [1]:

> The Consortium for Advanced Simulation of Light Water Reactors (CASL) is developing advanced modeling and simulation (M&S) capabilities to provide predictive performance of nuclear reactors with a special focus on several identified Challenge Problems (CPs). These CPs are intended to support development of advanced reactor analysis capabilities that apply high performance computing (HPC) capabilities to analyses of critical issues to commercial nuclear power plants (NPPs). The capabilities being developed by CASL are intended to provide analytical capabilities (methods, models, and computational tools) that can be applied to support NPP power uprates, life extension, and use of higher burnup fuels. A critical element for the success of the CASL M&S hub will be the ability to transfer the technology developed during the research and development effort (both methods and software) to end users (including the industry, regulatory and research communities) and for these end users to be capable of successfully applying these methods and tools to address critical issues related to the long-term efficient and safe operation of commercial NPPs. An important element to enable the achievement of this objective is the development and deployment of industry Test Stands. These Test Stands are intended to serve as a primary mechanism for initial early stage deployment of CASL developed technology to key stakeholders. The Test Stand concept was included in the CASL proposal to the US Department of Energy as an important means to achieve early deployment of the M&S technology and to provide a mechanism to obtain stakeholder feedback. Because the CASL technology is in an early stage of development at this time, the initial Test Stand applications are intended to be applied by the CASL core partners that are directly engaged in the operation of commercial NPPs (hereafter referenced as CASL industry partners), i.e. the Electric Power Research Institute (EPRI), Tennessee Valley Authority (TVA) and Westinghouse Electric Corporation (Westinghouse). Since these partners represent a broad spectrum of industry stakeholders (i.e. an industry funded research and development organization, an owner / operator of an integrated fleet of commercial NPPs, and a primary reactor vender involved with the design, construction and

technical support for commercial NPPs respectively), these partners provide an ideal initial environment to demonstrate and evaluate the capabilities and tools developed by CASL. It is expected that these organizations can provide constructive criticism and recommendations to CASL and facilitate actions that will enhance the capabilities methods and tools to meet the needs of the broad array of envisioned end users. Additionally, as partners in CASL, these organizations have participated in the CASL research and development and thus have familiarity with the CASL developed methods and tools. Because the CASL developed methods and tools are at a relatively early stage of development, this familiarity enables these organizations to compensate (to some extent) for items that currently are incomplete (e.g. documentation).

To support selection of appropriate Test Stand applications the AMA FA developed a process for evaluation of possible applications proposed by an organization interested in hosting a Test Stand. This selection process was then applied to evaluate several proposed applications from each of the CASL industry partners. The results of this effort were published in the CASL Report "Proposed Test Stand Selection Criteria" [2] which specified applicable evaluation criteria and a process for selecting the initial Test Stand applications. As a result the following applications were chosen for each of the CASL industry partners:

- Westinghouse – analysis of initial core load for the **AP1000**® reactor using VERA-CS.
- EPRI – pellet to clad interaction (PCI) analysis using the Peregrine fuel performance code with comparison to results obtained from the EPRI Falcon code.
- TVA – evaluation of the Lower Plenum Flow Anomaly (LPFA) phenomenon using Hydra-TH.

As indicated previously, AMA reported on the experiences obtained from these initial Test Stand applications [1]. The present report (which also represents a L2 CASL milestone in PoR 9 – L2.AMA.P9.01) provides an update on these experiences since completion of the PoR 8 milestone. Similar to the approach taken there, the intent of this report is *not* to provide detailed descriptions of technical results achieved (which, at this time are available for both the Westinghouse and EPRI Test Stands). Rather the focus of this report is to describe the experiences each partner has had with using VERA since the end of PoR 8. This experience includes either work conducted as part of the CASL Test Stand (EPRI and TVA) or, as in the case of Westinghouse, additional follow-on work using VERA since the completion of the Test Stand). As in the previous effort the intent is to provide relevant recommendations to CASL that result from those experiences. Additionally this report also provides a discussion of actions taken by CASL based on feedback from these initial Test Stands and the resulting outcomes achieved from those actions. Finally, we note that detailed technical results associated with the Westinghouse and EPRI Test Stands can be found in references [3] and [4] respectively.

As in the original report that described the experiences of each CASL industry partner [1], each partner wrote their particular section of this report independently. Thus, each section provides that partner's perspective on their experience using VERA for their particular application. In the compilation of this summary report, each section was incorporated essentially as provided by each partner to permit each partner's perspective to stand on its own. To provide the reader with some additional perspective, the relevant characteristics of each Test Stand application are summarized in Table 1-1. This summary provides an updated status of the Test Stand for each partner that was presented in the original report [1].

CASL Partner	Application	Tool / Characteristics	Approach	Status
Westinghouse	ZPPT modeling of **AP1000**® PWR first core design	Application of VERA-CS. Status of VERA-CS at time of Test Stand deployment included an initial demonstration of VERA-CS but did not include all elements necessary for conduct of analyses. At the time of Test Stand deployment VERA-CS capabilities needed for execution were still undergoing active development and some issues were fixed during the execution. Since the completion of the Test Stand additional analyses of the **AP1000**® PWR first core design have been performed.	Principal Investigator (PI) is experienced in core design, method validation and use of advanced reactor analysis tools. PI has been previously engaged with CASL AMA FA but had limited direct experience with VERA-CS when the analysis was started.	Complete
EPRI	Fuel performance analysis using Peregrine	Application of Peregrine fuel performance analysis module. At the time of Test Stand deployment the Peregrine capabilities needed for execution were still undergoing active development. Many Peregrine enhancements were completed over the course of the Test Stand. Additionally numerous CASL process improvements were implemented during execution of the Test Stand. These enhancements were instrumental in permitting successful completion of the proposed work scope.	PI is a recent PhD graduate with HPC experience and minimal prior interaction with CASL. EPRI mentor has extensive experience in fuel performance modeling (served as EPRI lead for the development of the Falcon code) and has had previous engagement with CASL AMA; however he has had minimal interaction with the Peregrine development team.	Complete
TVA	Evaluation of Lower Plenum Flow Anomaly (LPFA) using Hydra-TH	Application of Hydra-TH CFD methodology / code. At time of Test Stand deployment Hydra-TH capabilities needed for execution are still undergoing active development.	Test Stand in progress. Analyses being conducted on the Oak Ridge National Laboratory TITAN computer.	In Progress

Table 1-1: Summary of Characteristics for Initial CASL Test Stands

2. WESTINGHOUSE TEST STAND

The initial focus for the Westinghouse Test Stand was to employ the Core Simulator (CS) capabilities of VERA to conduct Zero Power Physics Test (ZPPT) simulations for the **AP1000**® pressurized water reactor (PWR) core design. This activity was conducted during PoR-8 (October 2013 – March 2014) by Westinghouse as part of CASL AMA milestone AMA.VDT.P8.01. This milestone was completed on 31 January 2014 with results documented in CASL report "Westinghouse VERA Test Stand: Zero Power Physics Test Simulations for the **AP1000**® PWR", revised in March 2014 [3]. This work represents the first completed application of CASL developed technology in a Test Stand environment and it has been a highly successful endeavor exceeding its objectives. VERA-CS was exercised, experience feedback was obtained and provided to CASL and important data to support the **AP1000**® PWR startup was obtained from Westinghouse.

Since the work performed and documented in references [3] and [1], Westinghouse has performed additional activities including extending the application of VERA-CS to other plants. These activities are summarized below.

The VERA Monte-Carlo capabilities provided by the SHIFT code have been applied to the **AP1000**® PWR startup core. The intent was to obtain a 3D core low-uncertainty Monte-Carlo solution for power distribution comparisons, specifically aimed at analyzing core configurations with multiple control rod banks inserted as these occur in the **AP1000**® PWR as part of the MSHIM™ advanced operational and control strategy[a].

Thanks to the SHIFT massively parallel capabilities, 3D core simulations emulating the **AP1000**® PWR MSHIM control bank position tracking up to 1 Trillion (10^{12}) particle histories have been performed on 240,000 cores at the ORNL "Titan" Leadership Computing Facility. These simulations were conducted as part of a 60 million core hour allocation that an ORNL and Westinghouse team was awarded during this project (Ref. [5]), and produced power distributions with very low statistical uncertainty that are of unique value for code benchmarking. Also as a result of this activity, the ORNL-Westinghouse team received the High-Performance Computing Innovation Excellence Award "for successfully performing innovative applications of HPC with significant benefits to industry and the general public"[b].

Westinghouse is now continuing to apply VERA-CS to the AP1000 PWR analysis, and specifically by using the MPACT code. Some issues related to the application of the 2D/1D approach to the **AP1000**® PWR have been identified and a resolution is underway; the preliminary results obtained show that further potential improvements are possible by adopting the 2D/1D approach compared to the original results obtained with INSILICO SP_N and documented in [3].

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[a] MSHIM is an advanced operational strategy that provides robust core reactivity and axial power distribution control with minimal changes to the soluble boron concentration in the reactor coolant, during both normal operation and power maneuvering scenarios. This strategy takes advantage of an increased presence of control rod clusters in the reactor core during at-power operation, which entails additional challenges on simulation.

[b] The HPC award is selected by international representatives from the HPC User Forum Steering Committee, and is sponsored by International Data Corporation (IDC), a premier global provider of market intelligence, advisory services and information technology events. Past winners of the award include Boeing, Rolls Royce, the Department of Defense, Procter & Gamble, GE Global Research and other organizations cutting across a wide range of the industry and scientific community.

As the depletion and coupling capabilities of VERA mature, Westinghouse plans to continue the AP1000 startup core analysis to encompass cycle depletion simulations. The results from this analysis can provide Westinghouse with valuable information to support the **AP1000**® PWR operation as the units under construction begin operation.

Following the successful application of VERA on the **AP1000**® PWR, Westinghouse has also extended its application to the analysis of currently operating reactors, besides Watts Bar Unit 1. The objective is to provide a wider validation basis for the adoption of VERA in the industry by verifying its performance on different cores and fuel geometries while identifying and resolving possible issues in due time.

With the above rationale, the Krško core is being analyzed by Westinghouse using VERA-CS and the predictions are being compared to plant measurements and to the Westinghouse in-house predictions. Krško is a 2-loop Westinghouse PWR situated in Slovenia that began electricity production in 1981. The startup core had a rated thermal capacity of 1,876 MWt; currently the thermal rating is 1,994 MWt with 696 MWe gross electric output. The Krško core consists of 121 fuel assemblies which is significantly smaller than a 4-loop core and potentially presents additional challenges to the power distribution predictions from typical core simulators as a result of the higher importance of transport-related effects. The fuel assembly is based on the Westinghouse 16x16 fuel lattice design, with 235 fuel locations, 20 guide thimbles and 1 instrumented thimble. Due to the asymmetry of the fuel and, thus, core design, full-core simulations need to be performed with VERA for the Krško core. This introduces a further computational challenge that VERA needs to be able to cope with as full-core simulations are sometimes necessary for the industry.

The Krško fuel active height is 144-in and encompasses a bottom grid and 6 mid grids, with a top grid outside of the active fuel height. The grids are made of Inconel with type 304 stainless steel sleeves. The presence of stronger neutron absorbers in Inconel and stainless steel leads to a larger flux depression in correspondence of the grids compared to Zr-based grids, which poses some challenges when modeling explicit grids with a lower-order neutron transport axially.

The clad is Zircaloy-4 with an outside diameter (OD) of 0.374 in, and a pellet OD of 0.3225 in; the fuel pitch is 0.485 in. This results in an H/U of ~3.6 and to a lower moderated lattice than other typical designs, e.g. ~ 4.0 for Westinghouse standard 17x17 fuel. This drier lattice and the ensuing harder spectrum lead to increased ^{238}U reasonance absorptions and higher Pu production, which can introduce some challenges to the self-shielding methods adopted in typical lattice codes.

The application of VERA to Krško is under way but the preliminary results show good performance at Hot-Zero-Power conditions [6] compared to the plants measurements, with the notable exception of the Isothermal Temperature Coefficient (ITC), showing a similar misprediction to what already has been reported in the past for the Watts Bar Unit 1 cycle startup analysis with VERA [7]. Code-to-code numerical benchmarks on power distribution from VERA-CS (MPACT) and SHIFT have also been performed for Krško, indicating excellent power distribution agreement on geometries up to full-core. The cycle depletion analysis is underway and will be reported in the future.

As a result of the VERA-CS application from Westinghouse, the following summary considerations on its performance are made.

- VERA-CS simulation decks are convenient to setup thanks to the VERA common input. Westinghouse has setup several cycle 1 cores already with reasonably small effort and short learning curve. VERA modeling capabilities provided are reasonably comprehensive, but limited to standard fuel lattices (e.g. square arrays, no CE-type lattices). One current limitation of VERA-CS that needs to be resolved is the lack of thermal expansion of fuel and structures from cold to hot conditions, which affects the reactivity and local power distribution predictions during actual operating conditions. More reflector geometrical options should also be provided beside the standard arrangement of a "jagged" (e.g. baffle-like) structure surrounded by water (e.g. it should be possible to model neutron pads and other neutronically relevant structures that may be present in some recent core designs).
- Computational time and computer resources required for 3D simulations with VERA-CS are still excessive for practical industrial usage, and at the current time exceeding the computer resources available on the Westinghouse VERA-dedicated computer cluster. Efforts towards mitigating VERA-CS computer resources are planned or underway, and it is understood that these detract resources from VERA development, but it is paramount to keep in mind that improvements in this performance area are crucial to ensure the long-term usability of VERA-CS.
- The power distribution agreement between VERA-CS and Monte-Carlo is excellent in most of the tested benchmark configurations, including entire 3D core geometries. The extent of the agreement and the level of detail provided in the prediction from VERA-CS (e.g. to the sub-pin level) are key areas of improvement compared to current industrial simulators. Some areas where additional investigation for potential improvements can be made are: a) radial power tilt between VERA-CS (MPACT) and SHIFT for core configurations including reflector region (this behavior is evident in 2D core slice configurations); for the **AP1000**® PWR there are specific challenges related to the fuel axial heterogeneities and presence of partially inserted control rod banks that may require further developments in the MPACT code and associated libraries. (This is an area currently under investigation.)
- The performance on the prediction of Hot-Zero-Power core parameters, like startup critical boron concentration, rod worth and boron worth is very satisfactory and, for most cases, within the expected measurement uncertainties. There appears to be a systematic negative bias in the ITC prediction of the simulated cores compared to the plant measurements. The reason for this need to be investigated and a resolution must be pursued.
- It is premature to judge the cycle depletion performance of VERA, but this should be targeted as one of the main validation areas in the near future.
- While VERA-CS has been applied to a relatively large extent by CASL, it has been tested only for a limited set of simulations and it is not yet a mature tool. It will still take time, effort and validation work before it can be considered to reliably perform simulations for the wider range of commercial PWR core physics analyses. Therefore the feedback on its performance as described in this report should necessarily be taken as limited and provisional.
- VERA-CS documentation and output need to be improved. Documentation with the methods, engineering usage, up-to-date validation results and associated input decks could be useful for the novice but also more experienced users.

3. EPRI TEST STAND

The EPRI Test Stand was responsible for testing the fuel performance components of the Virtual Environment for Reactor Analysis (VERA) software. Specifically, the EPRI Test Stand applied the Peregrine fuel performance code with the objective of performing pellet-cladding interaction (PCI) analyses. The primary technical objective of this Test Stand was to evaluate the cladding inside surface hoop stress which serves as an indicator of PCI stress corrosion cracking (SCC) susceptibility. The primary logistical objective was to provide enhanced testing and feedback on the usability of the software using a non-CASL industry-class High Performance Computer system to aid in future development and deployment of VERA software and components.

This Test Stand was completed as part of AMA milestone AMA.EPRITestStand.P8.01 on 1 August 2014 and is documented in CASL Report CASL-I-2014-0121-000-a [4]. The following work was performed as part of the EPRI Test Stand:

- Deployment of VERA on EPRI's high performance computer Phoebe.
- Training of the EPRI Test Stand team by the Peregrine development team.
- Execution of Peregrine on Phoebe for the seven EPRI-developed Test Stand progression problems.
- Preparation of a report describing the results and feedback from the Test Stand experience.

Since the initial deployment of the Test Stand and installation of VERA (VERA 3.3 DEV) on EPRI's high-performance computer in October 2013, three additional installations were performed in January, April, and July 2014 as additional Peregrine capabilities became. Similar to the initial installation, the CASL-developed tools, infrastructure and guidance documentation available for performing VERA installations greatly aided in updating the software and only minor issues were encountered which were resolved quickly with the help of CASL support staff. From the perspective of an industry end user the primary issues associated with this process included (1) the lag time between a VERA update request and a new version of VERA being made available to EPRI and (2) the lack of integration of the Peregrine test suite into the CASL quality assurance (QA) process. Although it is recognized that the Test Stands represent early application of CASL technology while it is undergoing active development, these two items did lead to unnecessary delays in the progress of the Test Stand. However it is believed that this situation could be rectified in future deployments as additional CASL process and infrastructure improvements are implemented.

The technical scope of the EPRI Test Stand included comparisons between the EPRI Falcon code and the Peregrine fuel performance code for a series of seven progression problems using three different geometric models, each with a different power history. These progression problems ranged from performing a thermal analysis of a single-cycle ramp and hold for a shortened test rod with a flat power history to performing thermal and mechanical analyses of a full-length pressurized water reactor (PWR) fuel rod using an axially-varying power history containing a first cycle ramp and hold followed by a short period of down time and a subsequent second-cycle ramp to full power. Both spatial and temporal analyses were performed along the axial mid-plane of the active fuel region as well as along the fuel centerline, fuel outer surface, and cladding inner surface. All results illustrated general agreement between the Falcon and Peregrine predictions for the model trends for temperature, displacement, and hoop stress. Significant differences in the magnitude of some of

these parameters during large power changes were observed and these differences are attributed thermal conductivity and/or volumetric heat generation rate model differences between the two codes.

The results obtained over the course of the Test Stand illustrated the potential of the Peregrine code to perform complex fuel performance analyses. The primary technical difficulties associated with running Peregrine included the following:

- The pellet-cladding contact implementation still experiences difficulties converging when complex real-world power histories are used on full length fuel rods.
- Some cases simply stall out and never reach completion; nor do they throw an error and terminate internally.
- Meshing and time step selection remain non-trivial and require numerous iterations by the user in order to obtain a well-behaved solution.

At the conclusion of the Test Stand (1 August 2014), these remain open issues requiring resolution. Since it is recognized that the Peregrine code is in a state of active development, issues such as this are anticipated to occur. As a result it is expected that these issues will be resolved as the Peregrine application (and the VERA tools in general) mature. Nevertheless, EPRI recommends that these items be specifically included in the Peregrine development plan and that the degree to which they have been resolved and the effectiveness of the implemented resolutions be tested and verified prior to a general VERA release that includes Peregrine.

Another outcome of the Test Stand experience is the evaluation of Peregrine for use by industry. In its current condition, which is uncoupled from the VERAIn framework, the learning curve for Peregrine is steep and its use, including input specification and output post-processing, is cumbersome. Therefore, EPRI recommends that Peregrine be integrated into VERA via VERAIn as well as the VERA common output structure when it is fully developed. Performing this activity will likely require development of a guidance document on Peregrine use in order to ensure that the most applicable models, constants, and solution methodologies are utilized for the targeted application(s). As an example, when performing PWR analyses using VERA, the *UO2Therm* fuel thermal conductivity model and *MechZry* cladding material model should be used and automatically set by VERA with the option made available to the user to override these selections.

In the previous report on Test Stand experiences [1] that was produced early in the EPRI Test Stand life cycle, EPRI characterized their experiences as neutral and provided suggestions to CASL on process changes that would improve the usefulness of Peregrine and the ability of CASL to respond to the end user needs. In response to the recommendations provided in the original report on Test Stand experience [1] and the ensuing discussions between CASL and the EPRI Test Stand team during the Test Stand, *EPRI now characterizes their experience as positive following the completion of the Test Stand*. The primary reasons for this change in outlook include the actions described below.

- The primary action taken that enhanced the Test Stand was implementation of a series of recurring meetings between CASL and EPRI personnel. These meetings consisted of two sets of alternating biweekly meetings. The first of these meetings constituted a detailed technical interchange between the Peregrine developers and EPRI Fuel Performance

technical staff who were actively running the Peregrine and Falcon codes. These meetings focused on discussing the technical elements associated with issues that were impacting the analytical tasks being evaluated in the Test Stand. The second set of meetings focused on project management between CASL support and quality assurance (QA) staff and EPRI. These meetings were instrumental in ensuring issues were proactively identified, prioritized and expeditiously resolved. As CASL enters into a Phase 2 effort where deployment (especially to end users which are not part of the CASL partnership) becomes a more significant focus, EPRI recommends that future Test Stands employ a similar support structure between CASL and the Test Stand sponsors to ensure effective and timely communication and resolution of issues as they arise.

- Another CASL process enhancement that was implemented during the EPRI Test Stand was the deployment of the CSICAT (CASL Support, Improvement and Corrective Action Tracking) system. This system provides an electronic mechanism to formally address and track support requests from users of CASL developed software. CSICAT provides a simple access via a dedicated e-mail address (support@casl.gov) where users can submit issues. These submissions are evaluated and prioritized. They are then routed to the appropriate CASL technical resource for resolution. CSICAT served as a useful system for effectively managing and resolving issues that arose over the course of the EPRI Test Stand as well as keeping individuals informed on the issues and their progression.
- An additional action that was helpful in increasing the efficiency of the EPRI Test Stand team was for the EPRI Principle Investigator to travel and meet / work with the Peregrine development team on several occasions. These opportunities to meet with developers and technical experts provided useful insight into the recommended usage of Peregrine. It is noted that the long-term solution to ensure successful usability of the CASL developed tools will be the development of adequate documentation and training. However, since Test Stands have been proposed as a critical activity during the CASL Phase 2 effort and the applications that will be addressed using Test Stands (at least in the early portion of Phase 2) will apply CASL tools that are still undergoing extensive active development, EPRI recommends that consideration be given to providing personnel engaged in Test Stand execution similar opportunities to interact directly with the relevant technical experts and code developers.

These actions and enhancements resulted in the successful development and integration of capabilities in Peregrine during the course of the Test Stand that were necessary to obtain reasonable estimates of hoop stress. The deployment of these code versions to the EPRI Test Stand team then permitted successful completion of the Test Stand within the revised project schedule. A fundamental conclusion reached as a result of the EPRI Test Stand experience is that communication between the Test Stand team, the software developers, and CASL leadership are critical to ensure a successful outcome. As a result EPRI recommends that future Test Stands implement appropriate planned communications between CASL and the Test Stand sponsors as part of the Test Stand deployment and execution to ensure effective and timely communication and resolution of issues as they arise.

At the conclusion of the EPRI Test Stand there are several recommendations provided in the original experience report [1] that require additional work to complete. These include the following recommended actions:

- Instructions for building and updating standalone Peregrine need to be included in the VERA Installation Guide until Peregrine is integrated into VERA and executable via the VERA common input.
- Improvement in the development process as it relates to the source code repositories such that Test Stand users can obtain code revisions in an expedited fashion. With respect to this recommendation, it is understood that at this stage VERA consists of research codes that are undergoing active development; however, to effectively support Test Stands a more rapid development cycle is needed.
- Establish configuration and control protocols to ensure that the correct documentation (including installation, testing, and user manuals) are provided for each capability contained within VERA.
- Prepare a description of capabilities for each VERA release to provide sufficient detail to support the end user determination which analyses VERA can support for a given application.
- A thorough review of configuration control and release protocols must be performed to ensure that sufficient capabilities are available to support the proposed Test Stand applications.
- Development of user support documentation for Peregrine to support potential near-term deployments.

4. TVA TEST STAND EXPERIENCE TO DATE AND STATUS

Over FY2014, Tennessee Valley Authority (TVA) began a Test Stand focused on simulating reactor flow in the lower plenum. The objective of the Test Stand is to see if a known reactor flow anomaly, Lower Plenum Flow Anomaly (LPFA), could be simulated with Hydra-TH and to develop a better understanding of the sensitivity of the flow distribution to differential inlet flow.

Additionally, TVA initiated, participated in, and supported a core cycle design and economic analysis of a Small Modular Reactor (SMR) using VERA-CS. While the work was primarily completed by a University of Tennessee – Knoxville (UTK) masters candidate, the work was a continuation of TVA-funded work that began in FY2013 when the student worked for TVA as an intern. While this work was not formally a Test Stand, it was an early application of the tools that provide an opportunity for industry user feedback.

Feedback experience from both of these activities is provided.

A. LPFA Test Stand Experience to Date

The TVA LPFA Test Stand application intends to primarily utilize the Hydra-TH capability. Output from Hydra-TH is intended to be used as input to VERA-CS to reflect the coolant flow distributions used to calculate the core power distribution; which is proposed by TVA as a follow-on activity. This Test Stand is in progress at the time of this report.

The primary workscope of the TVA LPFA Test Stand is divided into the following progression steps:

1. Demonstrate ability to create an appropriate mesh and determine the mesh density necessary to observe the desired flow granularity;
    - Three to five mesh versions (coarse, moderate, and fine) for the inlet, downcomer and lower plenum without internals;
        - Explore boundary layer mesh requirements
        - Understand turbulence model performance
        - Gain experience with Hydra-TH beyond the small example problems
    - Add lower internals and mesh with a few mesh versions, beginning at the density indicated by the previous study
        - Target optimum mesh size for this type of problem
        - Understand convergence and computational requirements
    - Add very coarse mesh in the core region for porous media representation of fuel
        - Build in consideration for baffle flow/bypass flow
        - Understand feedback in lower plenum resulting from variations
    - Add upper head/internals/outlet regions as needed
2. Study the effect of inlet variations on the flow in the downcomer and lower plenum
    - Pump startup sequence
    - Swirling inlet
    - Typical imbalance in loop flow with some sensitivity studies
    - Objective is to identify actions to reduce the variation (or at least control it)

3. If a periodic coolant density/velocity variation is observed, model its impact on core power using VERA-CS

Because TVA does not own an engineering computer cluster capable of supporting this type of VERA calculation, TVA applied for an industry allocation on the ORNL Titan cluster in June 2014. The request was approved in July, with the export control classification review completed at the end of August. Although a CASL Test Stand is nominally 6 months in duration, TVA initially requested 12 months to complete the work, as the personnel running this Test Stand must support TVA's operating plants as their first priority. The current target end date for completion of tasks 1 and 2 is April 2015.

Status of the Work

To date, TVA has developed several meshes, ranging from coarse mesh of just the inlet nozzle to a fine mesh representation of the inlets, downcomer, lower plenum and lower internals (full 3D, developed by the University of Tennessee – Chattanooga (UTC) using their SimGrid meshing tools). At this time several efforts have been made to run these models in Hydra-TH, without success; however, the efforts have not been aggressive to date. Thus, as of the date of this report, TVA is still working on the very first problem in the progression described above.

Observations and Experience to Date

- Mesh generation capability, while not a specific development objective for CASL, should be addressed in some manner within the VERA toolset. From the perspective of a complete package and in order to appeal to new users, it would be desirable to package a mesh tool that is compatible with the CASL tools within VERA. For CFD applications, meshing forms a substantial fraction of user time and issues.
    - It should be noted that the Hydra-TH team has recommended some non-CASL mesh generation tools that TVA has used to create meshes for this Test Stand, and that the tools have been useful.
    - The advantages of including a meshing tool within the VERA toolset may include long-term compatibility, improved interoperability, an ability to create more specific output formats and post-processing subroutines, and a higher probability of user success.
    - At the present time, the only code that would use the meshing tool is Hydra-TH.
- The same observations can be made on visualization; however, the selected visualization tool should be compatible across all of the VERA tools (VERA-CS, Peregrine, MAMBA, etc.).
- At the beginning of the Test Stand, it was suggested that the Hydra-TH user group would be a means of providing user support. However, TVA has concluded that user groups are not a good substitute for dedicated user support. The Hydra-TH user group meetings were discontinued within two months of the beginning of the TVA Test Stand. Further, new users are hesitant to highlight what could be a stupid question on a wide-distribution user group email.
- Error messages from the Hydra-TH code are cryptic. Unless one is an experienced Hydra-TH user, it is almost impossible to determine the source of the issue.

TVA intends to continue pushing forward with the LPFA Test Stand. An update to this report should be provided in the second quarter of FY2015.

B. SMR Simulations

TVA utilized VERA-CS to design and complete an economic analysis of a typical SMR cycle. TVA began work on the SMR core cycle design in FY2013; however, for various reasons, none of the codes available to TVA (vendor and other commercial codes) could be used to simulate the SMR cycle. Thus, utilizing VERA to complete the core cycle design and economic analysis was a good fit for a test activity that exercised VERA capability to simulate a problem of value and interest to TVA. TVA worked with UTK to execute the simulations during FY2014. The simulation utilized publicly available information applicable to the mPower SMR design. In the future TVA expects to substitute proprietary data and re-run the simulation on an industry-class computing cluster. It should be noted that this was a neutronics-only study; coupled thermal-hydraulics capabilities were not tested.

Status of the Work

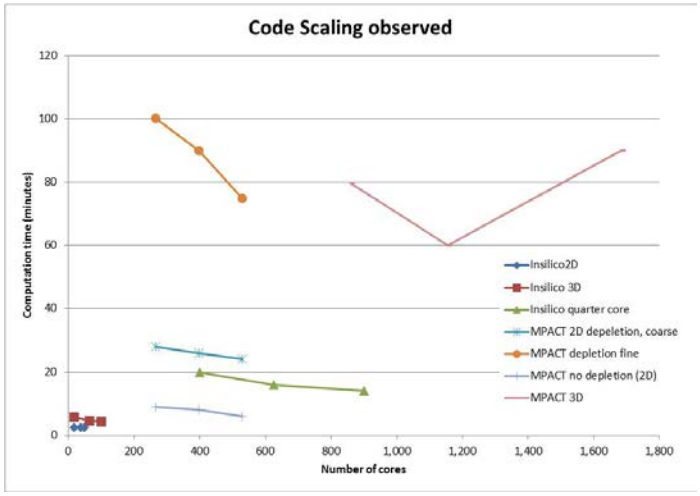
The TVA SMR analyses are considered to be complete, although some planned simulations were not completed. The final report which includes technical details associated with the analyses performed is available on the CASL website and is described in reference [8]. TVA plans to run follow up simulations with VERA (outside of CASL) with proprietary data in FY2015.

Observations and Experience to Date

VERA-CS and the common VERA input evolved by orders of magnitude during FY2014. At the beginning of the SMR analysis project there was very little documentation available, but by the end of the project the wiki had evolved sufficiently to provide some level of user guidance. Likewise, at the beginning of the SMR analysis project, depletion capability (among other necessary code capabilities) was not yet available, but by the end of the project, 3D depletion was available and was used as a part of the study. Thus, patience and flexibility were necessary.

Overall, learning to use the VERA-CS common input was fairly easy. However, there were several issues encountered that CASL should consider addressing in future development:

- The common input includes parameters that control the number of processors to be used that must be considered in conjunction with the mesh parameters that are input by the user. An inefficient specification of these parameters can lead to longer runtimes. This was observed within the SMR analysis project as a part of a small scaling study. Seven of the study runs were performed varying the number of processors used. The figure at the right (taken directly from ref. [8]) illustrates good scaling with the number of processors used with the exception of the point at the far right. It is believed that an unfavorable partitioning/processor scheme caused the upturn shown. Better guidance, examples, and/or a built-in specification for the parameters strongly influencing scaling should be considered.



- The same keyword is repeated in different input blocks; this is acceptable within the structure of the code but can be a source of confusion and error for users.
- It is not always clear when particular inputs are needed within each block of input. It is likely that this will be resolved with improved user documentation that is being prepared.
- Some aspects particular to SMRs could not be modeled with the current VERA-CS (Insilico), such as the thicker and denser core baffle region. In Phase 2 CASL should review VERA to determine if it can fully model the currently proposed SMRs.
- Several convenience codes were developed by PHI and are used to pre-process the VERA-CS output for visualization codes. The convenience codes are necessary to make sense of the VERA output and should be integrated to VERA after being QA'd. CASL should consider how it will ensure a standardized visualization capability for VERA users.
- In general, user support for this study was excellent, since TVA/UTK had direct access to PHI staff for quick resolution of issues. The one-on-one support model results in very good customer support but is likely to be untenable as more users are added. It is recommended that CASL establish more extensive documentation and a variety of example problems as soon as possible. Establishment of the TDO team in Phase 2 of CASL is expected to address some of the documentation and user support issues.

Because TVA doesn't currently own an engineering computing cluster capable of running the necessary simulations, several ORNL computing clusters were used, from the small Fissile Four cluster to the Titan Supercomputer. However, typical industry clusters should be capable of running the SMR analysis studies within a reasonable time frame (a few hours or overnight), including the 3D full core depletion simulations.

The work completed is currently incomplete as compared with the objectives of the analysis project, as the core cycle design did not consider control rod management. The depletion and 3D capabilities were available too late to support this study; however, it is likely that the work will be continued by others (e.g. either a SMR vendor or one of their potential customers). A tool that could be useful for

industry that hasn't yet been considered for VERA-CS is a core pattern optimization/search functionality. The technical results achieved with the Test Stand appeared to be accurate (see ref. [8]); however there is still much work to be done to validate VERA-CS to a point where financial decisions would be based upon its results.

5. CONCLUSIONS

This report describes experiences obtained from initial Test Stand deployments of VERA to CASL industry partners. It provides an update to experiences and recommendations previously described in the report CASL-U-2014-0036-000 [1]. At the writing of this update report, both the Westinghouse and EPRI Test Stands have been completed. In addition the TVA Test Stand has progressed from the planning phase to execution with work in progress.

As concluded in the original report on the Test Stand experiences described in ref. [1], these experiences to date have been positive. Key indicators for this conclusion are (1) continued use of VERA-CS by Westinghouse for **AP1000**® PWR assessments (after completion of their original test Stand) and (2) the progress made on Peregrine and the CASL support that supported a successful completion of the EPRI Test Stand. Given these successful outcomes, it is appropriate, however, to repeat the following from the conclusions section in the original Test Stand experience report.

> In assessing the experiences of each of the CASL industry partners that have implemented (or are in the process of implementing) a Test Stand, it is essential to remember that these Test Stands represent *very early deployments* of the VERA technology being developed by CASL. Since these deployments are being made using software that is in the process of undergoing substantial active development, it was anticipated that issues (associated with both technical capabilities of VERA and process issues associated with implementation) would occur. ... However, given the early stage of development / deployment of VERA, *one should view the primary value of the Test Stands as consisting of an opportunity to obtain critical feedback from eventual end users of the technology developed.* This feedback can then be evaluated and actions taken to ensure issues that could impact the broad community of external end users are addressed prior to a general deployment to them.

These observations remain relevant at this time and thus bear repeating. In anticipation of the CASL objective to continue with additional Test Stand deployments at external organizations (i.e. organizations that were not CASL partners during Phase 1), this perspective will have increased relevance for future deployments – thus leading to the enhanced emphasis included in the restatement of the conclusions from the original experience report.

Finally, the key observations and associated recommendations resulting from the Test Stand deployments that were described in this report and its predecessor [1] are summarized in Table 5-1. Several of these issues were previously identified in reference [1] and it is recognized that they are longer term issues that will take a significant amount of time to resolve; however they are of sufficient importance to be repeated in this summary as they are viewed as critical by AMA and the CASL industry partners for CASL to achieve its ultimate objective of having VERA be used and useful by the commercial nuclear power industry.

Issue	Recommendation
Large amount of computational resources and wall-time are required to execute VERA simulations. Computational time and required computer resources to conduct 3D simulations with VERA-CS continue to be excessive for practical industrial use.	Future CASL focus on calculation run-time optimization and making a broader range of capabilities available at the lower end of the HPC spectrum (i.e. industry class HPC) will be required.
Insufficient documentation currently is available to support effective end user applications of VERA.	Provide enhanced focus on end user documentation with particular emphasis on information necessary for end users to be able to successfully develop models and run the associated VERA modules that are necessary to obtain the desired analysis results.
Communications of VERA capabilities and expectations between CASL and end users.	CASL review configuration control and release protocols to ensure VERA technical capabilities meet needs / expectations of end users for proposed applications. Expand / enhance user support models developed and applied to EPRI Test Stand (e.g. frequent management and technical meeting between the domain experts, code developers and end users to ensure effective and timely communication and resolution of issues as they arise.
Challenges associated with generation of meshes to conduct analyses using VERA.	It is recognized that mesh generation capability is not a specific development objective for CASL. However because meshing issues continue to provide significant challenges in the use of VERA, the issue should be addressed in some manner within the VERA toolset. From the perspective of a complete package and in order to appeal to new users, it would be desirable to package a mesh tool that is compatible with the CASL tools contained within VERA.

Table 5-1: Summary of Key Test Stand Observations and Recommendations

REFERENCES

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[3] F. Franceschini, et al., "Westinghouse VERA Test Stand: Zero Power Physics Test Simulations for the **AP1000**® PWR"; Report CASL-U-2014-0012-000; March 2014 (Revision 1) (Accessible at the CASL website via the following link: http://www.casl.gov/docs/CASL-U-2014-0012-001.pdf)

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[6] F. Franceschini et al., "Simulation of the NPP Krsko Startup Core with CASL Core Simulator, VERA-CS"; Report CASL-U-2014-0182-000; September 2014 (Accessible at the CASL website via the following link: http://www.casl.gov/docs/CASL-U-2014-0182-000.pdf)

[7] Godfrey, A.; "MPACT Testing and Benchmarking Results"; Report CASL-U-2014-0045-000; March 2014 (Accessible at the CASL website via the following link: http://www.casl.gov/docs/CASL-U-2014-0045-000.pdf)

[8] Kenner, K.; CASL Report CASL-U-2014-0069-001 (Accessible at the CASL website via the following link: http://www.casl.gov/docs/CASL-U-2014-0069-001.pdf)