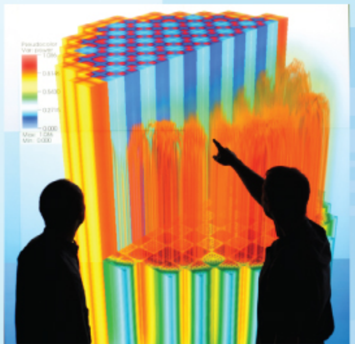
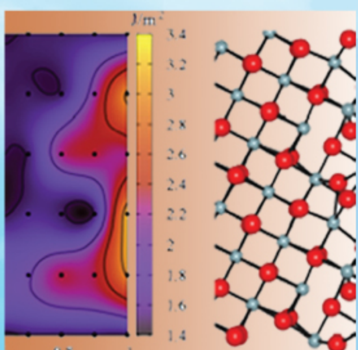
Power uprates
and plant life extension



Engineering design
and analysis

Science-enabling
high performance
computing



Fundamental science

Plant operational data

CASL-U-2013-0231-000

CASL
Consortium for Advanced Simulation of LWRs

High-Fidelity Neutronic Analysis of the Westinghouse AP1000

An Oak Ridge Leadership Computing Facility (OLCF) Early Science Demonstration using the GPU-accelerated Cray XK7 Titan System

Tom Evans
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Wayne Joubert
John Turner

U.S. DEPARTMENT OF ENERGY | Nuclear Energy

Oak Ridge National Laboratory

in partnership with

Electric Power Research Institute
Idaho National Laboratory
Los Alamos National Laboratory
Massachusetts Institute of Technology
North Carolina State University
Sandia National Laboratories
Tennessee Valley Authority
University of Michigan
Westinghouse Electric Company

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Southern States Energy Board
Texas A&M University
University of Florida
University of Tennessee
University of Wisconsin

EXECUTIVE SUMMARY

Title: High-Fidelity Neutronic Analysis of the Westinghouse AP1000

Application / Interest Areas:

- Advancing the clean energy agenda
- Broadening the community of researchers capable of using leadership computing resources

Principle Investigators:

- ORNL: John Turner, Tom Evans, Andrew Godfrey
- Westinghouse Nuclear: Fausto Franceschini

Co-Investigators (alphabetical):

- Wayne Joubert (ORNL)
- Steven Hamilton (ORNL)

Number of Processor Hours Requested/Awarded: 60M hours on ORNL's Titan Cray XK7 system

Primary funding source to support work: DOE Office of Nuclear Energy

The Consortium for Advanced Simulation of Light Water Reactors (CASL) is a Laboratory-Industry-University collaboration to develop and deploy advanced capabilities in the area of industrial nuclear power for electrical generation. The primary CASL software product is VERA, the Virtual Environment for Reactor Applications, which includes physics components for simulation of neutron behavior (neutronics), heat transfer and fluid flow (subchannel analysis and CFD), chemistry, and material behavior – all within a common software infrastructure.

The Oak Ridge Leadership Computing Facility (OLCF) was established in 2004 by the U.S. Department of Energy Office of Science Advanced Scientific Computing Research Program. In October of 2012, OLCF's Cray XT "Jaguar" system was upgraded to become "Titan", a Cray XK7 system with almost 300,000 conventional computational cores and over 18,000 NVIDIA Tesla K20x graphical processing units to become the fastest computer system in the world for open science.

As part of the OLCF Early Science program, a proposal to simulate Westinghouse AP1000 startup using three neutronics approaches implemented within the VERA neutronics package, Exnihilo, was granted an allocation of 60 million core-hours. This corresponds to over 8 days of continuous use of the entire Titan system, worth over $2M.

The three neutronics approaches to be applied to the AP1000 are:

- a low-order SP_N method of 3D deterministic neutron transport with pin-homogenized cross sections, which typically requires ~1000 compute cores,
- Denovo, a higher-order S_N method of 3D deterministic neutron transport using the KBA parallel algorithm, with excellent scaling up to the entire Titan system, including GPUs,
- Shift, a new high-fidelity continuous energy Monte Carlo based transport code that can also scale up to the entire Titan system and which will provide a reference solution for reactivity and nuclear fission rate distribution due to its rigorous spatial and energy treatment.

ACRONYMS

AMA	Advanced Modeling Applications
CASL	Consortium for Advanced Simulation of Light Water Reactors
DOE	U.S. Department of Energy
DOE-NE	U.S. Department of Energy Office of Nuclear Energy
EIH	Energy Innovation Hub
EPRI	Electric Power Research Institute
FA	Focus Area
HPC	high-performance computing
INL	Idaho National Laboratory
LANL	Los Alamos National Laboratory
LWR	light water reactor
M&S	modeling and simulation
MC	Monte Carlo
MIT	Massachusetts Institute of Technology
NCSU	North Carolina State University
NPP	nuclear power plant
NRC	Nuclear Regulatory Commission
NSSS	nuclear steam supply system
ORNL	Oak Ridge National Laboratory
PWR	pressurized water reactor
R&D	research and development
RSICC	Radiation Safety Information Computational Center
SNL	Sandia National Laboratories
T-H	thermal-hydraulics
TVA	Tennessee Valley Authority
UM	University of Michigan
V&V	verification and validation
VERA	Virtual Environment for Reactor Applications
WEC	Westinghouse Electric Company

Background on DOE Innovation Hubs

Energy Innovation Hubs bring together teams of scientists and engineers from academia, industry, and government to collaborate and overcome the most critical known barriers to achieving national climate and energy goals that have heretofore proven resistant to solution via the normal research and development (R&D) enterprise. A major new initiative within the United States (U.S.) Department of Energy (DOE) starting in Fiscal Year 2009, Hubs represent a new structure, modeled after notable research endeavors and institutes such as the Manhattan Project (nuclear weapons), the Massachusetts Institute of Technology Lincoln Laboratory (radar), and the AT&T Bell Laboratories (transistor), where a concentration of brainpower and resources enabled these integrated research centers to combine basic and applied research with engineering to accelerate scientific discovery in critical areas. Hubs are consistent with Brookings Institution's recommendations for *Energy Discovery-Innovation Institutes* to establish new research paradigms that leverage the unique capacity of America's research. Hubs focus on a single topic, with work spanning the gamut from basic research through engineering development to partnering with industry in commercialization, and consist of large, highly-integrated and collaborative teams working to solve priority technology challenges.

CASL Overview

The Consortium for Advanced Simulation of Light Water Reactors (CASL) is the first U.S. Department of Energy (DOE) Energy Innovation Hub, established in July 2010 for the modeling and simulation (M&S) of nuclear reactors. Led by Oak Ridge National Laboratory (ORNL), CASL is a consortium of ten core partner institutions and numerous contributing members that applies existing M&S capabilities and develops advanced capabilities to create a usable environment for predictive simulation of light water reactors (LWRs). This environment, the Virtual Environment for Reactor Applications (VERA), incorporates science-based models, state-of-the-art numerical methods, modern computational science and engineering practices, and uncertainty quantification (UQ) and validation against data from operating pressurized water reactors (PWRs), single-effect experiments, and integral tests. Using VERA, CASL develops and applies models, methods, data, and understanding to address three areas of nuclear power plant (NPPs) performance:

- Reducing capital and operating costs by enabling power uprates and lifetime extension for existing NPPs and by increasing the rated powers and lifetimes of new NPPs;
- Reducing nuclear waste volume generated by enabling higher fuel burnup, and
- Enhancing nuclear safety by enabling high-fidelity predictive capability for component performance through the onset of failure.

The CASL vision is to *predict, with confidence, the performance of nuclear reactors through comprehensive, science-based modeling and simulation technology that is deployed and applied broadly throughout the nuclear energy industry to enhance safety, reliability, and economics.*

Westinghouse and the AP1000

Westinghouse, one of the CASL industry partners and a world leader in nuclear technology, is deploying the **AP1000**® Pressurized Water Reactor (PWR), an advanced PWR with improvements in operational and safety performance with respect to current operating reactors. A VERA test stand focused on the core physics analysis of the **AP1000** advanced core design is currently under way using VERA-CS and the KENO MC-based code for the reference solution. The simulations performed here supplement and expand the test stand simulations with particular focus on analyzing the 3D power prediction capabilities of VERA-CS against the SHIFT MC-based solution. The **AP1000** with its heterogeneous advanced first core provides an ideal challenging scenario to test the prediction capabilities of the advanced tools developed by CASL. As an additional consideration, it is noted that the **AP1000** will operate following the MSHIM™ operation and control strategy. The MSHIM control strategy uses a combination of low worth (or gray) control cluster assemblies and standard (or black) control cluster assemblies to provide 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 necessitates an increased presence of control clusters (gray and black) in the reactor core during at-power operation. This operating scheme will further challenge core simulators, and can show and quantify the potential improvements fostered by adopting VERA for core analysis. As there are currently eight **AP1000** in various phases of construction, it will be possible in the relatively near term to obtain state-of-the-art measurements and startup physics tests to compare against the predicted values from the VERA tools.

OLCF Overview and the Early Science Program

The Oak Ridge Leadership Computing Facility (OLCF) was established in 2004 by the U.S. Department of Energy Office of Science Advanced Scientific Computing Research Program. OLCF systems are used by computational scientists across the country in academia and industry as well as at national laboratories to solve the largest computational challenges in the world. In October of 2012, OLCF's Cray XT "Jaguar" system was upgraded to become "Titan", a Cray XK7 system with almost 300,000 conventional computational cores and over 18,000 NVIDIA Tesla K20x graphical processing units to become at the time the fastest computer system in the world for open science. Titan's peak performance is now 27 thousand trillion floating point operations per second, approximately ten times the peak performance of Jaguar.

As part of the transition of the Titan system to broad operational use, simulation projects that had participated in the early efforts to demonstrate the effectiveness of an accelerated hybrid system such Titan were provided with the opportunity to apply the full computational power of Titan to new and compelling science and engineering challenges.

Application of the VERA neutronics components, Insilico and SHIFT, to analysis of the Westinghouse **AP1000** reactor was considered to be an ideal demonstration of both CASL technology and the OLCF Titan system.

Description of the OLCF Early Science Proposal

As part of the OLCF Early Science program, a proposal to simulate Westinghouse **AP1000** startup using three neutronics approaches implemented within the VERA neutronics component, Exnihilo, was granted an allocation of 60 million core-hours. This corresponds to over 8 days of continuous use of the entire Titan system, worth over $2M at current OLCF cost-recovery rates.

The three neutronics approaches to be applied to the **AP1000** are:

- a low-order SP_N method of 3D deterministic neutron transport with pin-homogenized cross sections, which typically requires ~1000 compute cores,
- Denovo, a higher-order S_N method of 3D deterministic neutron transport using the KBA parallel algorithm, with excellent scaling up to the entire Titan system, including GPUs,
- Shift, a new high-fidelity continuous energy Monte Carlo based transport code that can also scale up to the entire Titan system and which will provide a reference solution for reactivity and nuclear fission rate distribution due to its rigorous spatial and energy treatment.

Denovo, the deterministic neutron transport capability that has been under development at ORNL over the last several years, has been accelerated via CUDA implementation of the underlying wavefront algorithm as part of the Center for Accelerated Application Readiness (CAAR).

Although Shift has not yet been modified to take advantage of GPU acceleration, that effort is planned, and these results will also serve to provide performance data and inform that work.

One challenge, and novelty, of this project will be the extent of the simulations, which require a large fraction of Titan (up to the entire system) for up to 24 hours.

Together, these neutronics capabilities provide a range of approaches that trade fidelity and computational resource requirements. Choosing the most appropriate approach requires an understanding of these tradeoffs, and Exnihilo provides a unique ability to characterize these methods more directly than ever before, at unprecedented scales, on problems of immediate relevance for the nuclear industry.

Impact

Another unique aspect of this effort will be the potential to compare the results of these simulations to startup data from an advanced PWR, the **AP1000**. The advanced first core design and the novel MSHIM operation, together with a standardized first core (same in all the first wave of **AP1000**), as well as state-of-the-art measurement capabilities, add another dimension to the scientific value of this project. The goal is to complete at least some of the simulations by the end of December and to provide Westinghouse with the VERA prediction for the initial AP1000 startup physics tests

The Shift Monte Carlo results will rival, and potentially exceed, previous simulations, with respect to both fidelity (1 trillion particles or more) and geometry (a full reactor core), and these results have the potential to provide reference benchmark solutions to the reactor analysis community for years to come.

REFERENCES AND MORE INFORMATION

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