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The Virtual Environment for Reactor Applications (VERA) Design and architecture ☆

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A B S T R A C T

VERA, the Virtual Environment for Reactor Applications, is the system of physics capabilities being developed and deployed by the Consortium for Advanced Simulation of Light Water Reactors (CASL). CASL was established for the modeling and simulation of commercial nuclear reactors. VERA consists of integrating and interfacing software together with a suite of physics components adapted and/or refactored to simulate relevant physical phenomena in a coupled manner. VERA also includes the software development environment and computational infrastructure needed for these components to be effectively used. We describe the architecture of VERA from both software and numerical perspectives, along with the goals and constraints that drove major design decisions, and their implications. We explain why VERA is an environment rather than a framework or toolkit, why these distinctions are relevant (particularly for coupled physics applications), and provide an overview of results that demonstrate the use of VERA tools for a variety of challenging applications within the nuclear industry.

1. Introduction

The Consortium for Advanced Simulation of Light Water Reactors (CASL) is developing a collection of modeling and simulation (M&S) tools known as VERA, the Virtual Environment for Reactor Applications. VERA provides a software environment for the development and deployment of tools for analysis of operating light-water nuclear reactors, including:

- *Nuclear-specific input and output* to define, model, and analyze the performance of a reactor during nominal operation and anticipated operational transients;

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- *Nuclear-specific software* such as reactor neutronics, sub-channel thermal-hydraulics, and nuclear fuel performance, and cladding-coolant chemistry; and
- *Nuclear-specific physics integration* enabling coupling across physics domains while utilizing best-in-class algorithms for each domain to provide efficient nuclear-specific solutions.

VERA is neither a general-purpose numerical library such as Trilinos [1] or PETSc [2], a domain-specific framework such as OpenFOAM,[1] libMesh [3] or Deal.II [4], nor a monolithic application like those traditionally used in the nuclear industry such as COBRA-TF, RELAP5, or MELCOR. Instead, VERA combines capabilities such as these to enable development of nuclear-specific solutions, and as such provides an extensible platform on which nuclear reactor analysis applications can be built for decades to come.

VERA comprises four elements: 1) physics components, 2) numerical tools for solving coupled-physics problems, 3) drivers that execute the individual and coupled components, and 4) the infrastructure to develop high-quality software in a collaborative environment. In Section 2, the primary use cases and physics requirements are described. Section 3 describes constraints, defines terminology such as “software environment”, outlines the coupling strategy and physics components in VERA, as well as the general infrastructure required for collaboratively developing high-quality software from diverse, distributed institutions. This infrastructure includes a build/test system and strategy for input/output/restart. Finally, Section 4 provides specific application examples and Section 5 describes future directions for VERA.

Using VERA, CASL has developed a set of coupled applications for analysis of challenge problems of particular relevance to its industry partners, and these tools have been deployed and are being used for real-world applications [5–11].

2. Requirements

2.1. Challenge problems

A primary goal of CASL is to develop an understanding of several key “Challenge Problems” for the nuclear industry. The CASL Challenge Problems are described in detail in [12], and each requires a specific combination of physics, spatial and temporal resolution, and level of coupling/feedback between components. For example, the Pellet–Clad Interaction (PCI) Challenge Problem requires two tools: a scoping tool and a high-fidelity tool. The scoping tool is used to model every fuel pin in the reactor using lower fidelity two-dimensional models during an operating cycle and determine the operational procedures that would simultaneously maximize power generation and minimize the risk of fuel cladding failure. The high-fidelity tool includes a three-dimensional nuclear fuel performance code that can predict the detailed behavior of fuel to determine the likelihood and consequences of a fuel failure due to manufacturing defects or operational transients. The high fidelity tool is applied to fuel pins identified by the scoping tool as possible PCI failure candidates.

In each of the primary physics components, two levels of fidelity are required to solve the various challenge problems, but not all levels of fidelity need to be coupled. The following section discusses each of the physics components and their level of fidelity with respect to traditional nuclear industry tools. The VERA core simulator, referred to as VERA-CS, integrates each of the lower-fidelity components to provide a high-resolution (with respect to traditional tools) prediction of the operating history of the entire lifetime of a nuclear reactor over many fuel-loading cycles. This provides the initial and boundary conditions for many of the Challenge Problem high-fidelity analyses.

2.2. Physics components

Simulation of commercial light water reactors (LWRs) requires modeling capabilities for neutronics (generation and transport of neutrons through the reactor core), fuel performance (thermomechanical response of the fuel rods to generated fission energy, fission products, and material property evolution), and thermal-hydraulics (the removal of the energy generated within the core by the flow of water coolant). In addition, models for specific chemical and mechanical phenomena and the capability to represent a variety of geometric features are important for simulation of specific Challenge Problems being addressed by CASL.

Traditional approaches to simulating these phenomena have focused on modeling the relevant physics individually with separate codes, treating coupled phenomena with simplified models or as boundary conditions, and averaging the results over phase space (e.g. space, time and/or neutron energy) to simplify the coupled problem. A major objective of CASL is to achieve tighter integration and coupling of these phenomena within a unified multiphysics environment, with rigorous numerical approaches incorporating key feedback effects.

Table 1 lists in more detail the general needs for each of the relevant phenomena, including foundational physics, specific capabilities and quantities of interest needed to simulate CASL Challenge Problems, and the effects and variables important for coupling with the other phenomena areas. The subsections below discuss the needs for each of these phenomena.

[1] http://openfoam.org/.