Developing a Comprehensive Software Suite for Advanced Reactor Performance and Safety Analysis

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OUTLINE

Motivation
Approach
Target Applications
Innovations and Results
Pathway to Validation
Motivation

Approach

Target Applications

Innovations and Results

Pathway to Validation
The objective of the NEAMS program is to enable the design of future nuclear power stations and reactor cores:

- Implement enhanced safety and security features
- Enable more cost effectively producing power
- Plan for better utilization natural resources
Development

Applications and Usability

Validation and UQ

SQA including Verification
Applications and Usability

MOOSE, CouPÉ, MOAB, MB Coupler, NiCE, MeshKit

SQA including Verification
NEAMS ToolKit

Nuclear Energy
NEAMS Reactor Product Line
Participating Organizations

- Argonne National Laboratory
- Brookhaven National Laboratory
- Idaho National Laboratory
- Lawrence Livermore National Laboratory
- Lawrence Berkeley National Laboratory
- Oak Ridge National Laboratory
- Sandia National Laboratory
- City Colleges of New York
- George Washington U.
- Northwestern University
- Texas A&M University
- Univ. of California-Davis
- University of Idaho
- University of Illinois
- University of Michigan
- University of Tennessee
- University of Wisconsin
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Reactor Technology Neutral ToolKit

- Sodium-cooled Fast Reactor
  - Challenge: capture multi-physics, multi-scale reactor dynamics during transients

- Very High Temperature Reactor
  - Challenge: predict performance and safety consequences of core deformation over long times

- Small Modular Light Water Reactor
  - Challenge: evaluate performance and safety of coupled natural circulation systems
Reactor Technology Neutral ToolKit

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The Reactor IPSC toolset makes use of modern programming practices

- Modular approach
- Object-oriented programming
- Leverage existing code libraries
- Rigorous version control
  - Change tracking
  - Version recovery
- Automated documentation
- Automated verification
High-fidelity unstructured mesh neutronics tools enable exact representation of complex reactor geometries

- Minimize homogenization
- Make use of high resolution cross-section data
- Provide accurate predictions of local reaction rates
- Enable more accurate assessment of reactivity coefficients
  - Treat core distortion explicitly (when coupled to other physics)
Enables application of high-fidelity CFD tools to large reactor problems

- More accurate predictions of temperature and flow effects
- Reduced reliance on engineering correlations with limited applicability
- Capability for benchmarking or calibrating lower-fidelity methods
- Improved understanding of pin bundle flow and heat transfer phenomena
Enables structural analysis of reactor components in full geometric detail using advanced implicit finite element analysis toolset

- More accurate predictions of stress and deformation
- Integrated multi-physics simulations with structural deformation using adaptive mesh refinement or dislocation
- Reduced reliance on engineering correlations with limited applicability
- Capability for benchmarking or calibrating lower-fidelity methods
Provides next generation reactor system analysis capability

- Finite element approach
- 2nd order in both time and space
- Modern mesh-based data management approach
- Mix of advanced numerical solvers to enable both rapid and long term transient solutions
- Isolate reactor-specific models and data to external driver
  - RAVEN for LWR
  - BADGER for SFR
Advanced tools enable automated generation of computational meshes describing complex reactor assembly and core geometries.

- Problem definition using conventional text input file or CAD descriptions of geometries
- Automatic generation of high quality meshes for common reactor components
- Simplified integration of component meshes generated separately
Major Innovations of NEAMS Reactor IPSC

Provides first-of-a-kind capability for coupled multi-physics

- Enable split-operator integration of large high-fidelity physics simulations
- Do not require existing codes to be re-written within a Framework
- Support a wide range of mesh types
- Make use of higher-order information
Single EBR II assembly simulation
Artificial transient to show causality in multi-physics simulation
- Sudden increase in total power by 40%
- No change in flow or inlet temperature
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Objectives

- Support deployment of advanced simulation tools for nuclear systems
  - Time-resolved, high-spatial-resolution data on a high-field of view
  - Measurement time scale significantly smaller than smallest turbulence time scale of interest
  - Quantify differences between very large experimental dataset and very large simulation dataset
- Establish integrated experimentalist/analyst teams
  - Often don’t speak the same technical language
  - Rarely co-located (Very rarely the same person!)
- Provide mechanism for preservation of data, metadata and provenance
- Identify gaps in available data
- Begin to characterize specific contributors to overall validation uncertainty
- Define data requirements for future experiments
- Define requirements for multi-physics validation
Validation Experiment Hierarchy

Increasing Relevancy to Complete System

Complete System

Subsystem Cases

Benchmark Cases

Unit Problems

Rigorous Error Quantification is challenging

- Reported instrumentation error
- Instrumentation bias
- Repeatability error
  - Phenomenological time scale error
- Environmental bias
- Experimentalist bias
- End user bias
  - Comparison method bias
SHARP CFD Validation Foundation

- Initial focus problem area: thermal striping and stratification phenomena.
- Four co-developed jet experiments that are currently in progress have been identified as the source of preliminary data sets.
  - Each has been designed and operated as collaboration between experimentalists and the computational analysts.
  - Simulations have been used to make design decisions, place instrumentation, and interpret start-up testing results.
- Argonne MAX thermal mixing experiment
  - Examines the mixing of multiple temperature controlled air jets in a large air volume
  - Uses high resolution optical methods suitable for CFD validation.
- Nuclear Energy University Program Project
  - University of Idaho, - two jet mixing experiment using liquid sodium
  - University of Tennessee - two two-jet mixing experiments using water and liquid mercury