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Building Digital Laboratories for Nuclear Energy Innovation

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Consortium for the Advanced Simulation of Light Water Reactors

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CASL The Consortium for Advanced Simulation of LWRs
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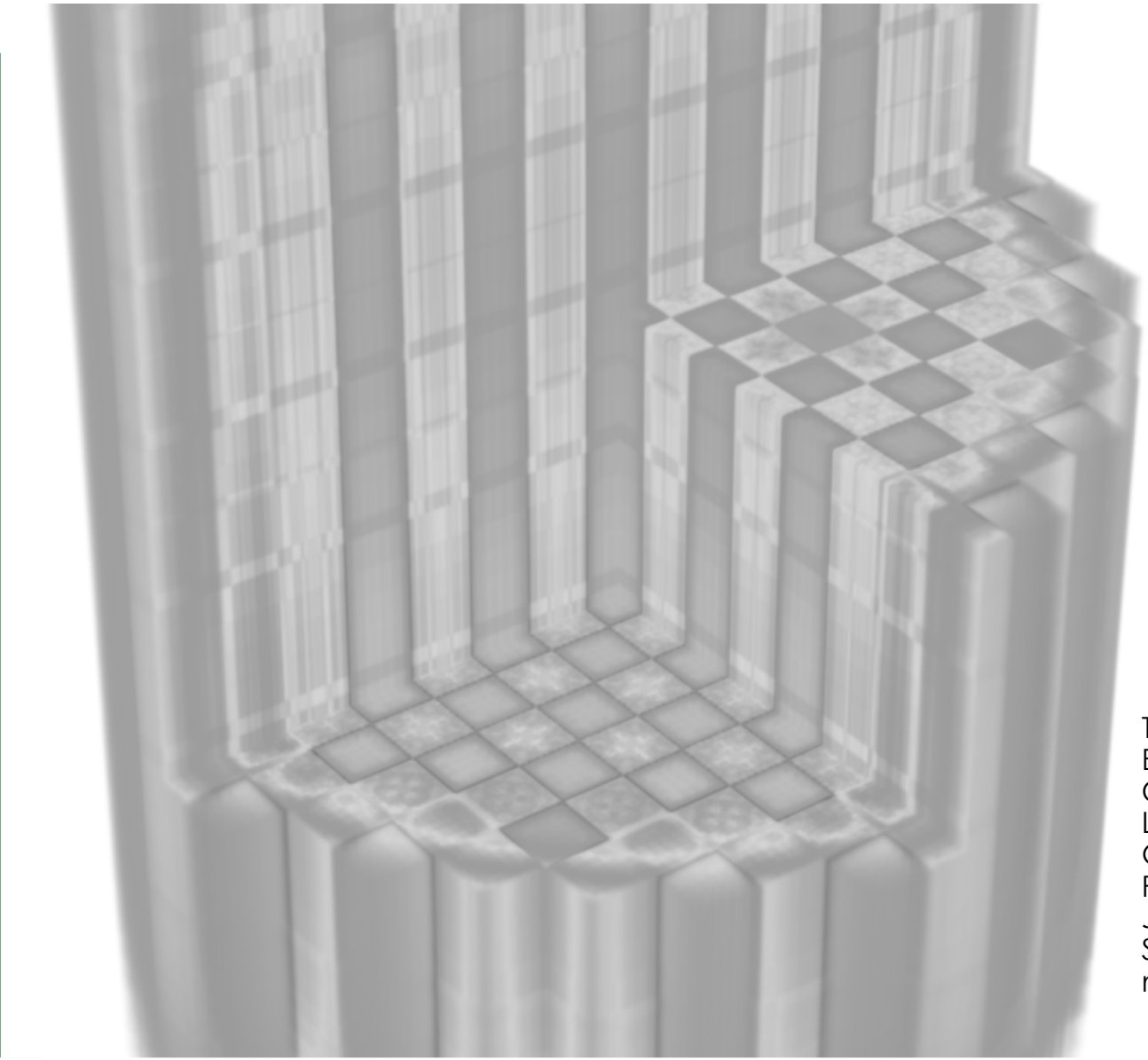
U.S. DEPARTMENT OF ENERGY



Acknowledgements

Thanks to Brian Ade, Emilio Baglietto, Igor Bolotnov, Robert Brewster, Sacit Cetiner, Kevin Clarno, Ben Collins, Marco Delchini, Jess Gehin, Lindsay Gilkey, Andrew Godfrey, Scott Greenwood, Will Gurecky, T. Jay Harrison, Prashant Jain, David Kropaczek, Rob Lefebvre, Jordan Rader, Bob Salko, Ramanan Sankaran, Stuart Slattery, John Turner, Aaron Wysocki, and many others for their input

What Drives Advanced Modeling and Simulation?

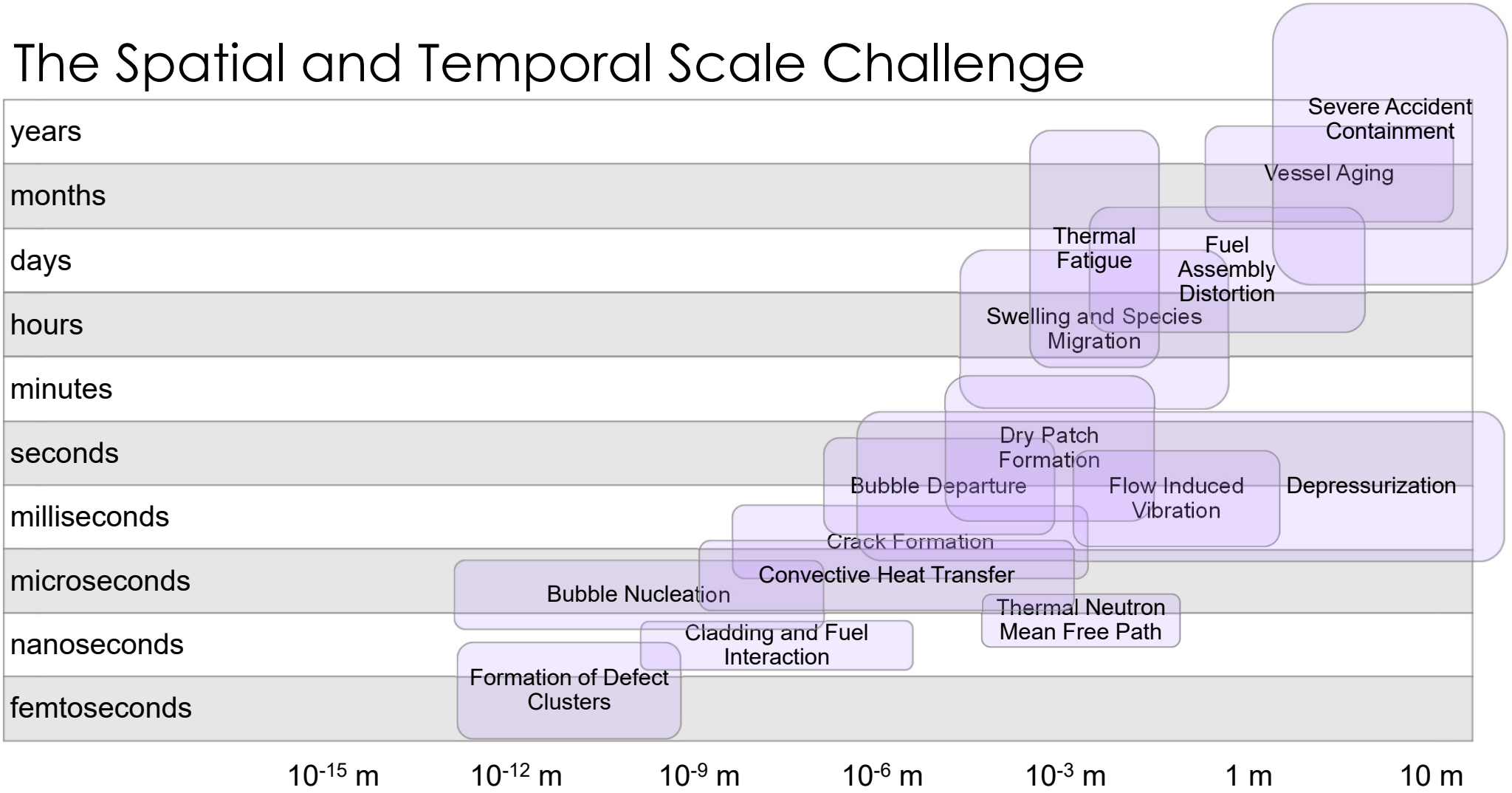
Address operational challenges in today's systems

- Understand causes of fuel failures that lead to premature replacement
- Understand causes of component failures that lead to premature replacement

Enable deployment of new systems, processes, components and features

- Load Follow
- Non-electric applications
- Advanced Technology Fuels
- Accident Tolerant Fuels
- Advanced Manufacturing
- Passive Safety
- Small Modular Reactors
- Microreactors
- Digital/Autonomous Control

The Spatial and Temporal Scale Challenge



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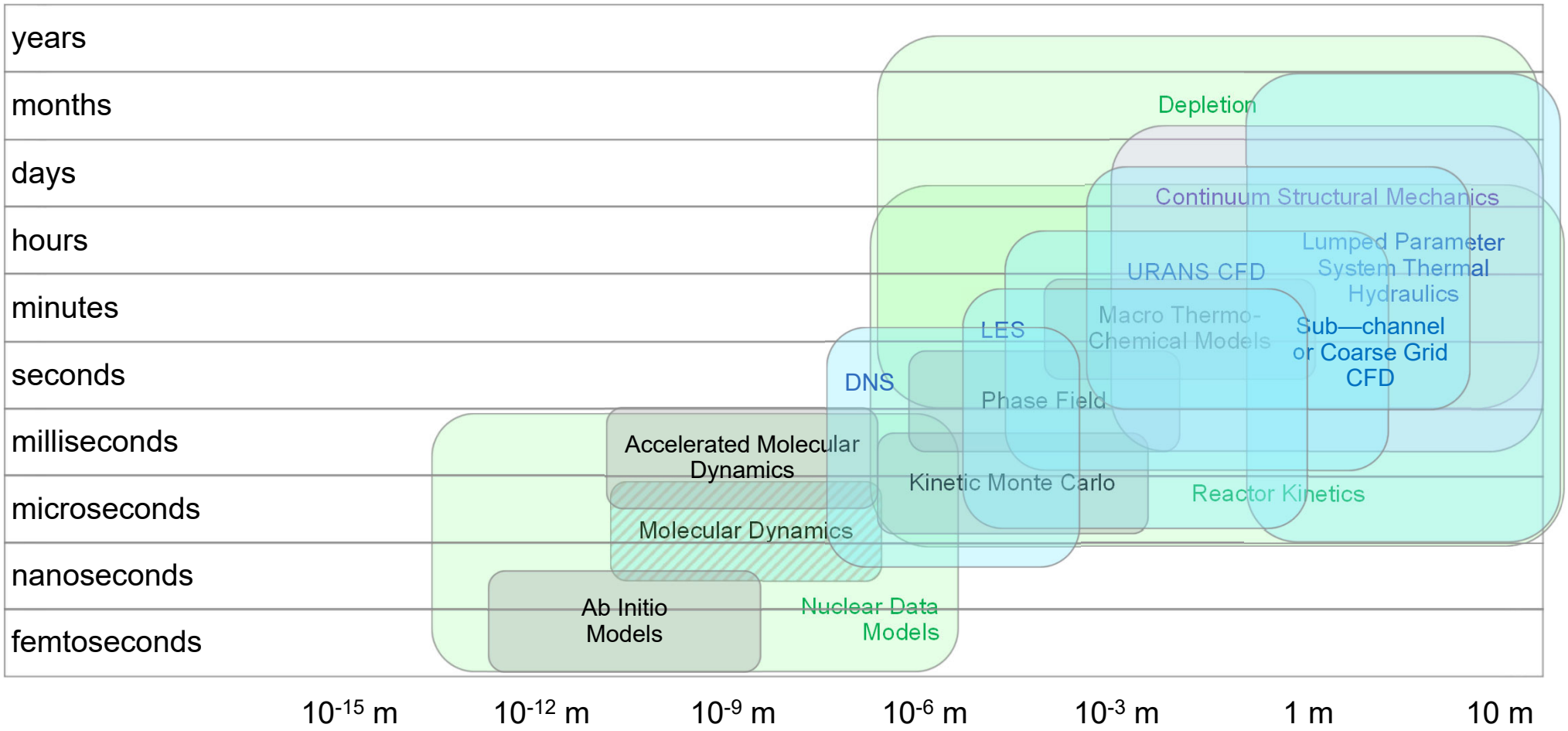
The Spatial and Temporal Scale Challenge



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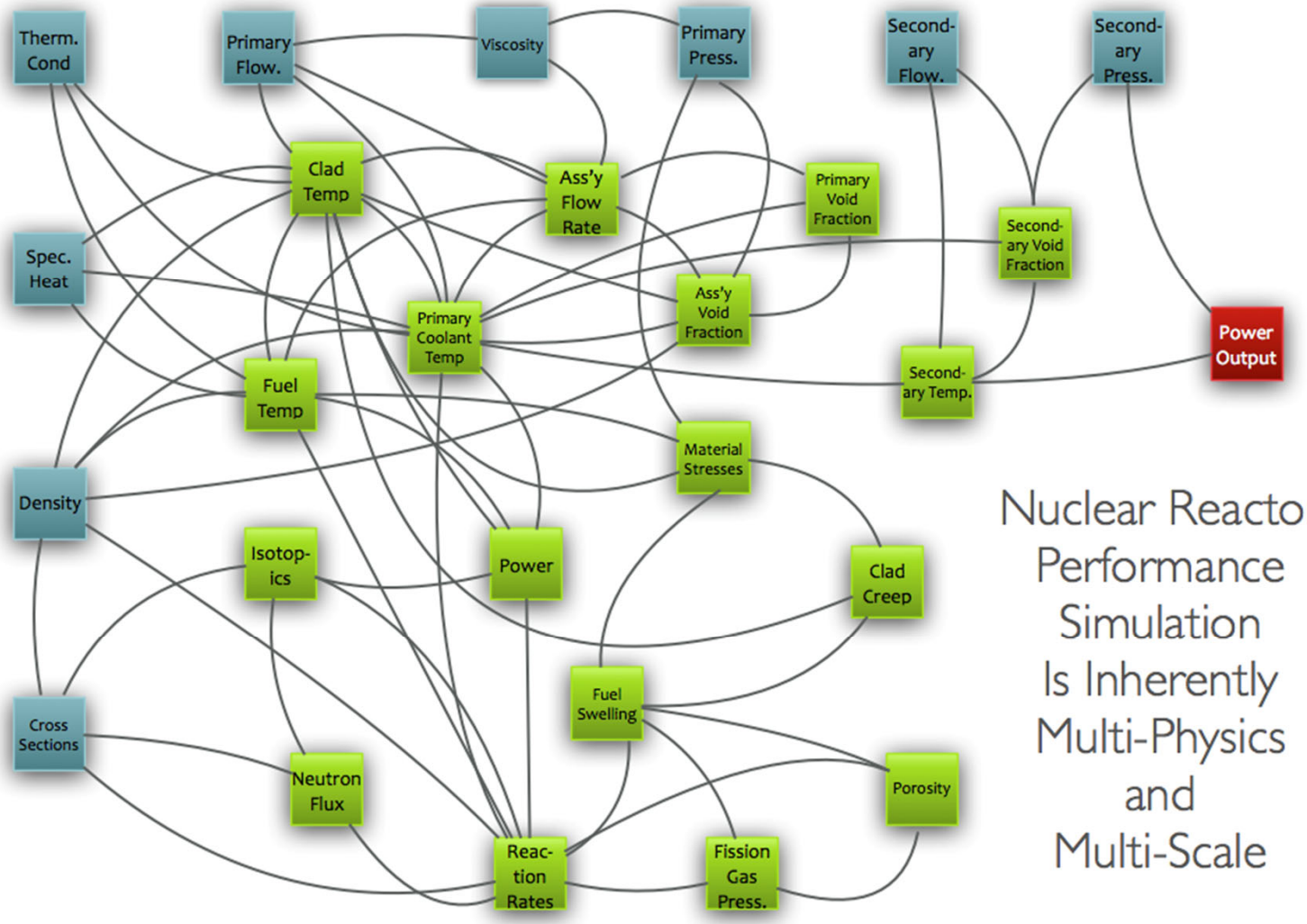
Reactor Transient Simulation



Nuclear Reactor Performance Simulation Is Inherently Multi-Physics and Multi-Scale

W. D. Pointer, et al., "Developing a Comprehensive Software Suite for Advanced Reactor Performance and Safety Analysis", 2013 International Conference on Fast Reactors, Paris, France, March 4-7, 2013

VERA Core Simulator Methods

Virtual Environment for Reactor Applications

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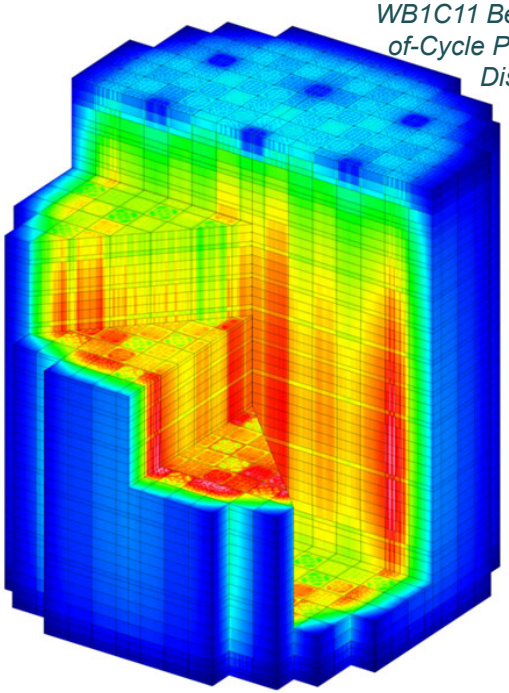
WB1C11 Beginning-of-Cycle Pin Power Distribution

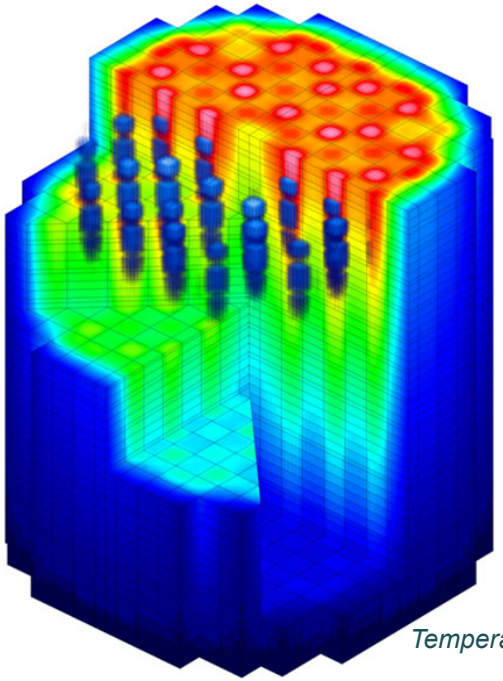


MPACT

Advanced pin-resolved 3-D whole-core neutron transport in 51 energy groups and >5M unique cross section regions

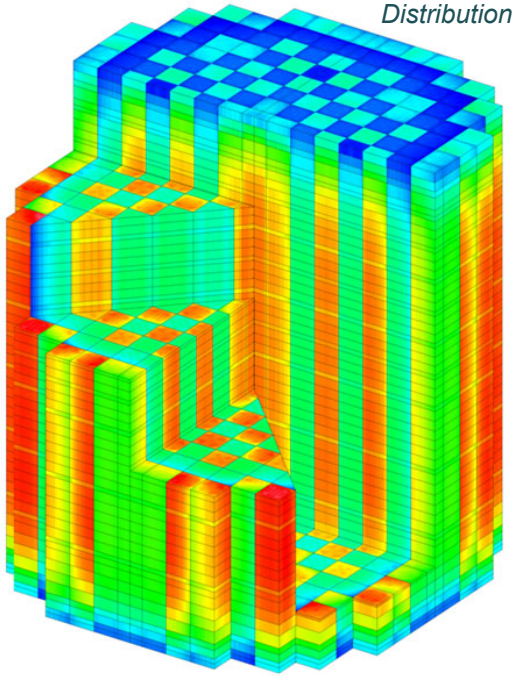
CTF

Subchannel thermal-hydraulics with transient two-fluid, three-field (i.e., liquid film, liquid drops, and vapor) solutions in 14,000 coolant channels with crossflow



WB1C11 Middle-of-Cycle Coolant Temperature Distribution

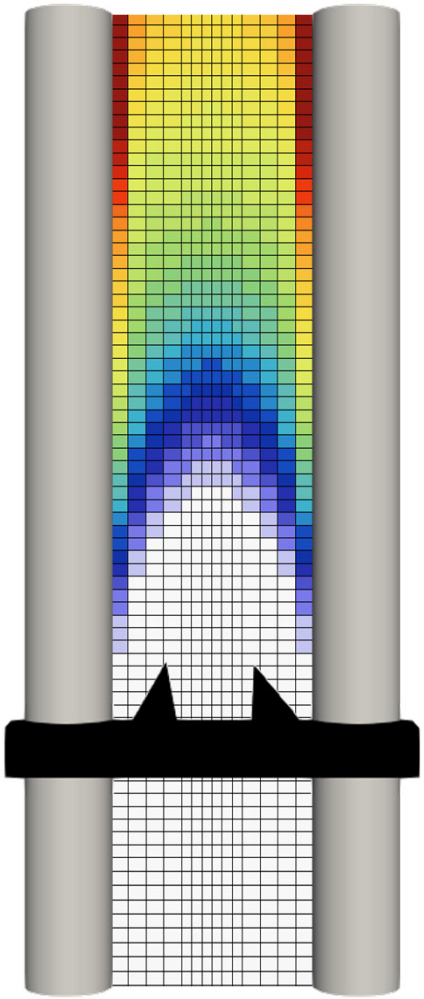
WB1C11 End-of-Cycle Pin Exposure Distribution



ORIGEN

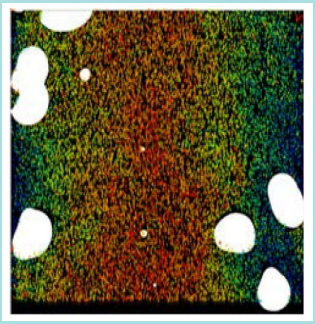
Isotopic depletion and decay in >2M regions tracking 263 isotopes

Reaping the fruits of an extended effort

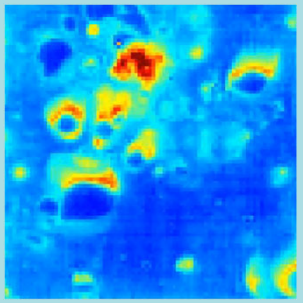


CASL Closure Models
E. Baglietto [MIT]

Experiments

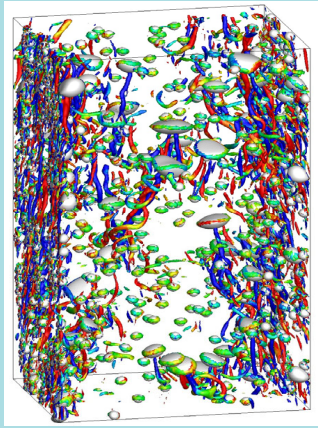


Y. Hassan [TAMU]

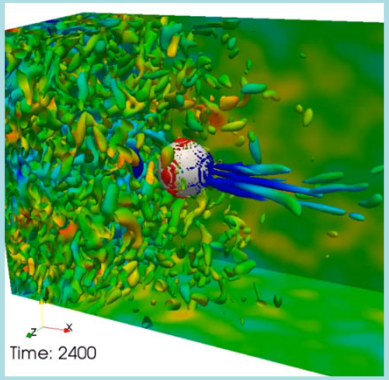


M. Bucci [MIT]

DNS



G. Tryggvason [JHU]



I. Bolotnov [NCSU]

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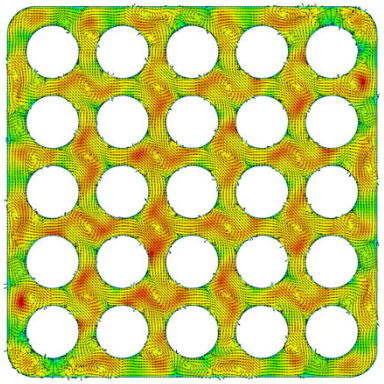
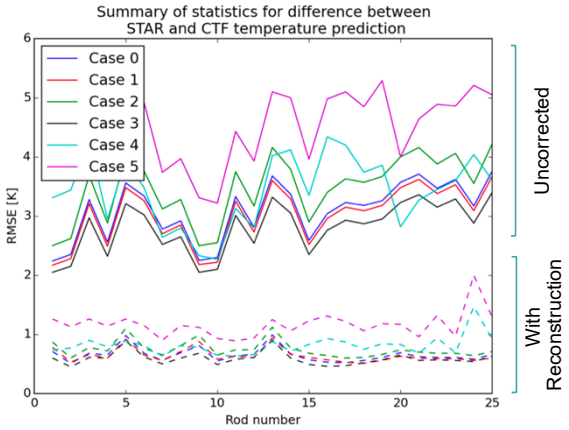
ROTHCON multiscale CFD-informed Hi2Lo Model

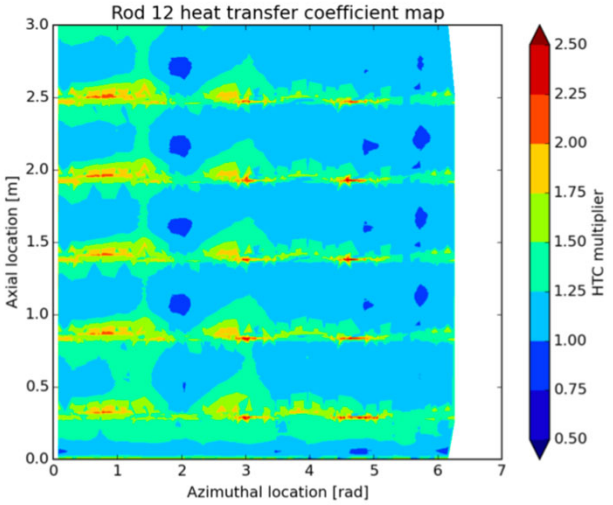
- Introduce data-driven models to improve prediction of local heat transfer and crud growth



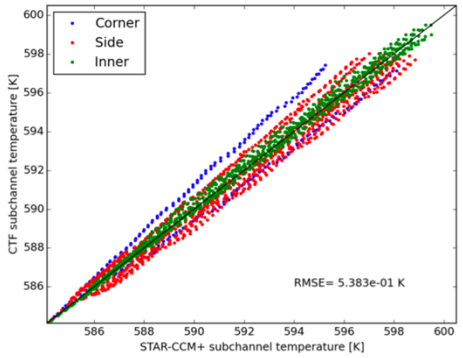


Sub-channel RMSE
With and Without Reconstruction Map

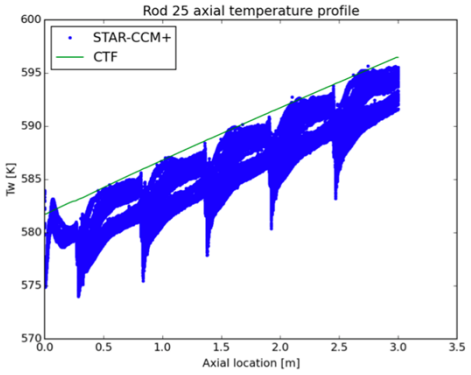
CTF coarse mesh date is projected to a finer reconstruction mesh using a projection model calibrated based on CFD data.



Heat Transfer Coefficient Map
Calibrated vs. CFD



Sub-channel coolant temperatures

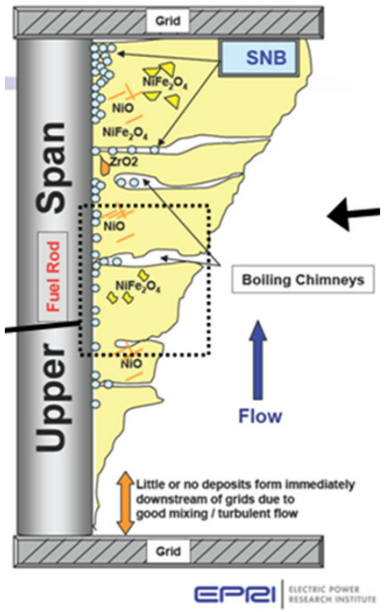


Clad surface temperatures

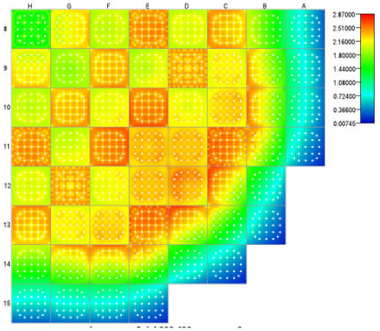
Multi-physics Simulations of CRUD Growth in LWRs

– Multiphysics simulation of core power distribution, fluid flow, heat transfer and surface chemistry

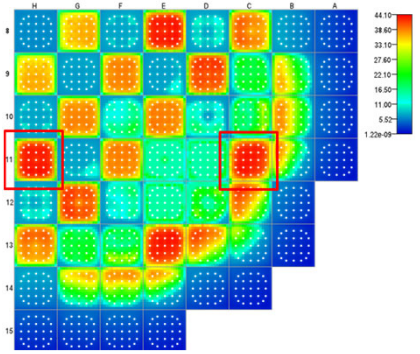
- Power distribution predictions from nuclear physics code MPACT
- Fluid flow and heat transport from CFD code STAR-CCM+
- Surface chemistry from surface chemistry code MAMBA
- Picard iteration among all physics through DataTransferKit



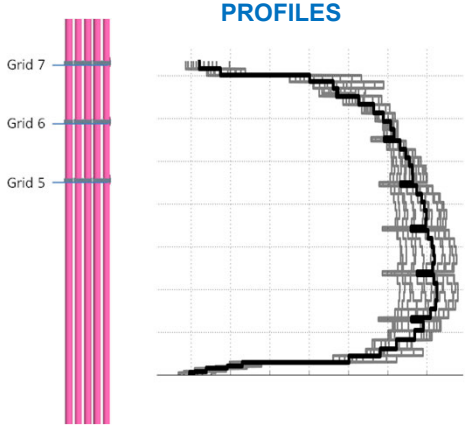
PREDICTED POWER DISTRIBUTION



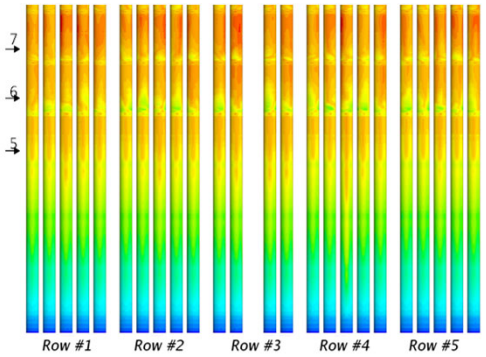
PREDICTED CRUD DISTRIBUTION



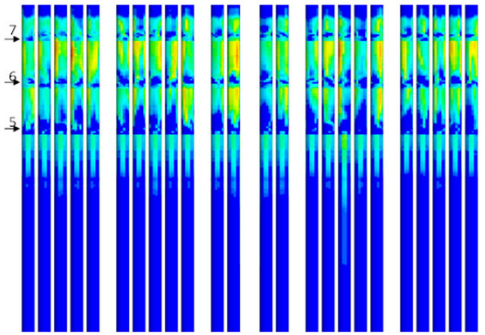
PREDICTED TEMPERATURE PROFILES



PREDICTED CLADDING TEMPERATURES



PREDICTED CRUD THICKNESS



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Beyond

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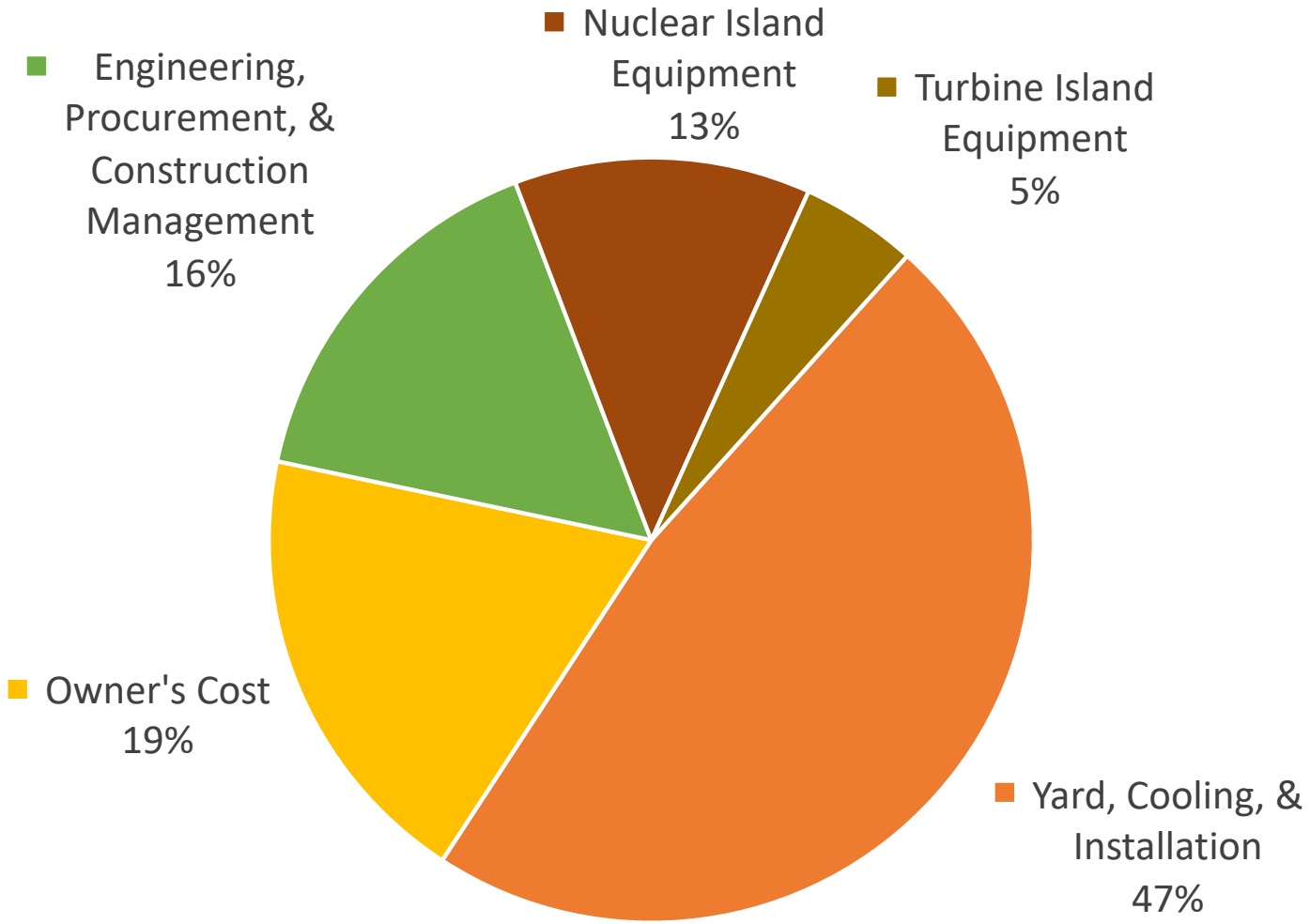
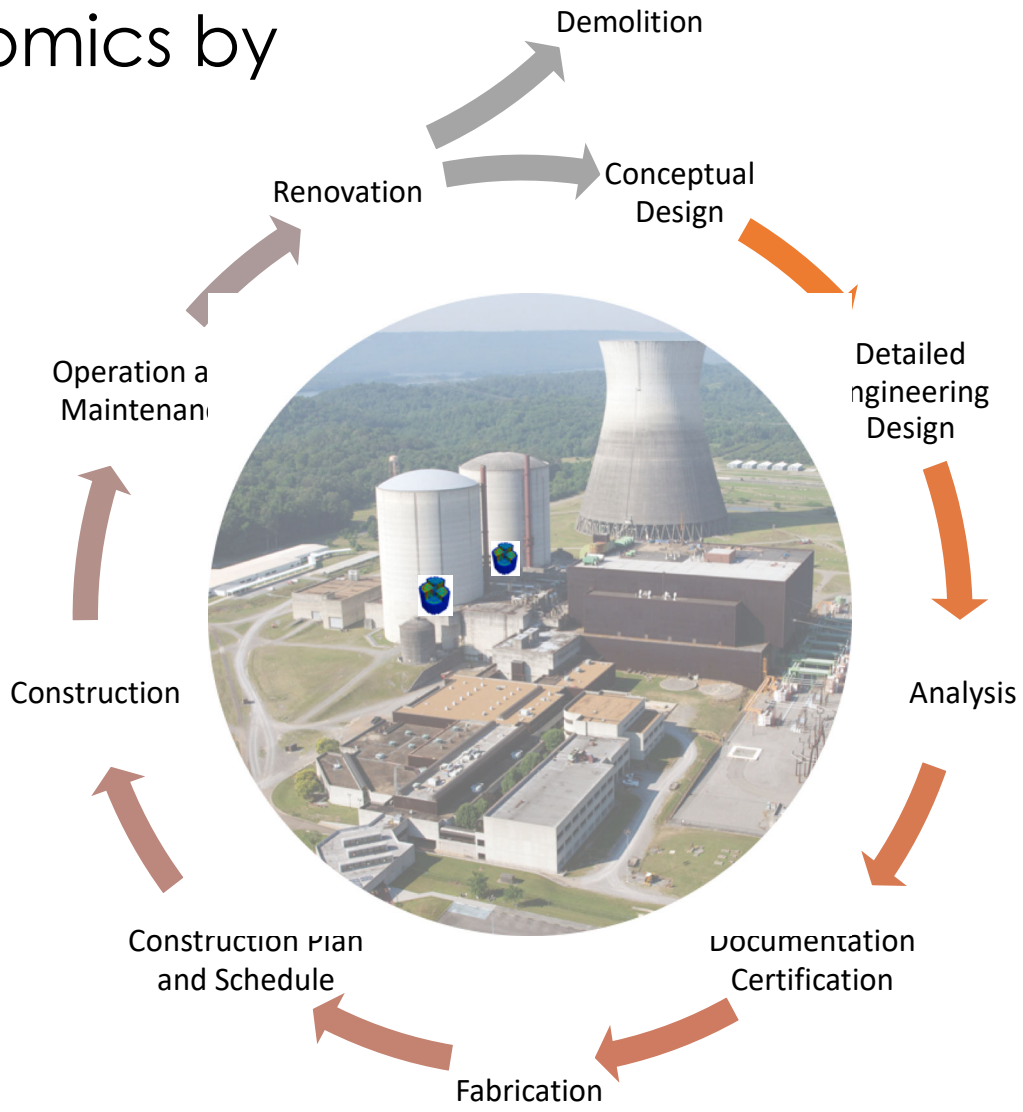
Cost of Nuclear Deployment



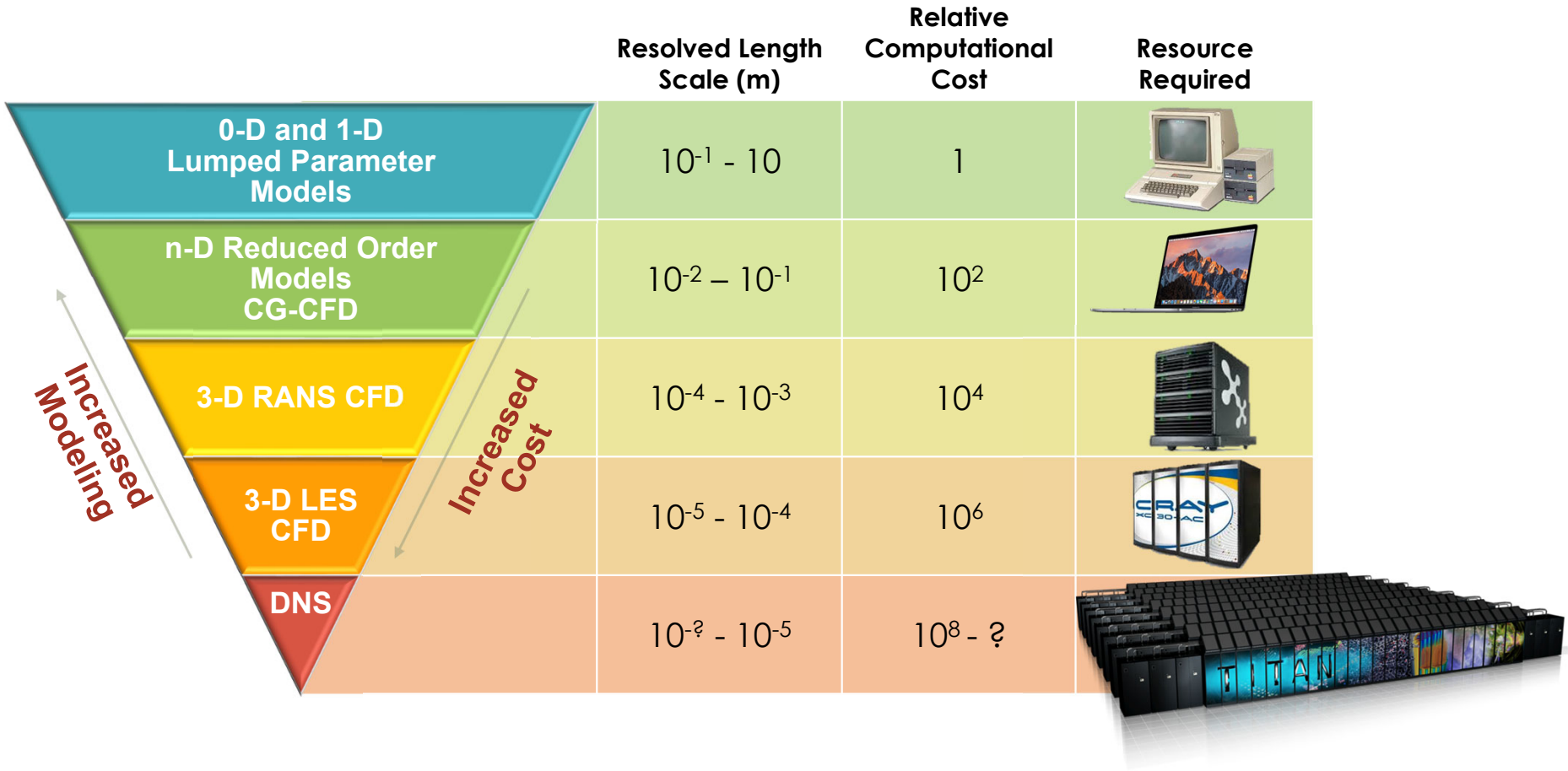
Based on data presented in "Cost and Performance Data for Power Generation Technologies." Black and Veach Holding Company Report to National Renewable Energy Technology Laboratory. (2012).

Address deployment economics by

- Moving beyond the core
  - Virtual twin integrated product life cycle management
  - Reactor core design simulation
  - Dynamic energy system performance
  - Dynamic reliability assessment
    - With integral operation and maintenance schedule optimization
  - Siting database integration

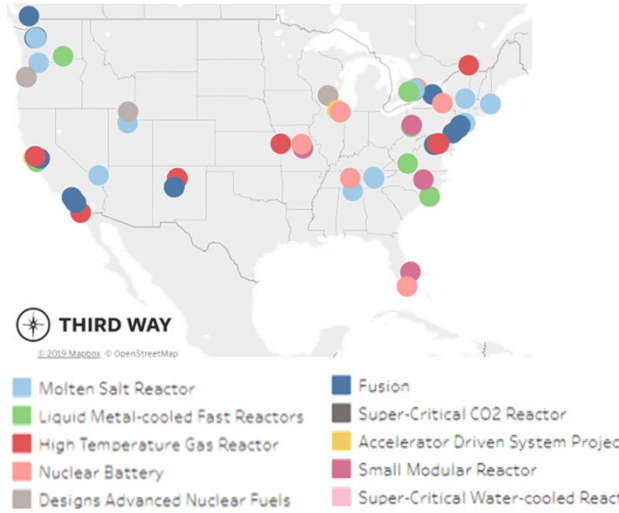


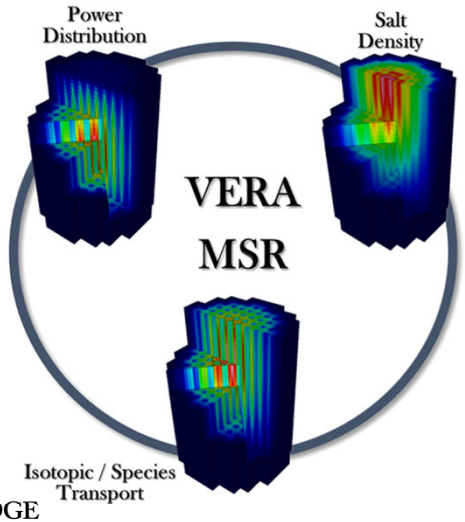
Hierarchical Multiscale Simulation

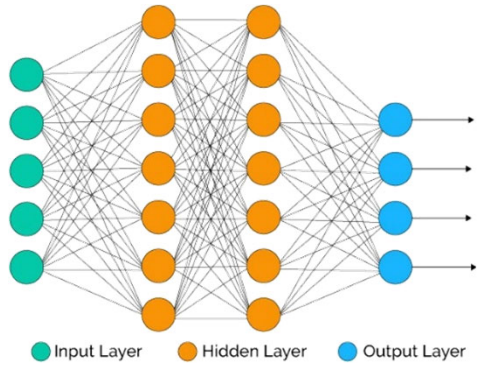


Advancing Advanced Reactor Technology

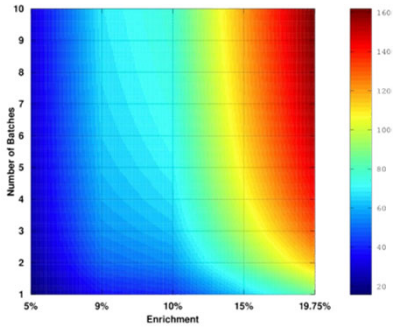
- Aging nuclear fleet and increasing demands for clean energy are driving development of next generation reactor technologies
- DOE strongly promotes advanced reactor research, and private companies are significantly investing in reactor development
- Analysts and developers require fast, accurate, high-fidelity simulation tools to accelerate design deployment



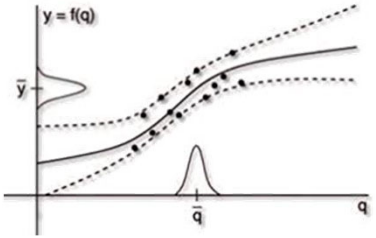




Deep neural networks (DNNs)



Design optimization



Uncertainty quantification / sensitivity analysis

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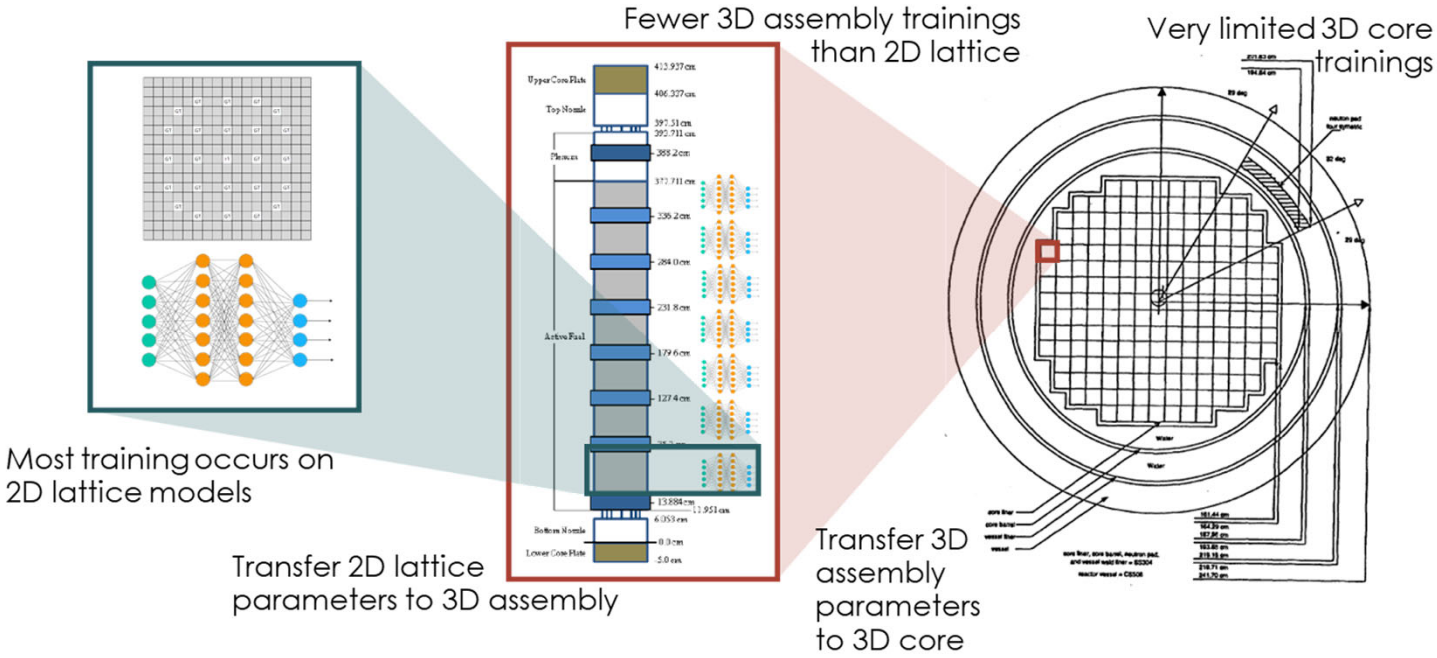
Data Challenges

Full models can consist of millions of input features:

Will determine an appropriate compressed form for input that is both sufficiently descriptive and information dense

Full core outputs are costly to generate and are multiple GBs in size:

Will explore DNN parameter seeding from subdomain, models as well as transfer learning

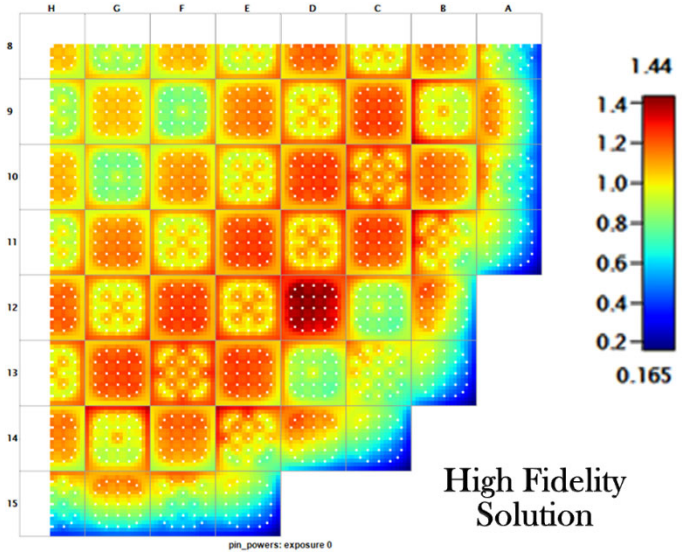


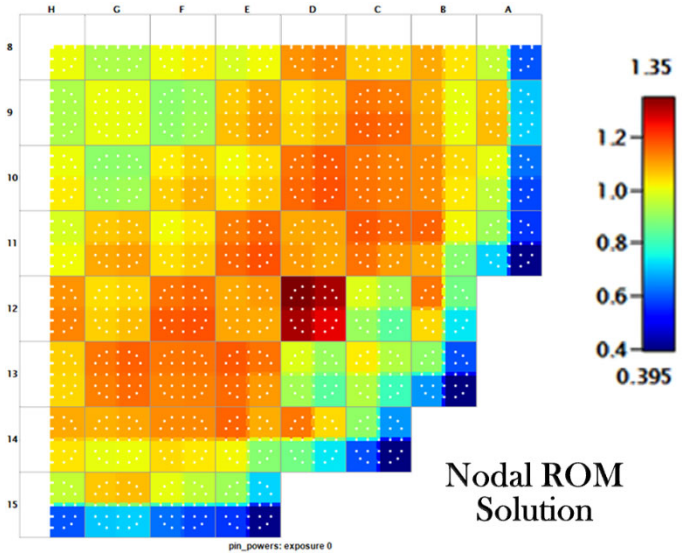
DNN have shown considerable ability to predict within the training domain but is not guaranteed to generalize well

Research community is currently looking at physics embedding as a solution

Physics-informed Nodal ROM development

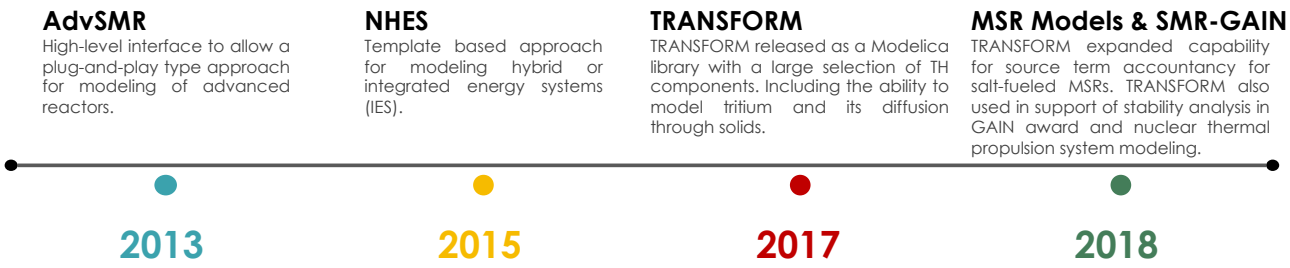
- Developed infrastructure for rapidly generating synthetic data
- Implemented 3D neutronics nodal solver in MPACT to support ROM approach
- Started early explorations into physics informed learning
- Currently building model complexity from 2D lattice up to full core

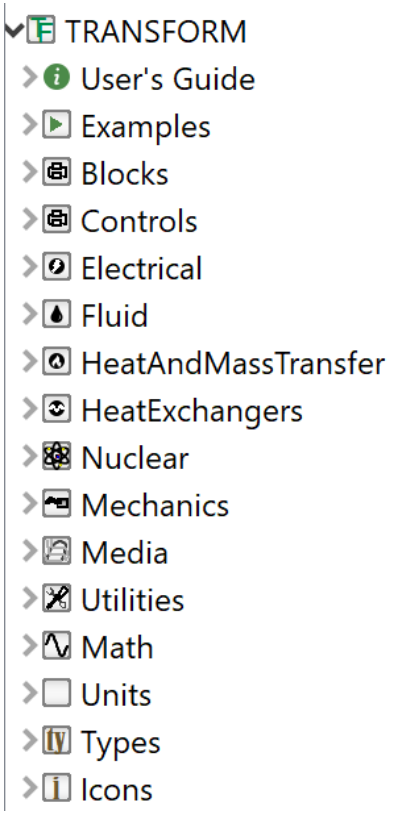




TRANSFORM – Transient Simulation Framework of Reconfigurable Models

- **2013–2015** – Originally conceived as a high-level interface approach for modeling of advanced reactors. Including exploration of deployment and collaboration methods.
  - Lack of standard fluid or heat transfer libraries led to difficulty/limited usefulness in developing a high-level interface which had no components with which to model
- **2015–Present** –Re-imagined TRANSFORM to be a general library of components for modeling a variety of thermal-hydraulic and other multi-physics systems.
  - The "Library" consists of a variety of models
  - Additional models are added as needed by the user
  - The general structure of the library attempts to "feel" similar to the Modelica Standard Library to improve approachability





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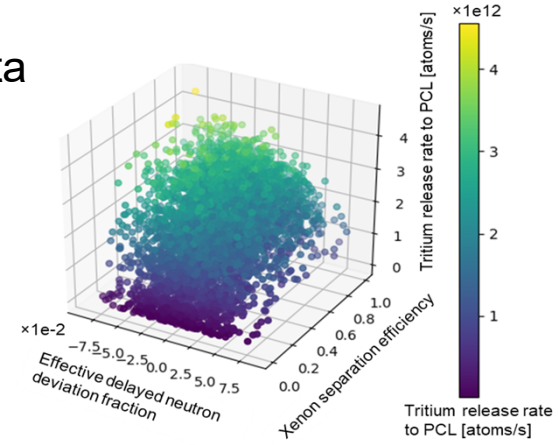
MSDR Example: Steady-State Sensitivity Analysis using RAVEN

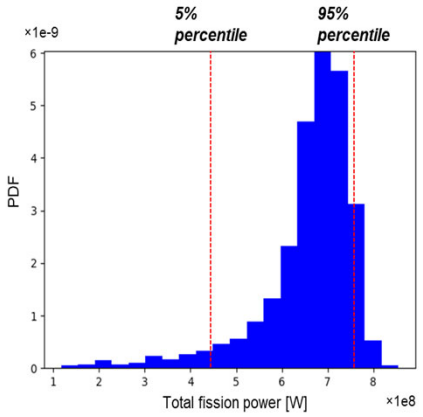
- Models can be exported to advanced tools such as RAVEN and Dakota
  - E.g., executables or python-FMU interfacing
- Use RAVEN to run N number of cases for desired analysis

Selected Input Parameters to Perturb

Input parameter	Distribution	Sigma (σ) %	Bounds
Fraction deviation from the nominal effective delayed neutron fraction	Normal	3.0	±3σ
Fraction deviation from the nominal delayed neutron generation time	Normal	3.0	±3σ
Delayed neutron fraction (groups 1–6)	Normal	3.0	±3σ
Delayed precursor decay constant (groups 1-6)	Normal	3.0	±3σ
Absorption coefficient of fission product (e.g., ^{135}Xe)	Normal	5.0	±3σ
Fuel temperature feedback	Normal	3.0	±3σ
Graphite temperature feedback	Normal	3.0	±3σ
Correction factor on heat transfer coefficient	Normal	12.0	±3σ
Mass flow rate of primary loop	Normal	0.5	±3σ
Separation efficiency of ^{135}Xe	Uniform	-	0–1



Multidimensional (3D) statistical analysis



Distribution Plots

Integration with dynamic PRA for reliability analysis and maintenance planning

- Establish Reliability as a New Figure Merit
  - track the simulated condition of a component to identify its departures from normal operation
  - update the change in failure rates at each time step
  - translate component estimated life into maintenance, downtime, cost and map into the cost optimization model
- Three levels of reliability assessment under development:
  - Component Reliability (Bayesian-Weibull Model)
  - Subsystem Reliability (includes subsystems interactions) via stochastic petri nets models
  - System Reliability using PRA (fault tree/event tree)

Reliability Demonstration Case Nuclear Hybrid Energy System

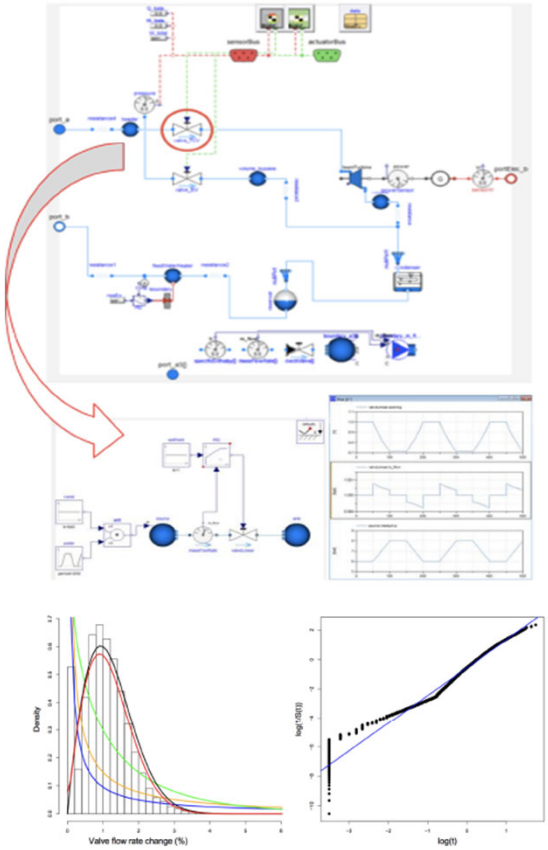
Dynamic characterization of **turbine control valve (TCV)** reliability performance measurements are calculated and updated

Input: Time-Dependent Load & Component Operational Data

- The maximum and minimum values for the valve positioning and minimum amount of occurrences for each period are considered, stated percentage of the maximum frequency at the histogram.
- The TCV valve has a time requirement of 0.3s and this define functional thresholds for failure state.

Output: Time Dependent Failure Probability on Demand & Economical Value

Characteristic life time of the TCV for different time histories calculated as 10.29, 9.11 and 7.86 years.



Weibull Parameters and Reliability Estimations

Time Interval	Beta (β)	Eta (η) hours	R (%)
Period #1	1.358	90,129	76.63
Period #2	1.372	79,797	69.26
Period #3	1.383	68,854	63.71

Next steps

- Continued maturation of component physics codes
- Continued maturation of hierarchical multi-scale coupling
  - Bayesian calibration and direct-data models based on large data sets
- Introduce limited direct multi-scale integration to multi-physics component simulations
- Integration of parametric geometry data with CAD models
  - Leverage existing APIs in commercial codes
- Integration of results with Building Information Models
  - Leverage existing APIs in commercial codes
- Introduction of game theory models to determine staffing requirements

Enable direct translation of design innovations to impact on construction schedule, reliability and operating costs

Conclusions

- Advanced modeling and simulations provides an opportunity to gain design and safety insights that cannot be attained through experiment alone
- Sophisticated core modeling capabilities are a foundational tool for better optimization of current and future reactor designs
  - Fuel performance
  - Fuel utilization
- Broader integration is needed to enable optimization based on impacts on deployabilty
  - Prioritized safety Investments
  - Component life, system availability/robustness
  - Design, construction, maintenance and operating costs
  - Deployment and operations schedule

Questions?

Acknowledgements

- This research was supported by the Consortium for Advanced Simulation of Light Water Reactors (www.casl.gov), an Energy Innovation Hub (http://www.energy.gov/hubs) for Modeling and Simulation of Nuclear Reactors under US Department of Energy Contract No. DE-AC05-00OR22725.
- An award of computer time was provided by the ASCR Leadership Computing Challenge (ALCC) Program. This research used resources of the Oak Ridge Leadership Computing Facility at the Oak Ridge National Laboratory, which is supported by the Office of Science of the US Department of Energy under Contract No. DE-AC05-00OR22725.
- This research made use of the resources of the High Performance Computing Center at Idaho National Laboratory (INL), which is supported by the Office of Nuclear Energy of the US Department of Energy under Contract No. DE-AC07-05ID14517.