Modeling and Simulation Needs and Capabilities for Artificial Intelligence Based Plant Reload Optimization Platform

LWRS
LIGHT WATER
REACTOR
SUSTAINABILITY

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Background and Objective

- The fuel is ~20% of the total generating cost
  - Cost of a typical fuel reload for a LWR is about $50M
- Need of innovative fuel reload analysis platform
  - Traditional methods (*developed decades ago)* is labor-intensive and time-consuming
  - Automatized simulation based generic fuel reload analysis platform
- Development of innovative plant fuel reload optimization platform
  - Applicable to load follow and flexible operations, ATF, high burn-up and longer cycle
  - Aims 5-10% reduction in fuel reload costs ($2.5–5M)

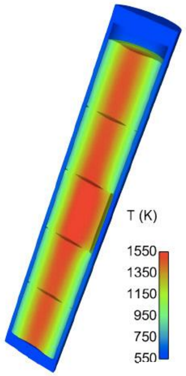
Cost summary ($/MWh) in 2019

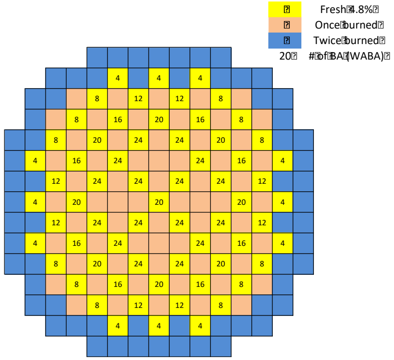
Type	Sites	Fuel	Capital	O&M	Total
All U.S.	58	**$6.15**	$5.71	$18.55	$30.41
BWR	22	**$6.07**	$5.83	$19.62	$31.52
PWR	37	**$6.20**	$5.65	$18.00	$29.85

Source: NEI, Nuclear Cost in Context, Oct. 2020

Optimization of Reactor Fuel Reload

- RISA Pathway plant fuel reload optimization framework
  - Provides optimized reactor core configuration with key safety parameters
  - Flexible code independent framework
  - Consider uncertainties in all driven physics
  - Applicable to risk-informed approach
- Genetic Algorithm (GA) produces high-quality optimization solutions
  - Based on metaheuristic evolutionary algorithm
  - Artificial Intelligence (AI) approach
  - Suitable for high order combination problems
    - >10e30 combinations for 17×17 quarter of core
- Multi-physics simulation
  - Core configuration
  - Fuel performance
  - System analysis





🟨 Fresh 4.8%
🟧 Once burned
🟦 Twice burned
20 # of BA (WABA)

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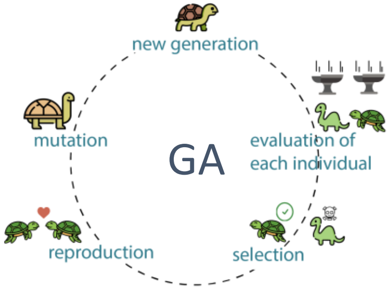


new generation

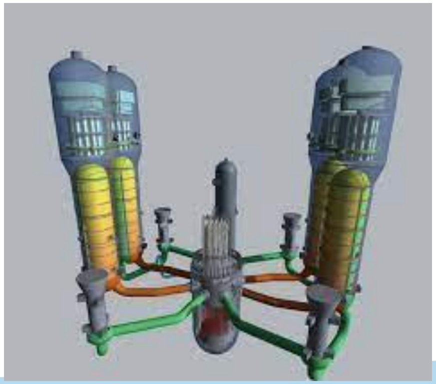
evaluation of each individual

selection

reproduction

mutation

GA



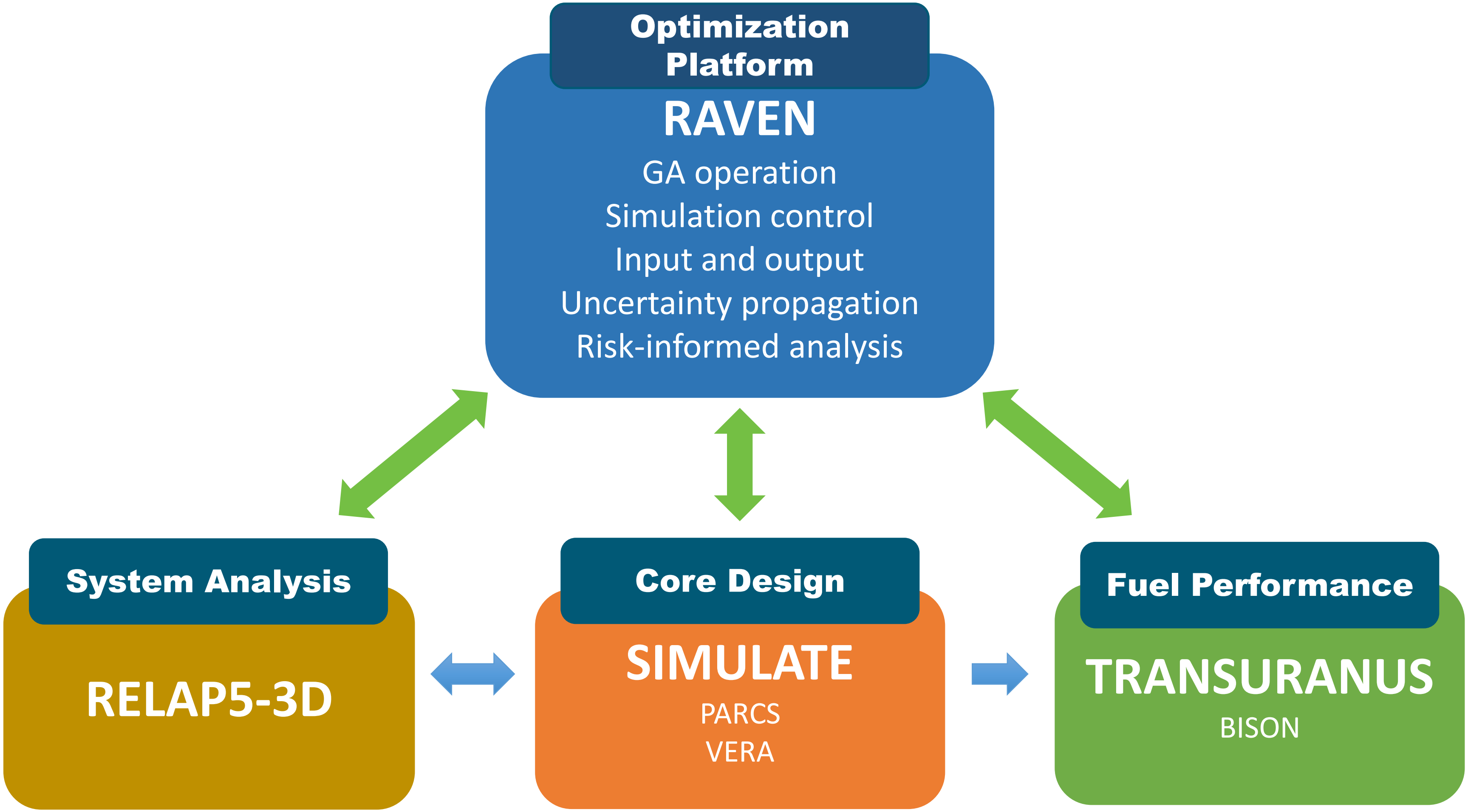
Technology Roadmap

Phase 1 (FY19-20) Methodology development	Phase 2 (FY21-22) Framework Improvement	Phase 3 (FY22-23) Demonstration of benefits	Phase 4 (FY24-25) Improvement and expansion
Setup tools and methods	Update tools and methods	**Improve of optimization method (ML/AI)**	Demonstration with ATFs
Set plant based scenarios	Optimization method for fuel reloading pattern	**Demonstrate generic optimization framework**	Demonstration for BWRs
Simulate DBA with deterministic method	Analyze uncertainties	Maximize capability of framework	Demonstrate with equilibrium scenarios
Use fixed core loading pattern	**Assess constraints and issues of tools**	Initiation BWR and ATF core optimization	Finalize framework for the use in license applications
Evaluate recoverable margin	**Apply risk-informed approach**	Assess economic benefits	

Planning & development → **Early demonstration** → **Industry engagement** → **Industry deployment**

Reaching higher maturity for industry (utilities/vendors) engagement from 2021

Schematic of Optimization Platform



Optimization Platform

RAVEN

GA operation
Simulation control
Input and output
Uncertainty propagation
Risk-informed analysis

System Analysis

RELAP5-3D

Core Design

SIMULATE
PARCS
VERA

Fuel Performance

TRANSURANUS
BISON

Code Benchmark Criteria

- Computational speed
  - Optimization algorithm (e.g., GA) requires a order of 100~1000th of simulations.
  - The tools need to be run fast as possible, preferably in order of 10th of seconds.
- Higher technical maturity
  - Optimization framework aims at immediate industrial deployment.
  - The tools under the framework need to have at least higher than TRL level 7 (out of 9).
- Coupling with RAVEN
  - RAVEN is the main software to control the optimization platform.
  - Tight coupling with RAVEN and verification is needed.
- Capability on ATF and/or high burnup operation analysis
- PWR and BWR applicability

Selection of Core Design Codes

- **VERA-CS (DOE CASL, USA)**
  - High-fidelity physics code
  - MPACT using MOC approach for whole core transport
  - Subchannel code COBRA-TF internally coupled for thermal-hydraulics simulation
- **SIMULATE-3 (Studsvik, Sweden)**
  - 3-D two-group nodal code
  - Embedded INTERPIN code for TH calculation
  - Parametric cross section: CASMO-4E
- **PARCS (US NRC, USA)**
  - 3-D core nodal diffusion calculator
  - TH feedbacks computed using a simplified 1D mass energy balance solver
  - Parametric cross section: SCALE/POLARIS

Core Design Codes Benchmark Specification

Benchmark Choice

- Experimental data available and based on an operating reactor
- Complete specifications available for calculation models
- Benchmark includes ZPPTs, HFP BOC physical reactor, depletion, fuel shuffle and decay
- Available reference results

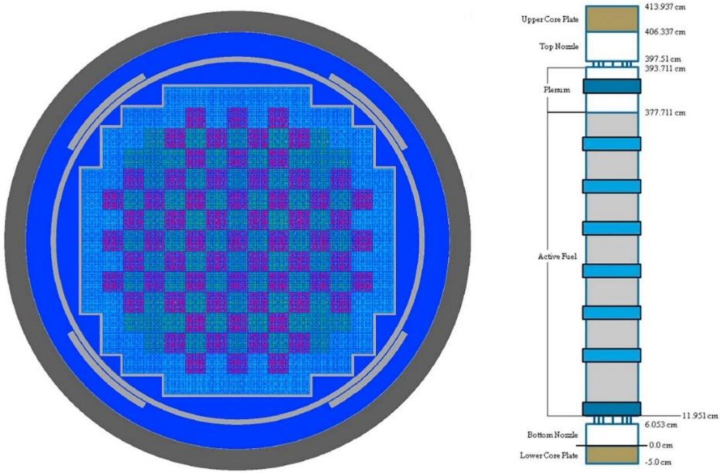
Watts Bar Nuclear Unit 1

- Westinghouse four-loop PWR with 3411 MW_{th} power rating
- 193 fuel assemblies with 17×17 design
- Three regions of enrichments: 2.11%, 2.619% and 3.10%

Core operating conditions and design parameters

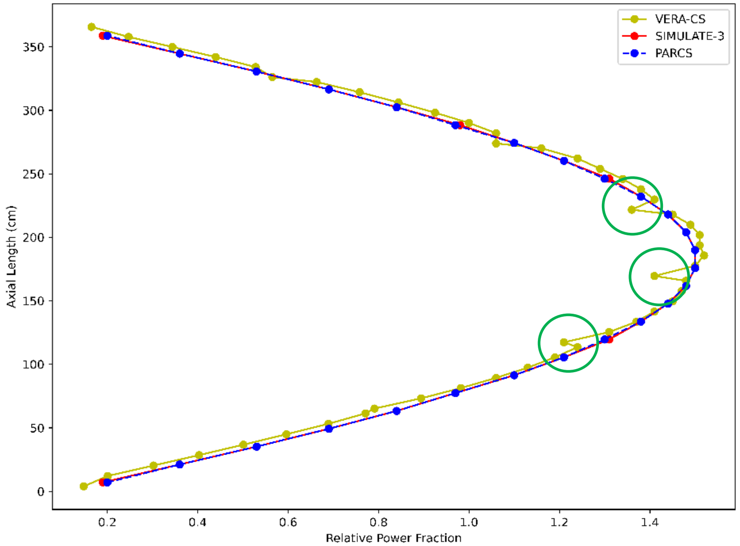
Description	Value
Rated Core Power (MW)	3411
Reactor system pressure (MPa)	15.51
Coolant Inlet Temperature (K)	565
Coolant Core Bypass flow rate (%)	9
Cycle 1 HZP BOC ARO critical soluble boron concentration (ppm)	1291
RCCA Control Bank overlap (steps)	128
Cycle 1 Uranium Fuel Loading (MT)	88.808
Rated Coolant total flow rate (kg/s)	18231.89
Cycle 1 EOC Exposure (GWd/MT)	16.939

Watts Bar Nuclear Unit 1 core diagram

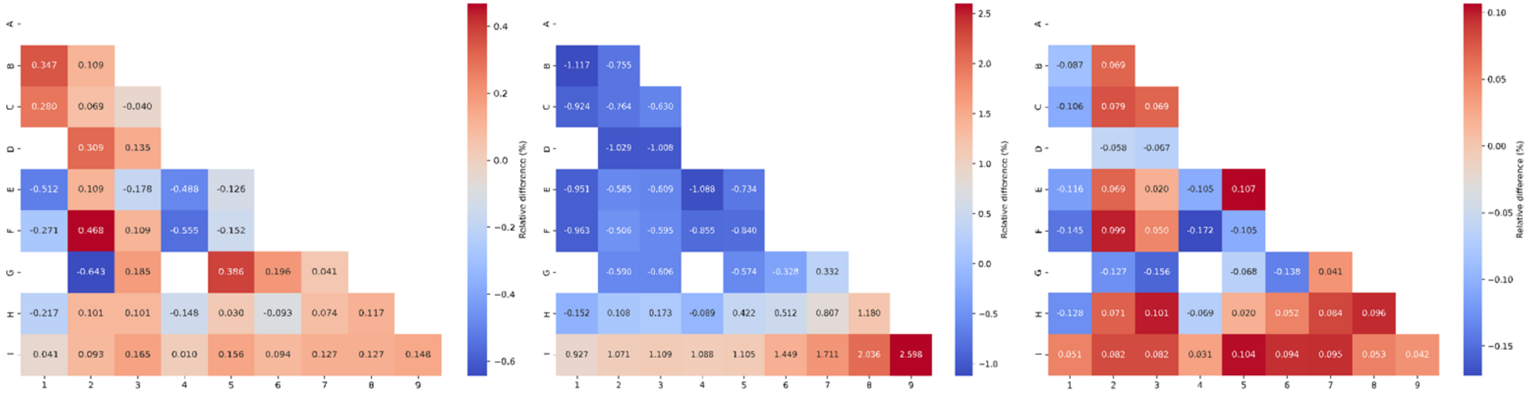


Benchmark Case Studies

- Case 1: 2D eigenvalue lattice problem at HZP BOC
- Case 2: 2D central core assembly lattice problem at HZP BOC
- Case 3: 2D fuel assembly interface and control rod effect lattice problem at HZP BOC
- Case 4: Zero Power Physics Tests (ZPPTs) of reactor core problem
- Case 5: 3D reactor problem at HFP BOC.



Case 4: Core Average Axial Power Profile in Benchmark



Case 2: Pin Power Distribution Benchmark (from left: VERA-CS, Polaris, CASMO)

Core Design Codes Computational Time

- Efficiency comparison include the accuracy, modeling effort, code capability, license and computational cost
- Computational cost represented as CPU runtime to mitigate the impact of parallel computing
- VERA-CS has the longest runtime as it is a high-fidelity code
- Notable longer run time in Case 3 for PARCS
  - Increased discretization at reflector region

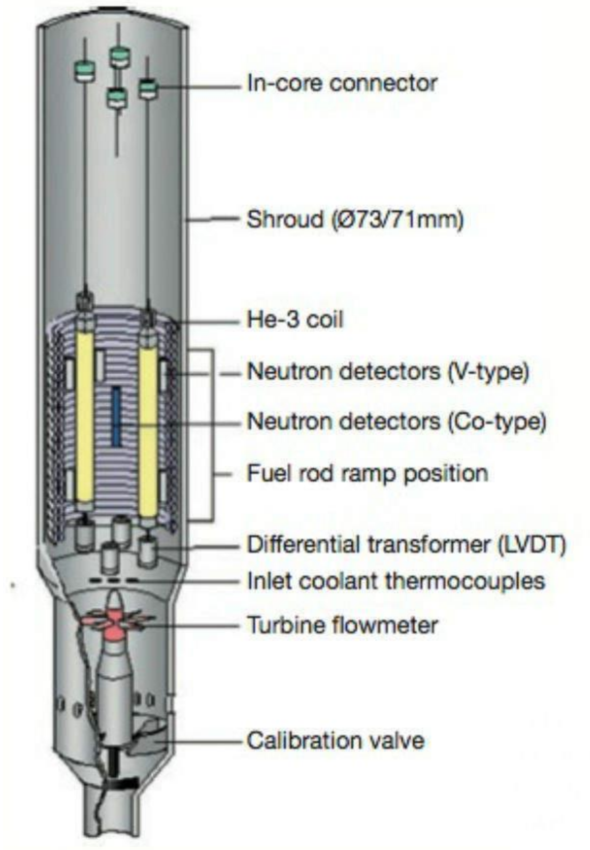
CPU runtime comparison

Cases	VERA-CS (hr:min:sec)	POLARIS/PARCS (hr:min:sec)	CASMO-4/SIMULATE-3 (hr:min:sec)
Case 1	0:00:02	0:00:11/--	0:00:01/--
Case 2	--	0:01:00/--	0:00:05/--
Case 3	--	0:55:00/--	0:00:35/--
Case 4	20:44:15	01:30:00/0:00:02	0:11:05/0:00:14
Case 5	45:01:14	01:30:00/0:00:02	0:11:17/0:00:07

Fuel Performance Analysis Codes

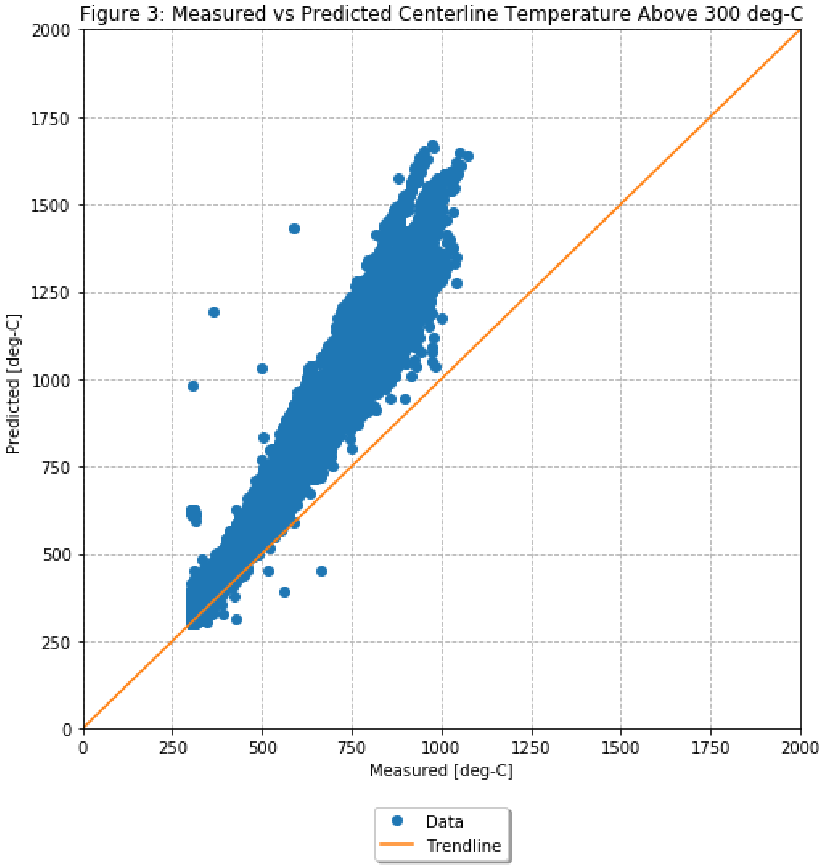
- **BISON (Idaho National Laboratory, USA)**
  - MOOSE (Multiphysics Object Oriented Simulation Environment) based High-fidelity finite element-based code
  - Solves fully coupled equations of thermomechanics and species diffusion
  - Includes important fuel physics such as fission gas release and material property degradation with burnup
- **TRANURANUS (Joint Research Center, EC)**
  - Approximates the fuel rod behavior with an axisymmetric, axially stacked, one-dimensional radial representation in steady-state and transient analyses
  - Incorporates models accounting for the different and interrelated phenomena occurring in the fuel rod
  - Includes material data bank for oxide, mixed oxide, carbide, and nitride fuels, zircaloy, and steel claddings, in addition to several different coolants

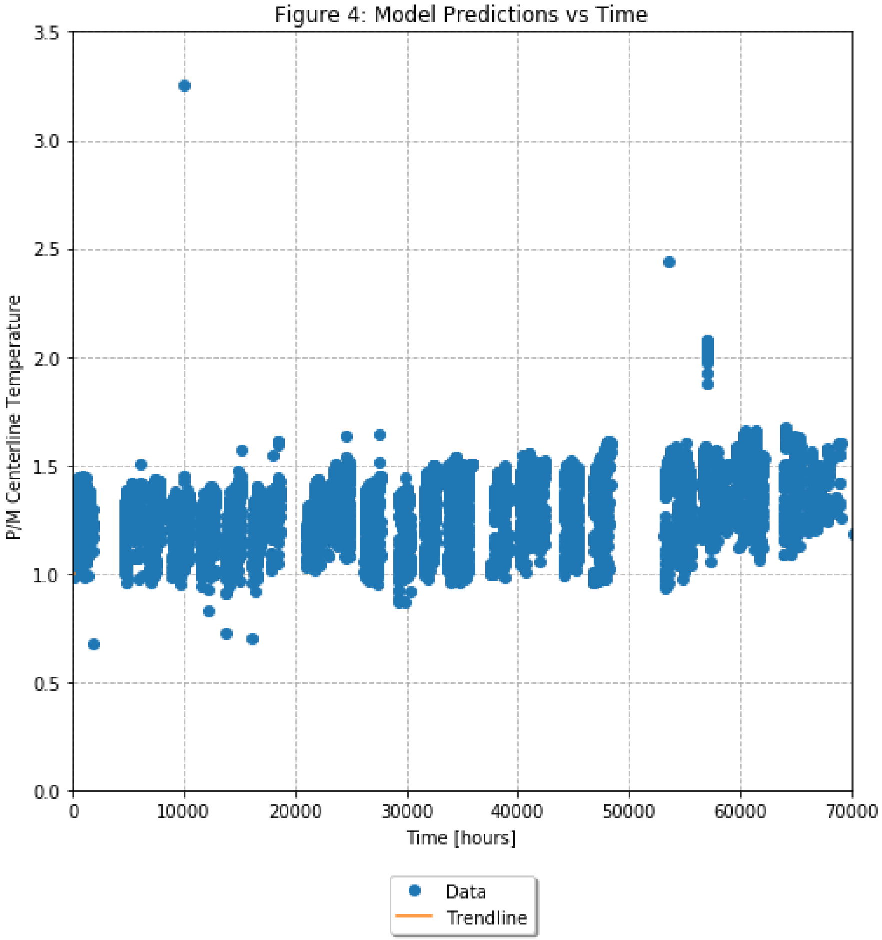
Fuel Performance Analysis Code Benchmark Specification



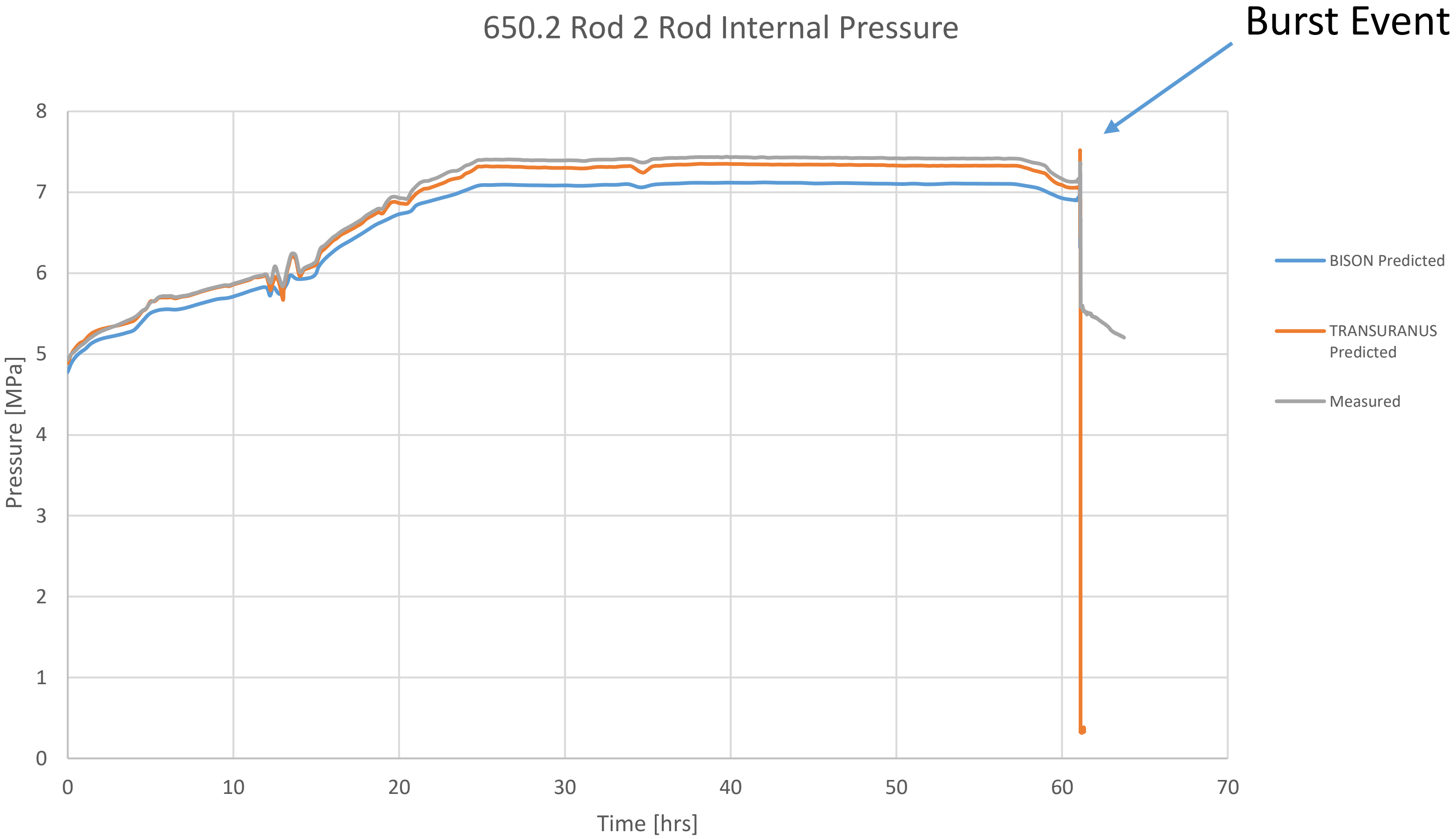
- Halden IFA-432 Rod 3
  - The main objectives were measurements of fuel temperature response, fission gas release and mechanical interaction on BWR-type fuel rods up to high burn-ups
- Halden IFA-650.2 Rod 2
  - Tests concentrated on embrittlement and mechanical properties of high burnup cladding. The Loss of Coolant Accident (LOCA) experiments are integral single pin in-pile tests on fuel behavior under simulated LOCA conditions.

IFA-432 Rod 3 Centerline Temperature





IFA-650.2 Rod 2 RIP



Comparison of Fuel Performance Analysis Codes

Criteria	BISON	TRANSURANUS
Benchmark Results	Reasonable prediction of IFA-650.2	Moderate overprediction of centerline temperature for IFA-432 Good prediction of IFA-650.2
Computational speed	Linux Run Time: IFA-423: 6030 s IFA-650.2: 410 s	Linux Run Time: IFA-432: 54 s IFA-650.2: 38 s
Commercial Readiness	Partial V&V Tool of choice for advanced reactor developers. Built on MOOSE Framework	Extensively verified and validated. Proven use in commercial/ licensing application
Coupling with RAVEN	Indirectly (via input/output files)	Indirectly (via input/output files)
ATF and/or high burnup	Developed for accident tolerant fuel (ATF) analyses. Limited data availability	Able to model accident tolerant fuel (ATF). Limited data availability
PWR and BWR	Developed for PWR analyses. Modelling options available for BWR conditions	Developed for both PWR and BWR conditions

Conclusion and Remarks

- CASMO/SIMULATE for core design tool
- TRANSURANUS for fuel performance
- Benefits
    - Faster simulation time
    - Already use in the industry and fully validated / QA support
    - ATF and high burnup simulation capable
    - P/BWR simulation capable
- Remarks
    - Benchmark details will be published in September 2022
    - Need tight coupling with RAVEN/RELAP5-3D including verification
    - Demonstration with limiting DBAs

LWRS LIGHT WATER REACTOR SUSTAINABILITY

Sustaining National Nuclear Assets

http://lwrs.inl.gov