BISON Fuel Performance Code: Capability Overview and V&V Status and Plans

Rich Williamson, Ben Spencer, Al Casagranda, Charlie Folsom
Idaho National Laboratory

Joe Rashid and Wenfeng Liu
ANATECH Corp

Brian Wirth and Nathan Capps
University of Tennessee

CASL Industry Council Meeting
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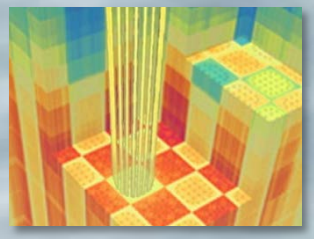
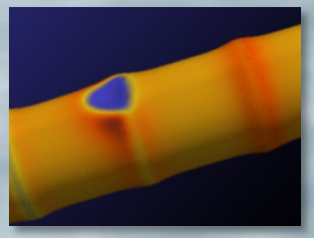
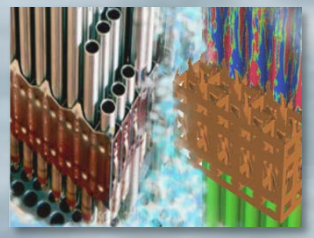






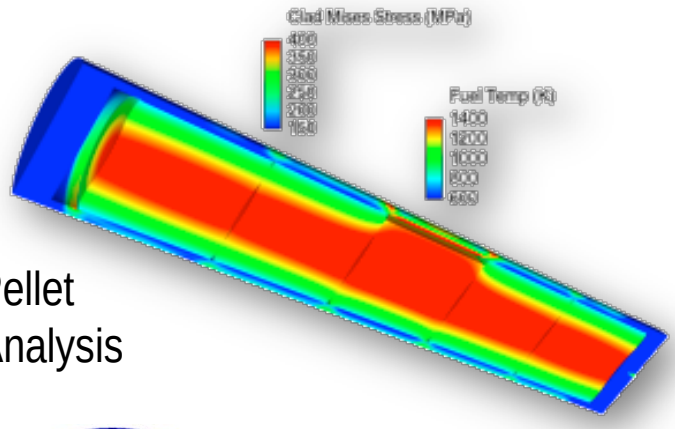
The Consortium for Advanced Simulation of LWRs
A DOE Energy Innovation Hub

CASL-U-2016-1089-000

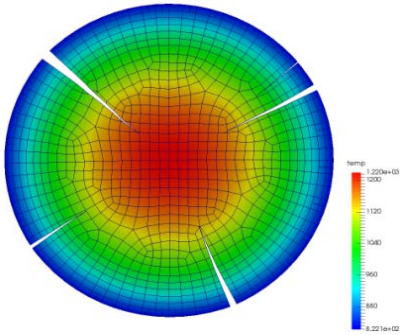
U.S. DEPARTMENT OF ENERGY

Outline

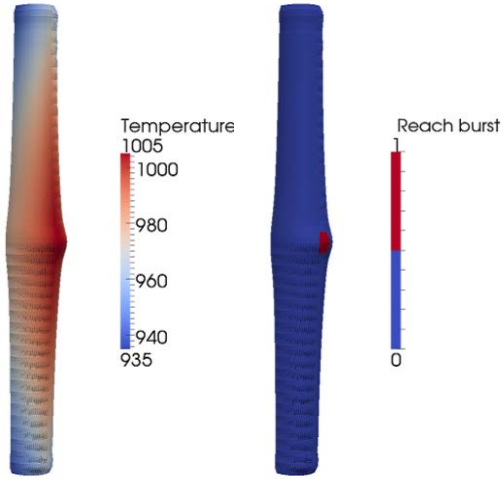
- Background and high level capability summary
- Recent results
  - Missing Pellet Surface
  - Halden Experiment Design
- Users and Collaborations
- Verification and Validation
  - Software Quality Assurance
  - V&V Status and Plans for LWR fuel
  - PCMI and RIA Benchmarks
  - Uncertainty Quantification



Missing Pellet Surface Analysis



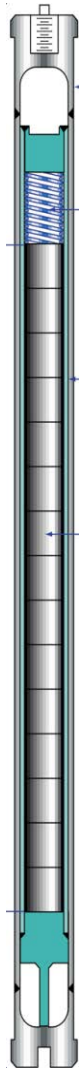
Fuel cracking via XFEM



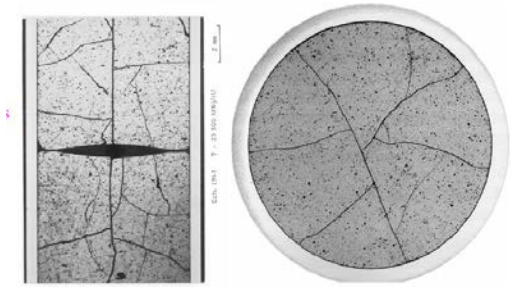
LOCA Burst Tests

Fuel Behavior During Irradiation

At beginning of life, a fuel element is quite simple . . .



but irradiation brings about substantial complexity

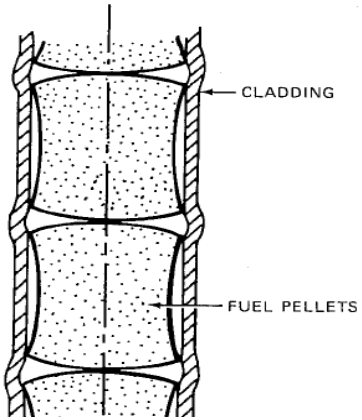


Michel et al, Eng Frac Mech, 75, 3581 (2008)

Fuel Fracture

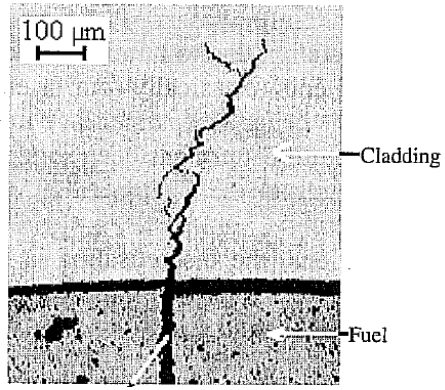
Olander, p. 323 (1978)

Fission gas



Olander, p. 584 (1978)

Multidimensional contact and deformation

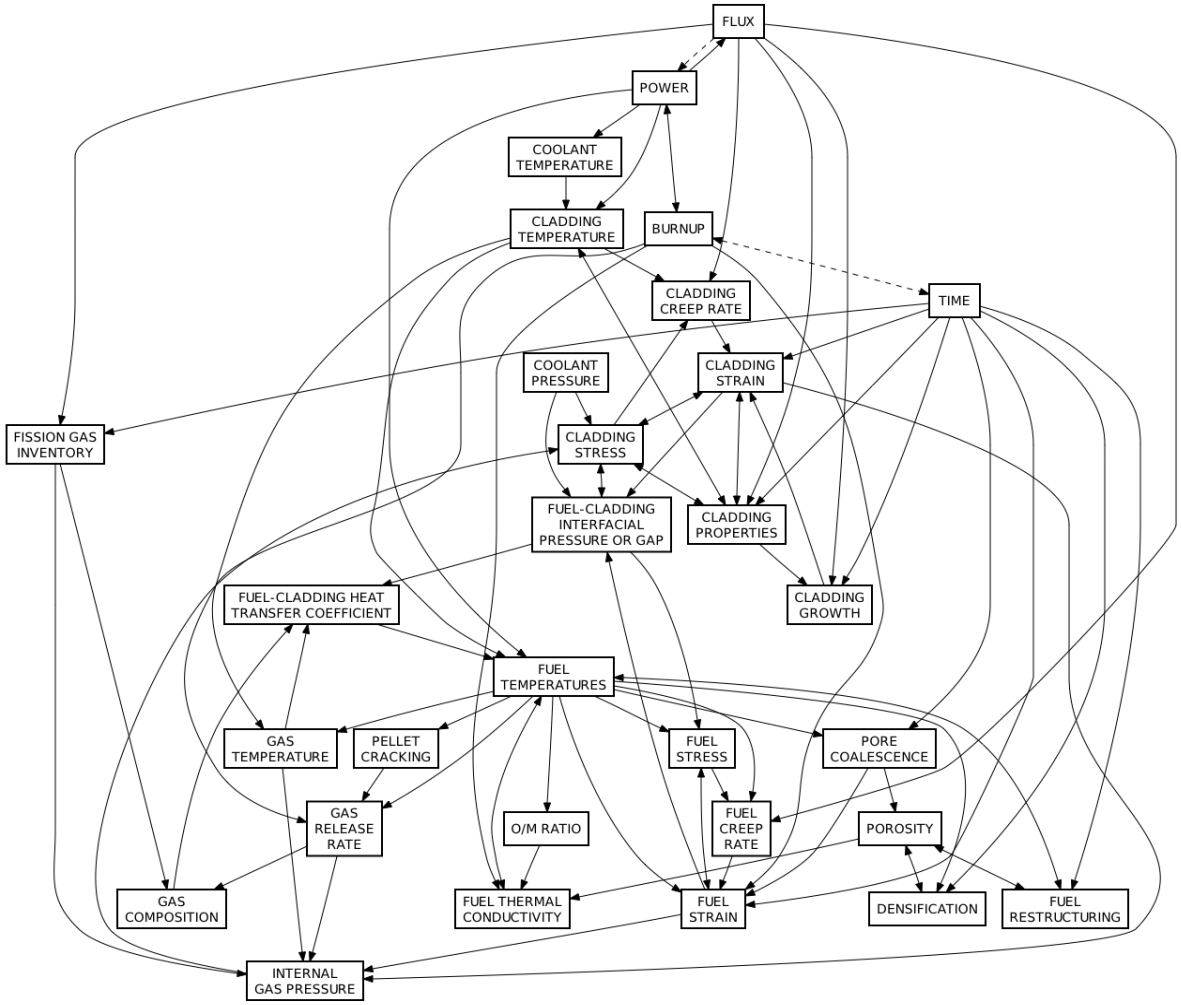


Bentejac et al, PCI Seminar (2004)

Stress Corrosion Cracking Cladding Failure

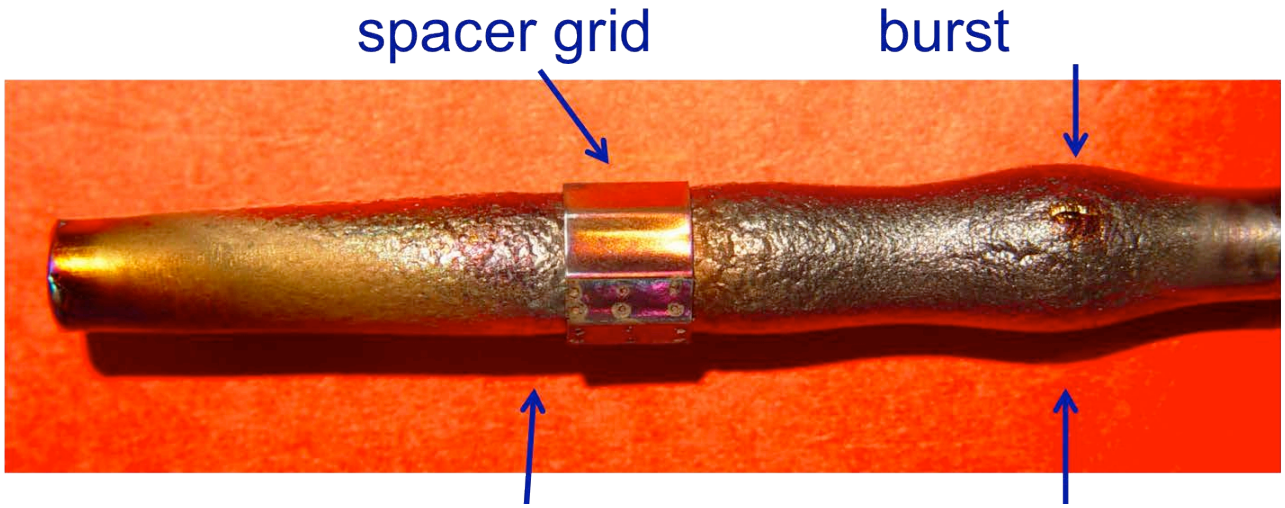
Fuel Behavior Modeling - Coupled Multiphysics and Multiscale

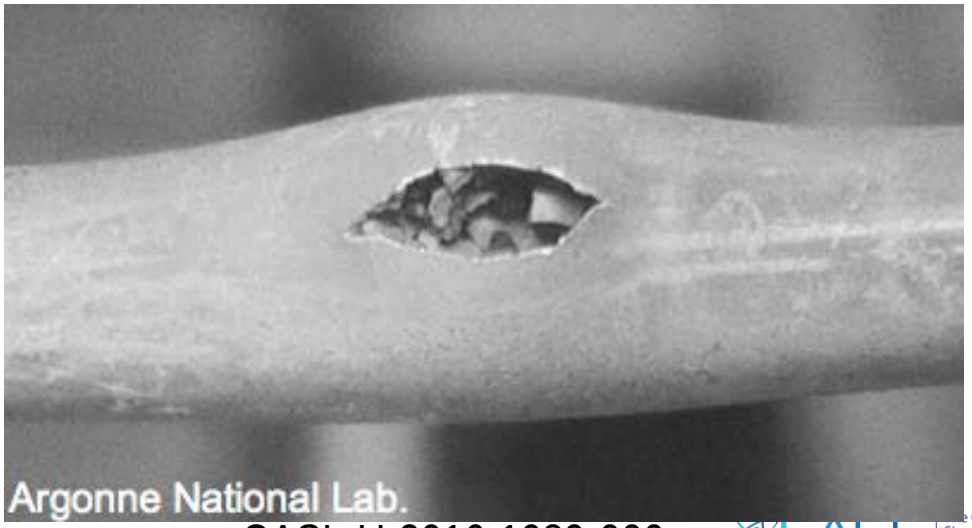
- **Multiphysics**
  - Fully-coupled nonlinear thermomechanics
  - Mass transport
  - Chemistry
  - Neutronics
  - Thermal-hydraulics
- **Multi-space scale**
  - Important physics operate at level of microstructure
  - Need real predictions at engineering scale
- **Multi-time scale**
  - Long, steady operation
  - Short power ramps
  - Rapid transients



Reproduced from Beyer et al., BNWL-1898, PNNL (1975)

… and complexity multiplies during accidents





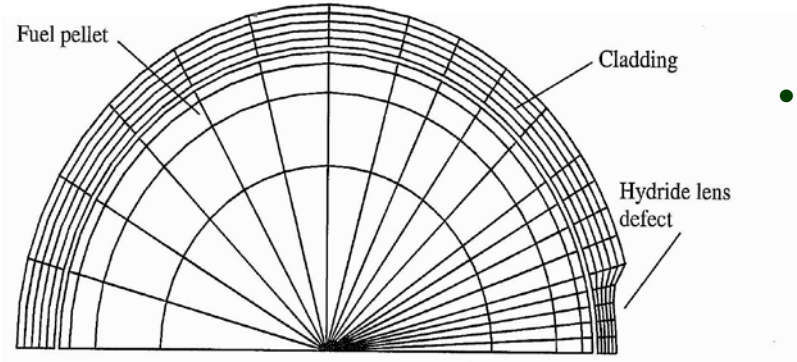
Fuel Behavior Modeling: Limitations of Legacy Codes

- Fuel performance codes are used for fuel rod design and determination of operational margins.
- However, industry standard codes (e.g. FRAPCON and FALCON, FRAPTRAN) have significant limitations:

Numerical Capabilities
- Serial
- Inefficient Solvers
- Loosely Coupled
- High Software Complexity

Geometry representation
- 1.5 or 2-D
- Restricted to LWR Fuel
- Smeared Pellets

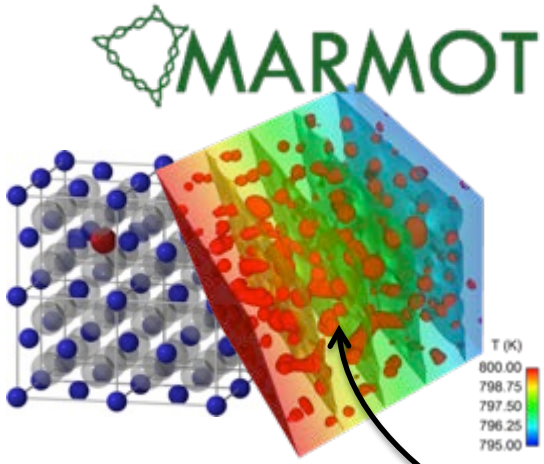
Materials models
- Largely empirical
- Valid for narrow range of operating conditions
- Valid for limited fuel/cladding types
- Limited applicability in accident scenarios

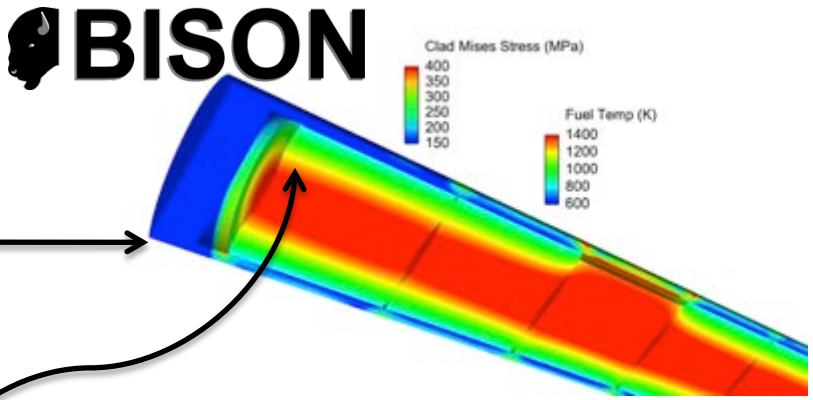


FALCON model to investigate clad failure due to defect

MBM: MOOSE-BISON-MARMOT

- MOOSE-BISON-MARMOT toolset provides an advanced, multiscale fuel performance capability





Mesoscale Material Model Development Tool

- Simulates microstructure evolution in fuels under irradiation
- Used with atomistic methods to develop multiscale materials models

MOOSE

Multiphysics Object-Oriented Simulation Environment

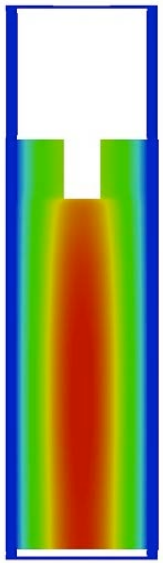
- Simulation framework enabling rapid development of FEM-based applications

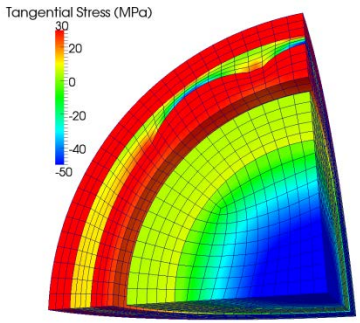
Engineering-scale Fuel Performance Tool

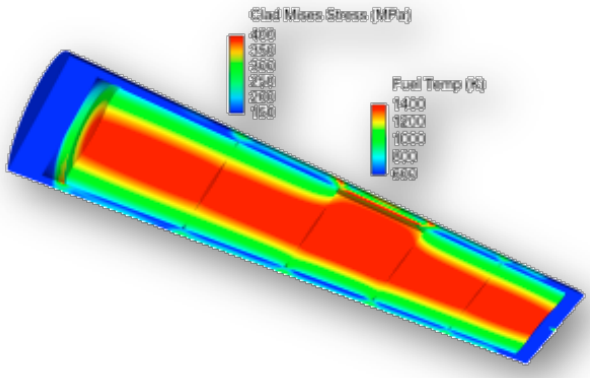
- Models LWR, TRISO and metallic fuels in 1D spherical, 2D axisymmetric and plane strain and fully 3D
- Steady-state and transient reactor operations
- BISON Theory, Users, & Validation Manuals (plus other good info) can be found at: http://bison.inl.gov

BISON Fuel Performance Code

- Finite element-based engineering scale fuel performance code based on INL's open-source MOOSE framework
- Solves the fully-coupled thermomechanics and species diffusion equations in 1D symmetric, 2D axisymmetric or generalized plane strain, or 3D
- Applicable to both steady and transient operation
- Used for LWR, TRISO, and metal fuels
- Easily coupled to lower length scale material models
- Designed for efficient use on parallel computers
- Working to establish needed accident capability







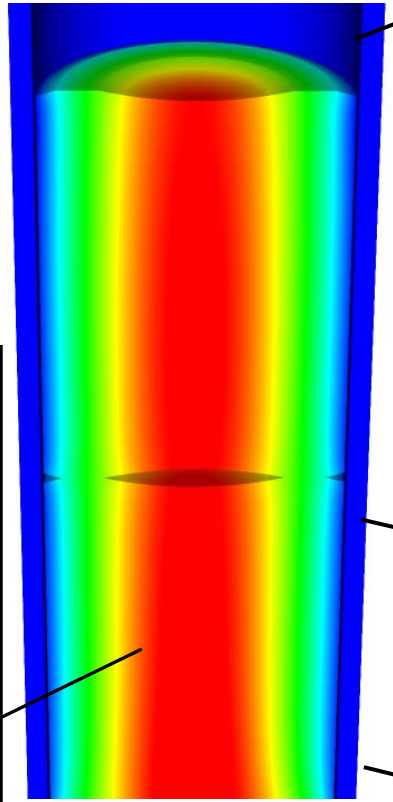
BISON LWR Capabilities

General Capabilities

- Finite element based 2D-RZ axisymmetric and Cartesian and 3D fully-coupled thermo-mechanics with species diffusion
- Linear or quadratic elements with large deformation mechanics
- Steady and transient operation
- Parallel computation
- Meso-scale informed material models

Gap/Plenum Behavior

- Gap heat transfer with $k_g = f(T, n)$
- Mechanical contact (master/slave)
- Plenum pressure as a function of:
  - evolving gas volume (from mechanics)
  - gas mixture (from FGR model)
  - gas temperature approximation



Temperature

Oxide Fuel Behavior

- Temperature/burnup dependent conductivity
- Heat generation with radial and axial profiles
- Thermal expansion
- Solid and gaseous fission product swelling
- Densification
- Thermal and irradiation creep
- Fracture via relocation or smeared cracking
- Fission gas release (two stage physics)
  - transient (ramp) release
  - grain growth and grain boundary sweeping
  - athermal release

Cladding Behavior

- Thermal expansion
- Thermal and irradiation creep
- Irradiation growth
- Gamma heating
- Combined creep and plasticity

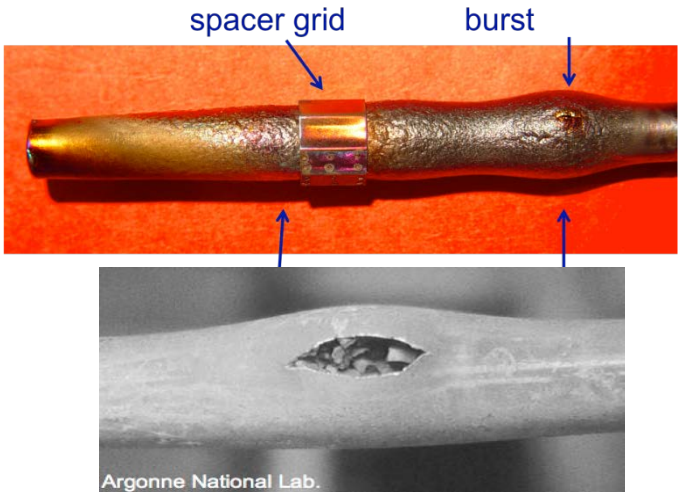
Coolant Channel

- Closed channel thermal hydraulics with heat transfer coefficients

Accident Capability Development

- BISON inherently well-suited for accident analysis (transient heat transfer, large strain formulation)

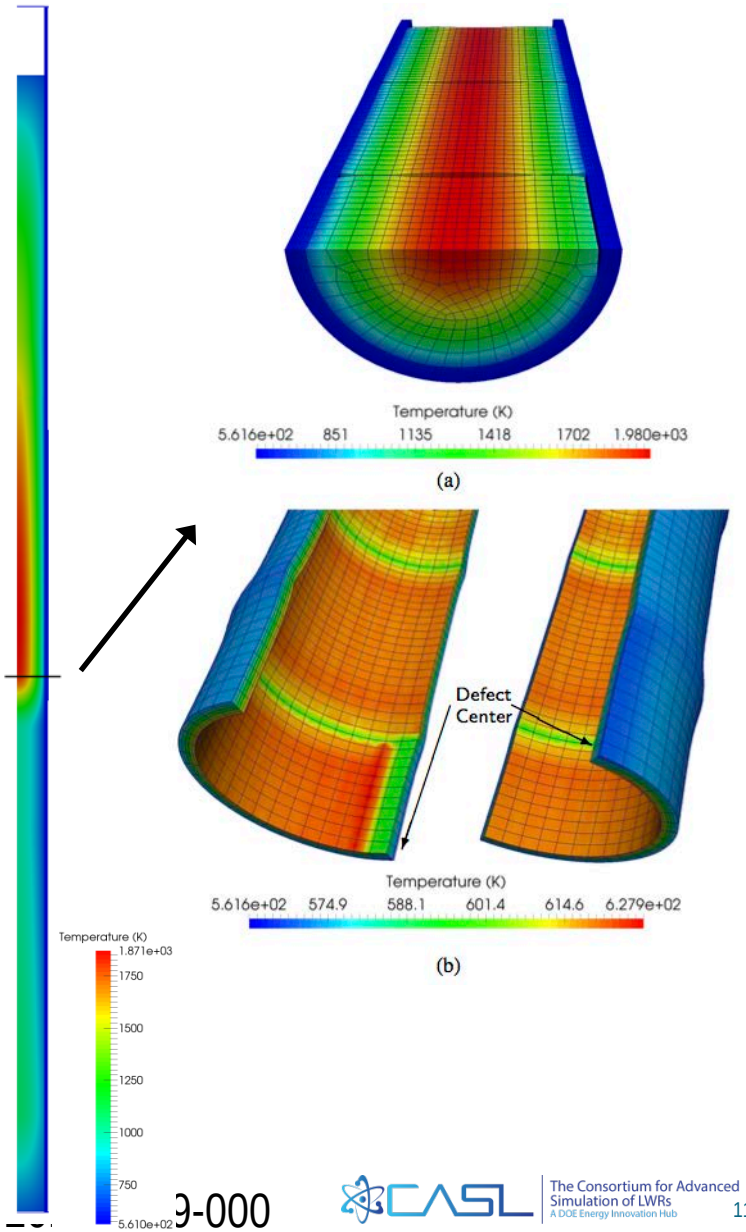
- LOCA: Substantial new capability developed under NEAMS and INL-LDRD funding
  - Thermal Hydraulics
    - Coolant channel model enhancements: full boiling curve, reflood model
    - Coupled to RELAP7
  - UO_2
    - Transient fission gas release model
  - Zircaloy Clad
    - High temperature thermal creep
    - Simple waterside corrosion
    - Microstructure phase transition
    - Large plasticity (ballooning)
    - Burst failure model
    - Hydrogen/hydride behavior
    - Steam oxidation with moving material interface (under development)
  - Preliminary validation (shown below)
  - Participation in CASL LOCA Challenge Problem Implementation Plan



- RIA: New capability established under NEAMS funding
  - Zircaloy cladding plasticity model (temperature, irradiation and strain-rate dependent)
  - Participation in RIA OECD benchmark and CASL RIA Challenge Problem Implementation Plan

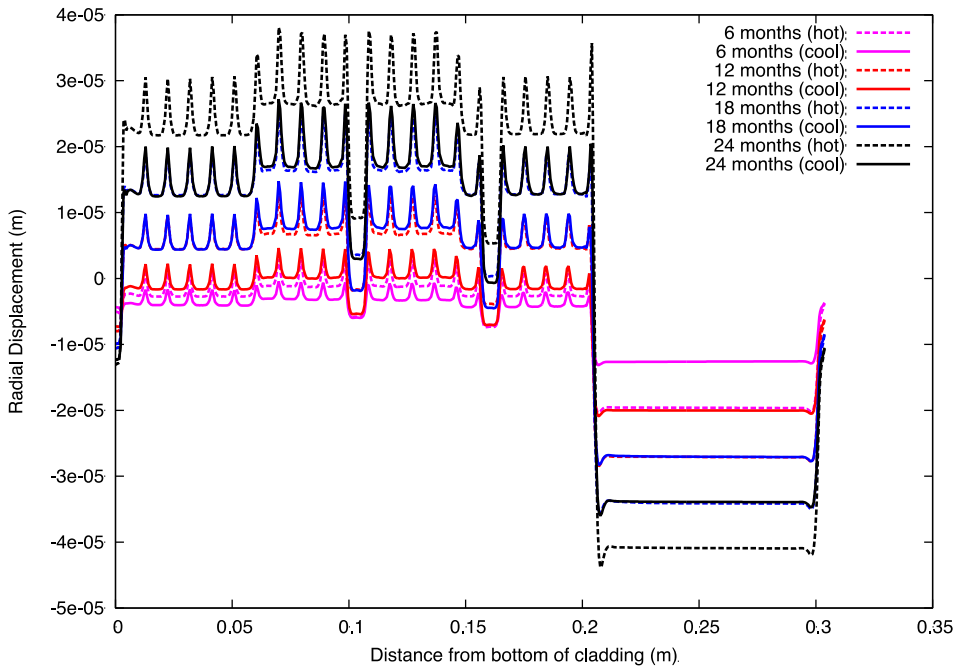
Fuel Defect Models: 2D-3D Coupling

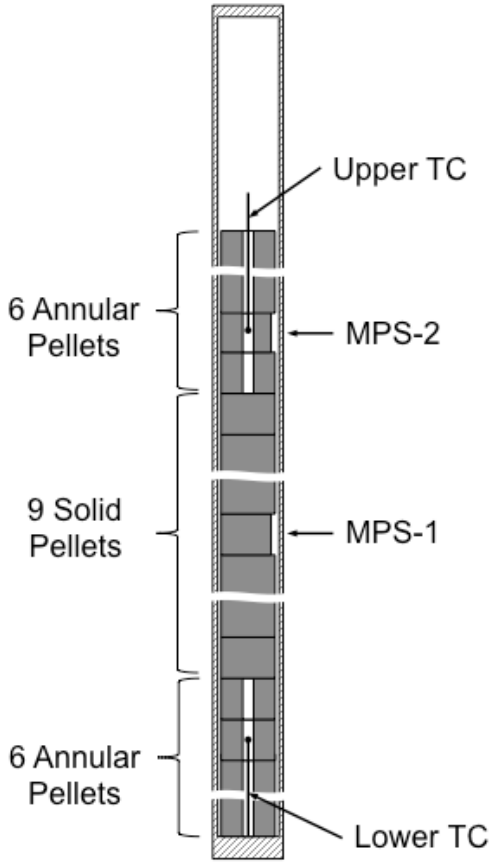
- Efficient modeling of local effects requires:
  - Global model of full fuel rod (2D for efficiency)
  - Local submodel (3D for accuracy)
  - Transfer of boundary conditions
- BISON recent enhancements permit variable transfer from 2D axisymmetric model to prescribe boundary conditions on 3D submodel
  - Global scalar variables
    - Fission gas released
    - Plenum gas temperature and volume
  - Field variables
    - Displacements at submodel ends (providing relative motion between fuel and clad)
    - Cladding temperature beyond submodel region

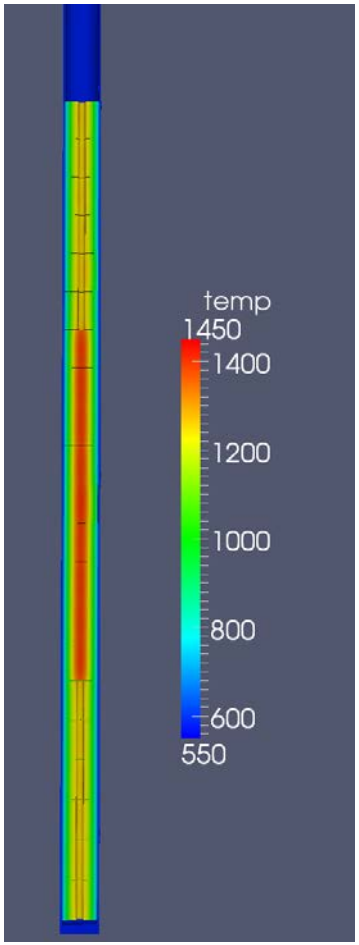


3D Halden MPS Experiment

- Working with Halden to design unique 3D MPS experiment for BISON validation
- Generated 21 pellet model (full rod) and simulated behavior for two year irradiation
- Determining final experiment configuration (defect size) and power history







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Leveraging to Support Multiple DOE Programs

- MBM is the NEAMS code platform for fuel rods and lower length scales
- BISON is the CASL fuel performance code and is an integral part of the VERA platform
- BISON is supporting experimental design analysis and being used to explore Accident Tolerant Fuel concepts for the Fuel Cycle Research and Design (FCRD) campaign
- BISON is used to investigate novel clad materials for the Light Water Reactor Sustainability (LWRS) program
- BISON is used to investigate multidimensional defects in TRISO coated-particle fuel, beneficial to the Next Generation Nuclear Plant (NGNP)
- BISON is used to study plate fuel for the Reduced Enrichment for Research and Test Reactors (RERTR) program

BISON Licensees – Nov. 2015

US Labs
- ANL
- INL
- LANL
- ORNL
- PNNL
- SNL

Industry
- CASL
- ANATECH Corp
- EPRI
- AREVA
- Westinghouse
- Bechtel Marine
- RNET Technologies

Foreign Labs/Univ/Institutions
- NNL
- CNL
- CER (Hungary)
- Halden
- Korea Adv. Inst. of Sci. & Tech.
- Politecnico di Milano
- Royal Military College

US Universities
- Kansas State
- MIT
- Ohio State
- Oregon State
- Penn State
- Texas A&M
- U of Illinois
- U of Michigan
- U of South Carolina
- U of Tennessee Knoxville
- U of Wisconsin Madison
- UC Berkeley
- Virginia Commonwealth

International Collaborations

- **OECD Halden Reactor Project**
  - Member of BISON team on 1 yr out plant assignment
  - Source for many of our current validation cases including accident behavior
  - Currently participating in design of a unique 3D MPS experiment specifically intended for BISON validation
- **IAEA research project FUMAC**
  - Participating in the Fuel Modeling in Accident Conditions (FUMAC) research project
    - Source of quality LOCA experimental data
    - Comparison to established fuel codes
  - Further international collaboration (e.g., European Commission – ITU)
- **National Nuclear Laboratory**
  - Source of LWR validation data and code comparisons
  - Contributing capability to model oxide fast fuel

The OECD Halden Reactor Project

AECL EACL

Institute for Transuranium Elements

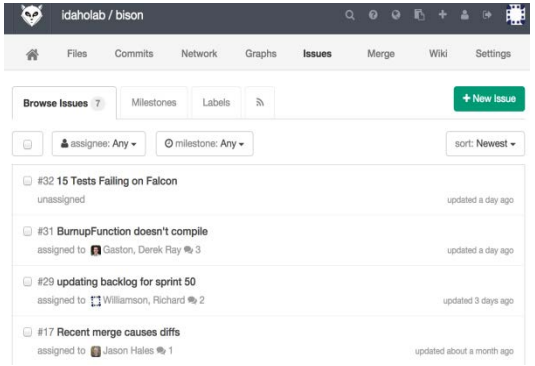
NATIONAL NUCLEAR LABORATORY

Software Quality Assurance

- Software quality is tightly controlled using issue tracking, merge requests and collaborative code review (via GitLab)

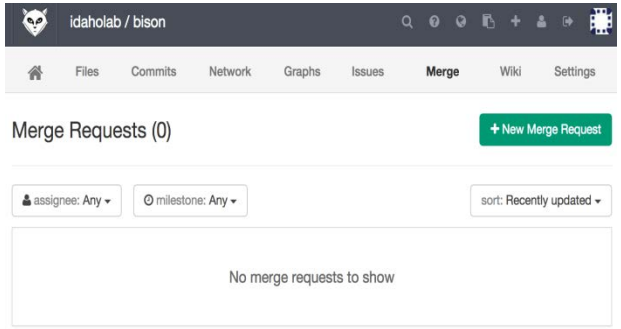
Issue Tracking

- Users can submit issues or request improvements
- Each issue is recorded and tracked to completion



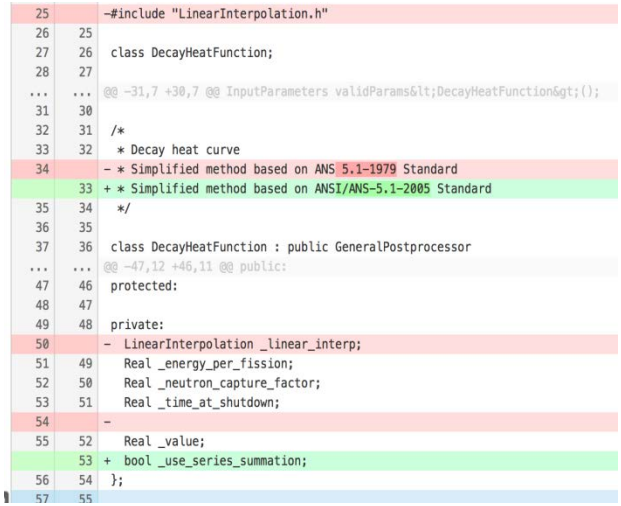
Merge requests and testing

- Code changes are submitted for review
- Review starts once the code updates pass all tests



Collaborative Code Review

- Code changes are posted on the GitLab site
- Users can comment and make suggestions on code
- Once satisfied with the changes, they are merged into the code



```
25      -#include "LinearInterpolation.h"
26  25
27  26  class DecayHeatFunction;
28  27
......  @@ -31,7 +30,7 @@ InputParameters validParams&lt;DecayHeatFunction&gt;();
31  30
32  31  /*
33  32   * Decay heat curve
34      - * Simplified method based on ANS 5.1-1979 Standard
    33  + * Simplified method based on ANSI/ANS-5.1-2005 Standard
35  34   */
36  35
37  36  class DecayHeatFunction : public GeneralPostprocessor
......  @@ -47,12 +46,11 @@ public:
47  46  protected:
48  47
49  48  private:
50      -  LinearInterpolation _linear_interp;
51  49     Real _energy_per_fission;
52  50     Real _neutron_capture_factor;
53  51     Real _time_at_shutdown;
54      -
55  52     Real _value;
    53  +  bool _use_series_summation;
56  54  };
57  55
```

- Recently (Nov 2015) underwent detailed software quality assessment. Deemed NQA-1 compliant for R&D software.

Code Verification

- BISON thru MOOSE is supported by >1000 unit and regression tests
- All new code must be supported by verification testing
- All tests are run and must pass prior to any code modification
- Current line coverage is at 85%
- Journal article published in FY-14 on BISON verification

LCOV - code coverage report

Current view: top level
Test: BISON Test Coverage
Date: 2015-11-12 17:54:42
Legend: Rating: low: < 70 % medium: >= 70 % high: >= 80 %

	Hit	Total	Coverage
Lines:	9805	11623	84.4 %
Functions:	1335	1555	85.9 %

Directory	Line Coverage		Functions	
include/actions	93.3 %	14 / 15	63.3 %	19 / 30
include/auxkernels	87.5 %	21 / 24	87.5 %	42 / 48
include/base	50.0 %	2 / 4	0.0 %	0 / 1
include/bcs	61.5 %	8 / 13	42.1 %	8 / 19
include/bcs/coolant	100.0 %	4 / 4	50.0 %	1 / 2
include/functions	62.0 %	116 / 187	84.2 %	16 / 19
include/kernels	77.8 %	14 / 18	47.2 %	17 / 36
include/materials	92.6 %	112 / 121	58.0 %	80 / 138
include/postprocessors	93.8 %	15 / 16	59.3 %	16 / 27
include/userobject	88.9 %	8 / 9	76.9 %	10 / 13
src	92.9 %	13 / 14	100.0 %	3 / 3
src/actions	83.8 %	629 / 751	95.9 %	71 / 74
src/auxkernels	81.6 %	666 / 816	92.9 %	118 / 127
src/base	98.9 %	180 / 182	83.3 %	10 / 12
src/bcs	76.4 %	446 / 584	86.1 %	62 / 72
src/bcs/coolant	81.7 %	522 / 639	87.3 %	62 / 71
src/functions	84.8 %	318 / 375	95.0 %	19 / 20
src/kernels	77.8 %	424 / 545	86.2 %	94 / 109
src/materials	85.8 %	5507 / 6422	94.6 %	542 / 573
src/mesh	94.8 %	236 / 249	80.0 %	8 / 10
src/parser	100.0 %	38 / 38	100.0 %	3 / 3
src/postprocessors	89.9 %	232 / 258	91.7 %	88 / 96
src/userobject	82.6 %	280 / 339	88.5 %	46 / 52

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Verification of the BISON fuel performance code

J.D. Hales *, S.R. Novascone, B.W. Spencer, R.L. Williamson, G. Pastore, D.M. Perez

Fuel Modeling and Simulation, Idaho National Laboratory, P.O. Box 1625, Idaho Falls, ID 83415-3840, United States

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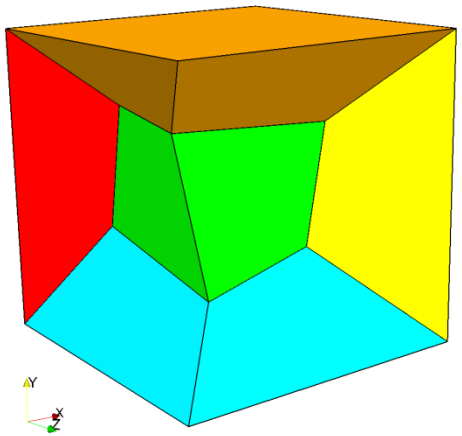
ABSTRACT

Complex multiphysics simulations such as those used in nuclear fuel performance analysis are composed of many submodels used to describe specific phenomena. These phenomena include, for example, mechanical material constitutive behavior, heat transfer across a gas gap, and mechanical contact. These submodels work in concert to simulate real-world events, like the behavior of a fuel rod in a reactor. If a simulation tool is able to represent real-world behavior, the tool is said to be validated. While much emphasis is rightly placed on validation, model verification is equally important. Verification involves showing that a submodel computes results consistent with its mathematical description. This paper reviews the differences between verification, validation, and calibration as well as their dependencies on one another. Verification problems specific to nuclear fuel analysis are presented. Other verification problems suitable to assess the correctness of a finite element-based nuclear fuel application such as

Two Verification Examples

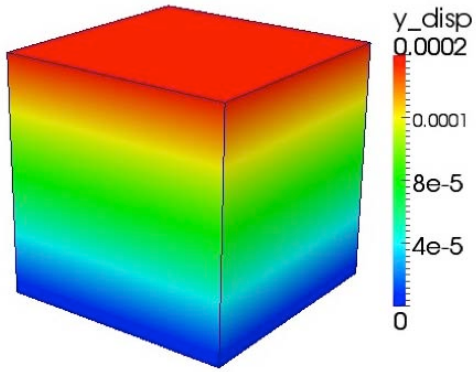
3D FEM Patch Test



Outer nodes displaced:
$u_x = 1\text{x}10^{-6}$, $u_y = 2\text{x}10^{-6}$, $u_z = 3\text{x}10^{-6}$
Outer faces sheared:
$1\text{x}10^{-6}$, $2\text{x}10^{-6}$, $3\text{x}10^{-6}$ for xy, yz, zx

Analytical solution is a spatially uniform stress/strain state:
$\sigma_{xx} = 1$, $\sigma_{yy} = 2$, $\sigma_{zz} = 3$
$\sigma_{xy} = 0.5$, $\sigma_{yz} = 1$, $\sigma_{zx} = 1.5$

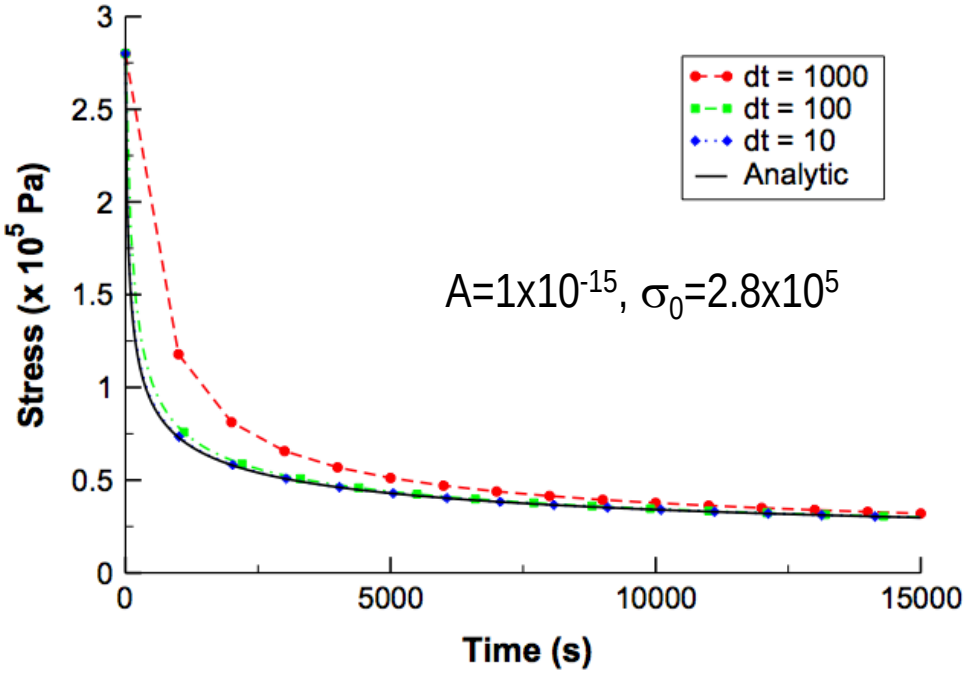
Power Law Creep



$$\dot{\epsilon}_{cr} = A\sigma^n e^{-Q/RT} t^m$$

For constant strain and
n = 4, Q = 0, m = 0

$$\sigma(t) = \frac{\sigma_0}{(3AE\sigma_0^3 t + 1)^{1/3}}$$



$A=1\text{x}10^{-15}$, $\sigma_0=2.8\text{x}10^5$

Validation for LWR Fuel

- Recently published summary article in Nuclear Engineering and Design
- Validation areas
  - Fuel centerline temperature through all phases of fuel life
  - Fission gas release
  - Clad diameter (PCMI)

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Validating the BISON fuel performance code to integral LWR experiments

R.L. Williamson[a,*], K.A. Gamble[a], D.M. Perez[a], S.R. Novascone[a], G. Pastore[a], R.J. Gardner[a], J.D. Hales[a], W. Liu[b], A. Mai[b]

[a] Fuel Modeling and Simulation, Idaho National Laboratory, P.O. Box 1625, Idaho Falls, ID 83415-3840, United States
[b] ANATECH Corporation, 5435 Oberlin Dr., San Diego, CA 92121, United States

HIGHLIGHTS

- The BISON multidimensional fuel performance code is being validated to integral LWR experiments.
- Code and solution verification are necessary prerequisites to validation.
- Fuel centerline temperature comparisons through all phases of fuel life are very reasonable.
- Accuracy in predicting fission gas release is consistent with state-of-the-art modeling and the involved uncertainties.
- Rod diameter comparisons are not satisfactory and further investigation is underway.

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ABSTRACT

BISON is a modern finite element-based nuclear fuel performance code that has been under development at Idaho National Laboratory (INL) since 2009. The code is applicable to both steady and transient fuel behavior and has been used to analyze a variety of fuel forms in 1D spherical, 2D axisymmetric, or 3D geometries. Code validation is underway and is the subject of this study. A brief overview of BISON's computational framework, governing equations, and general material and behavioral models is provided. BISON code and solution verification procedures are described, followed by a summary of the experimental data used to date for validation of Light Water Reactor (LWR) fuel. Validation comparisons focus on fuel centerline temperature, fission gas release, and rod diameter both before and following fuel-clad mechanical contact. Comparisons for 35 LWR rods are consolidated to provide an overall view of how the code is predicting physical behavior, with a few select validation cases discussed in greater detail. Results demonstrate that (1) fuel centerline temperature comparisons through all phases of fuel life are very reasonable with deviations between predictions and experimental data within ±10% for early life through high burnup fuel and only slightly out of these bounds for power ramp experiments, (2) accuracy in predicting fission gas release appears to be consistent with state-of-the-art modeling and with the involved uncertainties and (3) comparison of rod diameter results indicates a tendency to overpredict clad diameter reduction early in life, when clad creepdown dominates, and more significantly overpredict the diameter increase late in life, when fuel expansion controls the mechanical response. Initial rod diameter comparisons are not satisfactory and have led to consideration of additional separate effects experiments to better understand and predict clad and fuel mechanical behavior. Results from this study are being used to define priorities for ongoing code development and validation activities.

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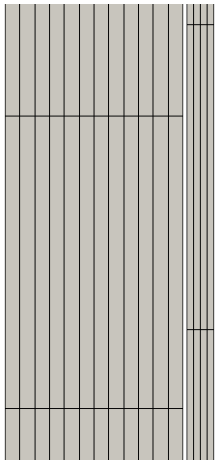
LWR Validation (48 cases)

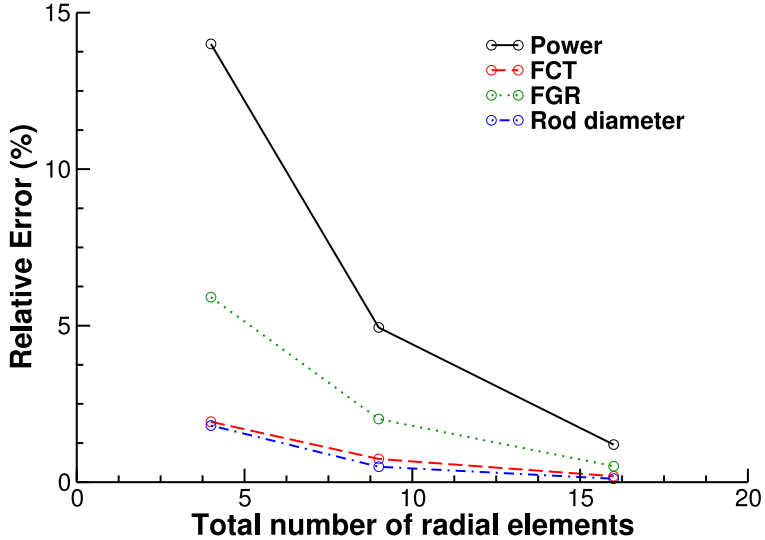
Experiment	Rod	Final Burnup (MWd/kgU)	BOL FCT	TL FCT	Ramp FCT	EOL FGR	EOC Rod Dia
IFA-431	1	≈ 4	X				
IFA-431	2	≈ 4	X				
IFA-431	3	≈ 4	X				
IFA-431 (3D)	4	≈ 4	X				
IFA-432	1	≈ 32	X				
IFA-432	2	≈ 32	X				
IFA-432	3	≈ 32	X				
IFA-515.10	A1	86.6	X	X			
IFA-534	18	59.0				X	
IFA-534	19	59.0				X	
IFA-535	809	54.4				X	
IFA-535	810	54.4				X	
IFA-562.2	15	56.7		X			
IFA-562.2	16	56.2		X			
IFA-562.2	17	56.2		X			
IFA-597.3	8	68.1			X	X	
Risø-2	GE-m	15.8				X	X
Risø-3	AN2	40.7				X	X
Risø-3	AN3	42.0			X	X	
Risø-3	AN4	42.0			X	X	
Risø-3	GE7	40.9			X	X	X
Risø-3	II3	17.6			X	X	X
Risø-3	II5	47.6			X	X	X
OSIRIS	H09	46.1				X	X
OSIRIS	J12	26.7				X	X
REGATE		47.0				X	X
USPWR 16x16	TSQ002	53.2				X	X
USPWR 16x16	TSQ022	58.1				X	X
R.E. Ginna	2	51.2				X	X
R.E. Ginna	4	57.0				X	X
HBEP	BK363	76.0				X	
HBEP	BK365	78.3				X	

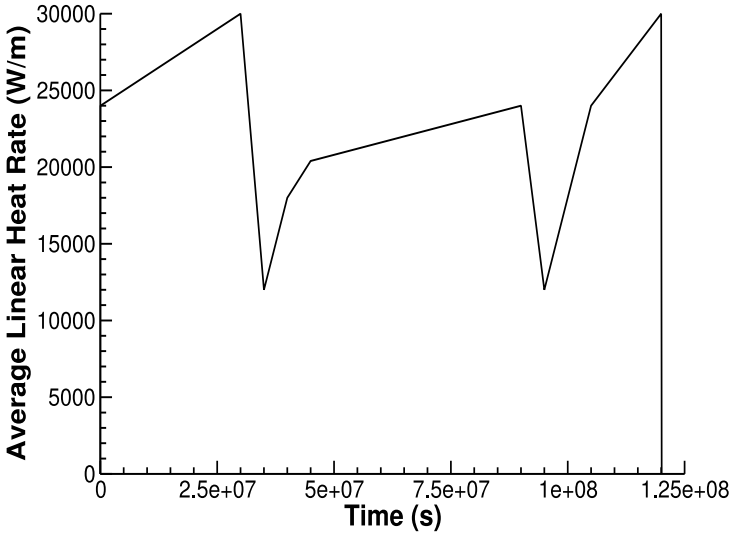
Experiment	Rod	Final Burnup (MWd/kgU)	BOL FCT	TL FCT	Ramp FCT	EOL FGR	EOC Rod Dia
Tribulation	BN1/3	50.7				X	X
Tribulation	BN1/4	50.6				X	X
Tribulation	BN3/15	51.1				X	X
Calvert Cliffs	UFE019	46.8				X	X
Calvert Cliffs	UFE067	54.8				X	X
Calvert Cliffs	BFM156	56.9				X	X
Calvert Cliffs	BFM071	57.1				X	X
Calvert Cliffs	BFG092	57.9				X	X
Calvert Cliffs	BFL009	58.1				X	X
Calvert Cliffs	BFL031	58.3				X	X
Calvert Cliffs	BFJ027	58.7				X	X
Calvert Cliffs	BEN013	59.8				X	X
Calvert Cliffs	BFM073	60.3				X	X
Calvert Cliffs	BFM043	60.5				X	X
Calvert Cliffs	BFM070	60.8				X	X
Calvert Cliffs	BFM034	63.5				X	X

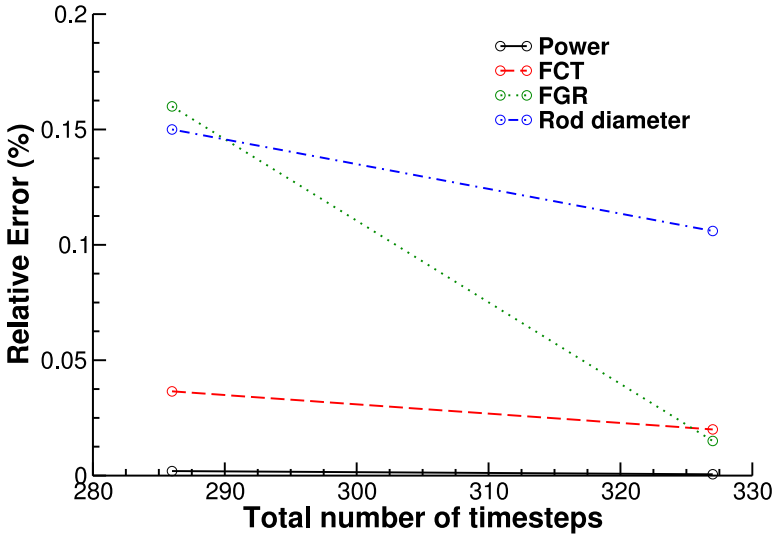
LWR Validation – Solution Verification

- Essential prerequisite to validation
- Used to demonstrate adequate spatial and temporal resolution for LWR validation cases

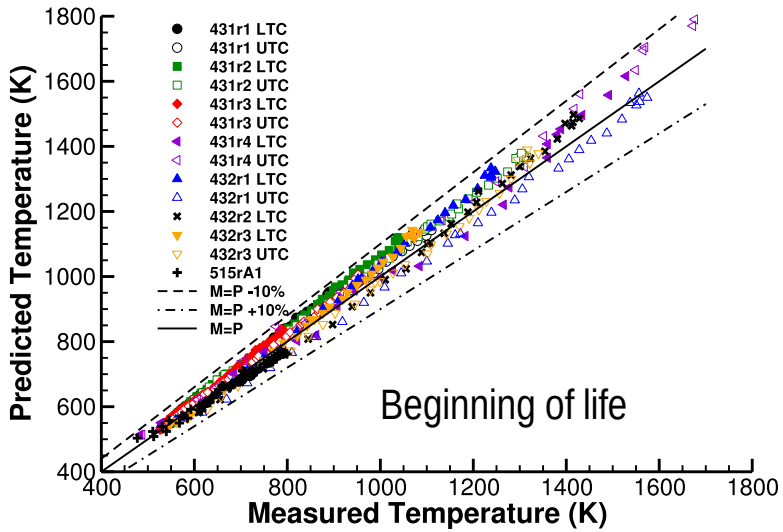


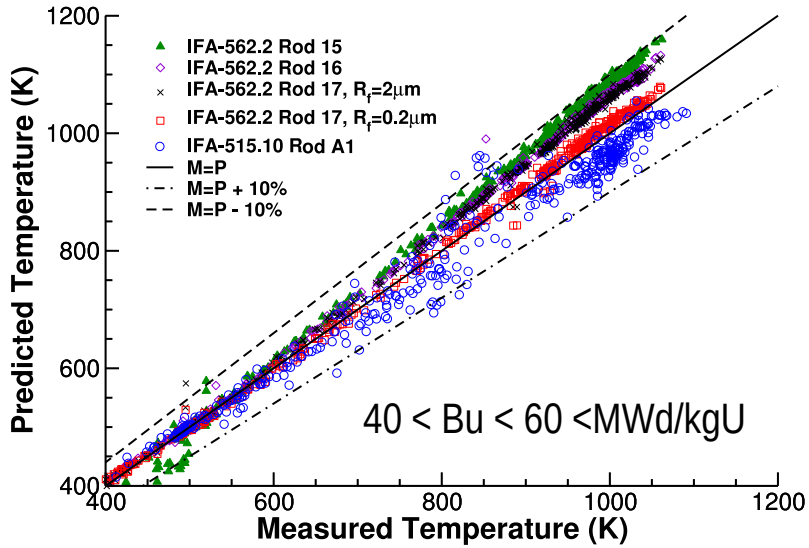


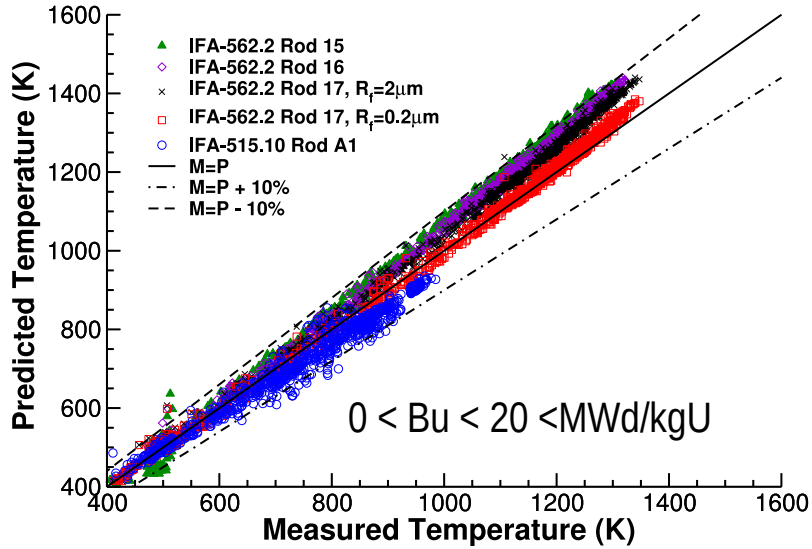


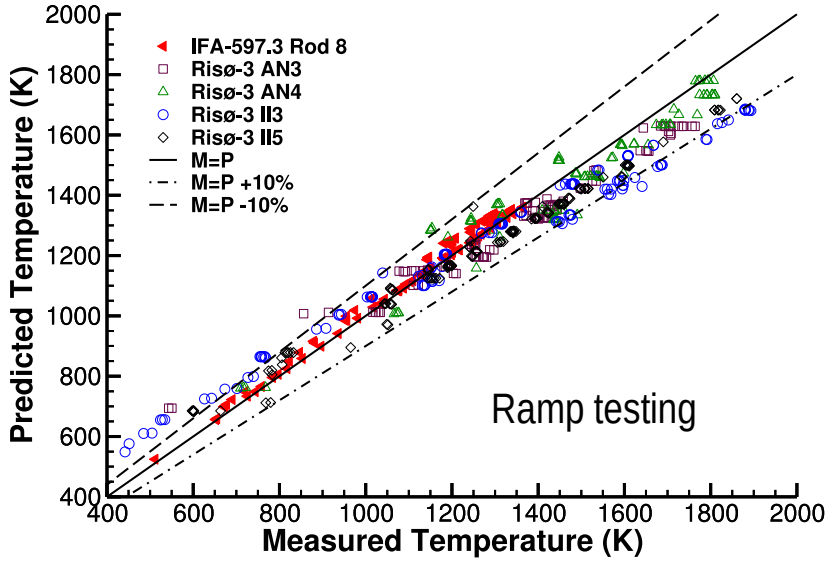


LWR Validation – Fuel Centerline Temperature









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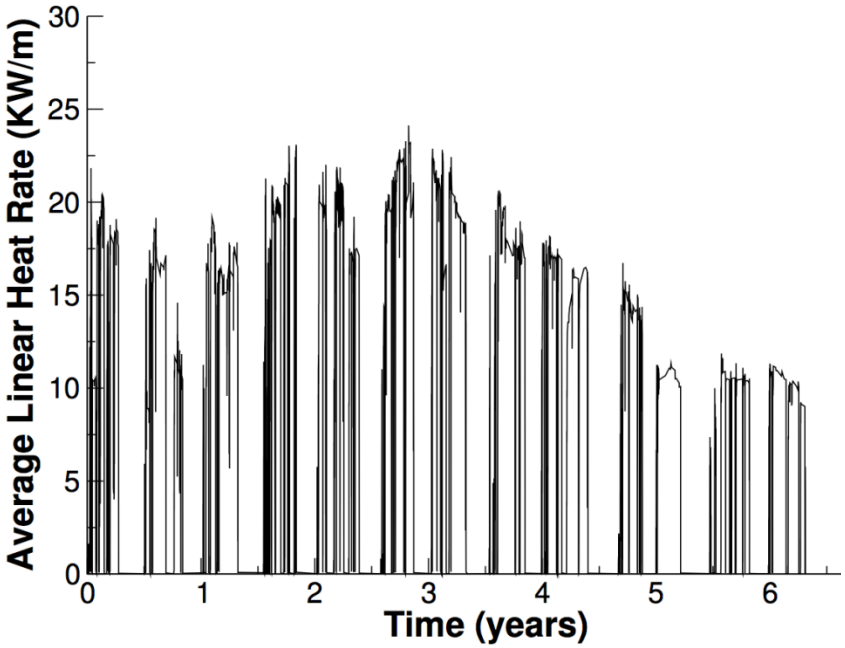
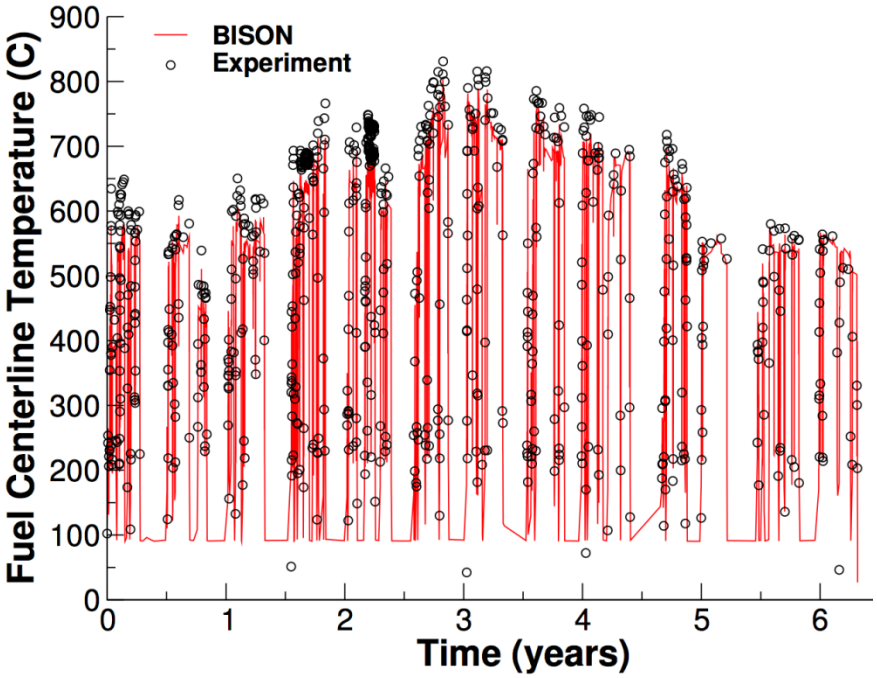
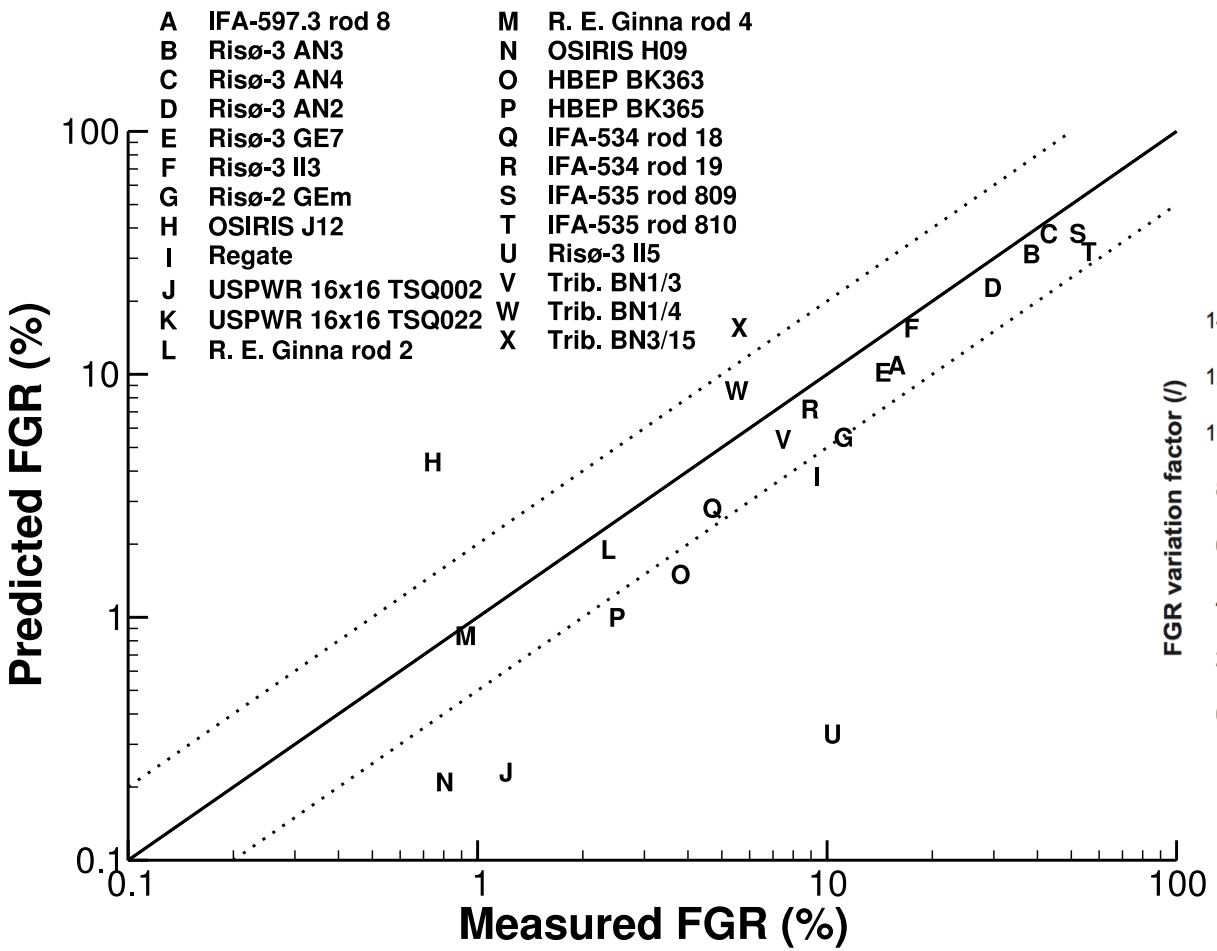
LWR Validation – IFA 515.10 Rod A1 Example of a Complex Power History

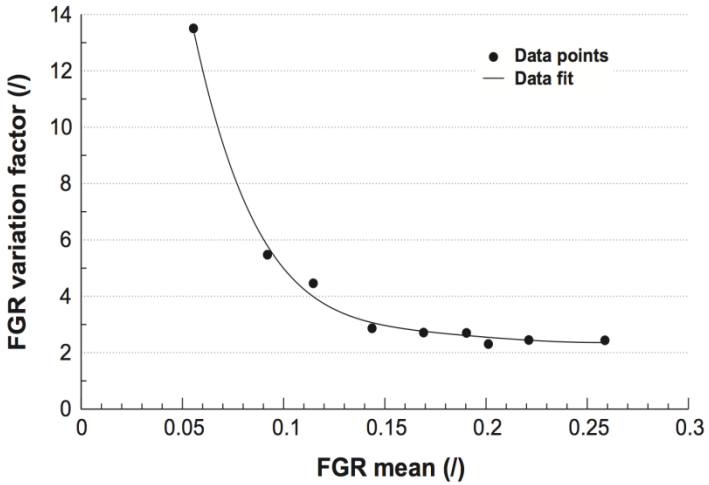




LWR Validation - Fission Gas Release

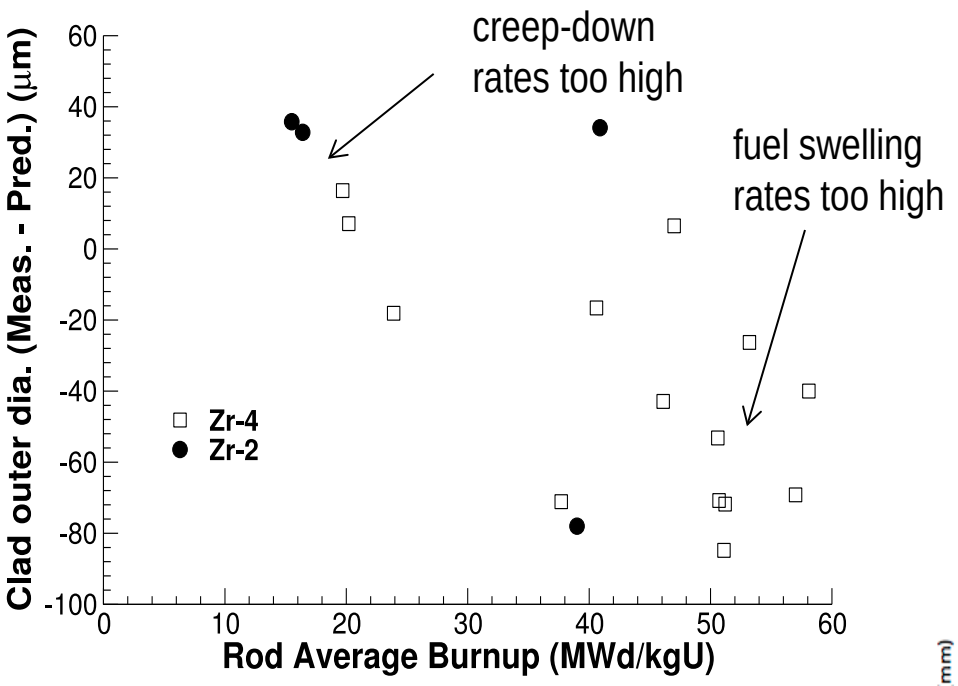


- Accuracy in predicting FGR is consistent with state-of-the-art modeling and with the involved uncertainties

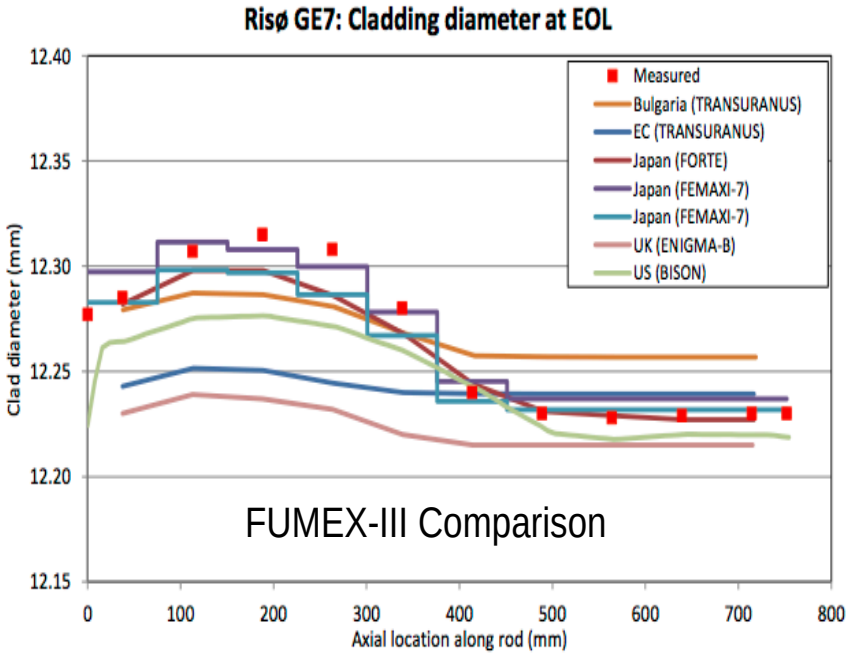


Pastore et al, Journal of Nuclear Materials, 456, 398 (2014)

LWR Validation – PCMI (rod diameter)



- Prediction of PCMI behavior remains difficult (for essentially all fuel performance codes)
  - FUMEX-II (2002-2007)
  - FUMEX-III (2008-2012)
  - Recent BISON efforts



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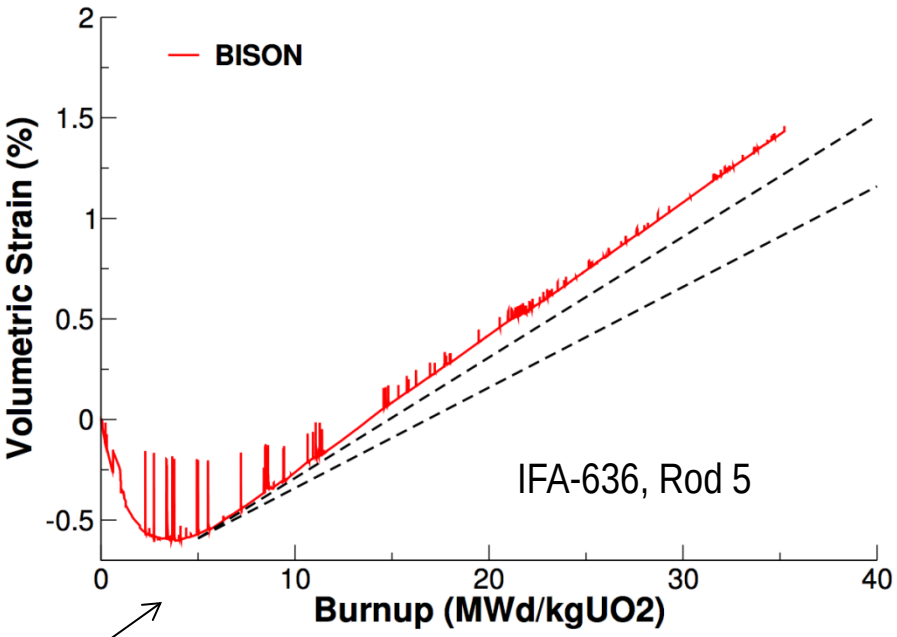
Why?

- PCMI is multiphysics and complex
- Large uncertainty in key models
  - Relocation
  - Fuel and clad creep
  - Frictional contact
  - Gaseous swelling (at high temperature)
- Model calibration likely needed
- Participating in OECD PCMI benchmark exercise to explore and improve this area

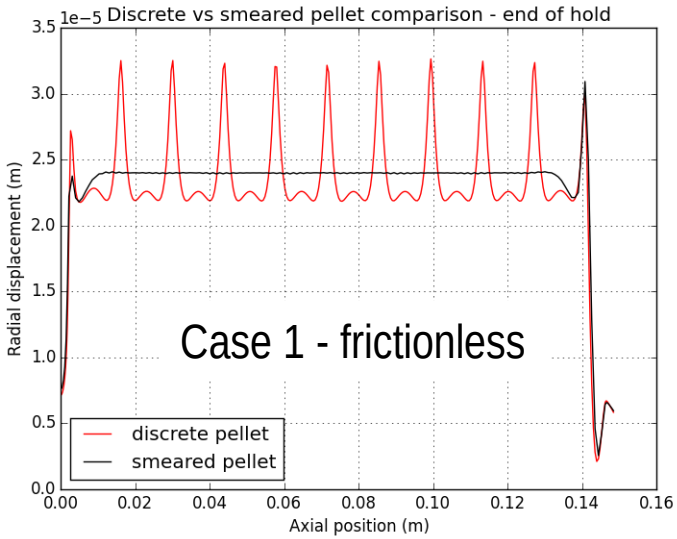


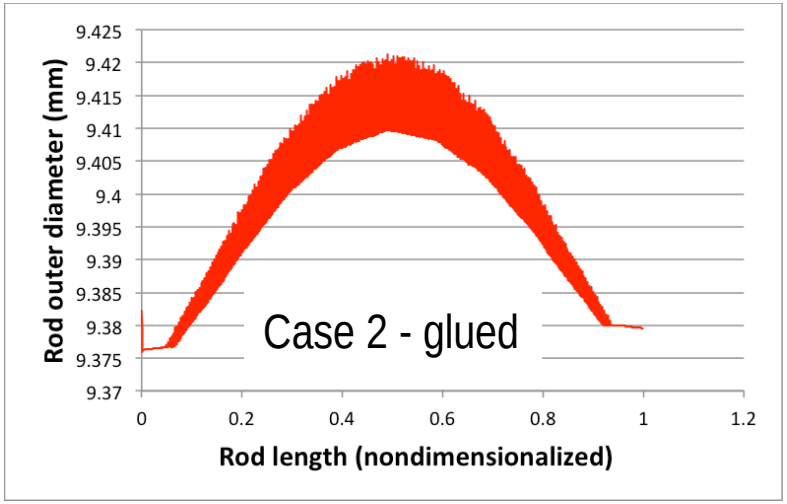
OECD PCMI Benchmark (2015-2016)

- Philosophy: Back away some from the complexity of full-rod, late-life comparisons
  - Only four cases (start simple and build in complexity)
  - Similar philosophy for ongoing RIA benchmark
- ~ 20 Participants, 12 codes
  - BISON (INL, U of Illinois, ORNL)
  - FRAPCON (Tractebel-Belgium, CIEMAT-Spain, IRSN-France)
  - TRANSURANUS (UJV - Czech Republic)
  - ENIGMA (NNL-Great Britian)
  - FEMAXI (JAEA-Japan)
  - ABAQUS (UJV-Czech Republic)
  - FRAPTRAN (CIAE - China)
  - DIONISIO (CNEA - Argentina)
  - ELESTRES (CNL-Canada)
  - FAST-COMSOL (CNL-Canada)
  - FTPAC (CIAE-China)
  - ANSYS (SEA - Spain)

PCMI Benchmark Cases

- Case 1 - Hypothetical beginning-of-life ramp of PWR rodlet
- Case 2 - Hypothetical beginning-of-life ramp of commercial PWR rod
- Cases 1 and 2 are completed: Predictions compare well to trusted legacy codes (e.g., ENIGMA and TRANSURANUS)





- Case 3 – Beginning-of-life ramps of experimental rods (Halden) with different pellet designs (8 rods)
- Case 4 – End-of-life ramp of PWR rodlet

BISON Verification and Validation Plan for LWR Fuel (CASL Milestone)

- Final draft completed March 31, 2016
- Provides current status and future plans
- Motivated by CASL Challenge Problems (PCI, LOCA, RIA) and LWR validation experience

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Validation Plan – PCMI and Overall LWR

Table 5.7: Prioritized summary table for the upcoming validation cases for validation areas 1-6 specified in section 5.3.1.

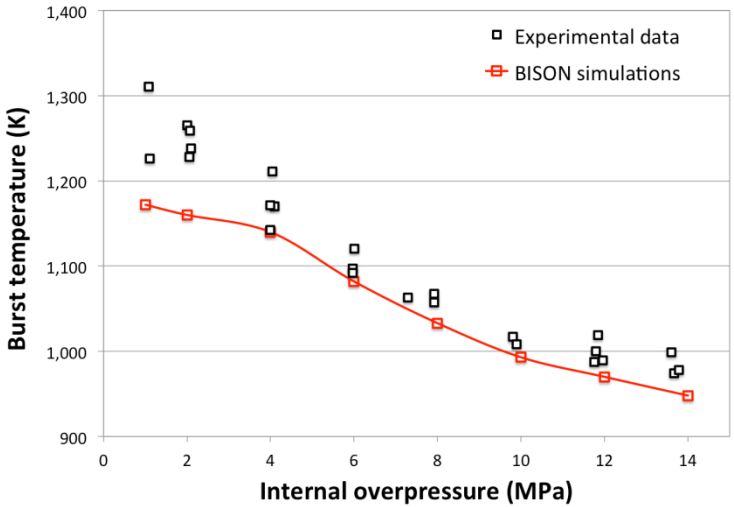
Experiment	Rod	BOL FCT	TL FCT	Ramp FCT	EOL FGR	EOC Rod Dia	EOC Ox Thick
SUPER-RAMP	PK2-1				X	X	X
SUPER-RAMP	PK2-3				X	X	X
SUPER-RAMP	PK2-S				X	X	X
IFA-118.2	1					X	
IFA-118.2	2					X	
IFA-118.2	4					X	
IFA-118.3	1					X	
IFA-118.3	3					X	
IFA-118.3	5					X	
IFA-118.3	6					X	
IFA-118.3	8					X	
IFA-629.4	7					X	
IFA-???	3D-MPS	X	X		X	X	
R. E. Ginna	2						X
R. E. Ginna	4						X
OSIRIS	H09						X
Risø-3	II5						X
IFA-535.5/6	809						
IFA-535.5/6	810						
IFA-535.5/6	811				X		
IFA-535.5/6	812				X		
IFA-534.14	18						X
IFA-534.14	19						X
HBEP	BK363						X
HBEP	BK365						X
Risø-3	II3						X
Risø-3	GE-m						
IFA-519.8/9	DH						
IFA-519.8/9	DK						
Risø-3	AN2						X

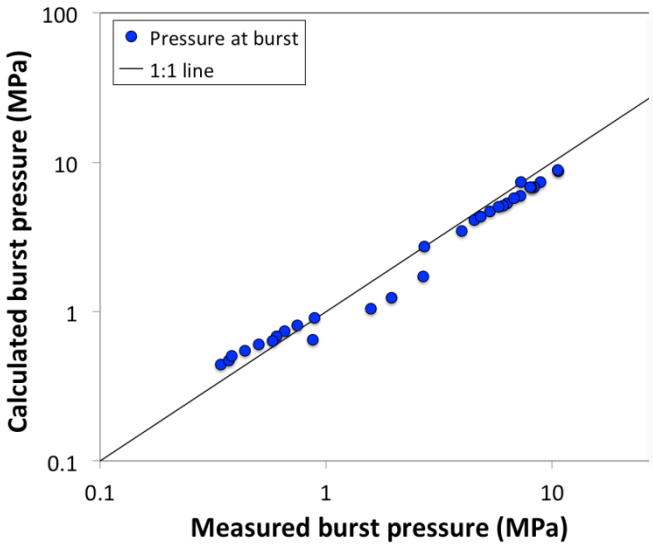
Table 5.8: Prioritized summary table for the upcoming validation cases for validation areas 7-12 specified in section 5.3.1.

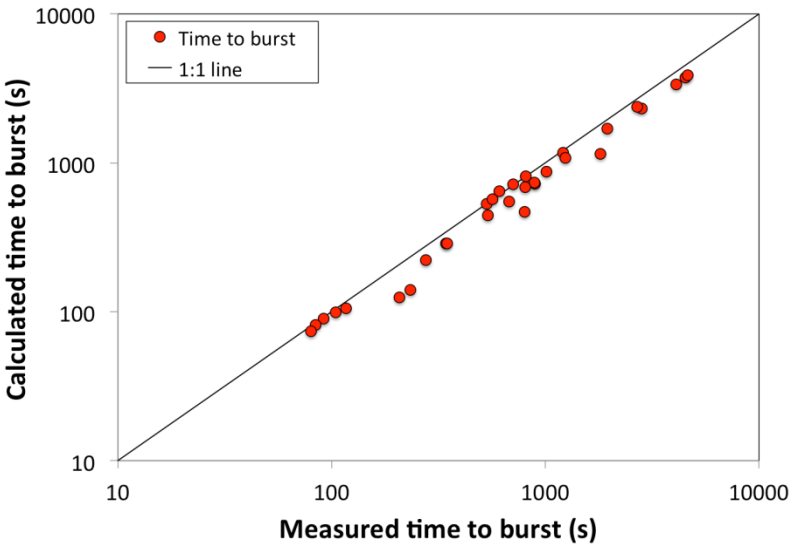
Experiment	Rod	Fuel Elong	Clad Elong	EOL Press	EOL Grain Dia	EOL Volume	EOL Density
SUPER-RAMP	PK2-1				X		
SUPER-RAMP	PK2-3				X		
SUPER-RAMP	PK2-S				X		
IFA-118.2	1		X				
IFA-118.2	2		X				
IFA-118.2	4		X				
IFA-118.3	1		X				
IFA-118.3	3		X				
IFA-118.3	5		X				
IFA-118.3	6		X				
IFA-118.3	8		X				
IFA-629.4	7		X				
IFA-???	3D-MPS						
R. E. Ginna	2	X				X	
R. E. Ginna	4	X				X	
OSIRIS	H09	X	X			X	X
Risø-3	II5		X			X	
IFA-535.5/6	809		X			X	
IFA-535.5/6	810		X			X	
IFA-535.5/6	811		X	X		X	
IFA-535.5/6	812		X	X		X	
IFA-534.14	18				X	X	
IFA-534.14	19				X	X	
HBEP	BK363				X		
HBEP	BK365				X		
Risø-3	II3				X	X	
Risø-3	GE-m				X	X	
IFA-519.8/9	DH			X		X	
IFA-519.8/9	DK			X		X	
Risø-3	AN2				X	X	

LOCA Validation - Clad failure (burst criterion)

- Clad burst model implemented
- Validation is in progress. Current comparisons with experimental data (cladding ballooning and burst failure) are in line with the state of the art.







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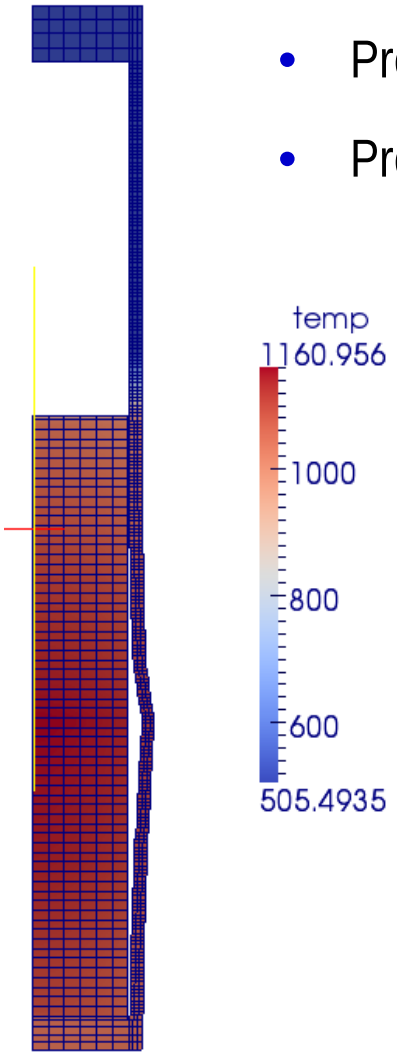
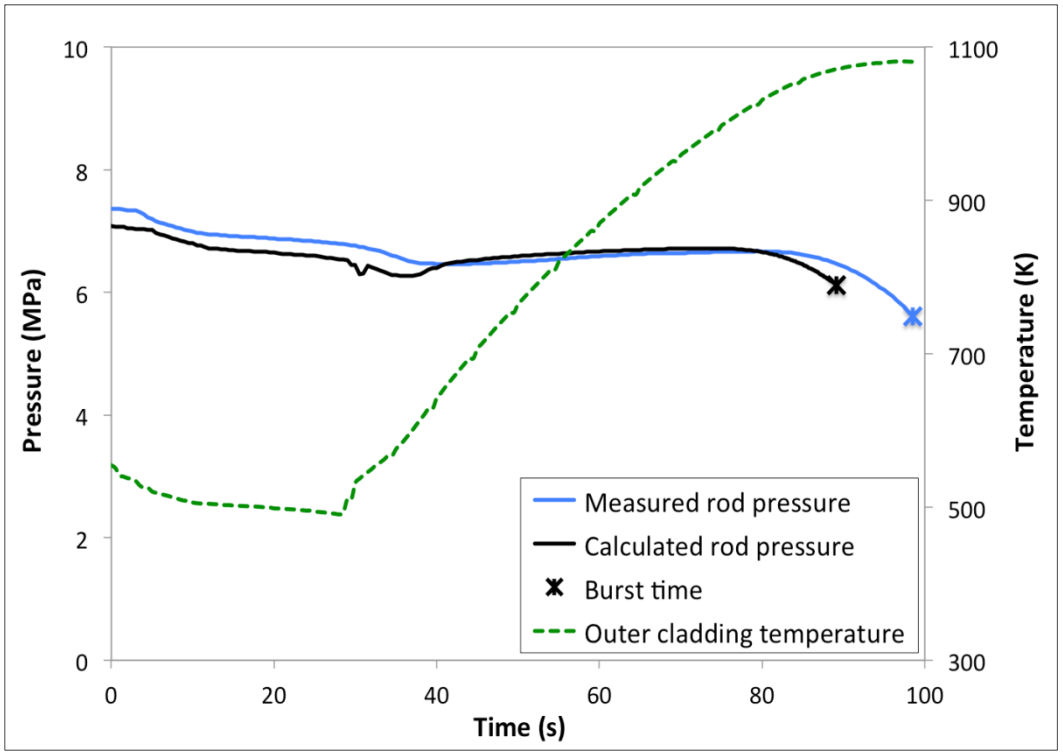
LOCA Validation – Halden 650.2



- Preliminary comparisons to early Halden LOCA experiment
- Predicted rod pressure and time to failure are very encouraging



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Validation Plan – LOCA

Table 5.9: LOCA related experiments considered to date.

Experiment	Rod/Test	Description
PUZRY	31 tubes	Zircaloy-4 burst pressure and time to burst
REBEKA	25 tubes	Zircaloy-4 burst temperature
IFA-650	2	Integral single PWR rod with fresh UO_2; included cladding rupture

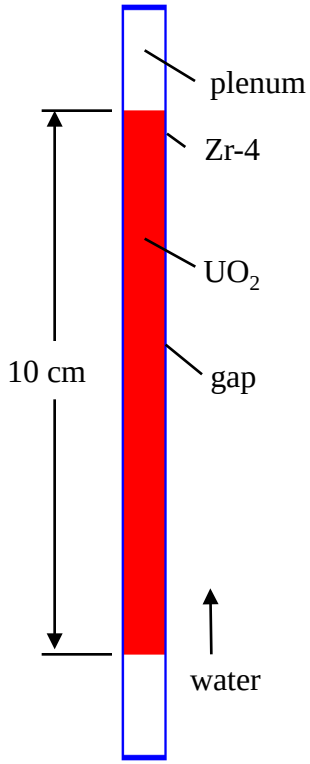
- Several of the cases recommended in the CASL LOCA Challenge Problem Implementation Plan

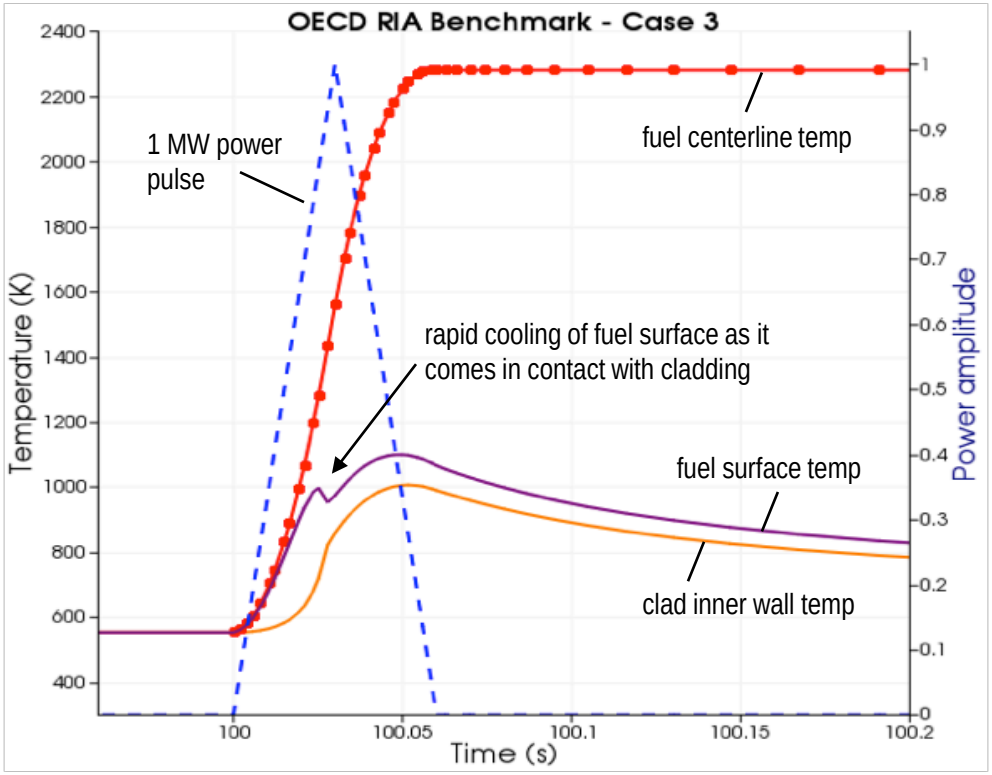
Table 5.10: Planned LOCA-related experiments for BISON validation.

Experiment	Rod/Test	Description
Hardy	Multiple tubes	Zircaloy-4 Expansion and Rupture
IFA-650	10	Integral single PWR rod with fresh UO_2; included cladding rupture
QUENCH	L1 bundle	Integral PWR rods with Zr-4 cladding; cladding temperature and burst
Studsvik	192	High burnup ZIRLO PWR burst test
Studsvik	198	High burnup ZIRLO PWR burst test
TREAT	FRF-1	UO_2 with Zircaloy cladding; in-reactor burst test
TREAT	FRF-2	UO_2 with Zircaloy cladding; in-reactor burst test
PBF PCM-2	UTA-008	UO_2 with Zircaloy cladding; normal and DNB coolant conditions

RIA Benchmark

- Participating in OECD RIA fuel codes exercise which includes 10 benchmark cases
- Phase 1: Cases build in complexity from a simple rapid thermal transient to inclusion of mechanics to inclusion of thermal hydraulic behavior
- Phase 2: Single case studied in detail including sensitivity analysis (BISON-Dakota)





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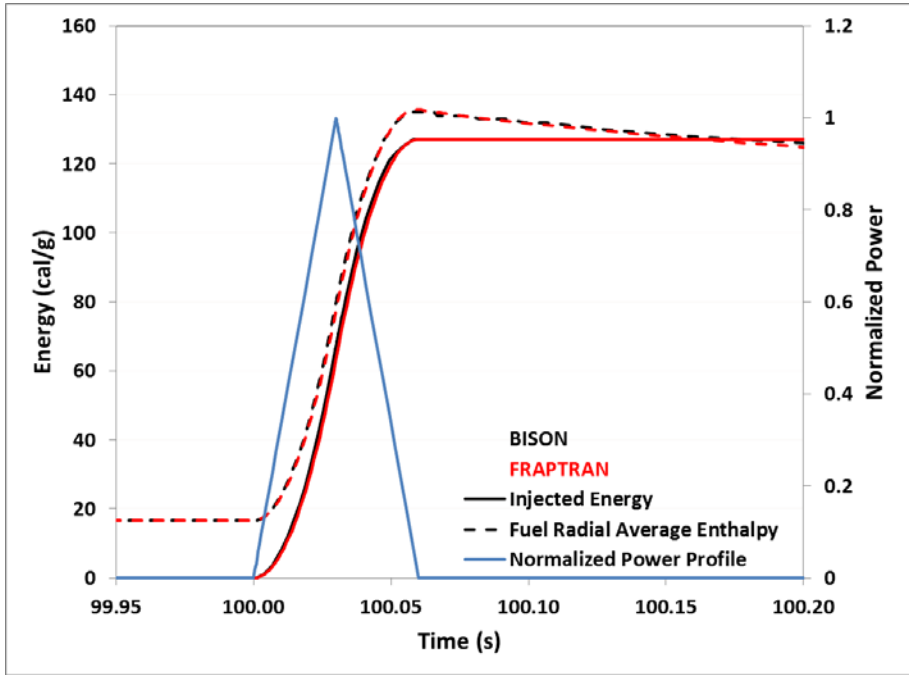
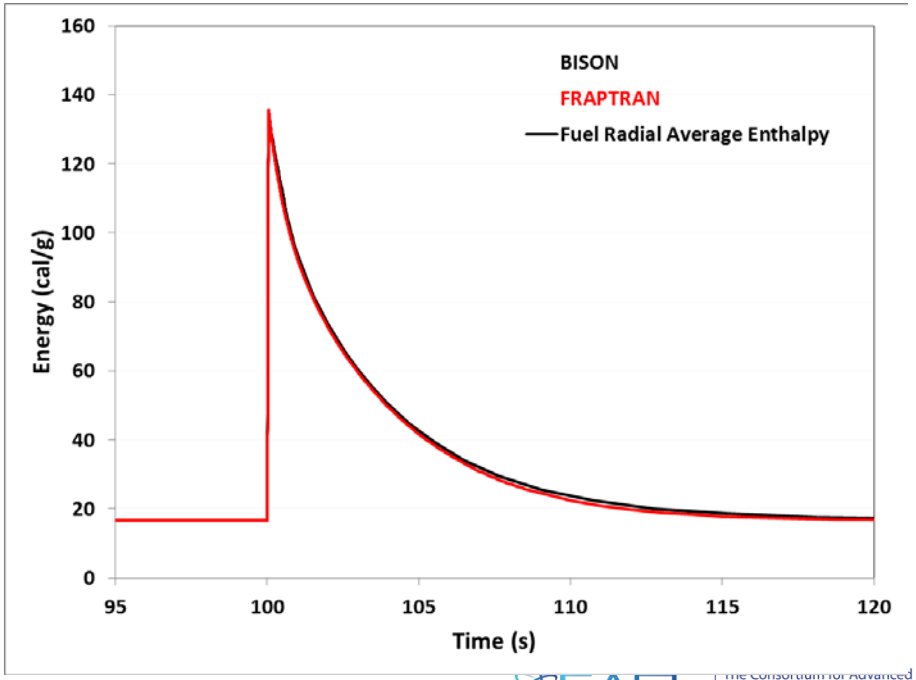
Results: Injected Energy & Fuel Enthalpy

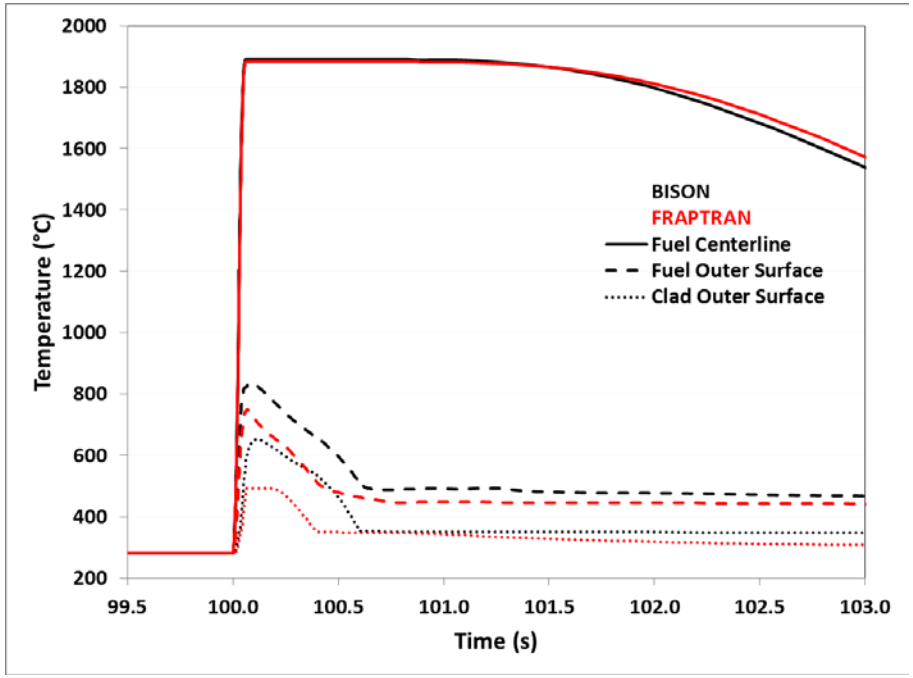
- 1 MW power pulse results in 127 cal/g of energy injected into the fuel rod
- The variation in fuel radial average enthalpy agrees well between FRAPTRAN and BISON
  - FRAPTRAN max value of 135.74 cal/g
  - BISON max value of 135 cal/g

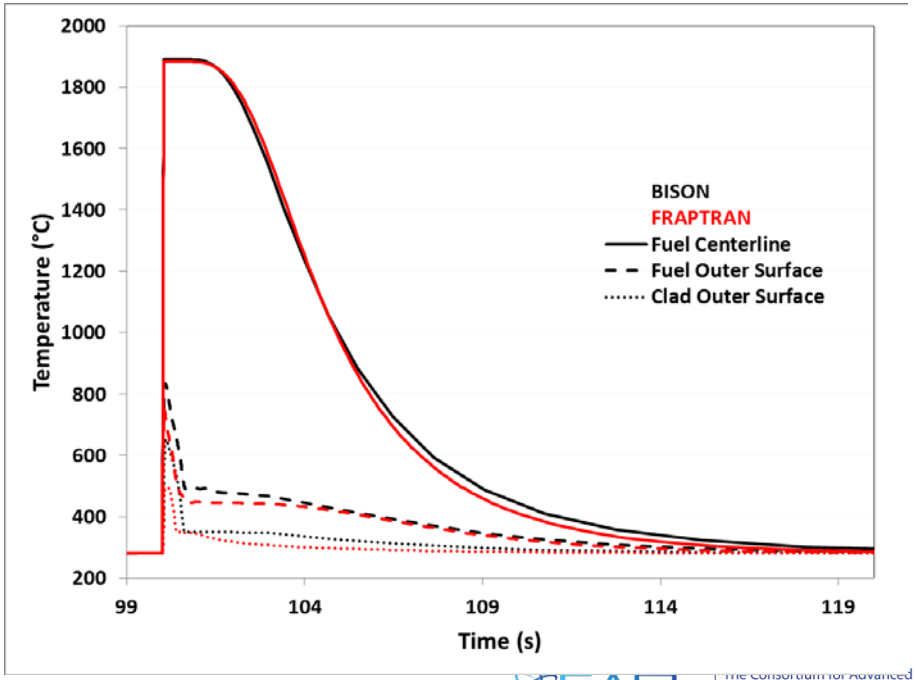




Results: Temperature

- Fuel centerline temperature profile agrees well
  - Max FRAPTRAN temperature is 1882.7 C
  - BISON max temperature is 1890.0 C
- Deviation between fuel outer surface temperature and cladding outer surface is likely due to differences in fuel to cladding and cladding to coolant heat transfer coefficients





Validation Plan – RIA Cases

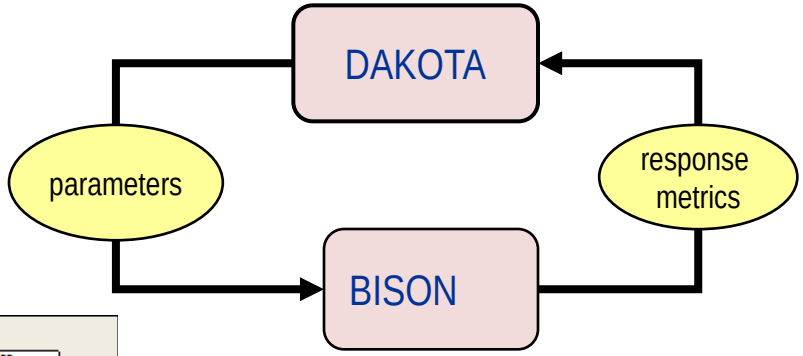
- No BISON validation cases yet
- Eight cases planned (as recommended in the CASL RIA Challenge Problem Implementation Plan)

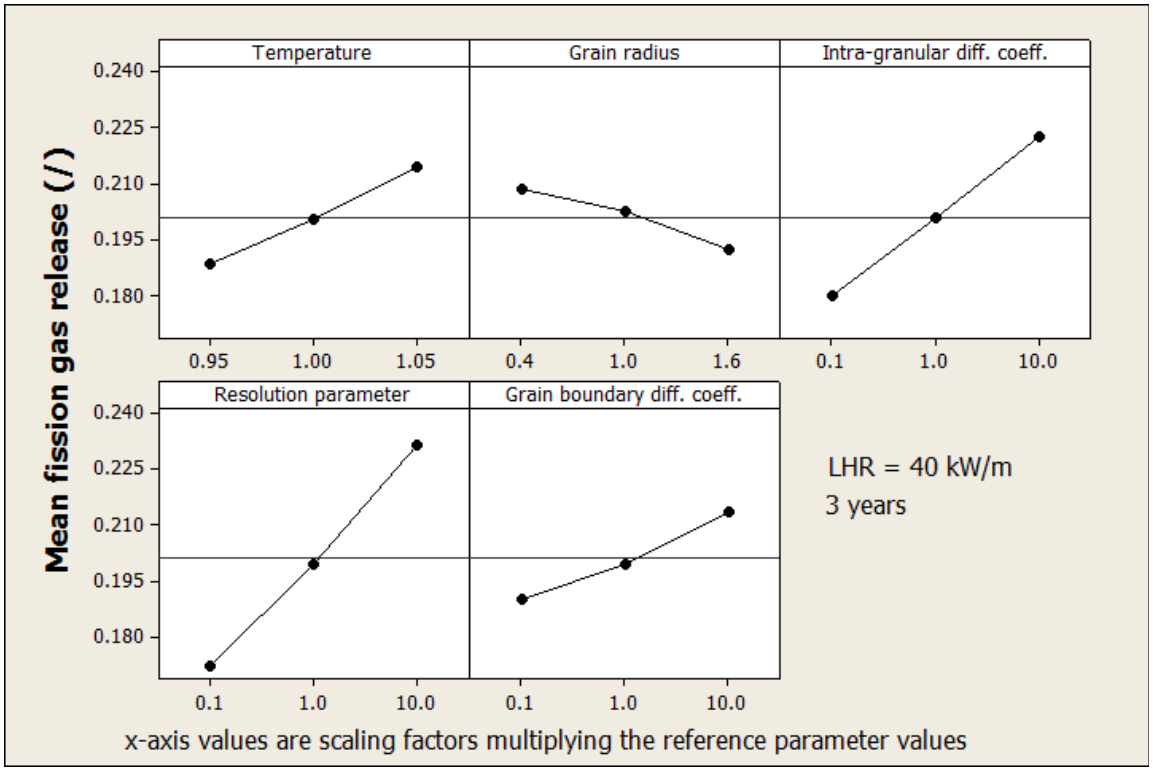
Table 5.11: Planned RIA experiments for BISON validation.

Experiment	Rod/Test	Description
CABRI	Na-2	PWR 17x17 fuel at 33 MWd/kgU, Na coolant, 9.5 μs pulse, 220 cal/g max enthalpy
CABRI	Na-3	PWR 17x17 fuel at 52 MWd/kgU, Na coolant, 9.5 μs pulse, 138 cal/g max enthalpy
CABRI	Na-5	PWR 17x17 fuel at 64 MWd/kgU, Na coolant, 9.1 μs pulse, 113 cal/g max enthalpy
CABRI	Na-10	PWR 17x17 fuel at 64 MWd/kgU, Na coolant, 31 μs pulse, 112 cal/g max enthalpy
NSRR	VA1	PWR 17x17 fuel at 71 MWd/kgU, ZIRLO clad, $\approx$5 μs pulse, 133 cal/g max enthalpy
NSRR	VA2	PWR 17x17 fuel at 77 MWd/kgU, MDA clad, $\approx$5 μs pulse, 130 cal/g max enthalpy
NSRR	VA3	PWR 17x17 fuel at 71 MWd/kgU, ZIRLO clad, $\approx$5 μs pulse, 108 cal/g max enthalpy
NSRR	VA4	PWR 17x17 fuel at 77 MWd/kgU, MDA clad, $\approx$5 μs pulse, 109 cal/g max enthalpy

Sensitivity Analysis and Uncertainty Quantification

- BISON has been coupled with SNL's DAKOTA code for constitutive model calibration, sensitivity analysis and uncertainty quantification





Main Effects Plot for Fission Gas Release from UO_2 Fuel

From G. Pastore, L. P. Swiler, J. D. Hales, S. R. Novascone, D. M. Perez, B. W. Spencer, L. Luzzi, P. Van Uffelen, R. L. Williamson, Uncertainty and Sensitivity Analysis of Fission gas Behavior in Engineering Scale Fuel Modeling, *Journal of Nuclear Materials*, **456**, pp. 398-408 (2015)

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