BISON: Engineering-scale Fuel Performance Application

BISON Team

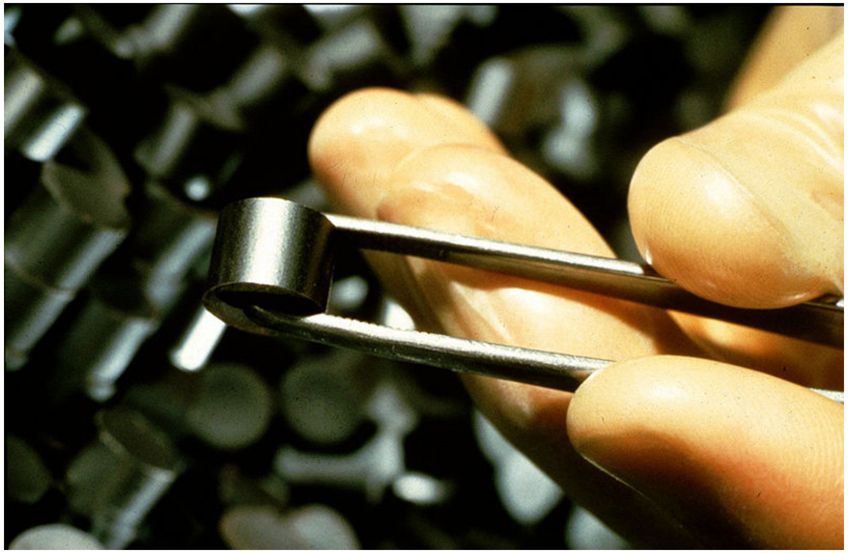
Jason Hales, Steve Novascone, Giovanni Pastore, Danielle Perez, Ben Spencer, Rich Williamson, Pavel Medvedev

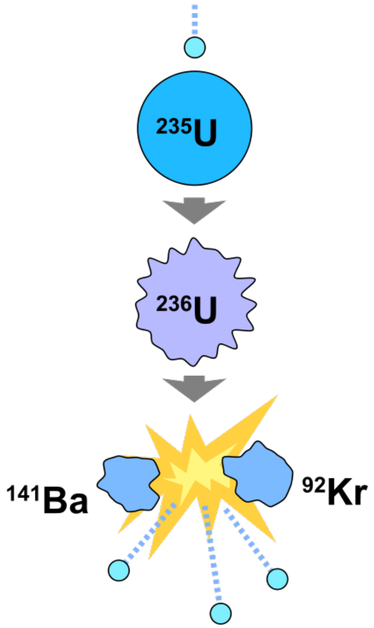
www.inl.gov

Idaho National Laboratory

Nuclear Reactor Fuel

- Nuclear fuel is a material that can be 'burned' by nuclear fission to produce power.
- When U-235 and P-239 are struck by neutrons, they break apart and emit neutrons, and can cause a sustained reaction to generate heat.





- Many fuel materials have been used, including oxides, metals, nitrides and carbides.

Fuel Design – Light Water Reactor

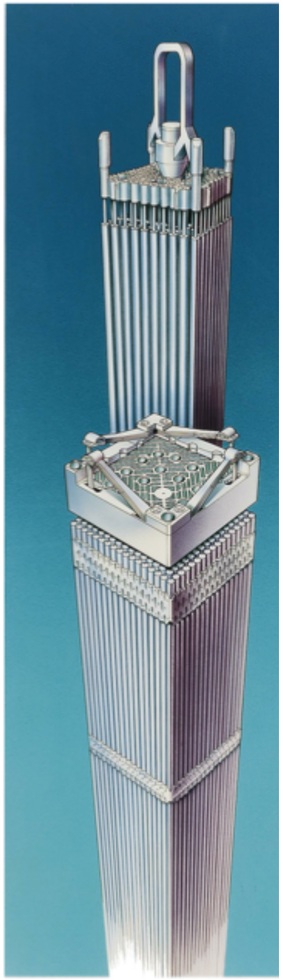
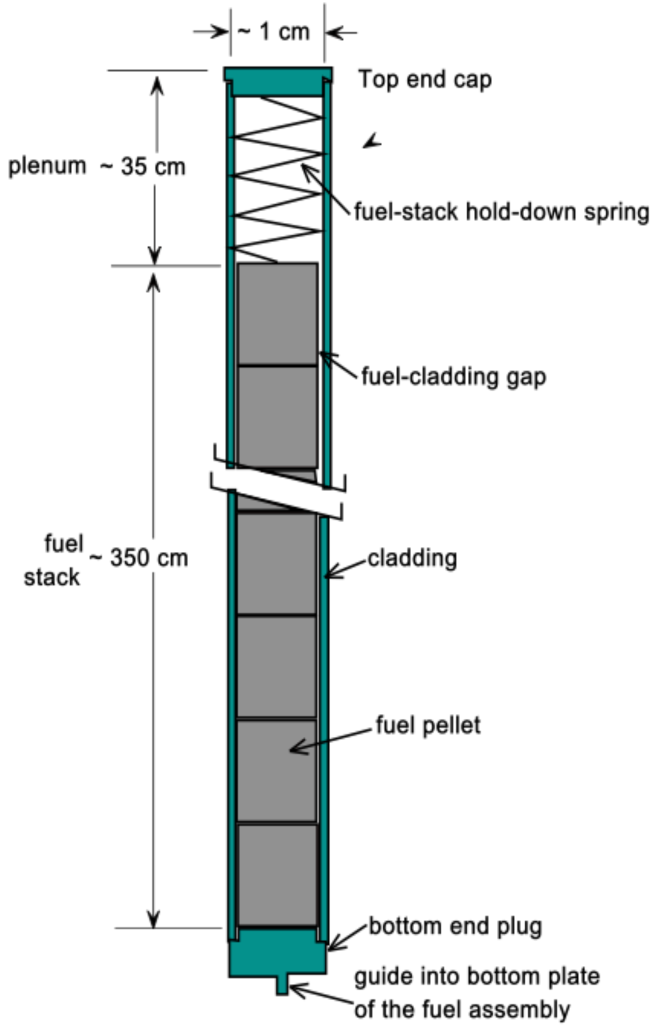
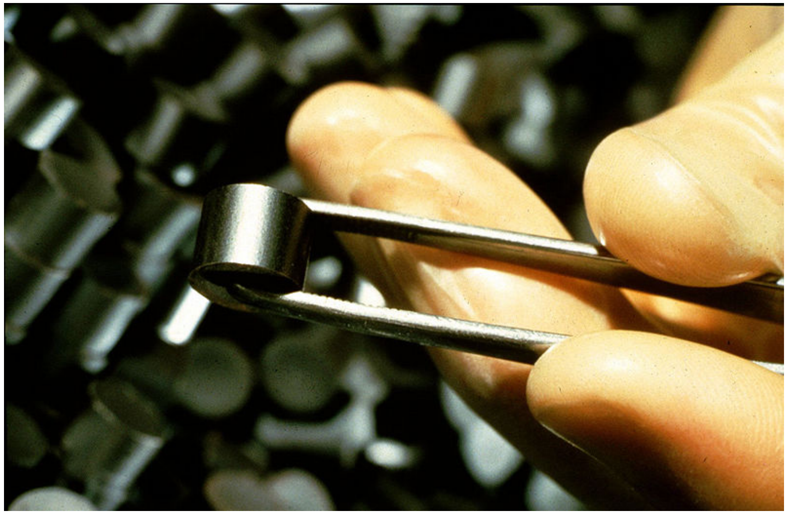


Figure 4
LWR fuel assemblies: BWR (top); PWR (botto
(courtesy of Siemens Power Corp.).



Olander, JNM, V389, p1, 2009



Westinghouse AP1000

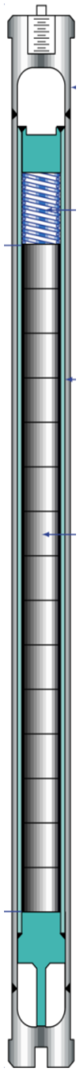
- 157 17x17 fuel assemblies
- 264 pins per assembly (41448 pins)
- 360 pellets per pin (~15 million pellets)

Fuel Design – High Temperature Gas Reactor

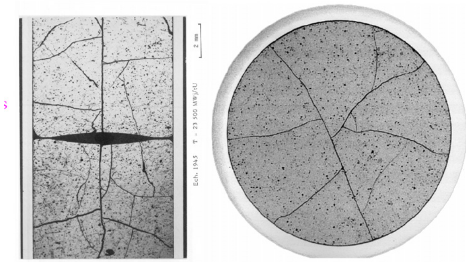
Figure from Olander, JNM, V389, p1, 2009.

Fuel Behavior During Irradiation

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

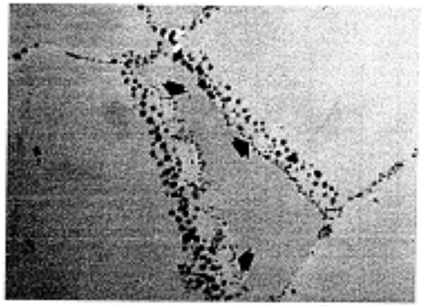


but irradiation brings about substantial complexity



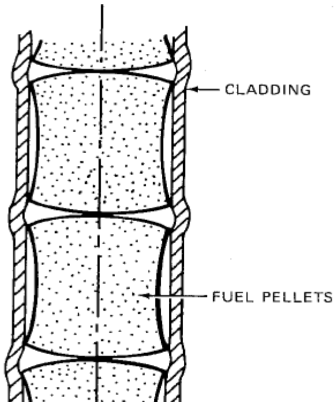
Michel et al, Eng Frac Mech, **75**, 3581 (2008)

Fuel Fracture



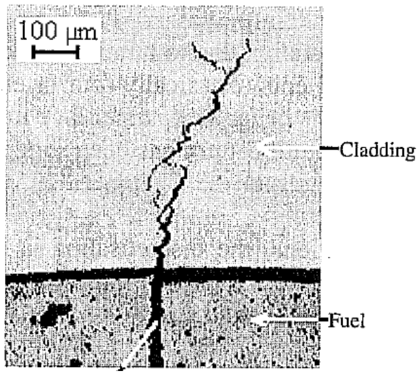
Olander, p. 323 (1978)

Fission gas



Olander, p. 584 (1978)

Multidimensional contact and deformation

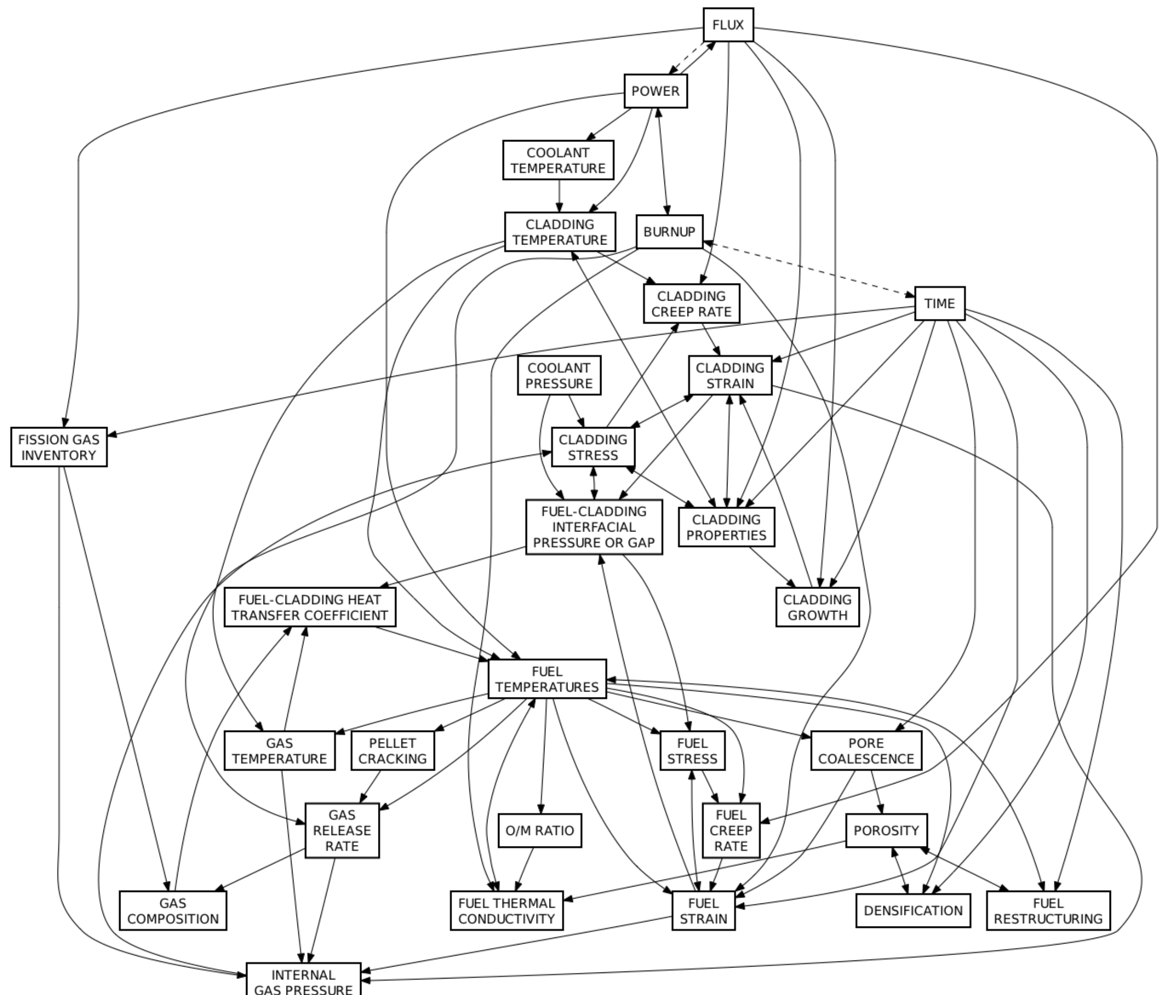


Bentejac et al, PCI Seminar (2004)

Stress Corrosion Cracking Cladding Failure

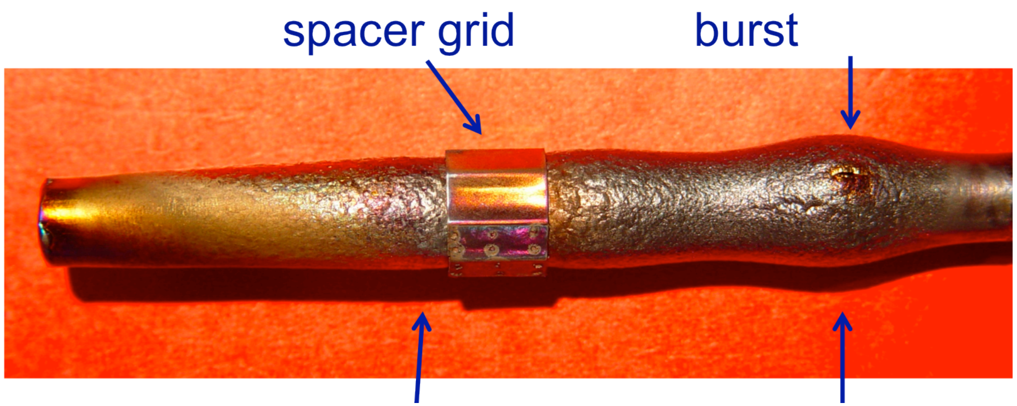
Fuel Behavior Modeling - Coupled Multi-physics and Multi-scale

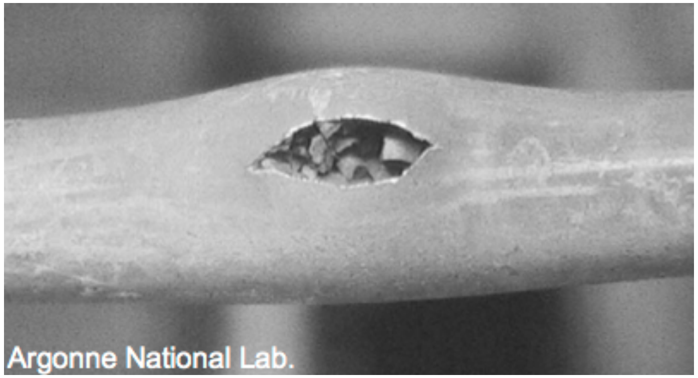
- **Multiphysics**
  - Fully-coupled nonlinear thermomechanics
  - Mass transport
  - Chemistry
  - Neutronics
  - Thermal-hydraulics
- **Multi-space scale**
  - Important physics operate at level of microstructure
  - Need real predictions at engineering scale
- **Multi-time scale**
  - Long, steady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



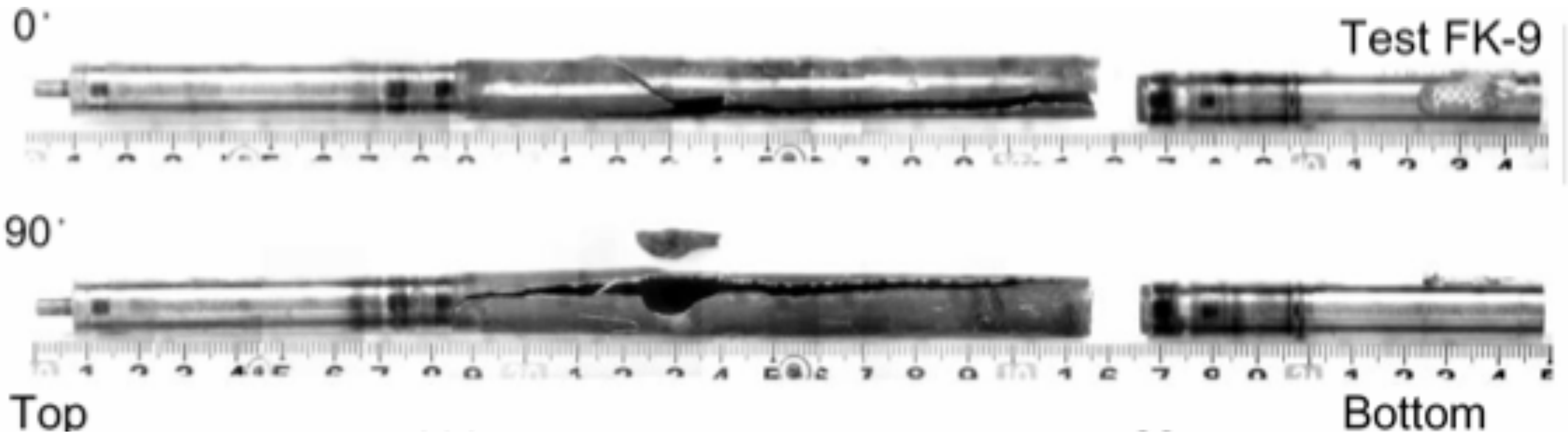
Reproduced from Beyer et al., BNWL-1898, PNNL (1975)

… and complexity multiplies during accidents





Rod failure during LOCA



Rod failure during RIA (NSSR FK-9, Nakamura 2002)

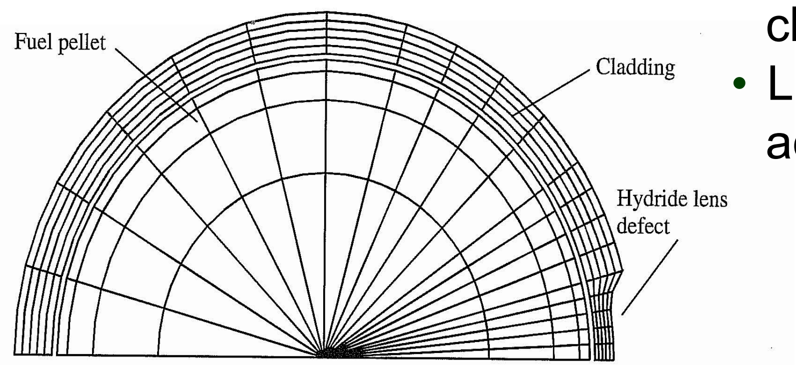
Fuel Behavior Modeling: U.S. State of the Art

- Fuel performance codes are used today for fuel rod design and determination of operational margins.
- However, current 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

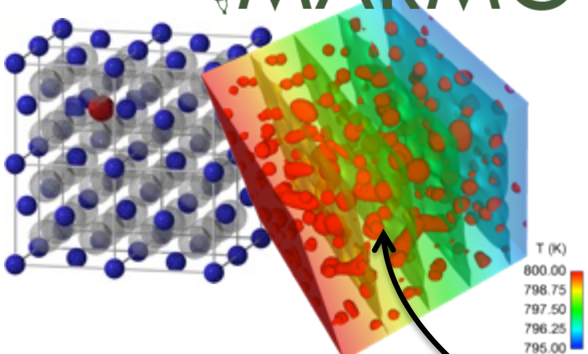


FALCON model to investigate clad failure due to defect

MOOSE-BISON-MARMOT

- The MOOSE-BISON-MARMOT codes provide an advanced, multiscale fuel performance capability

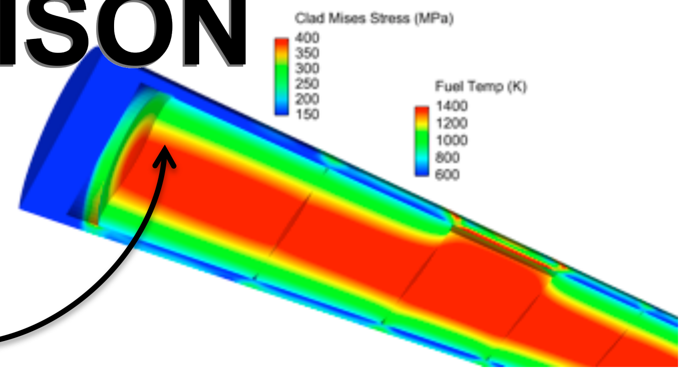
MARMOT



Atomistic/Mesoscale Material Model Development

- Predicts microstructure evolution in fuel
- Used with atomistic methods to develop multiscale materials models

BISON



Advanced 3D Fuel Performance Code

- Models LWR, TRISO and metal fuels in 1D, 2D and 3D
- Steady and transient reactor operations

MOOSE

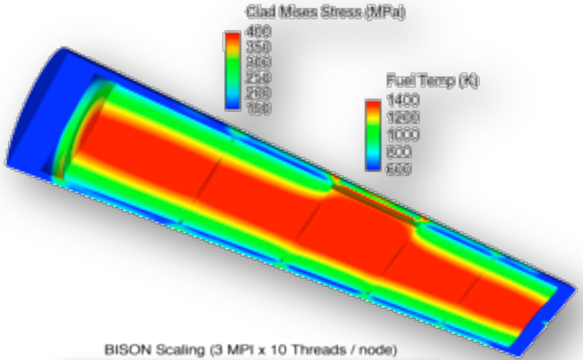
Multiphysics Object-Oriented Simulation Environment

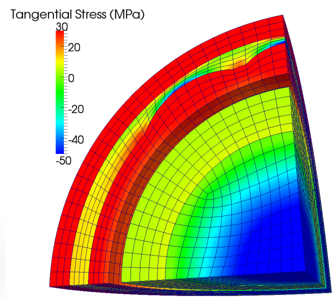
- Simulation framework allowing rapid development of FEM-based applications

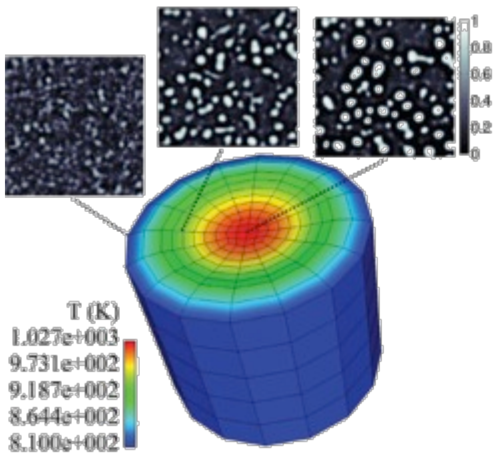
BISON *Fuel Performance Code*

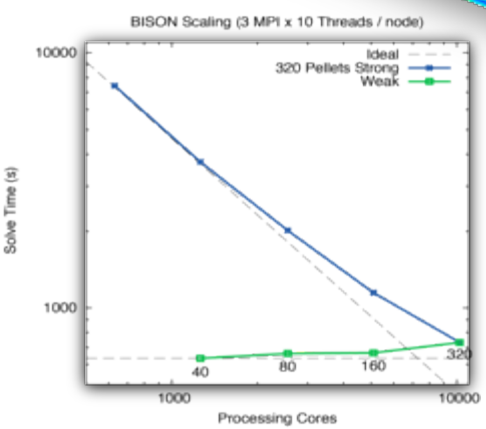
Solution method: Implicit finite element solution of the coupled thermomechanics and species diffusion equations using the MOOSE framework

Multiphysics constitutive models: large deformation mechanics (plasticity and creep), cracking, thermal expansion, densification, radiation effects (swelling, thermal conductivity, etc.).

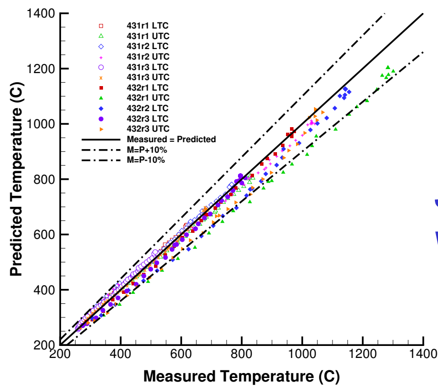








Massively parallel, has been run on 1 - 12,000 cpus.



Substantial experimental validation is underway

R. L. Williamson, J. D. Hales, S. R. Novascone, M. R. Tonks, D. R. Gaston, C. J. Permann, D. Andrs and R. C. Martineau, “Multidimensional Multiphysics Simulation of Nuclear Fuel Behavior,” *Journal of Nuclear Materials*, **423**, 149 (2012)

BISON Governing Equations

- Energy conservation (transient heat conduction with fission source)

$$\rho c_p \frac{\partial T}{\partial t} = \nabla \cdot (k \nabla T) + E_f \dot{F}$$

Fission density rate = f(**x**, t)

- Species conservation (transient oxygen or fission product diffusion with radioactive decay)

Fickian diffusion

Soret diffusion

$$\frac{\partial C}{\partial t} = \nabla \cdot D \left(\nabla C - \frac{C Q^*}{F R T^2} \nabla T \right) - \lambda C + S$$

Radioactive decay

- Momentum conservation (Cauchy's equation of equilibrium)

$$\nabla \cdot \mathbf{T} + \rho \mathbf{f} = 0$$

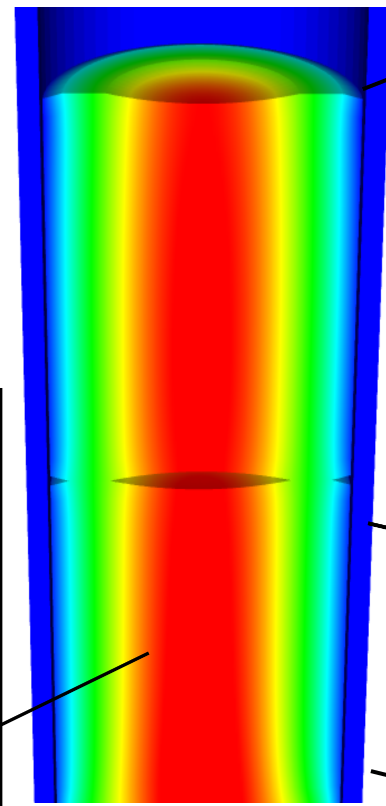
BISON LWR Capabilities

General Capabilities

- Finite element based 1D spherical, 2D-RZ and 3D fully-coupled thermo-mechanics with species diffusion
- Linear or quadratic elements with large deformation mechanics
- Steady and transient operation
- Massively parallel computation
- Meso-scale informed material models

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



Temperature

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

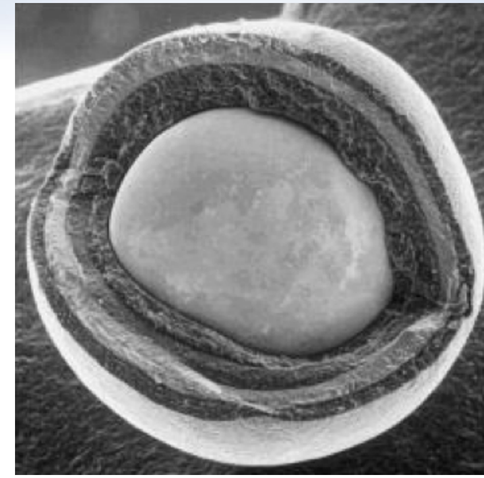
Cladding Behavior

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

Coolant Channel

- Closed channel thermal hydraulics with heat transfer coefficients

BISON Particle Fuel Capabilities



General Capabilities

- Finite element based 1D-Spherical, 2D-RZ and 3D fully-coupled thermo-mechanics with species diffusion
- Linear or quadratic elements with large deformation mechanics
- Elasticity with thermal expansion
- Steady and transient behavior
- Massively parallel computation

Gap Behavior

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

Fuel Kernel

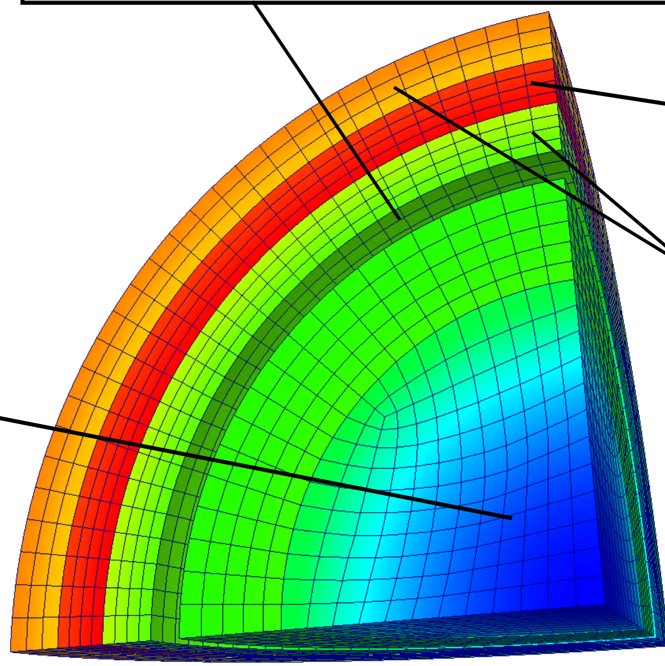
- Temperature/burnup/porosity dependent thermal conductivity
- Solid and gaseous fission product swelling
- Densification
- Thermal and irradiation creep
- Fission gas release (two stage)
- CO production
- Radioactive decay

Silicon Carbide

- irradiation creep

Pyrolytic Carbon

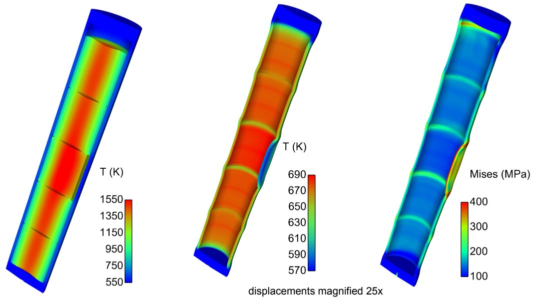
- Anisotropic irradiation-induced strain
- Irradiation creep



Tangential Stress

What makes BISON different?

Results – Missing Pellet Surface

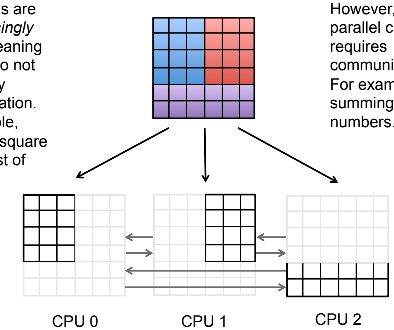


- MPS defect results in higher pellet temperatures and much higher clad stress; need for 3D analysis is clear

3D/Arbitrary Geometry

Parallel Computing

Some tasks are *embarrassingly parallel* meaning that they do not require any communication. For example, taking the square root of a list of numbers.

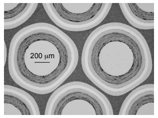


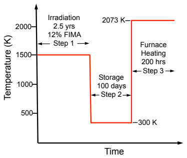
However, most parallel computing requires communication. For example, summing a list of numbers.

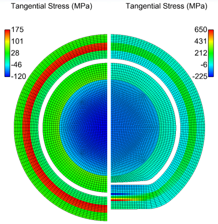
Parallel Computing

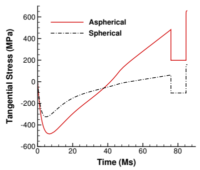
Simulation of Aspherical TRISO Particle

- Aspherical particles are fairly common
- Single facet aspherical particle problem has been solved in BISON assuming 2D axisymmetry





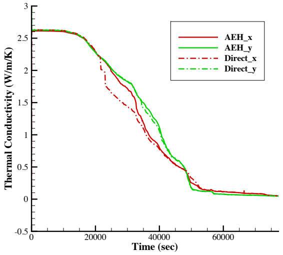




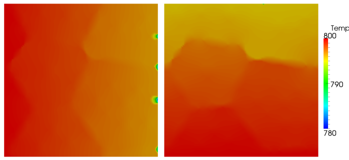
- During accident testing, asphericity raises peak tensile stress in SiC containment layer by almost 4x
- Typical run times of a few minutes on 8 processors

Fuel Types

Thermal Conductivity from MARMOT



- The direct method is sensitive to bubbles on the boundary
- Boundary bubbles result in low local temperature
- This results in a low average temperature and thus a low thermal conductivity
- The AEH technique is not sensitive to local effects



Temperature from the direct approach with flux applied in the x (left) and y (right) directions. Note areas of low temperature in the x-direction plot.

Coupling

Leveraging to Support Multiple DOE Programs

- MBM is the NEAMS code platform for fuel rods and lower length scales
- CASL is leveraging BISON to support the Materials Performance and Optimization (MPO) focus area for Pellet Clad Interaction.
- BISON is supporting analysis and experimental design for the Fuel Cycle Research and Design (FCRD) campaign
- BISON is being used to investigate novel clad materials for the Light Water Reactor Sustainability (LWRS) program
- BISON is being used to study plate fuel for the Reduced Enrichment for Research and Test Reactors (RERTR) program

NEAMS
NUCLEAR ENERGY ADVANCED MODELING & SIMULATION PROGRAM

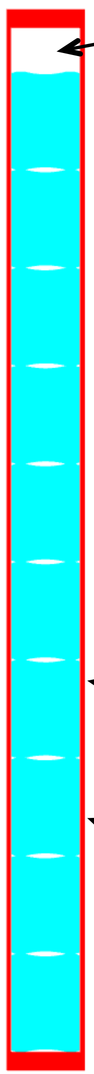
CASL
Consortium for Advanced Simulation of LWRs

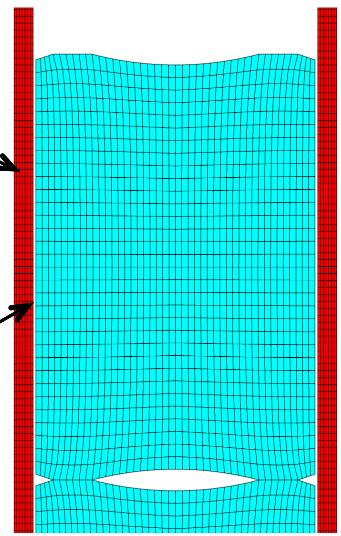
FCRD

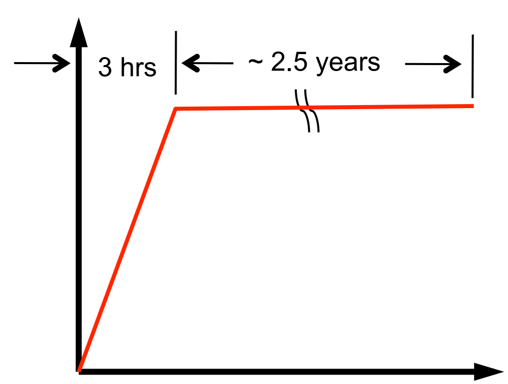
LWRS
Light Water Reactor Sustainability

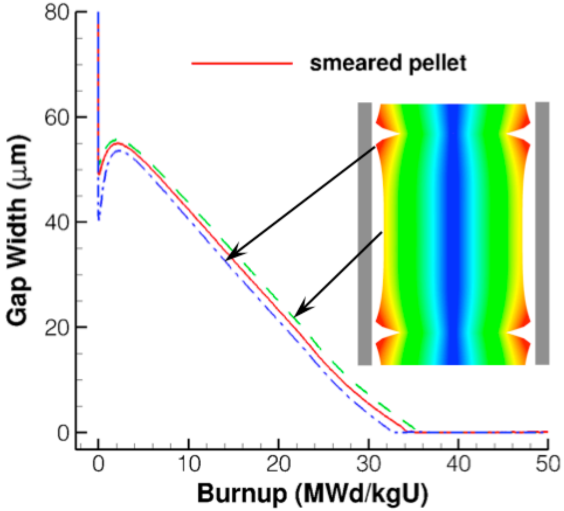
RERTR

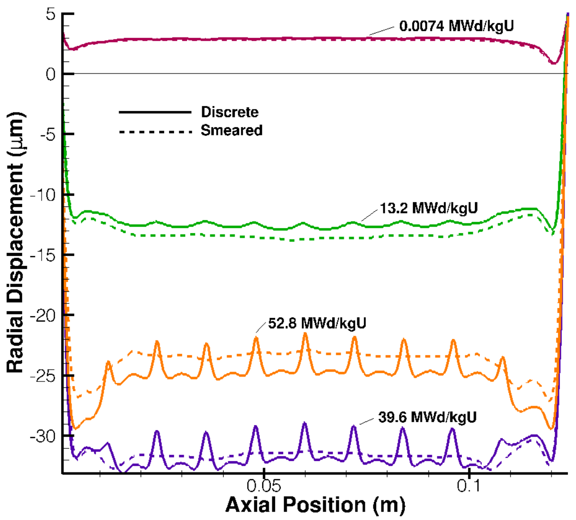
Discrete Pellet LWR Rodlet (2D-RZ multiphysics)



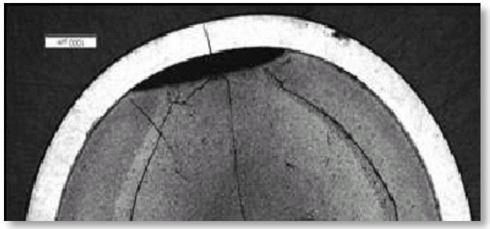




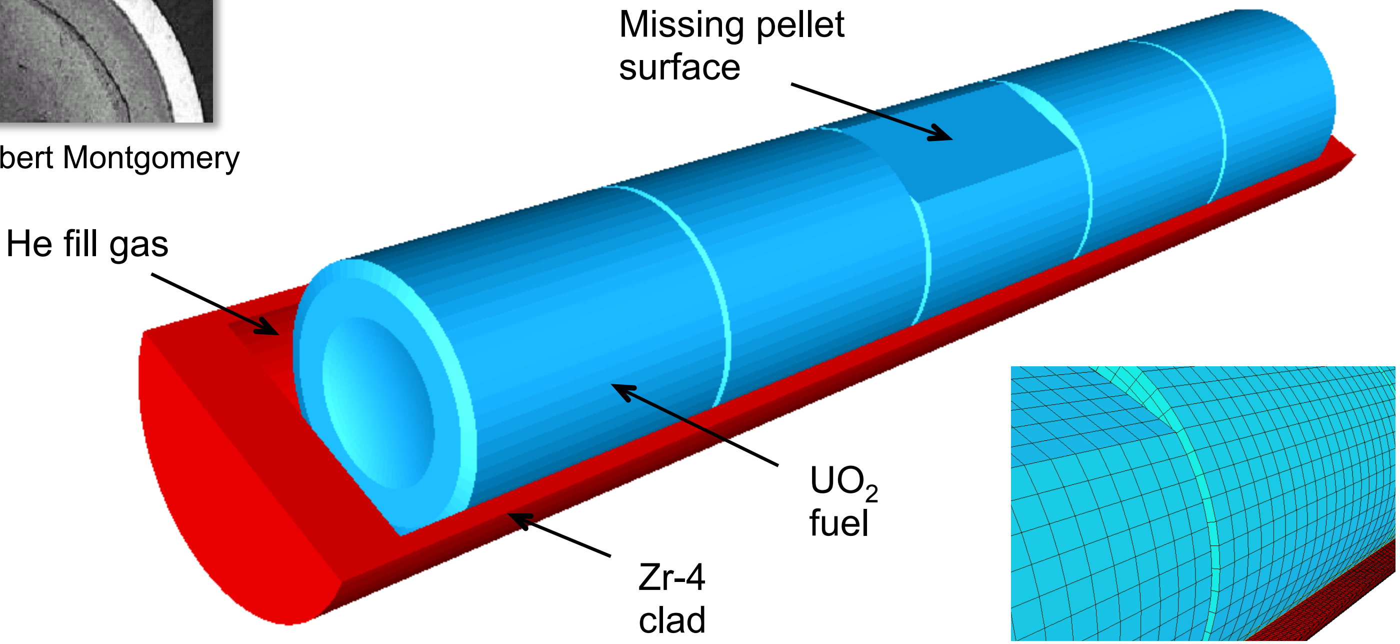




PCMI - Missing Pellet Surface Analysis

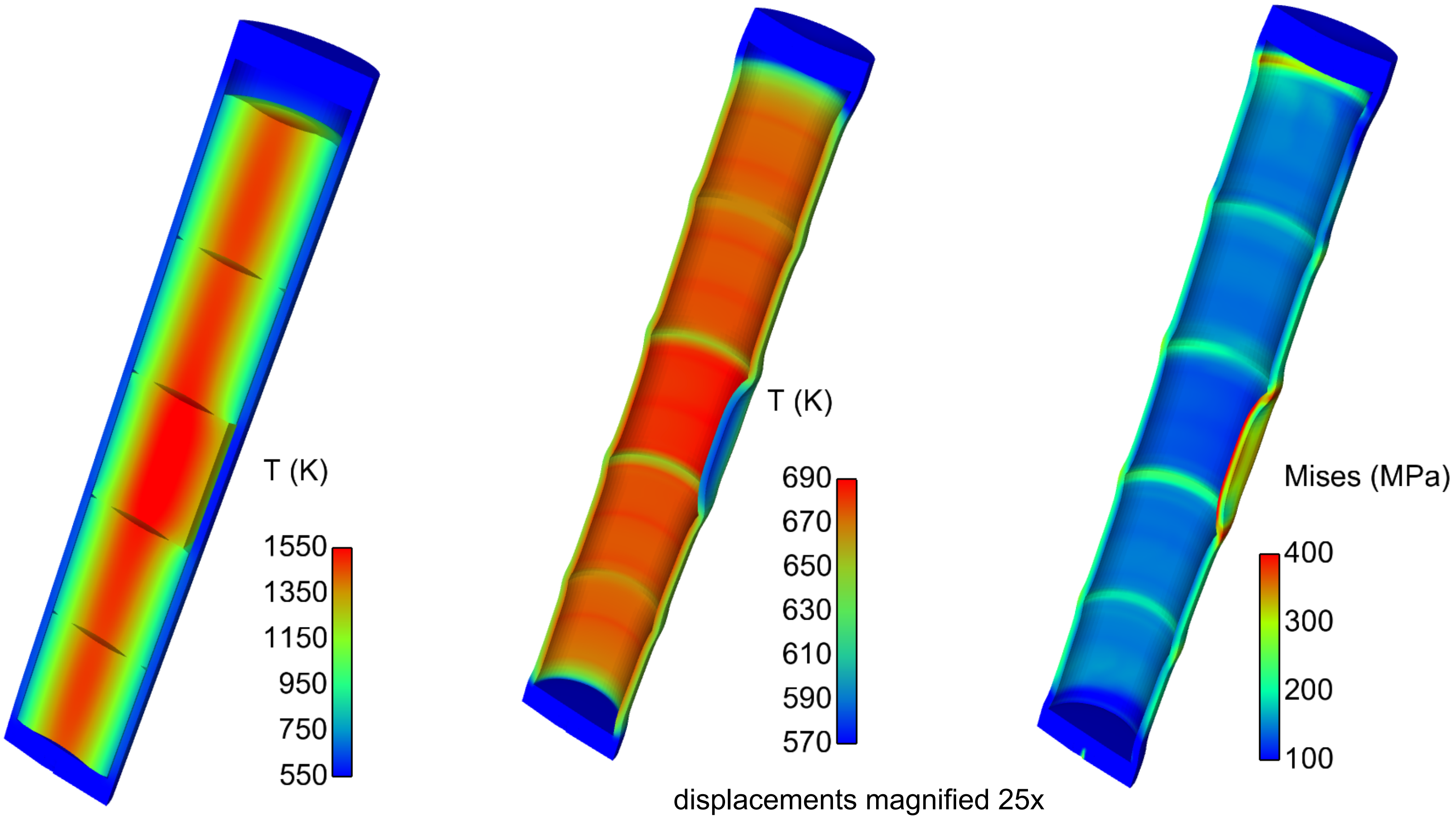


Micrograph from Robert Montgomery



- High resolution 3D calculation (250,000 elements, 1.1×10^6 dof) run on 120 processors
- Simulation from fresh fuel state with a typical power history, followed by a late-life power ramp

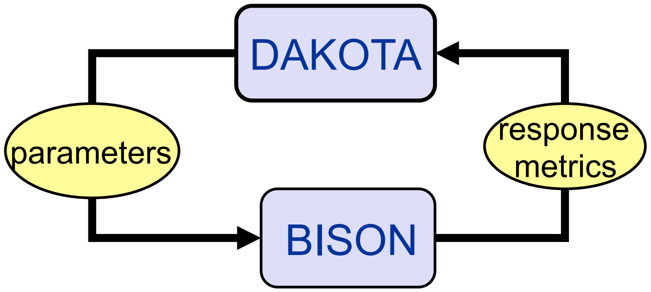
Results – Missing Pellet Surface

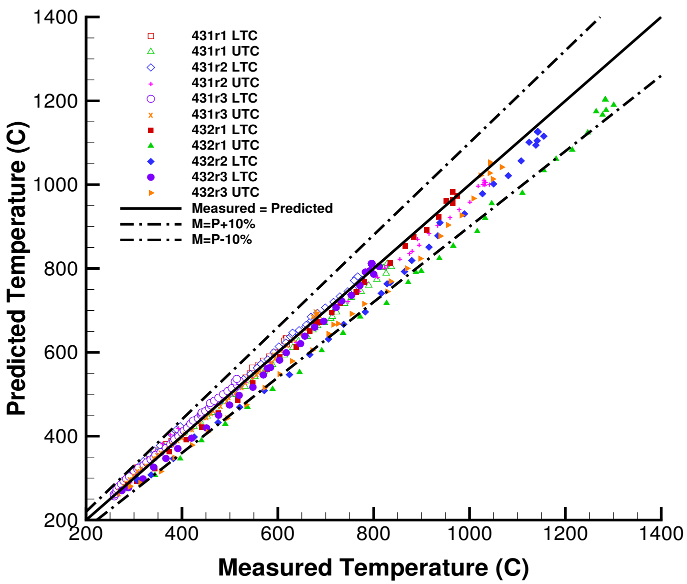


- MPS defect results in higher pellet temperatures and much higher clad stress; need for 3D analysis is clear

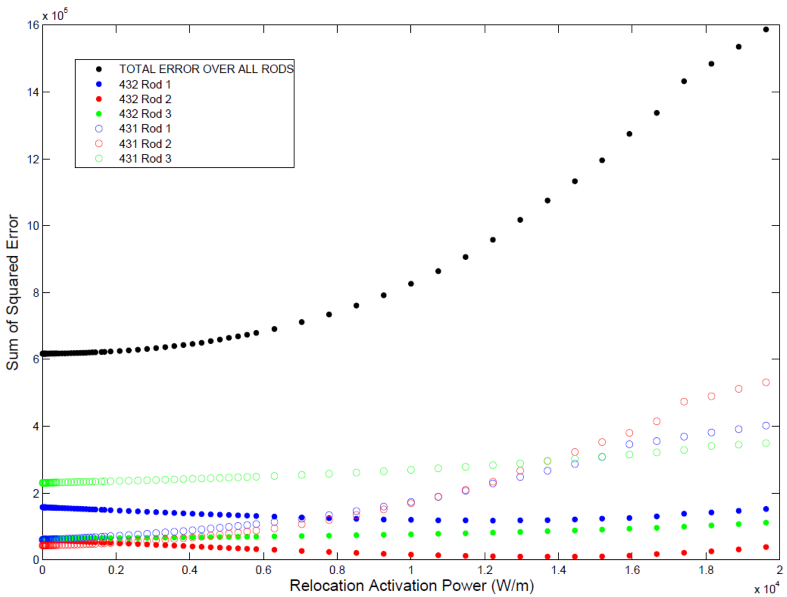
Verification, Validation, and Uncertainty Analysis

- BISON and associated software is supported by extensive regression testing (>800 tests for BISON thru MOOSE)
- Validation to a wide variety of integral rod tests in progress
- BISON has been coupled with SNL's DAKOTA code for systematic sensitivity analysis and uncertainty quantification





Beginning of life temperature validation



Calibration of relocation model using DAKOTA

BISON Code Assessment

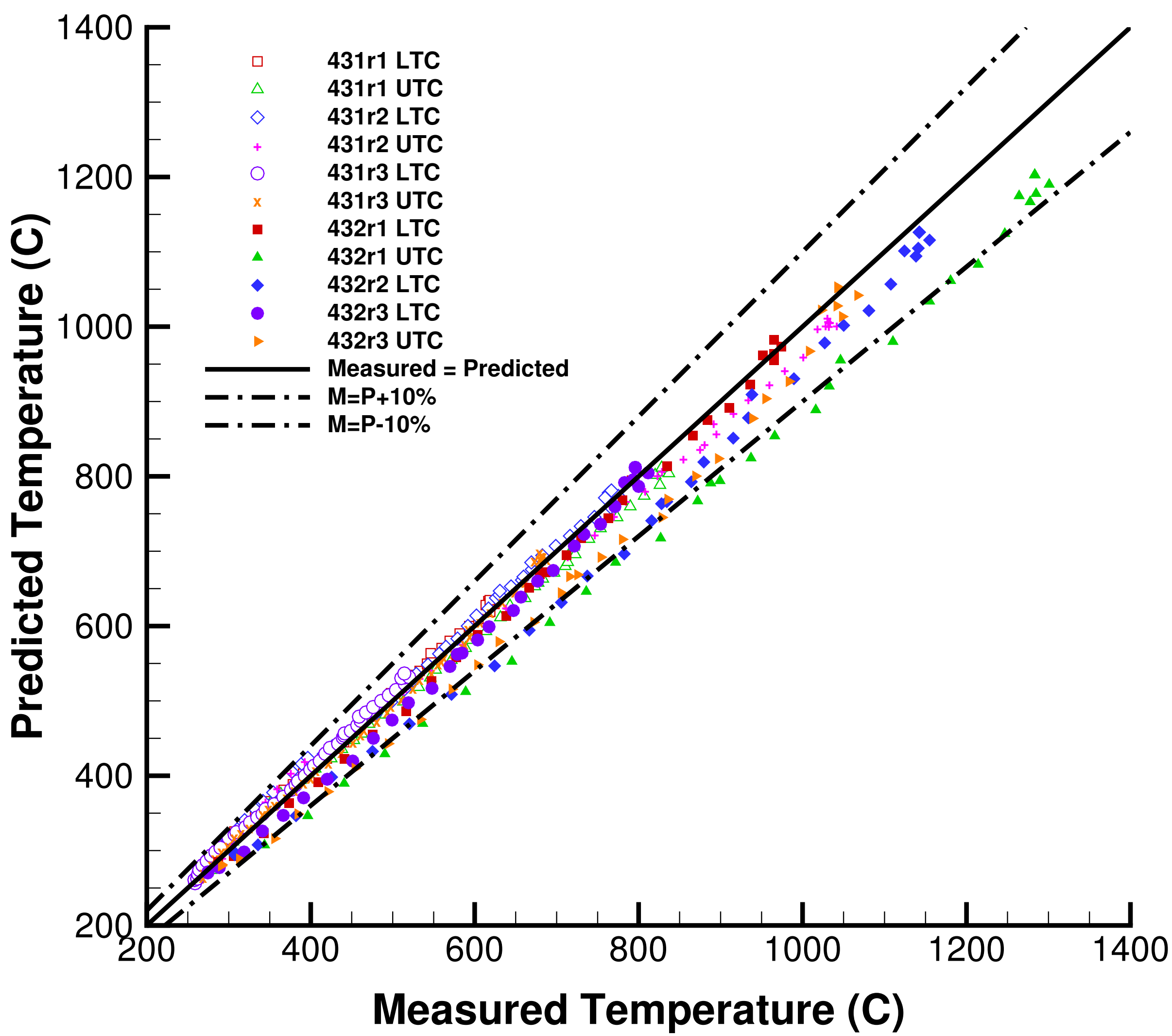
Comparisons to integral fuel rod data (21 rods, ~ 35 measurements)

Experiment	Rod	FCT - BOL	FCT – TL	FCT - Ramps	FGR	Clad - Elong	Clad – Dia (PCMI)
IFA-431	1, 2, 3	X					
IFA-432	1, 2, 3	X				X	
IFA-513*	1, 6	X	X				
IFA-515.10	A1	X	X				
IFA-597.3	7			X		X	
IFA-597.3*	8			X			
RISO-3*	AN3			X	X		
RISO-3*	AN4			X	X		
FUMEX-II	27(1)				X		
FUMEX-II	27(2a)				X		
FUMEX-II	27(2b)				X		
FUMEX-II	27(2c)				X		
RISO-3	GE7				X		X
OSIRIS	J12						X
REGATE					X		X
IFA-431 (3D)	4	X					

*Early User Assessment problems

D. M. Perez, R. L. Williamson, S. R. Novascone, T. K. Larson, J. D. Hales, B. W. Spencer and G. Pastore, *An Evaluation of the Nuclear Fuel Performance Code BISON*, Int. Conf. on Mathematics and Computation Applied to Nuclear Science & Engineering (M&C 2013) Sun Valley, Idaho, May 5-9, 2013.

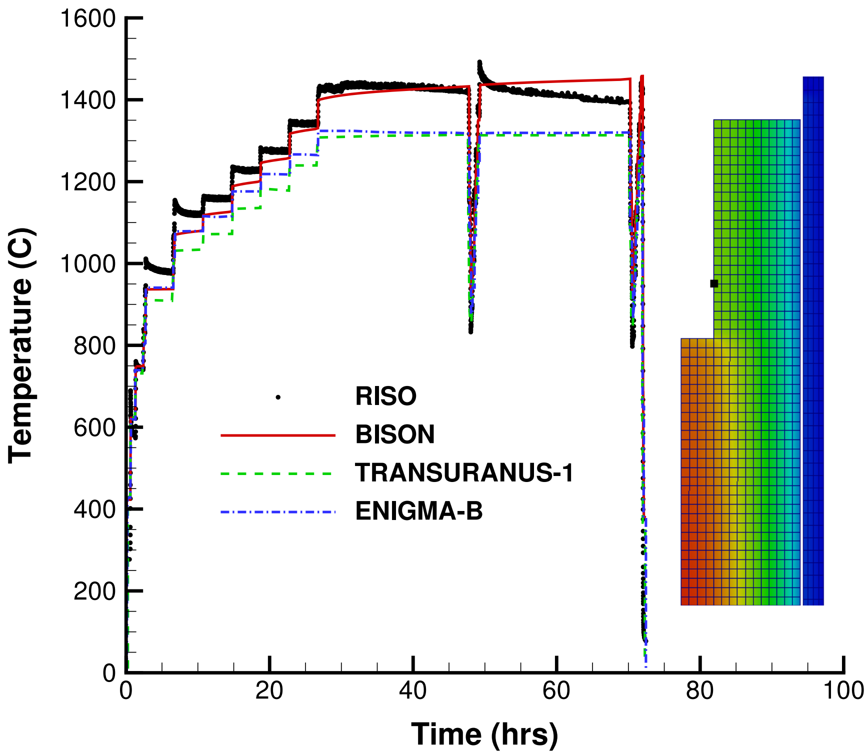
Beginning of Life Fuel Centerline Temperature



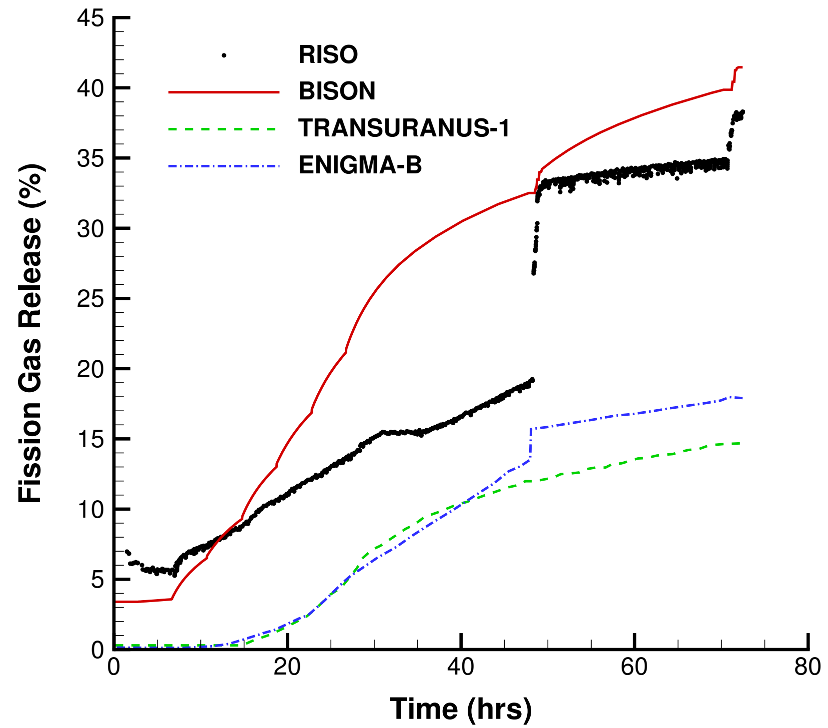
- Very good comparisons for the eleven measurements considered to date
- BOL comparisons validate important physics such as power input, fuel and clad thermal conductivity, gap gas conductivity, fuel and clad thermal expansion, gap closure and fuel relocation

RISØ-AN3 Power Ramp

- Base irradiated in the Biblis A PWR over four reactor cycles. Re-fabricated rod was shortened and instrumented with a fuel centerline thermocouple and pressure transducer.
- Ramp tested at the RISØ DR3 water-cooled HP1 rig
- Assumed short rod length through base irradiation and ramp



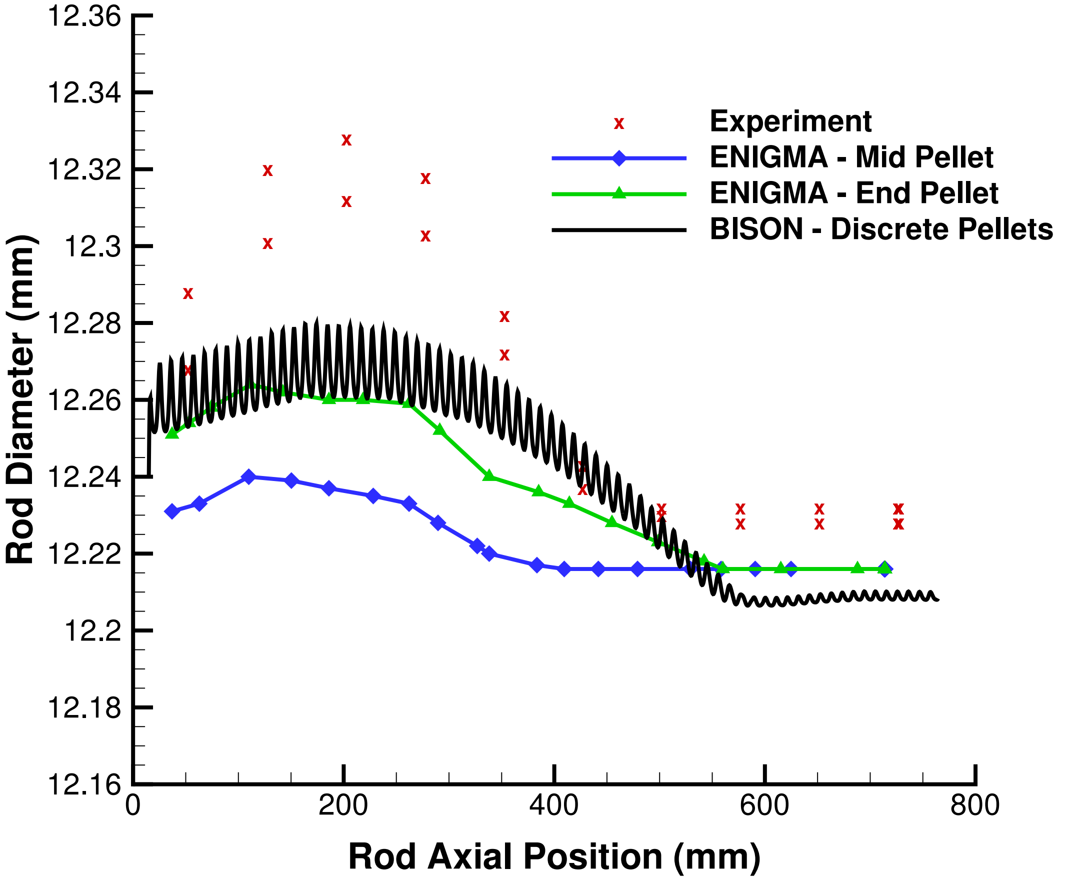
Fuel Centerline Temperature

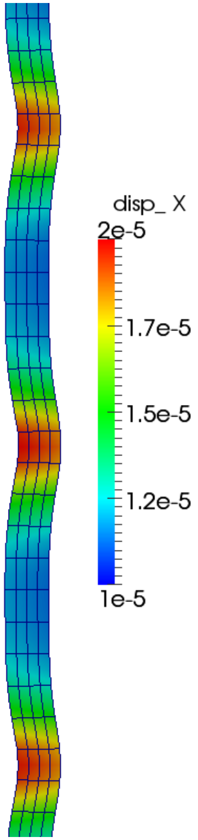


Fission Gas Release

RISØ-3 GE7 – PCMI During Power Ramp

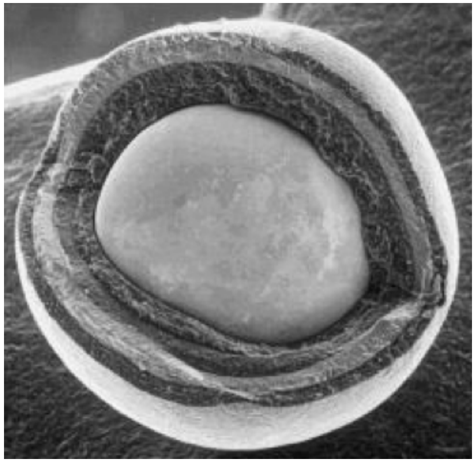
- Base irradiated in the Quad Cities-1 BWR for ~5 years; Ramp tested in the RISØ DR3 water-cooled HP1 rig under BWR conditions
- 72-pellet stack modeled in axisymmetry with discrete pellets
- Strong axial power profile during ramp test

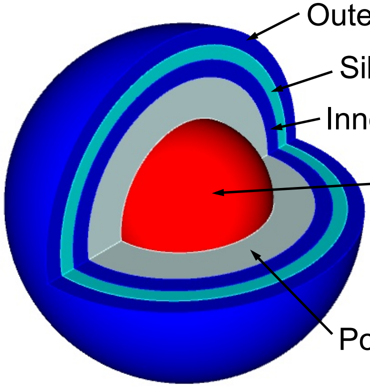




Simulation of TRISO-coated HTGR Particle Fuel

- TRISO-coated particle fuel is the accepted HTGR fuel form and is being developed/produced in several countries
- Current fuel performance modeling capabilities are limited to 1D closed form solutions assuming spherical symmetry [PARFUME (US), STRESS3 (UK)] or FEM assuming 2D axisymmetry [ATLAS (France)]
- Recent review article: (Powers and Wirth, JNM, V. 405, p. 74, 2010) *Modeling 3D effects remains a substantial challenge… remains one of the most challenging areas especially considering that multi-dimensional effects are increasingly thought to be the limiting failure mode for TRISO fuel performance*
- Required models have recently been implemented in BISON to permit simulation of 3D fully-coupled thermomechanics and fission product species diffusion, including radioactive decay
- Parallel capability permits application to complex multidimensional phenomena while very efficient solutions for either 1D spherically symmetric or 2D axisymmetric geometries are straightforward

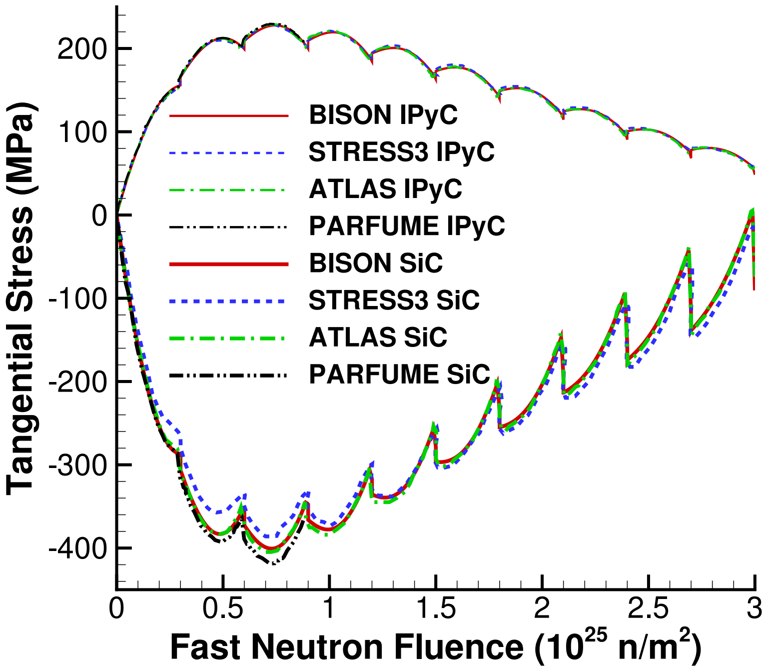




J. D. Hales, R. L. Williamson, S. R. Novascone. D. M. Perez, B. W. Spencer and G. Pastore, **Multidimensional Multiphysics Simulation of TRISO Particle Fuel**, *Journal of Nuclear Materials, **443**, 531, 2013*.

Validation

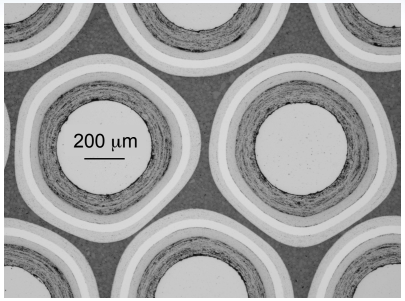
- BISON validated against current 1D state-of-the-art codes: PARFUME (INL), ATLAS (French), STRESS3 (UK)
- Code comparisons are excellent, demonstrating BISON's ability to duplicate current state-of-the-art
- For spherical particles (1D spherical mode in BISON) run times of ~1 s are typical

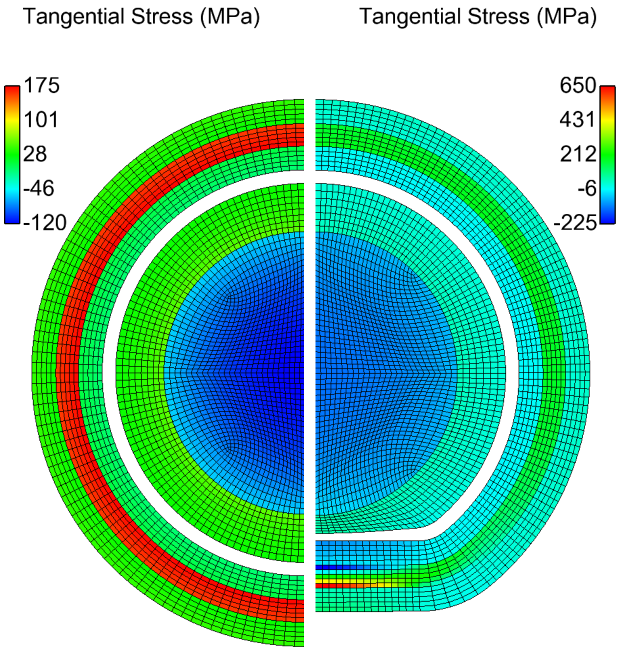


Cyclic particle temperature in PBR reactor

Aspherical Particles

- Aspherical particles are common
- Single facet particles can be modeled using 2D axisymmetry

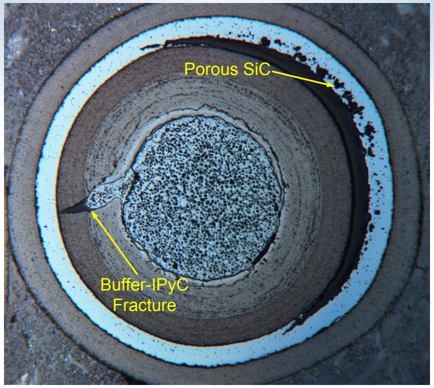


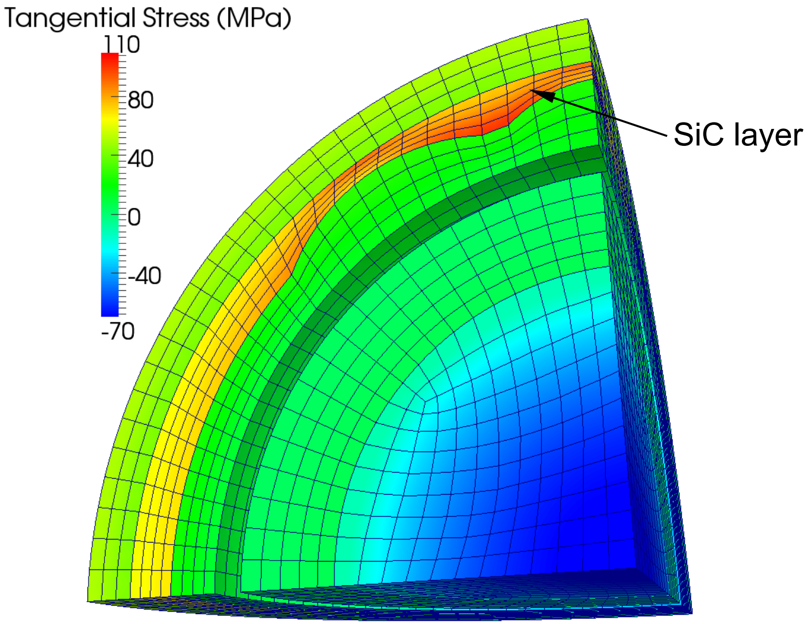


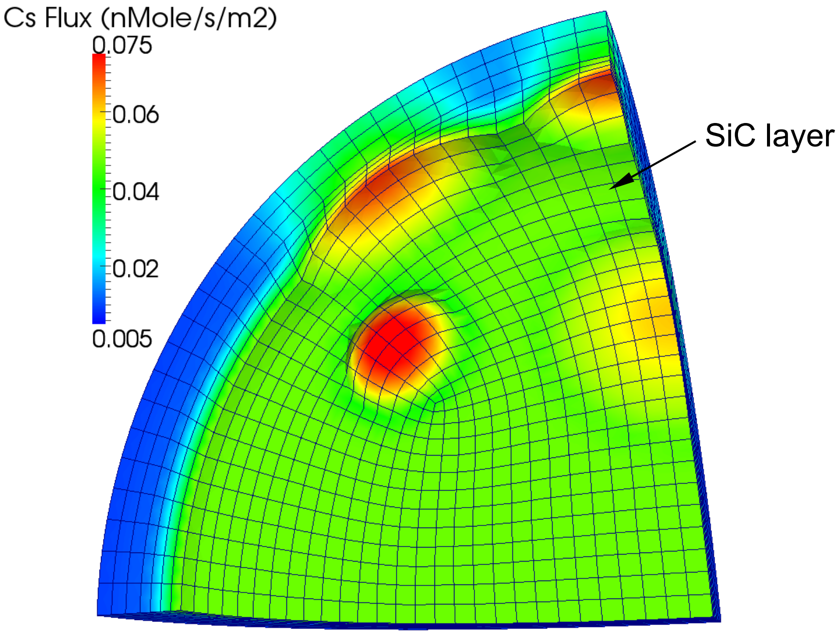
- During accident testing, asphericity raises peak tensile stress in SiC containment layer by almost 4x
- Typical run times of a few minutes on 8 processors

3D Simulation of Thinned SiC layer

- Localized thinning of SiC layer can occur due to soot inclusions or fission product interaction
- BISON 3D capability demonstrated on an eighth-particle with localized thinning of the SiC layer at random locations







- Thinned SiC regions experience significantly higher tensile stress and greater cesium release; impossible to predict with 1D analysis
- Typical run times of a few hours on 8 processors

Full-life Fuel Rod Simulation

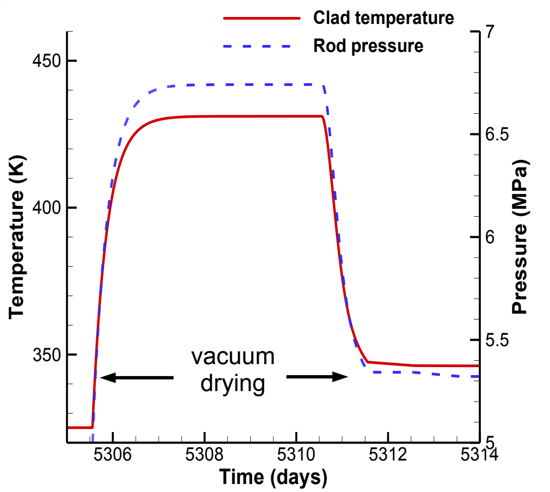
- MOOSE-BISON-MARMOT (MBM) is ideally suited for spent fuel analysis. Rods can be simulated through the entire life cycle, including high burnup irradiation, spent pool storage, vacuum drying, and long term dry storage. Output includes:
  - Thermal history
  - Stress, strain, deformation history
  - Clad property evolution during irradiation
  - Hydrogen uptake, diffusion and hydride precipitation
  - Clad damage and failure
- Modeling will play an important role in projecting the condition of the clad at the end of storage (addressing retrievability and confinement concerns)
- Transportation events can also be addressed

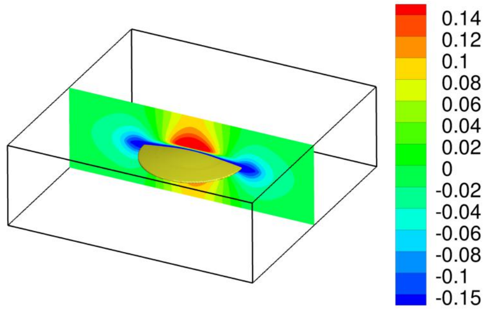
Initial Focus: Simulation of Clad Behavior

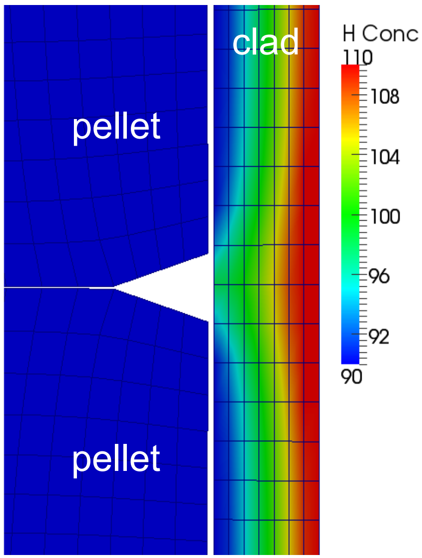
- Recent "gap analysis" identified hydride effects in cladding as a high priority degradation mechanism

- Focused early MBM demonstration in four areas:

  1. LWR discrete-pellet rodlet with fully coupled heat transfer and solid mechanics through base irradiation and all phases of storage
  2. Coupled thermomechanics and mass diffusion simulating detailed hydrogen behavior (with PSU collaborators)
  3. Mesoscale (phase-field) modeling to predict hydride orientation as a function of microstructure, stress and temperature
  4. Clad damage/failure prediction based on evolving hydride concentration and orientation (EPRI model, with UC Davis collaborator)

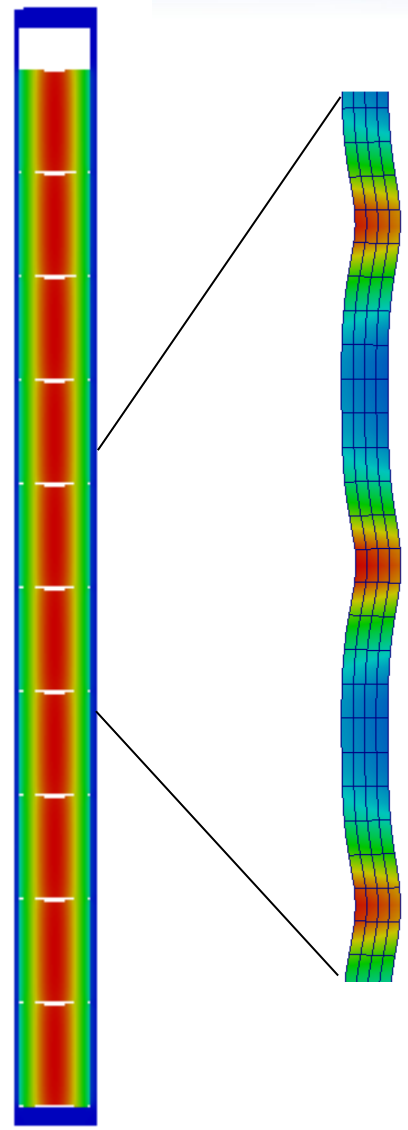




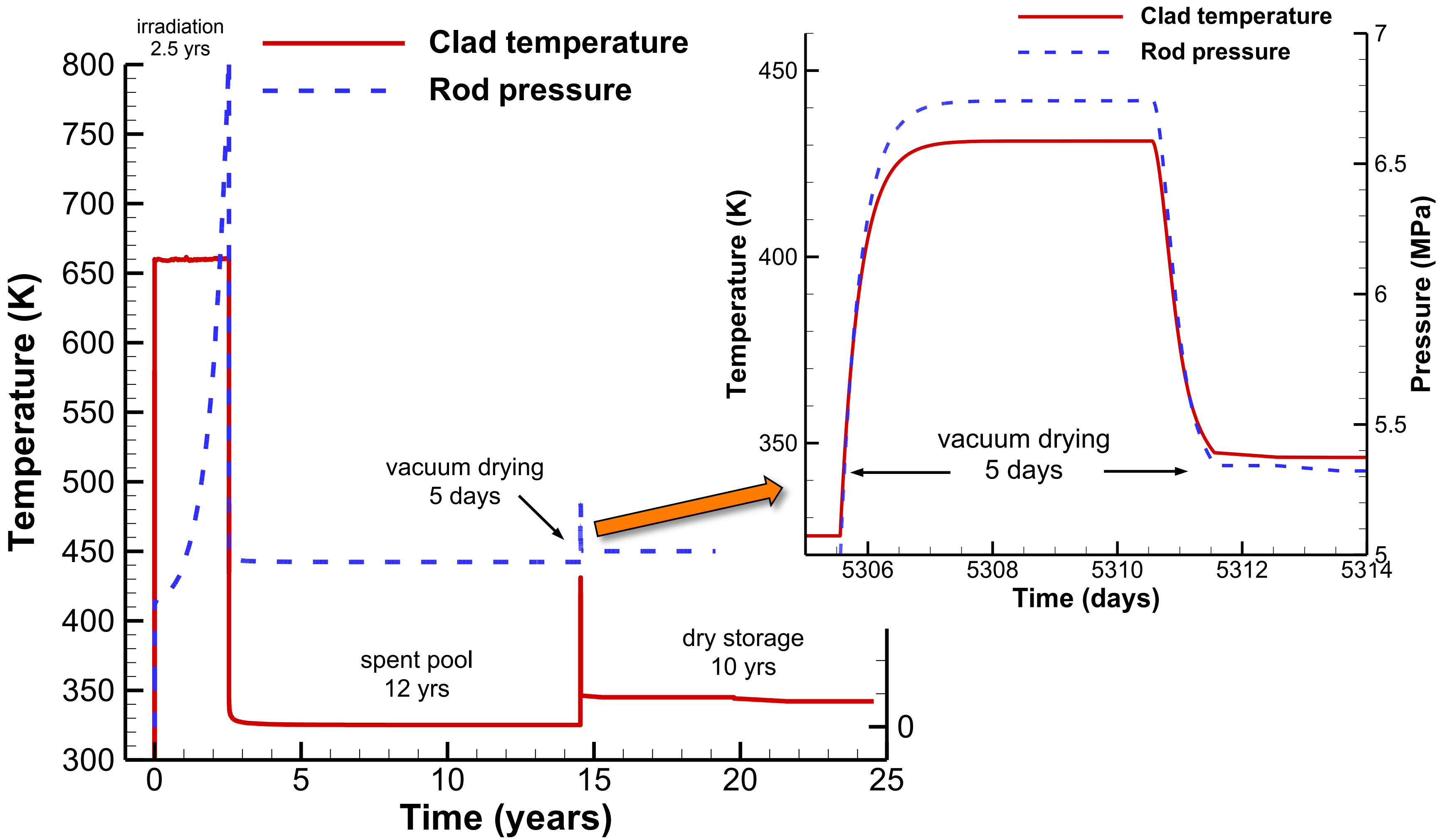


Fuel Rod Behavior Through Full Life

- Demonstration on 10 pellet rodlet (2D-RZ) assuming:
  - Constant fission power of 25 kW/m for 2.5 years to an average burnup of ~50 MWd/kgU
  - 12 years in spent fuel pool
  - 5 days in vacuum drying
  - 10 years in dry storage
- Full irradiation physics
- Decay heat curve based on 1979 ANS Standard
- Thermal behavior governed by typical natural convection coefficients



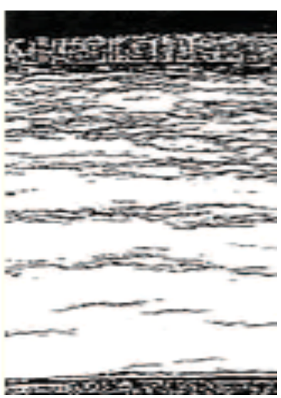
Fuel Rod Through Full Life – Rod Conditions



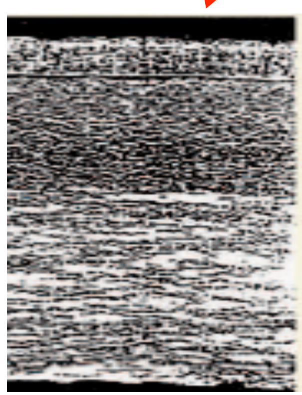
Hydrogen Distribution Depends Strongly on Temperature Gradients

Inter Pellet Gap

Inter-pellet gap



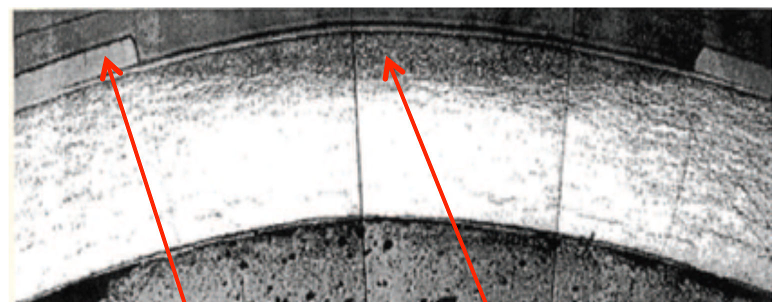
Cladding near mid pellet



Cladding near inter pellet gap

Smith G, 1994

Oxide Spallation



Oxide Layer

Hydride “blister”

Cladding

Hydrogen/Hydride Behavior

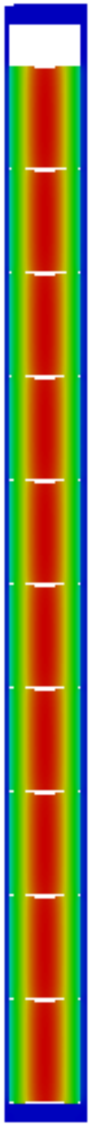
- Demonstrated on 10 pellet rodlet (2D-RZ):
- BISON model computes coupled:
  - Fuel rod thermomechanics
  - Hydrogen diffusion via concentration and thermal gradients

Fickian diffusion

Soret diffusion

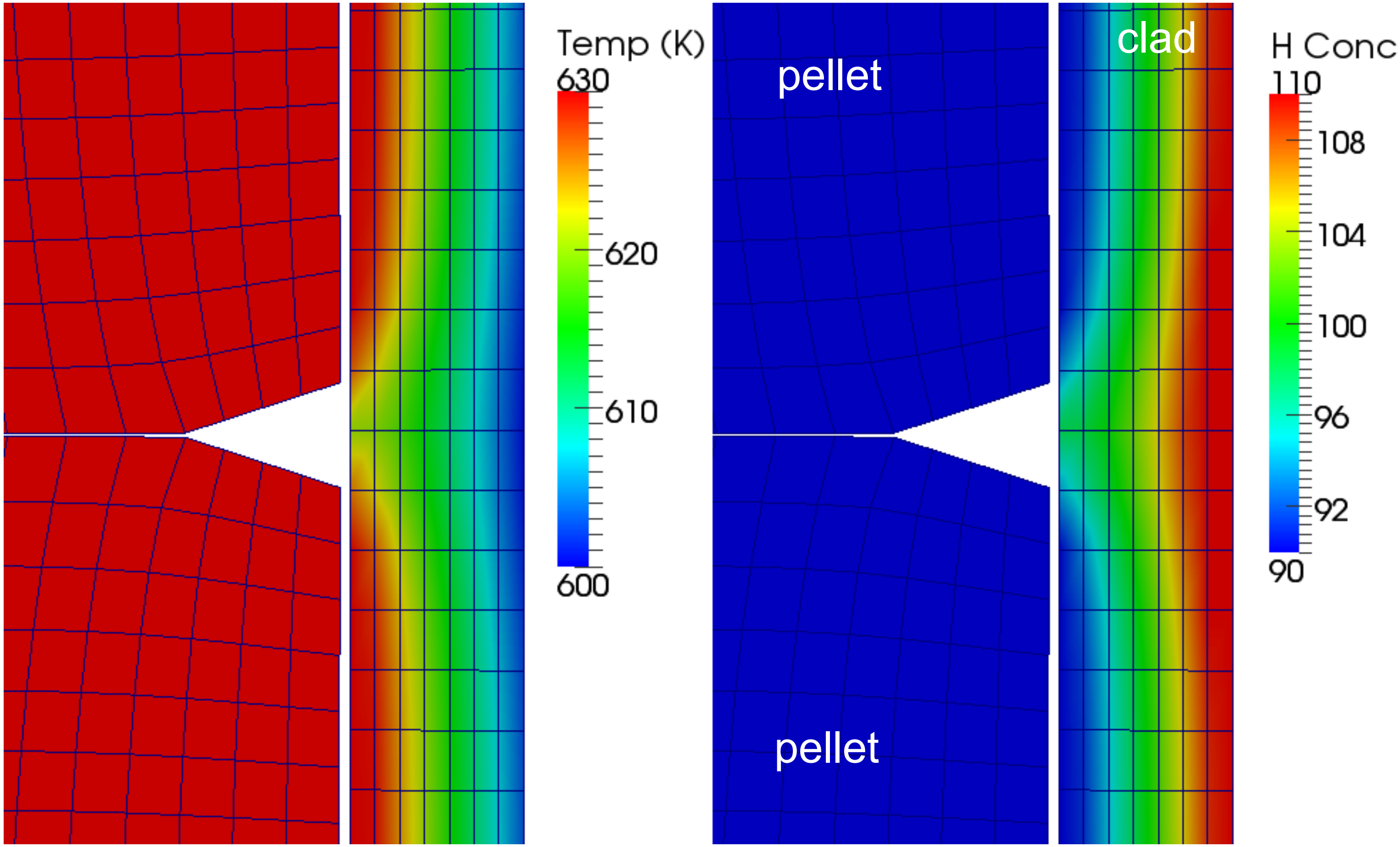
$$\frac{\partial C}{\partial t} = \nabla \cdot D\left(\nabla C - \frac{CQ^*}{FRT^2}\nabla T\right)$$

  - Hydride precipitation and dissolution kinetics
- Simulated from fresh fuel to end of storage



Hydrogen Evolution – BISON Results

- Thermal gradients in clad lead to hydrogen concentrations at the outer clad radius (rim effect) and near pellet-pellet interfaces
- Qualitatively confirmed by measurements



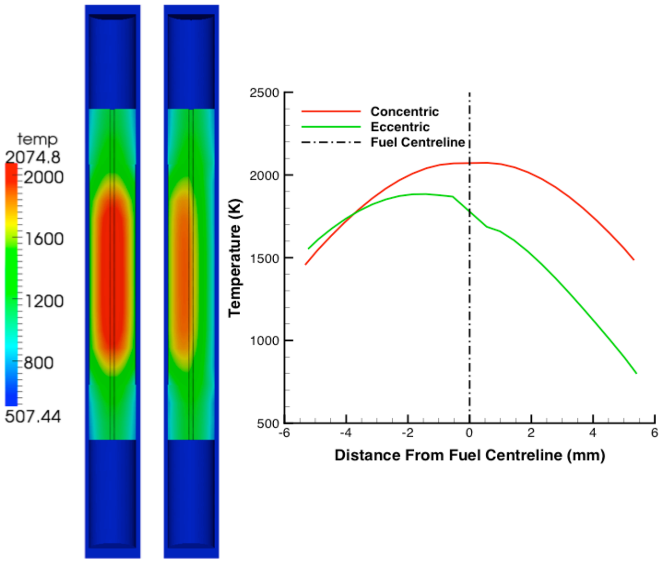
Collaboration with Halden Reactor Project

- Several Halden experiments considered in our existing validation suite; raw data are available

- Validation to 3D experiment
  - Invited paper - J. D. Hales, D. M. Perez, R. L. Williamson, S. R. Novascone, B. W. Spencer, and R. C. Martineau, *Validation of the BISON 3D Fuel Performance Code: Temperature Comparisons for Concentrically and Eccentrically Located Fuel Pellets*, Extended Halden Program Group Meeting, Gol, Norway, March 11-14, 2013.

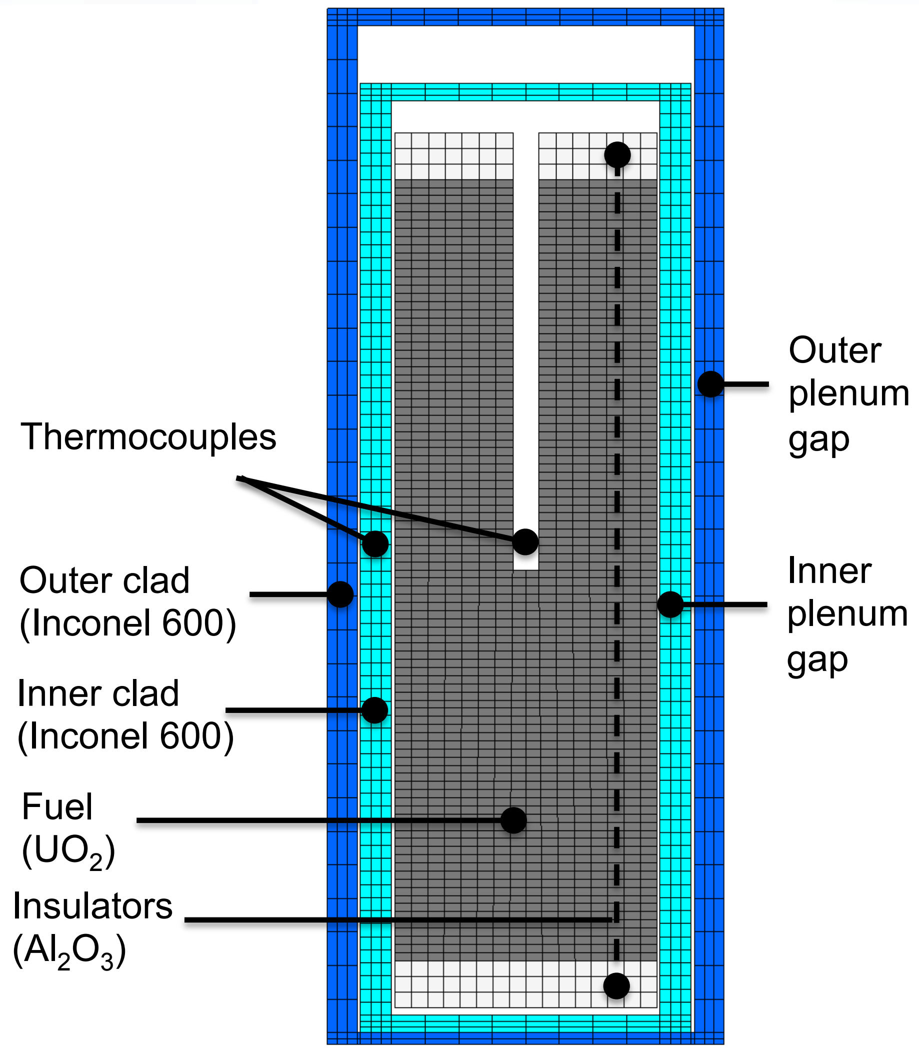
- Jason Hales invited to guest lecture at the OECD-Halden Reactor Project Summer School, August 26-29, 2013
  - Topic - Special Modeling: 3D Models and their Application

- Currently simulating a unique double-encapsulated fuel thermal conductivity experiment for installation in 2014; aiding in experimental design

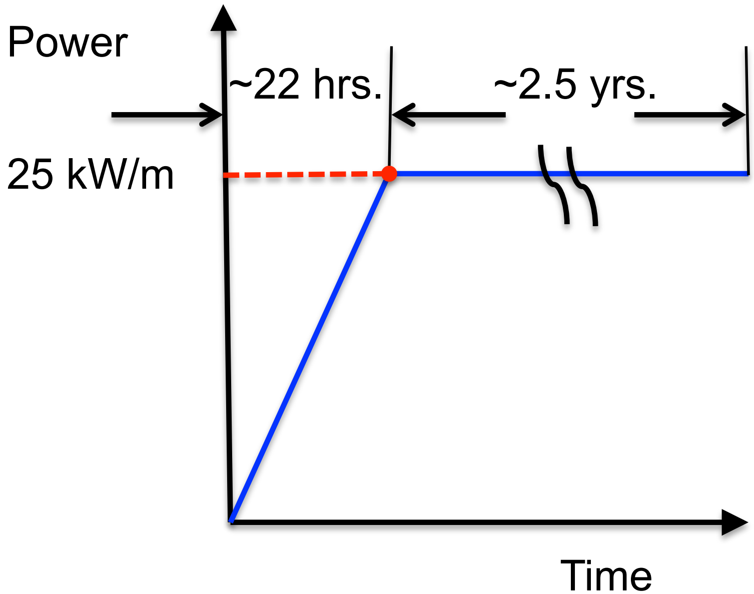


Halden IFA-744 Experiment

- Double-encapsulated fuel thermal conductivity experiment
- Molten lead bond between fuel and inner cladding
- Gas (initially helium) between inner and outer cladding
- Simplified 2D axisymmetric geometry, with view scaled 4x radially
- Quadratic (8 node) finite elements (coarse mesh shown)
- Gap heat transfer via thermal contact (gaps not meshed)



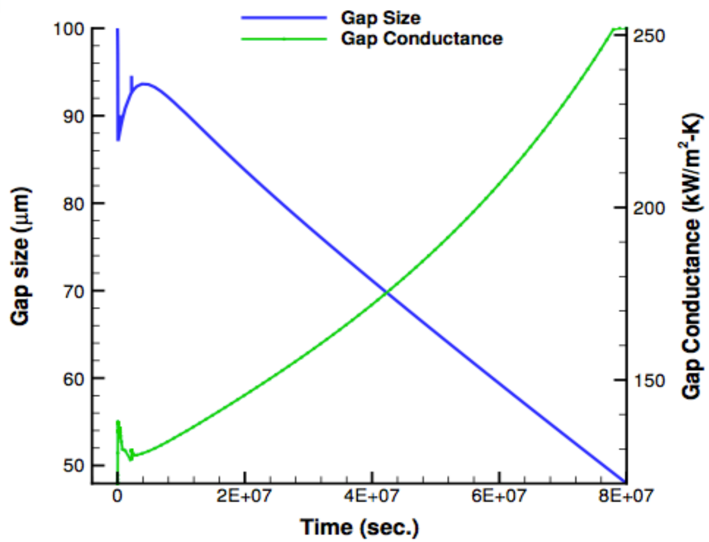
Halden IFA-744 Preliminary Simulation

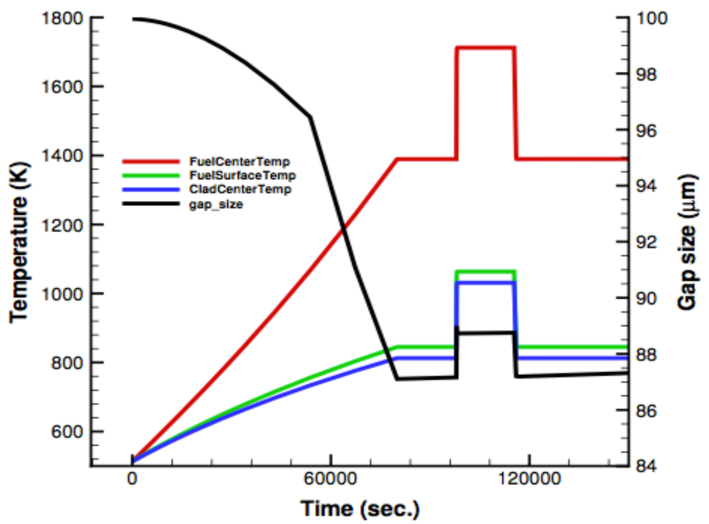


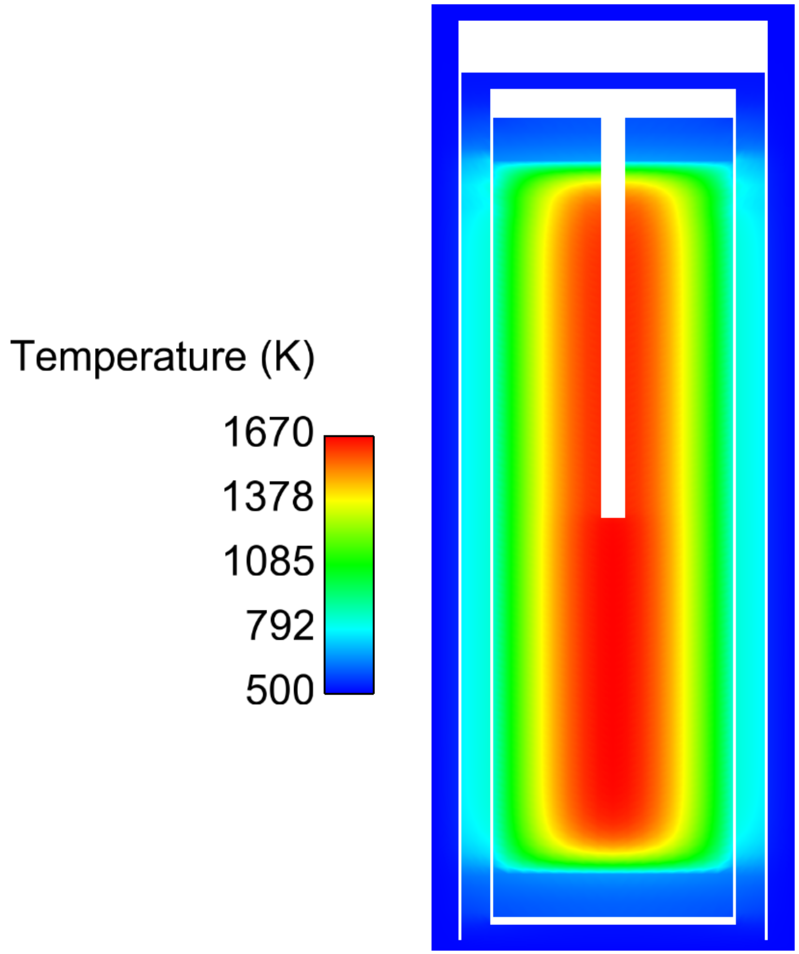
- Measuring $k_{fuel} = f\ (T, Bu)$: The outer plenum gas is periodically cycled from He to 50/50 He/Ar, resulting in a large increase in fuel centerline temperature; repeated at higher burnups.

- Mechanical and thermal contact models are activated
- Inner plenum metal bonded gap thermal conductivity is constant at 12 W/m-K
- Fuel relocation, swelling, and FGR models are active
- NFIR model used for fuel thermal conductivity

Halden IFA-744 Preliminary Results

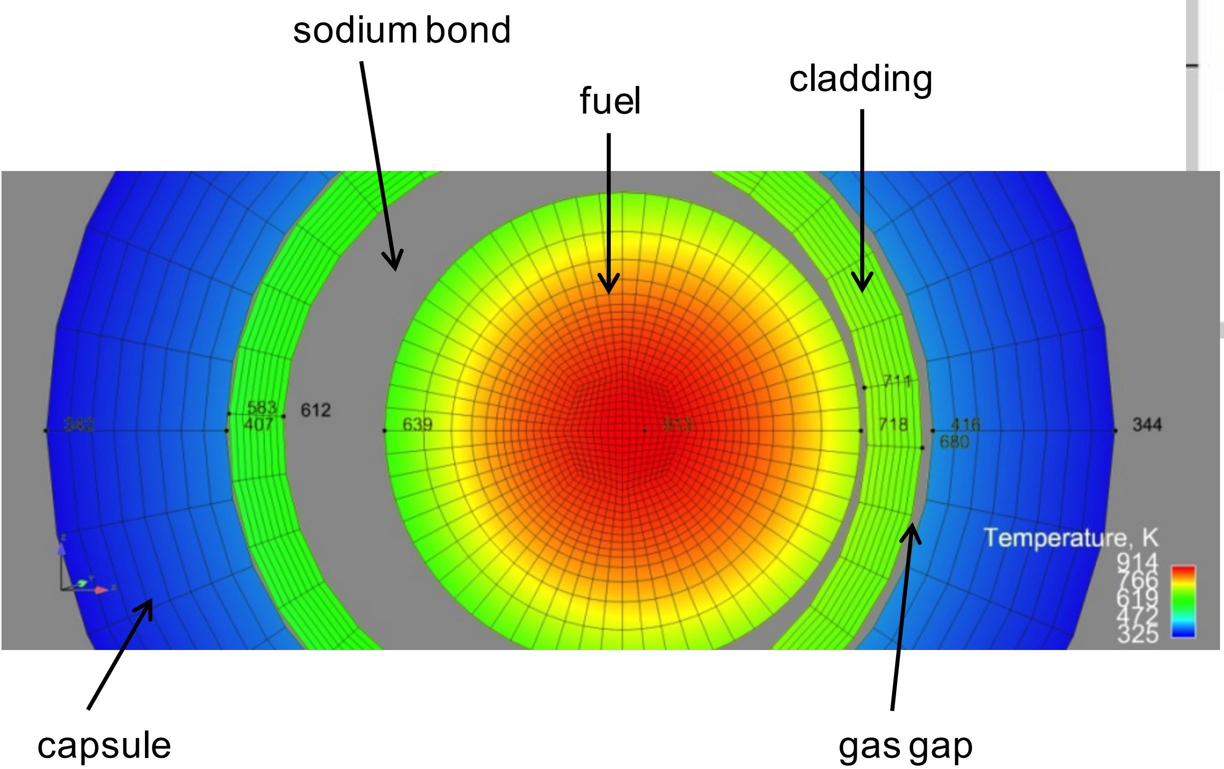






Thermoelastic analysis of FCRD metal fuel irradiation in ATR

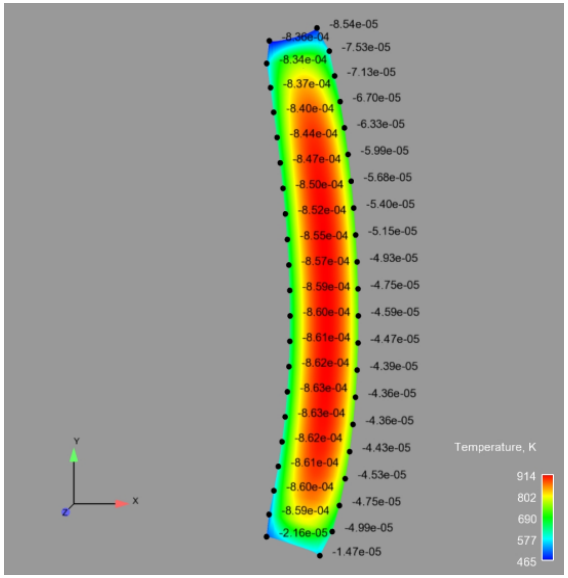
- BISON was used to assess the effects of asymmetry and axial heat flow on the temperature and deformation of the double-encapsulated FCRD metal fuel irradiation experiments



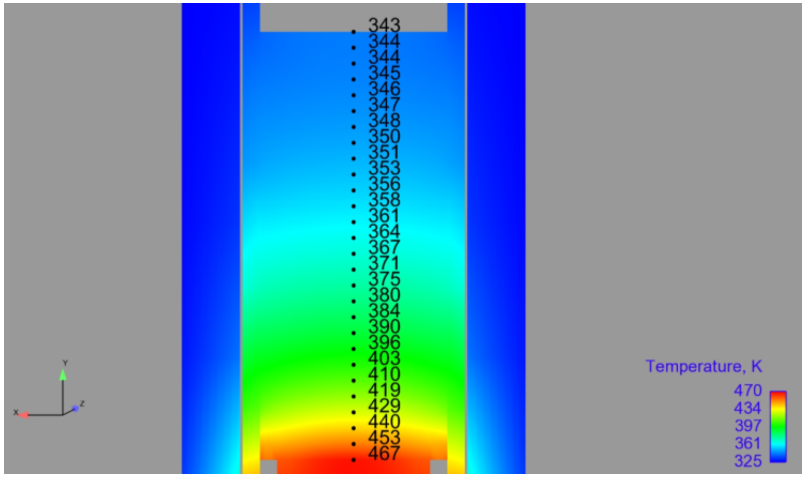
Cross-sectional metallography of a representative metallic fuel rodlet featuring an offset fuel slug

Thermoelastic analysis of FCRD metal fuel irradiation in ATR

- Key findings on the effects of asymmetry
  - insignificant effect on the fuel slug peak temperature, a key metric of the irradiation tests
  - slight fuel bowing of the fuel and cladding
  - noticeable effect on the cladding temperature, temperature difference of 148°K between diametrically opposed locations of the cladding
- Key findings on the effects of axial heat flow
  - plenum sodium may not melt, trapping the fission gas



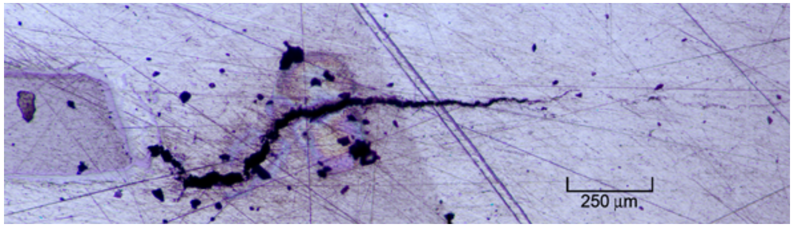
Shape of the fuel specimen subjected to bowing due to temperature asymmetry. Displacements magnified by 100 times.

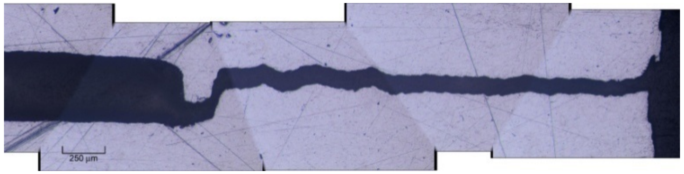


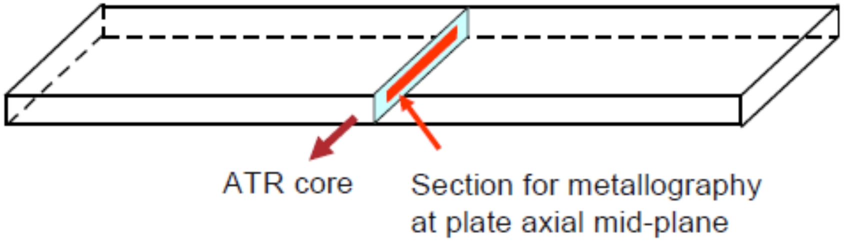
Temperature in the upper half of the plenum sodium column is below melting temperature of 370.87 K

Root Cause Analysis of Plate Fuel Failure (RERTR)

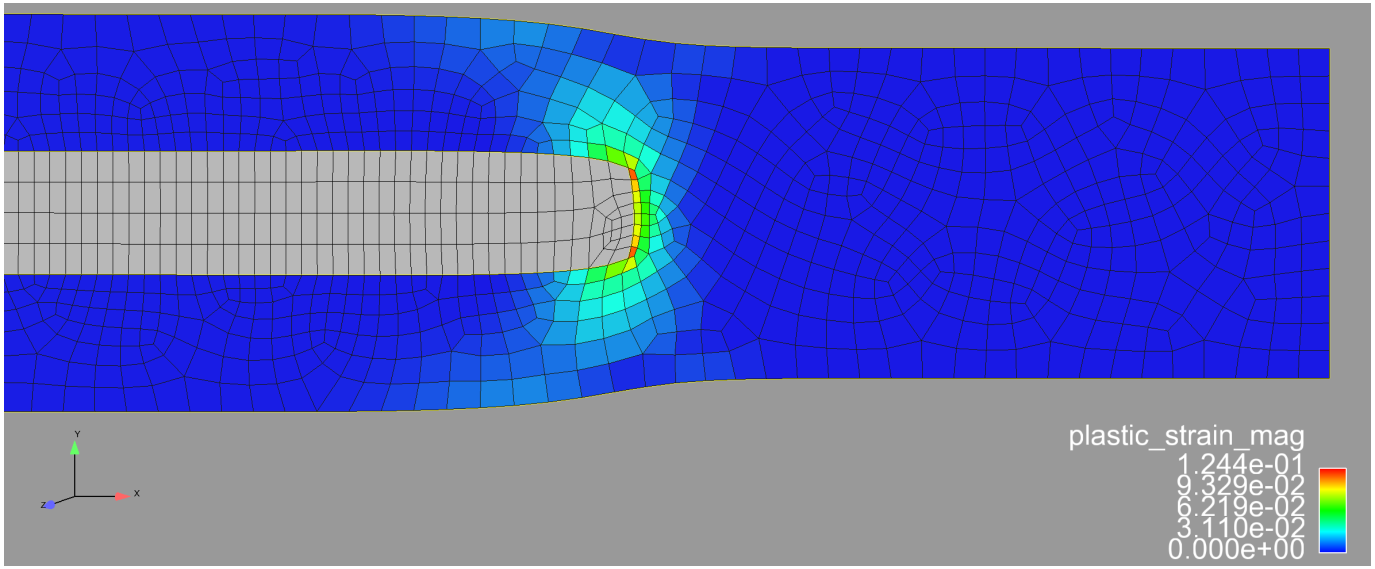
Metallography of a breached RERTR-7 plate





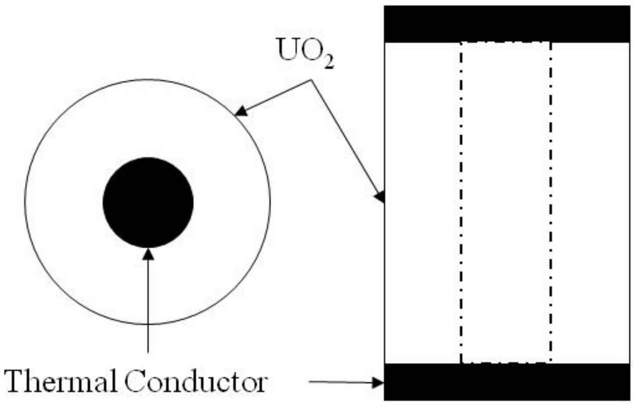


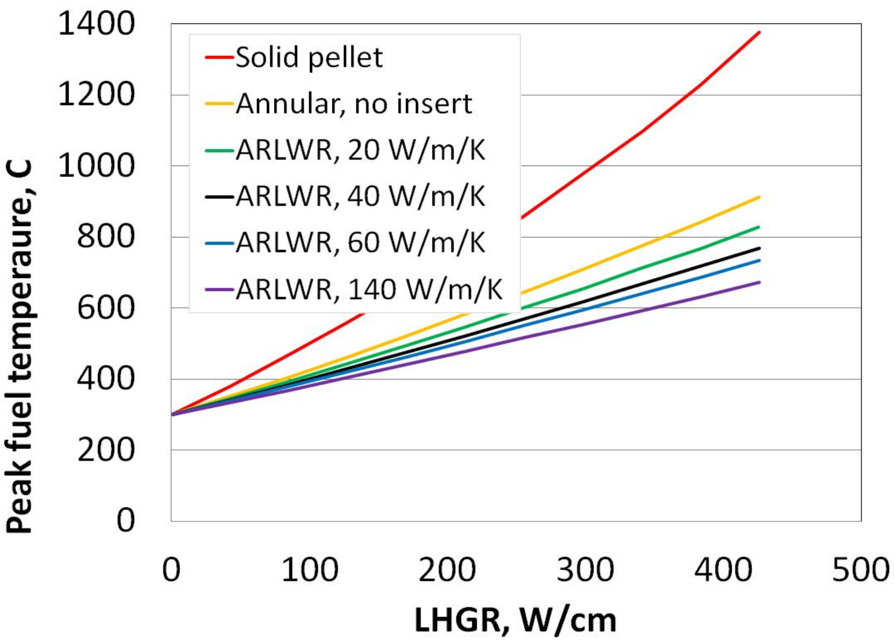
Peak plastic strain locations in cladding at the end of irradiation

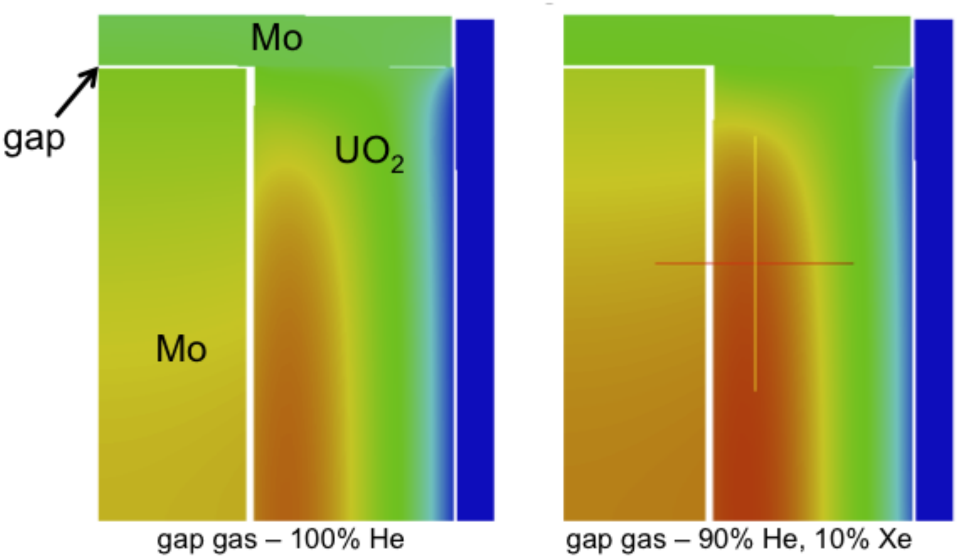


Investigation of Accident Tolerant Fuel Design

- Innovative oxide fuel design to lower peak fuel temperature
- Annular UO_2 pellet with highly conductive metal inserts and spacers

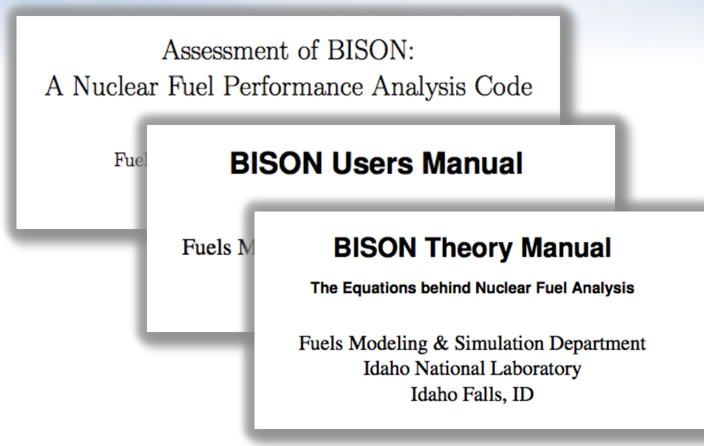






BISON Release and Documentation

- Code Release (Ver 1.0) on Sept. 30, 2013
- Theory, User and Assessment Manuals


Assessment of BISON:
A Nuclear Fuel Performance Analysis Code

Fuel

BISON Users Manual

Fuels M

BISON Theory Manual

The Equations behind Nuclear Fuel Analysis

Fuels Modeling & Simulation Department
Idaho National Laboratory
Idaho Falls, ID

- Journal and Conference Papers (2013)

1. J. D. Hales, R. L. Williamson, S. R. Novascone, D. M. Perez, B. W. Spencer, and G. Pastore, "Multidimensional Multiphysics Simulation of TRISO Particle Fuel," *J Nuc Mat*, in press (2013).
2. M. C. Teague, M. R. Tonks, S. R. Novascone, and S. R. Hayes, "Microstructural Modeling of Thermal Conductivity of High Burnup Mixed oxide Fuel," *J Nuc Mat*, in press (2013).
3. M. R. Tonks, P. C. Millett, P. Nerikar, S. Du. D. Andersson, C. R. Stanek, D. Gaston, D. Andrs, and R. Williamson, "Multiscale Development of a Fission Gas Thermal Conductivity Model: Coupling Atomic, Meso and Continuum Level Simulations," *J Nuc Mat*, 440, 193-200 (2013).
4. J. D. Hales, M. R. Tonks, M. R. Chockalingam, D. M. Perez, S. R. Novascone, and B. W. Spencer, "Multiscale Nuclear Fuel Analysis via Asymptotic Expansion Homogenization," Transactions of SMiRT-22, San Francisco, California, 18-23 August 2013.
5. S. R. Novascone, B. W. Spencer, R. L. Williamson, D. Andrs, J. D. Hales, and D. M. Perez, "The Effects of Thermomechanics Coupling Strategies in Nuclear Fuel Performance Simulations," Transactions of SMiRT-22, San Francisco, California, 18-23 August 2013.
6. F. N. Gleicher, S. R. Novascone, B. W. Spencer, R. L. Williamson, R. C. Martineau, M. Rose, and T. Downar, "Coupling the Core Analysis Program DeCART to the Fuel Performance Program BISON, Proceedings of the International Conference on Mathematics and Computational Methods Applied to Nuclear Science and Engineering, Sun Valley, Idaho, 5-9 May 2013.
7. J. D. Hales, D. Andrs, and D. R. Gaston, "Algorithms for Thermal and Mechanical Contact in Nuclear Fuel Performance Analysis," Proceedings of the International Conference on Mathematics and Computational Methods Applied to Nuclear Science and Engineering, Sun Valley, Idaho, 5-9 May 2013.
8. D. M. Perez, R. L. Williamson, S. R. Novascone, T. K. Larson, J. D. Hales, B. W. Spencer, and G. Pastore, "An Evaluation of the Nuclear Fuel Performance Code BISON," Proceedings of the International Conference on Mathematics and Computational Methods Applied to Nuclear Science and Engineering, Sun Valley, Idaho, 5-9 May 2013.
9. S. R. Novascone, B. W. Spencer, D. Andrs, R. L. Williamson, J. D. Hales, and D. M. Perez, "Results from Tight and Loose Coupled Multiphysics in Nuclear Fuels Performance Simulations using BISON," Proceedings of the International Conference on Mathematics and Computational Methods Applied to Nuclear Science and Engineering, Sun Valley, Idaho, 5-9 May 2013.
10. L. P. Swiler, R. L. Williamson, and D. M. Perez, "Calibration of a Fuel Relocation Model in BISON," Proceedings of the International Conference on Mathematics and Computational Methods Applied to Nuclear Science and Engineering, Sun Valley, Idaho, 5-9 May 2013.
11. J. D. Hales, D. M. Perez, R. L. Williamson, S. R. Novascone, B. W. Spencer, and R. C. Martineau, "Validation of the BISON 3D Fuel Performance Code: Temperature Comparisons for Concentrically and Eccentrically Located Fuel Pellets," Enlarged Halden Programme Group Meeting: Proceedings of the Fuels and Materials Sessions, Storefjell Resort Hotel, Norway, 10-15 March 2013.

BISON Documentation

- Journal and Conference Papers (2012)

1. R. L. Williamson, J. D. Hales, S. R. Novascone, M. R. Tonks, D. R. Gaston, C. J. Permann, D. Andrs, and R. C. Martineau, “Multidimensional Multiphysics Simulation of Nuclear Fuel Behavior,” *J Nuc Mat*, 423, 149 (2012)
2. J. D. Hales, S. R. Novascone, R. L. Williamson, D. R. Gaston, and M. R. Tonks, “Solving Nonlinear Solid Mechanics Problems with the Jacobian-Free Newton Krylov Method, *Comp Mod in Eng and Sci*, 84, 123 (2012)
3. D. Gaston, L. Guo, G. Hansen, H. Huang, R. Johnson, H. Park, R. Podgorney, M. Tonks, and R. Williamson, “Parallel Algorithms and Software for Nuclear, Energy, and Environmental Applications. Part I: Multiphysics Algorithms,” *Comm in Comp Phy*, 12, 807 (2012)
4. D. Gaston, L. Guo, G. Hansen, H. Huang, R. Johnson, H. Park, R. Podgorney, M. Tonks, and R. Williamson, “Parallel Algorithms and Software for Nuclear, Energy, and Environmental Applications. Part II: Multiphysics Software,” *Comm in Comp Phys*, 12, 834 (2012)
5. S. R. Novascone, R. Williamson, J. Hales, M. Tonks, D. Gaston, C. Permann, D. Andrs, and R. Martineau, “Multidimensional and Multiphysics Approach to Nuclear Fuel Behavior Simulation,” Proceedings of PHYSOR 2012, Knoxville, Tennessee, April 15-20, 2012.
6. B. W. Spencer, J. D. Hales, S. R. Novascone and R. L. Williamson, “3D Simulation of Missing Pellet Surface Defects in Light Water Reactor Fuel Rods,” Proceedings of TopFuel 2012, Manchester, UK, September 2-6, 2012.
7. S. Novascone, J. Hales, B. Spencer, and R. Williamson, “Assessment of PCMI Simulation Using the Multidimensional Multiphysics BISON Fuel Performance Code,” Proceedings of Top Fuel 2012, Manchester, UK, September 2-6, 2012.

User Training

Workshop Materials

- ~ 200 slides
- Overview, Getting Started, Theory,
  Example Problem, Mesh Generation,
  Post Processing,
  Adding a New Material

BISON 2-day Workshops

- INL – January 2012
- MIT – January 2012
- Anatech – Feb 2012
- INL – May 2012 (23 participants)
- NNL (UK) – September 2012
- INL – December 2012 (15 participants)
- INL – June 2013 (11 participants)
- WEC – Aug 2013 (10 participants)
- INL – Dec 2013 (planned)

Summary

- BISON is being leveraged across multiple DOE programs and is in use at multiple national and international laboratories, many universities and in industry
- Roughly 20 integral rod LWR and 13 TRISO validation cases have been completed… many more are needed
- BISON used to do first-ever simulation of 3D pellet eccentricity experiment (invited paper at Halden Reactor Program Meeting)
- Major new capability completed for TRISO-coated particle fuel (journal article published)
- Numerous new applications (metal plate fuel, fast reactor oxide fuel, accident tolerant fuel designs) demonstrate BISON's versatility
- First official code release on September 30, 2013

Idaho National Laboratory

The National Nuclear Laboratory