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BISON:
A Next-Generation
Nuclear Fuel Performance Code

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25 January 2017

Advanced Reactor Modeling and Simulation Workshop
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NEAMS
NUCLEAR ENERGY ADVANCED MODELING & SIMULATION PROGRAM

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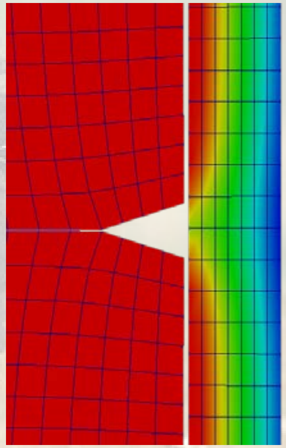
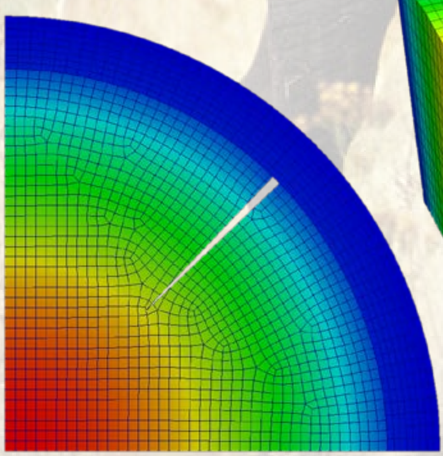
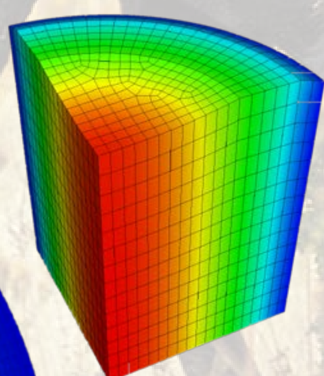
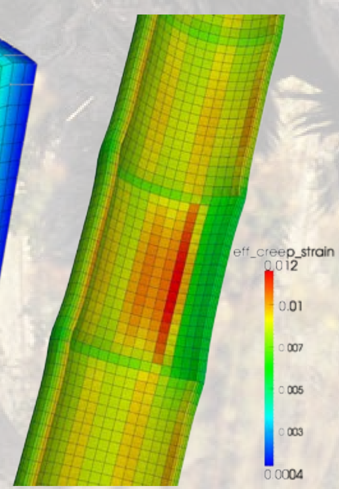
BISON: What is it?

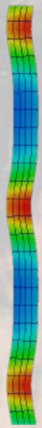
- **A finite element, thermo-mechanics code with material models and other customizations to analyze nuclear fuel**
  - Accepts user-defined meshes/geometries
  - Runs on one processor or many
  - Analyzes a variety of fuel types
  - Couples to other analysis codes

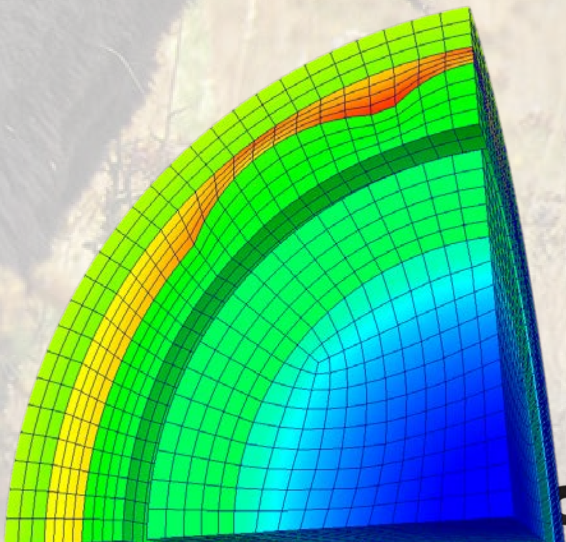












BISON Requirements and Limitations

- **BISON requires:**
  - An input file that describes thermal and mechanical material models, boundary conditions, initial conditions, power history
  - A mesh provided either directly in the input file or through a separate mesh file
- **BISON cannot currently model:**
  - Very high strain rate analyses (e.g., car crashes)
  - Structural elements (membranes, shells, beams)
  - Melting or flowing material
- **BISON is not:**
  - A thermal-hydraulics or CFD code
  - A neutronics code

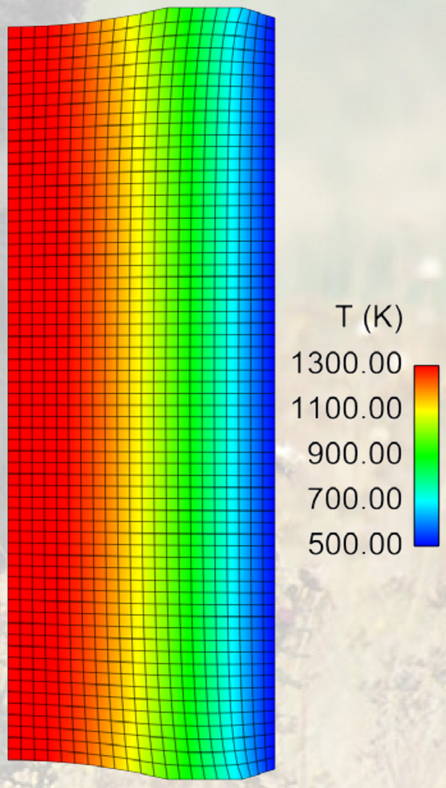
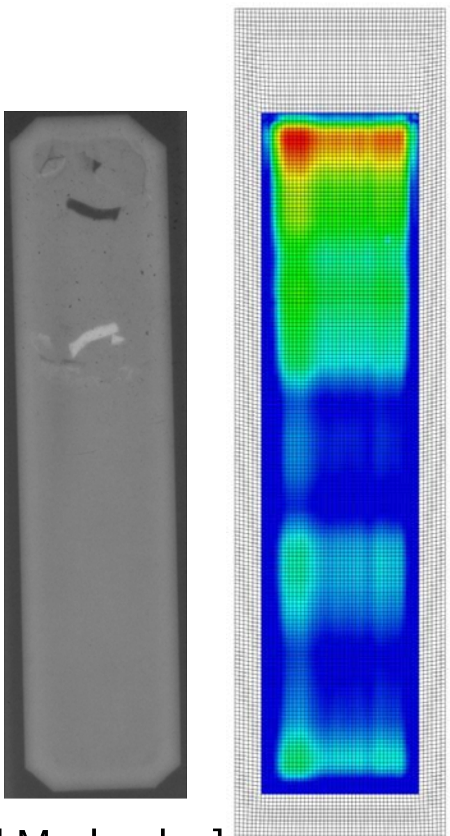
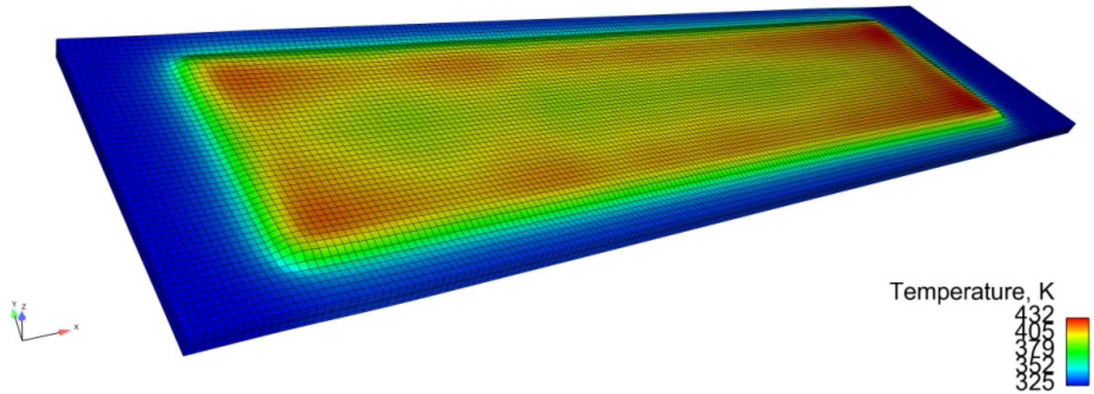
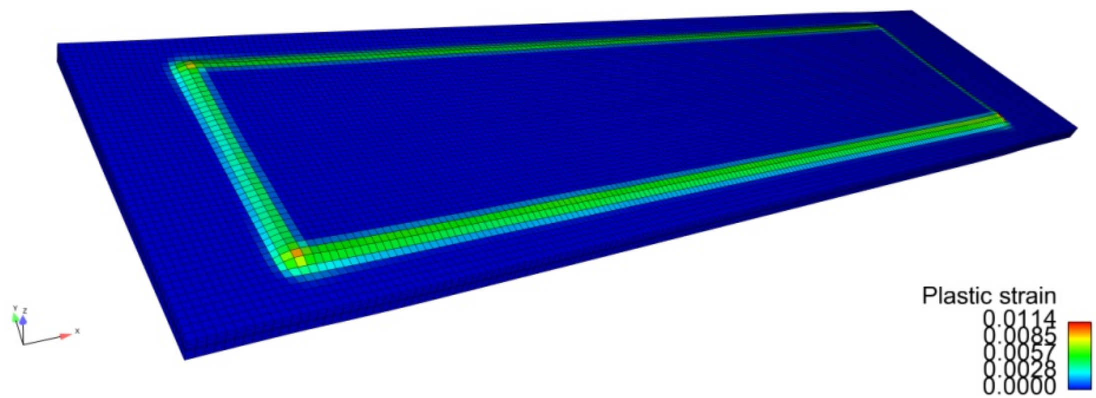


Plate Fuel Analysis

- **BISON has been used to analyze plate fuel for research reactors**



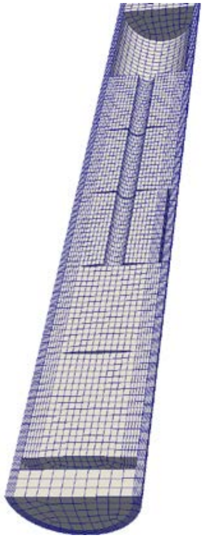


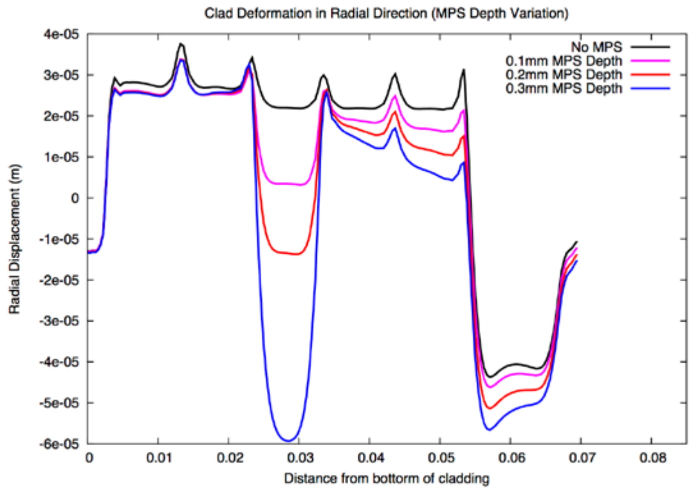


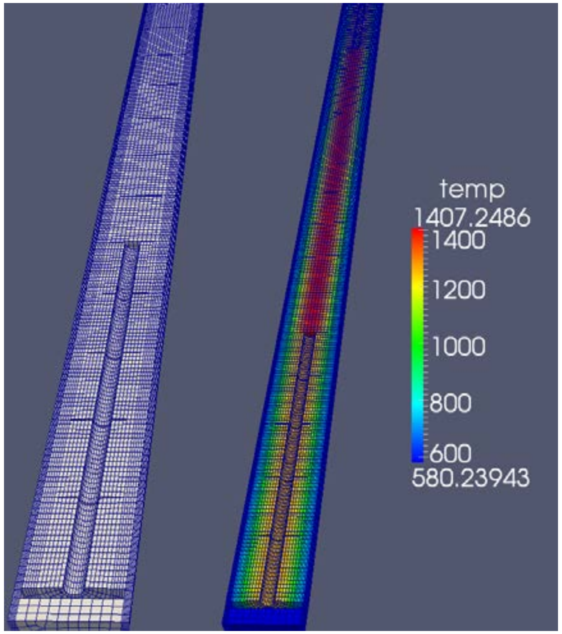
[Pavel Medvedev]

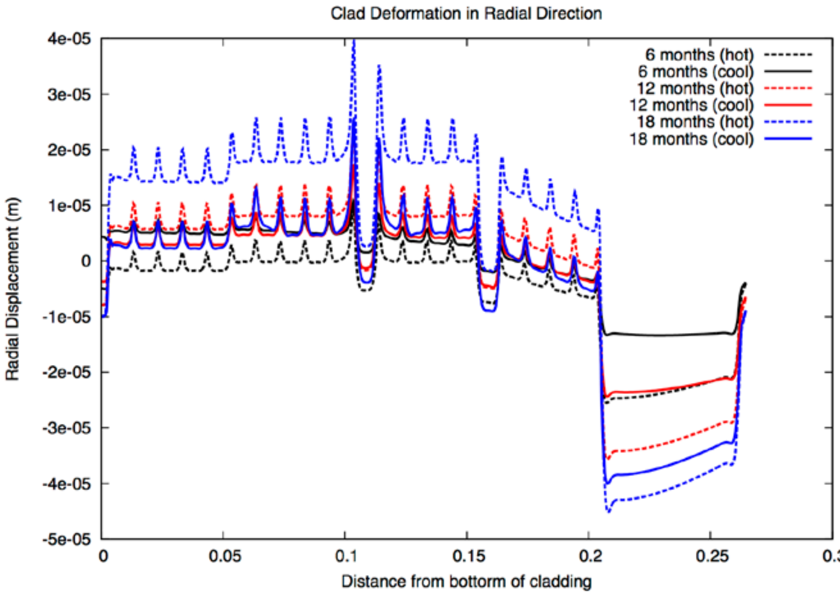
3D Halden Experiment

- **Design irradiation experiments**
  - Halden Reactor Project and INL are working on a 3D fuel experiment for BISON validation
  - Analyzing 5 and 20 pellet models to predict cladding deformation



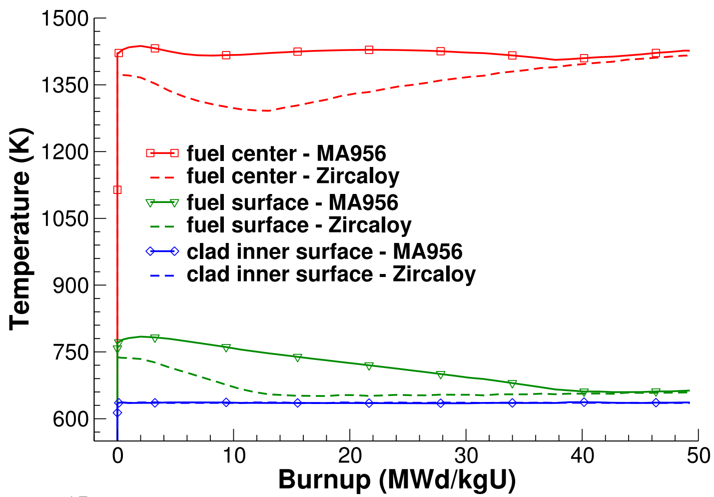


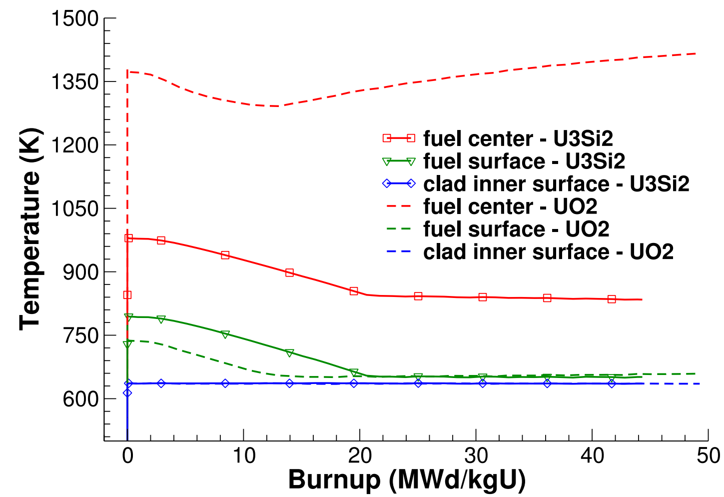


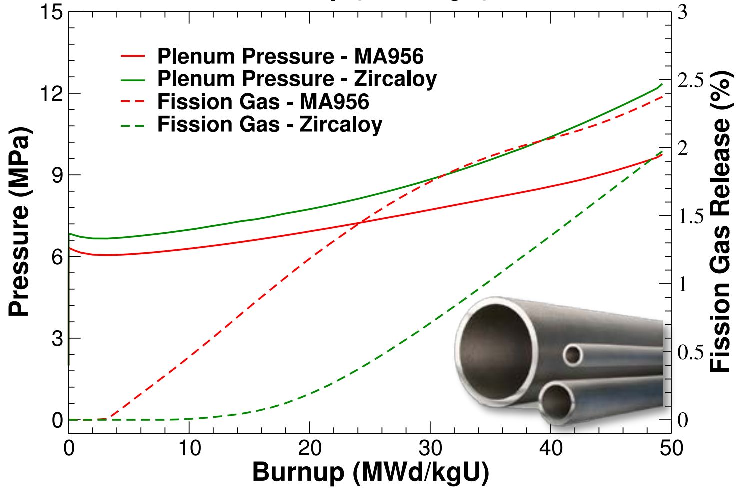


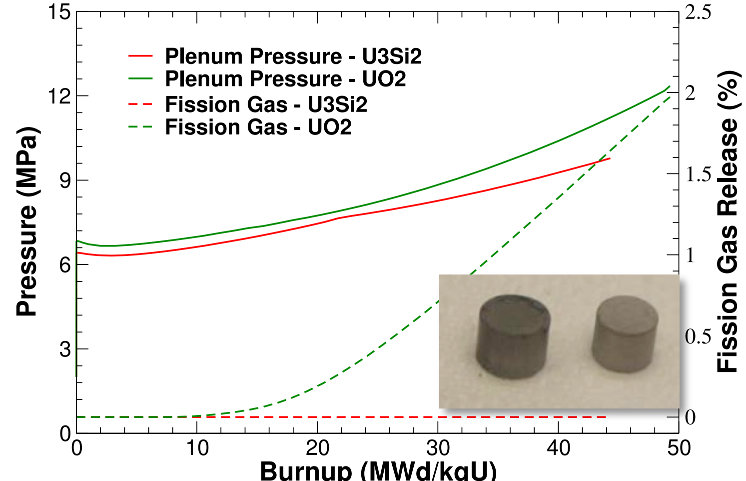
ULATION PROGRAM

LWR Accident Tolerant Fuel









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High Temperature Gas Reactor Applications

- **M&S Gap:**
  - Need to model graphite behavior as a function of temperature and dose
- **BISON:**
  - No graphite models today, but…
  - Modeling material behavior as a function of temperature and dose is common in BISON

```
void
CreepSiC::computeCreep( SymmTensor & creep_strain_increment,
                        SymmTensor & stress_new )
{
```

```
  //   csi = dev_trial_stress * 1.5 * dt*k*fnf / (3*dt*k*G*fnf + 1)

  // compute deviatoric trial stress
  SymmTensor dev_trial_stress(stress_new);
  dev_trial_stress.addDiag( -dev_trial_stress.trace()/3.0 );

  const Real k( _k_function.value( _temperature[_qp], _q_point[_qp] ));

  const Real p_by_ets( _dt * k * _fast_neutron_flux[_qp] /
      (3 * _dt * k * _shear_modulus * _fast_neutron_flux[_qp] + 1));

  creep_strain_increment = dev_trial_stress;
  creep_strain_increment *= 1.5*p_by_ets;

  // update creep strain
  _creep_strain[_qp] = creep_strain_increment;
  _creep_strain[_qp] += _creep_strain_old[_qp];
}
```

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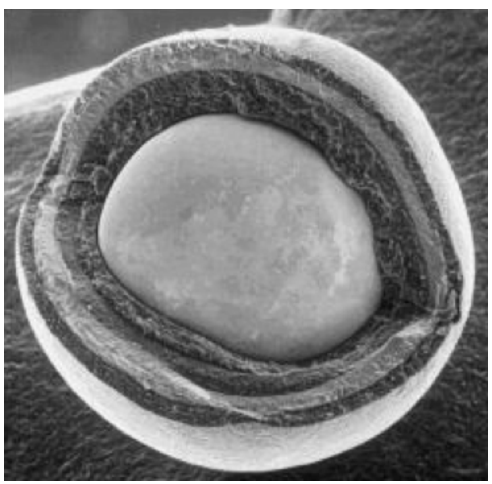
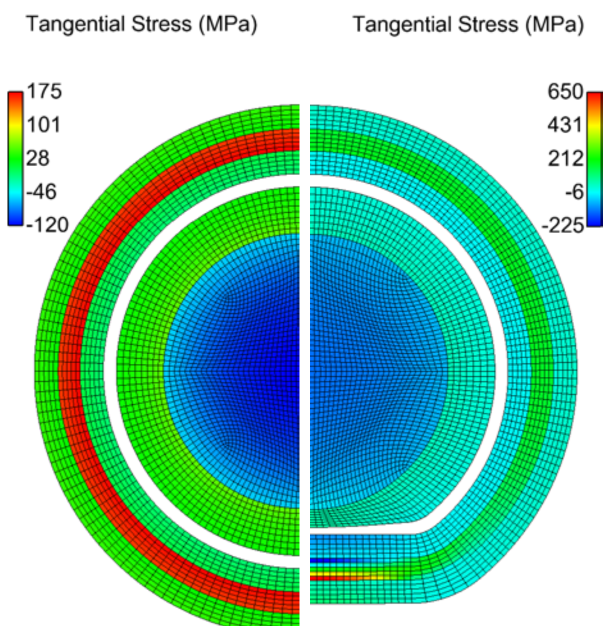
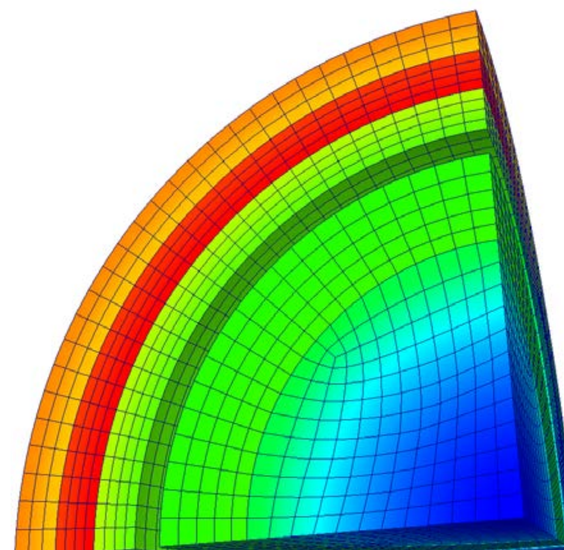
High Temperature Gas Reactor Applications (Also for FHR)

- **M&S Gap:**
  - Fuel performance code for steady state and transient conditions
- **BISON:**
  - BISON *is* a fuel performance code for steady state and transient conditions
  - TRISO capabilities already exist







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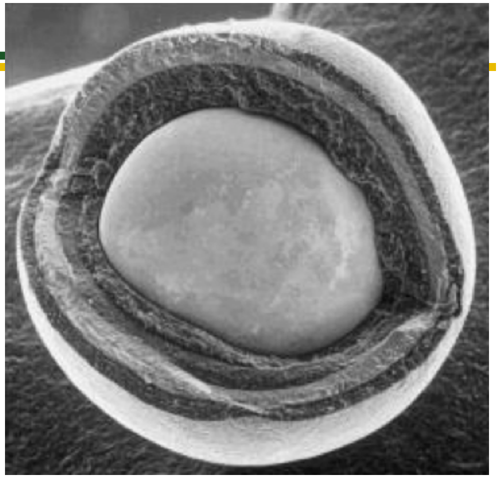
BISON Application: Particle Fuel

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

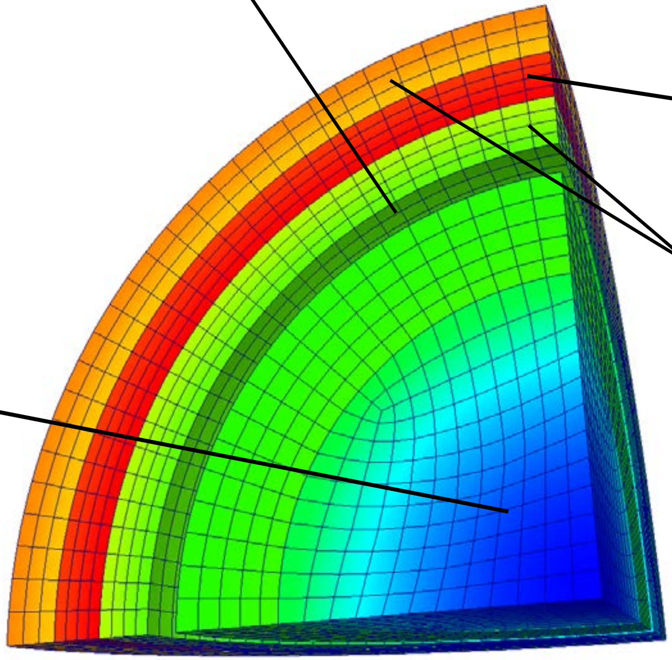
Gap Behavior

- 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



Tangential Stress

Silicon Carbide

- irradiation creep

Pyrolytic Carbon

- Anisotropic irradiation-induced strain
- Irradiation creep

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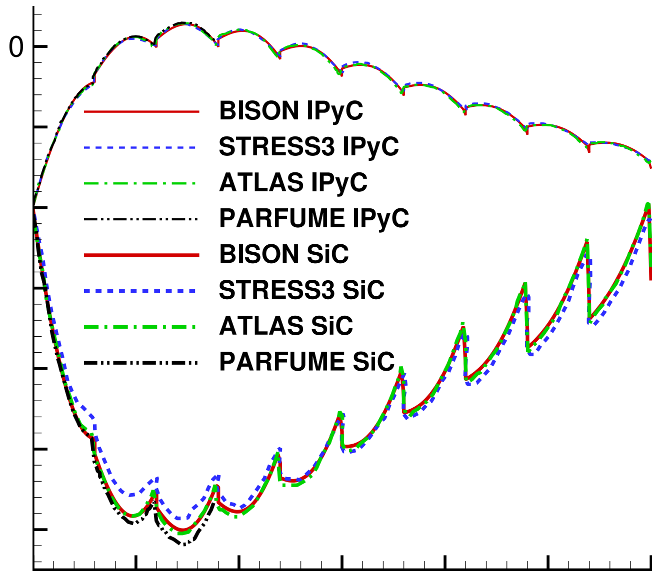
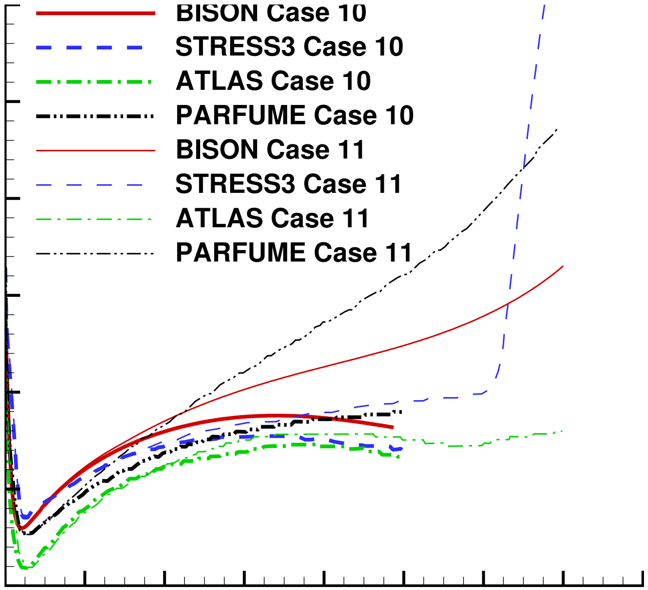
Evaluation of TRISO capability

- BISON compared 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 as observed in pebble-bed reactor



Irradiations based on German HFR-K3 and HFR-P3 experiments

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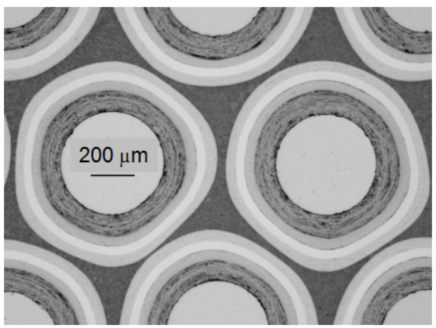
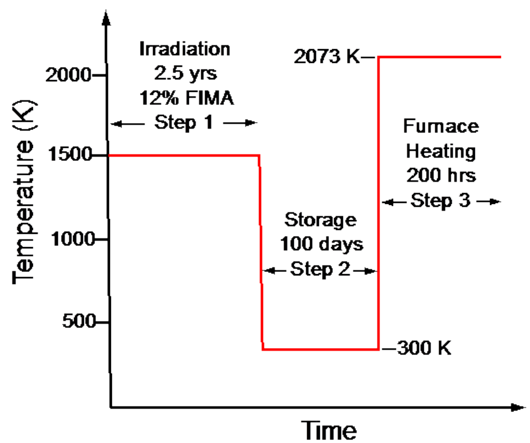
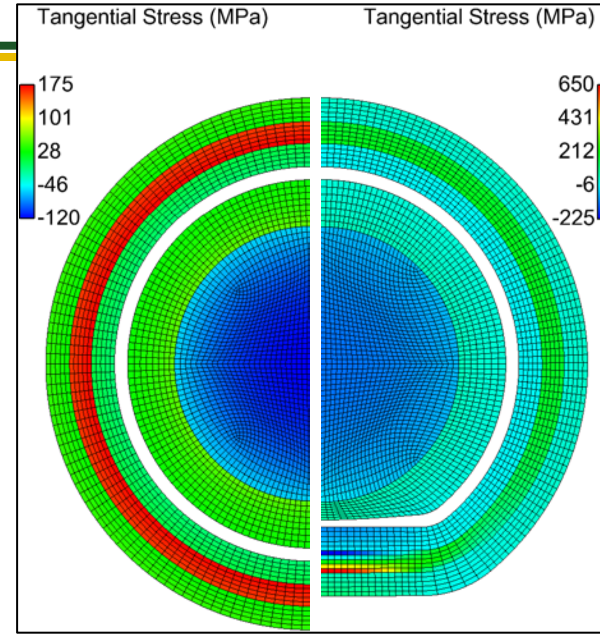
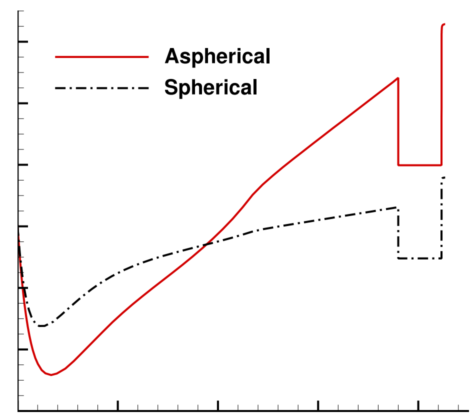
Simulation of Aspherical TRISO Particle

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



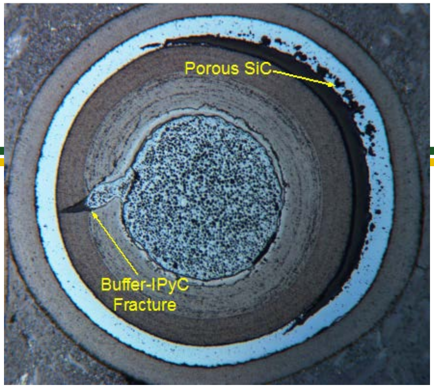




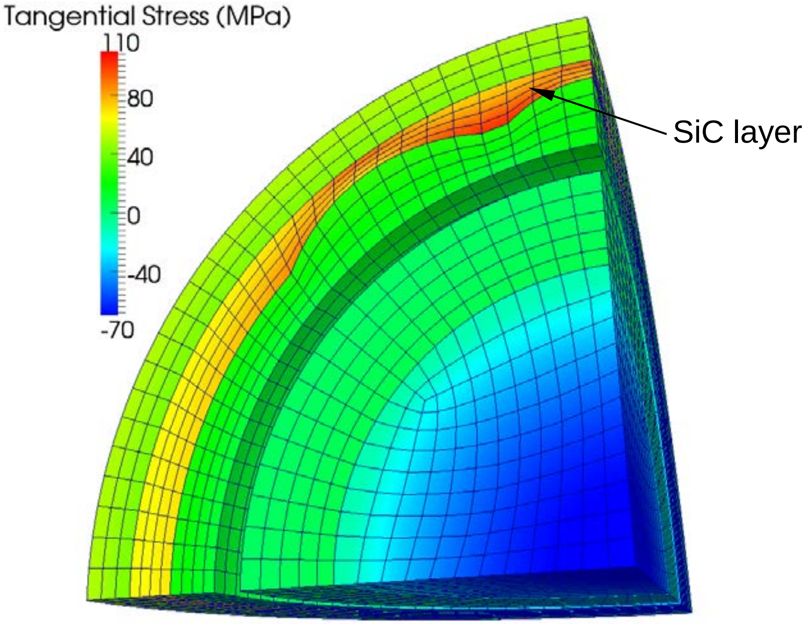


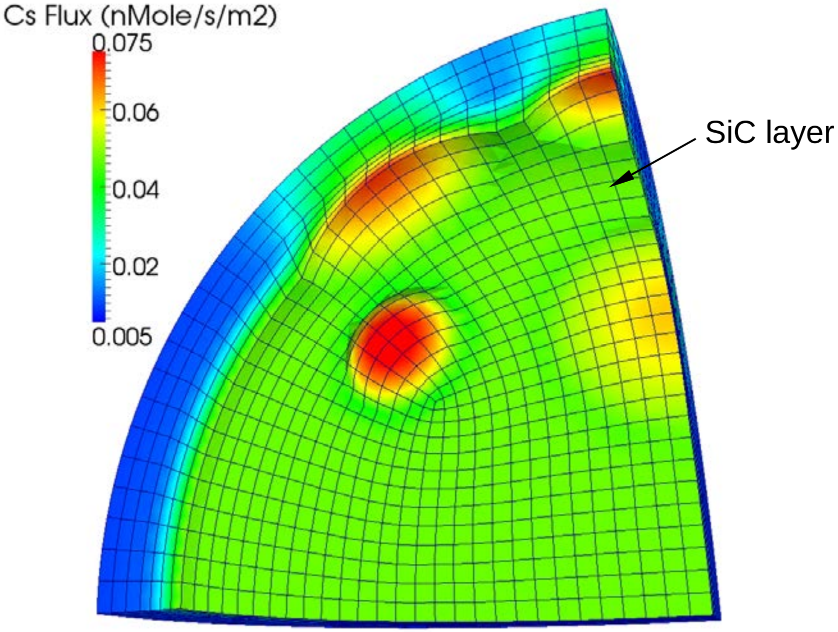
- During accident testing, asphericity raises peak tensile stress in SiC containment layer by almost 4x
- Typical run times of a few minutes on 8 processors

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

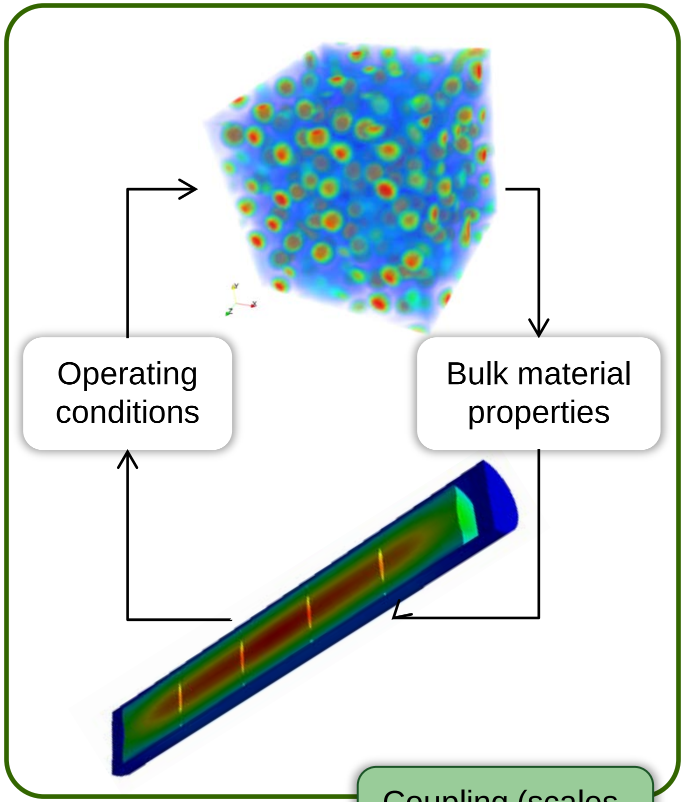




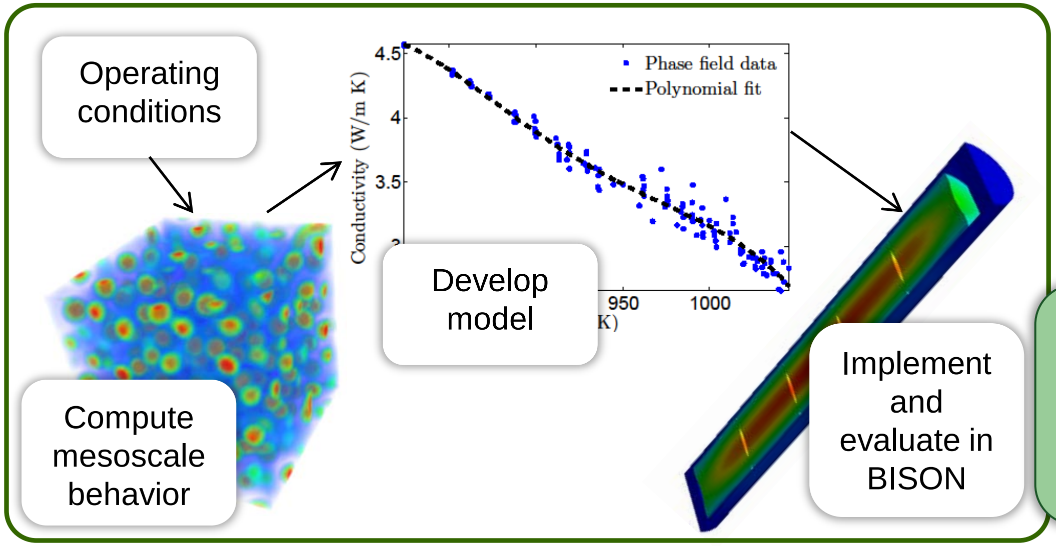
- Thinned SiC regions experience significantly higher tensile stress and greater cesium release; impossible to predict with 1D analysis
- Typical run times of a few hours on 8 processors

Fast Reactor Applications

- **M&S Gap:**
  - Multi-physics, tightly-coupled analysis tool
- **BISON:**
  - BISON could be coupled to SHARP and SAM
  - BISON has already been coupled:
    - With MPACT, and COBRA-TF in CASL
    - With Marmot, Rattlesnake, and RELAP-7 at INL
  - BISON follows NQA-1 procedures



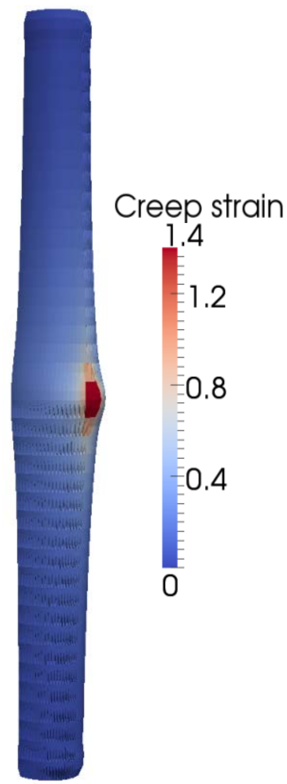
Coupling (scales, physics)

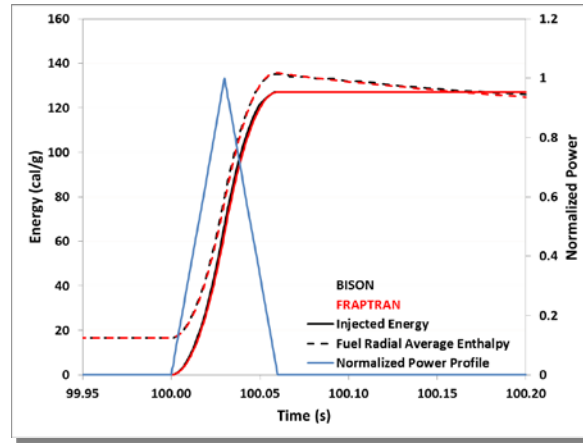


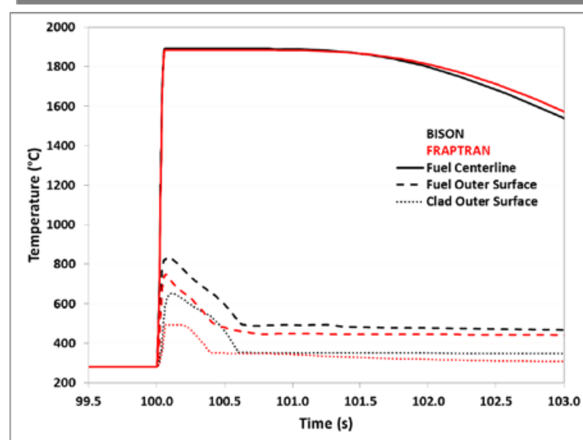
Data handoff (initial conditions, boundary conditions, models, etc.)

Fast Reactor Applications

- **M&S Gap:**
  - Fuel performance analysis code covering the full life cycle and under accident scenarios
- **BISON:**
  - BISON has some metal fuel capability now
  - Metal fuel capability development continues
  - BISON has been used for accident analysis for LWR fuel (LOCA and RIA)



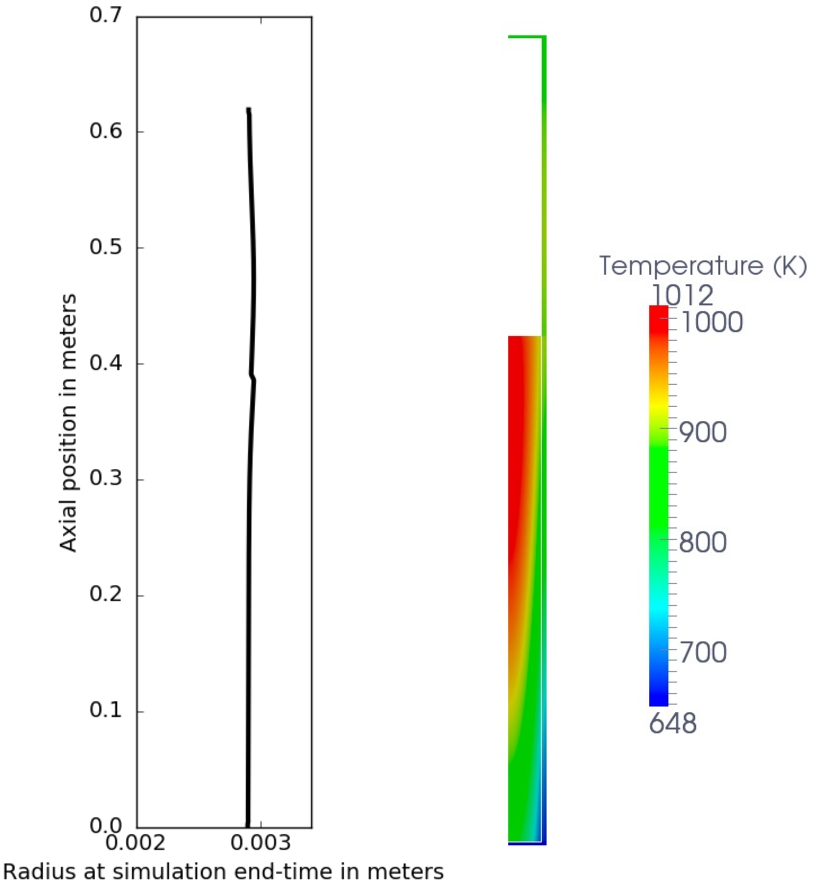




[Charles Folsom; Patrick Raynaud (NRC)]

Metal Fuel Example Problem

- **Sodium-filled gap**
- **Sodium coolant**
- **UPuZr models**
  - Thermal and irradiation creep
  - Thermal conductivity
  - Swelling
  - Fission Gas release
  - Zr distribution
- **HT9 Models**
  - Thermal and irradiation creep
  - Thermal conductivity
  - Damage accumulation



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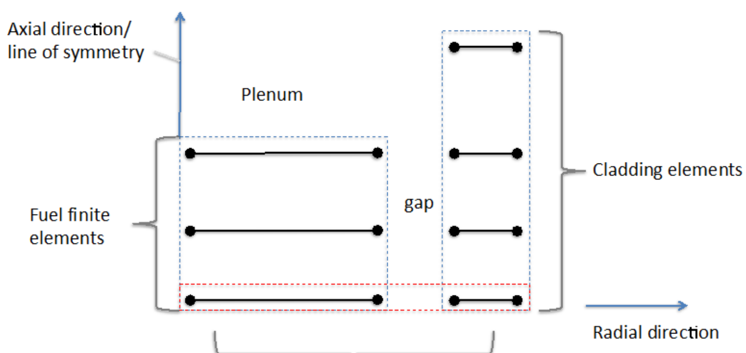
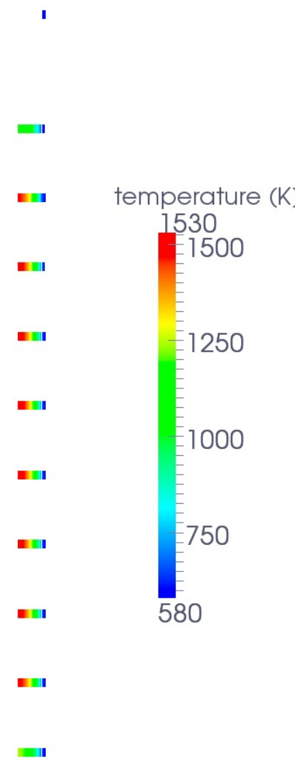
Fast Reactor Applications

- **M&S Gap:**
  - Fuel performance analysis code that is easy to access, modify, and use. Low fidelity solutions are adequate.
- **BISON:**
  - BISON is freely available, is built to be modified, and is hopefully user friendly.
  - A fast-running, 1.5D capability has been added to BISON for LWR fuel.



Energy conservation and stress divergence are solved along these horizontal lines using finite elements in 1D with thermal and mechanical contact. Axial effects are accounted for by summing displacements in each slice using a generalized plane strain formulation.



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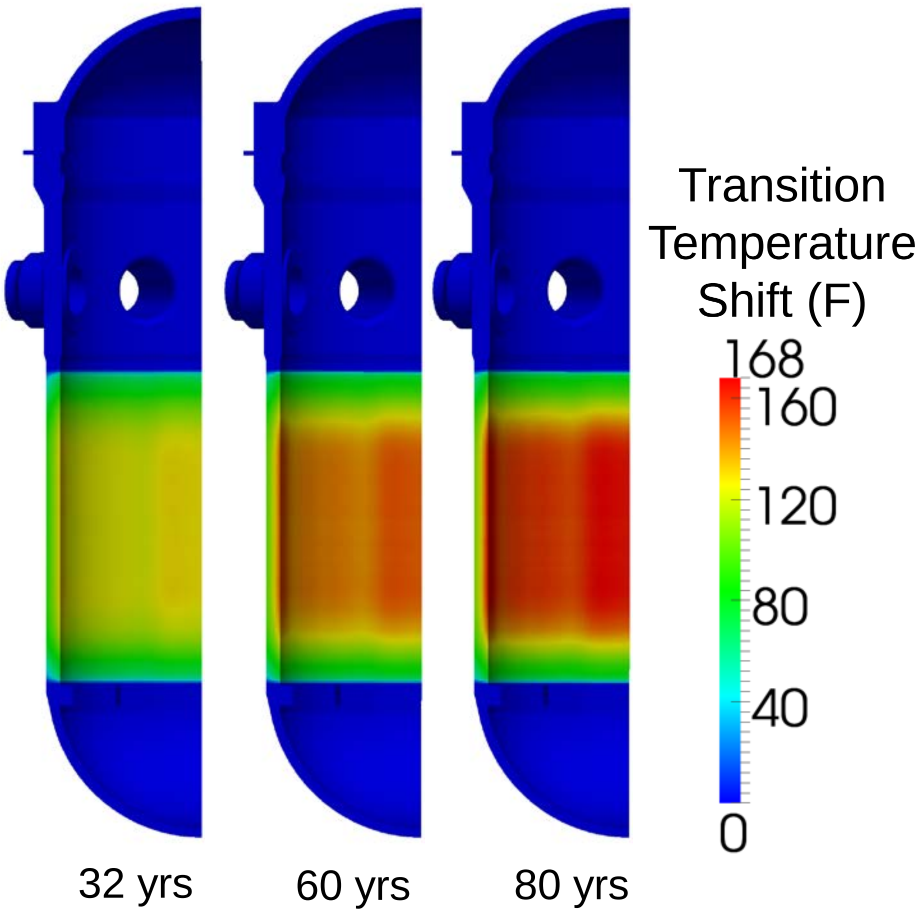
Flouride-salt cooled High Temperature Reactor Applications

- **M&S Gap:**
  - High-fidelity simulation of key degradation mechanisms for structures and fuels that limit life and determine replacement frequency.
- **BISON:**
  - BISON is applicable to TRISO and pebble fuel.
- **Grizzly:**
  - Grizzly is an application focused on material ageing and degradation that might also be applicable.

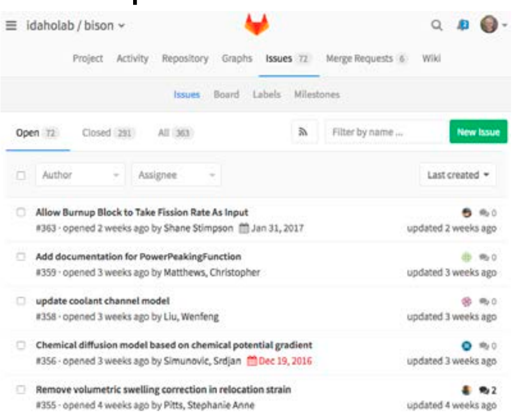


Software Quality Assurance

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

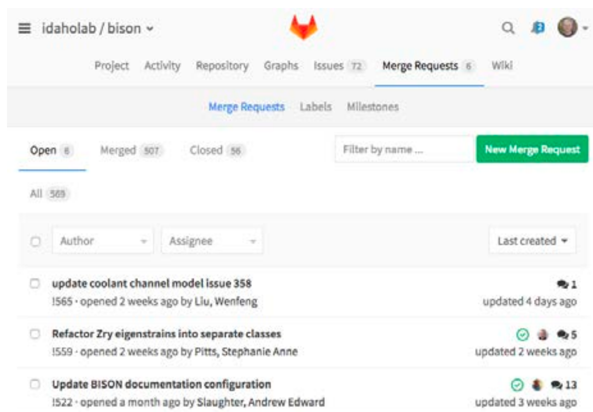
Issue Tracking

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



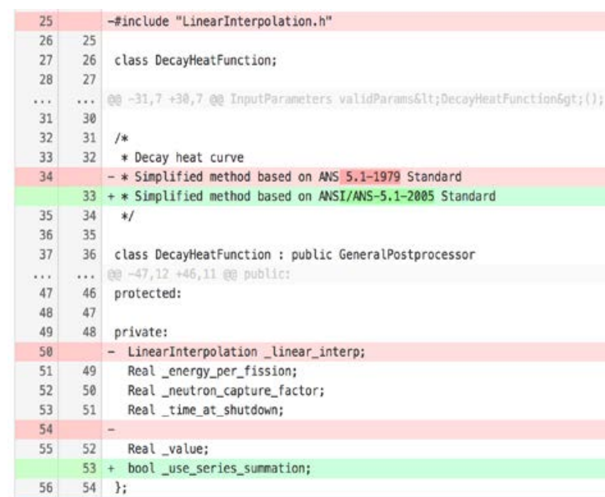
Merge requests and testing

- 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



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

Code Testing and Verification

- BISON thru MOOSE is supported by >2000 unit and regression tests
- All new code must be supported by regression 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: 2017-01-10 14:48:50
Legend: Rating: low: < 70 % medium: >= 70 % high: >= 80 %

	Hit	Total	Coverage
Lines:	14070	16450	85.5 %
Functions:	1736	2020	85.9 %

Directory	Line Coverage		Functions	
include/actions	93.3 %	14 / 15	63.3 %	19 / 30
include/auxkernels	89.7 %	26 / 29	46.6 %	27 / 58
include/auxkernels/tensor_mechanics	100.0 %	1 / 1	50.0 %	1 / 2
include/base	100.0 %	2 / 2	-	0 / 0
include/bcs	69.2 %	9 / 13	36.4 %	8 / 22
include/bcs/coolant	100.0 %	4 / 4	50.0 %	1 / 2
include/functions	61.0 %	111 / 182	78.6 %	11 / 14
include/ics	100.0 %	1 / 1	100.0 %	2 / 2
include/kernels	80.0 %	12 / 15	43.3 %	13 / 30
include/materials	78.6 %	121 / 154	58.2 %	96 / 165
include/materials/tensor_mechanics	92.9 %	39 / 42	56.8 %	21 / 37
include/postprocessors	100.0 %	19 / 19	60.6 %	20 / 33
include/userobject	91.7 %	11 / 12	82.4 %	14 / 17
src	92.3 %	12 / 13	100.0 %	3 / 3
src/actions	85.4 %	634 / 742	97.3 %	72 / 74

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ELSEVIER

Verification of the BISON fuel performance code

CrossMark

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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

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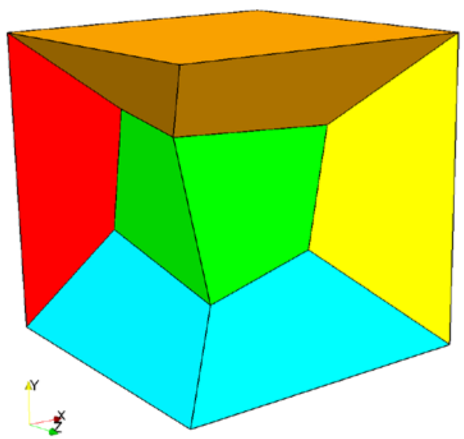
Two Verification Examples

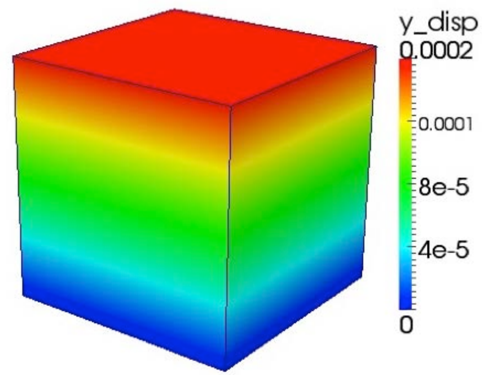
3D FEM Patch Test



Outer nodes displaced:
$u_x = 1\times10^{-6}$, $u_y = 2\times10^{-6}$, $u_z = 3\times10^{-6}$
Outer faces sheared:
1×10^{-6}, 2×10^{-6}, 3×10^{-6} for xy, yz, zx

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

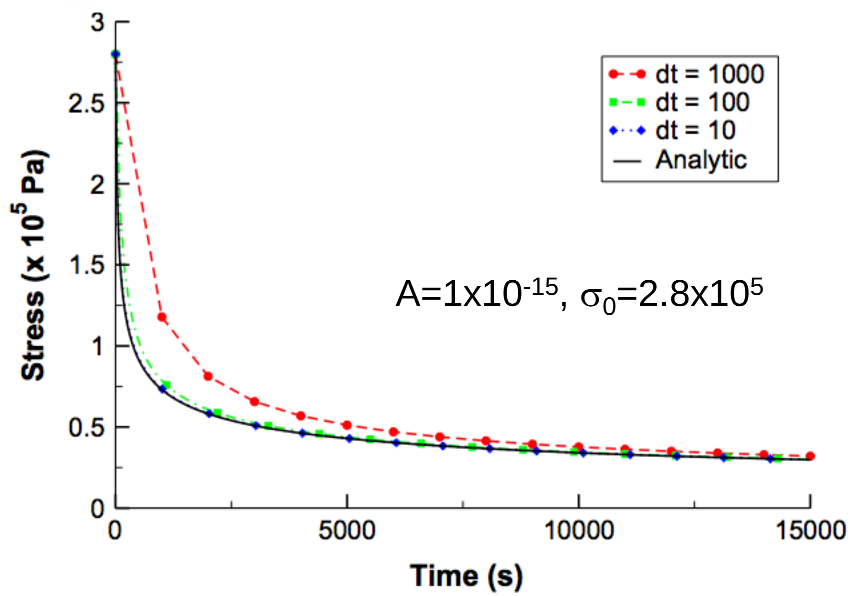
Power Law Creep



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

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

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



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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ELSEVIER

Validating the BISON fuel performance code to integral LWR experiments

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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.

BISON Training

- **A BISON workshop is held on demand, about twice each year**
- **No fee**
- **Topics include:**
  - Getting started
  - Thermomechanics
  - Mesh generation
  - Postprocessing
  - Adding new materials
  - Adding new tests
- **The workshop materials are available at https://bison.inl.gov**

Computing Requirements

- BISON runs on one processor on a laptop
- BISON runs on hundreds of processors on a cluster

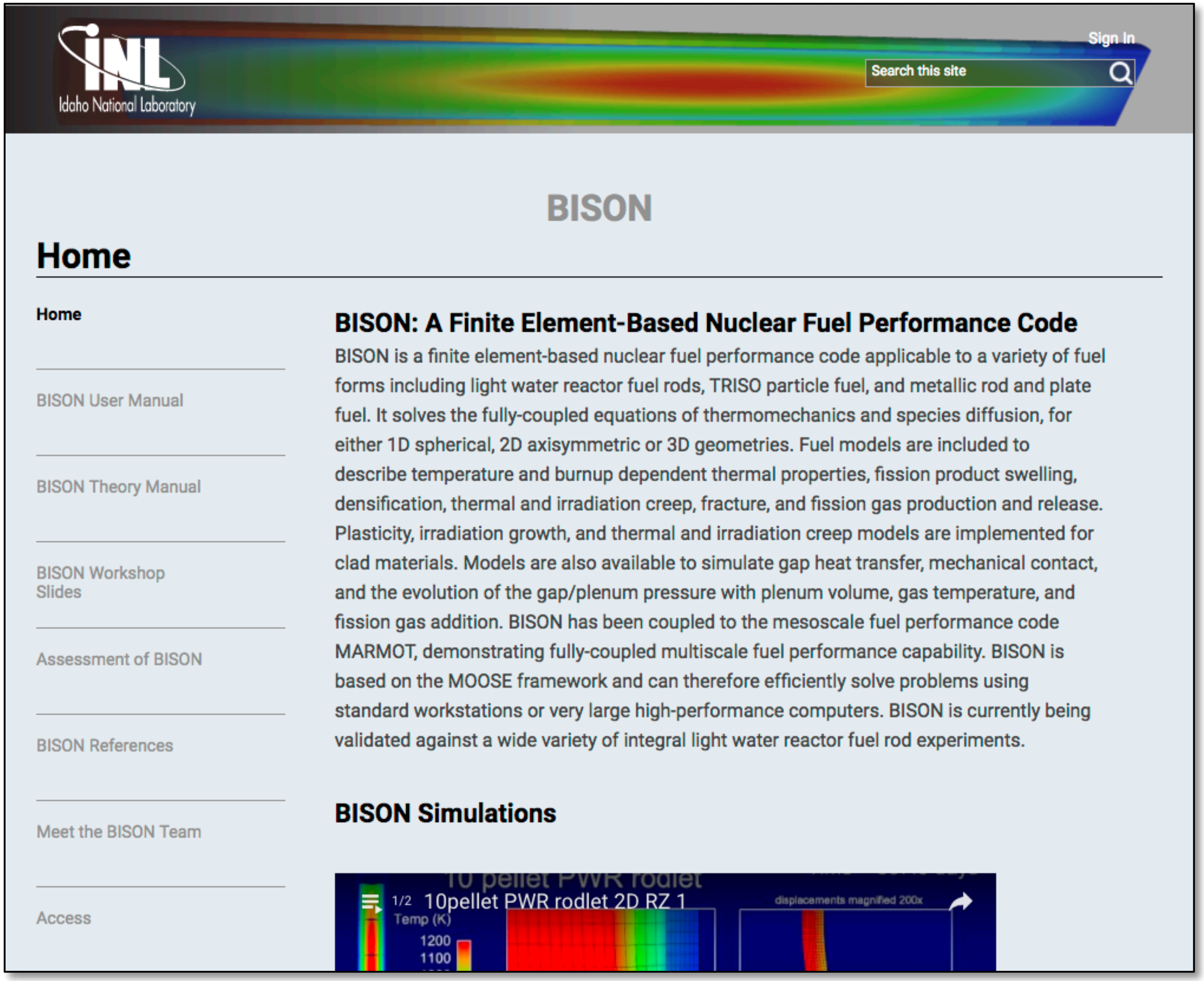
MacBook Pro

Falcon Supercomputer at INL

Getting BISON

- BISON is export controlled
- BISON requires a license
- The license is no fee
- Instructions to start the license process are at https://bison.inl.gov
- Or, contact me, jason.hales@inl.gov

More Information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BISON Theory Manual

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Assessment of BISON

BISON References

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Access

BISON: A Finite Element-Based Nuclear Fuel Performance Code

BISON is a finite element-based nuclear fuel performance code applicable to a variety of fuel forms including light water reactor fuel rods, TRISO particle fuel, and metallic rod and plate fuel. It solves the fully-coupled equations of thermomechanics and species diffusion, for either 1D spherical, 2D axisymmetric or 3D geometries. Fuel models are included to describe temperature and burnup dependent thermal properties, fission product swelling, densification, thermal and irradiation creep, fracture, and fission gas production and release. Plasticity, irradiation growth, and thermal and irradiation creep models are implemented for clad materials. Models are also available to simulate gap heat transfer, mechanical contact, and the evolution of the gap/plenum pressure with plenum volume, gas temperature, and fission gas addition. BISON has been coupled to the mesoscale fuel performance code MARMOT, demonstrating fully-coupled multiscale fuel performance capability. BISON is based on the MOOSE framework and can therefore efficiently solve problems using standard workstations or very large high-performance computers. BISON is currently being validated against a wide variety of integral light water reactor fuel rod experiments.

BISON Simulations

- https://bison.inl.gov
- jason.hales@inl.gov