INL/CON-22-66042-Revision-0

Bison Analyses of Fuel Forms used in Small Modular Reactors

May 2024

Changing the World's Energy Future

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15th International Conference on CANDU Fuel

Idaho National Laboratory

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Overview

- Introduction
- TRISO Fuel Capabilities
  - Failure modes
  - Failure analysis
  - Fission product diffusion in a pebble
- Metallic Fuel Capabilities
  - TREAT transients
  - X430 assessment
- Summary

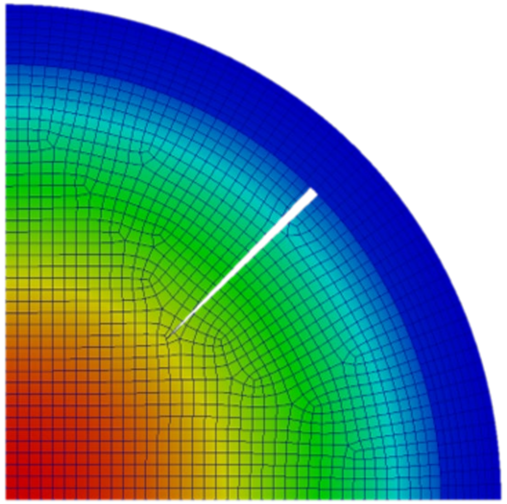
Small Modular Reactor (SMR) Overview

- Designed for small scale electrical generation, flexible operation, and remote usage
- Many companies are pursuing their own designs using a wide variety of fuel concepts including light-water reactor, tri-structural isotropic (TRISO), and metallic fuels
- In the United States, since 2018 the U.S. Department of Energy has enabled research in advanced SMRs through funding opportunity announcements (FOAs)
- This talk focuses on capabilities of the BISON fuel performance code to simulation TRISO and metallic fuel concepts.

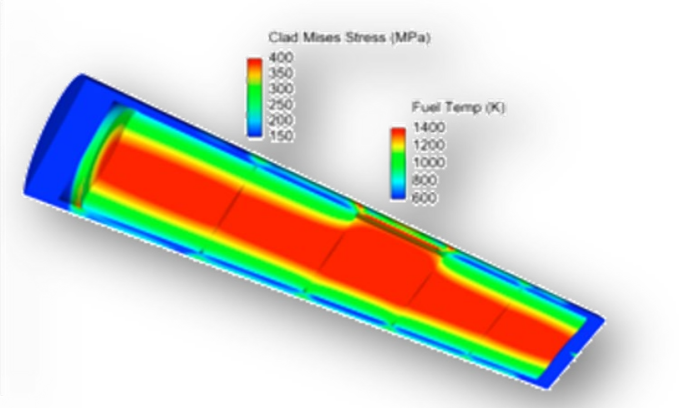
The BISON Fuel Performance Code

- Finite element-based engineering scale fuel performance code built on MOOSE
- Solves the fully coupled thermo-mechanics and species diffusion equations in 1D, 1.5D, 2D axisymmetric or plane-strain, 2.5D, or full 3D
- Applicable to both steady and transient operation including LOCA and RIA accidents
- Used for LWR, ATF, TRISO, and metallic fuels
- Readily coupled to lower length scale material models
- Designed for efficient use on parallel computers
- Fully coupled implicit analysis
- Constantly evolving

2D axisymmetric (or 1.5D)

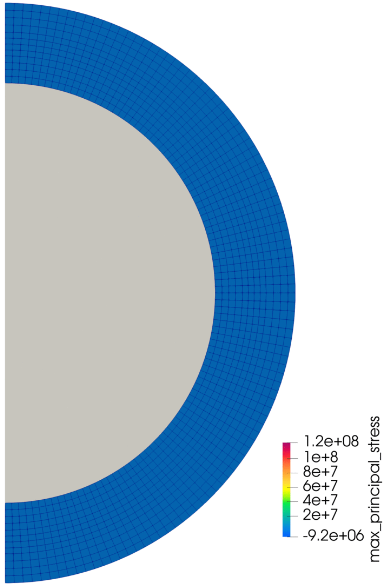


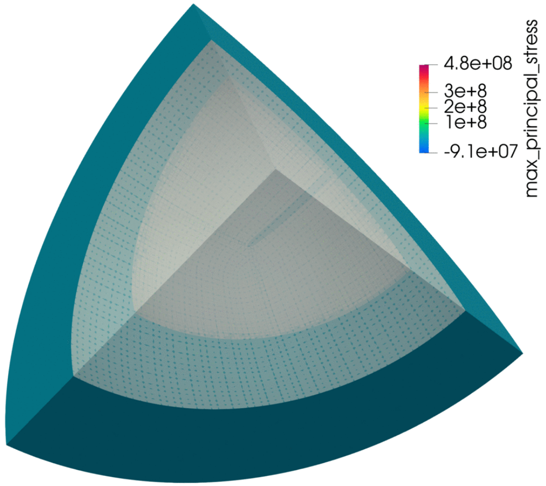
2D (or 2.5D) plane strain



BISON TRISO Fuel Capabilities

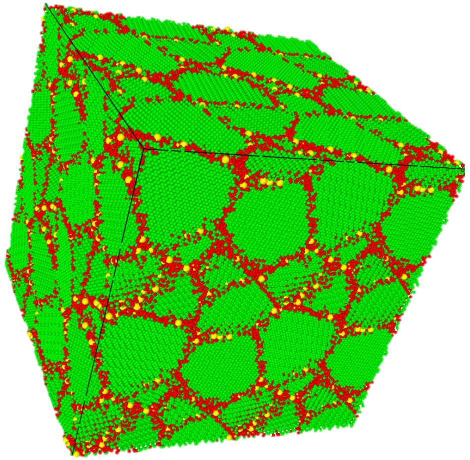
- TRISO Fuel Behavior
  - Kernel: volumetric swelling, burnup, thermal expansion, fission gas release
    - Fuel type: UCO, UO_2, and UN
  - Buffer and PyC: thermal expansion, irradiation-induced dimensional change (IIDC), and irradiation creep
  - SiC: elasticity and thermal expansion
  - Fission product transport/release
- Compact/Pebble Behavior
  - Graphite thermo-mechanical behaviors
  - Fission product transport through matrix

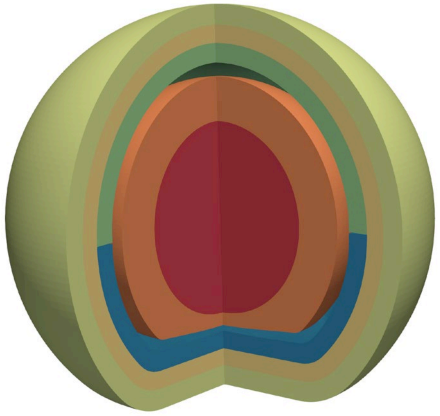


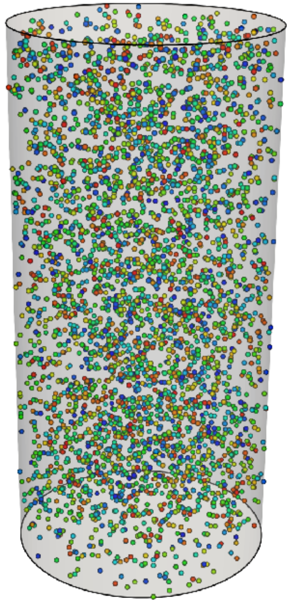


- TRISO Failure Modes
  - Pressure vessel failure (including asphericity)
  - Irradiation-induced PyC Cracking
  - Debonding
  - Kernel migration
  - Palladium penetration
  - SiC thinning
- TRISO Statistical Failure Analysis
  - Monte Carlo
  - Direct integration
  - Variance-reduction (importance sampling, subset simulation, etc.)

Multi-scale TRISO Modeling Overview







Lower-length scale modeling

- **Fission gas release model**
  Xe, Kr diffusivity in UCO
- **Fission product diffusivity**
  Silver diffusion in SiC, Pd Penetration

TRISO particle

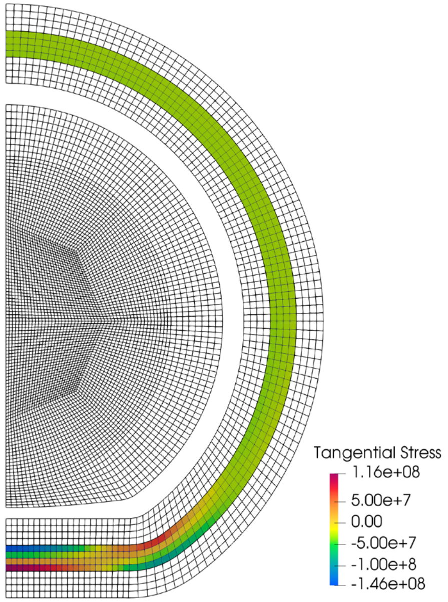
- **Thermal-mechanical modeling**
  - **Failure analysis:** asphericity, IPyC cracking, and debonding
- **Fission product diffusion through layers**

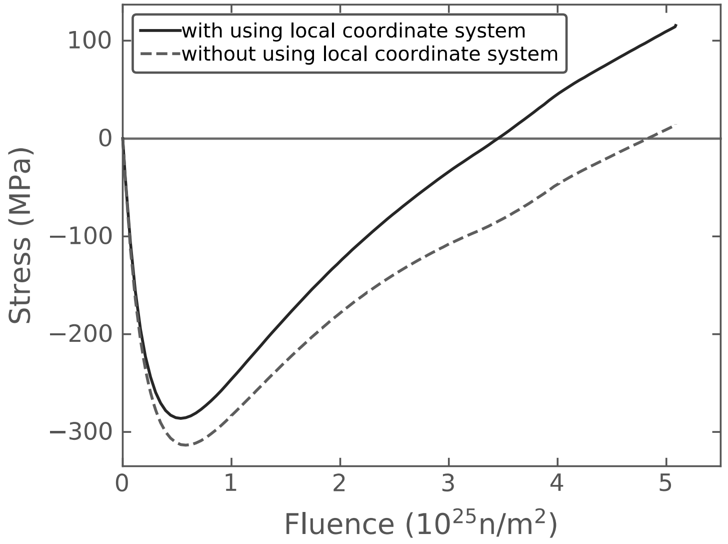
Pebble and compact modeling

- **Failure probability calculation**
  Monte Carlo and Fast Integration Approach
- **Fission product diffusion through matrix**
- **Particle-matrix interaction**

2D Axisymmetric Aspherical Particle

- Computing the stress in aspherical particles is highly dependent upon the coordinate system that is used
  - A local coordinate system is used to properly account for the anisotropic nature of the materials
  - The local coordinate system predicts failure at an earlier fluence

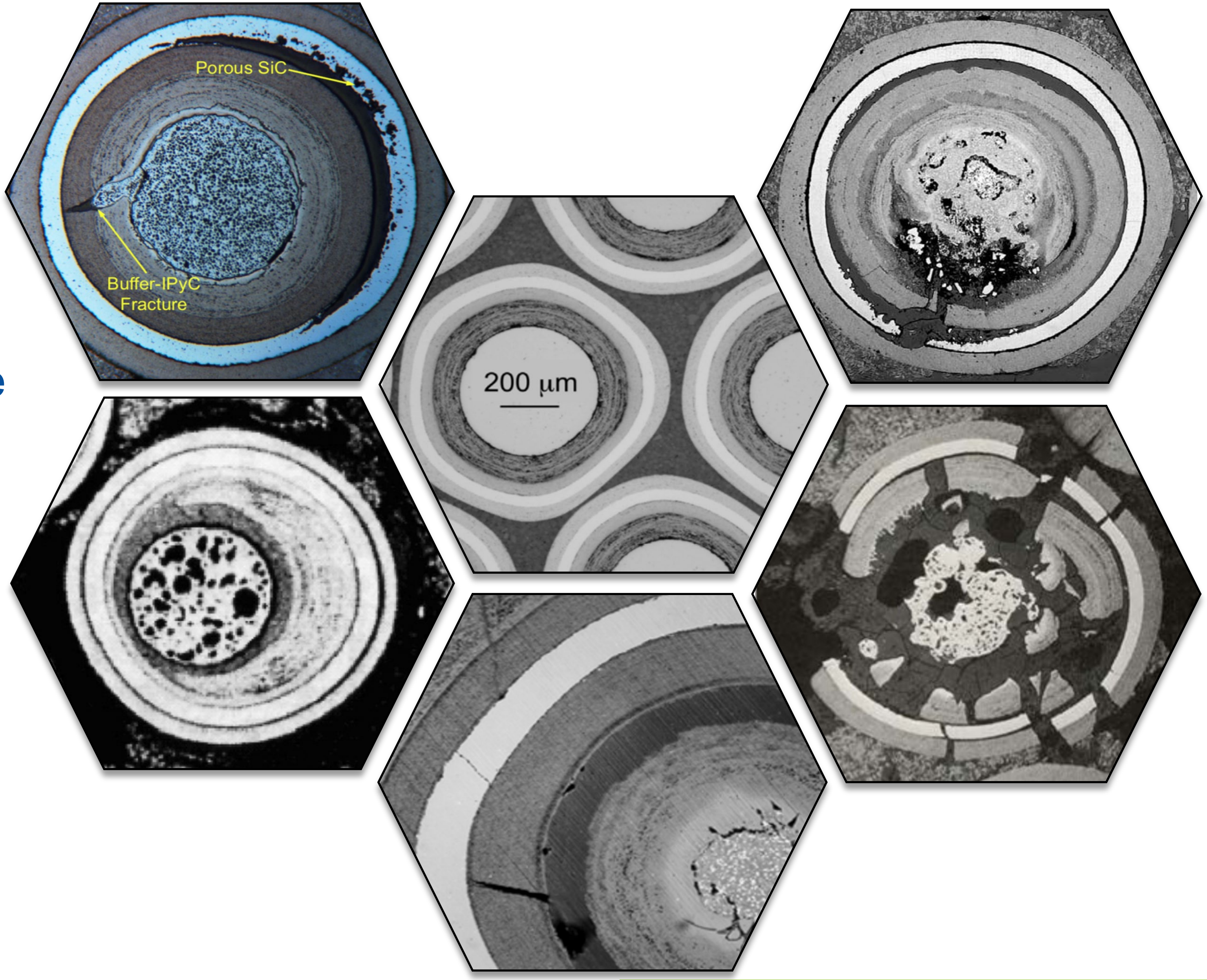




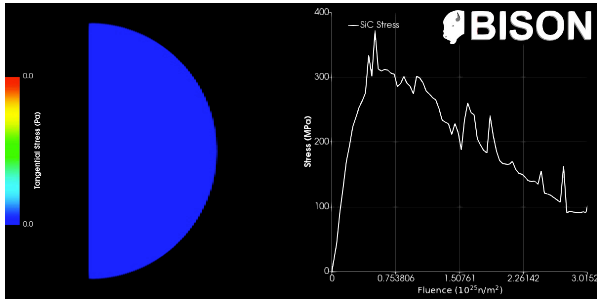
TRISO Failure Modes

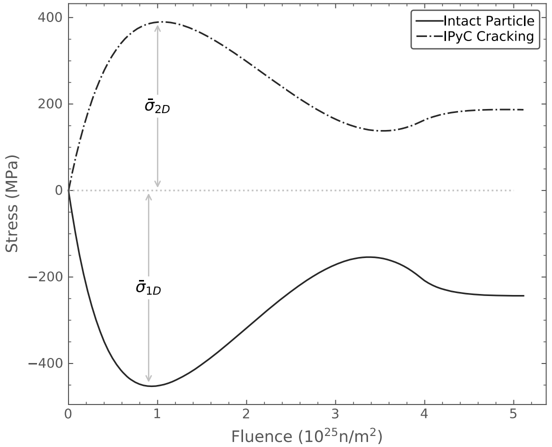
- **Mechanical**
  - Pressure vessel failure
  - Irradiation-induced PyC failure leading to SiC cracking
  - IPyC-SiC / Buffer-IPyC partial debonding

- **Thermochemical**
  - Kernel migration
  - SiC thermal decomposition
  - Fission product attack of SiC
  - Corrosion of SiC by CO

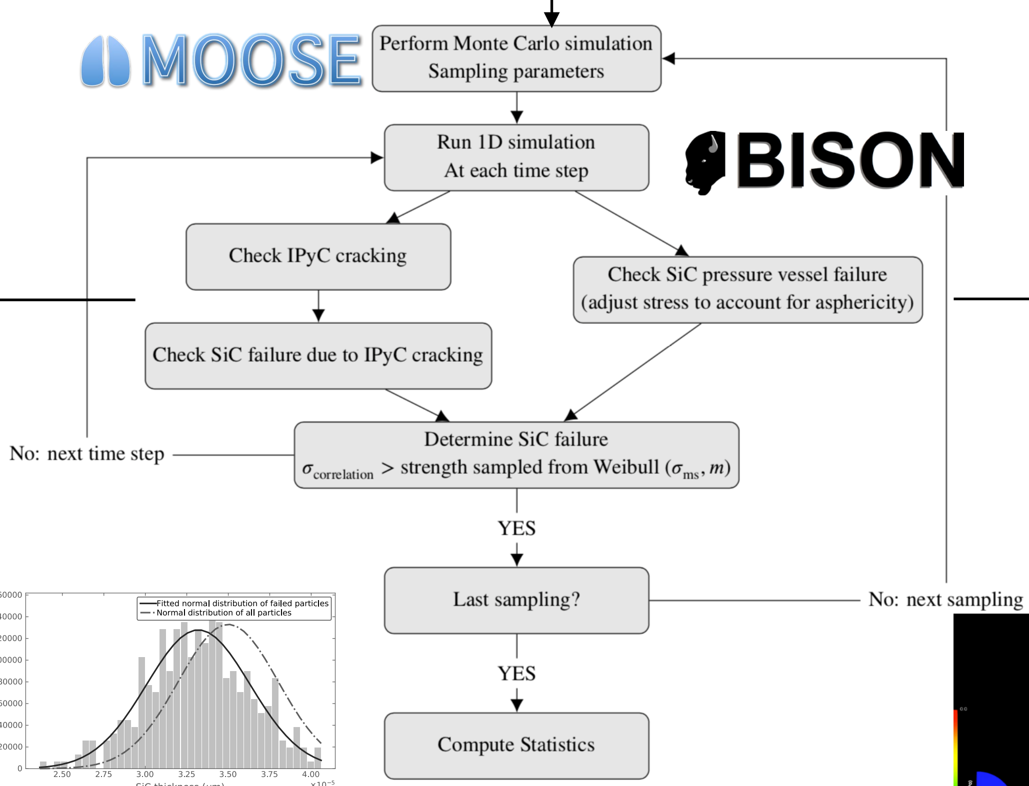


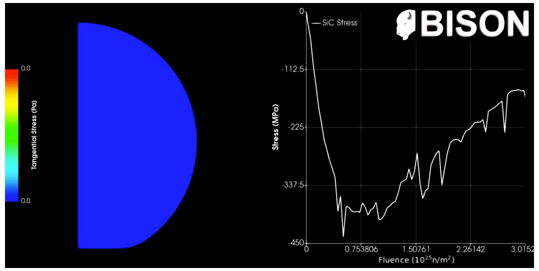
BISON Example: TRISO Failure Analysis

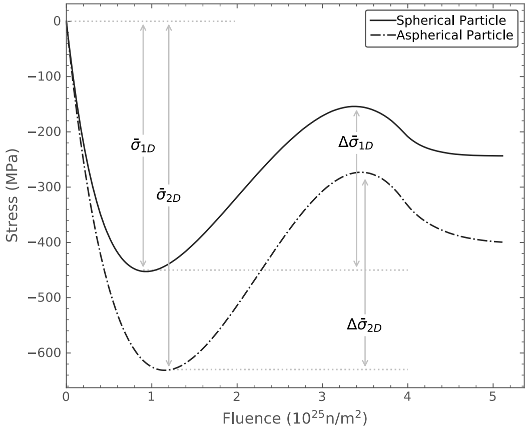


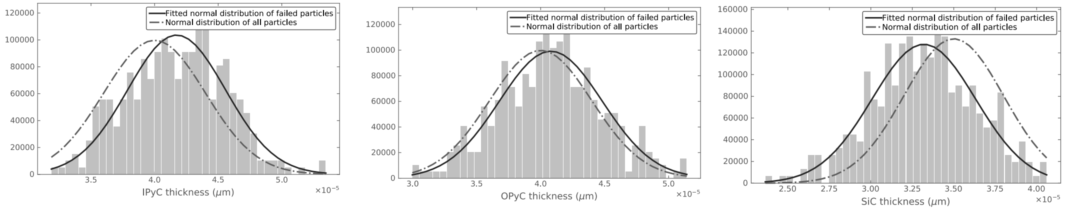


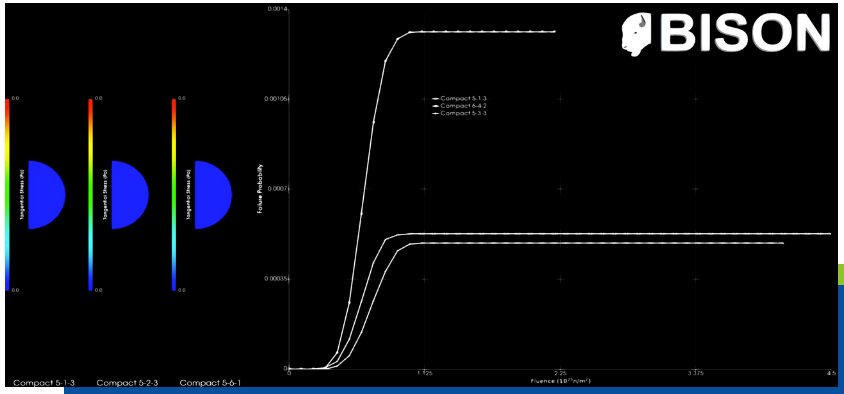
Category	Parameter	Nominal values ± Standard Deviation
Particle geometry	Kernel diameter (μm)	425±10
	Buffer thickness (μm)	100±10
	IPyC/OPyC thickness (μm)	40±3
	SiC thickness (μm)	35±2
	Particle asphericity (SiC aspect ratio)	1.04
Fuel properties	IPyC density (g/cm^3)	1.90±0.02
	OPyC density (g/cm^3)	1.90±0.02
	IPyC/OPyC BAF	1.05±0.005





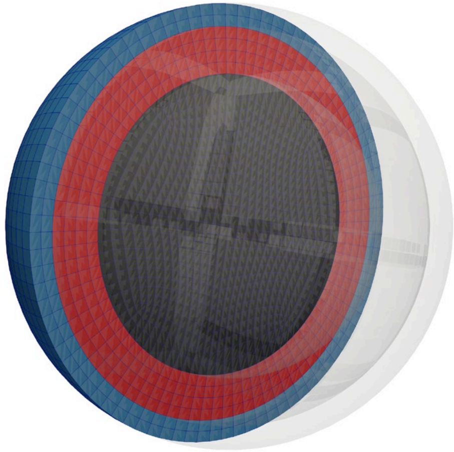


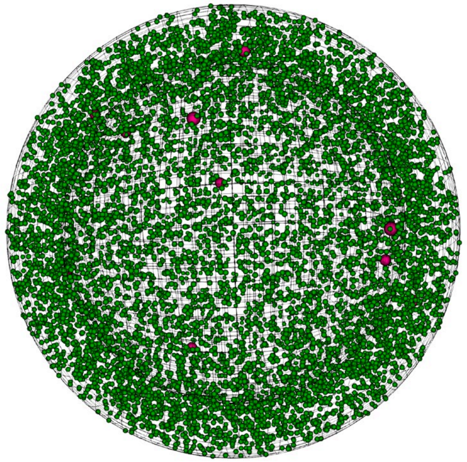


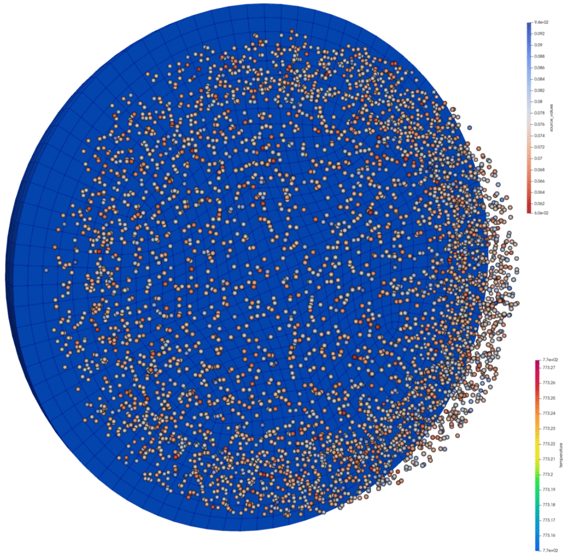


BISON Example: Fission Product Diffusion in Pebble

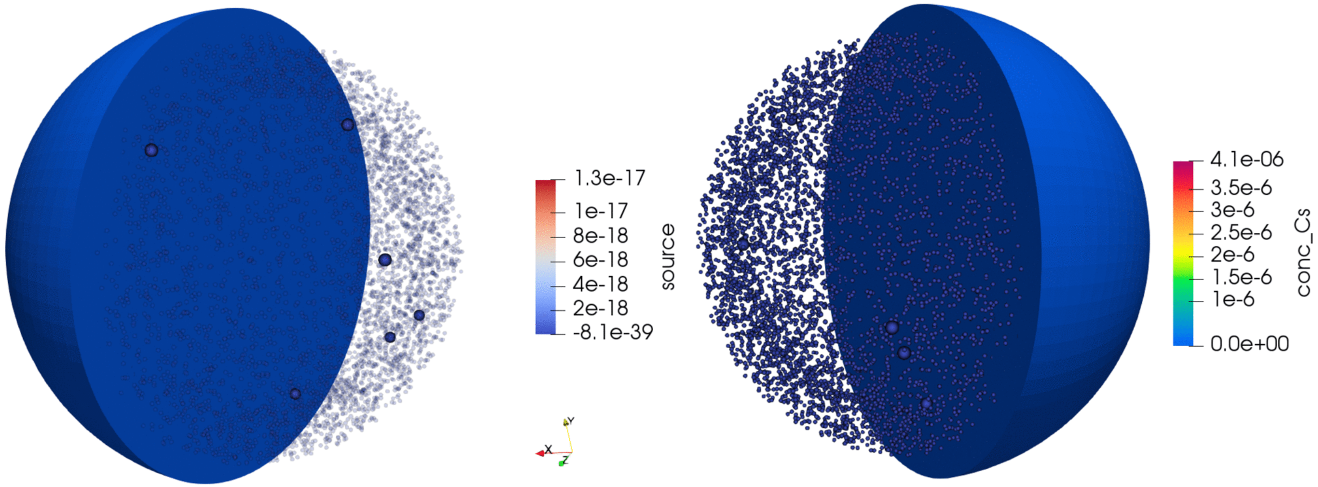
RADIUS (CM)	2.000
SHELL LAYER THICKNESS (CM)	0.200
FUEL LAYER THICKNESS (CM)	0.420
(AGR-5/6/7) TRISOS	9022
U-235 ENRICHMENT (% WT)	19.55



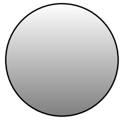




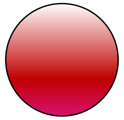
Heat point source



Cs point source



9012 intact particles



10 failed particles

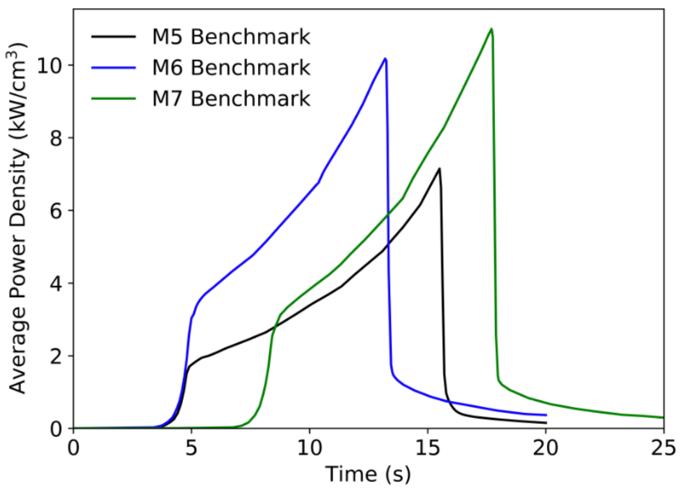
BISON Metallic Fuel Capabilities

- Metallic fuel behavior
  - Temperature/species dependent thermo-mechanical properties
  - Anisotropic irradiation swelling
  - Thermal and irradiation creep
  - Fission gas release (porosity based)
  - Zr diffusion
  - Hot pressing pore collapse
- Sodium-filled gap with minimum thickness

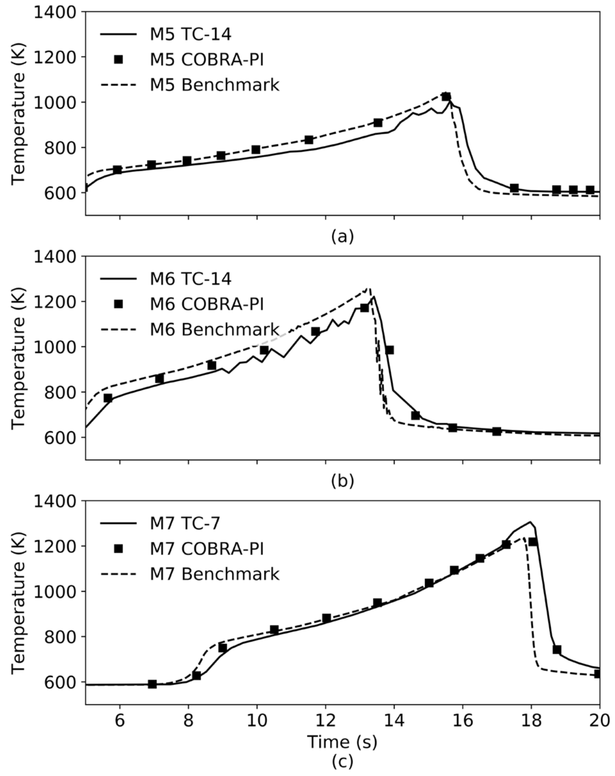
- Cladding behavior (HT9, D9, and 316 stainless steel)
  - Temperature dependent thermo-mechanical properties
  - Thermal and irradiation creep
  - Irradiation swelling
  - Failure and wastage correlations
- Sodium coolant channel
  - Fluid properties
  - Triangular subchannel
  - Single pin subchannel

TREAT Transient Benchmarks

- Reactivity insertion transients on both binary and ternary metallic fuels
- Different peak power densities and durations of the transients
- Comparisons between COBRA an thermocouples are reasonable



Power densities



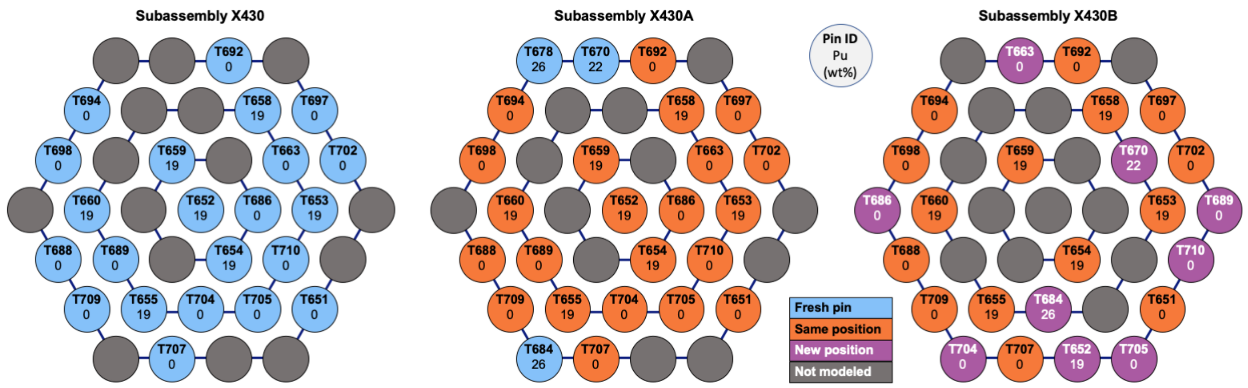
Coolant temperatures

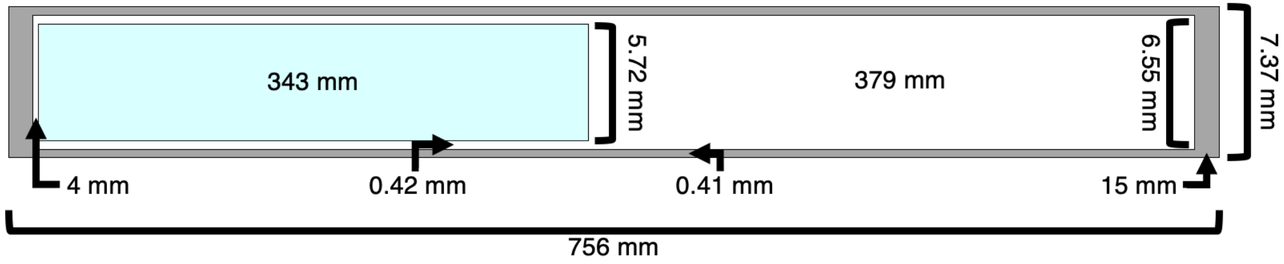
Characteristics of the TREAT transient benchmarks

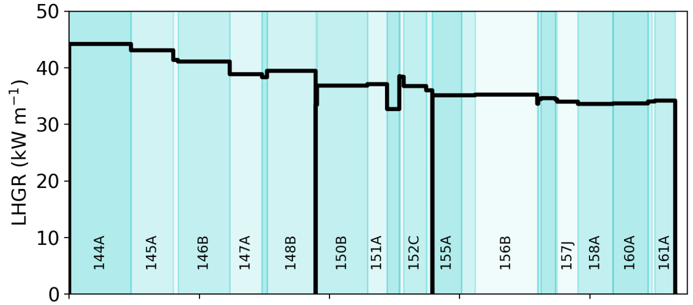
Characteristic	M5	M6	M7
Fuel type	U-19Pu-10Zr	U-19Pu-10Zr	U-10Zr
Cladding	D9	D9	HT9
Coolant channel	Annular tube	Annular tube	Annular tube
Peak burnup (at. %)	0.8	1.9	2.9
Slug radius (mm)	2.54	2.54	2.54
Gap width (mm)	0	0	0
Cladding thickness (mm)	0.38	0.38	0.38
Plenum height (cm)	24.4	25.24	25.24
Porosity	0.27	0.27	0.31
Bond sodium thermal conductivity (W/m-K)	73.7	73.7	73.7
Coolant	Sodium	Sodium	Sodium
Inlet temperature (K)	573	583	586
Inlet pressure (kPa)	413.7	413.7	455.1
Inlet mass flow rate (kg/m^2-s)	3761	3761	4521
Flow area (cm^2)	0.222	0.222	0.222
Hydraulic diameter (mm)	2.057	2.057	2.057
Heated perimeter (mm)	18.35	18.35	18.35
Heated diameter (mm)	4.84	4.84	4.84

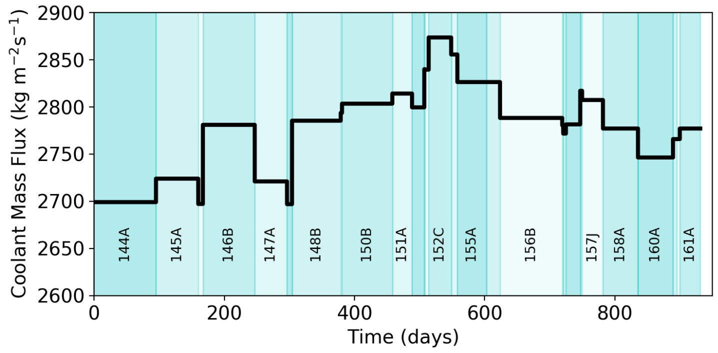
BISON Example: Metallic Fuel X430 Assessment

- EBR-II Experiment X430
  - 25 pins simulated (varying Pu)
  - Wide diameter in HT9 cladding
  - Varying power and coolant





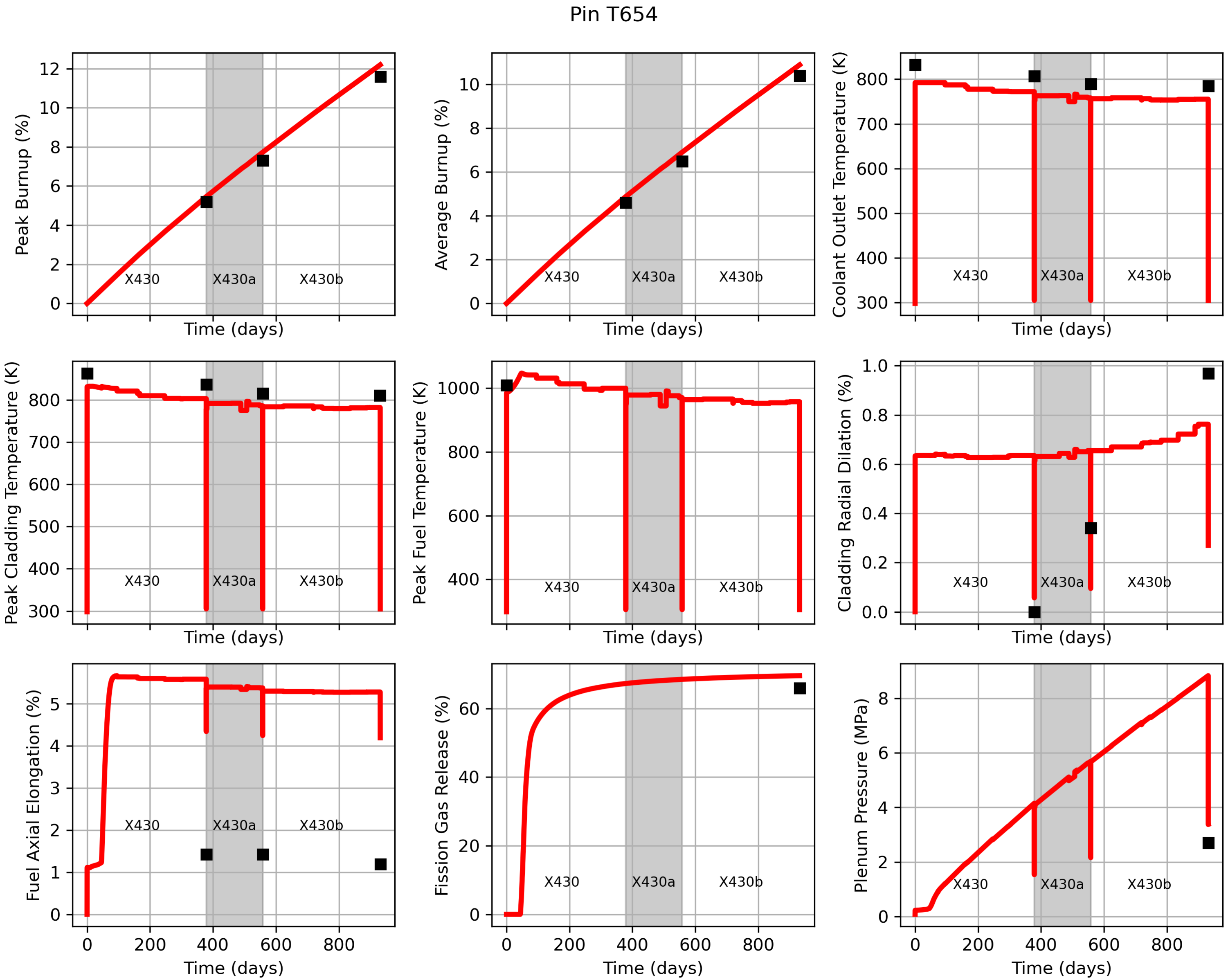




- 10 at% peak burnup
- Legacy calculations and PIE data available for comparison

* Special thanks to Ian Greenquist @ ORNL

BISON Example: Metallic Fuel X430 Assessment



- Good agreement of BISON (red) to legacy (black)
- Identified areas of improvement
  - Fuel axial elongation
  - Cladding radial dilation
  - Coolant and cladding temperature under-estimated
- Development continues in metallic fuel capabilities

Summary

- BISON is fuel performance code capable of simulating a wide variety of fuel forms using many different geometric representations
- Studies illustrating of some of the capabilities for TRISO and metallic fuel modeling were provided
  - Individual TRISO particle behavior
  - TRISO failure modes
  - TRISO pebble involving thousands of TRISO particles
  - RIA transients in metallic fuel
  - Where available, comparisons to experiments are reasonable, and areas of further development have been identified

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