GAS-COOLED REACTOR
ADVANCED REACTOR TECHNOLOGIES PROGRAM

July 18, 2024

Enabling targeted TRISO transient analyses using the Transient Reactor Test Facility

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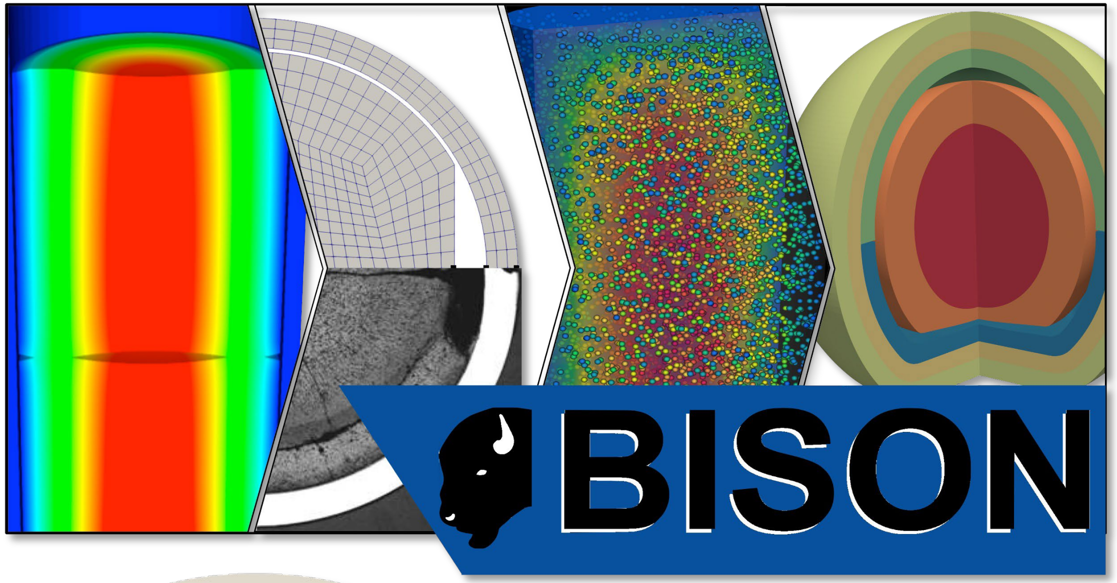
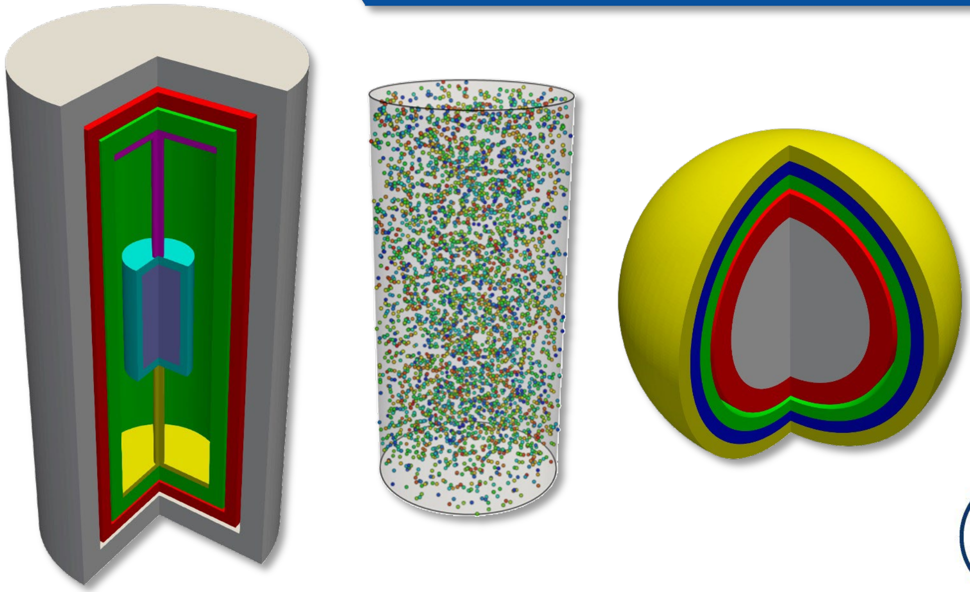
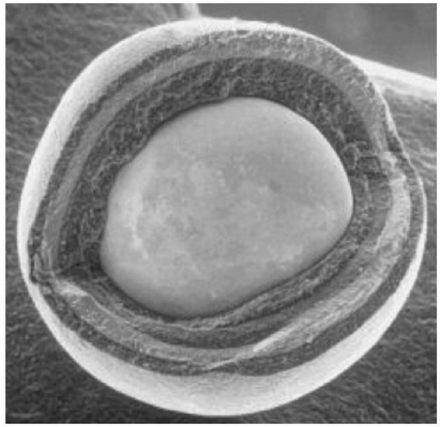
ART GCR Annual Program Review
Program Review Meeting
July 16-18, 2024

Outline

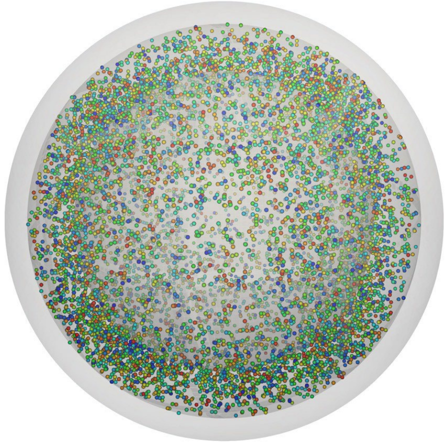
- Background
- TRISO transient gap analysis
- Reference transient
- TREAT transients
- Conclusions and future work



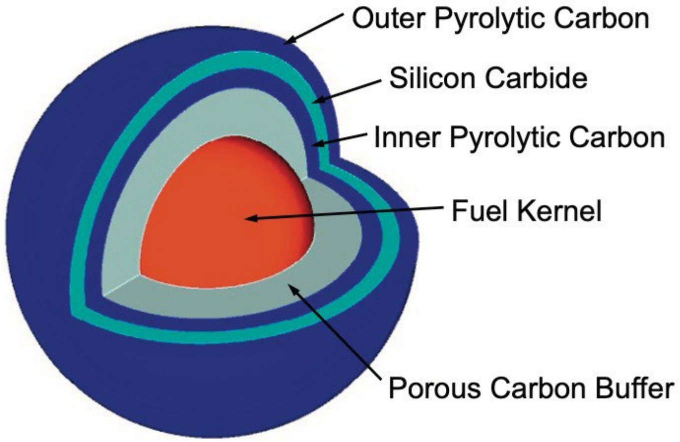




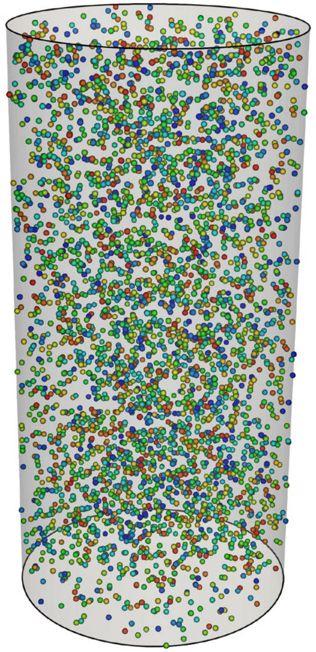
Anatomy of TRISO fuel forms

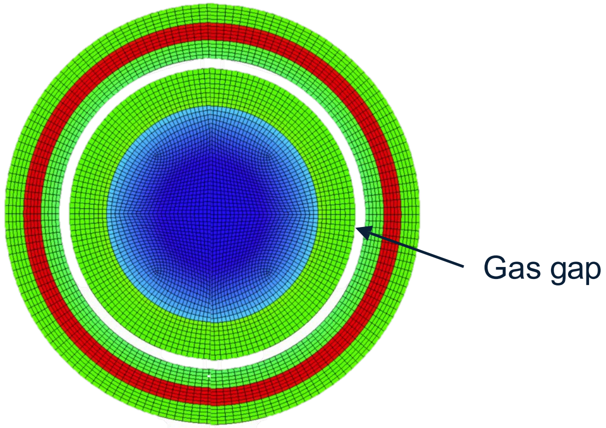


Tri-structural isotropic (TRISO) fuel forms consist of multi-layer, encapsulated fuel particles arranged within graphite, SiC, or other carbonaceous matrices into pebbles or compacts



Layer	Material	General Purpose(s)
Fuel kernel	UCO or UO_2	• Produces heat (and fission products)
Buffer	Low density carbon	• Accommodates mechanical deformation of neighboring layers • Provides free volume to accommodate fission gas release
Inner pyrolytic carbon (IPyC)	High density carbon	• Supports the silicon carbide • Contributes to retention of non-metallic fission products
Silicon carbide (SiC)	SiC	• Acts as primary pressure vessel • Contributes to retention of metallic fission products
Outer pyrolytic carbon (OPyC)	High density carbon	• Similar to the IPyC • Protects the SiC during the overcoating and compaction





J. Hales, et al., Journal of Nuclear Materials 443 (2013) 531-543.

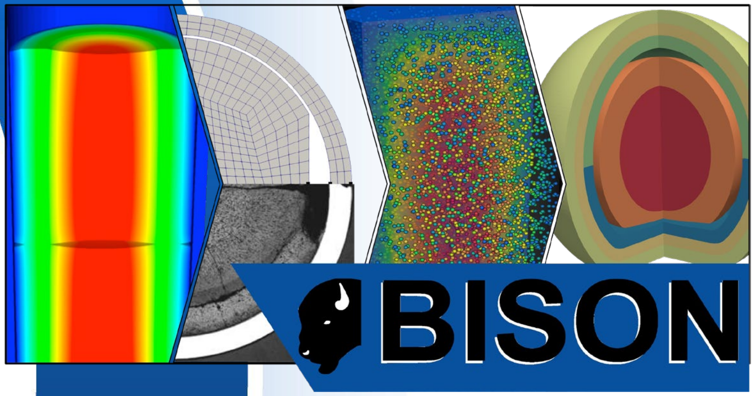
The goals for modeling TRISO fuel performance

- NRC provides guidance for nuclear power plants in 10 CFR Part 50 (primarily for monolithic LWR technology)
- Additional guidance SMRs and non-LWRs is given in NUREG-0800, NUREG-2246, and other topical reports

Specification	General Purpose(s)
Functional requirements	Maintain geometry, cooling, containment, and reloading capabilities
Operational requirements	Dictate power level, duty cycle, and requirements for performance during normal and off-normal operation (qualitative)
Fuel design criteria	Establish reactor- and fuel-specific specifications to ensure the above are met (quantitative)

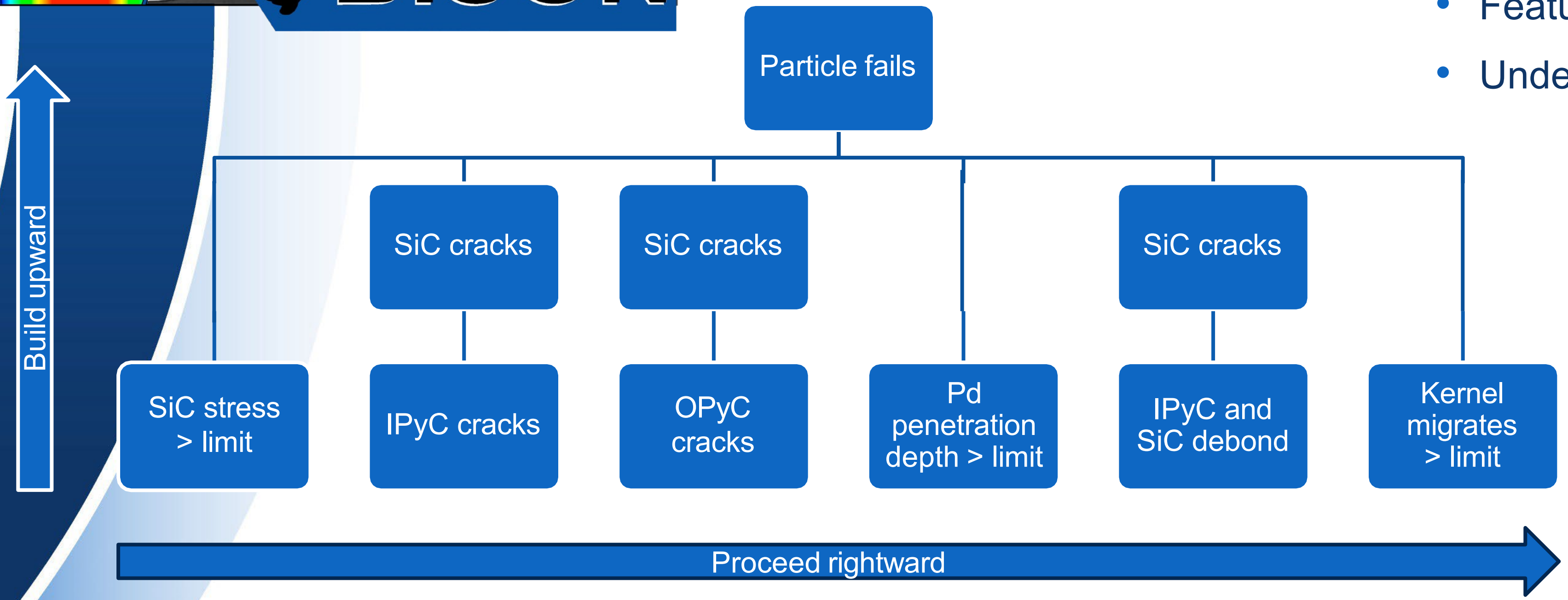
- General underlying goals include
  - Providing reactivity control
  - Maintaining cooling
  - Providing for fuel handling and storage
  - Enforcing quality standards
  - Recordkeeping
  - Containing radioactive nuclides
- Both intact and failed particles release fission products
- We need to calculate
  - The radioactivity released from each
  - The probability of particle failure

BISON failure mode evaluations and decision making



BISON is a finite element-based nuclear fuel performance code based on the MOOSE Framework

- Free to use
- Attracts diverse users
- Used for engineering & research
- Inherently considers multiphysics
- Can couple to multiscale codes
- Scales from laptops to clusters
- Features a flexible, modular design
- Under continuous development



Failure predictions must account for relevant thermomechanical, thermochemical, and irradiation physics active during normal operation and transient conditions

History of particle fuel transient analysis

Test reactor irradiations to support use cases for specific fuel and reactor designs

Modeling studies conducted to predict the transient performance of specific fuel designs and reactor types

1970	1980	1990	2000	2010	2020 //	2021	2022	2023	2024

In-pile and out-of-pile testing to characterize the steady-state performance, transient responses, and failure modes of various particle fuel designs

Integral transient demonstrations performed in operating HTGRs

Advanced Reactor Demonstration Program enacted to provide support commercial deployment of advanced reactor technologies

Increasing emphasis on development of TRISO fuel performance models

Advanced Gas Reactor Program conducts extensive in-pile steady-state and out-of-pile high-temperature testing for US TRISO design to reduce risk to entry into the domestic HTGR market

Lead Organization	Reactor	Type
Kairos Power	KP-FHR	FHR
Westinghouse	eVinci	Heat pipe
BWX Technologies	BANR	HTGR
X-Energy	Xe-100	HTGR
USNC	MMR	HTGR
Radiant	Kaleidos	HTGR
Holtec International	SMR-160	LWR

Historical transient tests of TRISO particle-based fuels.

Reference	Reactor	Kernel	Type of test	Energy deposition (J/g-fuel)	Pulse Width (ms)	Failure
Fukuda et al. [40]	NSRR	UO_2	Element and loose particle	500–2,300	~5	>1,400 J/g-UO_2 (fuel), >2,300 J/g-UO_2 (matrix)
Umeda et al. [45]	NSRR	UO_2	Loose particle	500–1,700	~5	>1,400 J/g-UO_2
IAEA [46]	HYDRA	UO_2	Element and loose particle	100 - 1,700	1–2	>1,300 J/g-UO_2
IAEA [46]	IGR	UO_2	Element	>10,000	700-30,000	Matrix

Integral engineering demonstration mHTGR DLOFC, PLOFC, and CRW tests. Both HTTR and HTR-10 use UO_2 fuel kernels.

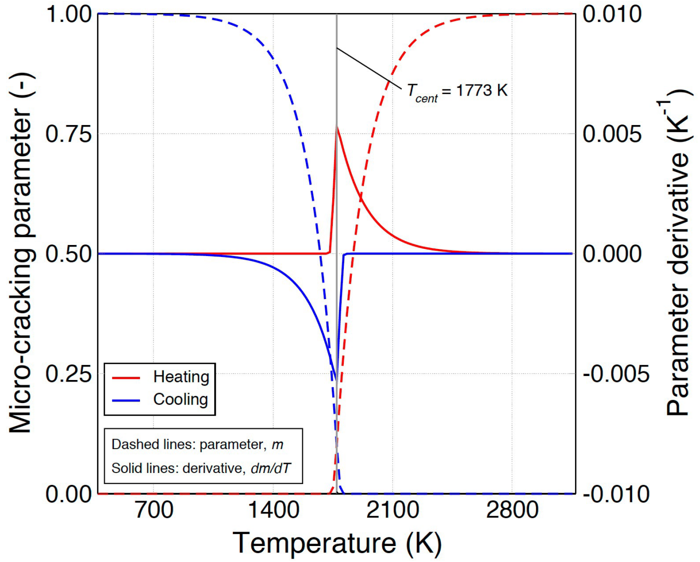
Study	Reactor System	Type of mHTGR	Event	Estimated Fuel Kernel Energy Deposition (J/g-UO_2)
Krüger et al. [50]	AVR	Pebble	DLOFC Test	Not applicable, ~120 h duration.
Hu et al., 2006 [51] and Gou et al., 2018 [52]	HTR-10	Pebble	Partial CRW Test	10-15 (max)
Hu et al., 2006 [53]	HTR-10	Pebble	PLOFC Test	Not applicable, ~2 h duration.
Nakagawa et al., 2004 [54]	HTTR	Prismatic	Partial CRW Test	2-3 (average)

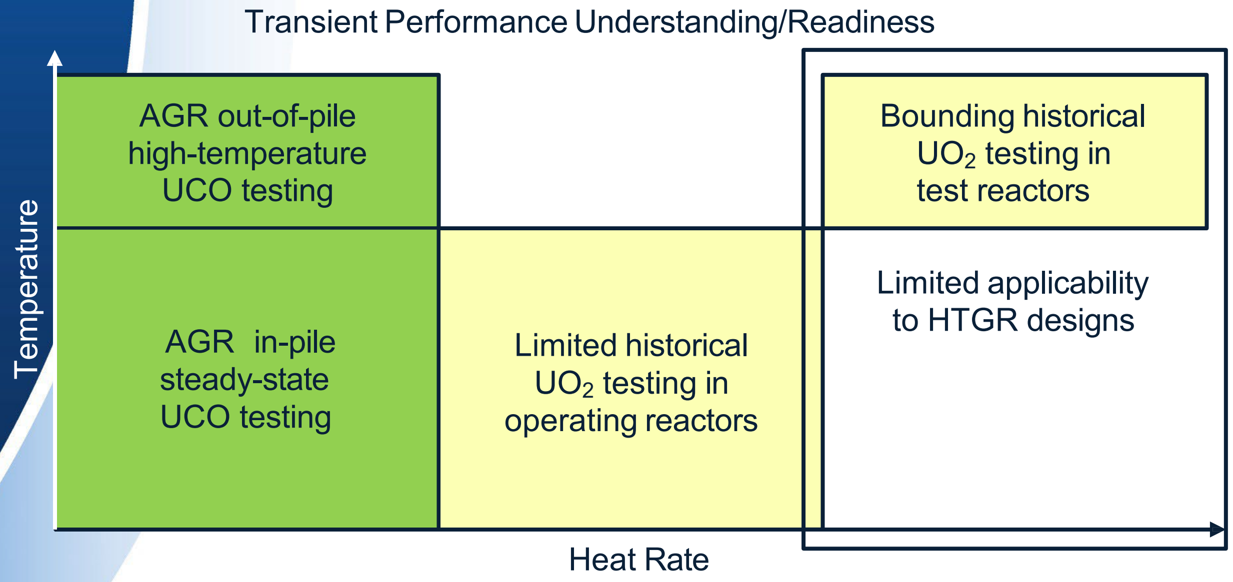
N. Brown, Journal of Nuclear Materials 534 (2020) 152139.

TRISO transient gap analysis

Historical summary

- Early in-pile and out-of-pile testing established the general behavior of various particle fuels
- Subsequent test and operational reactor irradiations improved confidence and confirmed acceptable performance of specific fuels
- Predictive TRISO modeling capabilities were developed to aid in design, deployment, and operation
- AGR demonstrated adequate UCO performance during in-pile steady-state and out-of-pile high-temperature operation





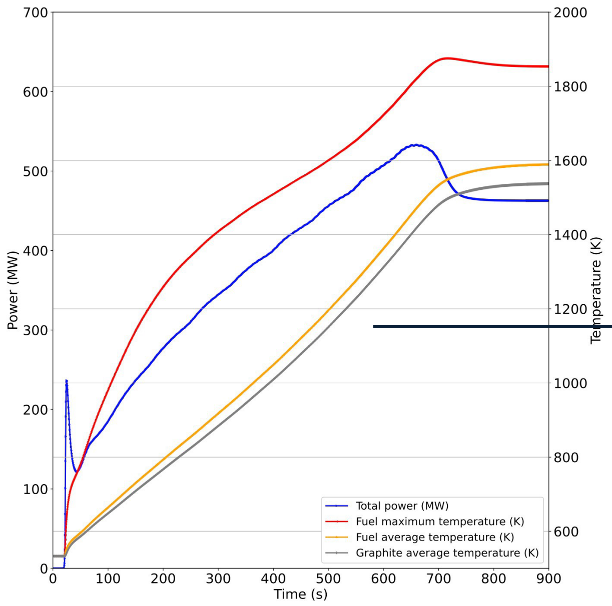
Gap analysis

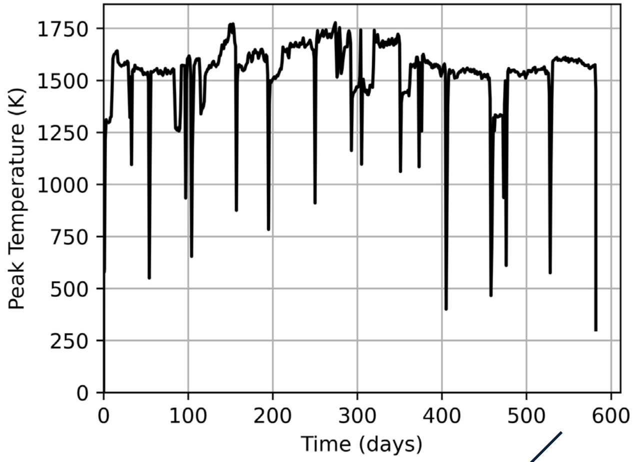
- Historical test reactor experiments with UO_2
  - Lack coverage for moderate heat rates
  - Convolute high temperature and heat rate
- In-pile UCO performance at moderate and high heat rates may be bound by historical UO_2 tests, but has not been observed directly
- Use of UCO in non-HTGRs may require additional targeted testing

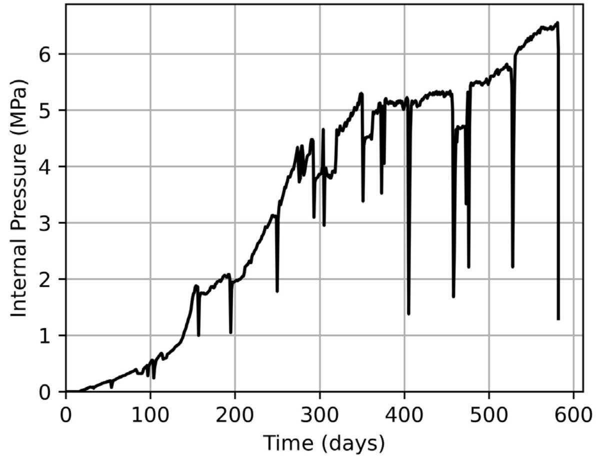
G. Pastore, et al., BISON/UO2Sifgrs (2014).

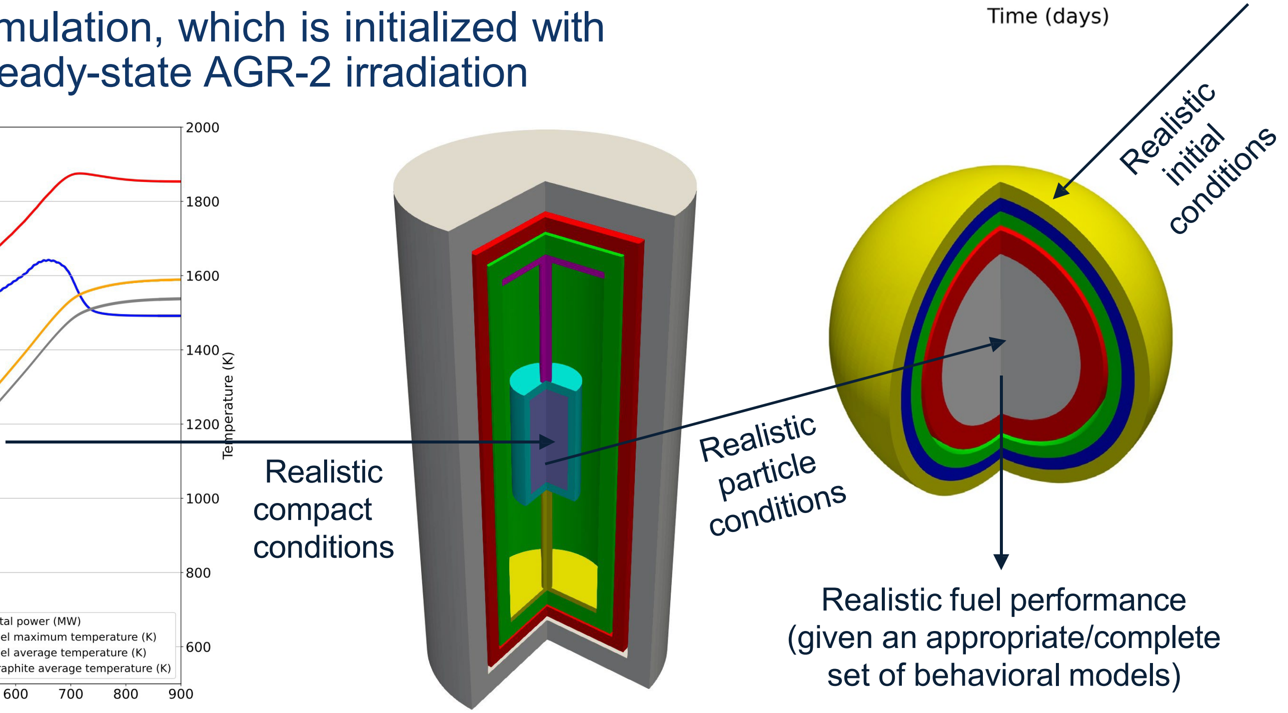
Reference transient setup and BISON model

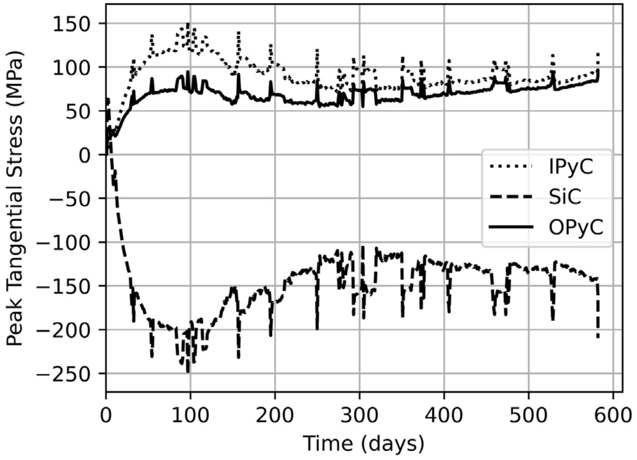
- A limiting reference transient was selected from a recent analysis of a prototypic pebble bed reactor
  - Control rod withdraw from cold-zero power
  - Defines realistic temperatures and heat rates
- A Transient Reactor Test (TREAT) Facility capsule recently applied for NTP analyses was modified to accommodate AGR-2 compacts
- The compact-scale transient simulation drives a particle-scale simulation, which is initialized with data from the steady-state AGR-2 irradiation





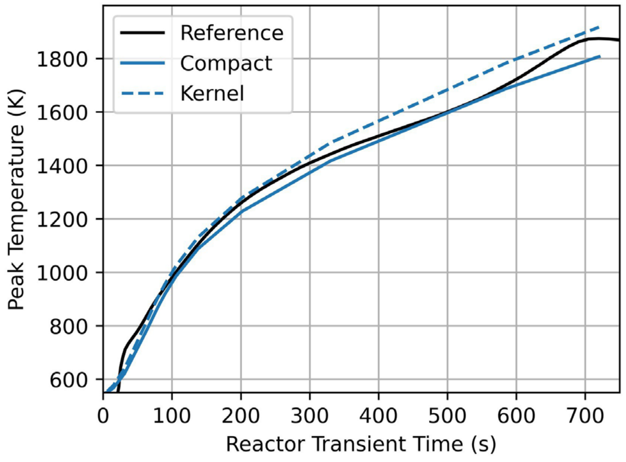


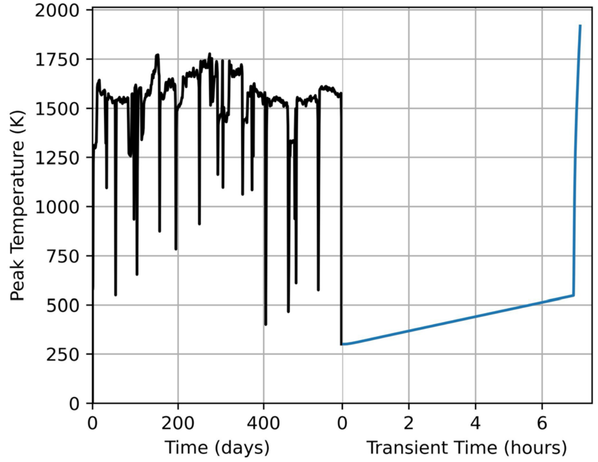


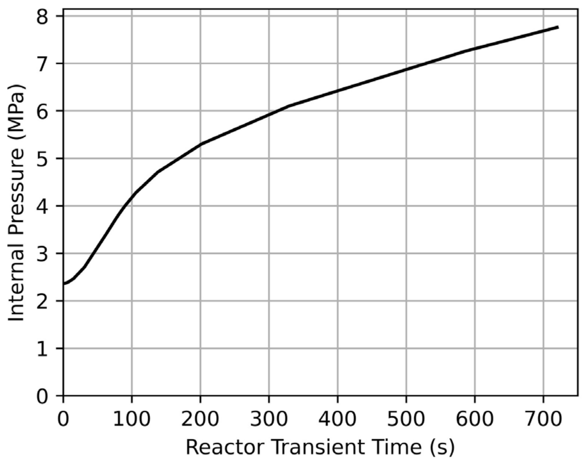


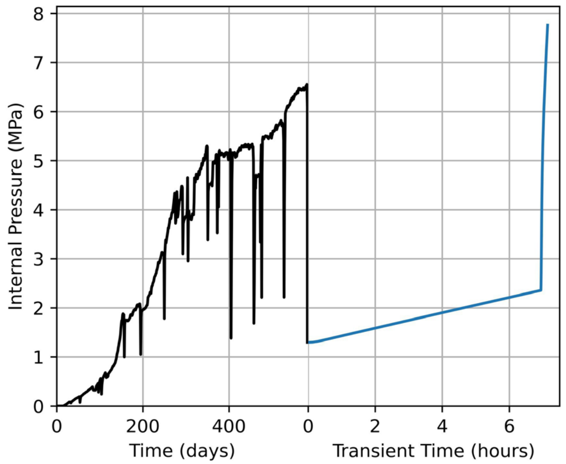
V. Laboure, et al., INL/RPT-23-74341 (2023) 1-27.

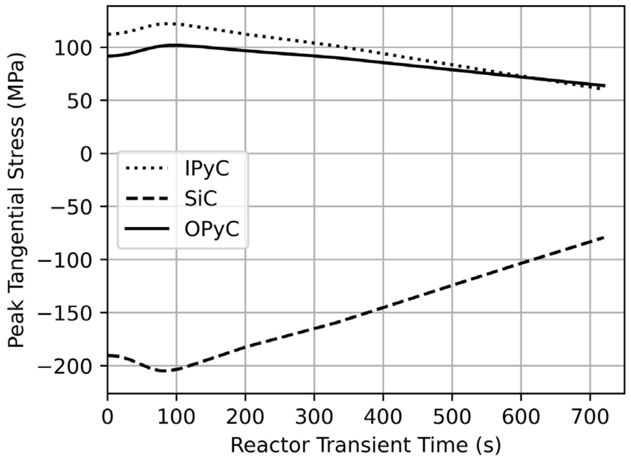
Reference transient fuel performance results

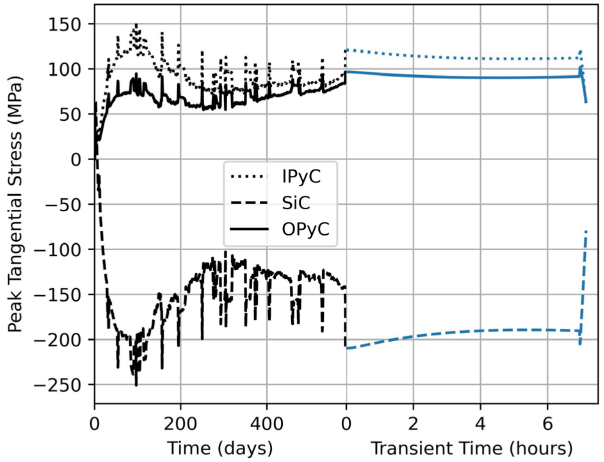






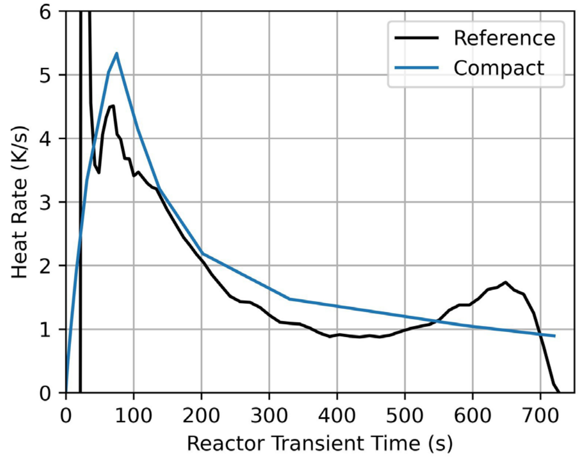






Using steady-state behavioral models

- Transient conditions are more limiting than steady-state conditions
- Limiting conditions correlate to high temperature rather than high heat rate



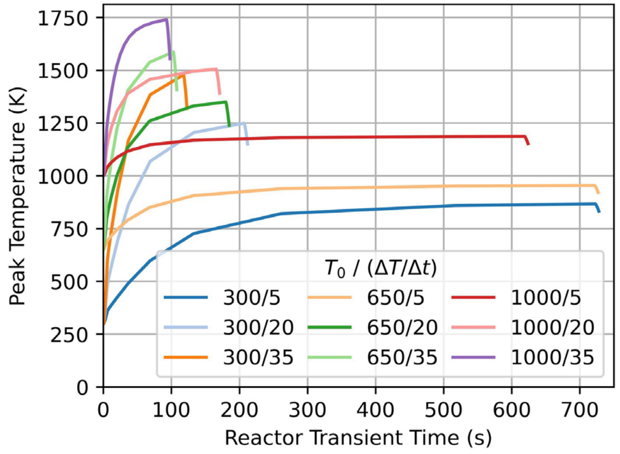
Conclusions

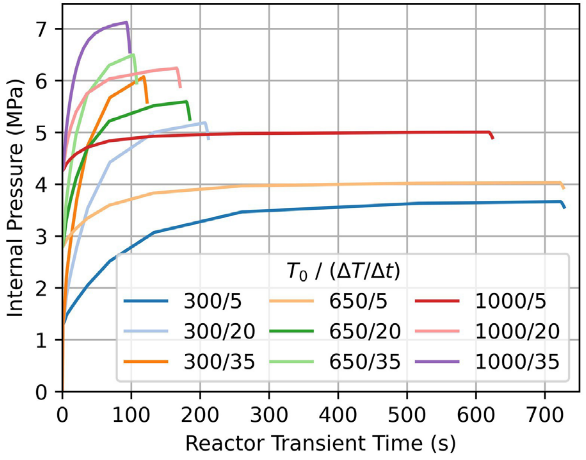
- The prescribed transient exceeds the TREAT energy deposition limit (the low fissile density of the sample produces weak power-coupling with the core)
- Different experiments are needed to
  - Observe TREAT operational limits
  - Deconvolute roles of temperature and heat rate
  - Support model development and validation

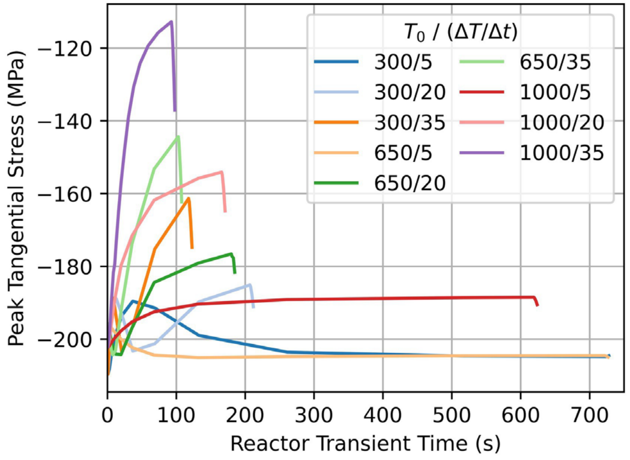
Potential TREAT transients and fuel performance predictions

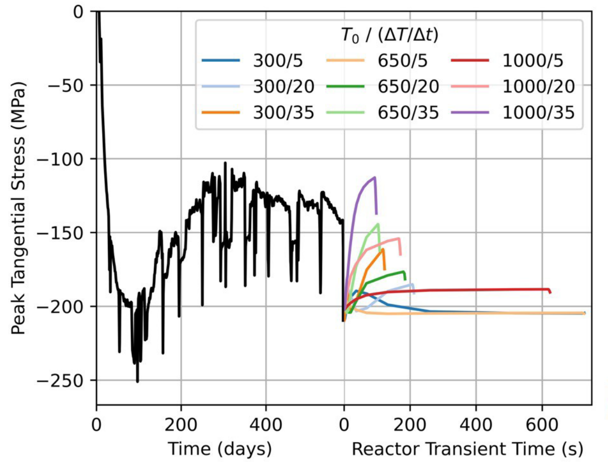
- Summary of objectives
  - Deconvolute roles of temperature and heat rate
  - Support model development and validation
- Existing TREAT capabilities can be leveraged to meet these objectives while observing TREAT operational limits
  - Resistive heating can be used to elevate initial sample temperatures (up to ~1000 K)
  - Flat-top transients can deliver rapid reactivity insertion to target desired heat rates

		Initial temperature (K)		
		300	650	1000
Peak heat rate (K/s)	5			
	20			
	35			



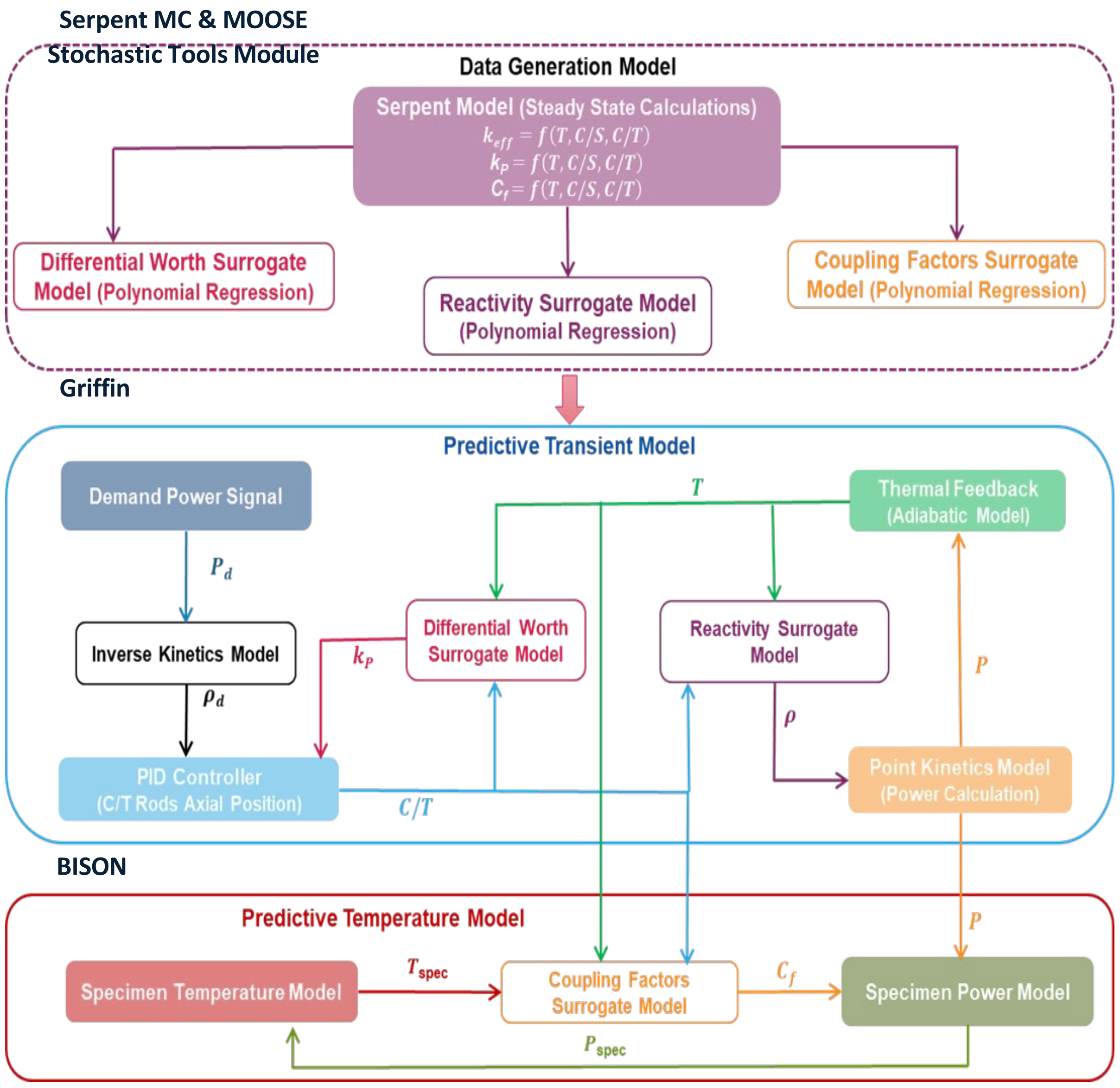






Predictive transient model of TREAT

- A predictive transient model was developed
  - Applied to transient analysis of NASA-sponsored SIRIUS experiments
  - Combines several constituent models to provide power and temperature predictions
- The model consists of three main parts
  - Data generation model (Serpent MC and MOOSE Stochastic tools Module)
  - Predictive transient model (Griffin)
  - Predictive temperature model (BISON)
- These models rely on surrogate models to simplify and enhance the calculation speed
  - A surrogate model for differential rod worth coefficients
  - A surrogate model to predict the reactivity introduced in the system
  - A surrogate model to estimate specimen power



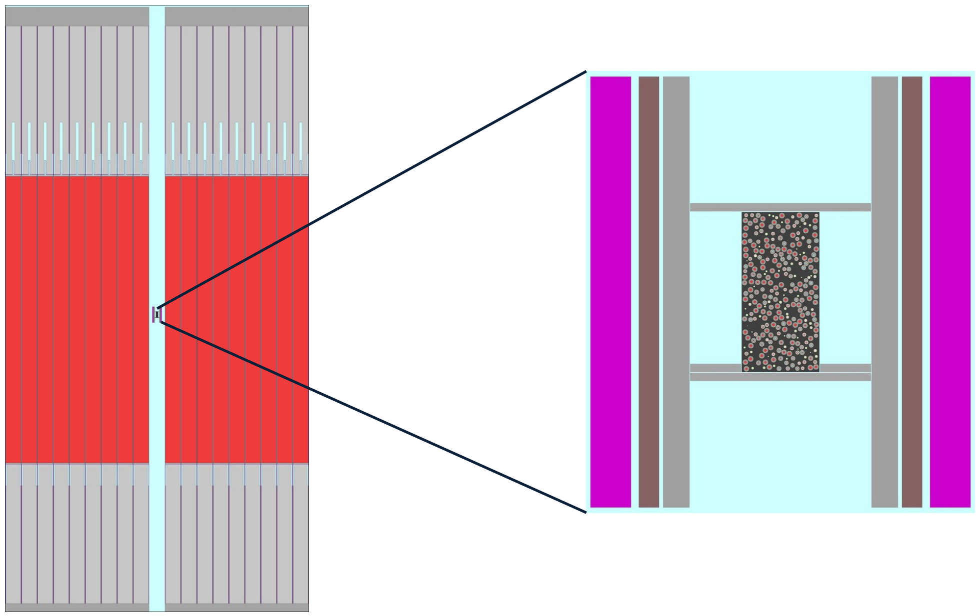
TRISO experiment capsule model

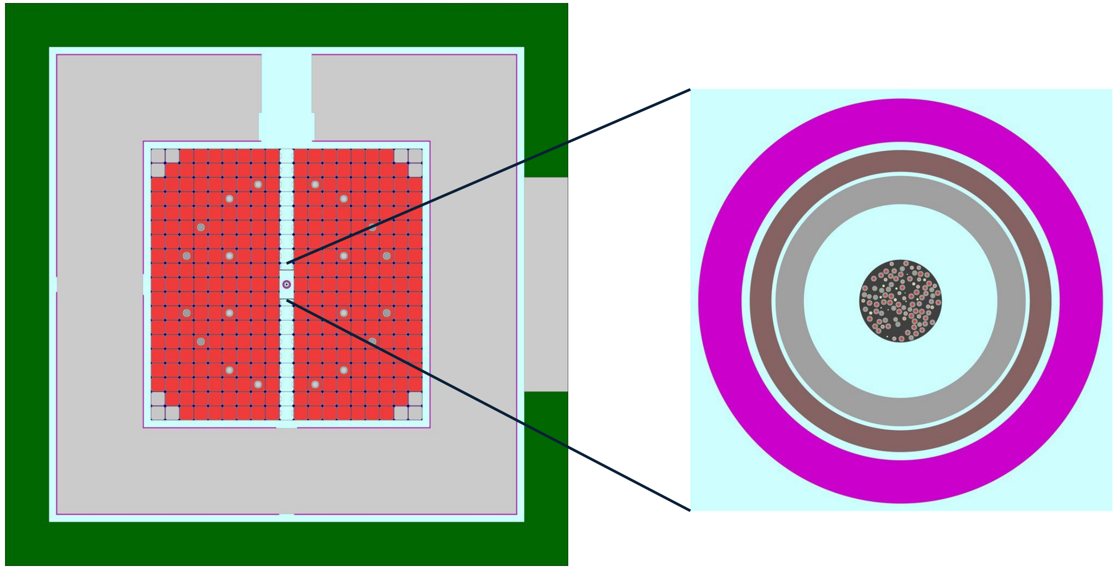
The experiment was modeled with Serpent to calculate the sample/TREAT coupling factors

Parameter	Value
Fuel type	UCO
Enrichment	19.95 wt. %
Packing fraction	36.87
Particles/compact	3176

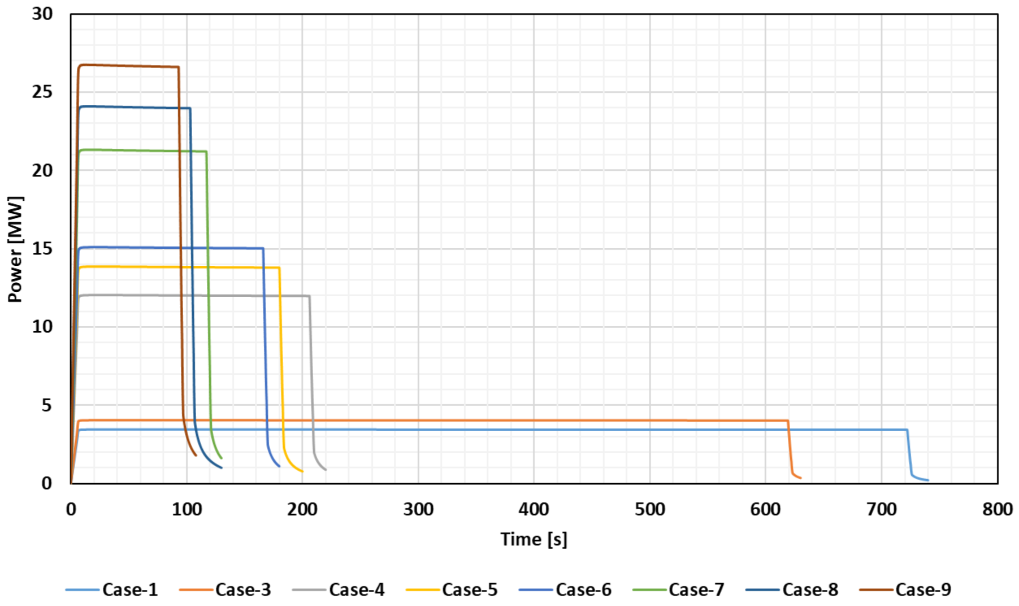
Isotope	Atom Fraction
U-235	6.651E-02
U-238	2.668E-01
O-16	3.325E-01
O-17	1.333E-04
O-18	6.667E-04
C-12	3.298E-01
C-13	3.567E-03

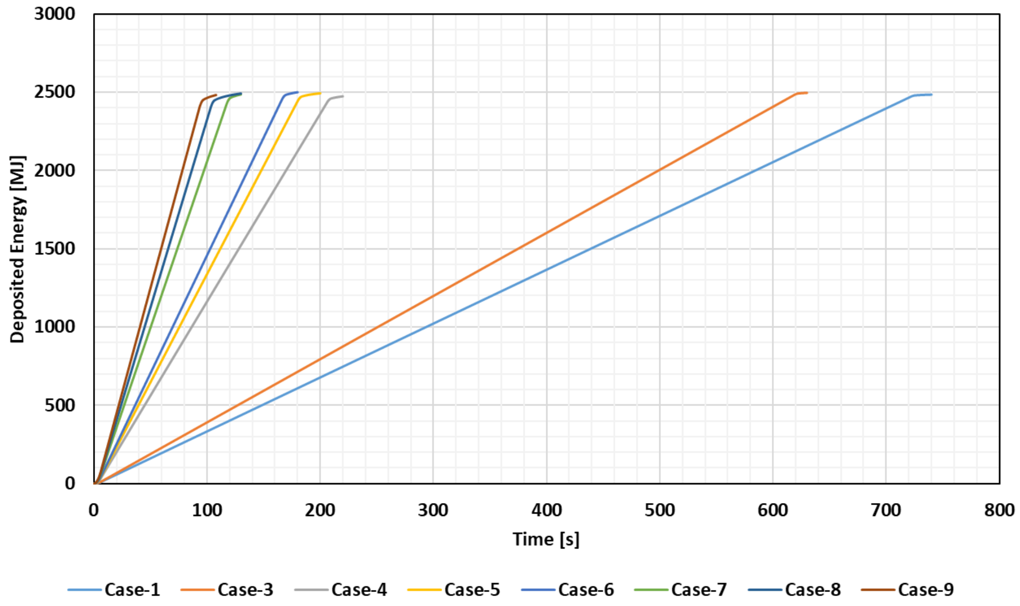
Layer	Density (g/cc)	Radius (um)
Kernel	10.966	213.35
Buffer	1.000	312.25
IPyC	1.890	352.65
SiC	3.197	387.85
OPyC	1.907	431.25

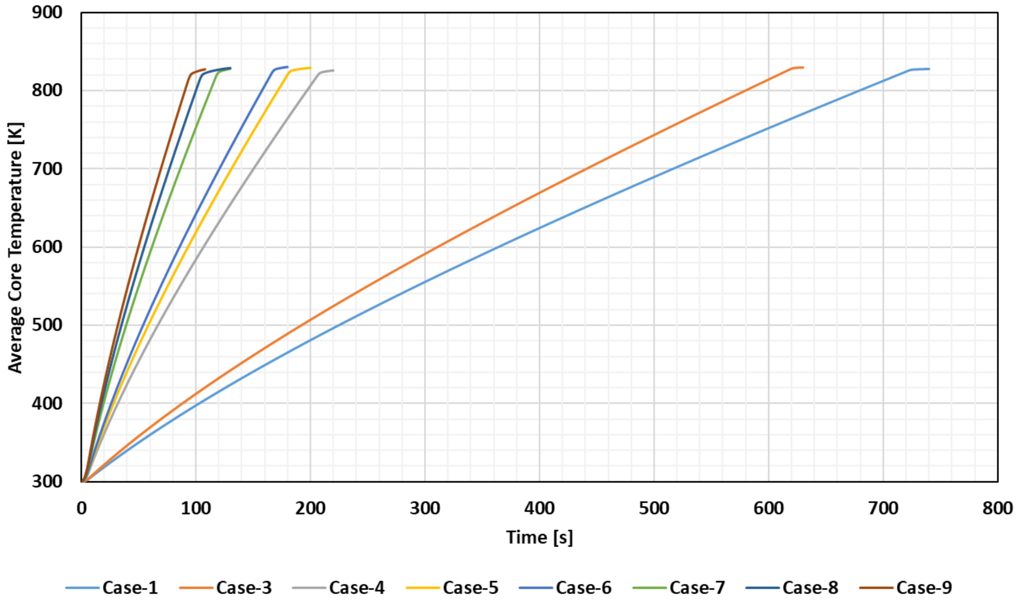


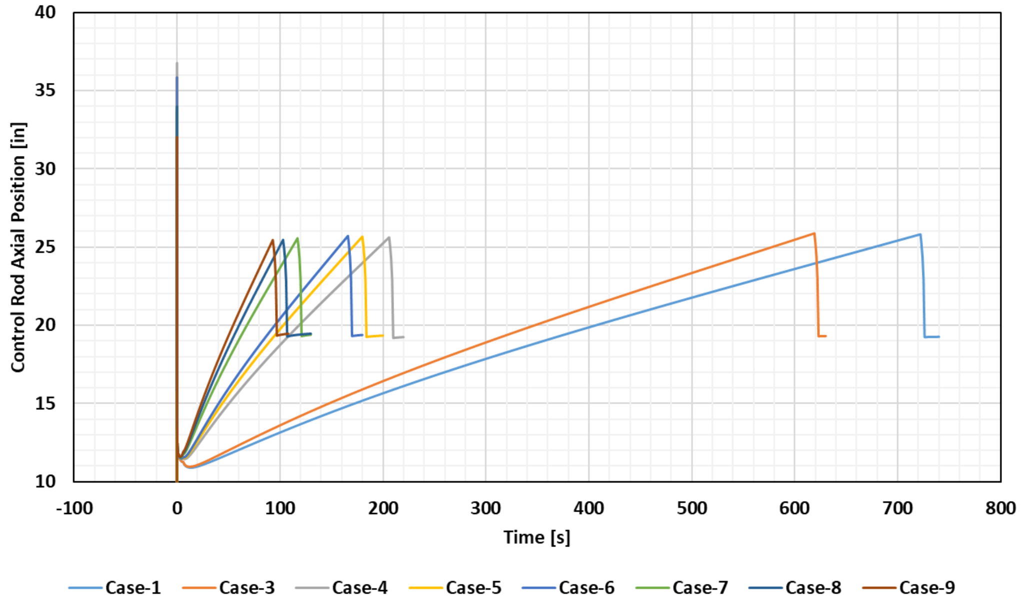


Potential TREAT transient conditions



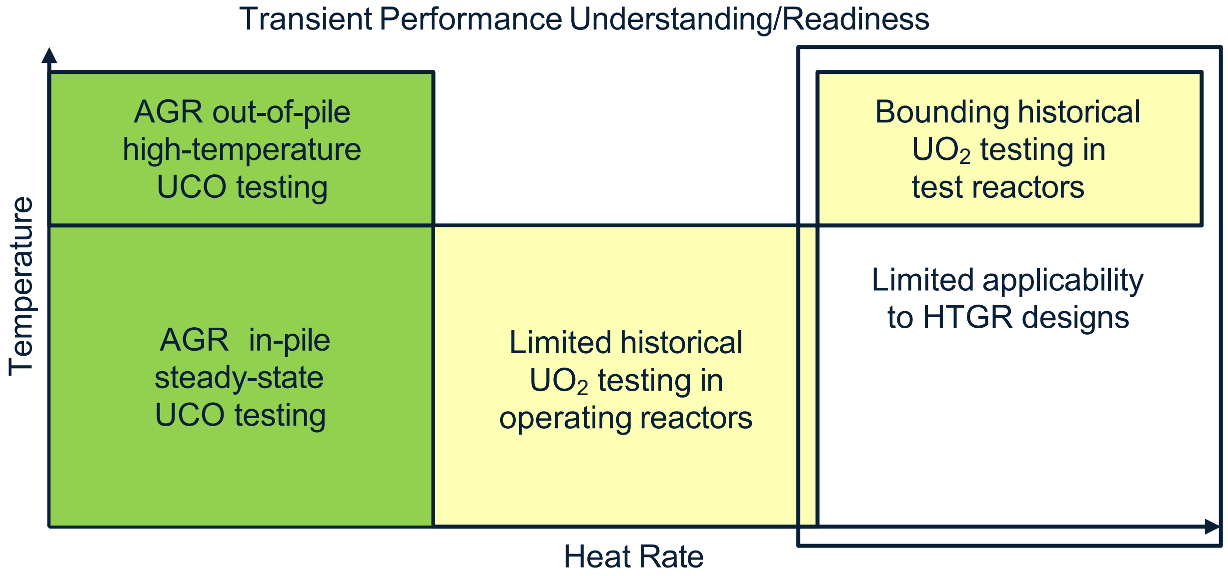






Conclusions and future work

- TRISO fuel performance analyses require us to calculate
  - How much radioactivity is released from intact and failed particles
  - The probability of particle failure
- Failure predictions must account for relevant thermomechanical, thermochemical, and irradiation physics active during normal operation and transient conditions
- Historical test reactor experiments with UO_2
  - Lack coverage for moderate heat rates
  - Convolute high temperature and heat rate
- Additional experiments may be needed to
  - Deconvolute roles of temperature and heat rate
  - Support model development and validation
- Existing TREAT capabilities can be leveraged to meet these objectives



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Transient kinetics approach of TREAT

Traditional

Control rod and thermal feedback computed separately

$$\rho_{TOT}(t) = \rho_{CR}(t) + \rho_{FB}(t)$$

Calculated from CRW curves → *Function of Temperature & other CR positions*

Calculated from Reactivity FB Coef. → *Function of CR positions*

vs.

Current Approach

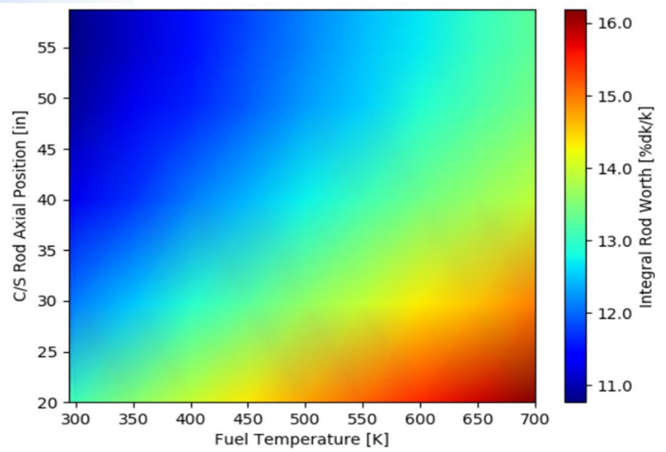
During the experiment k_{eff} is a function of:

- Fuel Temperature.
- Compensation/Safety Rod Positions.
- Transient Rod Positions.

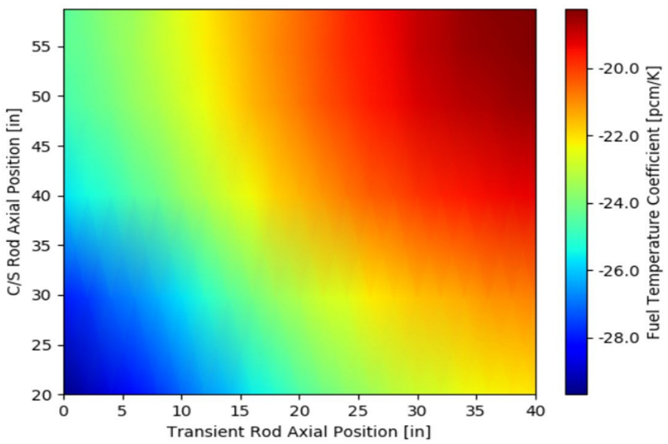
$$\rho_{TOT}(t) = f(T, CS, CT)$$

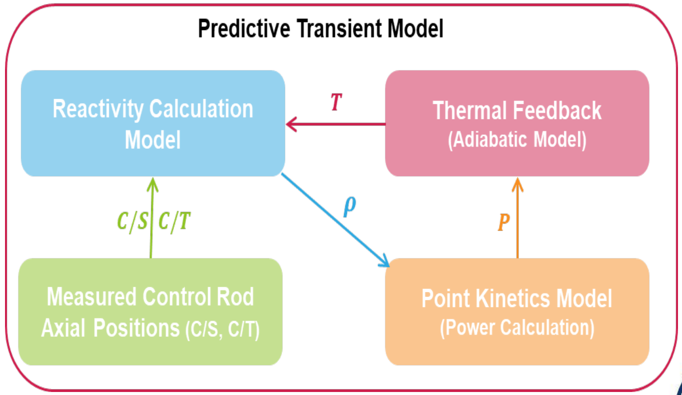
Function of Temperature & other CR positions

Transient CRW



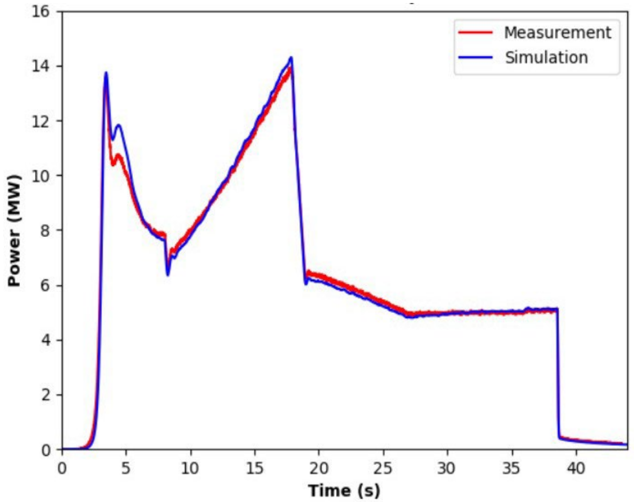
Temperature Feedback Coefficient



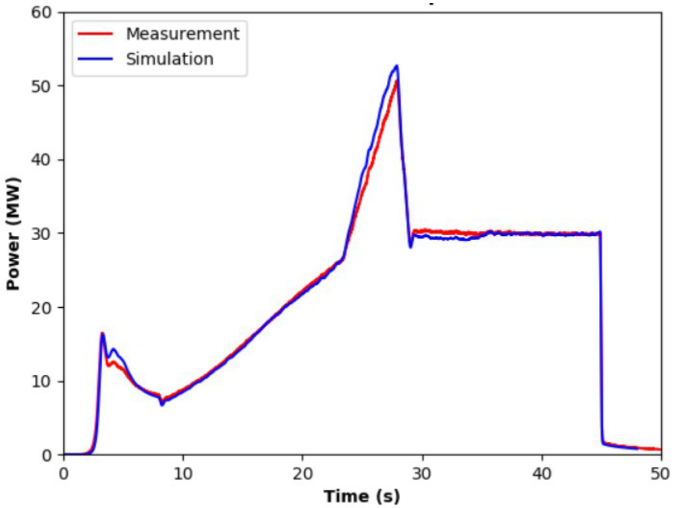


SIRIUS experiments results

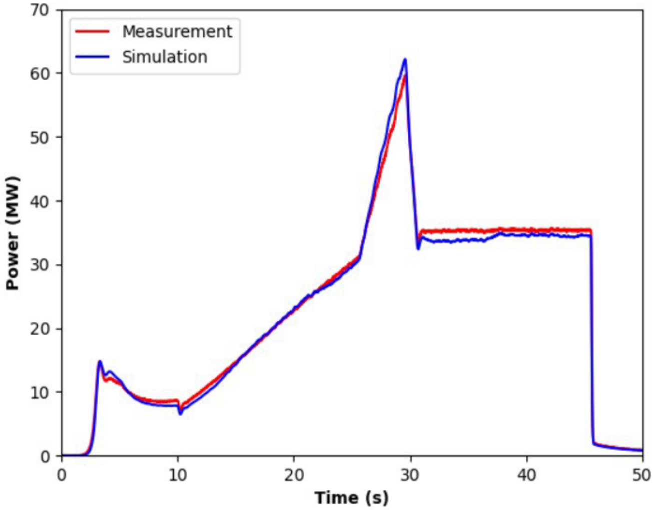
SIRIUS-1 Half Power Experiment



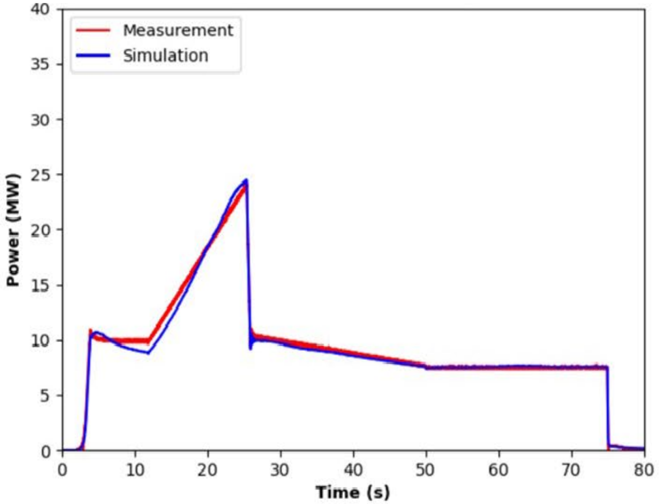
SIRIUS-1 Full Power Experiment



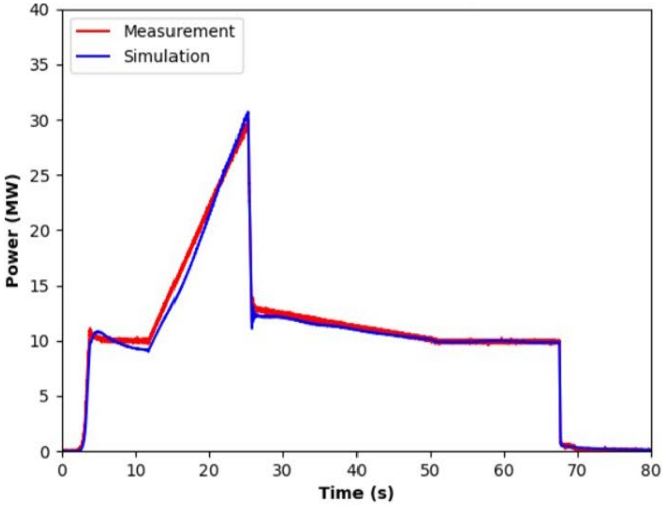
SIRIUS-1 Peak Power Experiment



SIRIUS-3 Full Power Experiment / Test-1

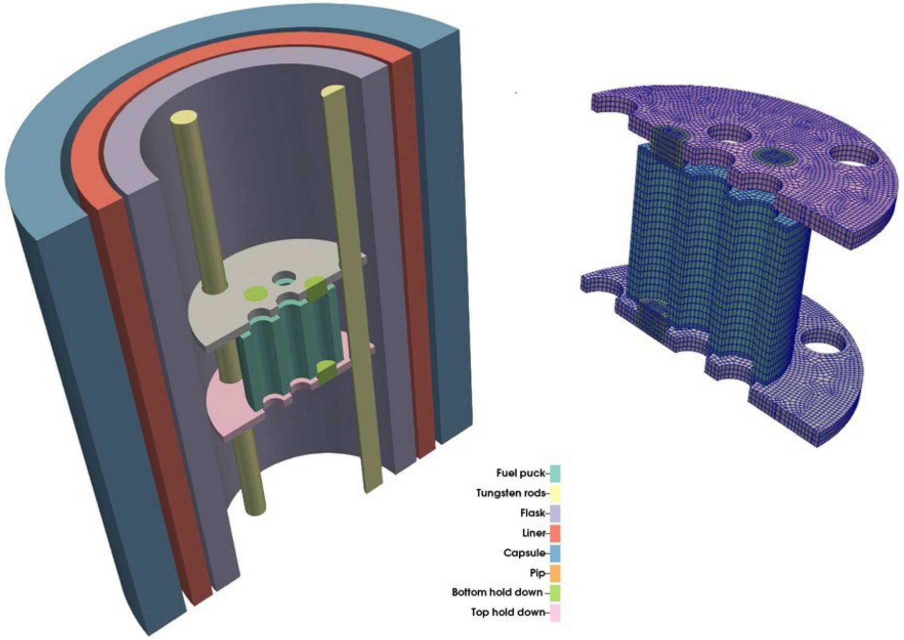


SIRIUS-3 Full Power Experiment / Test-2

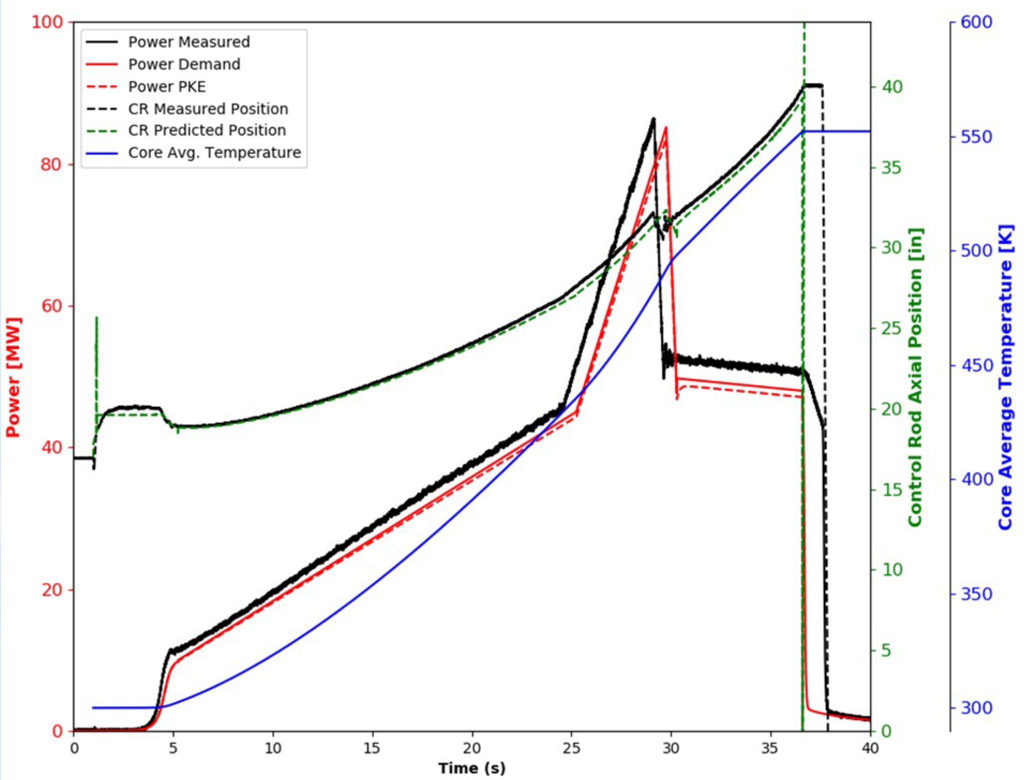


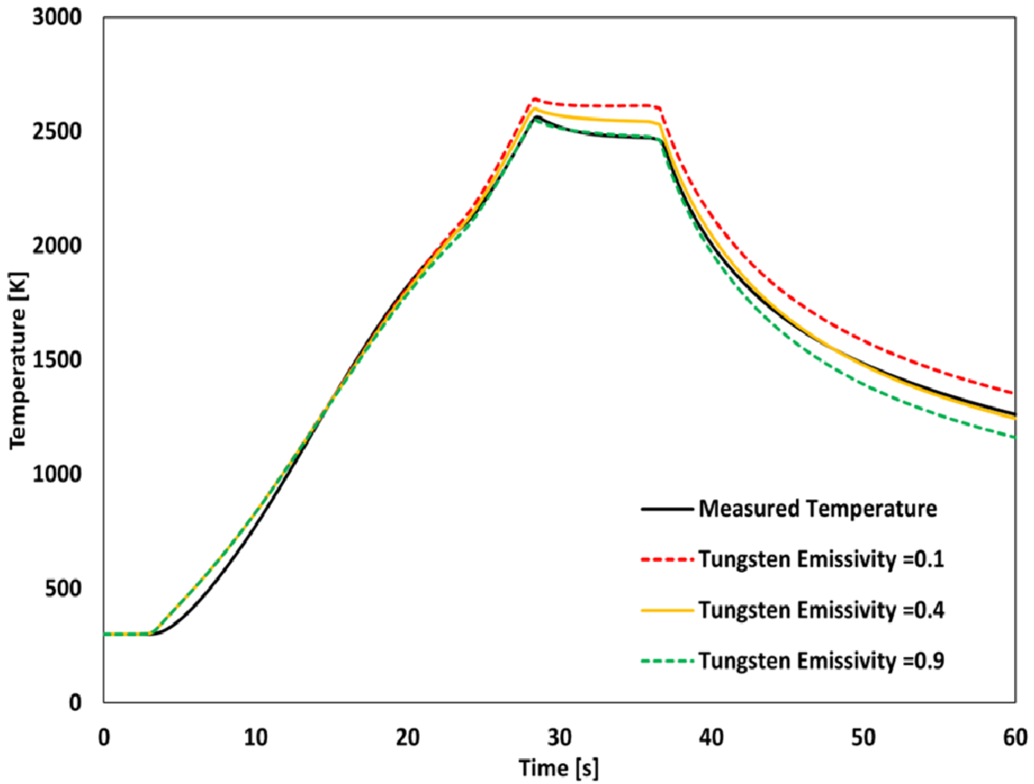
Modeling SIRIUS-2cin TREAT

- The SIRIUS-2c fuel element specimen has
  - A cylindrical fuel element made of ceramic fuel in a ceramic matrix (CERCER)
  - The ceramic fuel is uranium nitride (UN), and the matrix material is zirconium carbide (ZrC)
  - The specimen is positioned within a molybdenum flask, with three tungsten rods positioned within the flask
- A SIRIUS-2c thermal model was developed with BISON
  - Heat conduction in all solid parts of the domain was considered including the heat conduction in the gas
  - Radiation heat transfer between the specimen, hold down rings, tungsten rods, and flask is considered
  - The reactor temperature is imposed as a time dependent Dirichlet boundary condition on the outside of the capsule



Prediction results of SIRIUS-2c



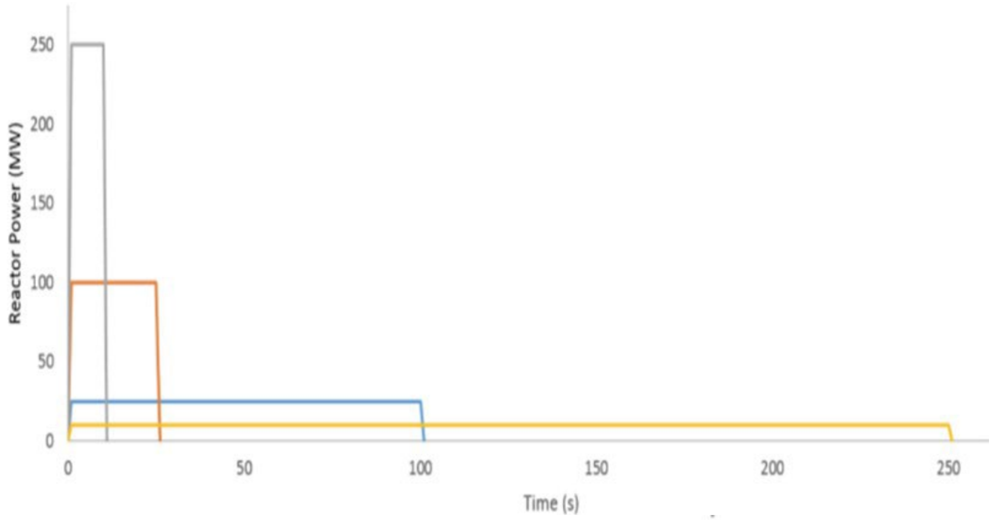


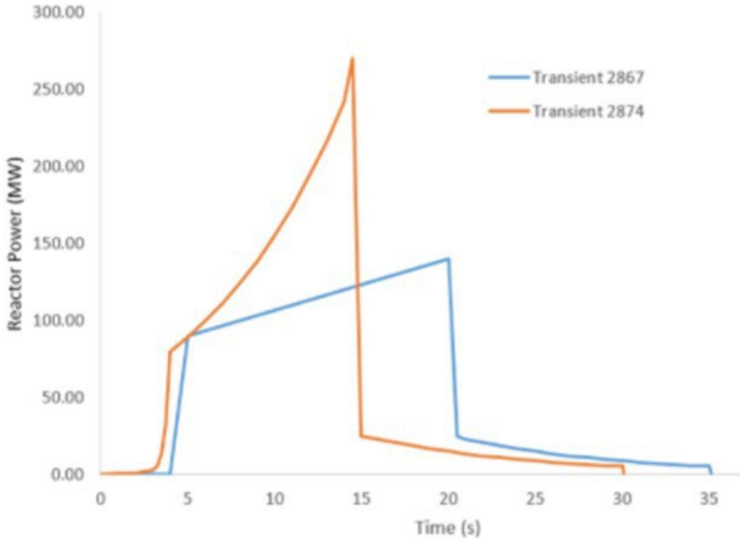
- Providing a demand power signal for SIRIUS-2c experiment, the motion of the control rods in the axial direction was determined
- The predicted power shape is in close agreement with the measured power

- The specimen temperature was calculated by providing heat source to temperature predictive model
- An uncertainty analysis was performed using the MOOSE Stochastic Tools Module

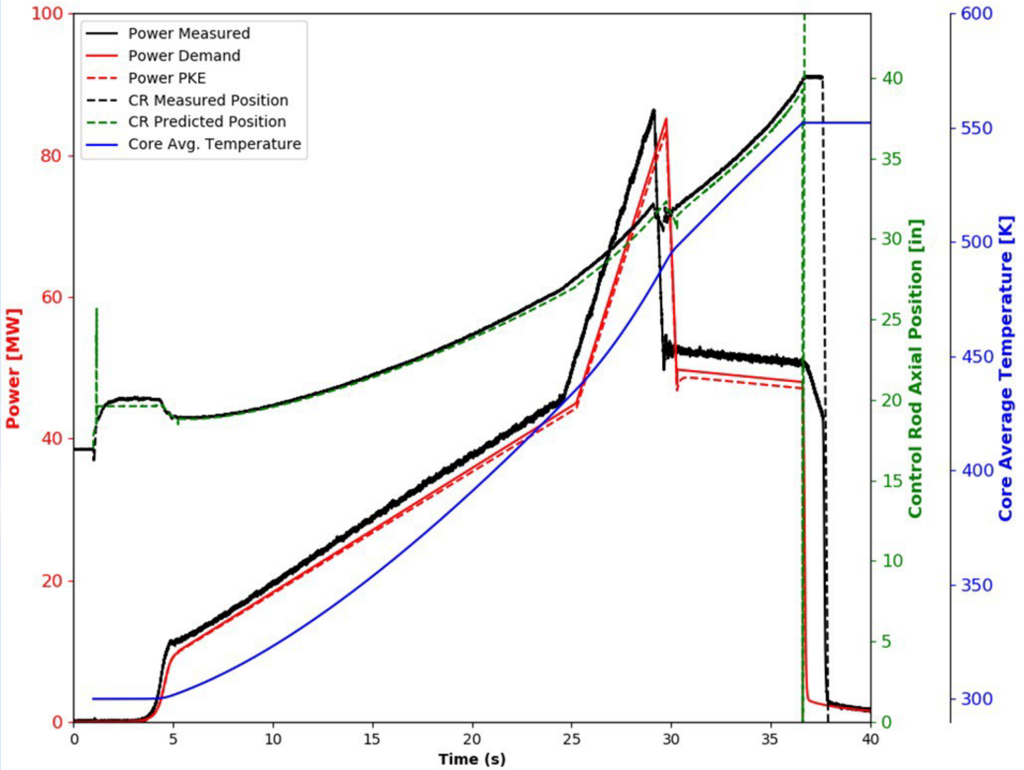
TREAT limits and transient capabilities

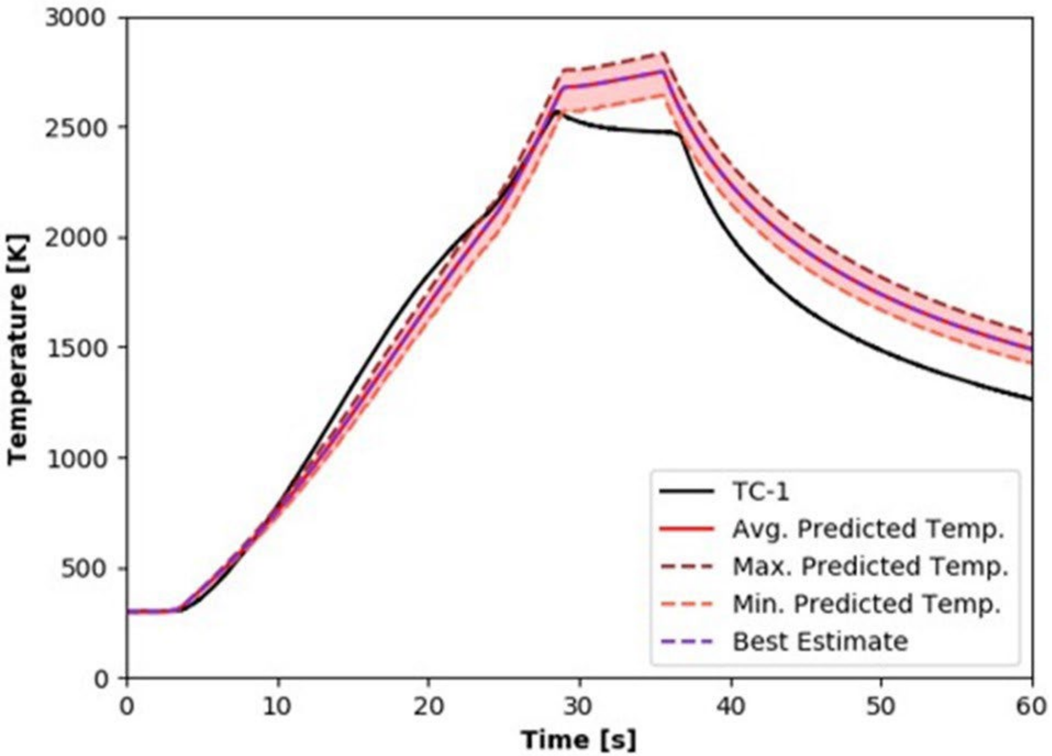
- Operation limits
  - Max transient rod speed: 3.6 m/s
  - Max core transient energy: 2500 MJ
  - Peak steady state power: 120 kW
  - Peak transient power: 19 GW
- Flat-top (>120 kW) transients
  - Virtually any power level
  - Time limited by 2500 MJ core energy capacity
- Unprotected transient over power (UTOP)
  - Tuned to achieve desired fuel temperature and power
  - Ramp, pulse, shutdown, etc.
- Pulse operations
  - Step insertion 4.5% $\Delta k/k \rightarrow$ 2500 MJ released in ~0.5 s
  - Large acute neutron dose for short-lived isotope effect studies
  - Step can start from near-zero power or follow a flat-top





Prediction results of SIRIUS-2c





- Providing a demand power signal for SIRIUS-2c experiment, the motion of the control rods in the axial direction was determined
- The predicted power shape is in close agreement with the measured power

- The specimen temperature was calculated by providing the heat source to the temperature predictive model
- An uncertainty analysis was performed using the MOOSE Stochastic Tools Module

Prediction results of SIRIUS-2c

- The predicted temperature evolution indicates that
  - Total power deposited in specimen volume is overestimated
  - Or heat loss rate of specimen is underestimated
  - Or both
- The specimen power relies on
  - Reactor total power
  - Power coupling factors
- The main heat loss mechanism of the specimen considered in the thermal model is radiative heat transfer which strongly depends on the surface emissivities
  - Emissivities are obtained from scarce literature references for each material
  - Depends greatly on chemical composition, geometrical structure, surface roughness, and machining of the specimen surfaces
  - Fuel, tungsten, and molybdenum emissivities are 0.75, 0.29, and 0.1, respectively