INL/MIS-24-82184-Revision-0

Fuel Performance Evaluation of THOR-C Experiments

December 2024

Changing the World's Energy Future

Matthew Phillip Mihelish, Aydin Karahan

Idaho National Laboratory

INL is a U.S. Department of Energy National Laboratory operated by Battelle Energy Alliance, LLC

INL/MIS-24-82184-Revision-0

Fuel Performance Evaluation of THOR-C Experiments

Matthew Phillip Mihelish, Aydin Karahan

December 2024

Idaho National Laboratory
Idaho Falls, Idaho 83415

http://www.inl.gov

Prepared for the
U.S. Department of Energy
Under DOE Idaho Operations Office
Contract DE-AC07-05ID14517

Fuel Performance Evaluation of THOR-C Experiments

Aydin Karahan, ANL

akarahan@anl.gov

Matt Mihelish, INL

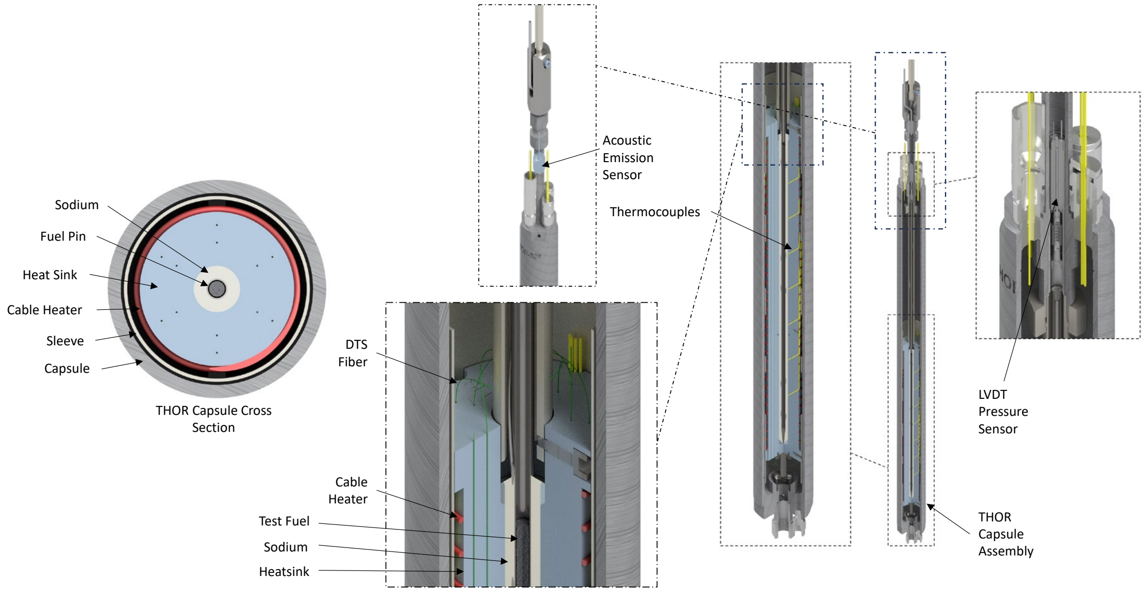
Matthew.Mihelish@inl.gov

Advanced Fuels Campaign

U.S. DEPARTMENT OF ENERGY | Office of NUCLEAR ENERGY

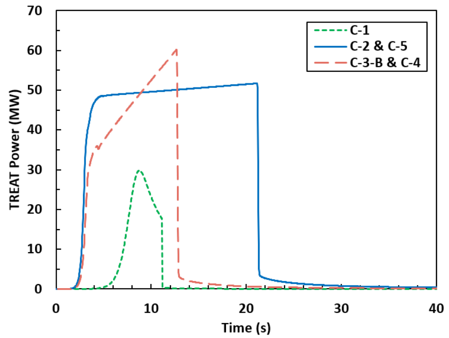
Experimental Design and Modeling

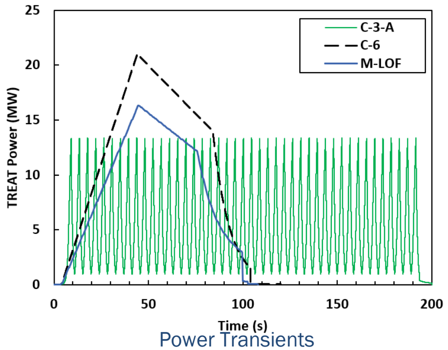
- Metallic fuel assessment and development
- ARES
- Overall THOR capsule design
- THOR Commission Testing
  - Calibrate/measure coupling factor
  - Baseline of unirradiated specimens
  - Perform in-pile qualification of instrumentation
- THOR-C share many components but differ in fuel geometry and cladding material
- Model THOR-C in BISON
  - Compare to other FEA software
  - Utilize fuel to cladding interaction models
  - Compare to experimental data
  - Develop methods and BISON



Experiment	C-1	C-2	C-3-A	C-3-B	C-4	C-5	C-6	M-LOF
Transient	C-1	C-2 and C-5	C-3-A	C-3-B and C-4	C-3-B and C-4	C-2 and C-5	C-6	M-LOF
Starting Temp	230 °C							
Fuel Type	U10Zr							
Heat Sink	Ti Gr 5							
Sodium	Rodlet and Heat Sink		Heat Sink Only		Rodlet and Heat Sink			
Cladding	HT9				SS 316			HT9

Experiment Configuration





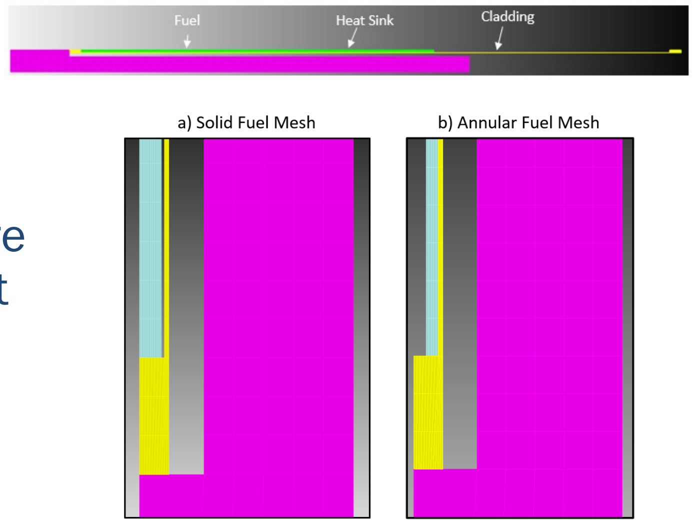
Power Transients

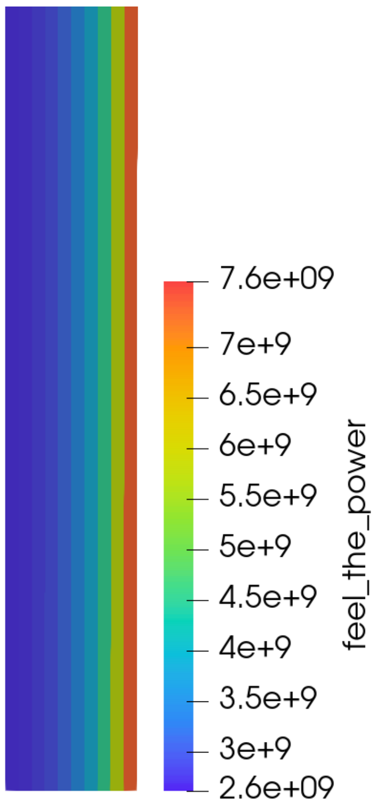
- Pulse with a clip: C-1
- Shaped ramp: C-2/C-3B, C-4/C-5
- Oscillating Power Function: C-3A
- Shaped slow ramp: C-6/M-LOF

Advanced Fuels Campaign

BISON Model Geometry, Physics and Boundary Conditions

- BISON fuel performance code
- Fresh Fuel
  - THOR-C
    - Heat Sink, Cladding, Fuel
- Irradiated Fuel
  - M-LOF
    - Base irradiation geometry
- No external convection
  - All energy retained and distributed
- Heat sink cable heater initial temperature of 230 °C to ensure effective thermal bond of sodium between cladding and heat sink
- Heat generation as a function of axial and radial position mapped onto the fuel
- M-LOF initial fuel burnup and its effects are inputs





Mapped axial and radial heat generation rate applied fuel rod

Advanced Fuels Campaign

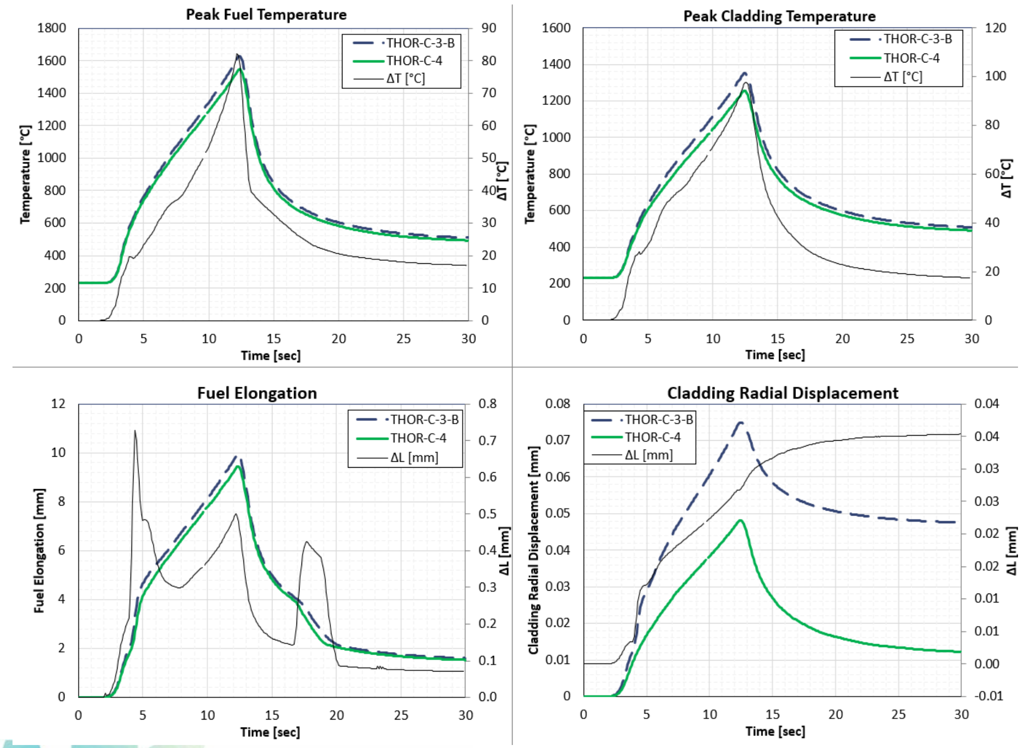
BISON Thermomechanical Results

- BISON material and behavior models
- Fuel and cladding predictions for annular and solid fuel
- Difference between HT9 and SS316 Cladding
  - Fuel elongation and cladding radial displacement

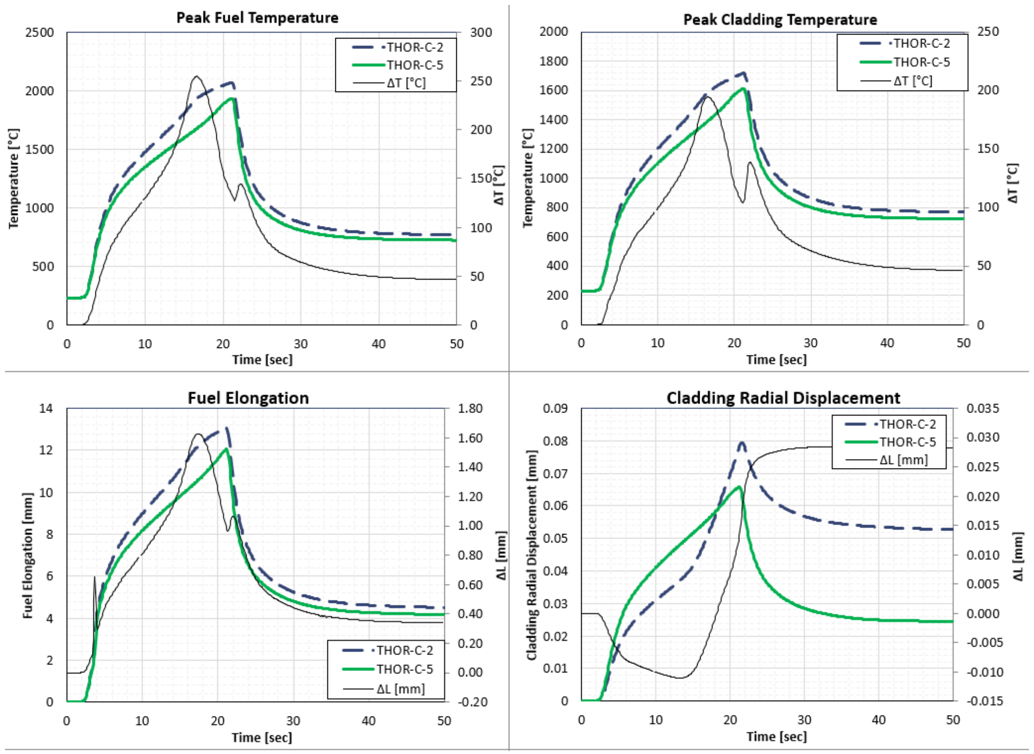
Fuel	Cladding
FissionRateAuxLWR	HeatConductionMaterial
ParsedMaterial	ComputeIsotropicElasticityTensor
HeatConductionMaterial	FastNeutronFlux
ParsedMaterial "Youngs & Poissons"	ComputeMultipleInelasticStress
ComputeIsotropicElasticityTensor	HT9ThermalExpansionEigenstrain
ComputeFiniteStrainElasticStress	HT9FailureClad
UPuZrCreepUpdate	D9FailureClad
UPuZrThermalExpansionEigenstrain	SS316CreepUpdate
MetallicFuelWastageDegradationFunction	SS316ThermalExpansionEigenstrain
MetallicFuelMeltingFunction	ADMetallicFuelLiquidCladdingPenetration

BISON Material and Behavior Models

Annular and Solid Fuel



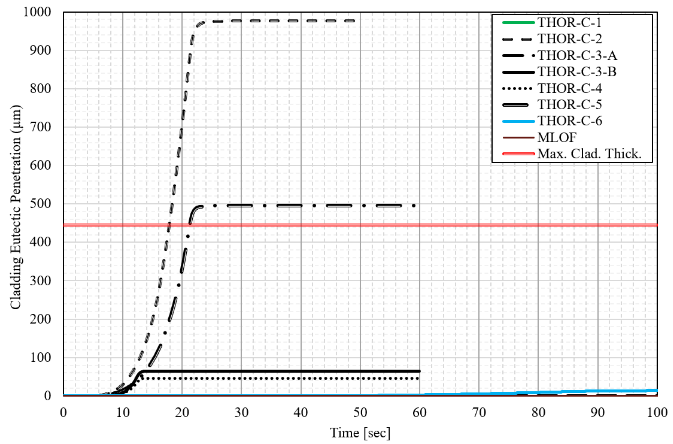
HT9 and SS316 Cladding

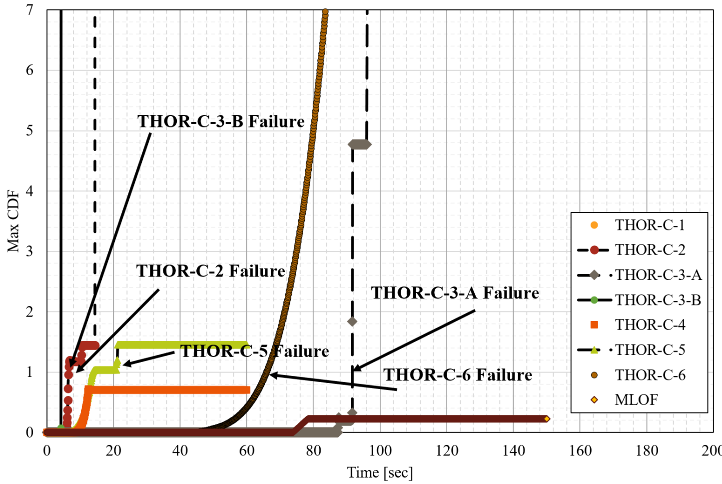


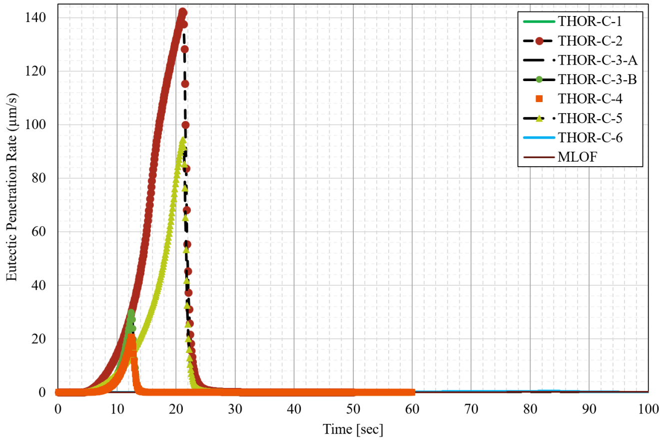
Advanced Fuels Campaign

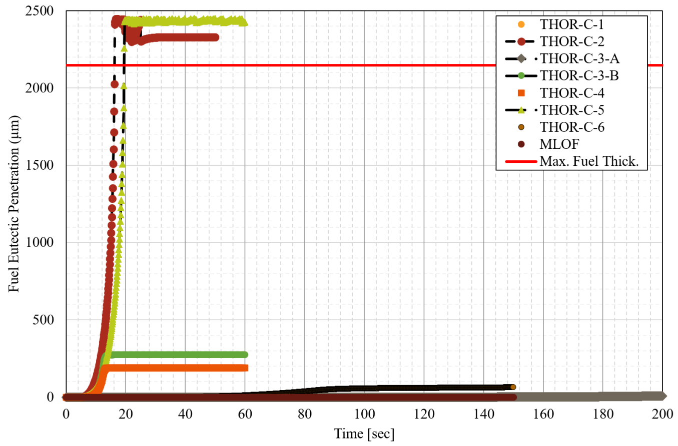
BISON CDF and Metallic Fuel Liquid Cladding Penetration

- Two cladding failure models for HT9 and D9 used to output maximum cumulative damage fraction (CDF)
- Recently added to BISON
  - Metallic fuel liquid cladding penetration interactions
    - Eutectic Penetration Rate
    - Fuel Eutectic Penetration
    - Cladding Eutectic Penetration









Advanced Fuels Campaign

Next steps - BISON

- Material model enhancements including heat of fusion into the fuel material model
- An expanded set of calculated results including cladding residual hoop strain (post cooldown), fuel-cladding gap
- Sensitivity study of fuel-cladding gap width in annular fuel, fuel-cladding mechanical interaction model, sodium heat generation and heat capacity effects, radial power peaking in the fuel
- Further investigation of the implementation of new eutectic models to thoroughly evaluate their impacts on predictions
- As-run/as-built analysis for each experiment including comparison to in-situ and post-transient examination results

Relevant Fuel models of SAS4A/SASSYS-1

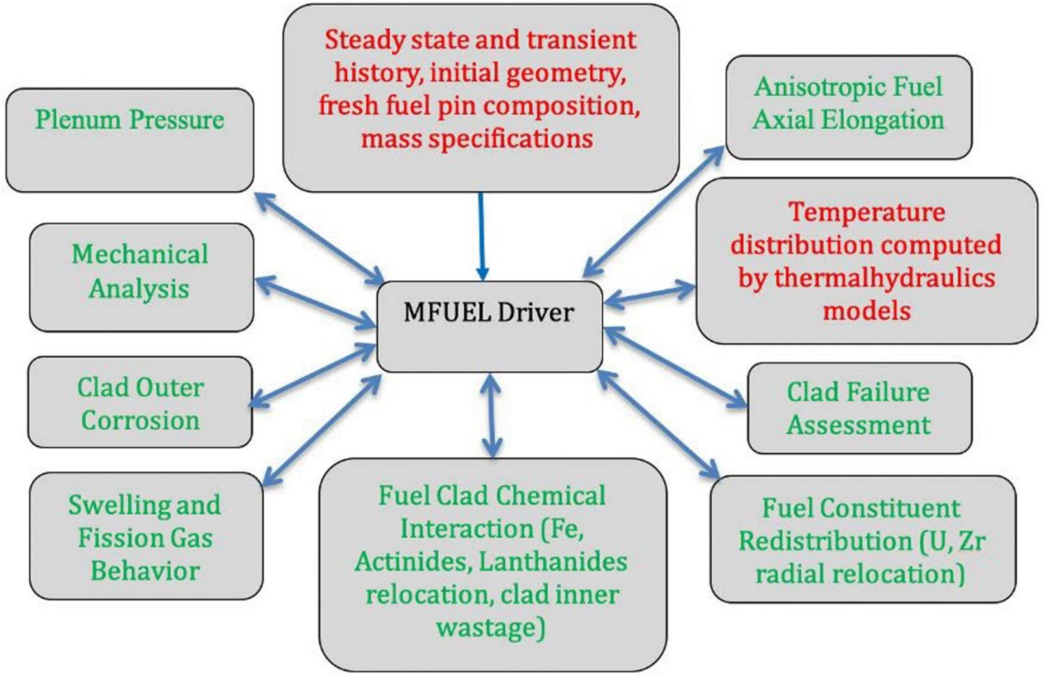
- SAS4A/SASSYS-1 is a multi-physics system analysis tool equipped with core thermal-hydraulics, neutronics, fuel performance and severe accident models as well as models for the primary loop components.

Fuel models include:

- MFUEL: Metal Fuel Performance
- OFUEL: Oxide Fuel Performance
- CDAP: Clad Damage Propagation
- LEVITATE: Post-Failure Fuel Relocation

MFUEL module of SAS4A/SASSYS-1

- Simulates pre-transient fuel irradiation, transient fuel response and margins to cladding failure.
- Equipped with a mix of mechanistic and empirical models to characterize the essential features.
- Built-in models for D9, HT9 SS-316 and 15-15Ti claddings.
- Advanced metallic fuel options for annular and liner fuels.
- Validation using available EBR-II, PHENIX,FFTF, furnace, and TREAT tests.



FY24 Accomplishments – MFUEL

- MFUEL Model Updates
  - A multi-dimensional heat transfer model capturing features of THOR capsule design such as stagnant flow, presence of a heat sink material, and heat losses.
  - Updated eutectic modeling for fresh metallic fuel pin

- THOR-C2 Capsule Test Simulation
  - Fuel pin temperature distribution
  - Fuel melting
  - Eutectic wastage formation
  - Creep damage and cladding failure margin

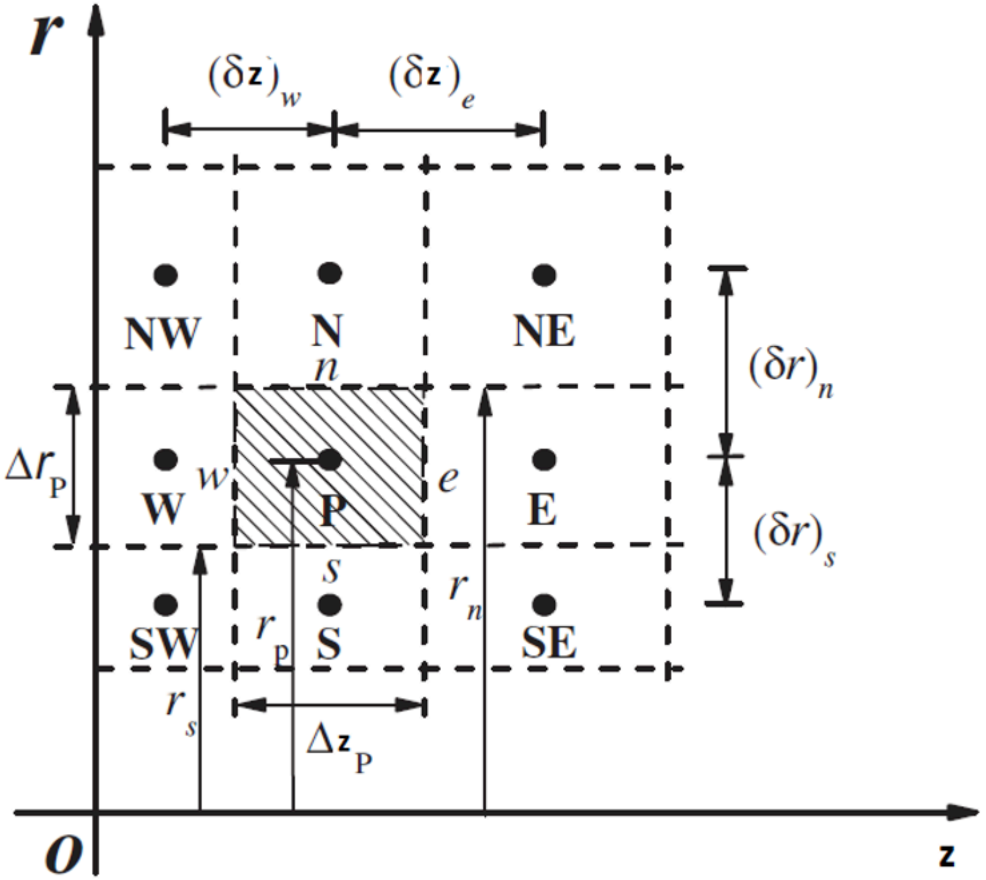
2D Axisymmetric Heat Transfer - MFUEL

- A 2D time dependent finite volume model has been utilized to compute the transient temperature distribution of the fuel pin, stagnant sodium, and titanium heat sink, including the gas plenum.

$$\rho c_p \frac{\partial T}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(rk\frac{\partial T}{\partial r}\right) + \frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right) + q'''$$

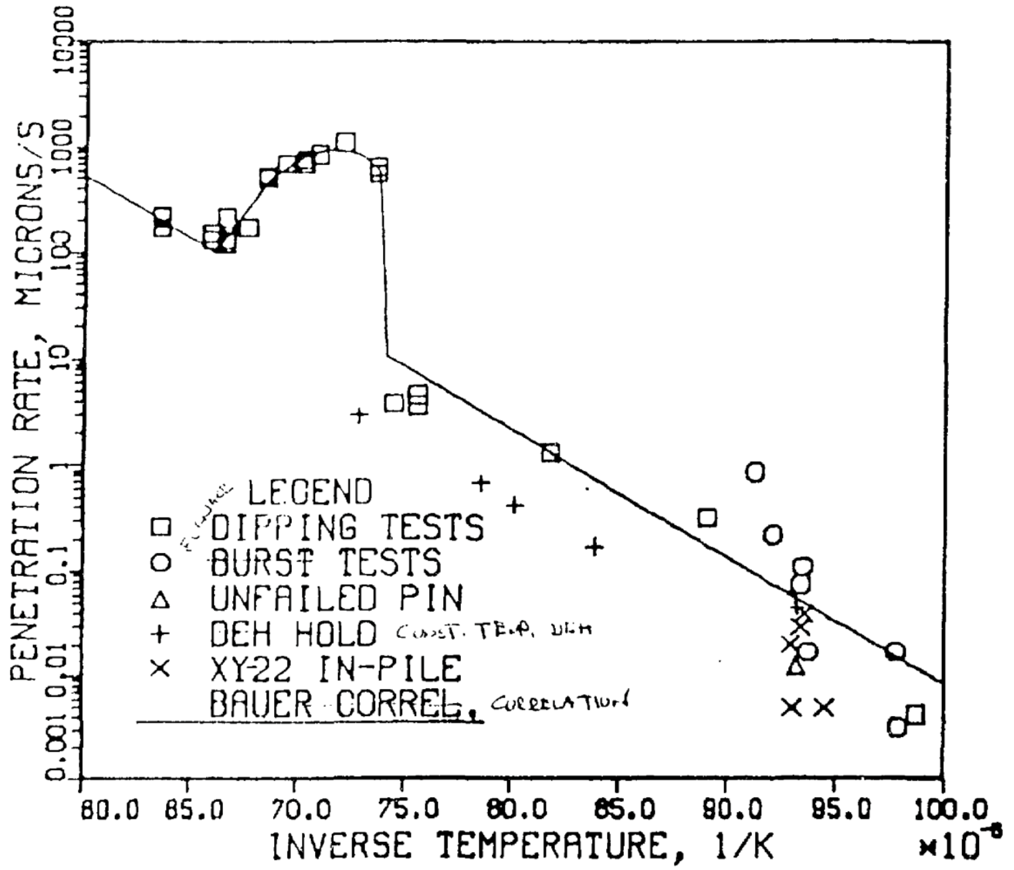
$$\rho c_p r_p \Delta r_p \Delta z_p \frac{T_P^{new} - T_p}{\delta t} = \left(k_n r_n \frac{T_N - T_p}{(\delta r)_n} - k_s r_s \frac{T_P - T_S}{(\delta r)_s}\right)\Delta z_P + r_p\left(k_e \frac{T_E - T_P}{(\delta z)_e} - k_w \frac{T_P - T_W}{(\delta z)_w}\right)\Delta r_P + q''' r_p \Delta r_P \Delta z_P$$

ρ: Density of node-P (kg/m³)
c_p: Specific heat of node-P (J/kg/K)
r_p: Radial position of node-P (m)
Δr_p: Radial size of node-P (m)
Δz_p: Axial size of node-P (m)
T_P^{new}: Computed temperature of node-P at the current time step (K)
T_p: Computed temperature of node-P at the previous time step (K)
k_n: Thermal conductivity at the surface-n (W/m/K)
$(\delta r)_n$: $r_N - r_P$ (m)
$(\delta z)_e$: $z_E - z_P$ (m)
q''': Heat source (W/m³)



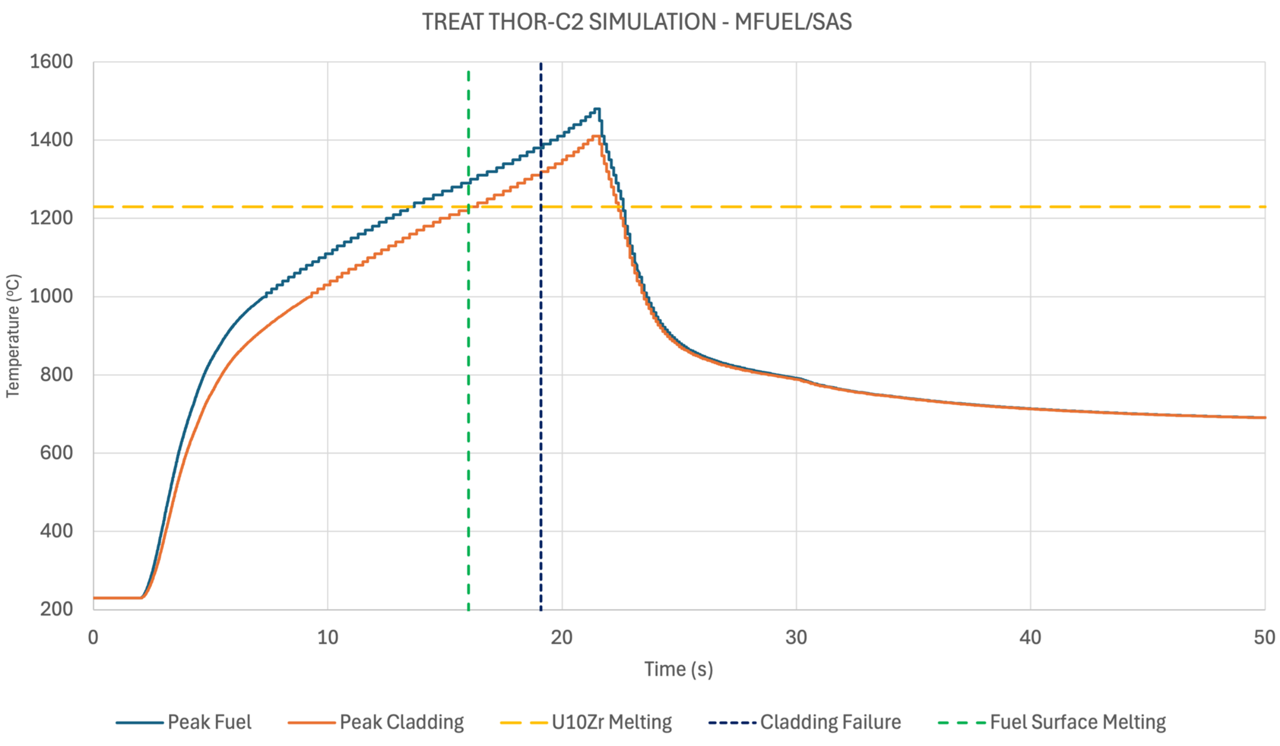
Eutectic Model Updates - MFUEL

- MFUEL includes mechanistic slow eutectic (below 1080 °C) and empirical rapid eutectic (≥1080 °C) models.
- Once activated, rapid eutectic can lead to loss of cladding integrity in a few seconds.
- THOR capsule experiments with fresh fuel indicated that activating eutectic models without an established contact between fuel and cladding results in very conservative predictions.
- MFUEL model has been updated such that eutectic interaction is initiated if
  - (1) Soft contact forms between fuel and cladding, or
  - (2) Solidus temperature is reached at the fuel surface.



THOR-C2 Capsule Simulation using MFUEL

- The MFUEL-SAS4A/SASSYS-1 simulation results for THOR-C-2 are shown in Figure.
- Fuel surface melting occurs near 16 seconds. This is when it is assumed that the fuel loses mechanical integrity and contacts the cladding. The rapid eutectic penetration model is activated.
- Cladding failure, due to thermal creep rupture augmented by eutectic wastage formation at the cladding's inner surface, is predicted to occur at around 19.7 seconds, consistent with the experimental observations.
- After the reactor shutdown, the capsule cools down toward the equilibrium temperature. The predicted equilibrium temperature aligns well with BISON and ABAQUS predictions.



Next Steps - MFUEL

- Simulation of MLOF capsule experiment
  - Model the pre-transient simulation of the selected EBR-II pin for MLOF
  - Simulate the selected reference MLOF transient scenario
  - Evaluate different MLOF transient scenarios that may lead to cladding failure below sodium boiling temperature, given the energy deposition limits in TREAT

- Complete Software Quality Assurance process and merge updates to the release version of SAS4A/SASSYS-1

- Longer term goal: Simulate molten fuel relocation behavior in TREAT THOR capsule tests using LEVITATE model

Summary

- BISON models of the THOR –C and MLOF experiments have been developed using the latest fuel and cladding eutectic predictive capability
  - The BISON models are under constant development to improve material and method definitions
    - Mapped HGRs, heat of fusion, cladding type failure
- MFUEL updated to incorporate 2D conduction with the THOR capsule heat sink
- The time of cladding failure due to thermal creep rupture predicted by MFUEL is consistent with experimental observations
- Analyzing the THOR-C experiments with two codes has the benefit of using a state-of-the-art code MFUEL with BISON as a development tool. Identify areas of to build upon and expand the predictive capability to improve future experiments

Questions?

Clean. Reliable. **Nuclear.**

Advanced Fuels Campaign