HERA Modeling and Simulation Exercise: BISON Results

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HERA Overview

- High-burnup Experiments for Reactivity-initiated Accident (HERA)
- Joint Experimental Program under the Nuclear Energy Agency (NEA) Framework for Irradiation Experiments (FIDES) program
- Project includes 3 main tasks:
  1. Six RIA tests with pre-hydrided cladding and oversized UO_2 pellets at different pulse widths
     - Irradiated at TREAT and NSRR
  2. Four RIA tests with actual high burnup material
  3. **Modelling and Simulation (M&S) Exercise**

Westinghouse

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United States Nuclear Regulatory Commission
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M&S Goal

- Evaluate the effect of power pulse width on the behavior of hydrided zirconium cladding
- Strategy:
  - Part I: Provide pre-test predictions that will ensure data objectives are achieved and captured appropriately
    - "Blind" predictions add unique perspective to evaluations
  - Part II: Post-test evaluations for final data synthesis, preservation, and project conclusions

HERA M&S Case Matrix

- Model “simulated” high-burnup fuel with a small fuel-cladding gap and pre-hydrided cladding
  - Hydrogen content in cladding between 300-500 ppm
  - All tests will target 650 J/gUO2 of peak radial average enthalpy increase in fuel
- Study the effect of pulse width on possible failure limits
  1. NSRR transient at ~5 ms
  2. TREAT transient at ~90 ms
  3. TREAT transient at ~50 ms (HENRI)
  4. TREAT transient at ~300 ms (HENRI alternative)
- Sensitivity evaluation on energy deposition and hydrogen content
  - +/- => vary only energy deposition or hydrogen content
  - Later 2 additional cases (13 & 14) were added to look at the sensitivity of fuel-cladding gap

Case #	HERA Test ID	Pulse Width at FWHM (ms)	Peak Radial Average Enthalpy Increase (J/g)	Hydrogen Content/Rim t (ppm/µm)	Fuel Outer Radius (mm)
1	HERA-PreH-1,2	7.5	650	400/80	4.1605
2			650	200/40	4.1605
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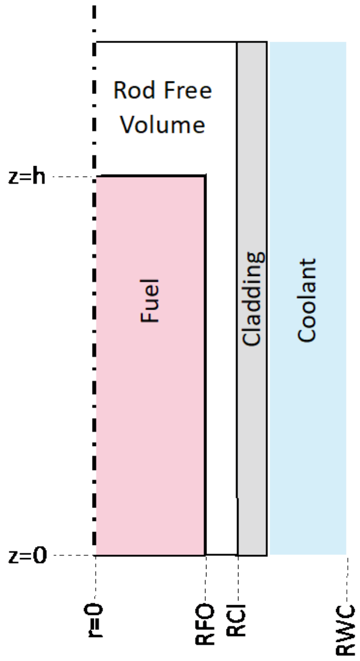
14			650	400/80	4.1305
11	HERA-PreH-5,6	50	650	400/80	4.1605
12	HERA-PreH-5,6	300	650	400/80	4.1605

Universal Model Inputs

- Specimen geometry (and density)
  - Fuel stack height and diameter
  - Cladding inner/outer diameter
  - Plenum volume and pressure
- Thermal Hydraulic conditions
  - Water pressure and temperature
- Transient Power Input
  - Uniform axial specimen power profile
  - Shape
    - Prediction (Part I) -> Gaussian w/ FWHM
      - Table of LHGR(t) was provided for each pulse width and energy deposition case
    - Post-test (Part II) -> As-run P vs t

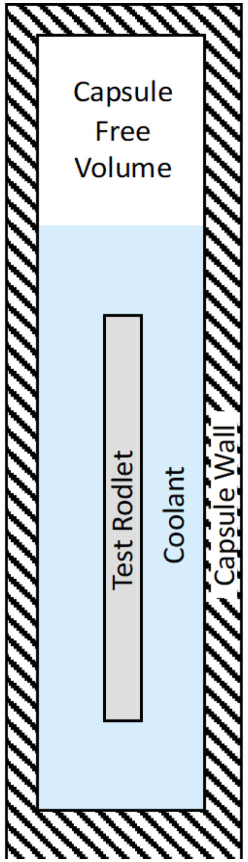
Test Parameter	TREAT	NSRR
Fuel Composition	Fresh UO2	
Fuel Density (kg/m³)	10475	
Cladding Type	Zry-4, stress-relief annealed (SRA)	
Hydride Composition	See Case Table	
Fuel Outer Radius (mm)	See Case Table	
Fuel Pellet Height (mm)	10.160	
# Fuel Pellets	10	12
Total Fuel Mass (g)	57.9	69.4
Cladding Inner Radius (mm)	4.1785	
Cladding Outer Radius (mm)	4.7500	
Plenum Pressure (MPa @ 20°C)	0.1	
Rod Free Volume (cc)	1.23	2.52
Bulk Water Temperature (°C)	20	
Capsule Pressure (MPa)	0.1	
All other parameters not specified (open porosity, fuel grain size, surface roughnesses, cladding properties, etc.) should be set by the performer using default values or best judgment in selection for fresh fuel in a pulse irradiation.		



Capsule Parameters

- Thermal-hydraulics model of capsule not necessary but provided if desired
  - Capsule thermal-hydraulic parameters can be used if desired
- Transient thermal-hydraulics is an area of significant uncertainty
  - Wanted each participant to use their best estimate or best judgement to model thermal-hydraulic boundary conditions
  - Some participants codes do not have thermal-hydraulic modeling capabilities so T-H boundary conditions provided upon request
    - RELAP5-3D

Test Parameter	TREAT	NSRR
Water Outer Radius (mm)	25	120
Capsule Water Volume (cc)	280	6250
Capsule Argon Free Volume (cc)	500	2350



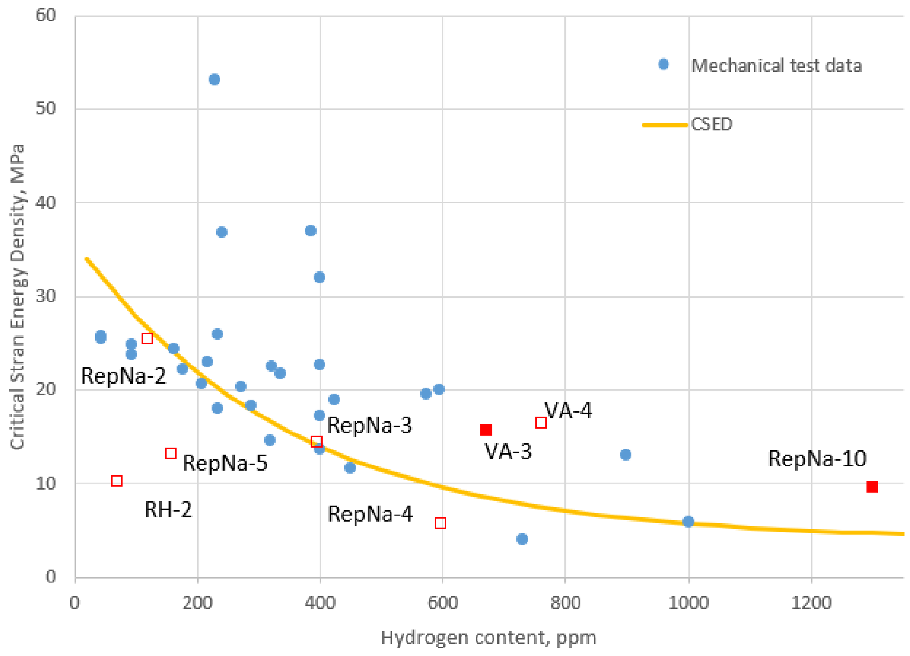
Requested Outputs

- Model Outputs
  - Unless specified otherwise, all values reported at axial fuel centerline as *f*(t)
  - Primary exercise targets
    - Radial average enthalpy increase
    - Cladding surface temperature
    - Apparent stress intensity factor, $K_I = \sigma_0 \cdot \mathrm{sqrt}(\pi \cdot a)$
      - Hoop stress at cladding outer rim
    - Cladding Failure Prediction
      - This can be different for each participant so each output was normalized by the critical value for failure
      - Any value larger than 1 predicts failure

Parameter	***Unit***	***Description***
CFP	**n/a**	**Cladding failure prediction defined as CFP(t) = max(X(t)/X_critical(t)).** X is any cladding failure parameter used by the participant and X_critical is the critical value for predicted failure.
RAE	**J/g**	**Variation of radial average enthalpy with respect to initial conditions of the transient in the rodlet (note that: RAE(t=0)=0)**
TCO	**°C**	**Temperature of cladding outer surface**
SIF	**MPa√ m**	**Apparent stress intensity factor (see Section 3.1)**; if other relevant parameter is calculated by a code, it can also be added as a new column in the results file
CFR	%	Cladding final hoop strain at cooled state (t = 200s), permanent hoop strain *as function of z where z= 0 is fuel stack bottom*
TDE	J/g	Total energy deposited per unit mass of fuel
TFC	°C	Temperature of fuel centerline
TFO	°C	Temperature of fuel outer surface
TCI	°C	Temperature of cladding inner surface
ECMH	%	Cladding mechanical (elastic + inelastic) hoop strain at the outer radius
ECMZ	%	Cladding mechanical (elastic + inelastic) axial strain at the outer radius
ECTH	%	Cladding total (thermal + elastic + inelastic) hoop strain at the outer radius
ECTZ	%	Cladding total (thermal + elastic + inelastic) axial strain at the outer radius
ECT	mm	Cladding total axial elongation
EFT	mm	Fuel column total axial elongation
SCH	MPa	Cladding hoop stress at outer radius
SCZ	MPa	Cladding axial stress at outer radius
RFO	mm	Fuel outer radius
RCI	mm	Cladding inner radius
HFC	$W/m^2/K$	Fuel to cladding heat transfer coefficient
HCW	$W/m^2/K$	Cladding to water heat transfer coefficient
PG	MPa	Free volume pressure
VOL	cc	Free volume

BISON Modeling Options

- Simple volumetric heat load applied to fuel
  - Uniform radial and axial power profile
- UO_2
  - NFIR thermal conductivity model
  - MATPRO specific heat, Young's Modulus, thermal expansion models
  - No inelastic models used
- Zircaloy-4
  - MATPRO thermal conductivity, specific heat, thermal expansion models
  - Plastic and creep inelastic models
- Failure
  - No built-in cladding failure model for RIAs in BISON
  - Used the Critical Strain Energy Density (CSED)** for PCMI failure
    - CSED is a function of hydrogen content in cladding
  - BISON calculates the SED
    - Requires modeling frictional contact between fuel and cladding which adds considerable computational time

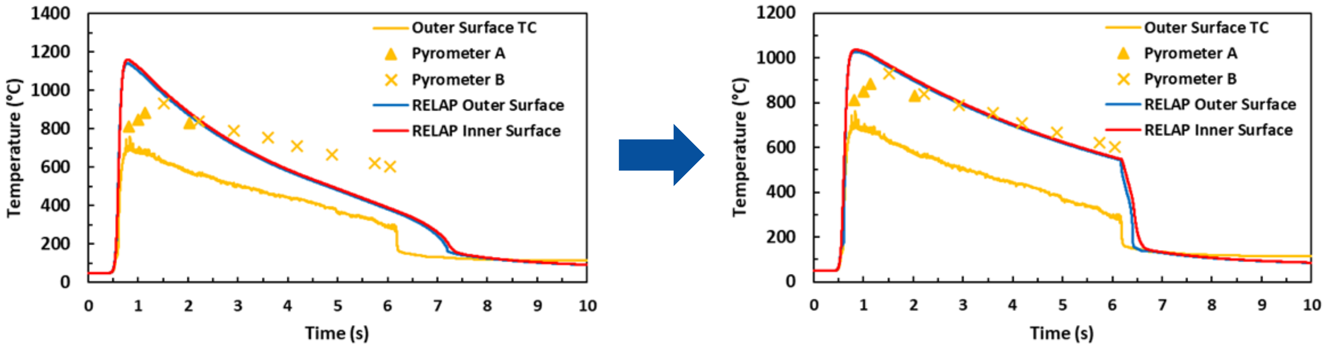


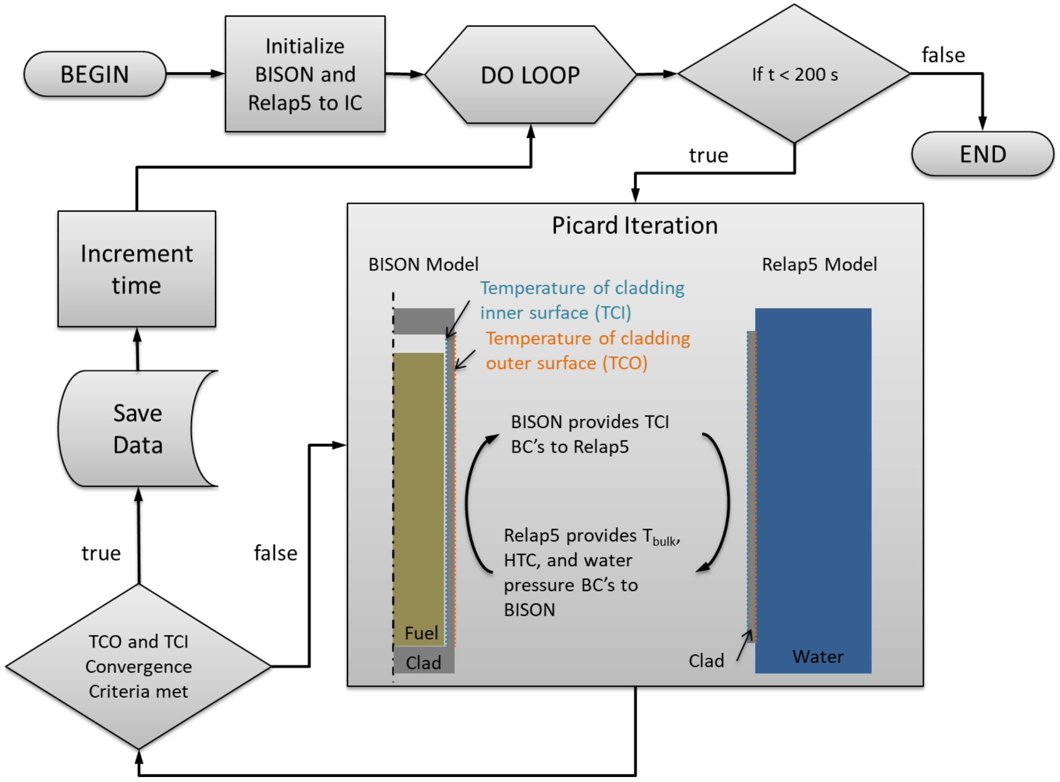
**Strain energy density calculated by BISON in comparison to a CSED (as a function of total hydrogen content) failure model; solid symbol represents failure case, and hollow symbol represents non-failure case

*Joe Rashid, Mark Rashid, Albert Machiels, and Robert Dunham. "A new material constitutive model for predicting cladding failure." *In Proceedings of Top Fuel 2009*. Paris, France, September 6-10 2009
**W. Liu, A. Mai, J. Alvis, J. Rashid, C. Folsom and R. Williamson, BISON Application to the Analysis of LWR Fuel Responses under Accident Conditions, Global/Top Fuel 2019, Seattle, WA, 2019

Thermal Hydraulic Modeling

- Calculations done with BISON *coupled to RELAP5-3D
  - Provides pool boiling thermal-hydraulic capabilities not available in BISON
  - Rely on built-in heat transfer model in RELAP5-3D
    - Can modify with multiplication factors
  - Using best-fit parameters for CHF from separate-effect in-pile experiments at TREAT
    - 90 ms pulse results in an ~3X factor on CHF





**CHF-SERTTA B-2 experiment results, Default vs Best-fit thermal hydraulic parameters

*C. Folsom, C. Jensen, R. Williamson, N. Woolstenhulme, H. Ban, and D. Wachs, BISON Modeling of Reactivity-Initiated Accident Experiments in a Static Environment, Top Fuel, Boise, ID, September 11-16, 2016.
*Folsom, C. P. (2017). Fuel Performance Modeling of Reactivity-Initiated Accidents Using the Bison Code (Doctoral dissertation, Utah State University).
**R. Armstrong, C. Folsom, A. Fleming and C. Jensen, Results of the CHF-SERTTA In-Pile Transient Boiling Experiments at TREAT, Top Fuel 2021, Santander, Spain, 2021
**R. Armstrong, C. Folsom, C. Hill and C. Jensen, Calculation of Critical Heat Flux Using an Inverse Heat Transfer Method to Support TREAT Experiment Analysis, International Conference on Nuclear Engineering, 2020

Modeling Results

- Peak Radial Average Enthalpy Rise very close to the specified targets
  - Case 12 overshot target (677 J/g)
- Cladding failure prediction shows effect of pulse width (1,6,11,12)
  - Cladding hydrogen affects failure (1,2,3 & 6,7,8)
  - Fuel-cladding gap impacts failure prediction (1,13 & 6,14)

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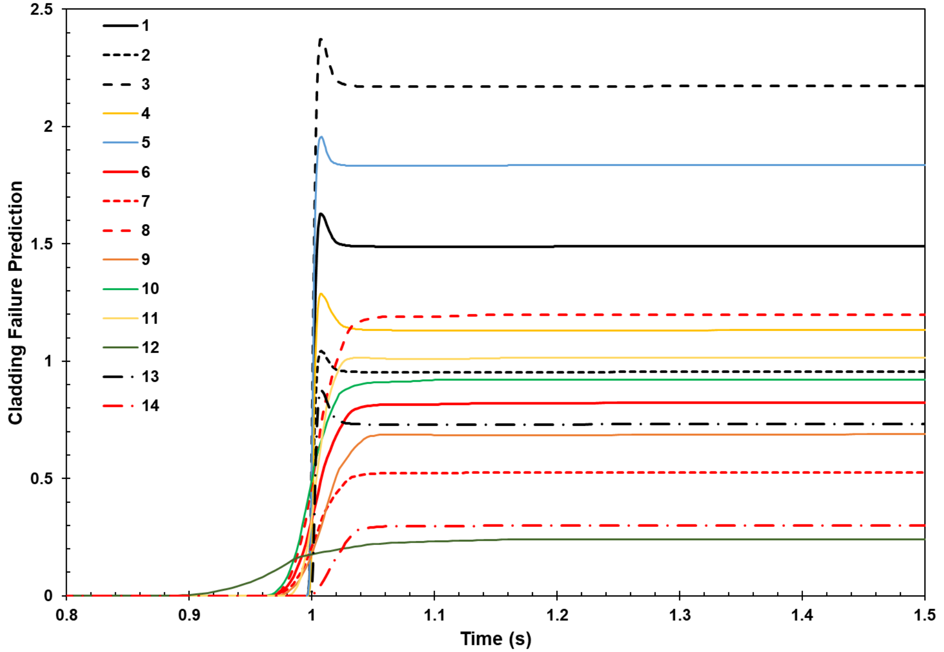

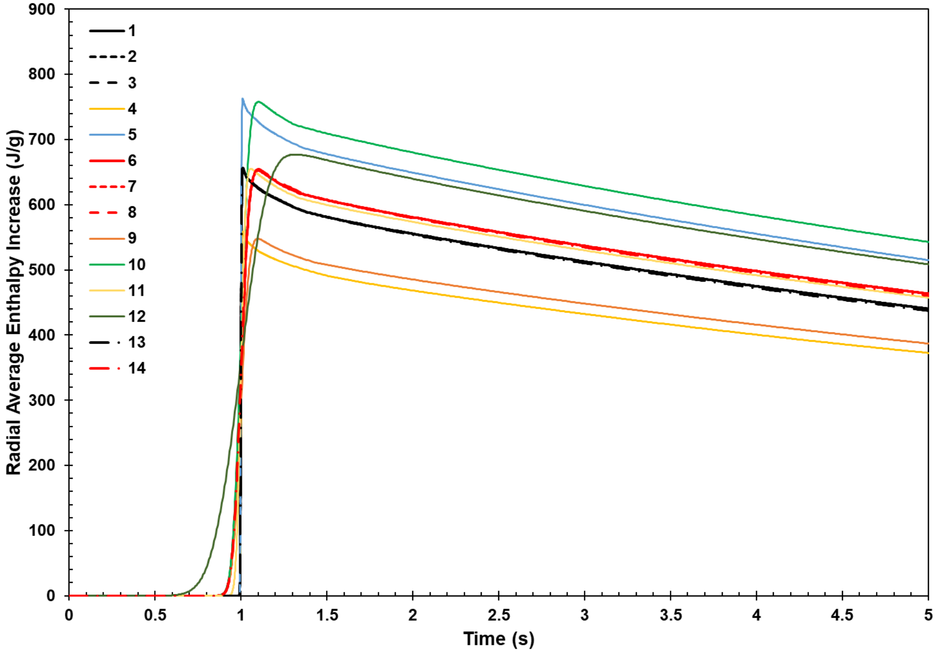

Modeling Results

- Large variation in cladding stress even though consistent strains (pulse width effect)
  - Cases 1, 6, 11, 12

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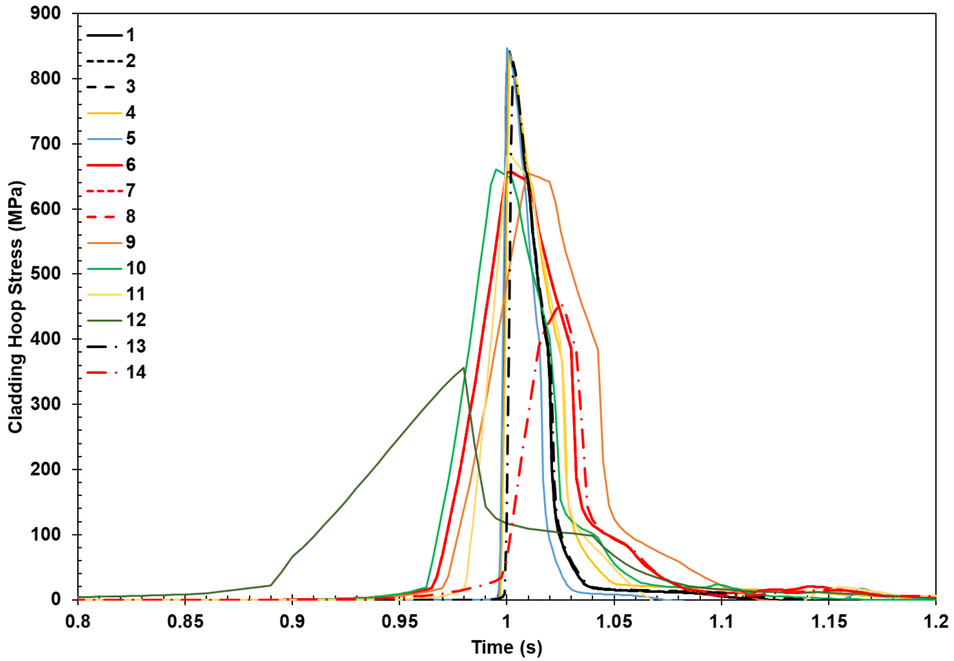

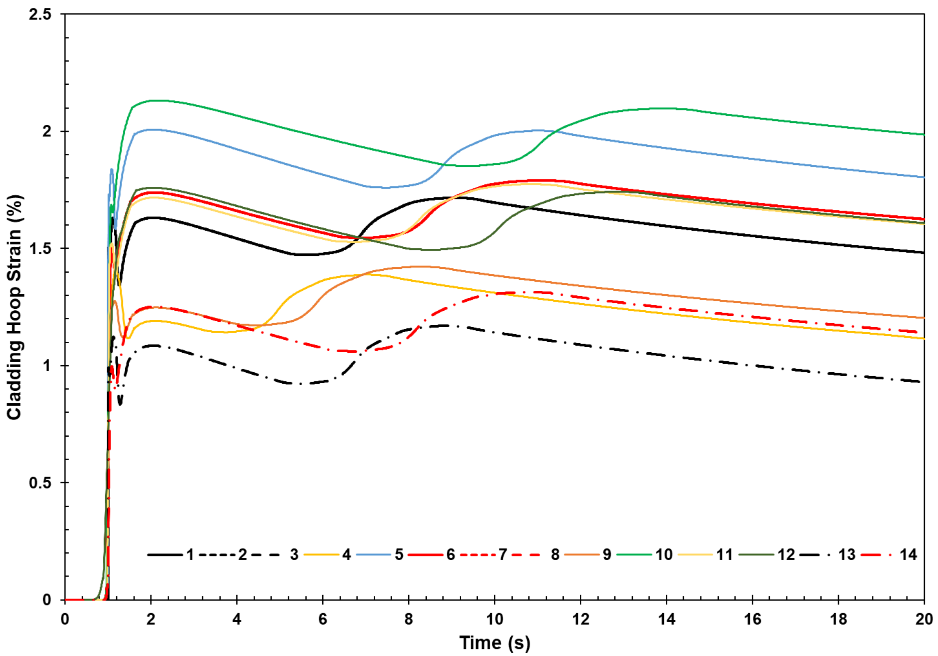

Modeling Results

- Fuel centerline temperature mainly dependent on energy deposition
- Cladding temperatures do not show a dependence on pulse width or fuel-cladding gap

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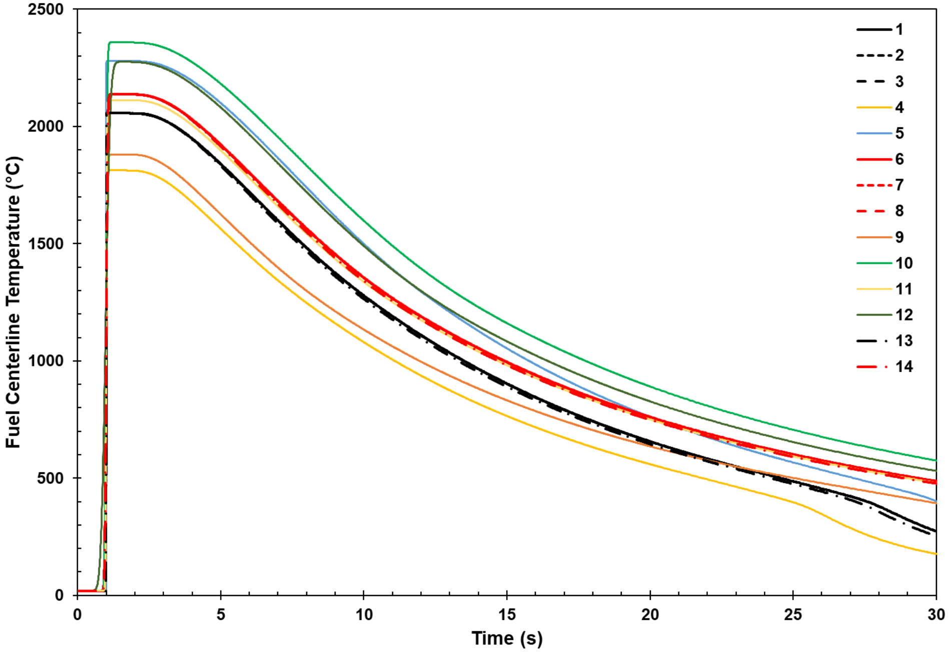
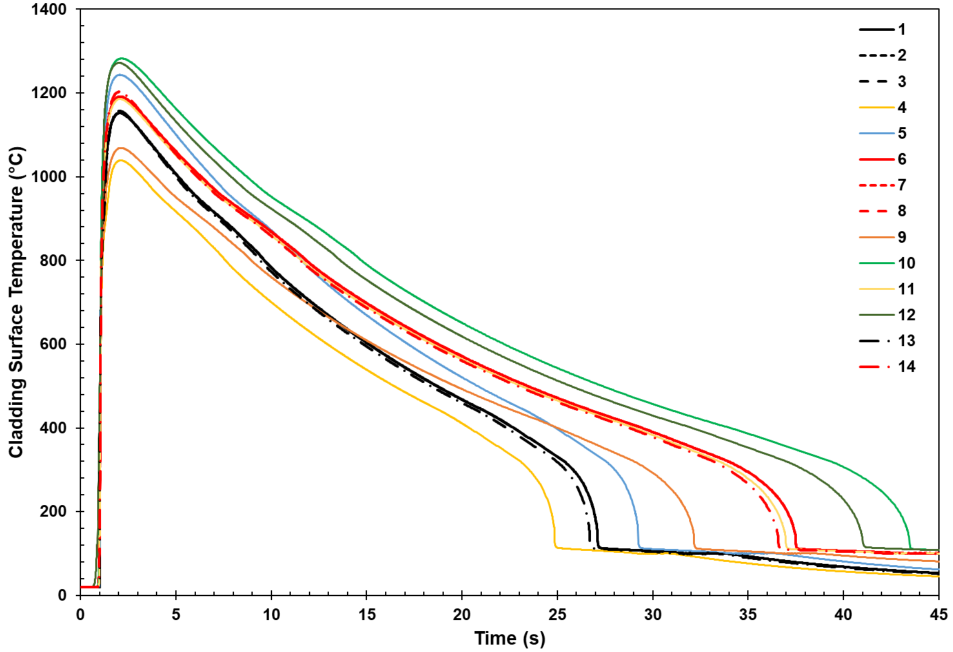




Benchmark Comparison Quick Look

- Submissions
  - 20 orgs including all 5 core group members (WEC via NCSU)
    - ~5 non-FIDES participants
    - 3 universities
  - 19 individual modelers
  - 15 different codes

Case #	HERA Test ID	Test Capsule/ Specimen	Pulse Width (ms)	Target Energy Deposition (J/g)	Hydrogen Content/Rim t (ppm/µm)
1	HERA-PreH-1,2	NSRR	7.5	**650**	**400/80**
2				650	200/40
3				650	600/140
4				550	400/80
5				750	400/80
6	HERA-PreH-3,4	TREAT	90	**650**	**400/80**
7				650	200/40
8				650	600/140
9				550	400/80
10				750	400/80
11	HERA-PreH-5,6	TREAT	~50	**650**	**400/80**
12	HERA-PreH-5,6	TREAT	~300	**650**	**400/80**

Next slides

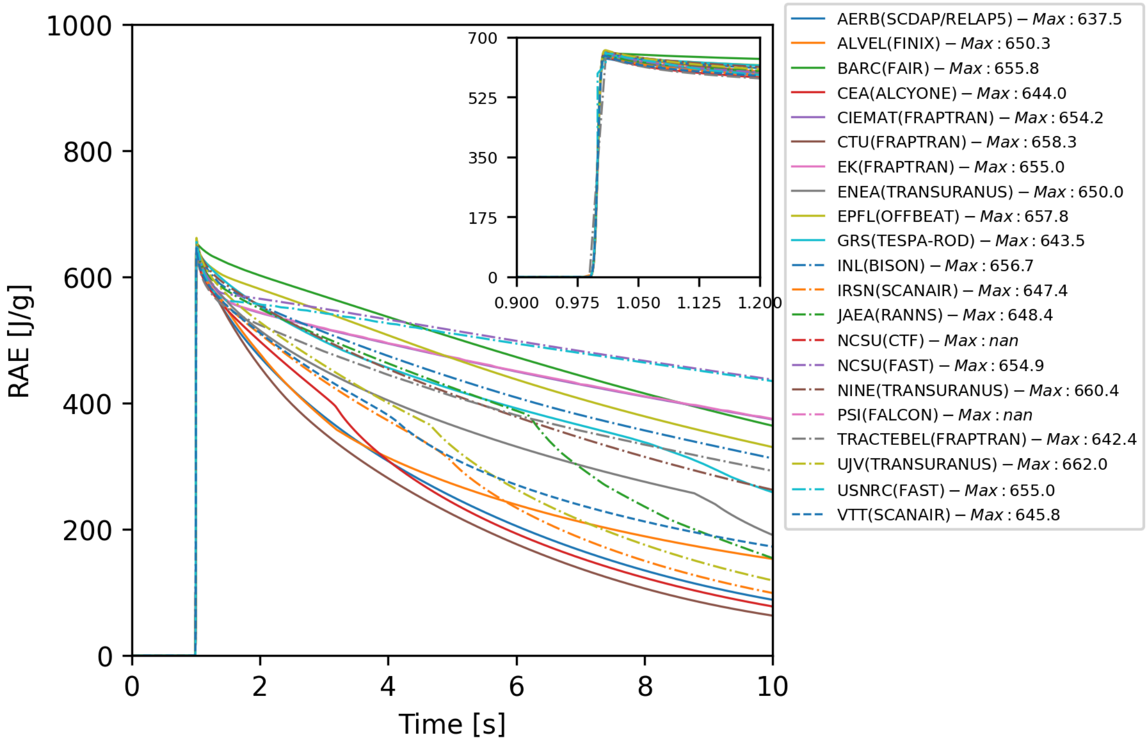
Table 4. Requested output parameters. Primary outputs are bolded while secondary are regular font.

Parameter	*Unit*	*Description*
CFP	**n/a**	**Cladding failure prediction defined as CFP(t) = max(X(t)/X_critical(t)).** X is any cladding failure parameter used by the participant and X_critical is the critical value for predicted failure.
RAE	**J/g**	**Variation of radial average enthalpy with respect to initial conditions of the transient in the rodlet (note that: RAE(t=0)=0)**
TCO	**°C**	**Temperature of cladding outer surface**
SIF	**MPa√ m**	**Apparent stress intensity factor (see Section 3.1)**; if other relevant parameter is calculated by a code, it can also be added as a new column in the results file

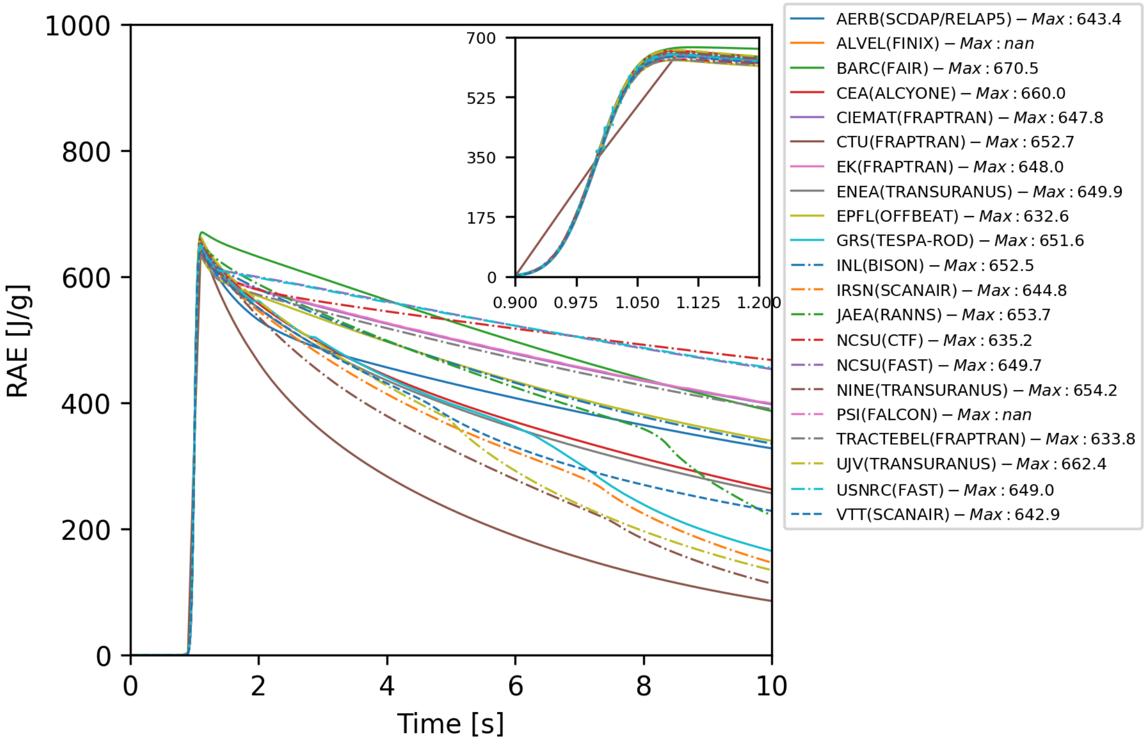
Examples of all Participant Results

Radial Average Enthalpy

Case 1 (NSRR)



Case 6 (TREAT)

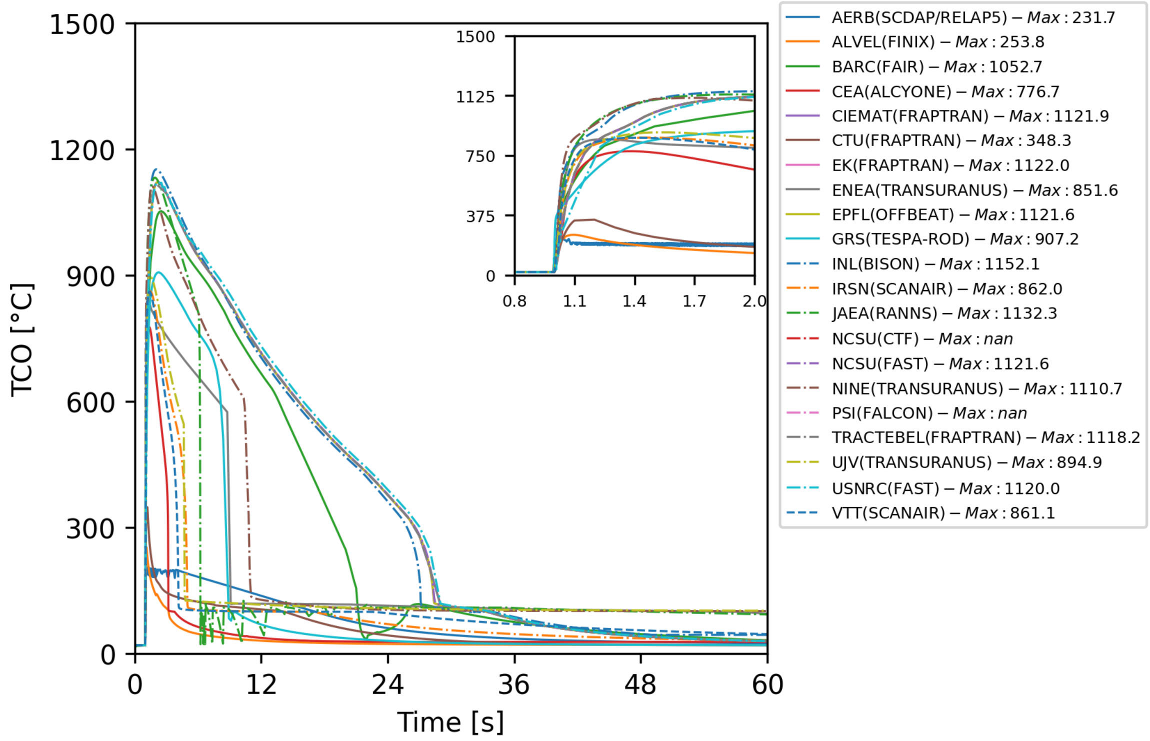


- Good consistency in Peak RAE for NSRR case, a bit less for TREAT
- Wide variation in RAE vs time (next slide)

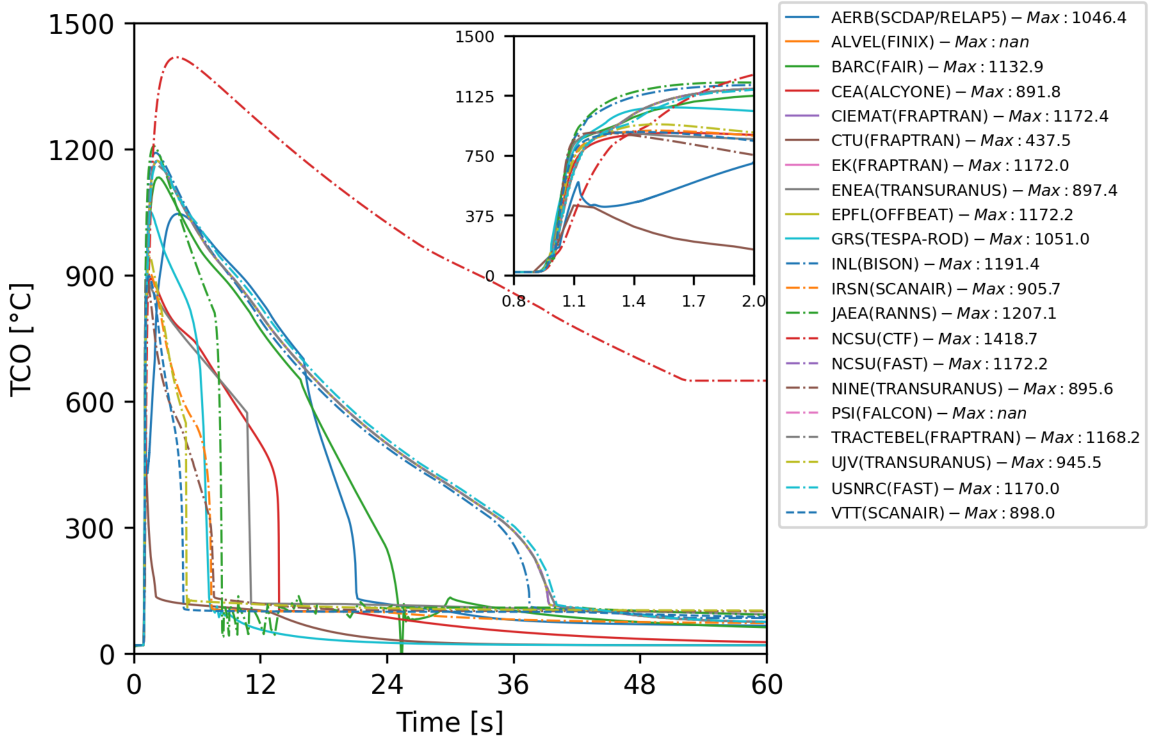
Examples of all Participant Results

Cladding Surface Temperature

Case 1 (NSRR)



Case 6 (TREAT)

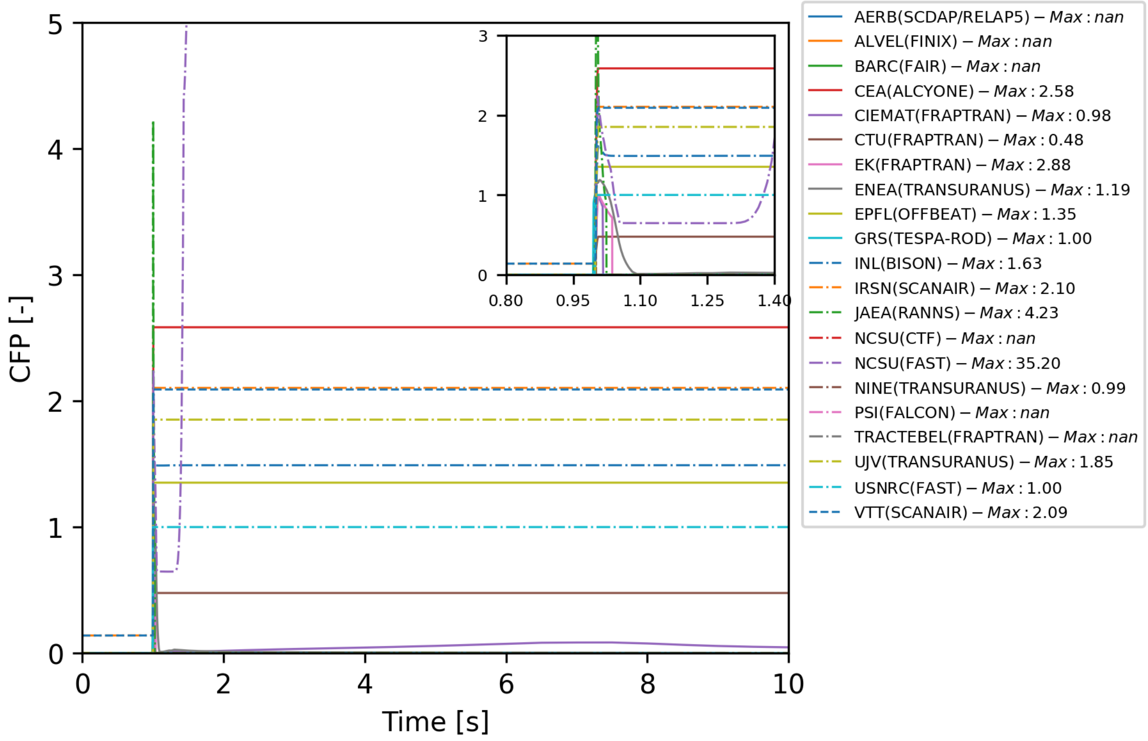


- Wide variation in peak temperatures and duration of DNB
  - Expected and consistent with previous RIA benchmarks

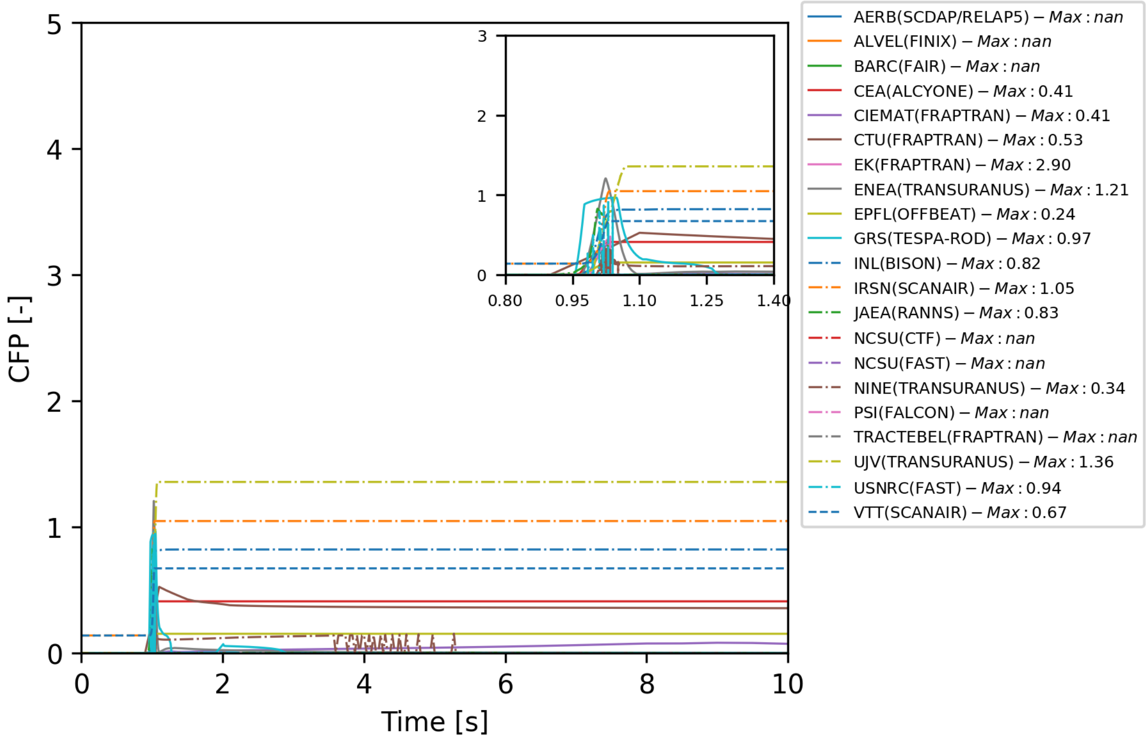
Examples of all Participant Results

Cladding Failure Prediction

Case 1 (NSRR)



Case 6 (TREAT)



- NSRR case predicted to fail; TREAT results is split
  - The experiment is designed to exploit this result.

Conclusions

- INL organized an international fuel codes benchmark as part of the HERA project
- Benchmark consisted of 14 cases targeting different
  - Pulse width, energy deposition, cladding hydrogen content, fuel-clad gap
- INL participated with BISON coupled to RELAP5-3D
- Results show that predicted failure is dependent on pulse width, hydrogen content, and initial fuel-clad gap
- Good participation from the international community in the benchmark