INL/CON-23-74019-Revision-0

Applications of Similarity Analysis of Reactivity-initiated Accident Experiments in TREAT

August 2023

Changing the World's Energy Future

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Nuclear Scaling and Applications Workshop 2023

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Motivation

- Time required for new advanced reactor development or new fuel development is economically prohibitive
  - >20 years for “evolutionary” technology (iterations of zirconium cladding)
  - Much longer for “revolutionary” technology
- Recent years there has been an explosion in new reactor or fuel development
  - ATF, SMR, microreactors, etc.
- Need to accelerate the development and qualification of advanced nuclear fuel technology
  - Dan Wachs (National Technical Director of the Advanced Fuels Campaign) has spoken repeatedly on this need

Advanced Fuels Campaign Driver

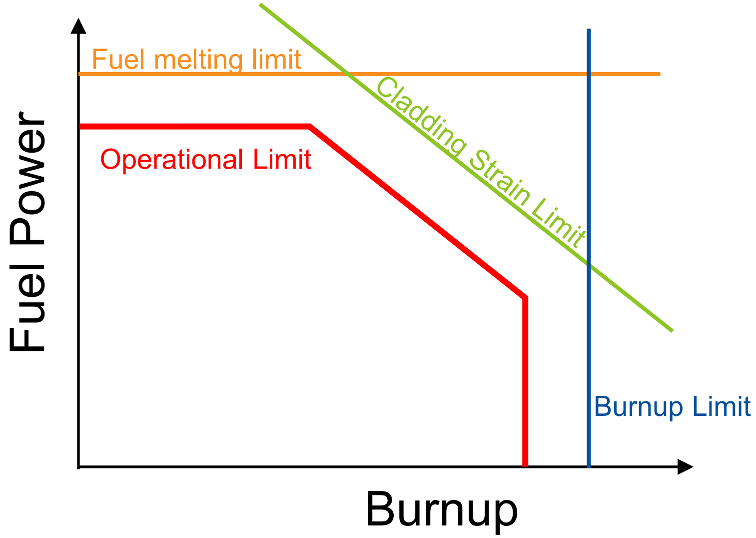
- Some of the main drivers for the Advanced Fuels Campaign
  - Burnup extension
  - Accident Tolerant Fuels - ***driver for the TREAT restart schedule***
- ***Industry Goals for ATF and High Burnup Fuels:***
  - 2023: Burnup extension to 68 GWd/t for current fuels with >5% enrichment; batch reload(s) of near-term ATF concept(s) in commercial reactor(s)
  - 2026: Burnup extension to 75 GWd/t for current fuels
  - 2027: LTA's of 2nd Gen-ATF concept(s) inserted into commercial reactor(s)
  - 2030: ATF concepts operating in multiple commercial reactors to high burnup and with safety benefits realized
  - 2030+: Batch reload(s) of 2nd Gen-ATF concepts in commercial reactor(s)
- Timeline does not allow historic way of qualifying fuel
  - Need to accelerate our process
    - Improve modeling capabilities as well as ways to accelerate irradiation experiments

Why Transient Test Nuclear Fuels?

- **Qualifying fuel requires accident/transient testing**
- **Transient testing is like car crash testing for nuclear fuels**

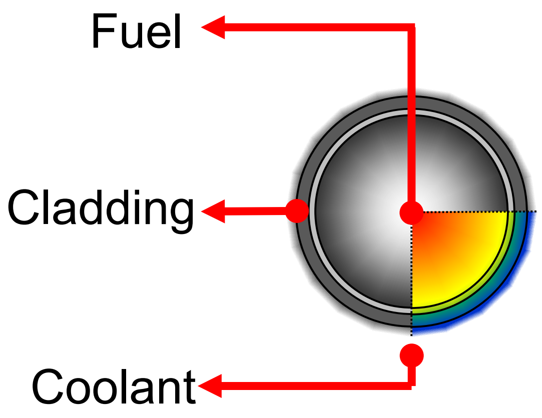
- Licensing a fuel system *requires* (see NUREG-0800):
  - identification of all **degradation mechanisms** and **failure modes**
  - definition of **failure thresholds** corresponding to each degradation mechanism
  - applies to normal operations, anticipated operational occurrences and design basis accidents

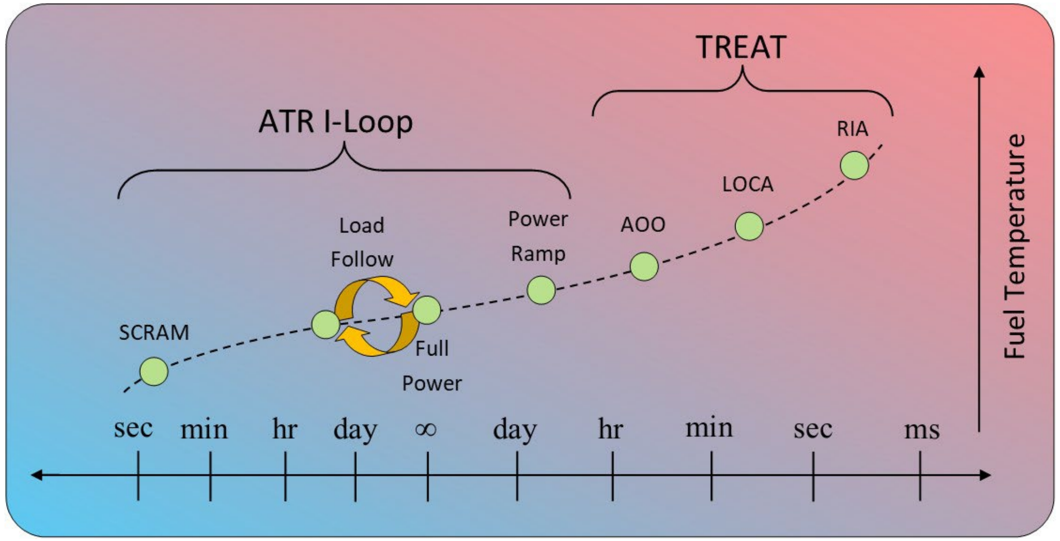
- Many operational limits are dependent on failure and degradation thresholds
- Understanding failure limits allows operation margins to be specified
- Enables economic reactor operations with improved fuel design and performance understanding



Transient Conditions of Interest

- Fundamentally defined by an **imbalance of heat generation and heat removal** from the core
  - Overpower (reactivity insertion) and Undercooling (loss of coolant/flow) tend to result in challenging temperature conditions
  - Includes expected and unexpected events



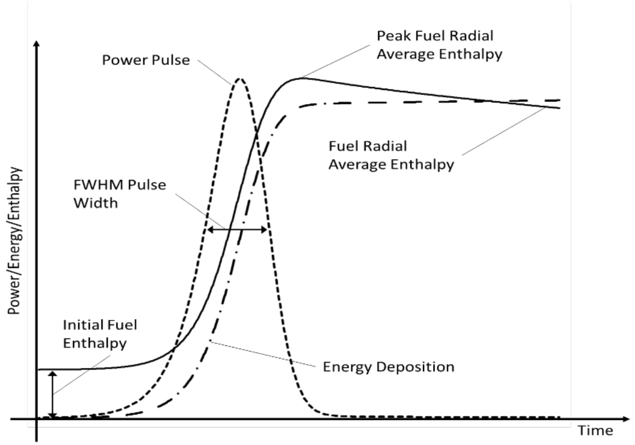


power-cooling mismatch spectrum

  - Reactivity-initiated accident (RIA) is a nuclear accident involving an unwanted increase in fuel fission rate and thus reactor power
    - Rod ejection accident or control rod drop accident results in localized/core wide reactivity increase

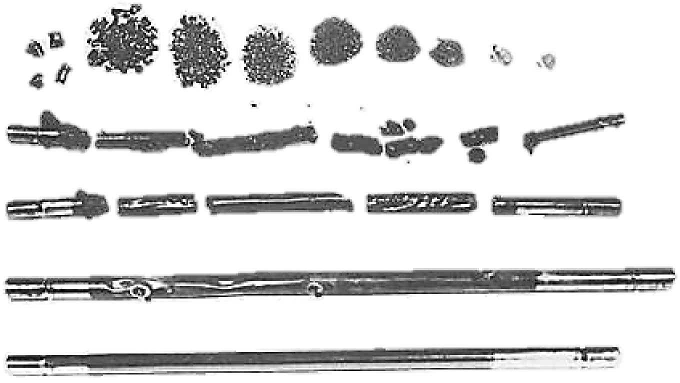
Integral Testing for Fuel Safety Criteria for RIA

- Fuel Safety Criteria defined by regulations developed from historical transient testing experiments
- ~100 tests to simulate RIA conditions and subsequently establish empirical fuel safety criteria for UO2/Zry. Still ongoing debate for modern claddings and high burnup fuels
  - Reactivity control system design
    - 10CFR50 Appendix A: General Design Criterion 28
      - Prevent damage to the pressure boundary
      - Maintain coolable geometry
    - Regulatory Guide 1.77 and NUREG-0800 Standard Review Plan
      - Compliance is demonstrated by accounting for:
        - Threshold for core coolability (rod deformation and fuel dispersal)
        - Threshold for fuel failure and associated fission product release fraction (plenum pressure) and cladding strain limits



LWR RIA Event

Experiments from the late 1960's in SPERT CDC in Idaho



Energy deposition (cal/g UO_2)

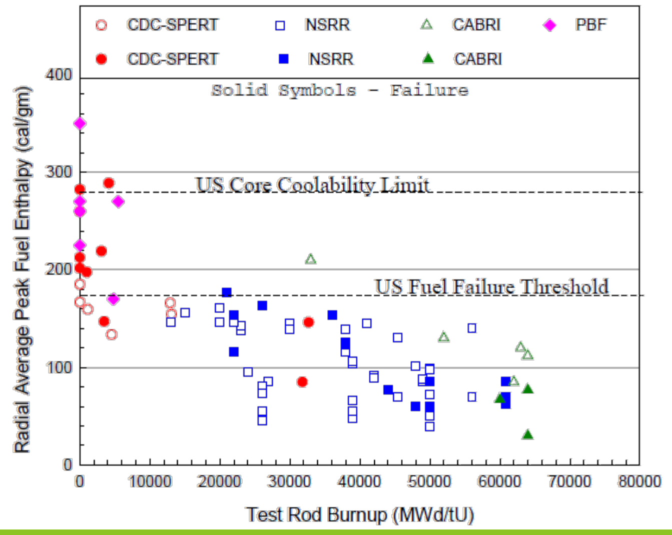
378

338

287

240

168



Road to RIA (LWR testing)

2018 | 2019 | 2020 | 2021 | 2022 | 2023

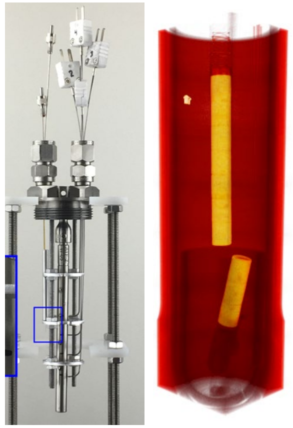
Phase I - Commissioning

- AFC TREAT Power Prescription for LWR transients
- AFC energy deposition studies and dry capsule commissioning
- AFC Dry capsule testing of ATF materials
- AFC Water capsule commission/ first irradiated fuel test
- LDRD In-pile boiling experiments
- ATR Loop 2A

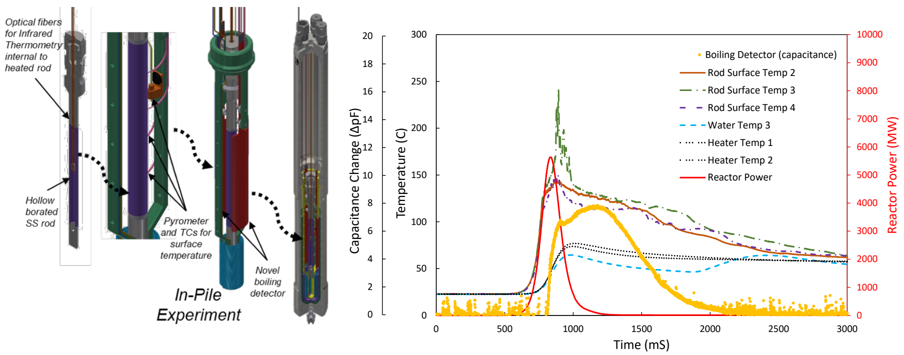
Phase II - HERA

- AFC/NEA HERA Phase I Simulated HBU fuel
- AFC/NEA HERA Phase II Commercial HBU Fuel from Byron Generating Station
- ATF FOA experiments on ATF materials
- NEUP RIA tests on coated cladding fuel

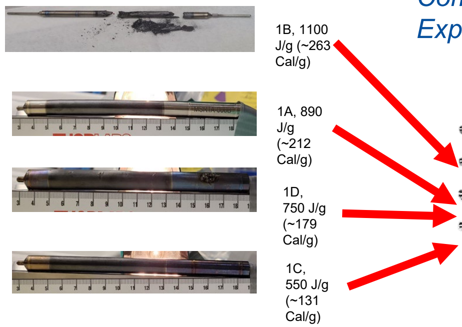
SETH Experiments

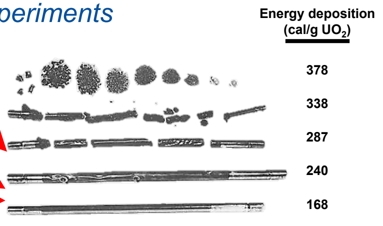


CHF Experiments



SERTTA (water capsule) Commissioning Experiments

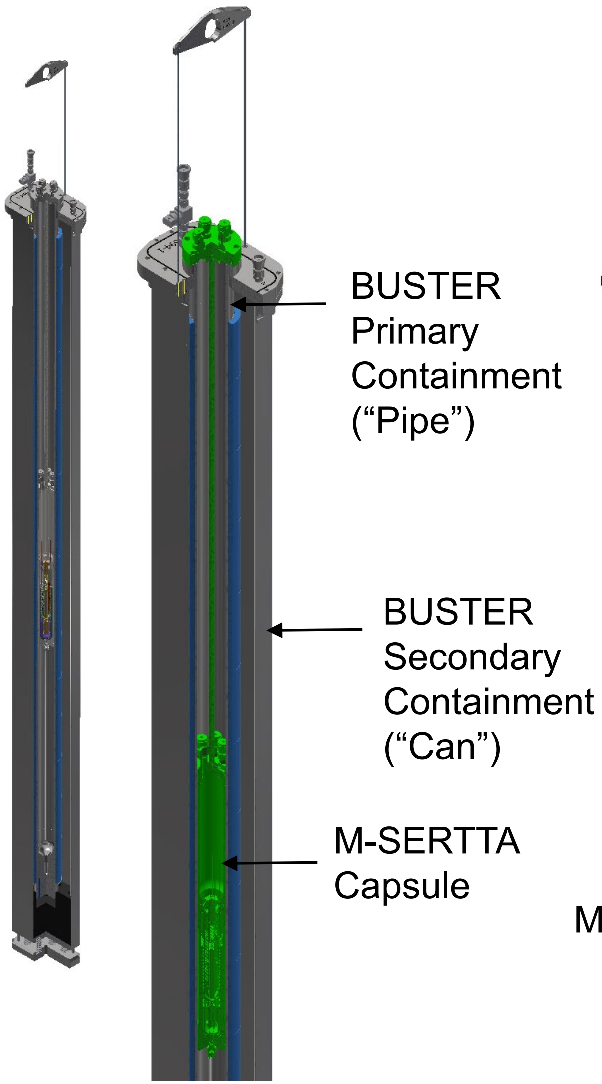


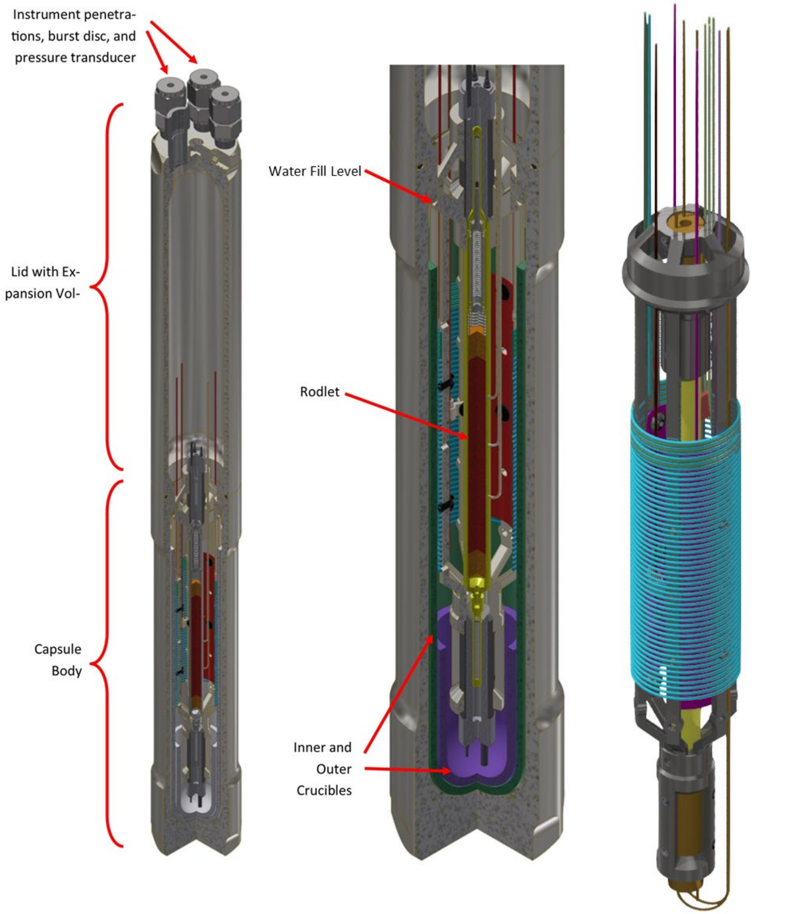


SPERT-CDC RIA Tests Results

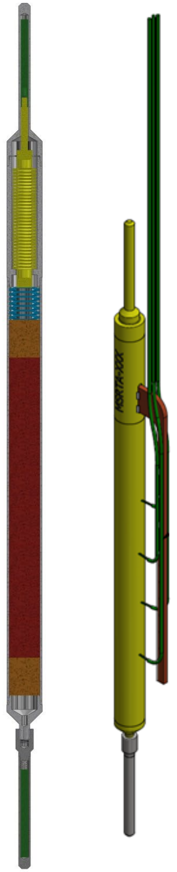
SERTTA Experiment Vehicle

- Static Environment Rodlet Transient Test Apparatus (SERTTA)
  - Capsule designed to fit within the BUSTER primary containment assembly
  - SERTTA Capsule allows for fuel tests in static water with a wide variety of instrumentation
  - Rodlet design
    - 8 “enriched” with 2 Zirconia end pellets





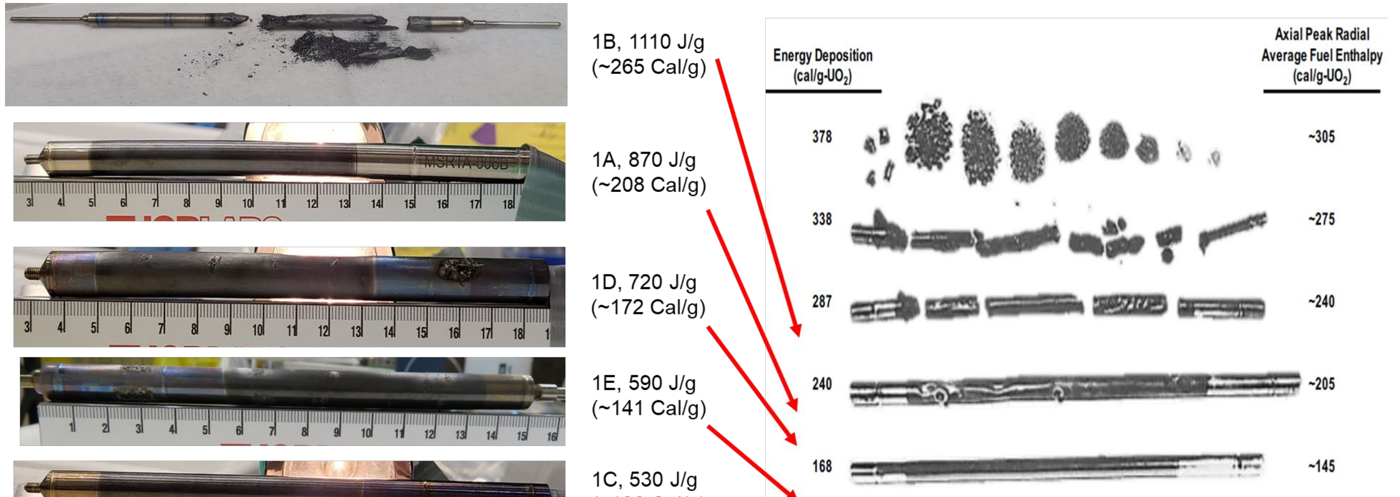
M-SERTTA Capsule (Left, Center), Rodlet Holder (Right)



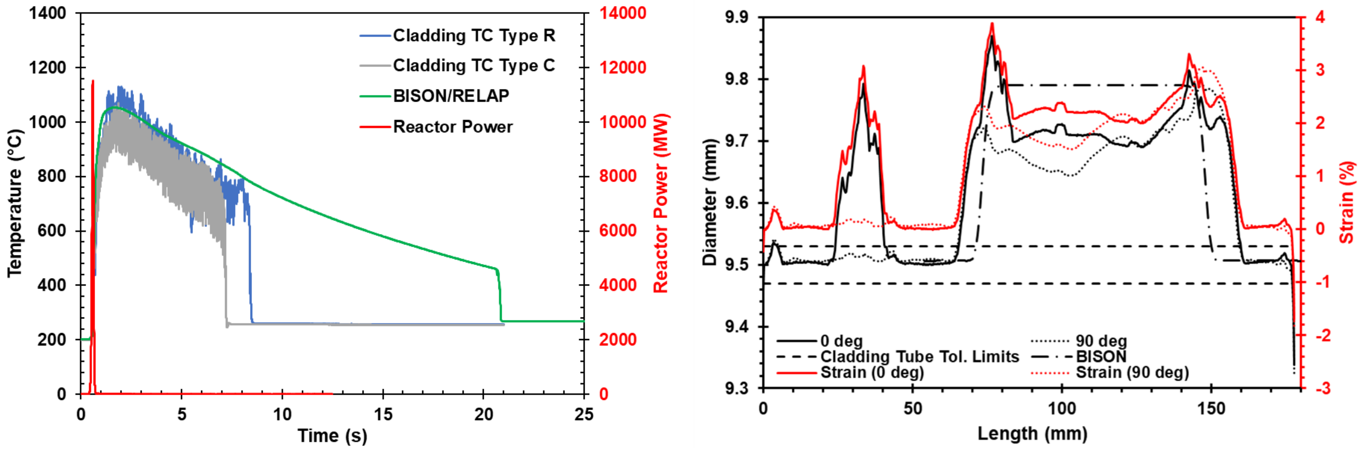
M-SERTTA rodlet

ATF-RIA-1 Experiments

- Experiment goal was to demonstrate capability to do RIA testing in TREAT
  - First in-pile water-based safety testing in the US in more than a generation
  - Five tests targeting different conditions for specific post-test analysis
    - Initial temperature/pressure, transient/energy deposition, instrumentation demonstration
- PIE of experiments show the fuel rodlet condition is similar to historical SPERT-IV tests
- Experiments provide valuable data for post-test analysis and validation of fuel performance codes
- Pros/Cons being used to improve further capsule/experiment designs



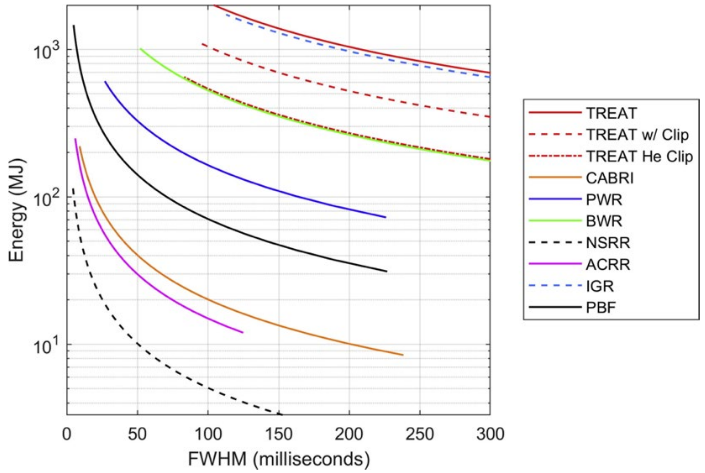
From SPERT-IV Fresh Fuel RIA Tests



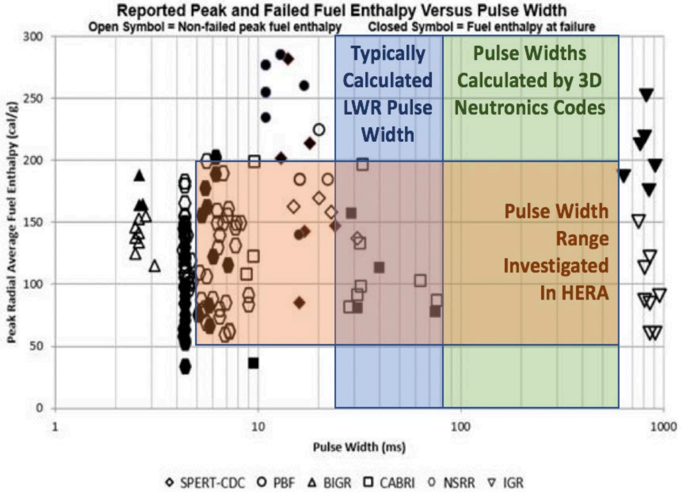
ATF-RIA-1-E experiment cladding thermocouple results (left) and post-transient profilometry measurements (right) along with coupled BISON/RELAP5-3D modeling predictions

Translating Prototypic Behavior ⇄ Experiments

- Similarity analyses could help to determine if planned experiments will be "similar" to or representative of prototypic event
  - Or similarity/scaling techniques used to help design accelerated tests so phenomena of interest is represented correctly
- What is a prototypic RIA?
  - Burnup, bundle location, reactor dependent
- Are TREAT (test reactor) experiments representative of a prototypic experiment
  - Data from historic experiments used to set current safety limits
    - Majority had pulse widths varying between 5-30 ms or 800 ms
      - Literature suggests PWR between 25-65 ms and BWR between 45-75 ms
    - Varying boundary conditions
      - Room temperature static water capsule to sodium loop experiments



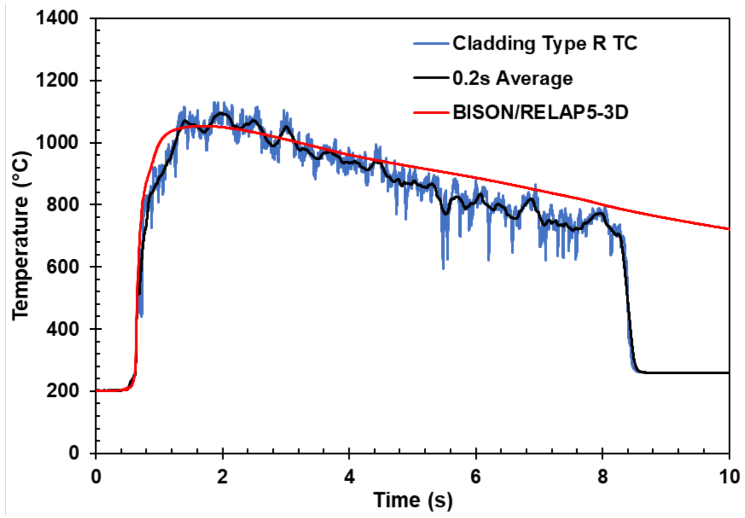
Bess, J., et al., (2019) Ann. Nucl. Energy, 124 548-571

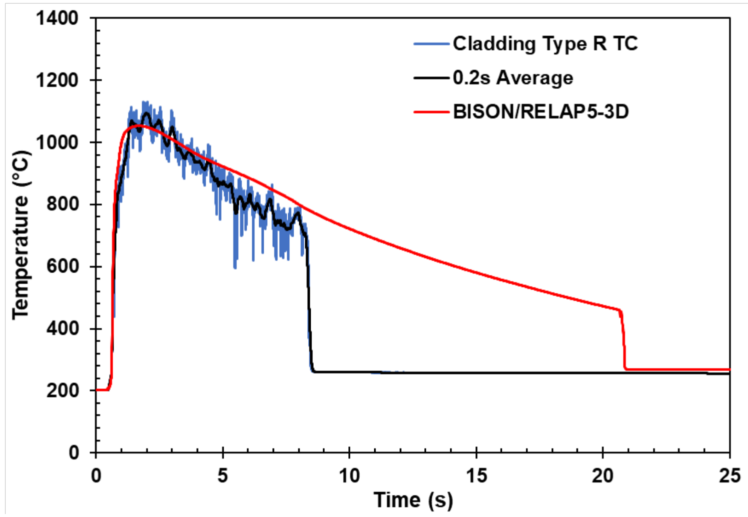


Courtesy Paul Clifford NRC and David Kamerman

SERTTA Similarity Studies

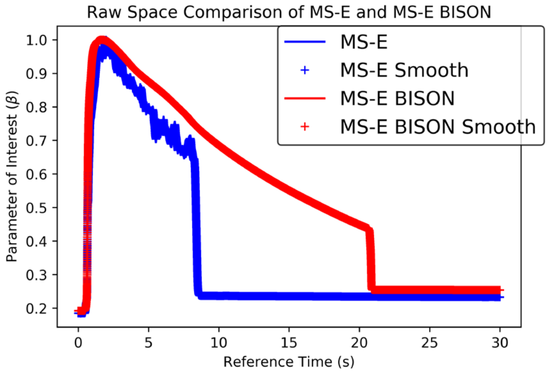
- Currently difficult to determine “prototypic” condition to compare similarity/scaling tools
- Use Dynamic System Scaling (DSS) to compare experiment results to BISON/RELAP5-3D modeling predictions
  - Model predictions similar to experiment results?
- Use one thermocouple from the ATF-RIA-1-E experiment
  - Type R thermocouple data
    - Raw data sampled every millisecond shows a lot of noise
    - Also calculated a 0.2s time average to smooth the results

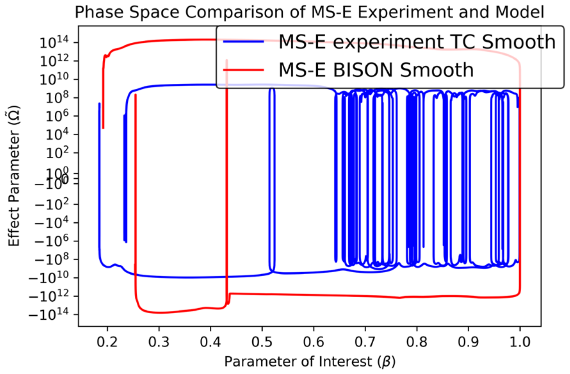


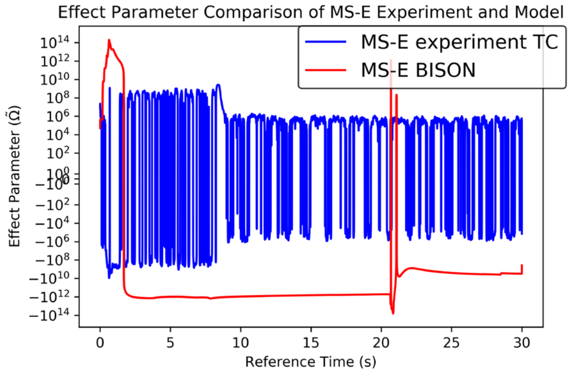


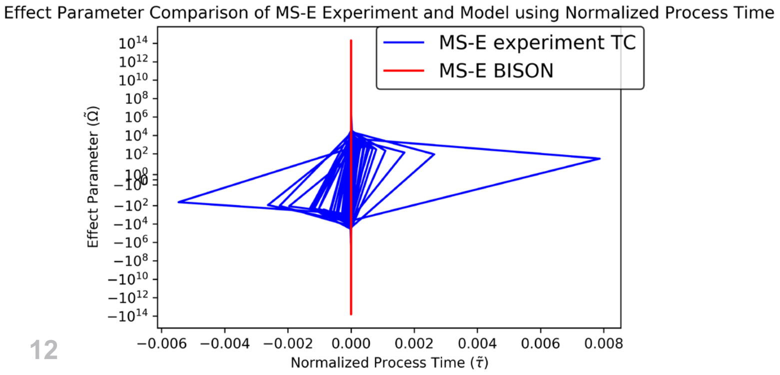
SERTTA Similarity Studies

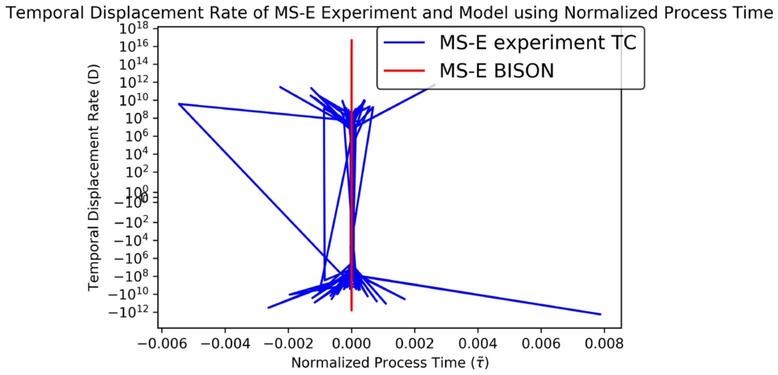
- Entire reference time using the 0.2 second time averaged data
  - TC oscillations
  - Recommended to separate into sections

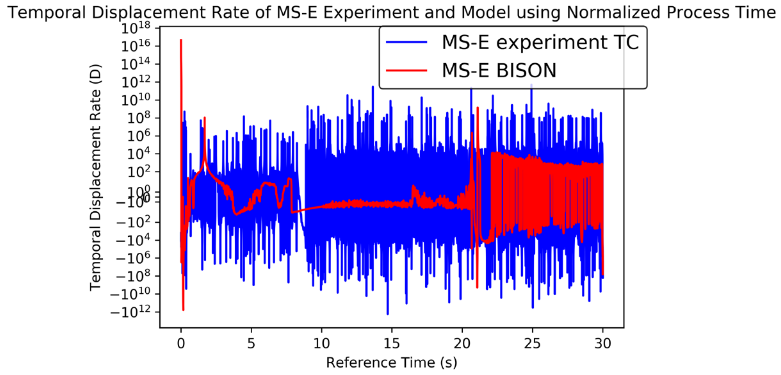






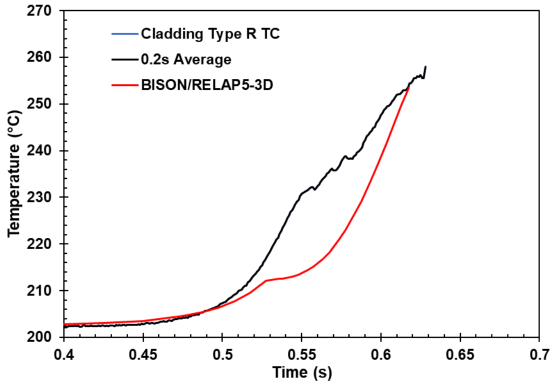


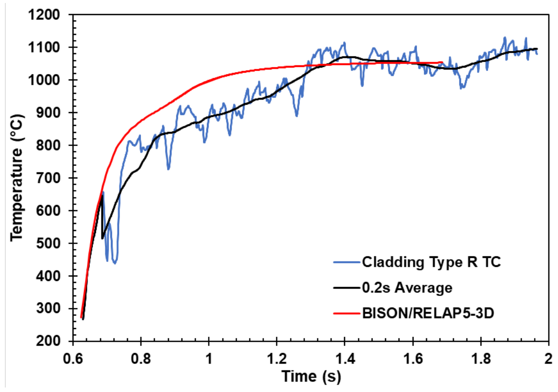


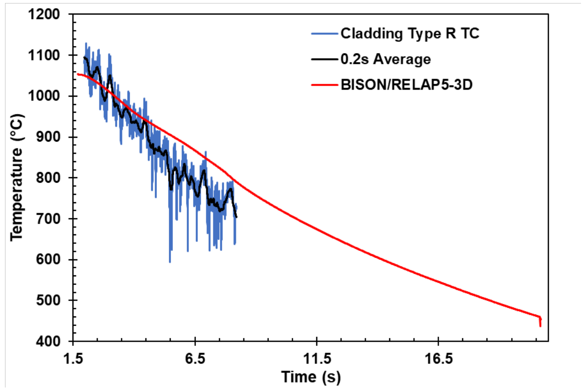


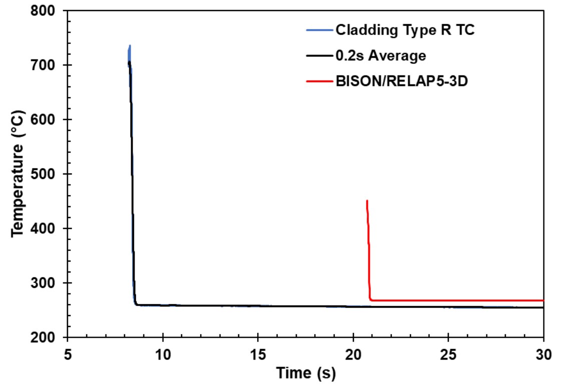
SERTTA Similarity Studies

- Separated the problem in 4 phases
  - Up to departure from nucleate boiling
  - DNB to peak temperature
  - Peak temperature to rewet
  - Rewet to end



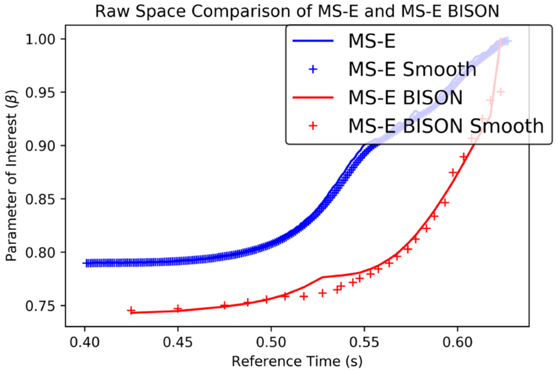


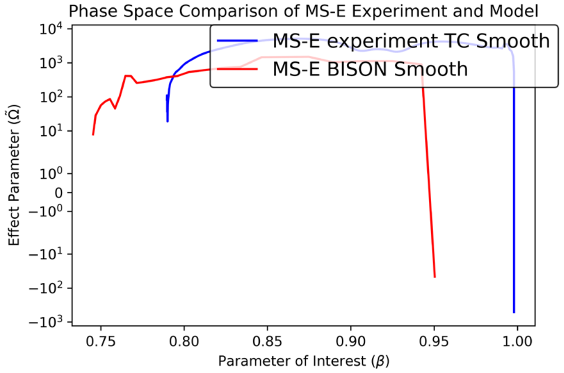


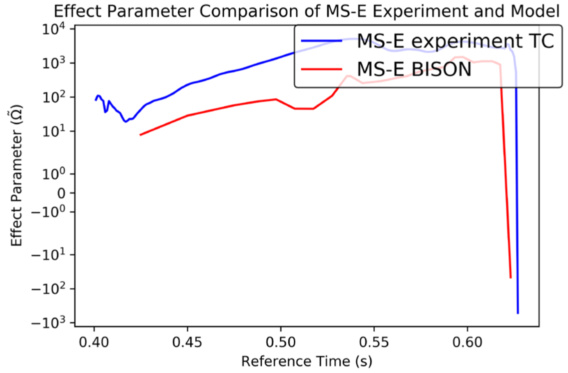


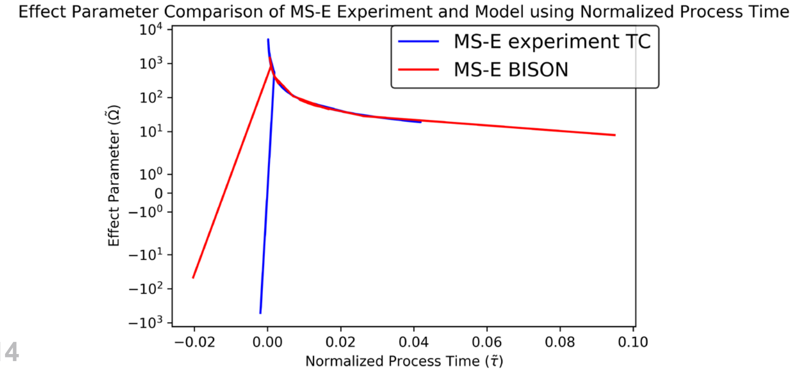
SERTTA Similarity Studies: Phase 1

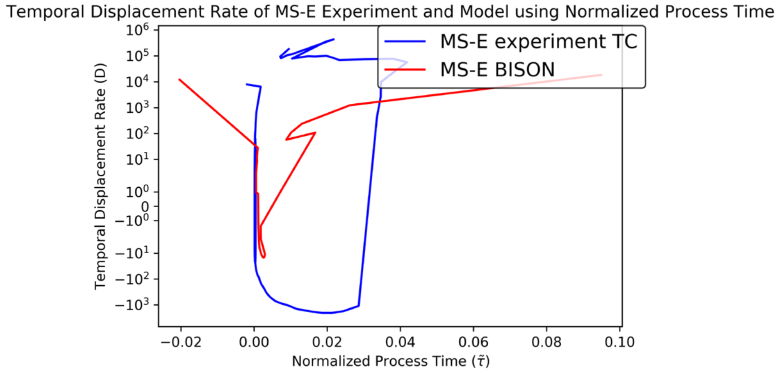
- Phase 1 - Up to departure from nucleate boiling
  - $(\widetilde{\Omega}, \beta)$ diagram: Lack of initial energy injection in BISON, possibly a scaling case of $\lambda_A = 1.05$ and $t_R = 1.1\dot{6}$ in respect to BISON as the model. In other words, the BISON case is a decelerated case of MS-E.
  - $(D, \tilde{\tau})$ diagram: Suggests BISON initial state is starting at $\tilde{\tau}_{BISON} = -0.02$ where $\tilde{\tau}_{MS-E} = 0.002$ but ending at $\tilde{\tau}_{BISON} = 0.097$ where $\tilde{\tau}_{MS-E} = 0.041$. Represents an over injection of energy as the change is larger in BISON $d\tilde{\tau} = 0.095$.

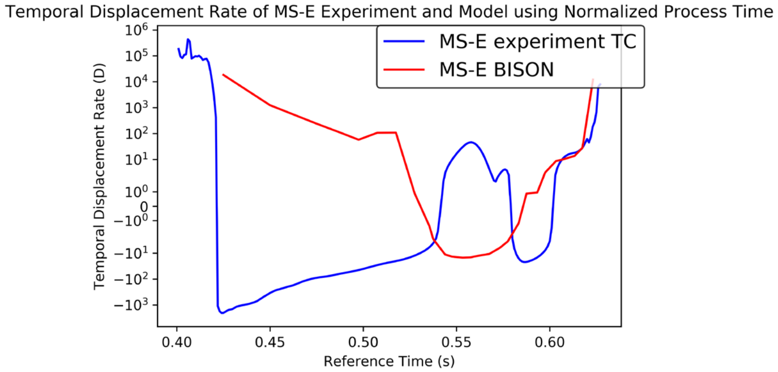






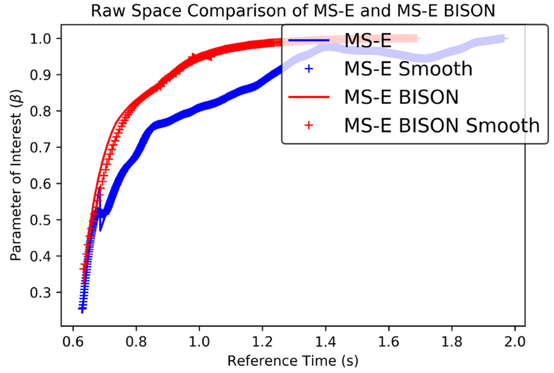


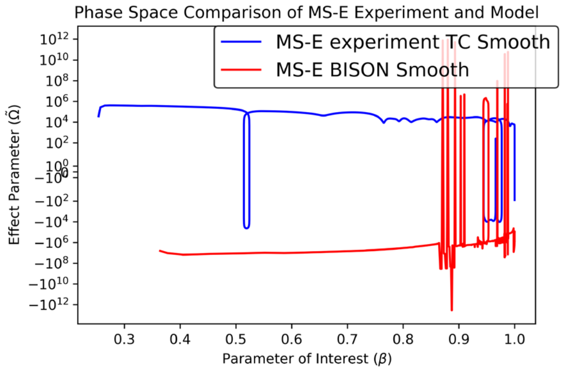


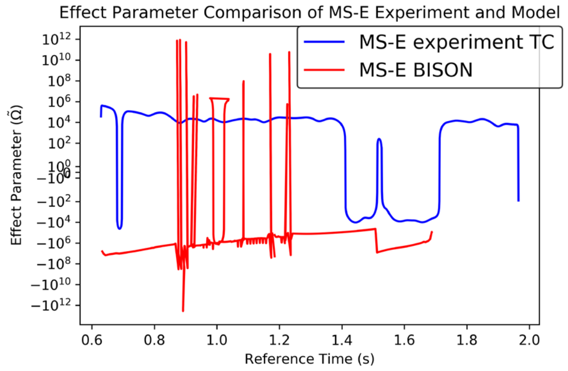


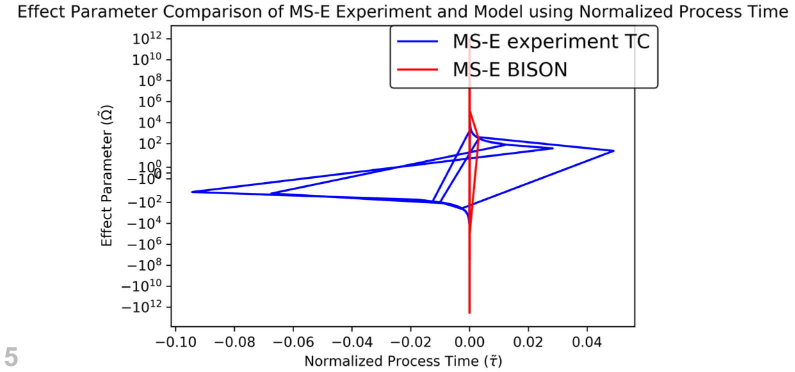
SERTTA Similarity Studies: Phase 2

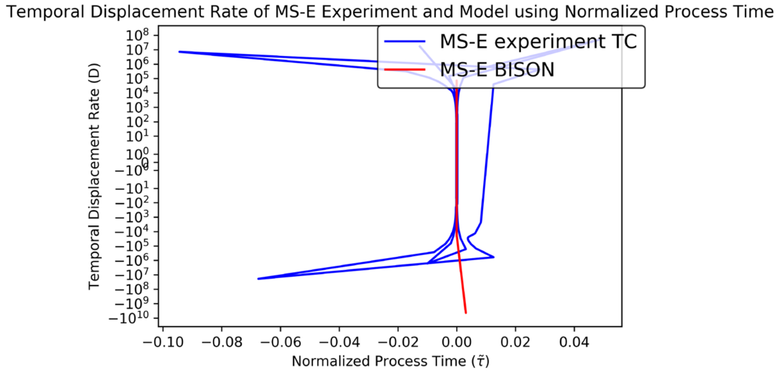
- Phase 2 - DNB to peak temperature
  - (β, t) diagram: BISON reaches critical heat flux before MS-E.
  - $(\tilde{\Omega}, \beta)$ diagram: Although reference time shows difference in timing, the phase diagram suggests both cases ending around similar states.
  - $(D, \tilde{\tau})$ diagram: State changes $(d\tilde{\tau})$ in BISON are significantly smaller than MS-E. Suggest much more process occurring in MS-E than BISON. Phase 2 BISON dataset should be evaluated from an earlier data point.

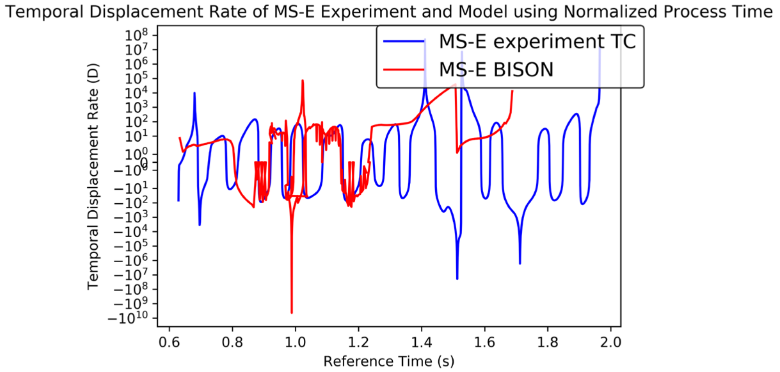






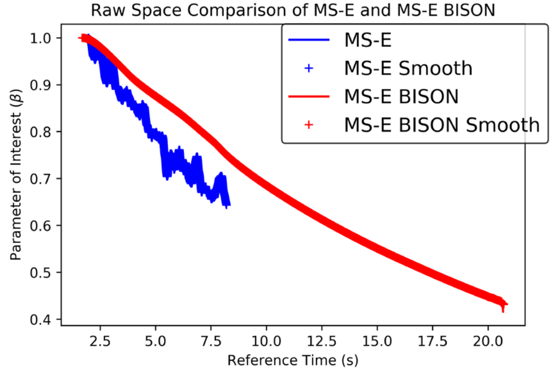


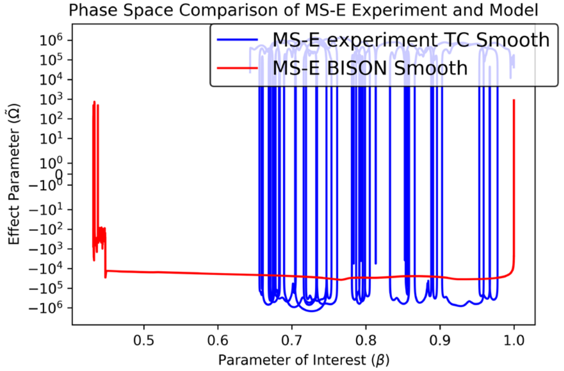


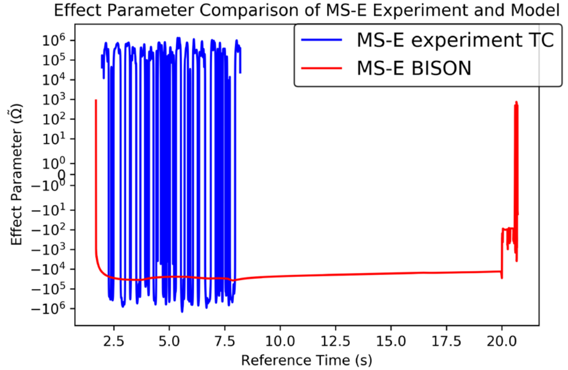


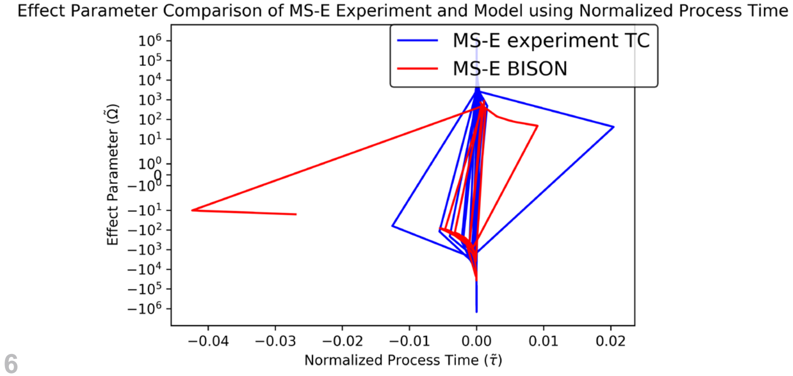
SERTTA Similarity Studies: Phase 3

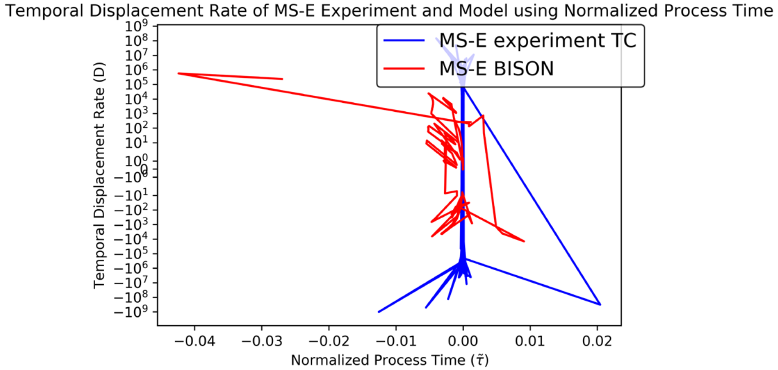
- Phase 3 - Peak temperature to rewet
  - (β, t) diagram: The BISON rewet duration is 2.85 times longer than MS-E.
  - $(\tilde{\Omega}, \beta)$ diagram: Due to the exhibited normalized temperature difference, rewetting models in BISON must be reviewed to ensure the same physics are being modeled. The magnitude of the effect parameter $(\tilde{\Omega})$ are 10^2 different and may suggest the amount of process change in BISON is not enough.
  - $(D, \tilde{\tau})$ diagram: Changes in normalized process time $(d\tilde{\tau})$ are close but more change in BISON is required. The relative change $\frac{d\tilde{\tau}-dt}{dt}$ are $10^3<$ larger for MS-E suggesting BISON is a dilated case of MS-E.

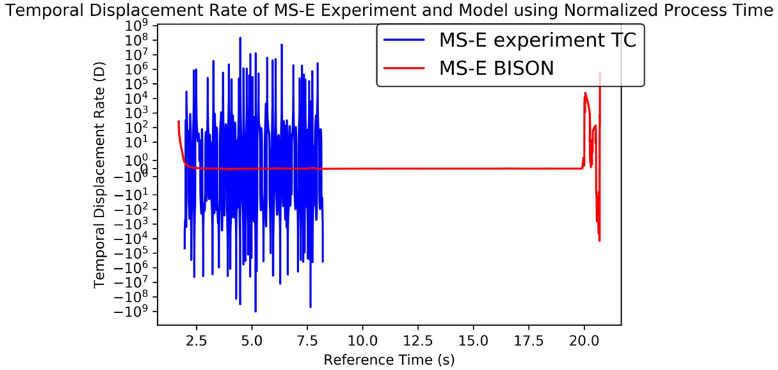












Future Work

- Participating in an international NEA/FIDES project to study High-Burnup Experiments in Reactivity-Initiated Accidents (HERA)
  - Six RIA tests with pre-hydrided cladding and oversized UO2 pellets at different pulse widths (TREAT and NSRR)
  - Four RIA tests with actual high burnup material
  - Modelling and Simulation Exercise
- Use DSS to compare experiments/models of tests under similar conditions in TREAT (90 ms pulse width) and NSRR (5 ms pulse width)
  - What changes in experiment design (fuel-pellet gap) to make experiments more similar
  - Expand the parameter of interest from just cladding temperature to cladding stress/strain

Conclusions

- Acceleration of fuel design and qualification is needed to meet demands
- Scaling/Similarity methods combined with modeling and simulation tools could help accelerating our current efforts
- Building our capabilities to perform transient testing for future qualification needs at TREAT
- SERTTA capsule designed and tested for water-based RIA testing
- Still a lot of work/potential for scaling/similarity tools to help with designing and analyzing transient testing needs

Thank you for your attention!