INL/MIS-16-40269



# Coordination of Efforts Between Restart, Experimentation and Modeling for the Transient Test Reactor

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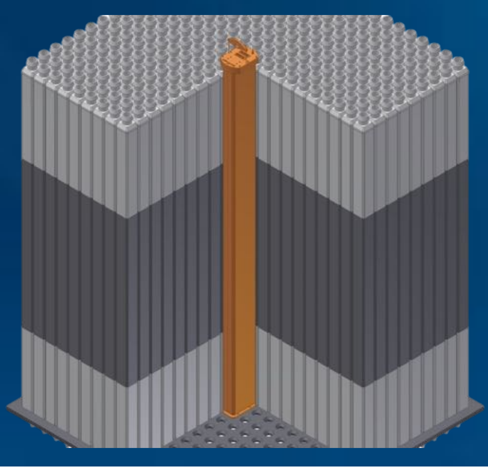
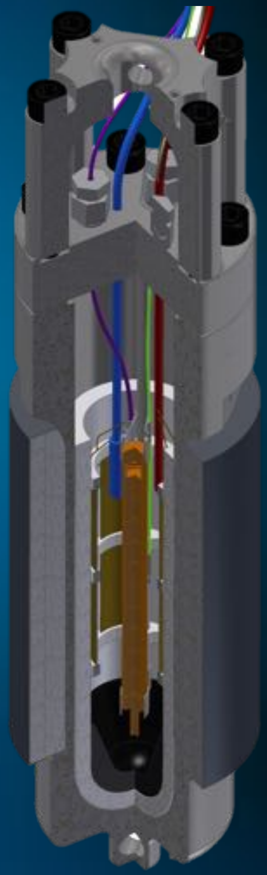
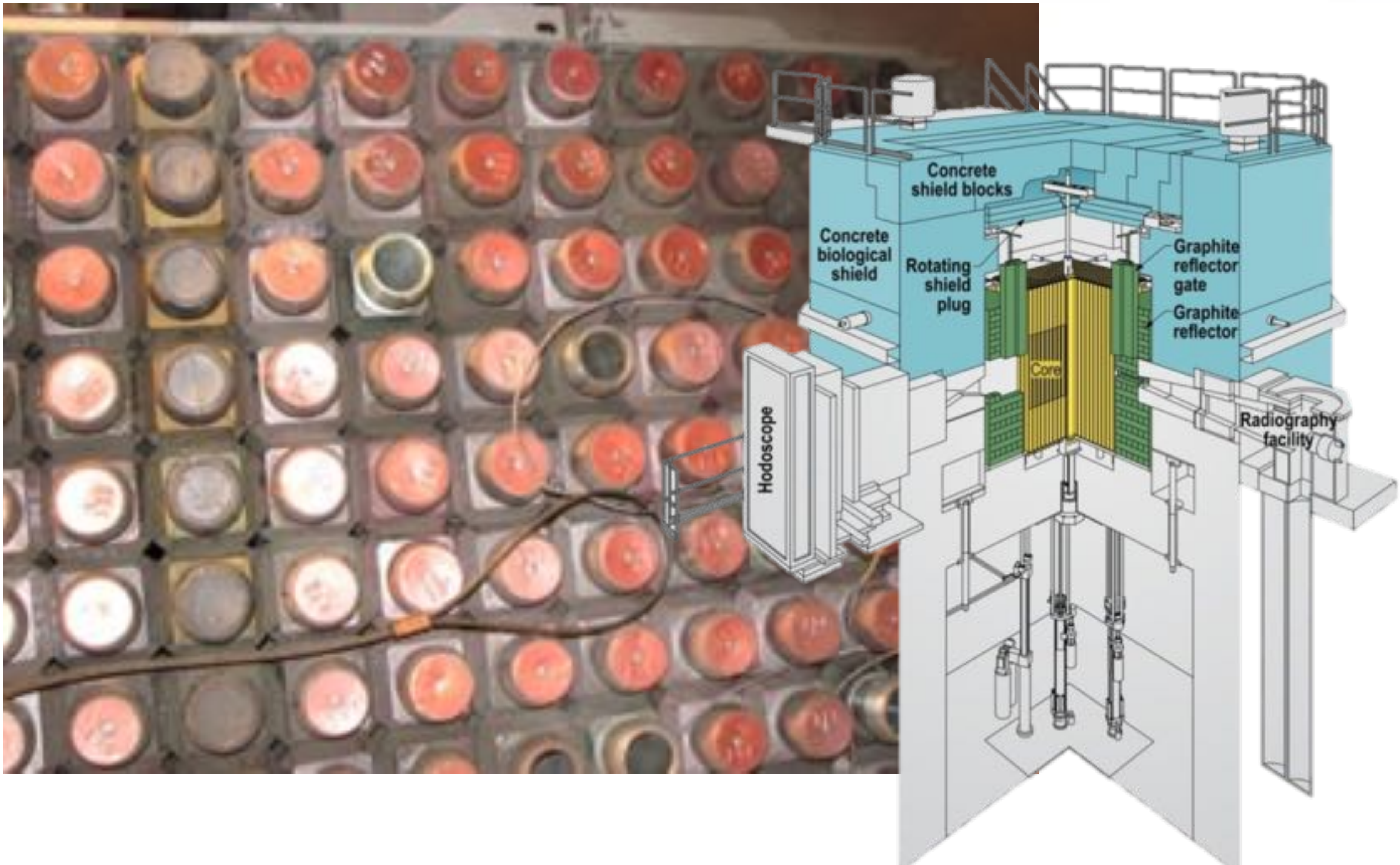
**Nuclear Science and Technology Directorate**
**Idaho National Laboratory**





# TREAT – The Transient Test Reactor Facility



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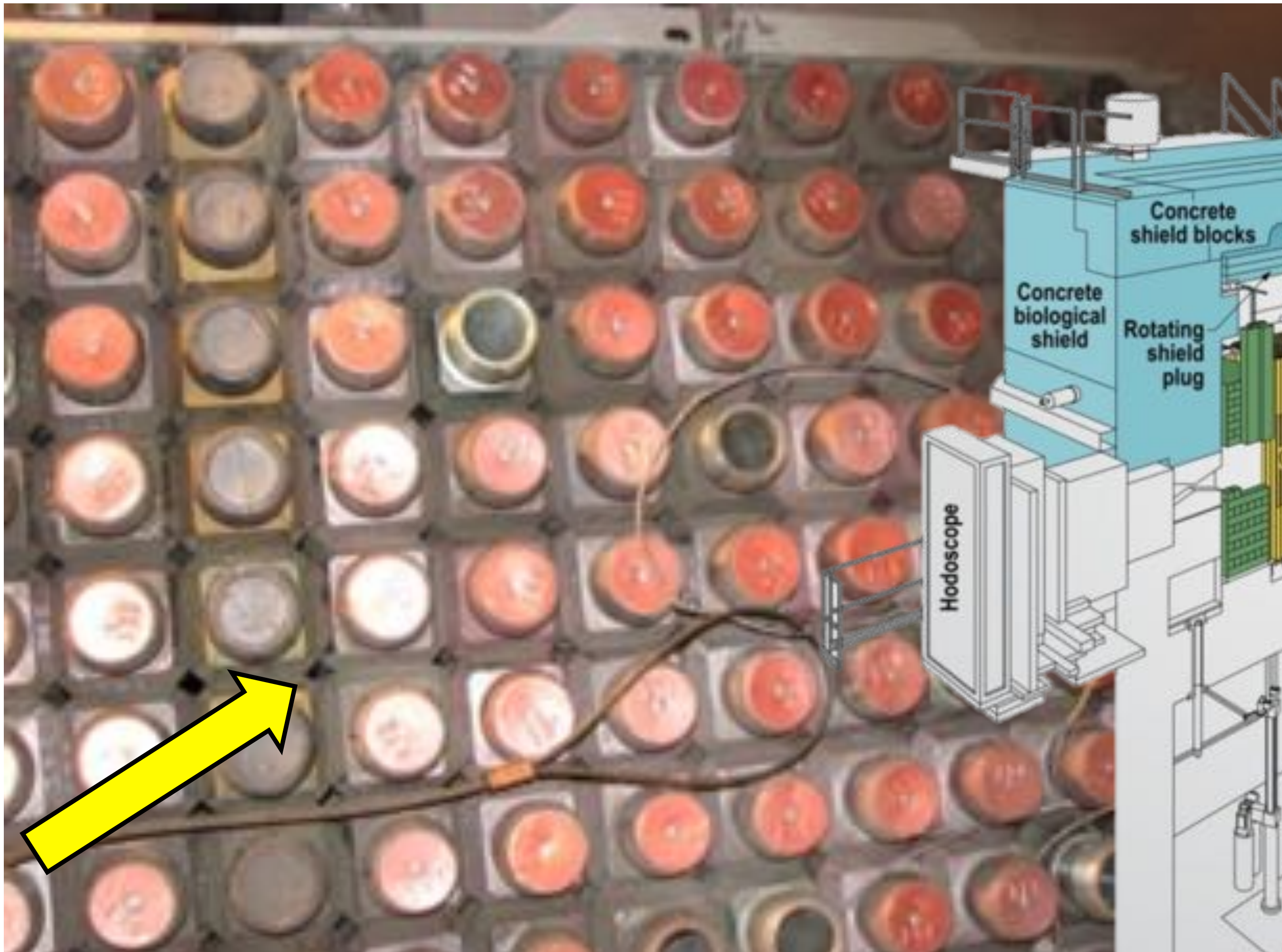

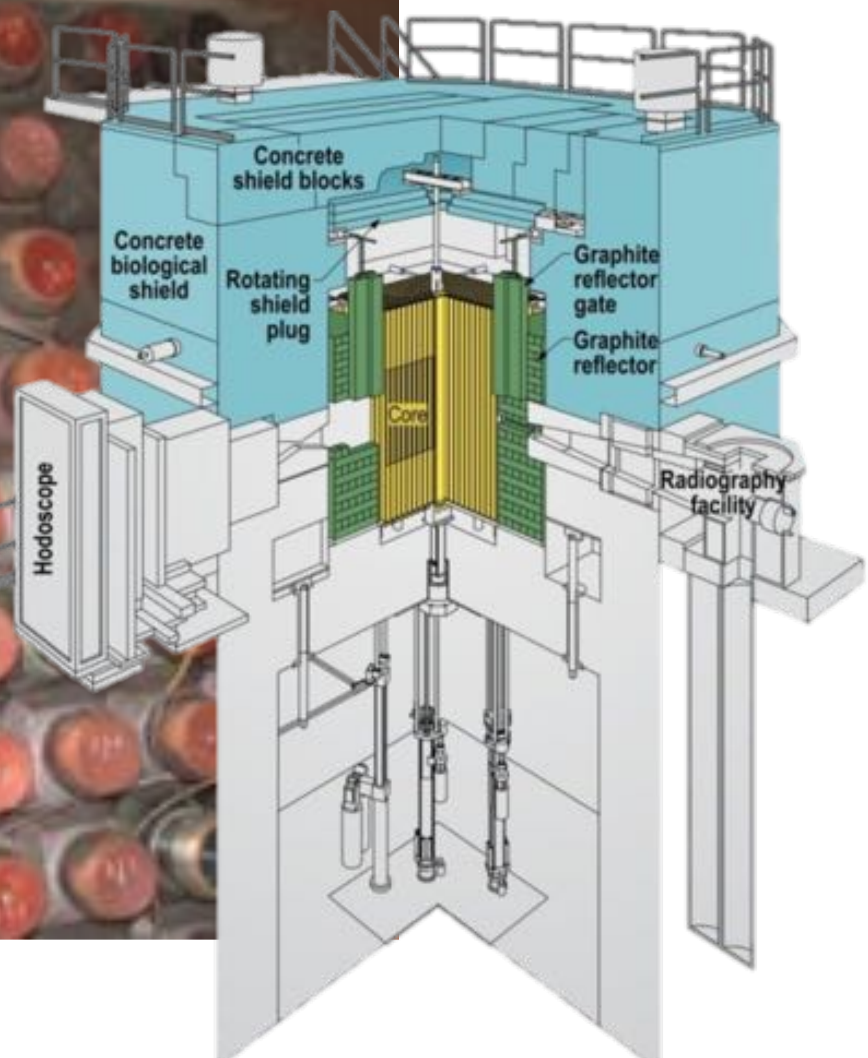

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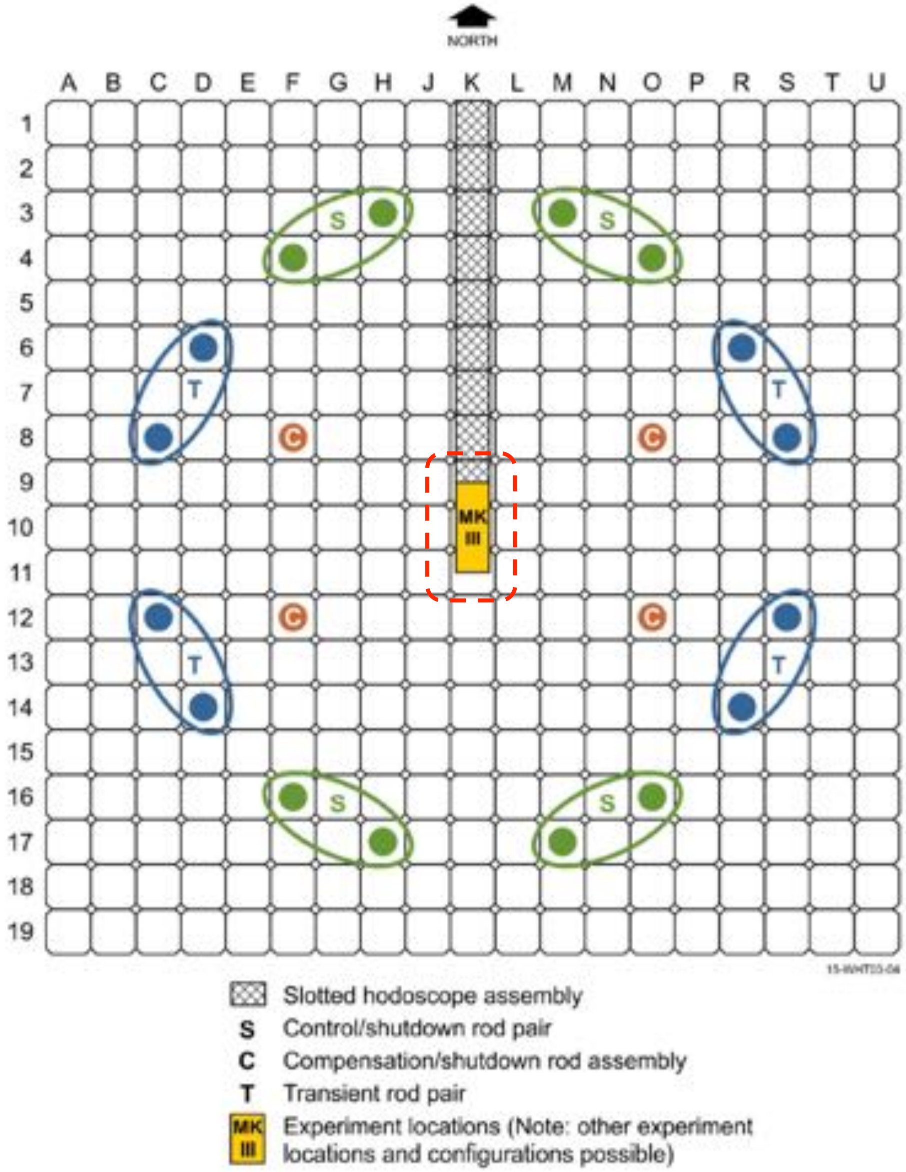
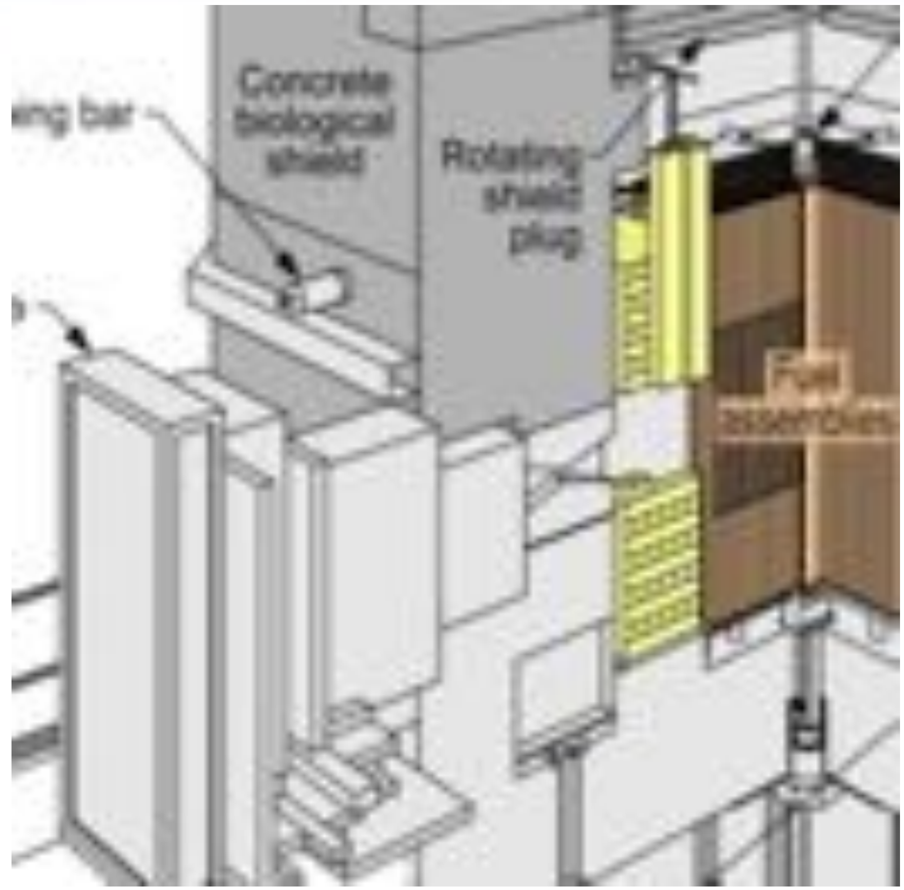


# TREAT's mission is to deliver transient energy deposition to a target or targets inside experiment rigs.

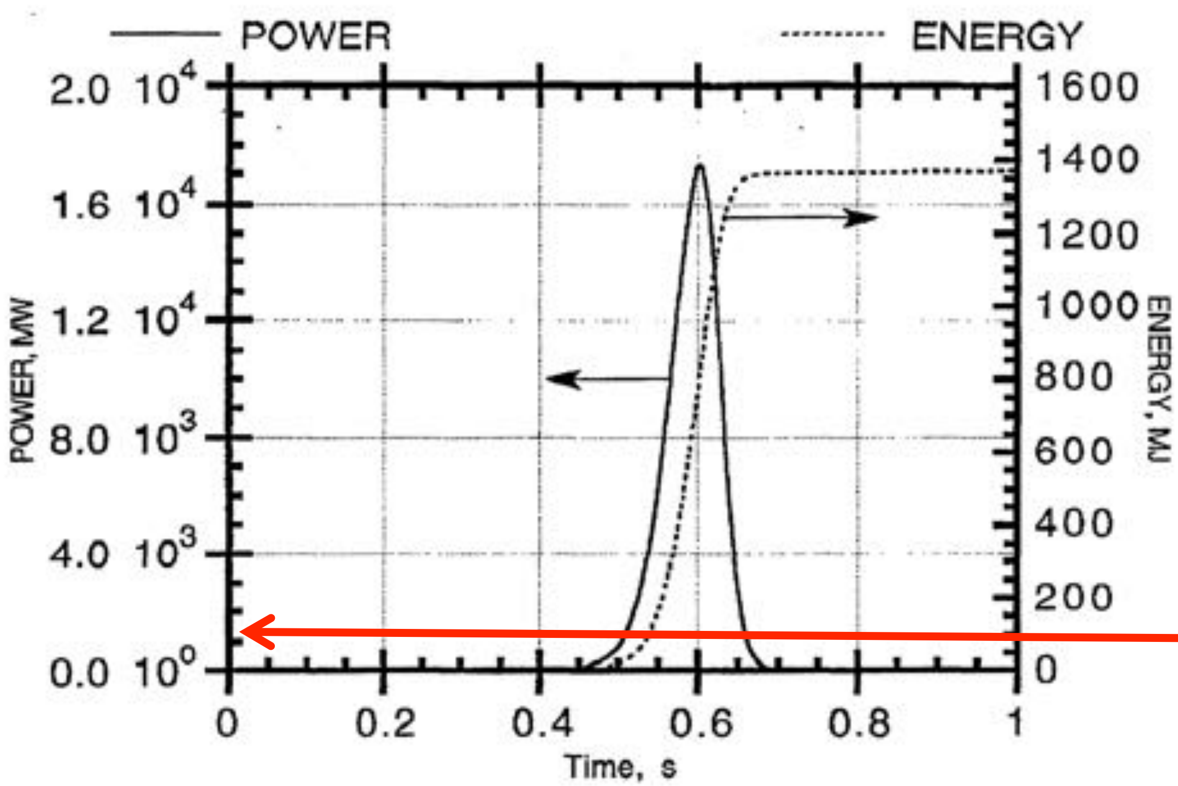
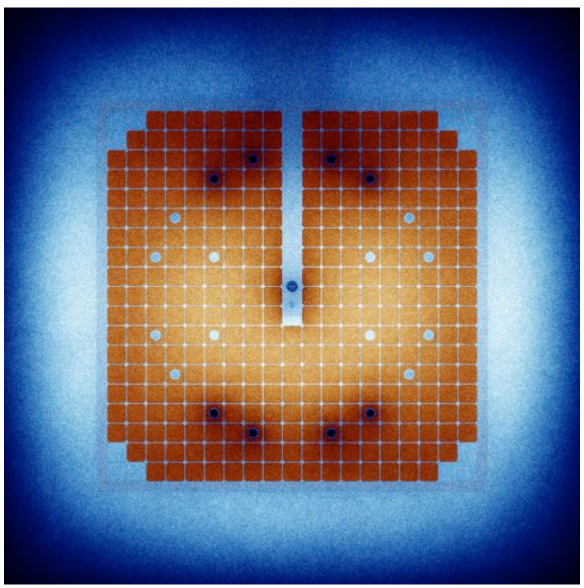


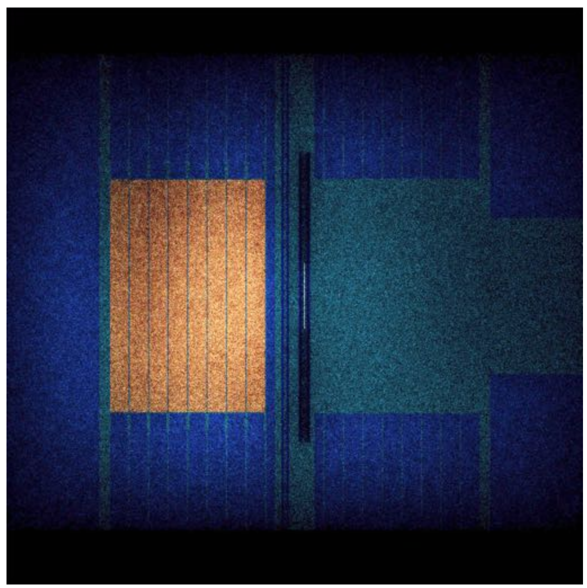

*FIG. 5. Plot of TREAT reactor power and energy for hypothetical RIA-type transient resulting in 1400-MJ pulse with a 72-msec FWHM capable of depositing 1200 kJ of energy per kg of fuel (290 cal/g).*

**1.21 Gigawatts**

# TREAT Modeling and Simulation

- The INL multi-physics modeling team is supposed to model such experiments in next generation experiment series!

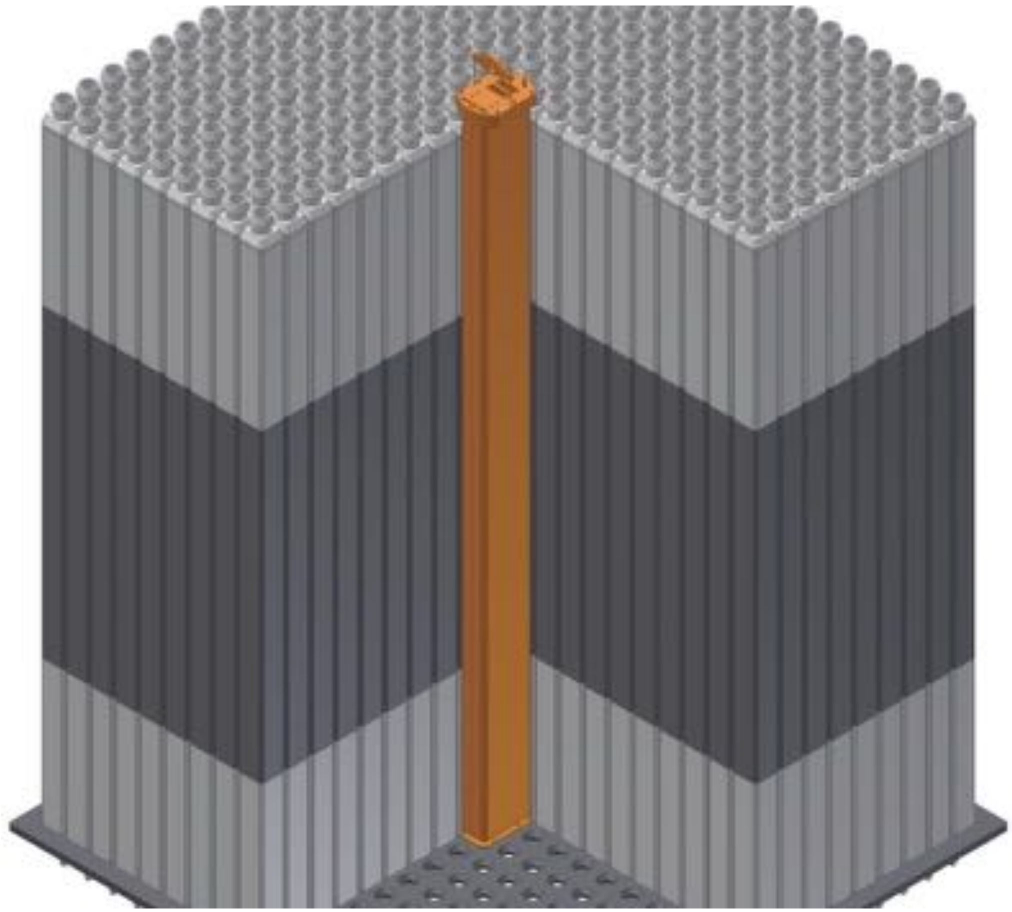




# First Experiments

Static Environment Rodlet Transient Test Apparatus (SERTTA)

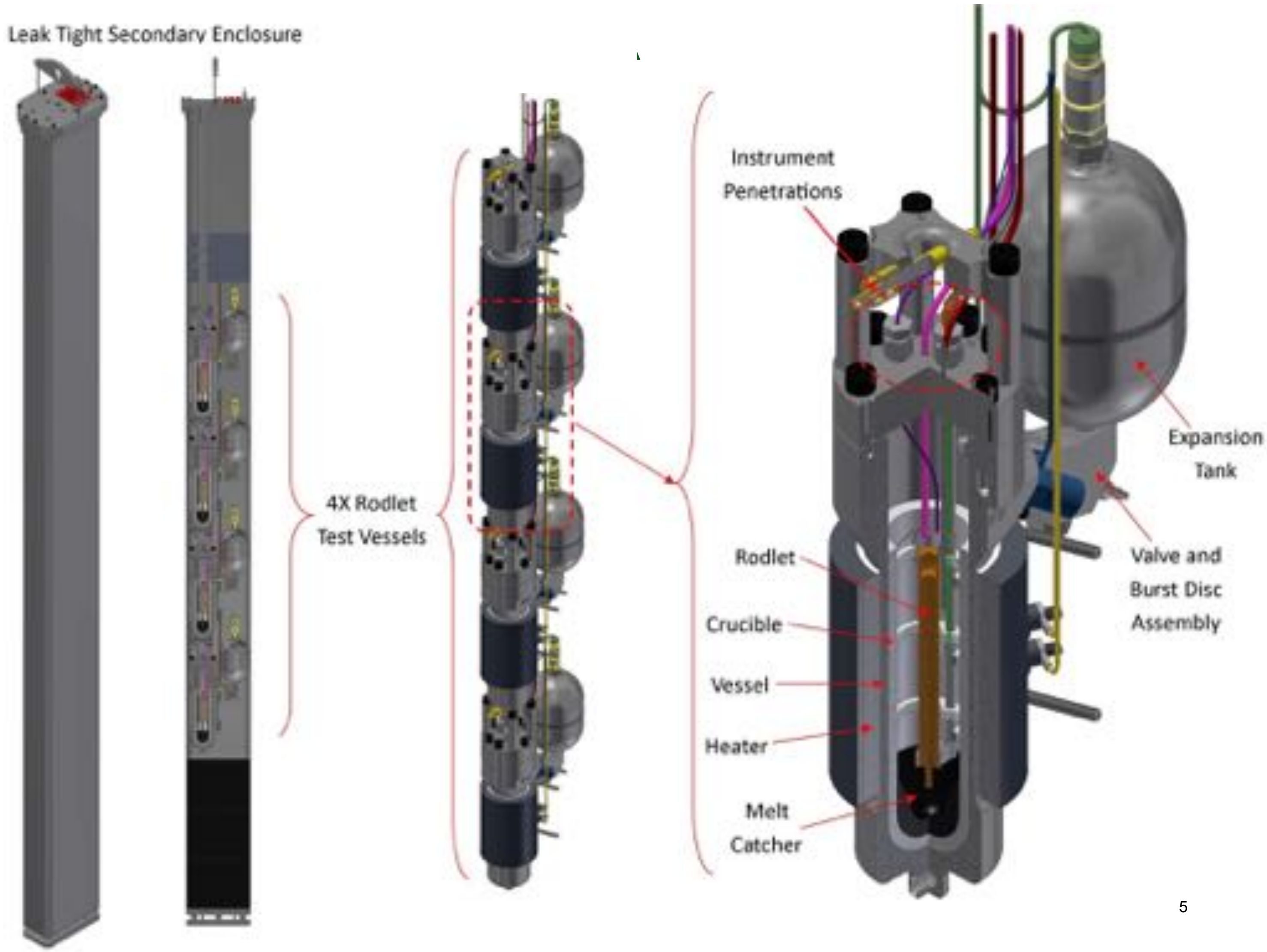
- General purpose devices <u>without</u> forced convection
- Pre-pressurized and electrically heated
  - Liquid water up to PWR condition (320˚C 16 MPa)
  - Inert gas or steam
  - Liquid sodium
- Two SERTTAs are under development
  - 4X capsule “Multi-SERTTA”
  - 1X capsule “Super-SERTTA”
- At present MAMMOTH is the only means available to assess the transient performance of these capsules.



SERTTA shown in TREAT core ¾ section view
Secondary containment shroud (“can”) visible

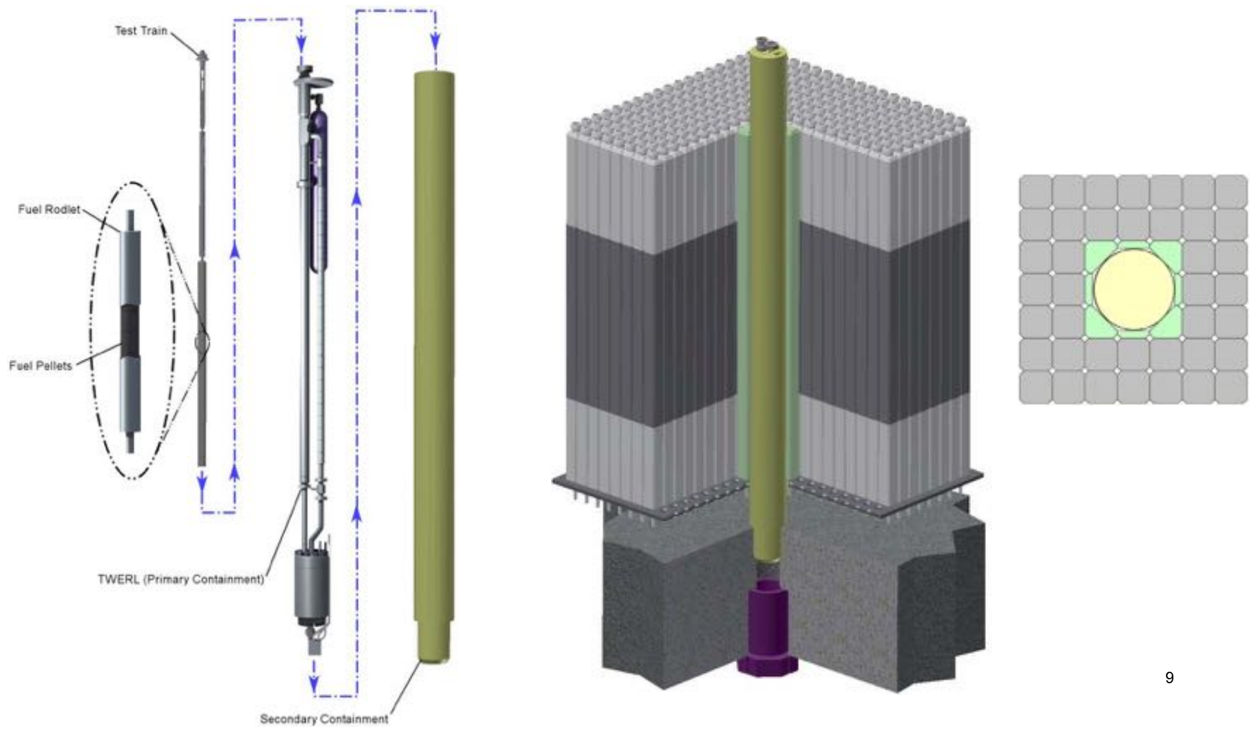
# Multi-SERTTA

- Best for smaller scale specimens and four-for-one testing (concept screening)
- Planned to be the first new test to be used in restarted TREAT



# TWERL

- TREAT Water Environment Recirculating Loop
- First forced-flow experiment configuration

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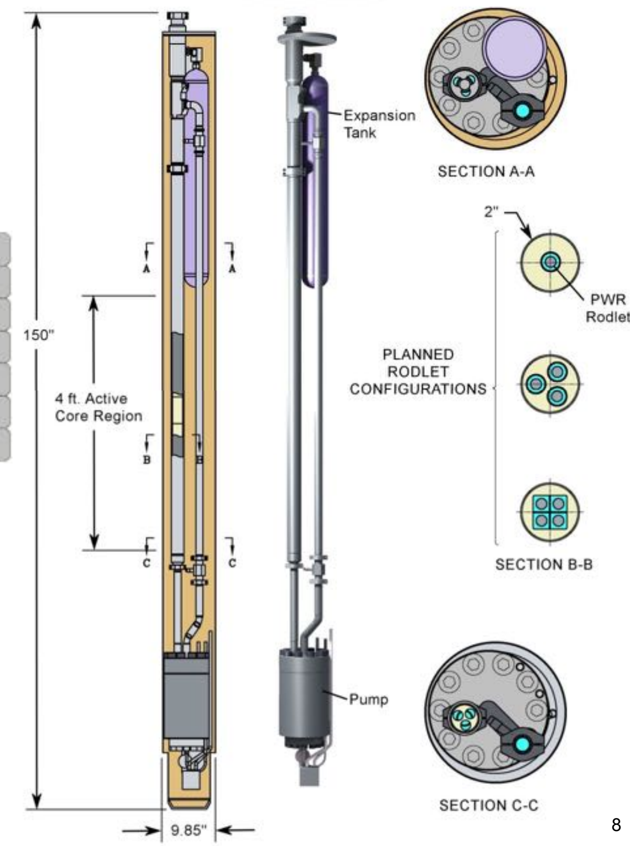


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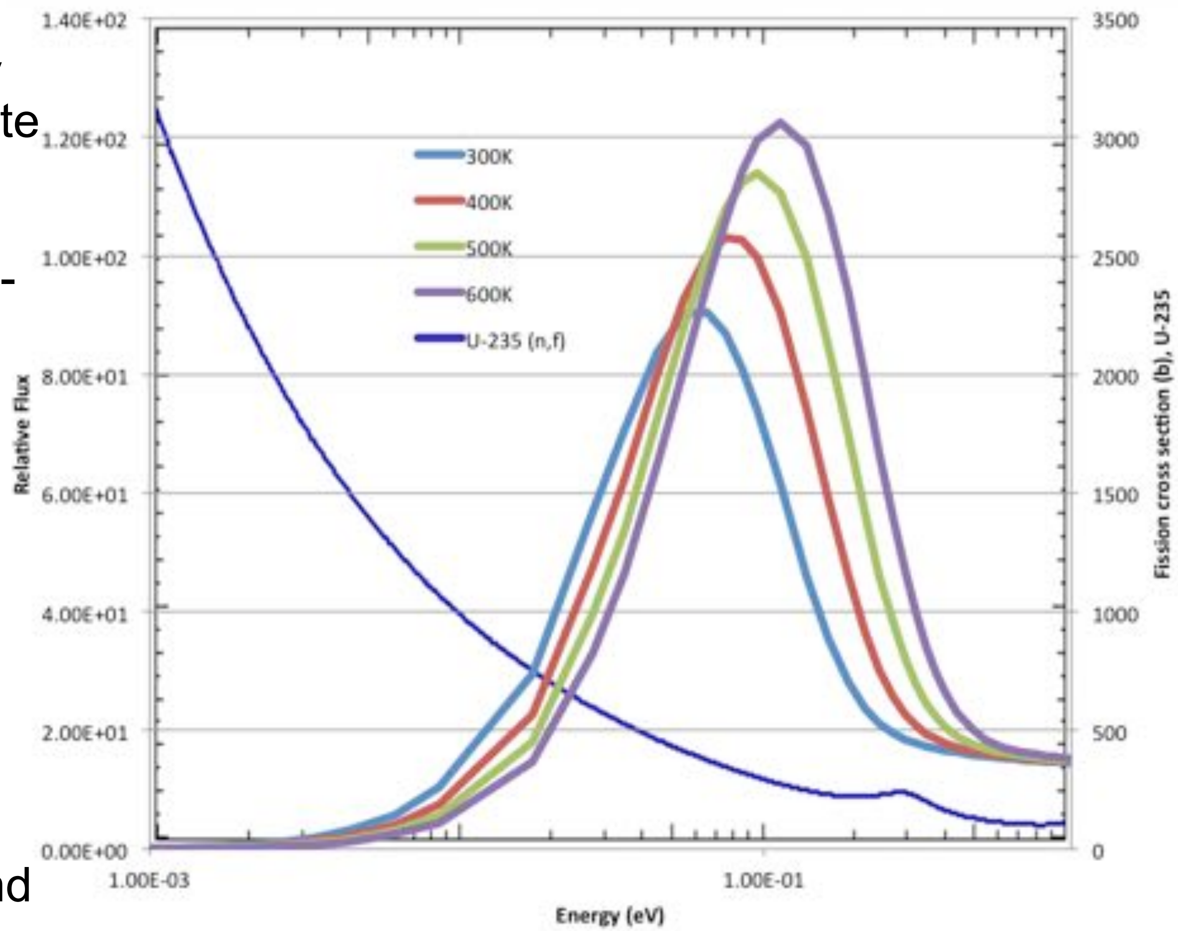
# How TREAT works

- Three sets of control rods:
  - Safety – fully out for transient
  - Compensation – partially inserted to set critical state pre-transient
  - Transient – partially inserted for desired delta-k, then rapidly fully withdrawn
- Core is 100 ppm highly enriched uranium – very little resonance absorption.
- As core heats, a shift in the thermal Maxwellian takes the core back to a new critical state; eventually rods are driven in to shut down.
- Temperature distributions (and thus feedback) are spatially distributed.

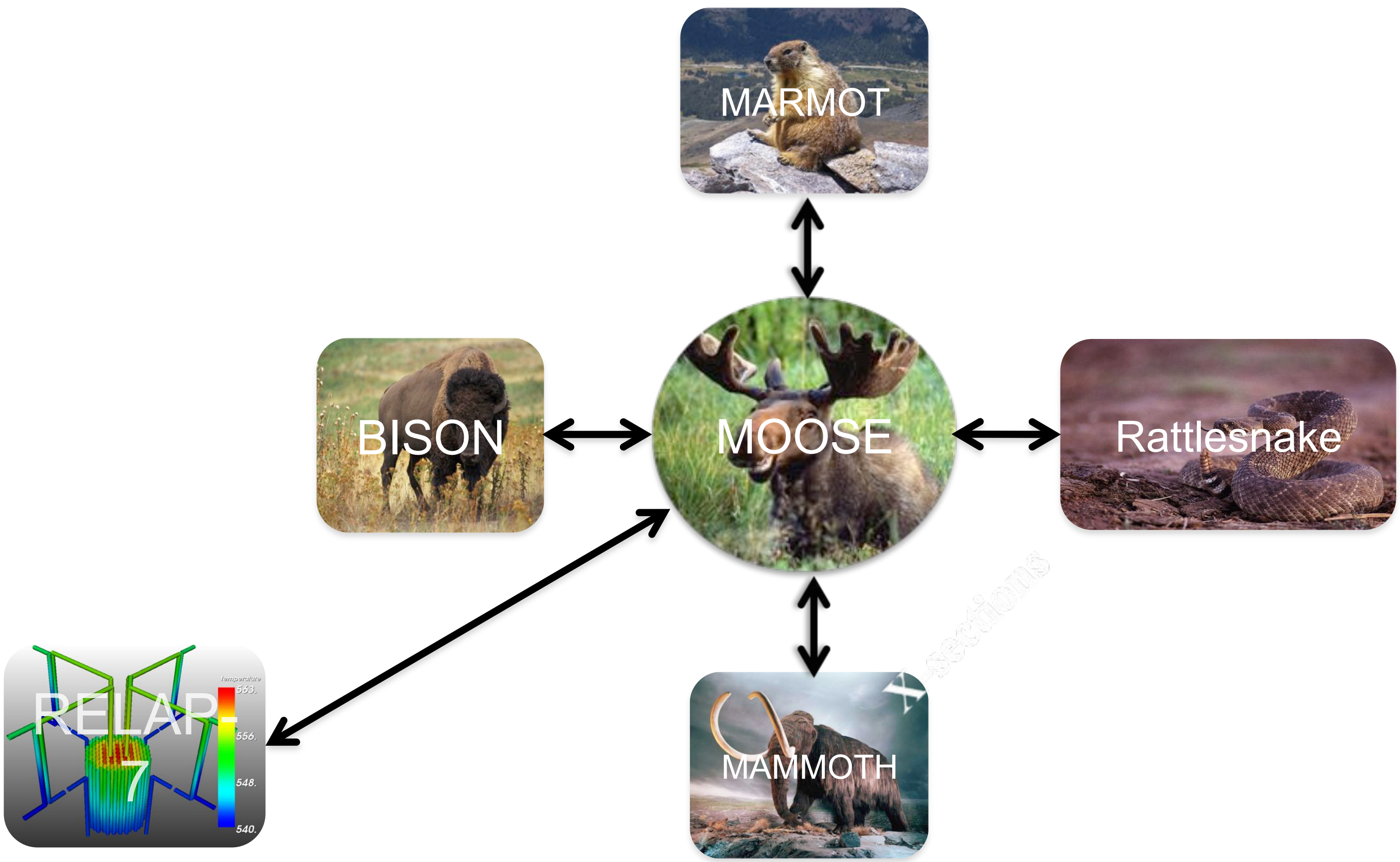


# How MAMMOTH Works

- MAMMOTH has been built using the MOOSE framework (Multi-physics Object Oriented Simulation Environment)
- MOOSE allows implicit, strong, and loose coupling of MOOSE animal solutions
- MAMMOTH is the MOOSE-based multi-physics reactor analysis tool.
- At present, TREAT core simulation efforts rely on BISON (fuel performance), Rattlesnake (time-dependent neutron transport) and MAMMOTH. LWR-type pin experiments are being evaluated using RELAP-7 as well.

- Note that MAMMOTH is a single executable code with multiple personalities all co-existing.
- All codes are based on FEM – MOOSE routines perform all solutions.
- All data from all codes is available to the solver(s) used.
- Nothing like this exists elsewhere – MAMMOTH is earth-shaking.

# *MAMMOTH Fuel Physics Coupling Process*



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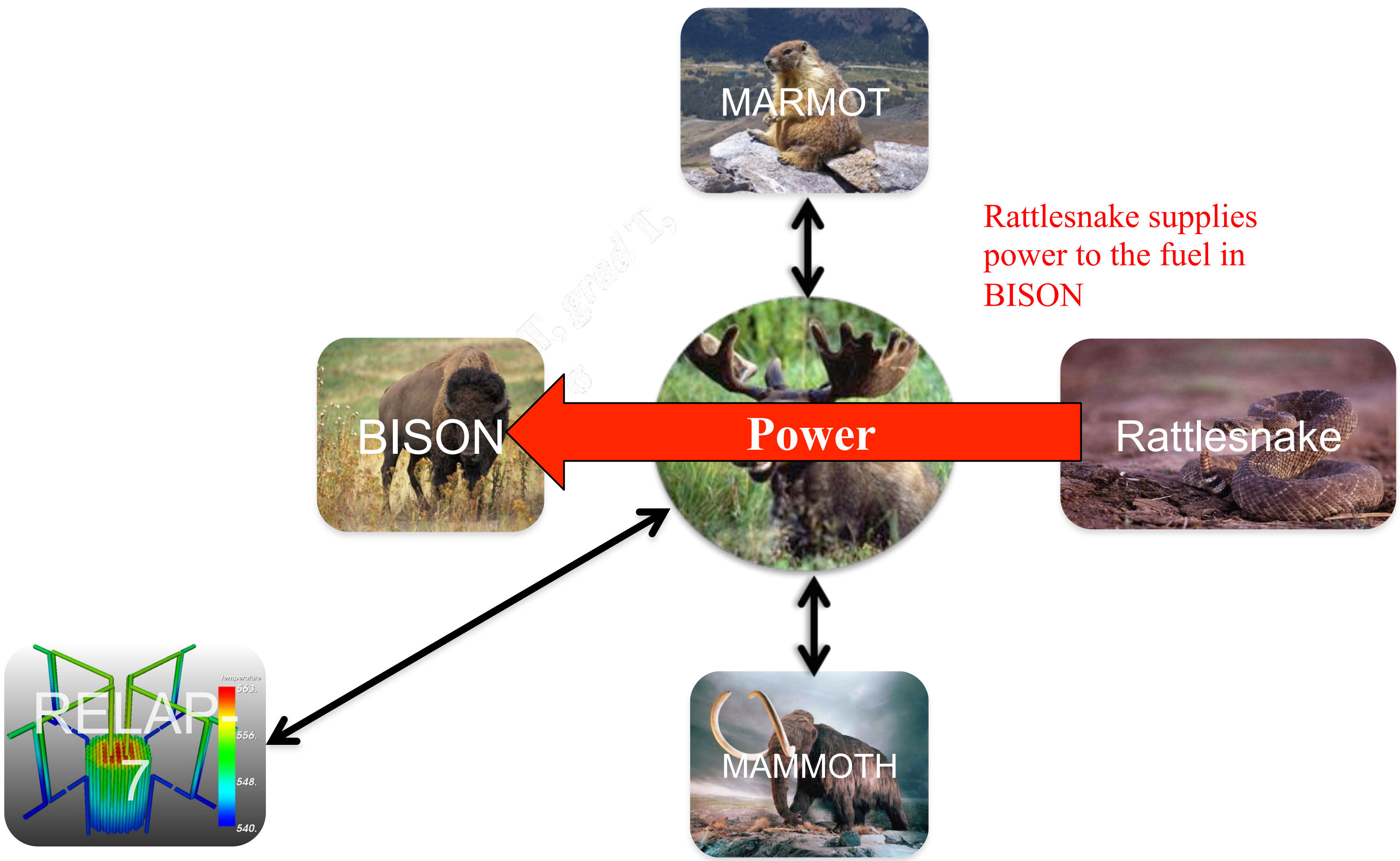
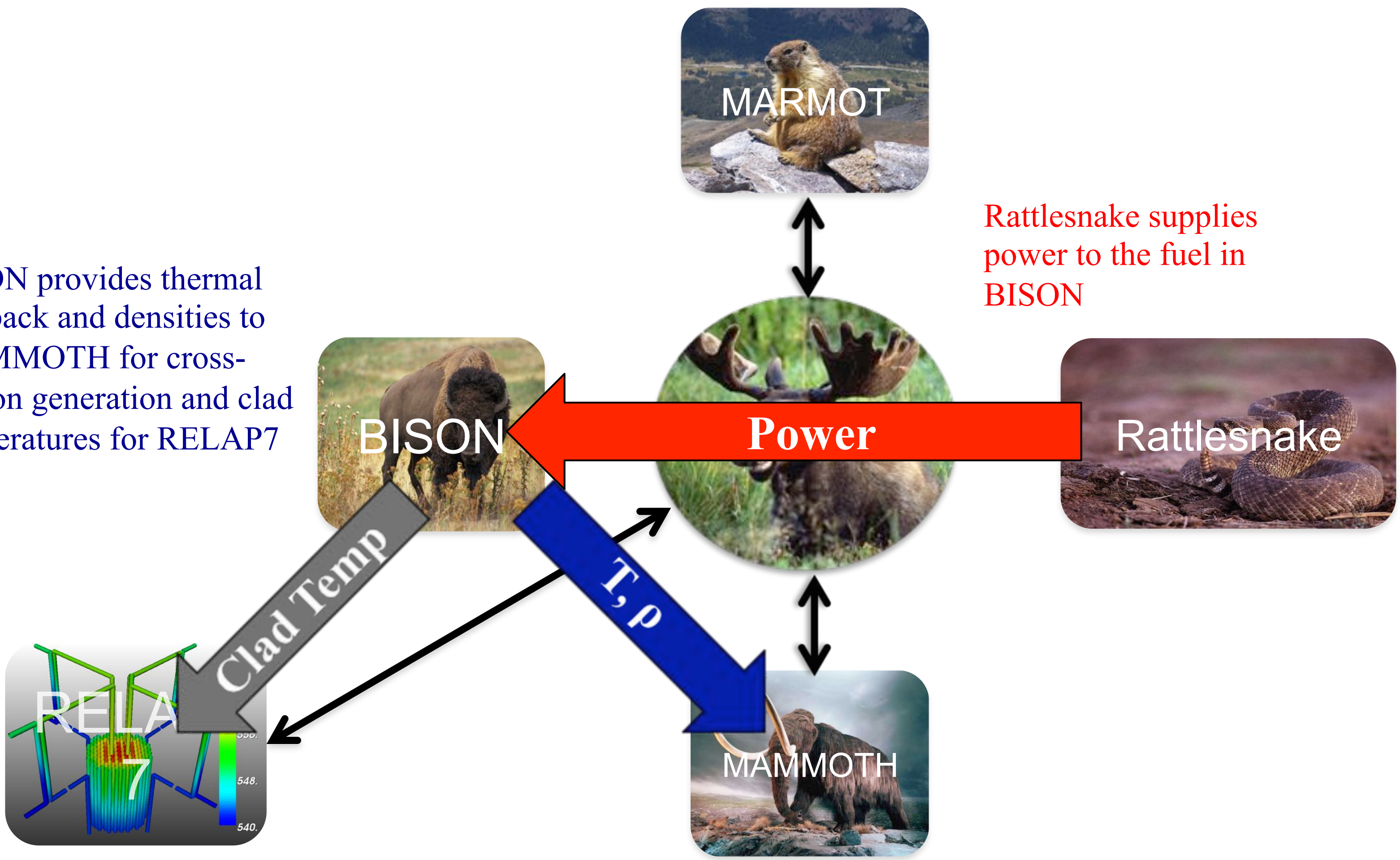


# MAMMOTH Fuel Physics Coupling Process

BISON provides thermal feedback and densities to MAMMOTH for cross-section generation and clad temperatures for RELAP7

Rattlesnake supplies power to the fuel in BISON



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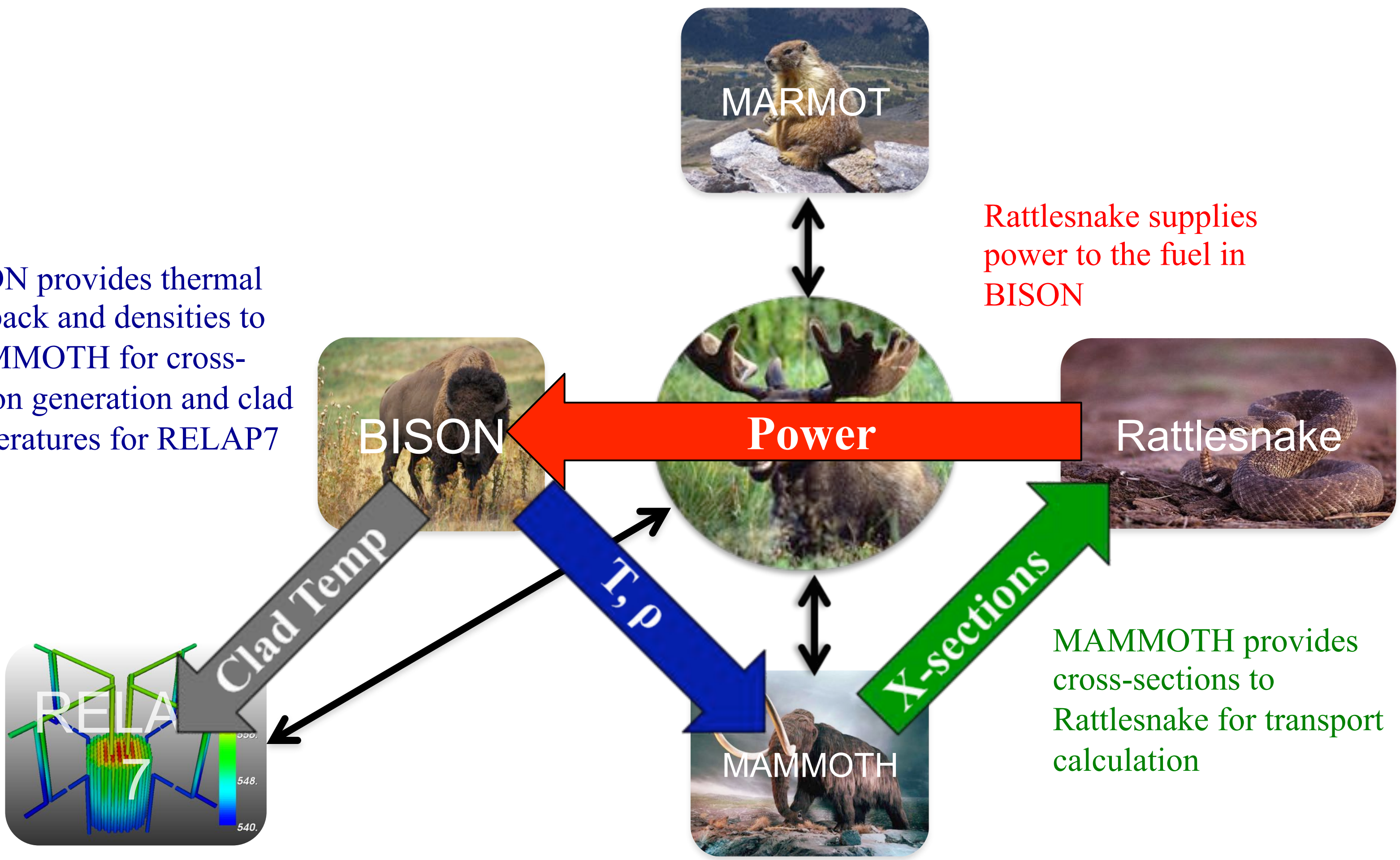


MAMMOTH provides cross-sections to Rattlesnake for transport calculation

# MAMMOTH Fuel Physics Coupling Process

MAMMOTH provides isotopic distribution (including fission gas components) and damage to MARMOT

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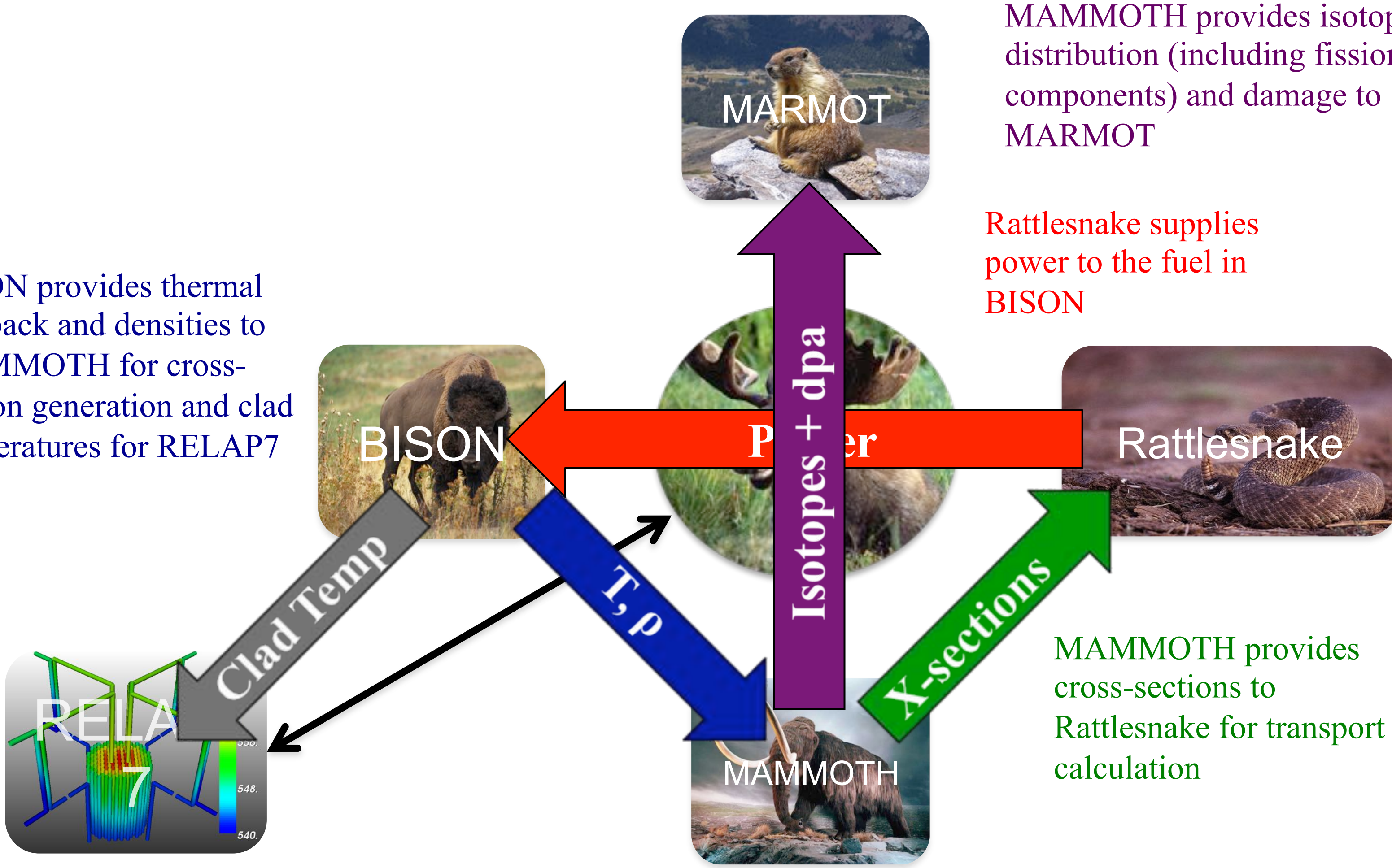


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BISON provides temperatures, gradients, and stresses to MARMOT

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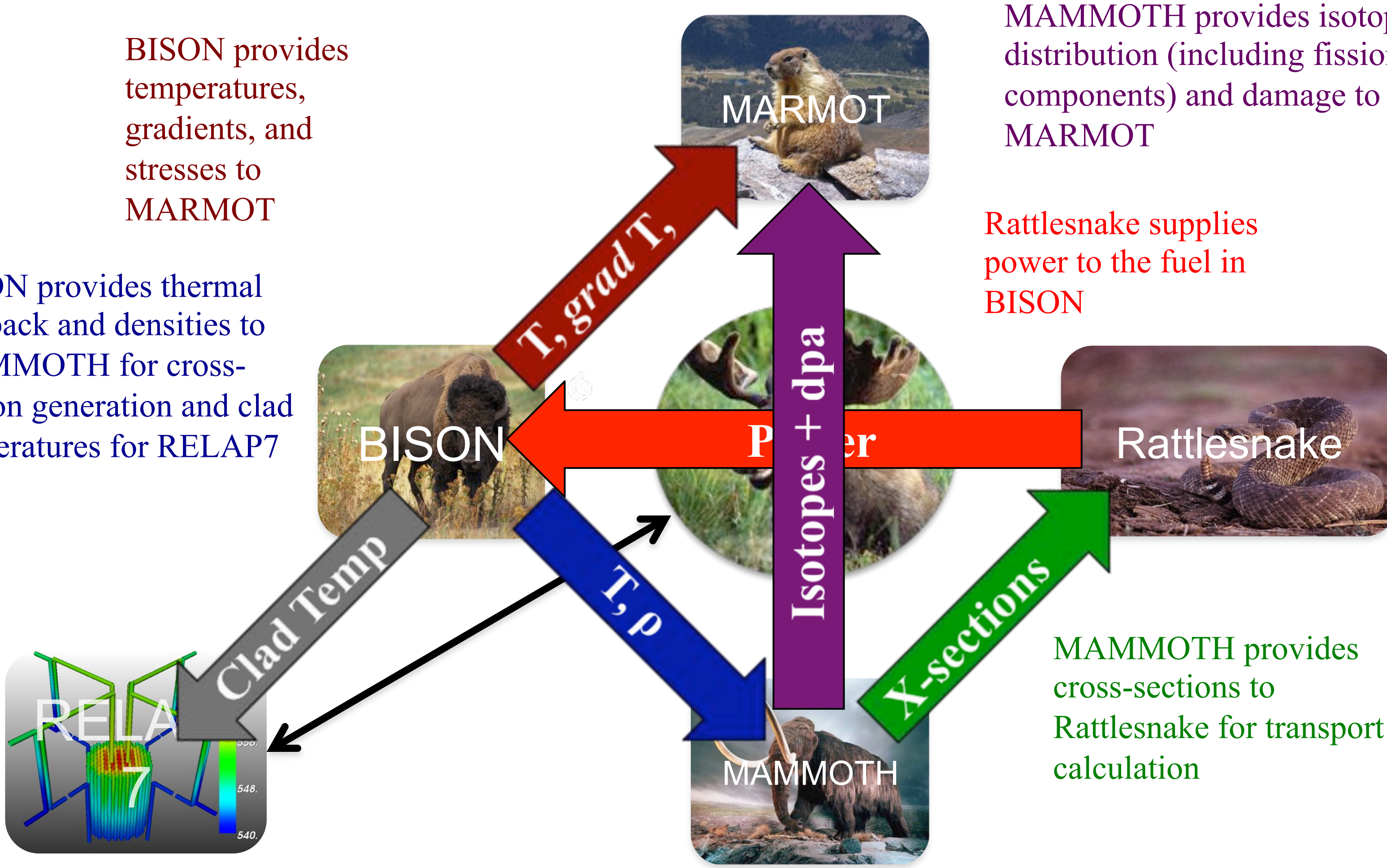


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BISON provides temperatures, gradients, and stresses to MARMOT

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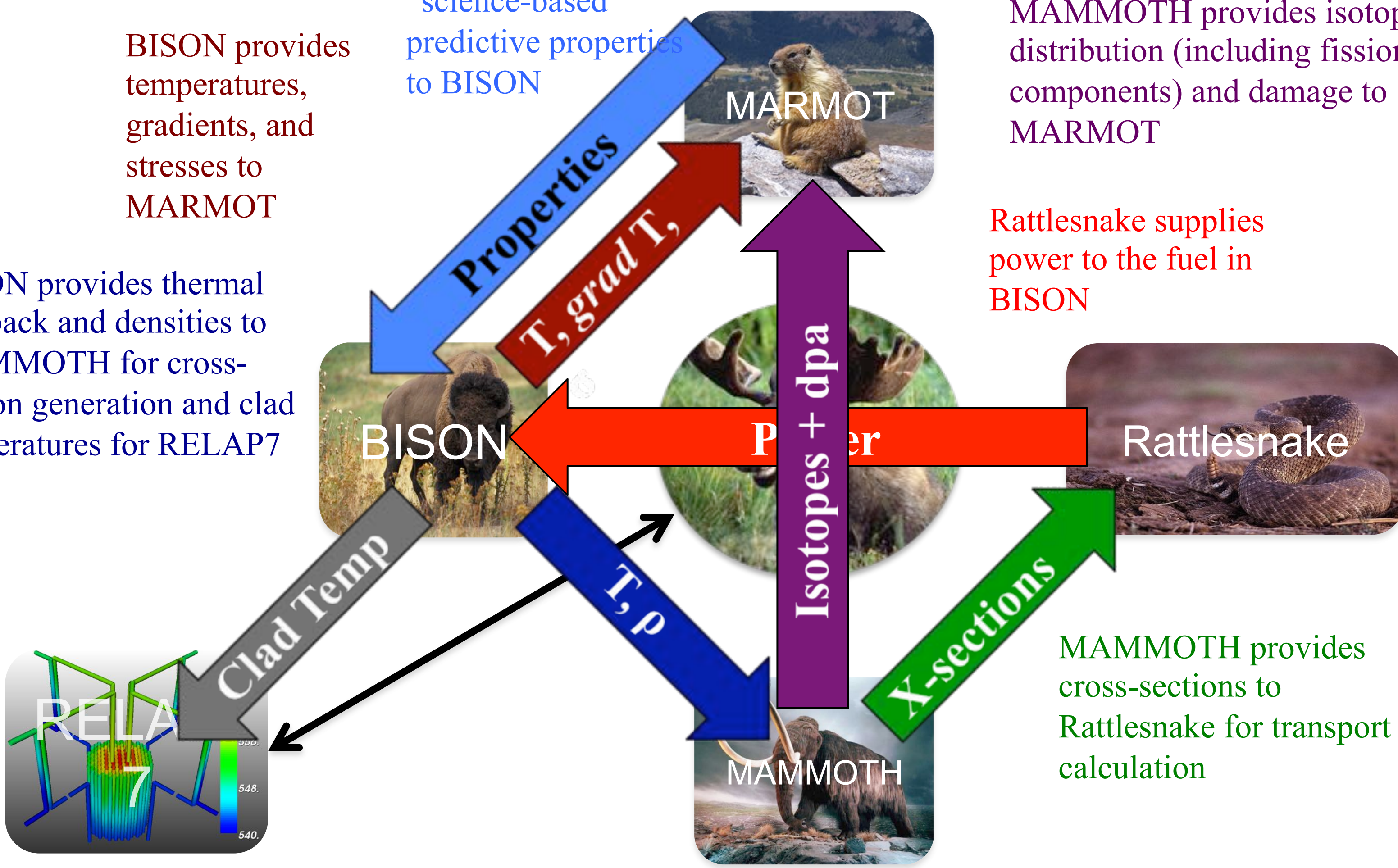

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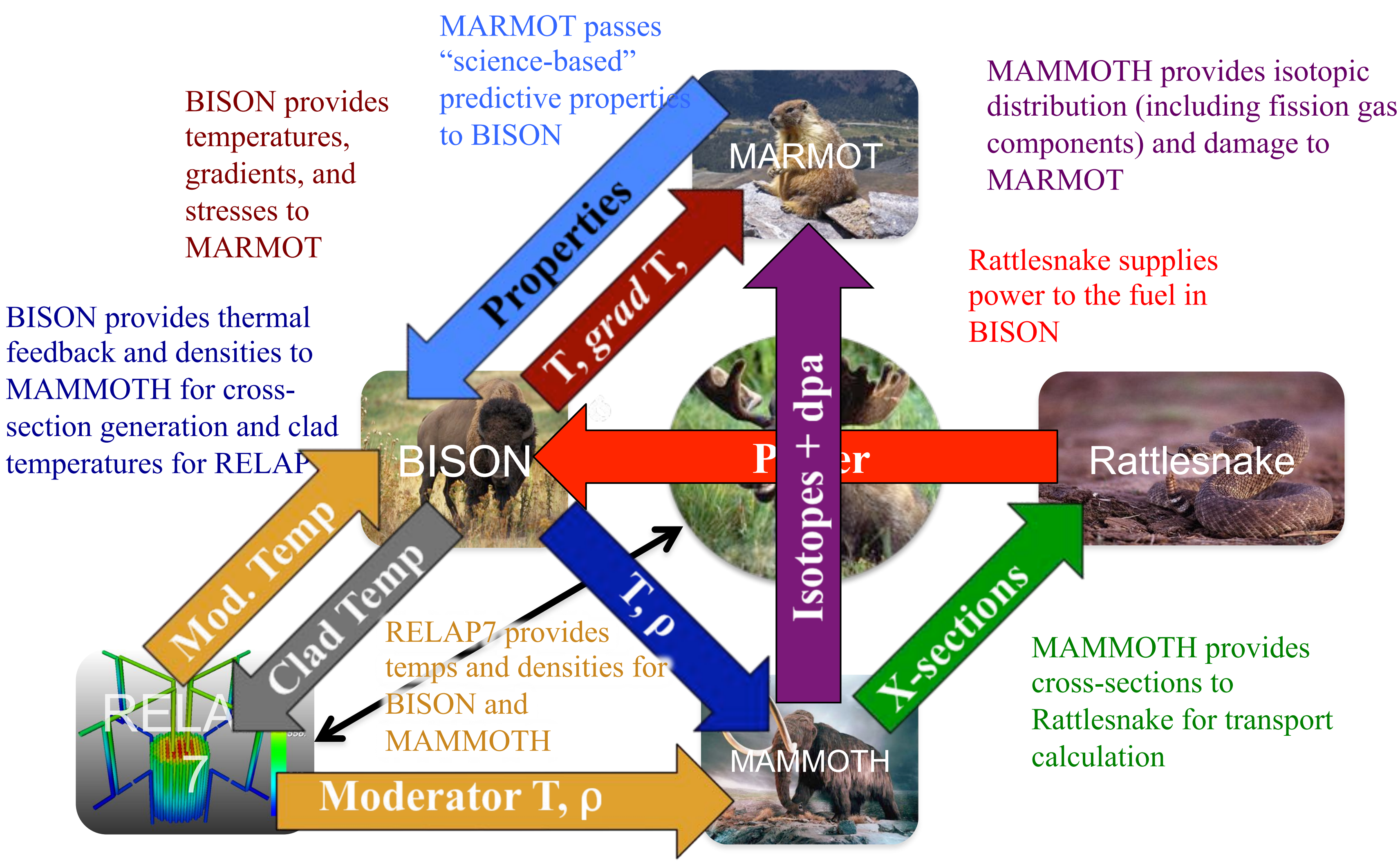

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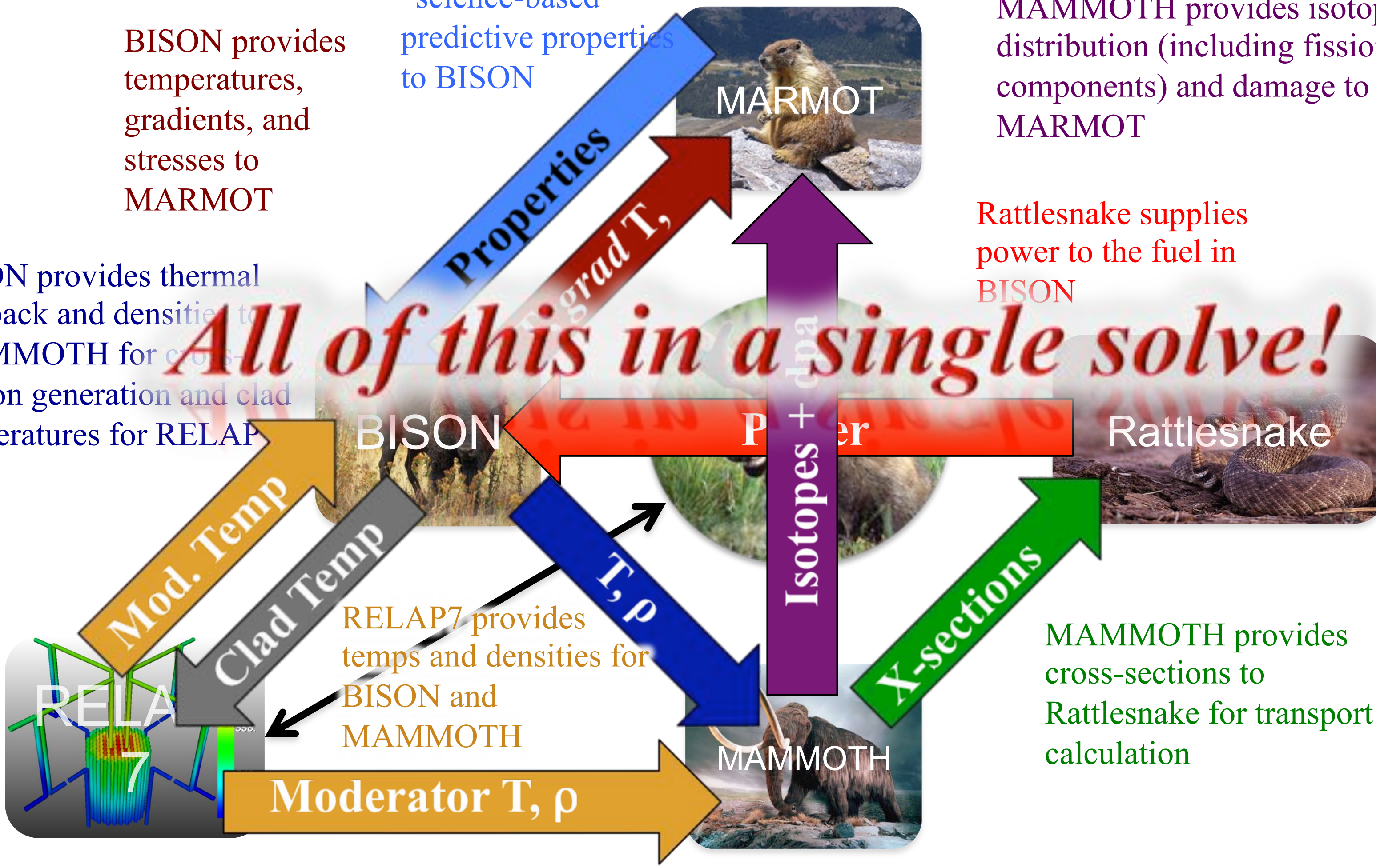
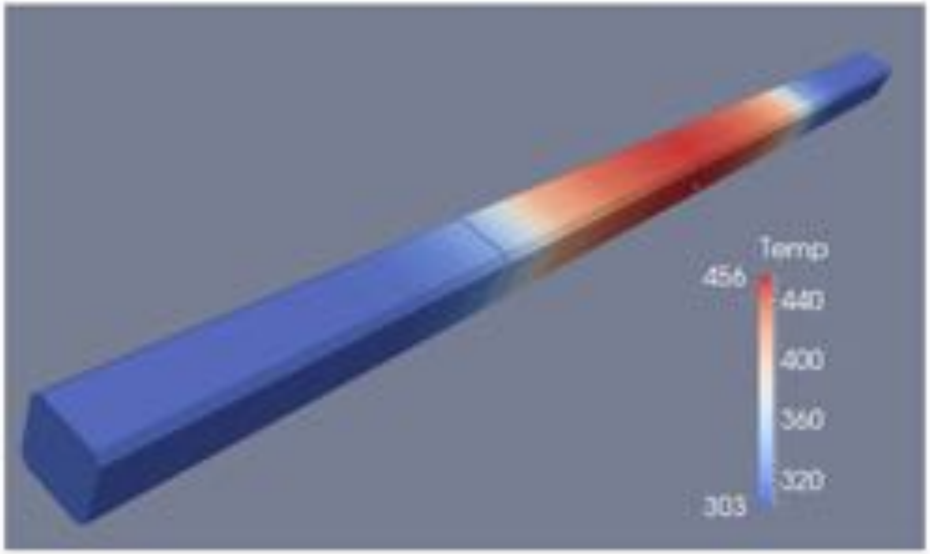
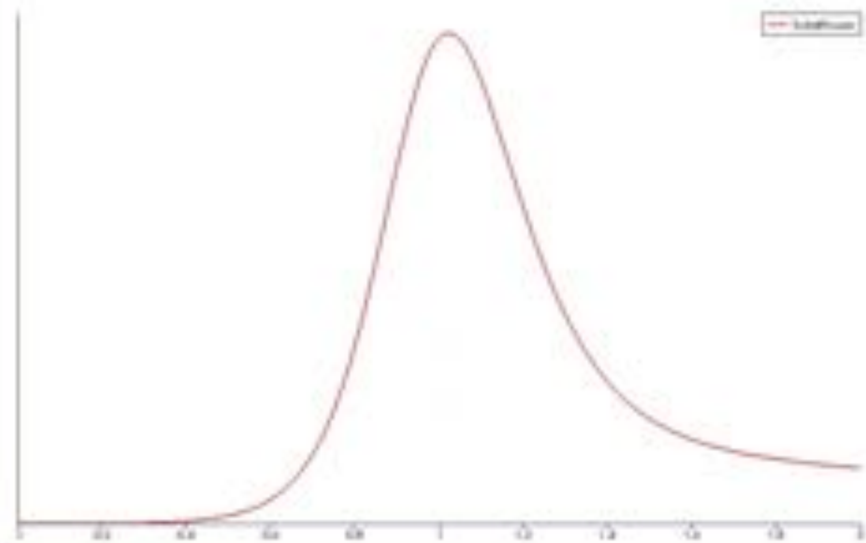



RELAP7 provides temps and densities for BISON and MAMMOTH

MAMMOTH provides cross-sections to Rattlesnake for transport calculation

# Coupled Physics in MAMMOTH

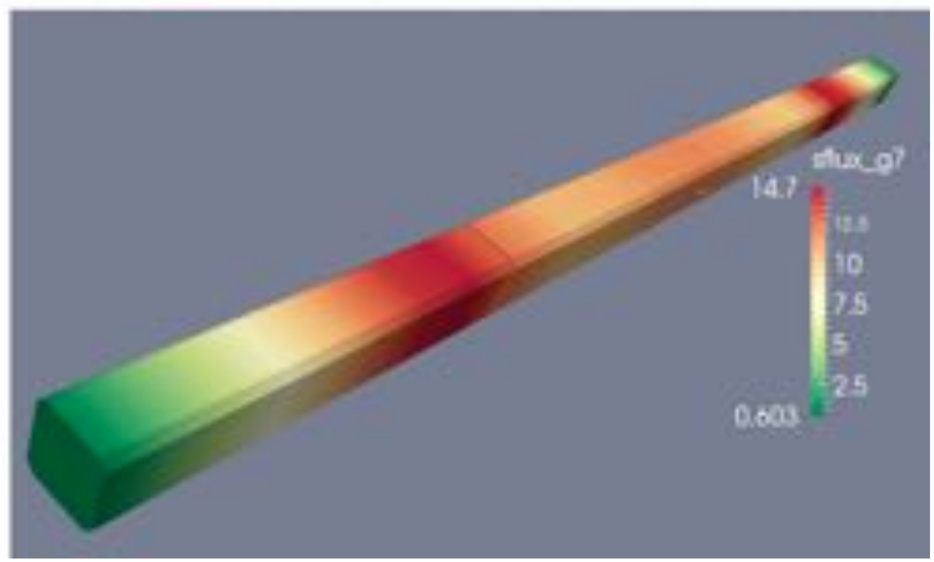


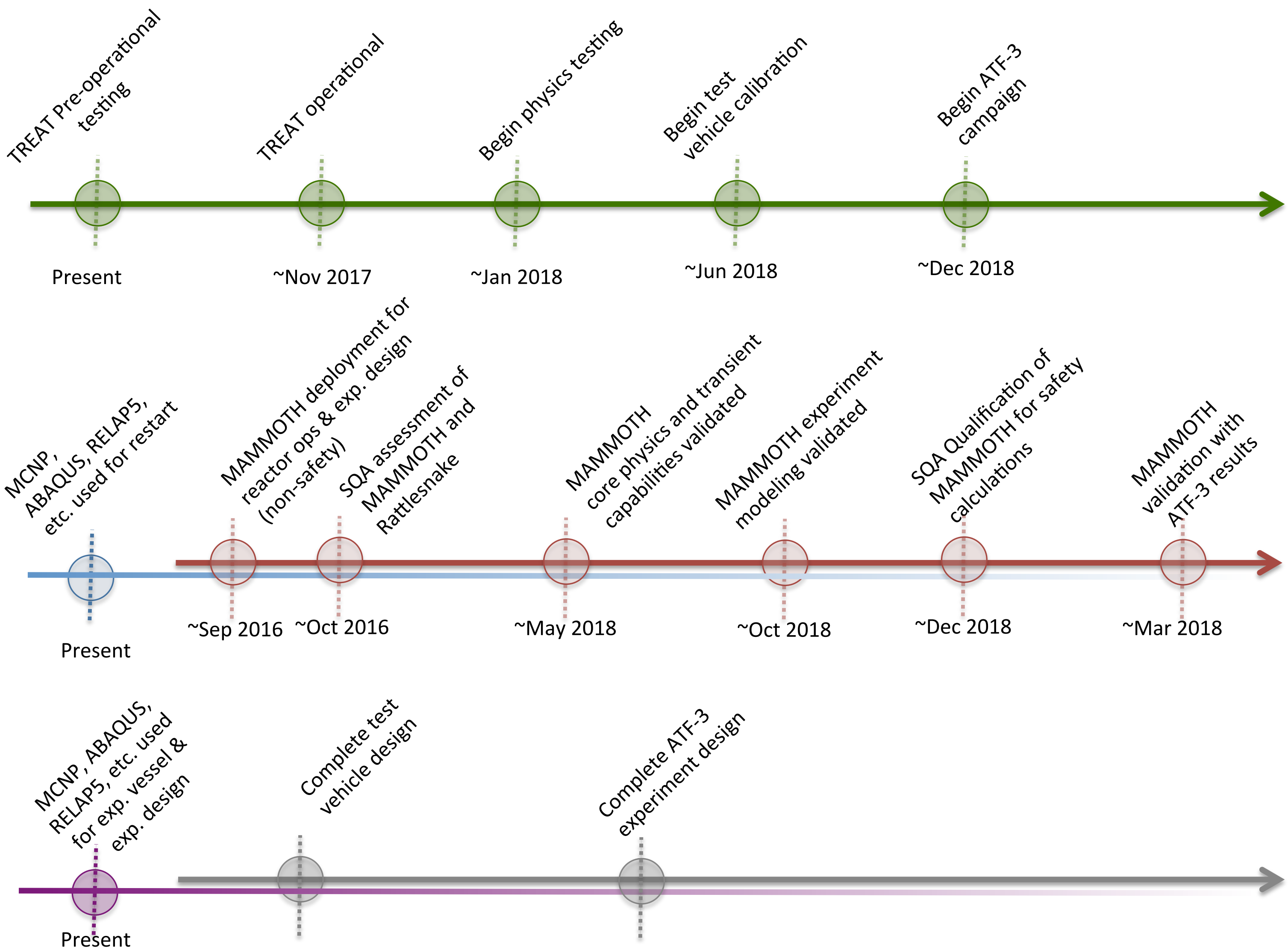
Temperature (K) ↑

- Reactivity increase (boron removal) between 0.01 and 0.1s
- Reactivity decrease is due to temperature feedback

**Thermal Flux →**



# Startup Testing Timeline and MAMMOTH

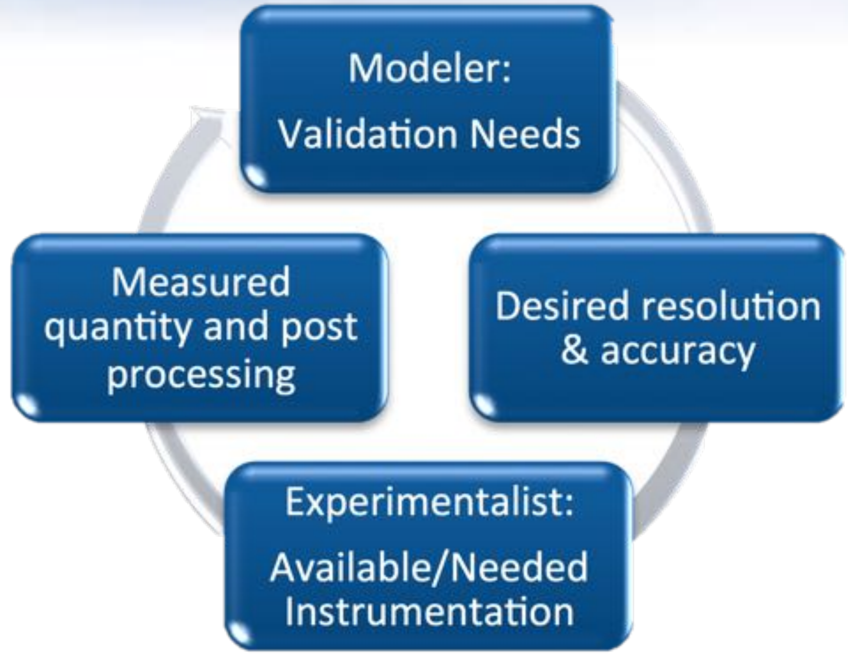


# Stakeholder Needs

- Stakeholders refers to the parties with near team interest in TREAT modeling and simulation
  - Restart and operations
    - Reduce operational costs through rigorous pre-experiment analysis
    - Provide more margin for experiments
  - Experiment design
    - Simulation of transients prior to reactor insertion
    - Understanding spatial variations and spectral changes
  - Instrumentation
    - Needs identification
    - Estimate of flux magnitudes and spectra inside and outside core
  - Benchmark Development
    - Support for ongoing NEUP and IRP benchmark development
    - Evaluation for historic transient configurations
  - Department of Energy
    - Nuclear Engineering Advance Modeling and Simulation (NEAMS) investments
    - Understanding of core behavior in licensing review

# *Modeling and Simulation Needs*

- Validation, validation, validation.
- User feedback
- Theoretical improvements
- Did I mention validation?
  - neutronics
  - fuel performance
  - thermal fluids
  - **coupled behaviors**




- Validation is a circular process
  - We are currently helping to design experiments and vessels
  - Data from those experiments will:
    - Validate the computational simulation or indicate shortcomings that must be addressed.
    - Identify instrumentation deficiencies or new needs
    - Highlight areas for improvement for PIE (methods, equipment, materials)
  - Following experiments will gain from these experiences.

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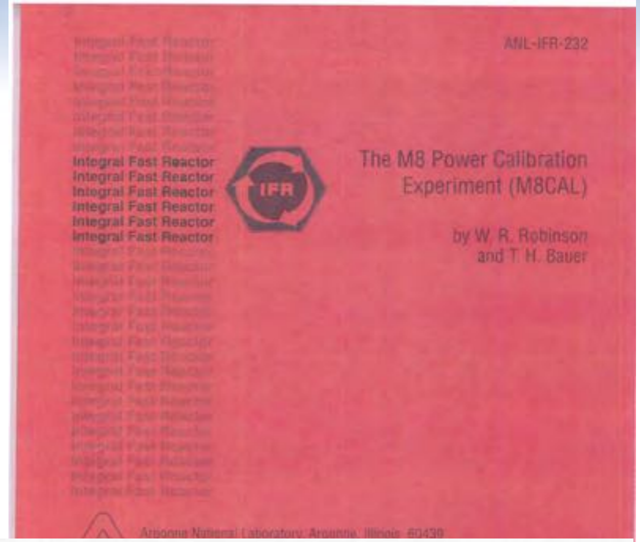
# Learning to Walk

- This analogy is not all that far off the mark
- TREAT has been idle for 22 years
- We're going to start off crawling first!
- The first tests to be performed in TREAT will be to reproduce the last set of measurements performed in TREAT – the M8 Series Power Calibration Experiment (M8CAL), 1990-1993.
- These measurements will be performed with existing equipment
  - No additional detectors
  - No additional flux/fission wires
  - Existing data acquisition system DAS and Automatic Reactor Control System (ARCS)
  - Wires and foils in test position will be gamma scanned and surveyed for FP inventory
- DOE-ID wants INL to demonstrate that we can reproduce historical data before resuming operations




| Core Configuration | TREAT Transient Number | Date of TREAT Operation | Control Rod Configuration | Wire Number | Test Train | Identification | Wire Holder | TREAT Energy, MJ | Hodoscope Operation? |
|---|---|---|---|---|---|---|---|---|---|
| Full-slotted | --- | 10/16/90 10/17/90 | B | | Fueled | Low-level, steady-state (LLSS) irradiation providing background signal for the hodoscope (NO FUEL) | --- | 437 | Yes |
| Full-slotted | --- | 10/19/90 | B | L91-8-10 | Unfueled | LLSS | LO3 | 667 | Yes |
| Full-slotted | 2811 | 10/25/90 | B | L91-8-11 | Unfueled | Full Heat Balance Transient | LO3 | 655.4 | No |
| Full-slotted | 2812 | 10/26/90 | B | L91-8-12 | Unfueled | Heat Balance Transient (Partial) | LO3 | 404.7 | No |
| Full-slotted | 2815 | 11/14/90 | D | L91-8-13 | Unfueled | 8-s Period Transient | LO3 | 996.0 | Yes |
| Full-slotted | 2816 | 11/15/90 | D | L91-8-14 | Unfueled | 8-s Period Transient (Partial) | LO3 | 661.8 | No |
| Half-slotted | --- | 8/24/92 | A | L91-60-1 | Unfueled | LLSS | LO3 | 576 | No |
| Half-slotted | --- | 8/26/92 | A | --- | Fueled | LLSS for hodoscope background signal measurement (NO FUEL) | --- | --- | Yes |
| Half-slotted | 2858 | 8/31/92 | C | L91-8-2 | Unfueled | Heat Balance Transient (Partial) | LO3 | 423.1 | No |
| Half-slotted | 2862 | 9/23/92 | C | L91-8-3 | Unfueled | Full Heat Balance Transient | LO3 | 655.0 | Yes |
| Half-slotted | 2864 | 10/14/92 | D | L91-8-4 | Unfueled | 8-s Period Transient | LO3 | 1868.4 | Yes |
| Half-slotted | 2867 | 10/27/92 | D | L91-8-7 | Unfueled | 30-s Period Transient | LO3 | 1956.7 | Yes |
| Half-slotted | 2868 | 10/29/92 | C | L91-8-8 | Unfueled | 30-s Period Transient (Partial) | LO3 | 1198.6 | No |
| Half-slotted | 2869 | 10/30/92 | C | L91-8-9 | Unfueled | 30-s Period Transient (Partial) | LO3 | 602.1 | No |
| Half-slotted | 2871 | 11/10/92 | D | L91-8-15 | Unfueled | 30-s Period Transient (with power roll-over) | LO3 | 1999.8 | No |
| Half-slotted | 2873 | 11/19/92 | D | L91-8-5 | Unfueled | 80-s Period Transient | LO3 | 1797.8 | Yes |
| Half-slotted | --- | 11/20/92 | A | L91-8-1 | Unfueled | LLSS | LO3 | 576 | Yes |
| Half-slotted | --- | 1/29/93 | A | T-433 T-462 | Fueled | LLSS | --- | 480 | Yes |
| Half-slotted | --- | 2/8/93 | A | L91-8-6 | Unfueled | LLSS | LO3 | 480 | Yes |
| Half-slotted | --- | 2/12/93 | A | H91-8-1 | Unfueled | LLSS | M2CAL | 576 | No |
| Half-slotted | 2874 | 2/17/93 | D | H91-8-2 | Unfueled | 8-s Period Transient | M2CAL | 1807.1 | No |
| Half-slotted | --- | 3/2/93 | B | L91-8-16 | Unfueled | LLSS | LO3 | 576 | Yes |
| Half-slotted | --- | 3/5/93 | A | H-316 H-307 | Fueled | LLSS | --- | 480 | Yes |

# Historical Approach for TREAT Calibration

- Steady state – calibration of detectors with experiments to calculate power coupling factor
  1. Heat balance measurements (calorimetry) were used to determine steady state power at one or more flux levels.
  2. A sample fuel rod(s) was placed within TREAT, and a steady-state test was performed for a set amount of time. The test rig was then removed and the number of fissions/sec/gm determined by destructive analytical chemistry techniques or gamma scan
  3. Fission wires of uranium alloy were irradiated at steady state and also assayed to obtain burnup data.
- Transient operation – determination of transient coupling correction
  4. TREAT would be operated in transient mode with a second set of fission wires with the planned transient
  5. Estimation of core power during transient, coupling to experiment in steady state, and transient correction factor.
- Finally the test rig was placed in the test volume within TREAT and the prescribed transient test was performed.
- This process could take a week or more.

# Is Modeling and Simulation Even Needed?

- Operations has pointed out (more than once) that they don't need new advanced M&S to restart.
  - True, they can perform operations in exactly the same fashion as was done historically
  - Inefficient, time consuming, limited accuracy, but it worked:
    - 6,604 reactor startups
    - 2,885 transient irradiations
  - No predictive capabilities on fuel performance
  - Science was based on push it until it breaks.

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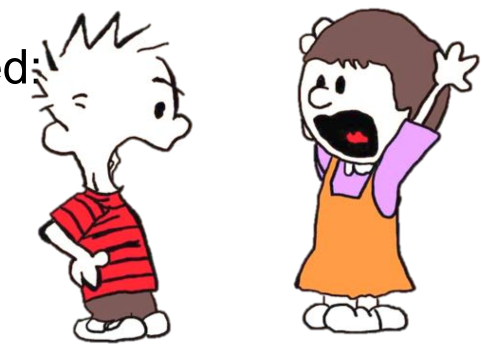
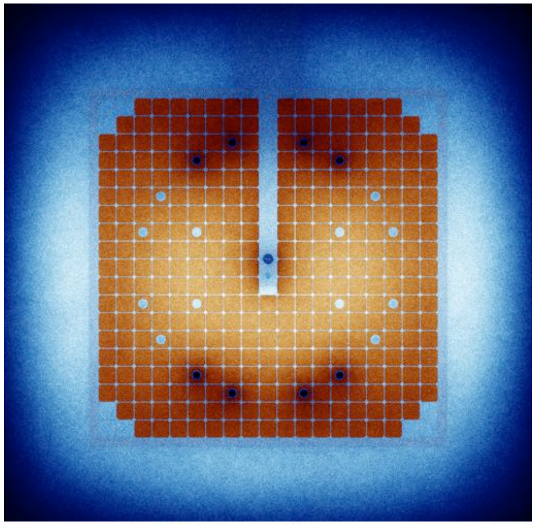
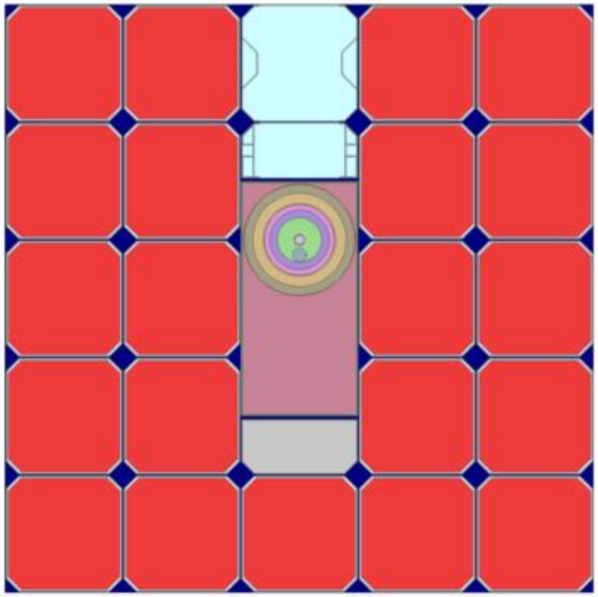


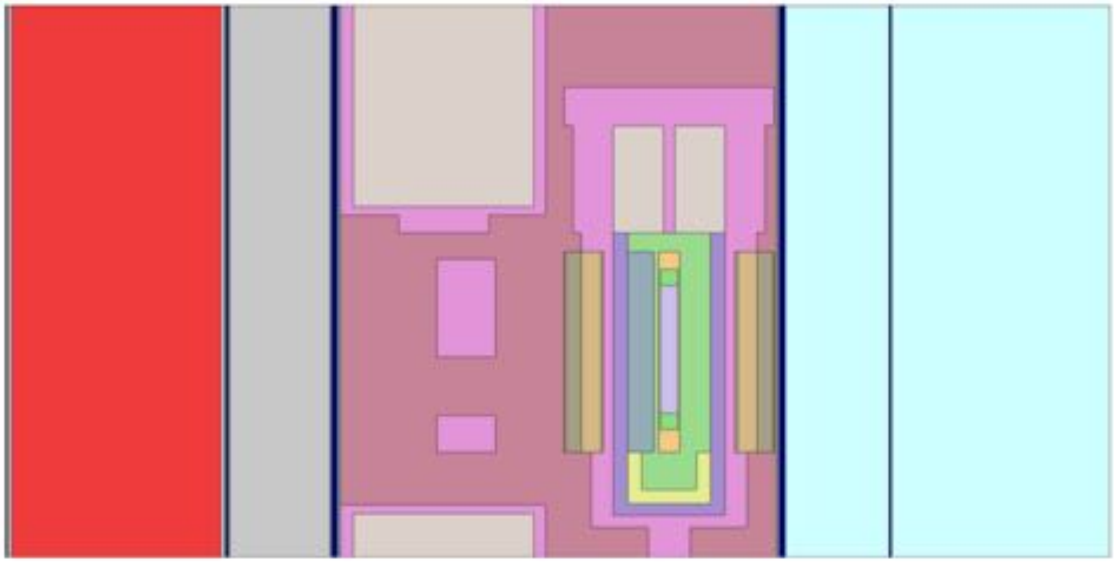
- The truth is operations doesn't need advanced M&S, but does want these capabilities.
  - Reduce a week's worth of pre-transient testing to perhaps a day.
  - Better quantify the behavior of the full core to reduce conservatisms
  - Tools for experiment, experiment vessel and instrumentation design
  - Increased throughput, better science coming out of measurements.
- DOE want the most bang for the buck on future TREAT operations
  - Increase throughput
  - Better utilization of reactor
  - Improved materials performance knowledge
  - Validation of single- and multi-physics methods

# Moving Forward on Advanced Modeling and Simulation

- Development of methods to handle cross section challenges
  - 3D effects – base cross sections generated using *Serpent 2*
  - Strong neutron streaming in hodoscope slot
    - Direction-dependent diffusion coefficients using Larsen-Trahan method added to Rattlesnake
  - Strong absorption near control rods
    - Superhomogenization correction
    - Also corrects for vertical leakage through air channels.

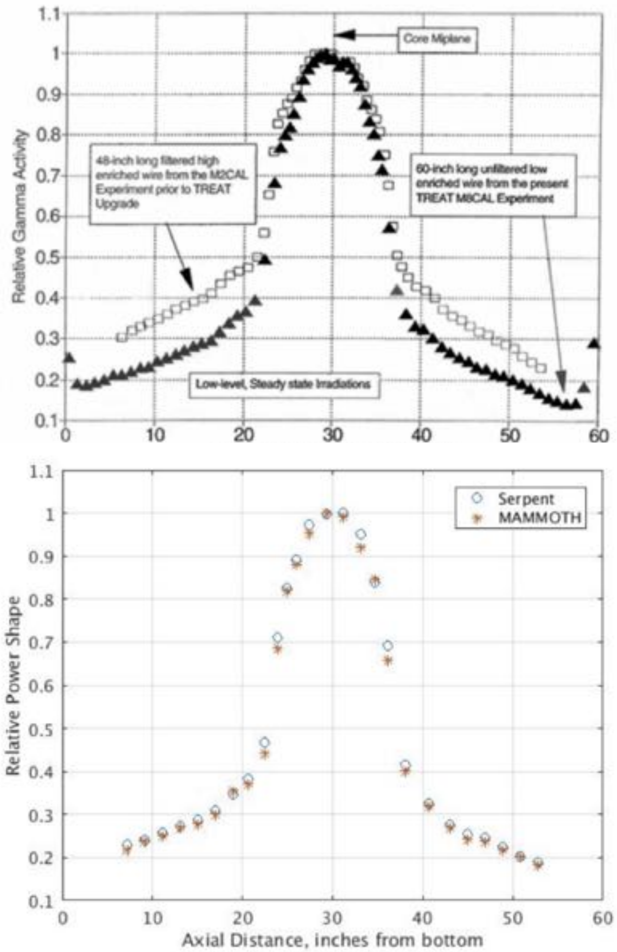


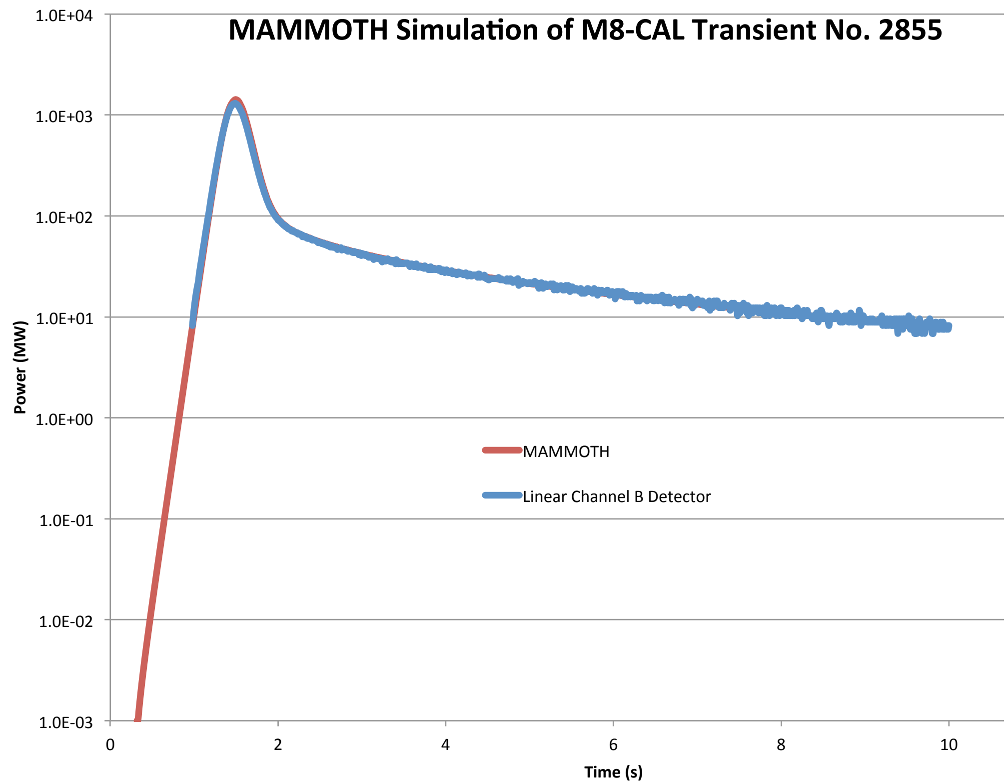




# Moving Forward on
# Advanced Modeling and Simulation

- Successful modeling of historical transients from M8CAL measurements with slotted core and in-core calibration vehicle.
  - transient power measurements
  - fission wires



# *Planning for Validation Measurements*

- Measurements to support validation from Feb – Nov 2018 (~130 working days)
  1. Develop Neutron Flux Map of the TREAT Core
     - Flux wires in strategic locations (x, y and z)
     - Fission wires together with flux wires
     - Strategy for wire insertion, removal, tracking, counting
  2. Characterize Neutron Spectrum (steady state)
     - Core center/experiment location
     - Performed as a function of temperature
     - Activation of foils with and without filters
     - Use procedure for flux unfolding and code comparison using techniques developed in ATR in 2011-2014
     - Temperature measurements
  3. Develop TREAT Core Temperature Profile/Negative Temperature Coefficient
     - Non-trivial – only clad temperature is readily measured
     - Thermocouple or infrared, other?
  4. Perform Neutron Lifetime and Beta Measurement
     - Noise techniques
     - Oscillation
  5. Evaluate new detector technologies (in-core and ex-core)

# Planning for Validation Measurements

- For wires and foils, post-irradiation counting will be performed (betas and gamma)
- TREAT currently has no in-house facilities.
- Counting labs are available at the Advanced Test Reactor (20 min. drive) and at the Materials and Fuels Complex (>5 min. drive)
  - Unfortunately, both facilities are being heavily utilized
  - Measurements should be made within 24 hours
- Justification for new counting facilities at TREAT
  - Budget is available
  - Decisions need to be made soon!

# Planning for Validation Measurements

- For wires and foils, post-irradiation counting will be performed (betas and gamma)
- TREAT currently has no in-house facilities.
- Counting labs are available at the Advanced Test Reactor (20 min. drive) and at the Materials and Fuels Complex (>5 min. drive)
  - Unfortunately, both facilities are being heavily utilized
  - Measurements should be made within 24 hours
- Justification for new counting facilities at TREAT
  - Budget is available
  - Decisions need to be made soon!
- February 2018 is just around the corner and much remains to be done by all parties!

# TREAT Team Leads

- Dan Wachs – Transient Testing Lead
- Bruce Nielson – Program Manager
- Rob O'Brien – ATF-3 Principle Investigator
- Andy Beasley – ATF-3 Experiment Manager
- Heng-Ban, Troy Unruh, Darrell Knudson, Josh Daw, Kurt Davis – Instrumentation
- Nick Woolstenhulme – Test Vehicle Design & Analysis Lead, SERTTA Lead Engineer
- Greg Housley – TWERL Lead Engineer
- Clint Baker – Hot Cell Prep. and Assembly Engineer, Sodium Loop Lead Engineer
- Lance Hone, Nathan Jerred – Engineering and Prototyping Support
- John Bess, Connie Hill, Jorge Navarro, Vishal Patel, Cliff Davis – MCNP Neutronics
- Colby Jensen, Cliff Davis – Thermal Analysis
- Spencer Snow – Structural Analysis
- Jim Parry, Lee Nelson, Doug Gerstner – TREAT Operation Interfaces
- Mark DeHart – Multi-physics Methods Development

# Questions?