INL/CON-25-82851-Revision-0

BYU-Idaho Colloquium Presentation

January 2025

Changing the World's Energy Future

Jacob E Hansen, Tyson L Williams

INL/CON-25-82851-Revision-0

BYU-Idaho Colloquium Presentation

Jacob E Hansen, Tyson L Williams

January 2025

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

January 20, 2025

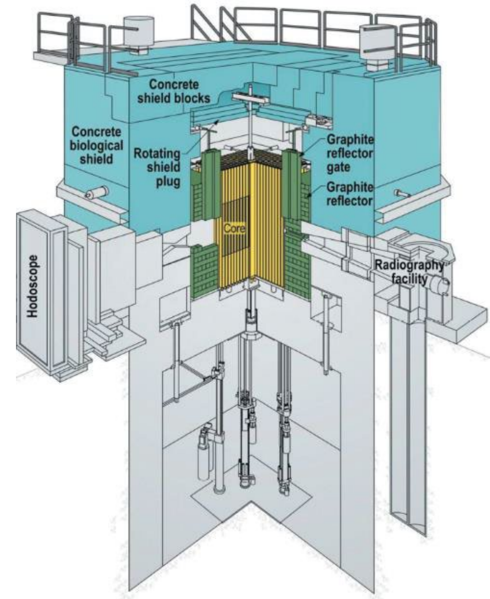
Jacob Hansen / Tyson Williams

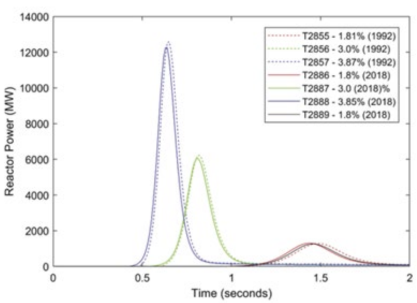
TREAT Overview

Transient Reactor Test Facility

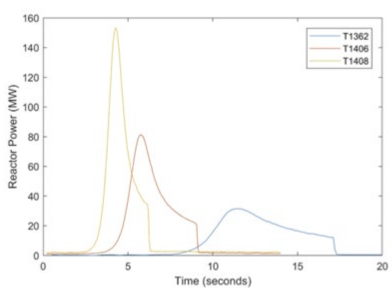
Introduction to TREAT

- TREAT is a transient reactor designed to test how different experiments behave in various scenarios
- Zircaloy-clad graphite/fuel blocks comprise core
  - Virtually any power history possible within core transient energy
  - From milliseconds to minutes: Pulses, overpower ramps, loss of coolant
- Fuel motion monitoring system “hodoscope” observes fast neutrons emitted from specimens to track fuel relocation in real time
- Reactor also can be a neutron source to adjacent radiography facility
- <u>Experiment vehicle does everything else</u>
  - Safety containment, specimen environment, and instrumentation

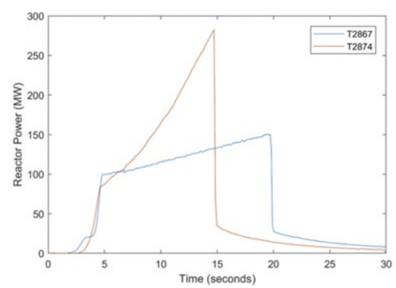




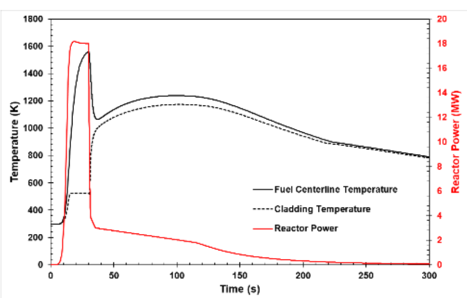
GW-Class Fast Pulses



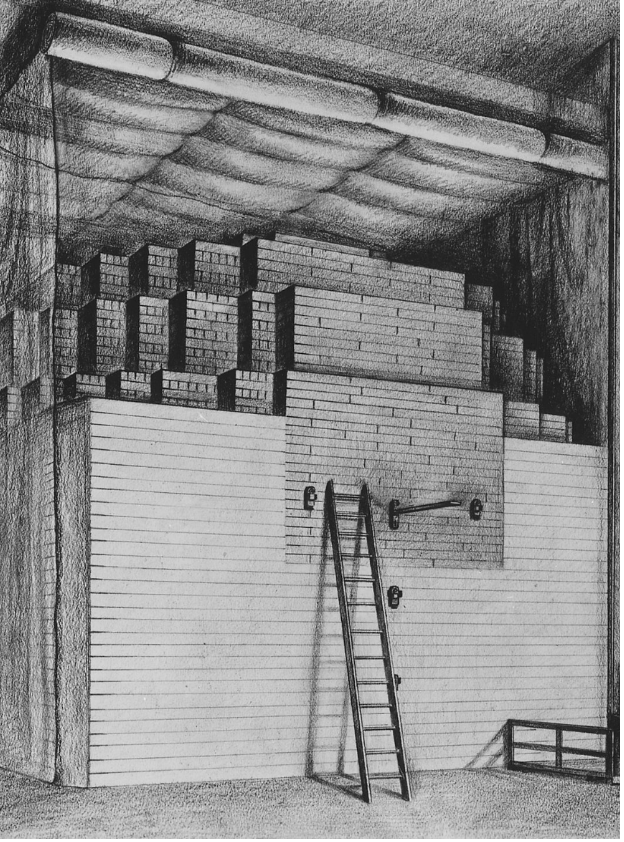
MW-Class “Slow” Pulses



Overpower Ramps



LOCA Shaped Transient

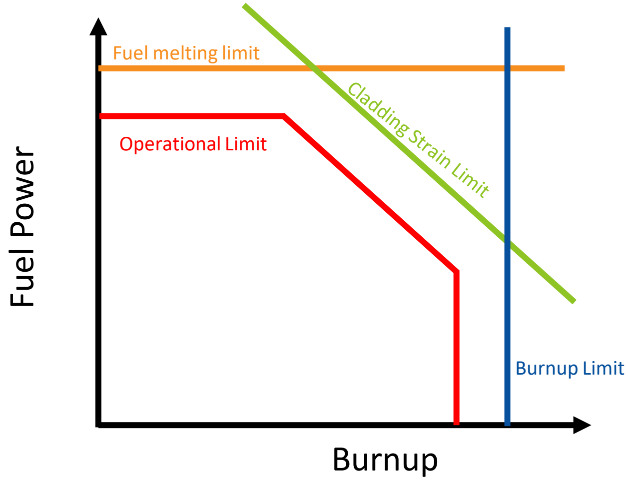
  

The History of TREAT

- TREAT was built in the summer of 1958
- Some of the graphite shielding used in TREAT is recycled from Chicago Pile 1, the very first artificial reactor
- TREAT operated from 1959-1994, was later refurbished, and resumed operations in 2017 to support fuel safety testing and other transient science

Why Transient Test Nuclear Fuels & Materials?

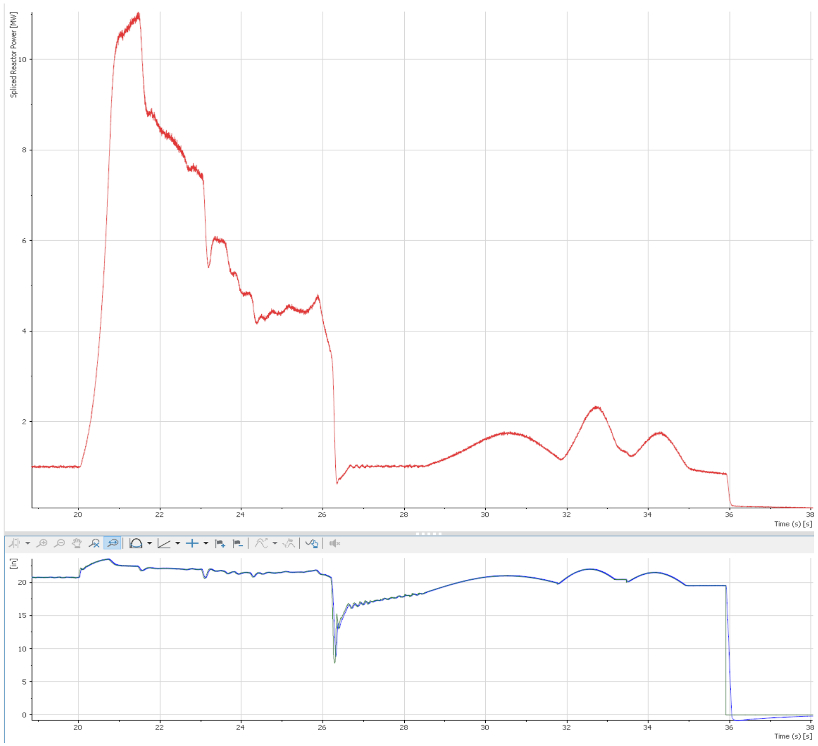
- **Transient testing is like car crash testing for nuclear fuels**
- Licensing a fuel system *requires* (see NUREG-0800):
  - identification of all **degradation mechanisms and failure modes**
  - definition of **failure thresholds** corresponding to each degradation mechanism
  - applies to **normal operations, anticipated operational occurrences and design basis accidents**
- Many operational limits are dependent on degradation and failure thresholds
- Enables economic reactor operations via improved fuel design and performance understanding



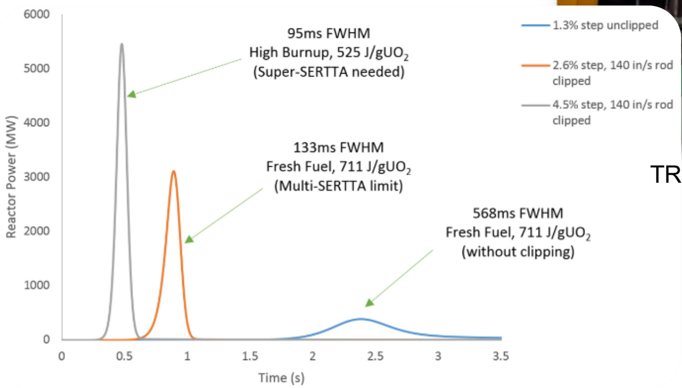
Reactor Power Control

- TREAT is a transient reactor, not only a pulse reactor
- Graphite heat sink, nimble control rod system → flexible power maneuvers
  - Transient rods can move from full-in to full-out in ~300ms
- Rod control system can accept feedback from experiment instrumentation

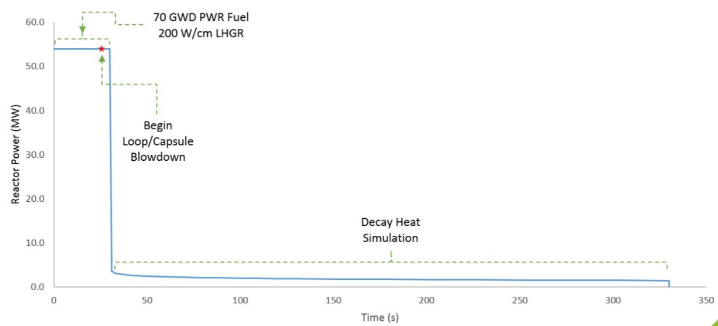
TREAT subpile room



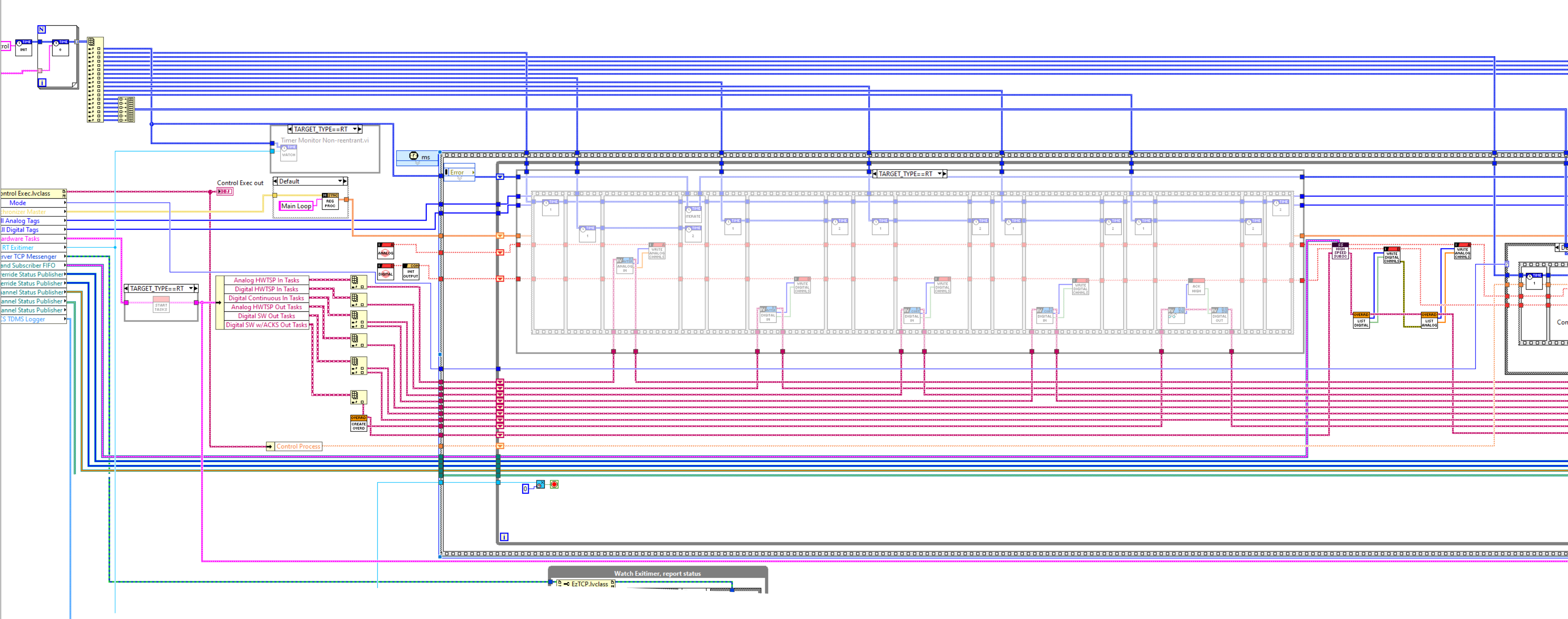
Shaped Transient



Pulse Transient



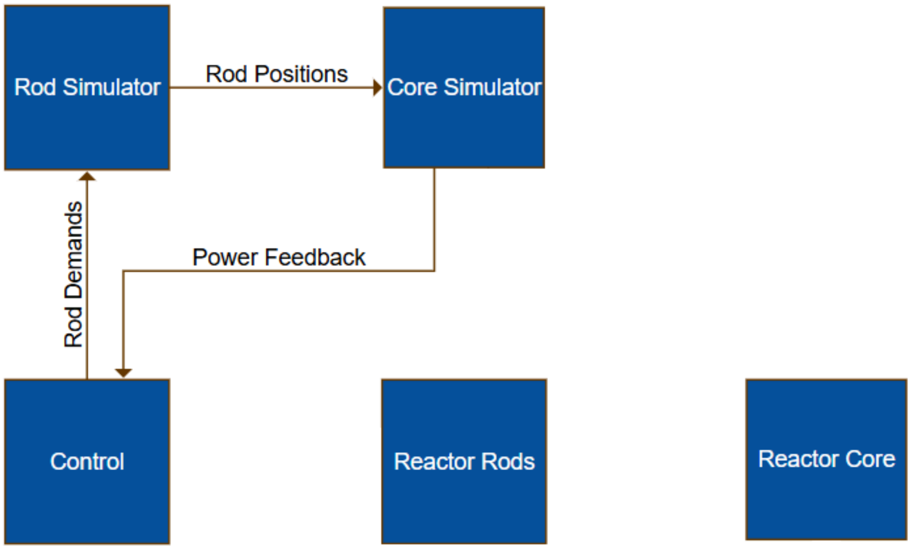
LOCA Transient



Automatic
Reactor
Control
System

- TREAT can produce just about any type of shaped transient
- This allows for testing of experiments in various disaster scenarios as well as creating specific test environments depending on the test campaign
- Team of reactor engineers design these shapes
- ARCS provides closed loop feedback to drive the transient rods in the reactor. This happens once every millisecond

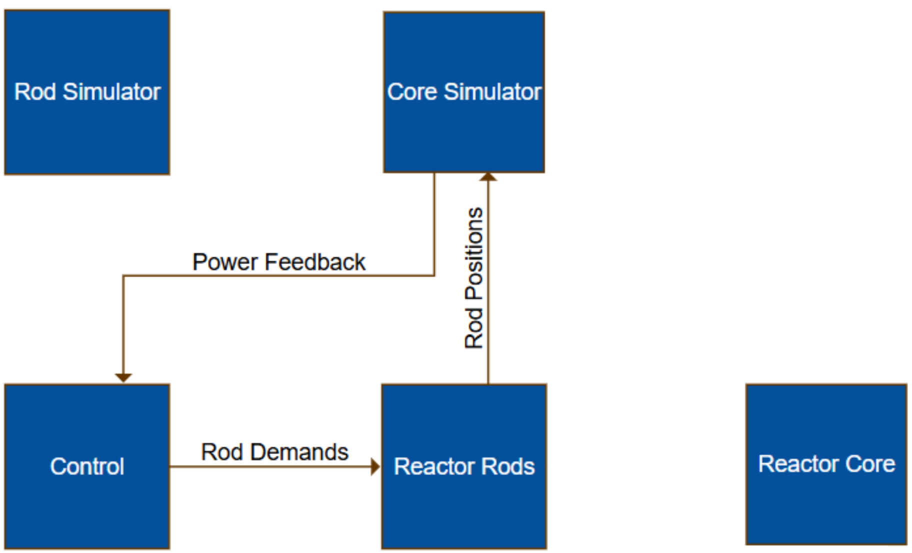
ARCS is a Control System
ARCS is a Simulation System



Full Simulations

- When a new transient is designed it is first run as a full simulation
- Using the simulator node of ARCS, reactor motion and physics are simulated letting engineers test before running live on a reactor
- These simulations build confidence that the reactor is capable of running the transient, and that all the trip setpoints are set correctly
- Full simulations simulate the responses of nuclear instruments by feeding the instruments simulated voltages bypassing the collection of neutrons

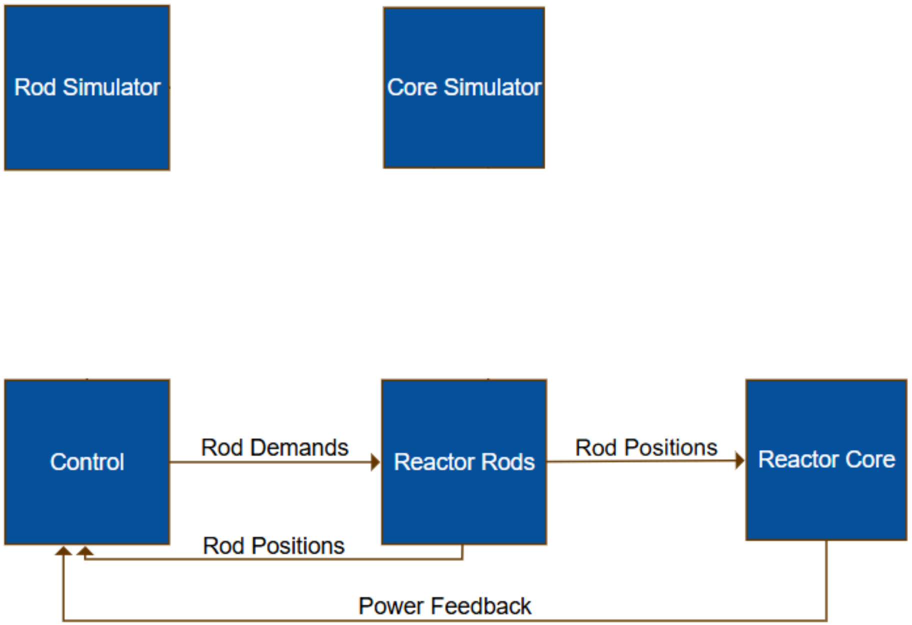
ARCS is a Control System
ARCS is a Simulation System



Partial Simulations

- After running a full simulation partial simulations are run to ensure that the plant is capable of the prescribed rod motion
- The core is kept subcritical by keeping the shutdown rods on the bottom
- Actual rod positions feed the reactor simulator which in turn simulates voltages on nuclear instruments like in a full simulation

ARCS is a Control System
ARCS is a Simulation System



Actual Transients

- After both simulations have been successfully run only then do we run an actual transient
- Transients require an evacuation of the reactor building as the core will go critical
- The setup to run a transient takes long enough that even if the transient is short, we can mostly only run a single transient per day
- Some of the experiments can only experience a single transient before they are ruined which is why we practice so much first

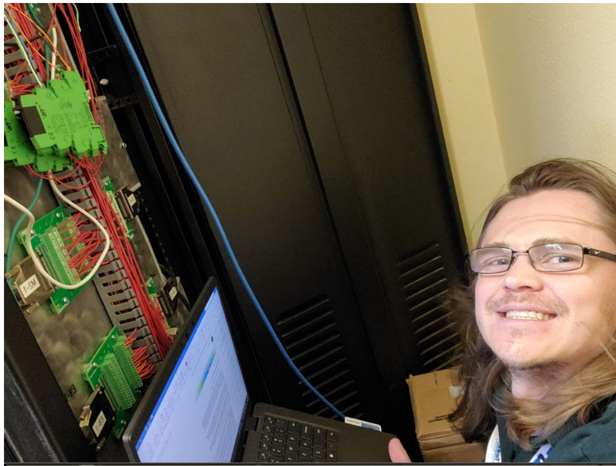
ARCS

- ARCS is a series of 3 nodes that control transient operation
  - Control
    - Controls the reactivity within the reactor
  - Monitor
    - Monitors the nuclear instruments for experiment limits
    - Is the first line of defense responsible for stopping the experiment if the experiment isn't going as planned
  - Simulator
    - Used during full and partial simulations to verify that the shape of the transient and the rod motion required to generate that shape will function as desired on the reactor
- The ARCS actively monitors 504 signals at a 1 ms period
- The ARCS uses a prescription file as an input. This file dictates the shape of the transient as well as lots of other options on how that shape is achieved

```
Initial Reactor Power Level (Watts) = 50.000000

Control & Monitor Clock Period = 2 (ms)

Control Node save once every 1 clock cycles
Monitor Node save once every 1 clock cycles

Rod Demand Averaging
[1E-3, 1E-4, 1E-5, 1E-6, 1E-7, 1E-8, 1E-9, 1E-10, 1E-11]=

Enable Low Power Splicing = FALSE
Enable High Power Splicing = FALSE
Disable Initial Rod Step = FALSE
Transient Bank Initial Rod Step (Inch) = 7.700000
All Rods Scram = TRUE
Increase Period Range = FALSE

ARCS Linear Starting Range = 10e-7
--------------------------------------------------------------

--------------------------------------------------------------
Program Timer Specifications
--------------------------------------------------------------
Port 1  : Mode = Pulse Width From -5.0000   to  5.0000
Port 2  : Mode = Pulse Width From 0.0000   to  18.0000
Port 3  : Mode = Pulse Width From 0.0000   to  18.0000
Port 4  :  is Not Used
Port 5  :  is Not Used
Port 6  : Mode = Pulse Width From -2.0000   to  18.0000
Port 7  : Mode = Pulse Width From -2.0000   to  18.0000
Port 8  :  is Not Used
Port 9  :  is Not Used
Port 10  :  is Not Used
Port 11  :  is Not Used
Port 12  : Mode = Level Change at 19.0000   sec   for  SC
--------------------------------------------------------------

--------------------------------------------------------------
Transient Prescription Definition
--------------------------------------------------------------
With a listing of 4 segments.

Segment 1 :  Rise or Fall on a period of 0.550000  (sec).
Power Target = 1000.000000  (MW).
Segment Termination: At 0.300000  (sec).
  DAS SCRAM allowed = False. Energy SCRAM level = 0.00000

Segment 2 :  Rod Stop
Segment Termination: At 100.000000  (MJ).
  DAS SCRAM allowed = False. Energy SCRAM level = 0.00000

Segment 3 :  Clip
Segment Termination: At 3.000000  (sec).
  DAS SCRAM allowed = False. Energy SCRAM level = 0.00000

Segment 4 :  End of Transient
Segment Termination:
  DAS SCRAM allowed = False. Energy SCRAM level = 0.00000
```

Developing Software for a Nuclear Reactor

- DARCS (Development ARCS)
- Plant time is valuable (it takes a lot of people to run the plant)
- We don’t test on the reactor until we know what is going to happen during the test
- DARCS emulates the plant letting us test software before it runs on the actual reactor
- DARCS has 4 nodes (as opposed to the reactors 3)
  - 3 ARCS nodes: Control, Monitor and Simulator
  - Emulator node
- The emulator node is responsible for being everything that isn’t ARCS
  - The reactor
  - Nuclear instrumentation
  - The reactor protection system
  - Timing and other integration hardware
- Because ARCS has a 1ms period, all the software subcomponents are required to return on the order of microseconds 99.9999+% of the time



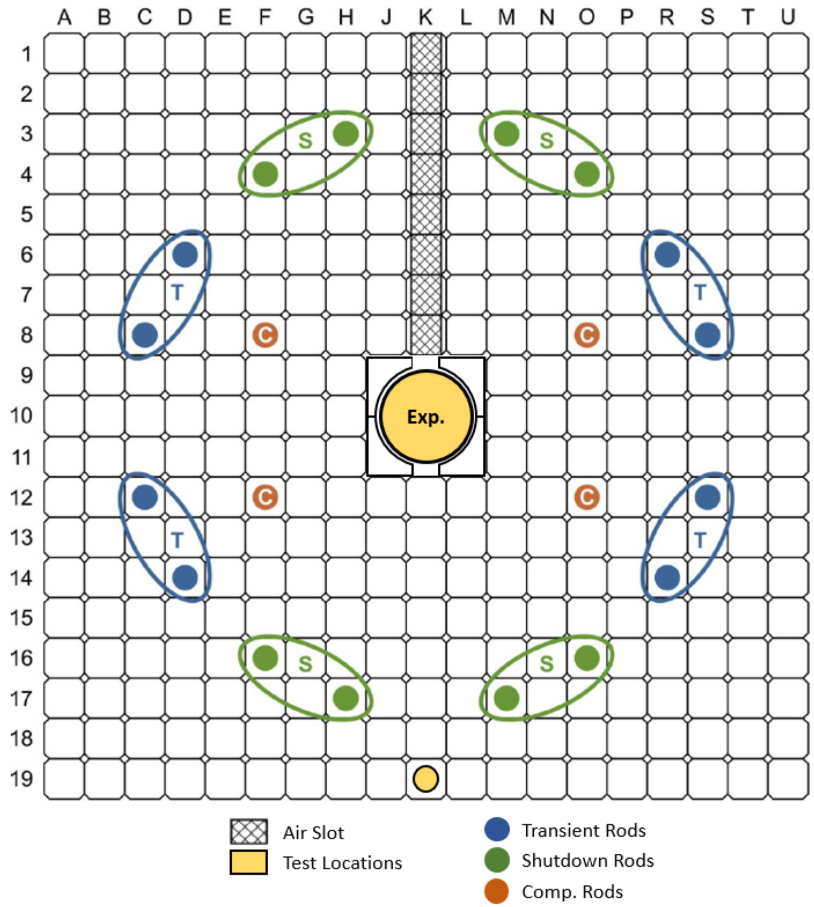
System Integration: E-DACS, RTS, Master Clock, & Auxiliary Panel

- The Experiment Data Acquisition System (E-DACS) is an important part of experiment campaigns at TREAT
  - This system is responsible for watching experiment specific instrumentation as well as controlling any experiment specific components such as heaters.
  - This system communicates with ARCS though a series of 11 signals that lets the experiment negotiate with the reactor.
  - These lines can let the experiment request a change to what is happening during a transient or request to stop the transient all together.
- The Reactor Trip System (RTS) is responsible for keeping the reactor within safe operating conditions.
  - ARCS communicates with this system to initiate shutdowns as well as to monitor various nuclear instruments
- The Master Clock is an instrument that insures that everything else is doing what it needs to do when it needs to happen. This piece monitors ARCS and reports to RTS

- **Any big engineering project takes a team of people all doing different things, one of the more difficult things on any project is making sure all the parts work together correctly**
- **The more pieces you are integrating this time to test grows exponentially**
- **When we first upgraded the ARCS the integration checkout out took a team of 5 people 3-4 weeks just to ensure everything was communicating properly**

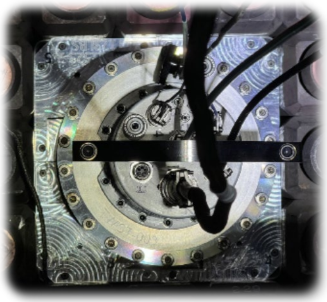
Transient Energy Capacity

- TREAT's total transient capability will be limited by one of two things:
- 600°C peak driver fuel peak temperature, only possible in large pulses ~2500 MJ core energy
  - Large step insertions typically clipped early by transient control reinsertion for narrower pulses
  - Only negative temperature feedback is credited for limiting energy release, thus 600°C limits step insertions to ~4.2% dk/k
- Total reactivity available in the transient rods, usually limits in longer shaped transients, especially for larger Big-BUSTER experiments
  - ~1200-1800 MJ core energy depending on reactivity worth of experiment hardware.
  - Use of low neutron cross section hardware (Zry) increases reactivity and heating rates in test fuel whereas iron, nickel, and titanium-based alloys do the opposite
  - Graphite reflector plugs in the experiment upper/lower reflector regions can recoup some reactivity
  - Fuel specimens are usually small and have little effect on reactivity
  - Light water tends to significantly increase specimen heating, but also causes modest negative change in reactivity

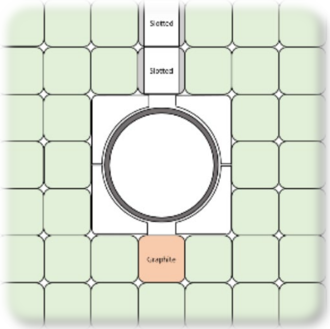


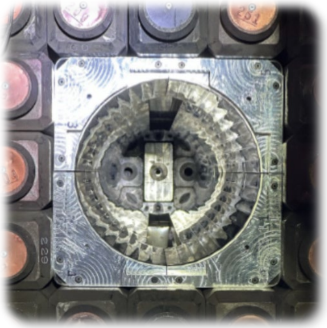
TREAT Test Geometry

- Broad Use Specimen Transient Experiment Rig (BUSTER) developed for modern experiments
  - Reusable nuclear grade outer safety containment
  - Houses commercial grade inner capsules/loops
- Enlarged “Big-BUSTER” recently commissioned
  - Provides 10X increase in test volume
  - Large as possible within existing transport casks



LOCA capsule in Big-BUSTER in TREAT core



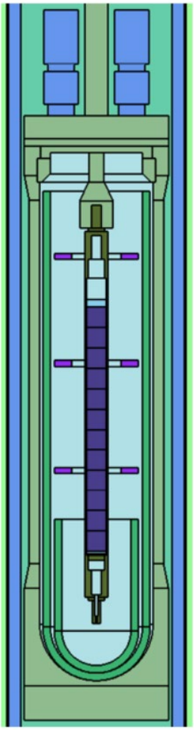


Moderator assemblies in TREAT core

TREAT Testbeds and Infrastructure

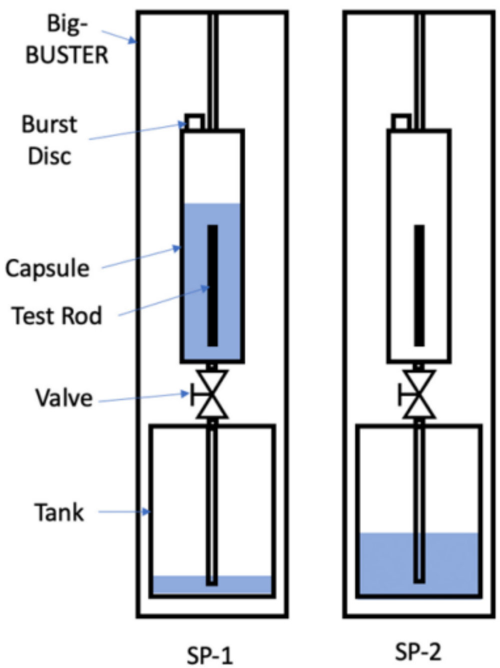
- TREAT programs fall within 5 product lines, each of which is supported by its own test bed infrastructure. From generic drop in capsule to flowing loop.

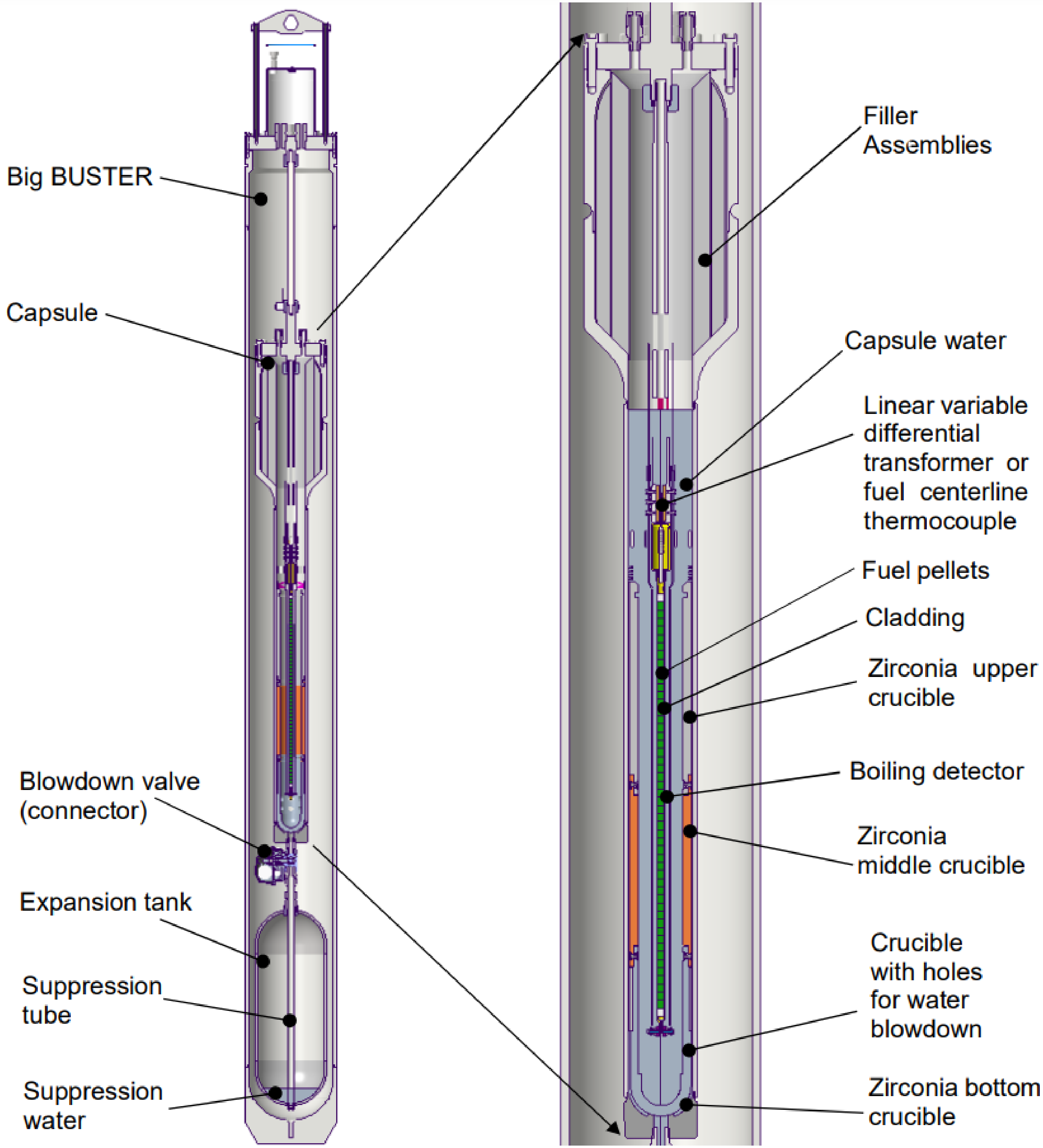
- Light Water Reactor
- Sodium Fast Reactor
- Other Advanced Reactors*
- Space Nuclear Propulsion
- National Security



TWIST

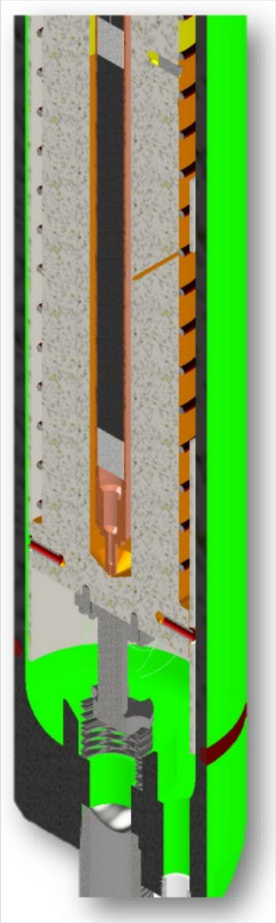
- The TWIST capsule is intended to support irradiations simulating LWR Loss of Coolant Accidents (LOCA) and Reactivity Initiated Accidents (RIA) in TREA[T] including accident tolerar[nt] fuels (ATF).





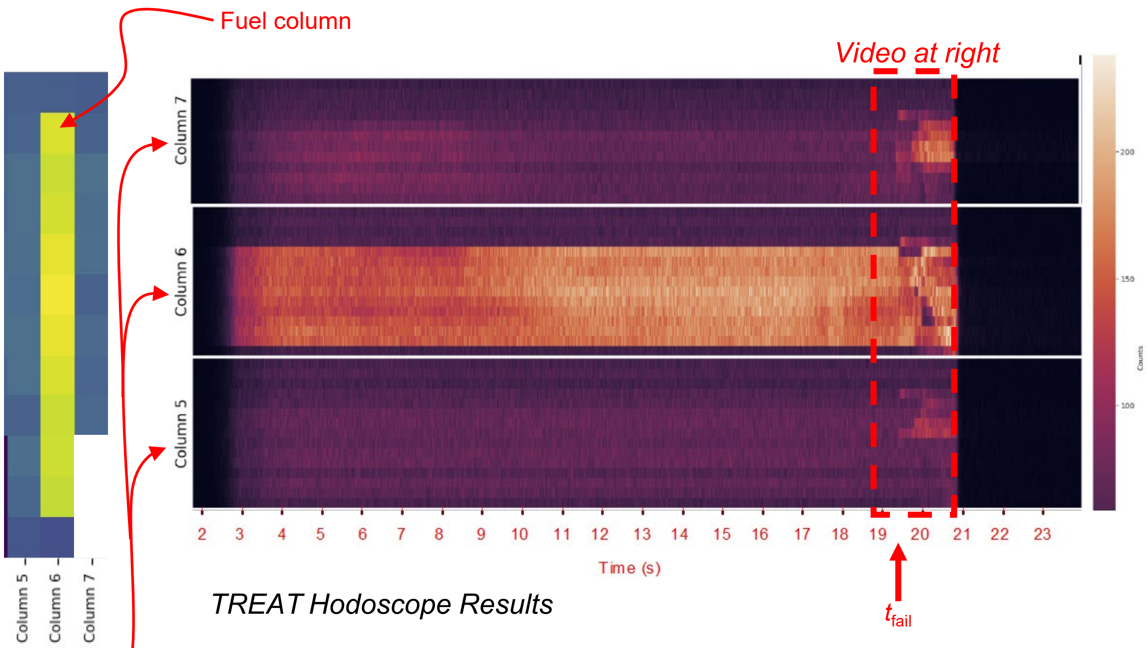
THOR (Temperature Heatsink Overpower Response)

- EPIC-THOR - Determine thermal conductivity of U-Pu-Zr fuels irradiated to various burnup levels.
- THOR-MOXTOP - Develop a threshold for fuel-cladding mechanical interaction in irradiated mixed oxide fuels. This threshold will be used for the qualification of oxide fuels for future commercial Sodium Fast Reactors.

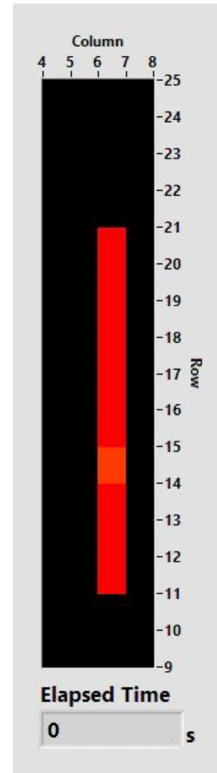


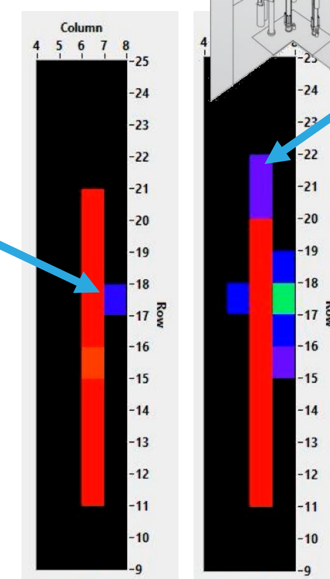
THOR-C-2 In-Situ Results: Hodoscope Results

- TREAT hodoscope results provide real-time description of fuel movement and likely first breach location



TREAT Hodoscope Results

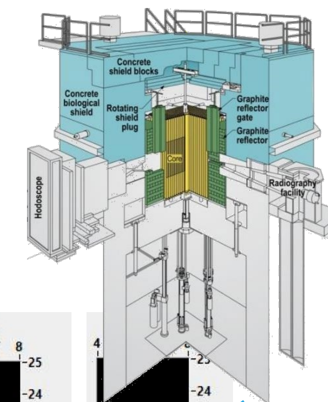




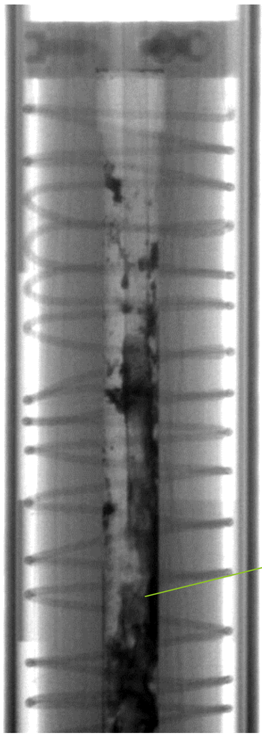
First indication of fuel relocation reveals likely failure location

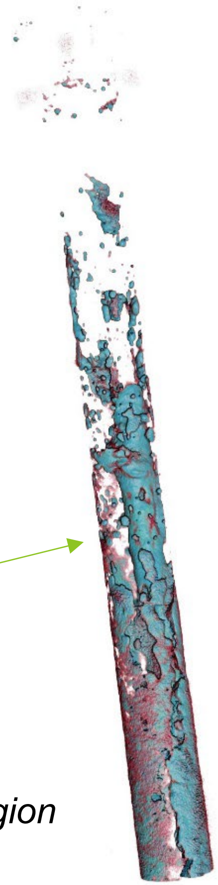
Axial in-pin fuel motion ~50ms later

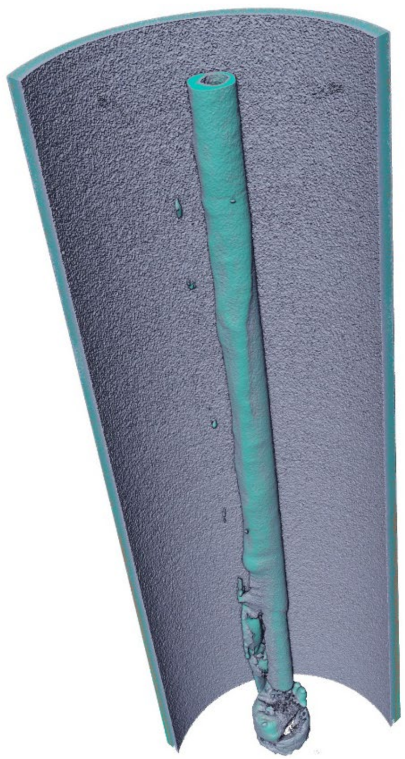
(prototypic failure expected at top of fuel column in flowing loop)



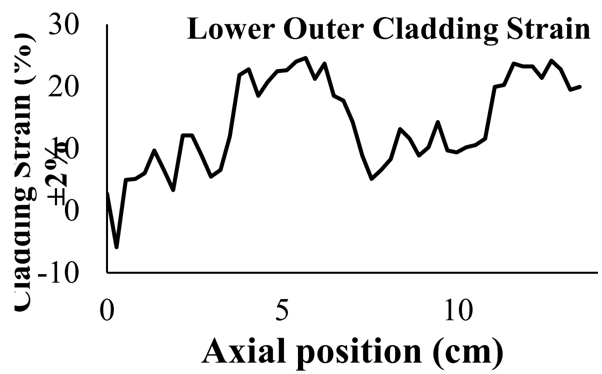
THOR-C2 neutron computed tomography







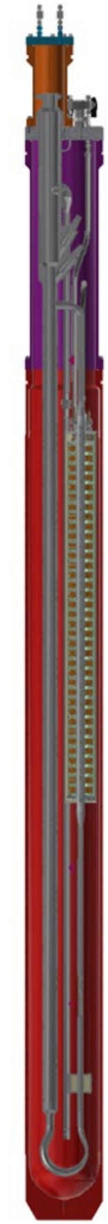
Lower Region



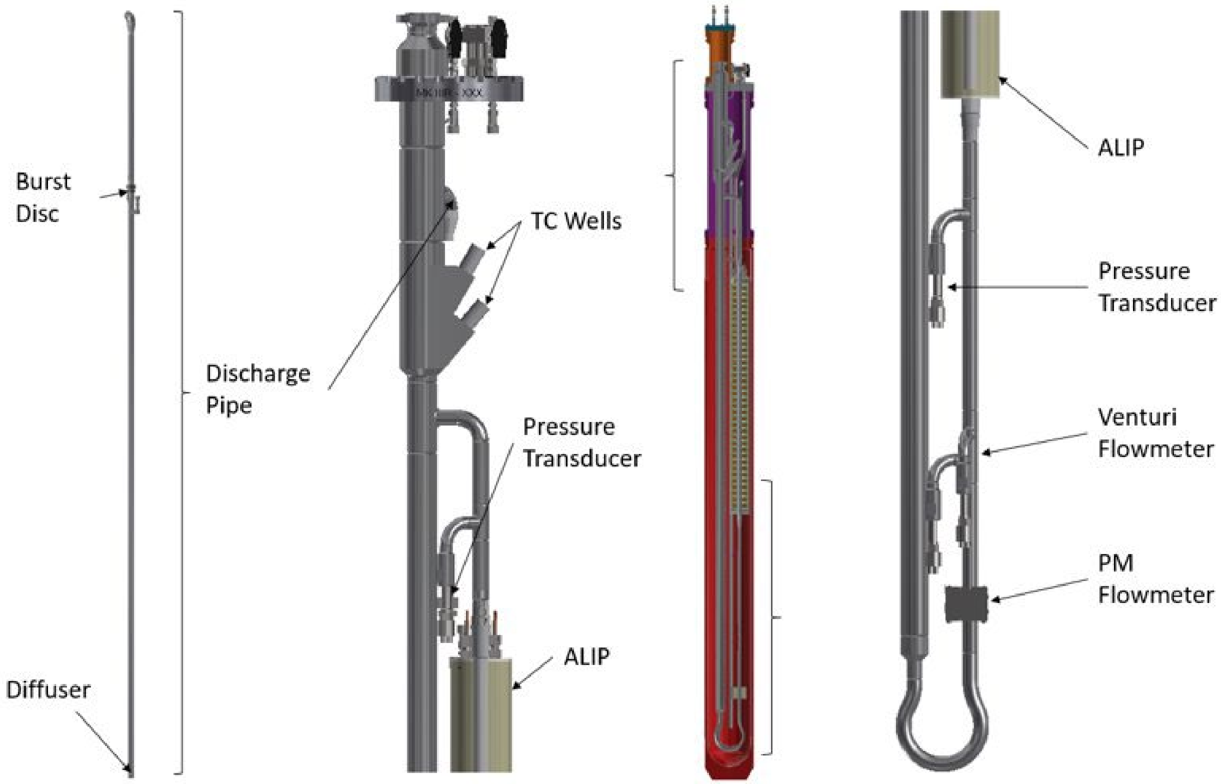
Upper Region

Destructive exams on C-2 to be performed later this year

Natrium Sodium Loop (conceptual Design)



- Develop a reusable experiment vehicle that provides research with prototypic thermal and hydraulic conditions of Sodium Fast Reactor (SFR) designs.
  -Fill a gap in SFR fuels testing and qualification infrastructure to support Natrium and other SFT fuel qualification programs.



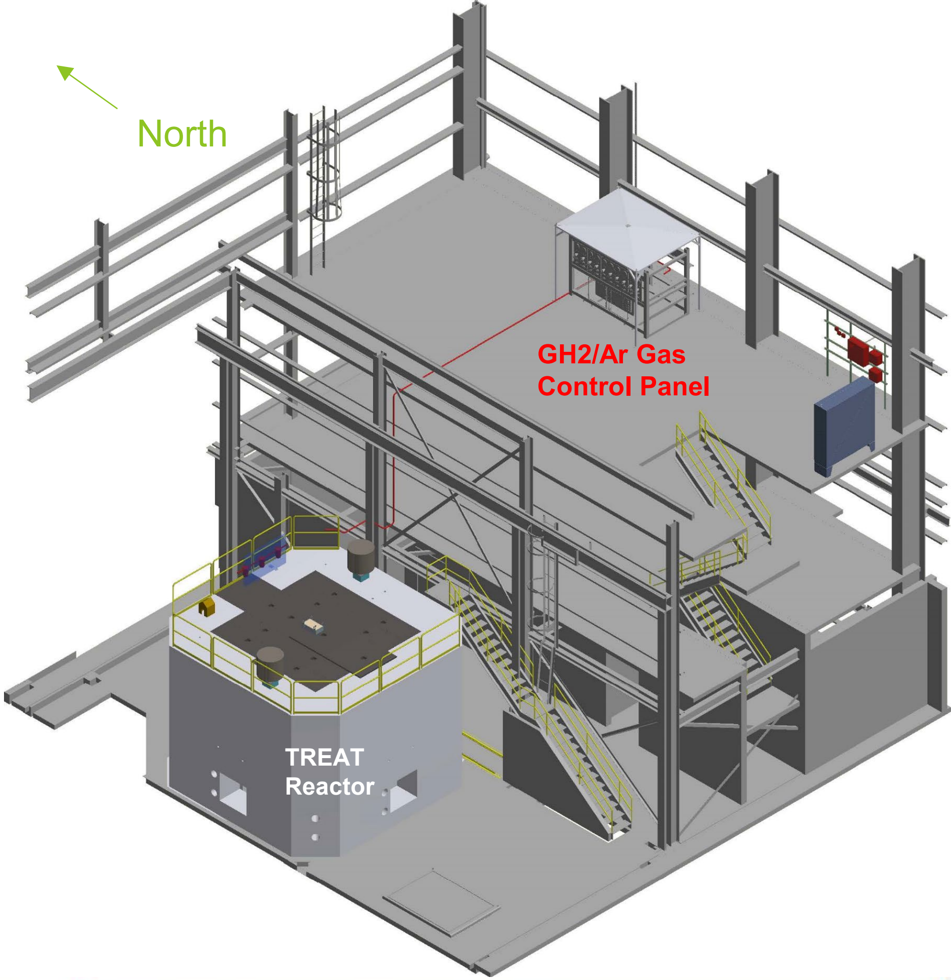
WATT

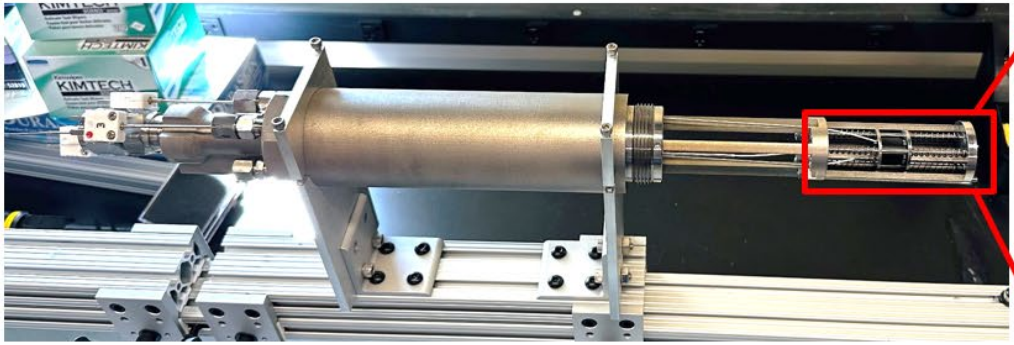
- Perform Tristructural Isotropic (TRISO) fuel capsule testing at Idaho National Laboratory (INL) in support of the eVinci™ microreactor.

SIRIUS (Conceptual)

NASA has been authorized to develop Nuclear Thermal Propulsion (NTP) systems for the peaceful exploration of the solar system.

NTP systems rely on a very high temperature once-through/open gas-cooled fission reactor to provide thermal energy and hence excite the coolant (H_2) that also serves as the propellant.





Idaho National Laboratory

Battelle Energy Alliance manages INL for the U.S. Department of Energy's Office of Nuclear Energy. INL is the nation's center for nuclear energy research and development, and also performs research in each of DOE's strategic goal areas: energy, national security, science and the environment.