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TREAT Test Design Considerations

April 2024

Nicolas E Woolstenhulme

Changing the World's Energy Future

Idaho National Laboratory

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Idaho National Laboratory
Idaho Falls, Idaho 83415

http://www.inl.gov

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N. Woolstenhulme*

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*Nicolas.Woolstenhulme@inl.gov

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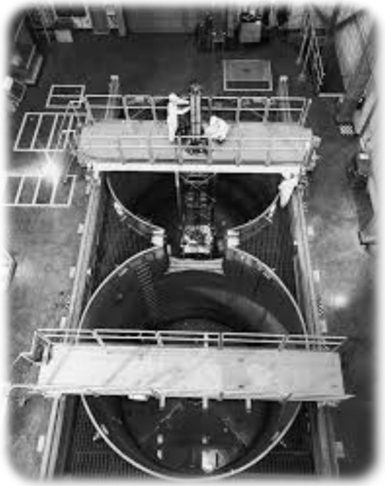
Part 1: Background Info

Introduction

PBF



SPERT-CDC

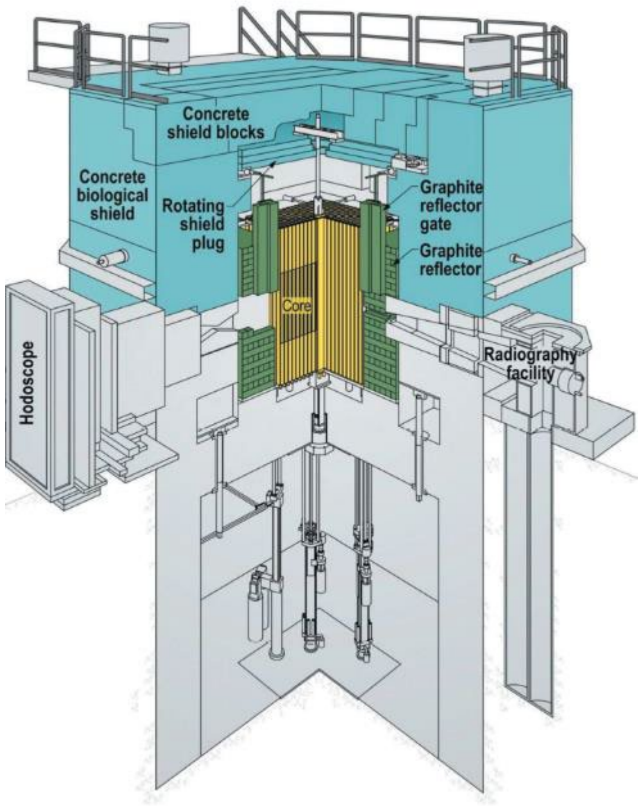
LOFT

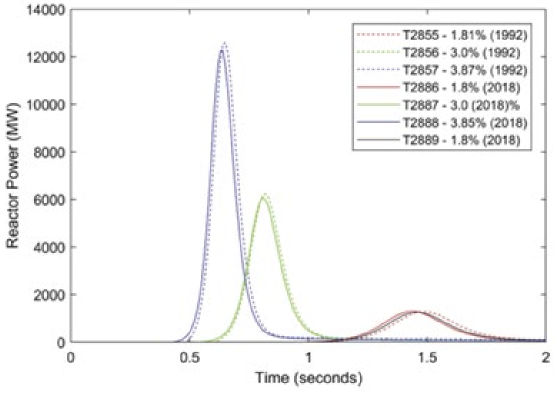
"Old TREAT"

- The "New TREAT" must absorb many of the missions from transient reactors of the past
  - Large programs relevant to water and sodium cooled reactors
  - Moderate-sized programs for gas-cooled reactors, national security, and space propulsion testing
  - Spanning needs from phenomena-identification, design bases accident simulation, and severe accident research

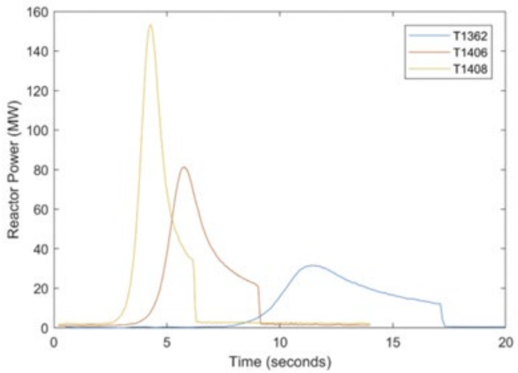
Introduction

- TREAT operated from 1959-1994, was later refurbished, and resumed operations in 2017 to support fuel safety testing and other transient science
- 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
- Experiment vehicle does everything else
  - Safety containment, specimen environment, and instrumentation

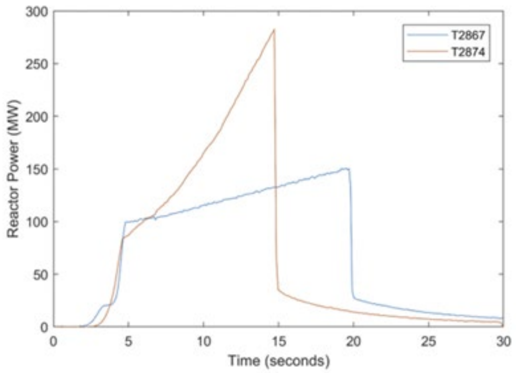




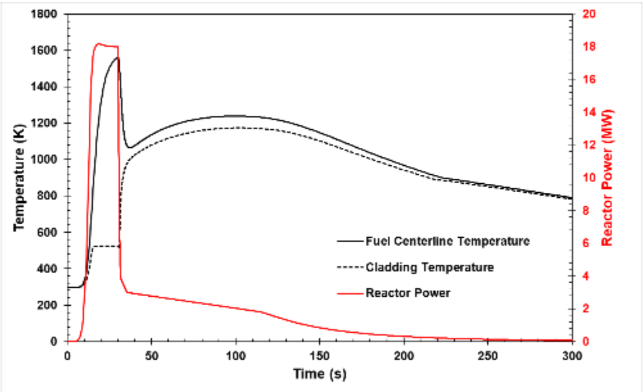
GW-Class Fast Pulses



MW-Class “Slow” Pulses



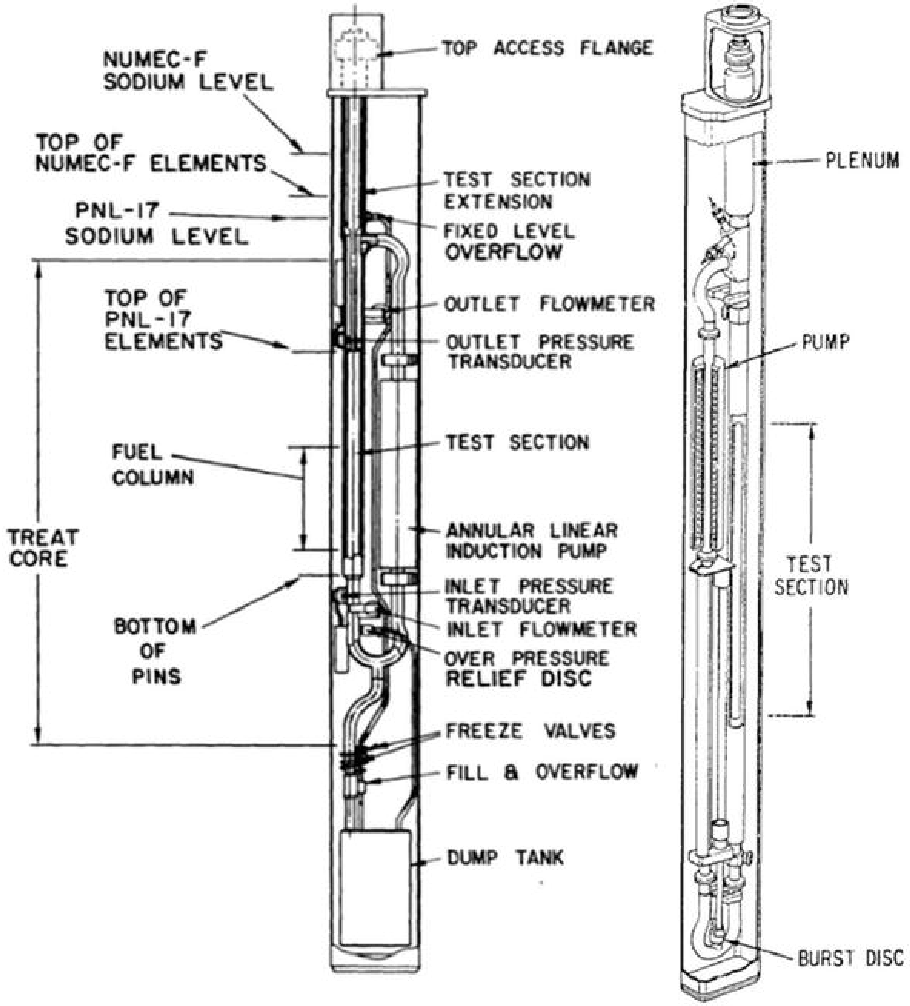
Overpower Ramps



LOCA Shaped Transient

Experiment Design

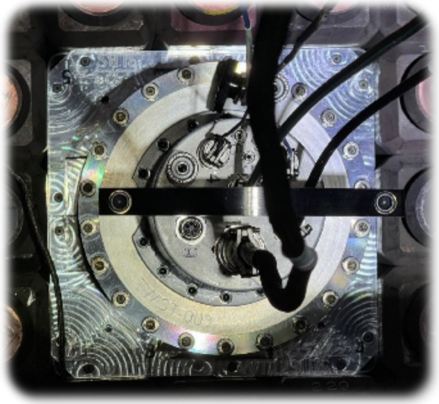
- TREAT is essentially a concrete-shielded block of graphite with a uranium "impurity"
  - No shielded cubicles or reactor pressure vessel
  - Cooled by air blowers during 80 kW steady state runs, and to cool core down after transients
- Supports one primary experiment at a time, and pivots between missions frequently
  - LWR tests one week, SFR tests the next
- Double-contained package type experiments most successful layout for TREAT experiments
  - Pre-irradiated specimens assembled into casks at HFEF, transported in casks
  - Electrical service and instrumentation leads connections on top of experiment rig
  - Fresh fuel experiments can be usually be irradiated and examined without using hot cells



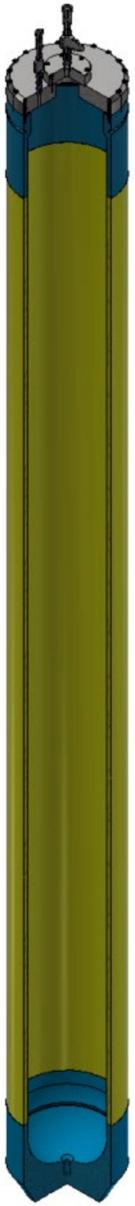
TREAT's Historic "Loop in a box" workhorse sodium loop, the inspiration for most modern TREAT tests

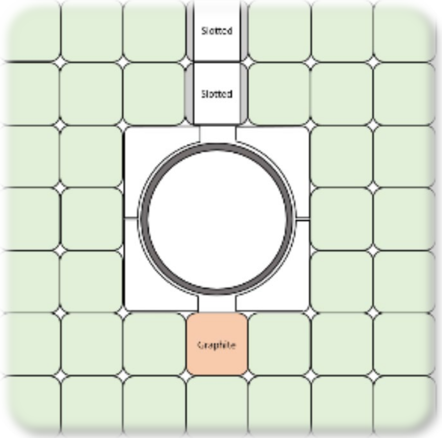
TREAT Test Geometry

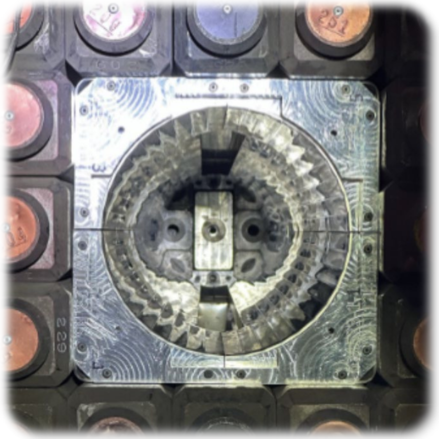
- Broad Use Specimen Transient Experiment Rig (BUSTER) developed for modern experiments
  - Reusable nuclear grade outer safety containment
  - Houses commercial grade inner capsules/loops
- Enlarged "Big-BUSTER" recently commissioned
  - Provides 10X increase in test volume
  - Large as possible within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



LOCA capsule in Big-BUSTER in TREAT core



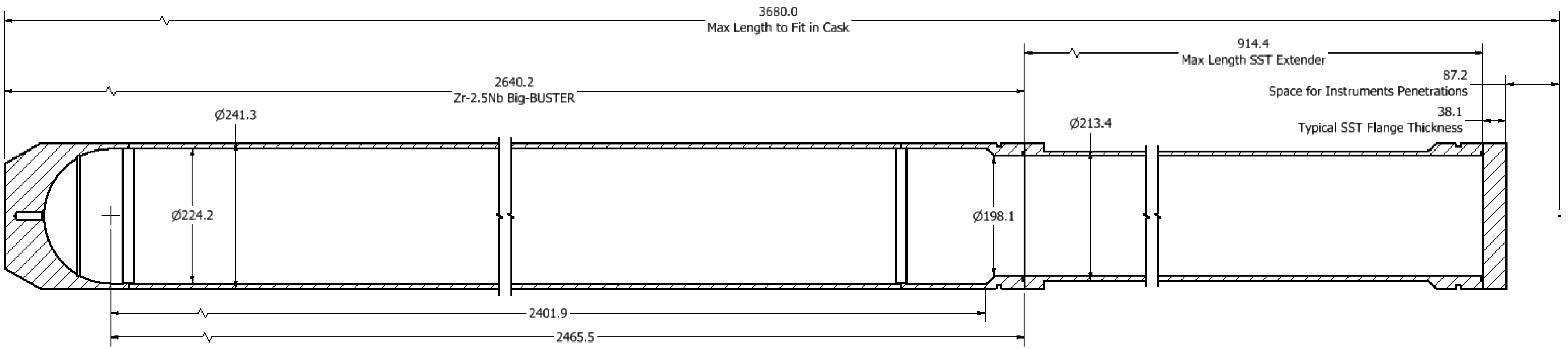




Moderator assemblies in TREAT core

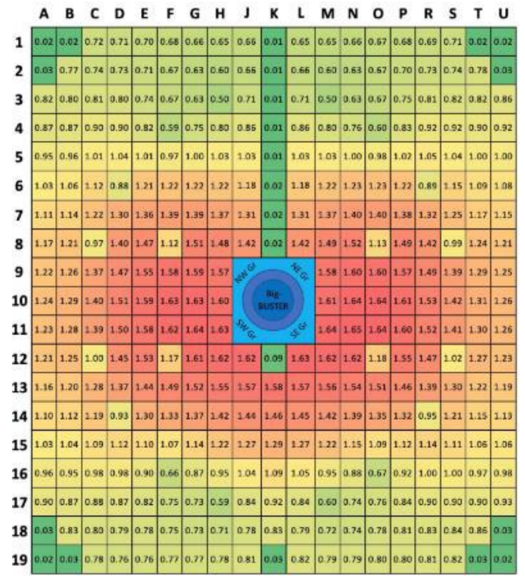
Big-BUSTER Dimensions

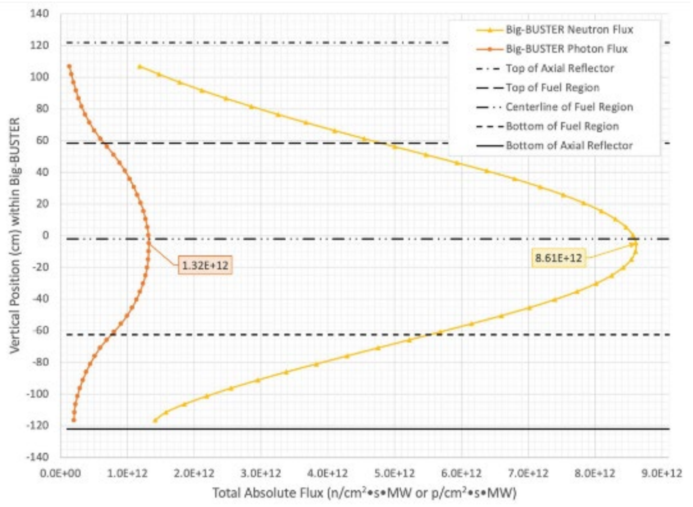
- Big-BUSTER Zr-2.5Nb weldment inner diameter 224 mm
- All test devices must fit through 198 mm diameter “bottle neck” region at bolt circle
- Flange can be placed directly on top of Big-BUSTER, or SST extender can be used to increase volume above core
- Design rating of 6.9 MPa (1000 psi) and 537 C (1000 F)



Neutronic Characteristics

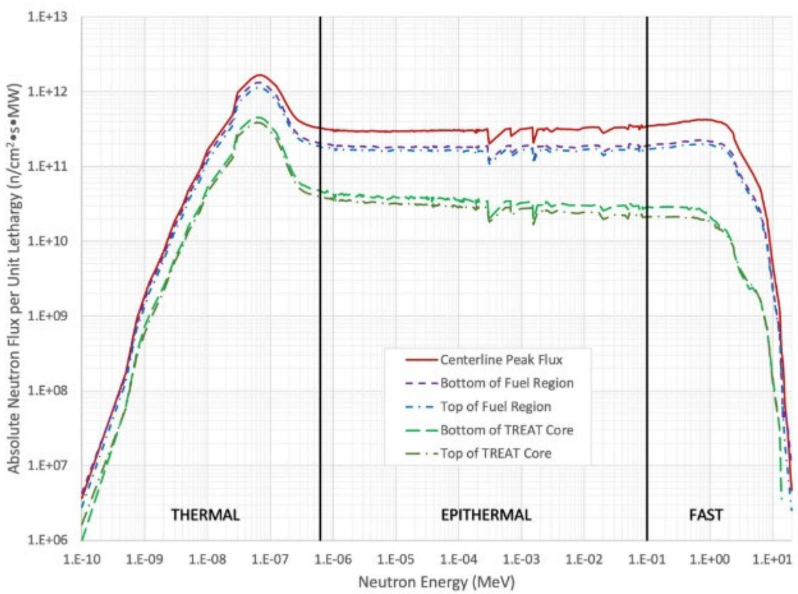
- Big-BUSTER core configuration
  - Graphite moderators and all Zry hardware delivers more, better-thermalized flux to test
    - Max transient fluence ~2.2E16 n/cm^2 (pulse)
    - Comprehensive dosimetry-based characterization recently performed in Big-BUSTER (data to be published shortly)
  - Maximizes nuclear heating capability in specimens
- Comparing fluxes to ATR at 50 MW lobe power
  - TREAT can essentially produce ATR like fluxes for 1-3 minutes
  - Not well suited to burnup accumulation, numerous power cycles, or ramp-and-hold PCI testing
  - Best suited to extreme transients, postulated accidents, etc.
- Safety basis and “loop in a box” approach enables fuel melting experiments with significant radioisotope inventories





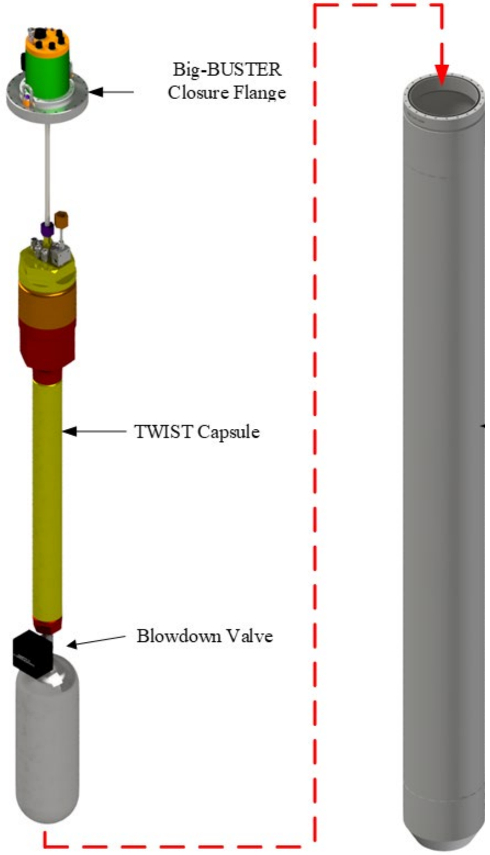
Axial flux profile

Neutron energy spectrum

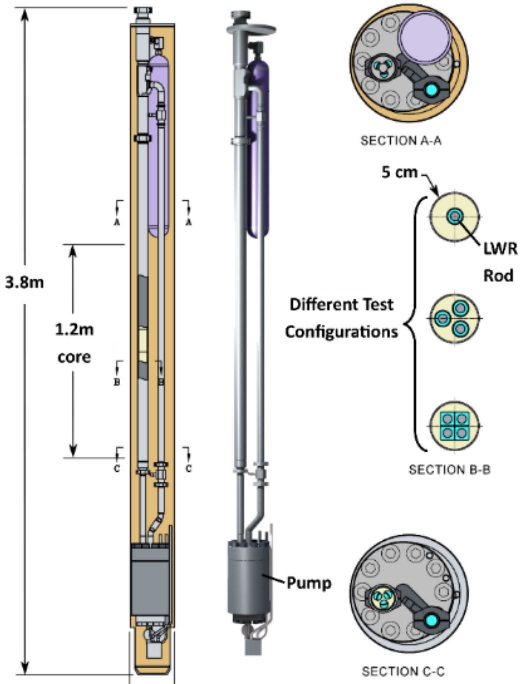


TREAT LWR Plans

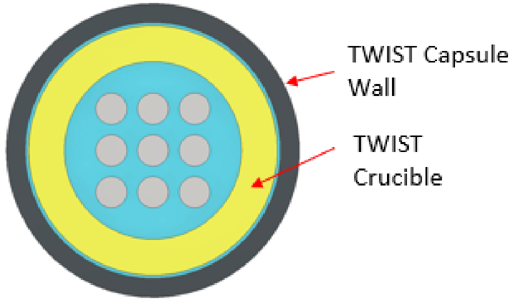
- Existing SERTTA capsule available now for low-cost irradiations
  - Capable of RIA pulses on 10 cm specimens
- Larger TWIST capsule under commissioning tests
  - Capable of RIA & LOCA on 60 cm rods or small bundles, currently designed to start from 20°° water
  - Steam control system PWR condition preheater design mods to begin shortly
- TWERL water loop
  - Full forced convection for multi-specimen assemblies
  - Project paused in ~2019 to focus resources on TWIST and I-Loop
  - TWERL reboot now beginning, focused on seconds-long events (AOO, ramps) rather than RIA and LOCA



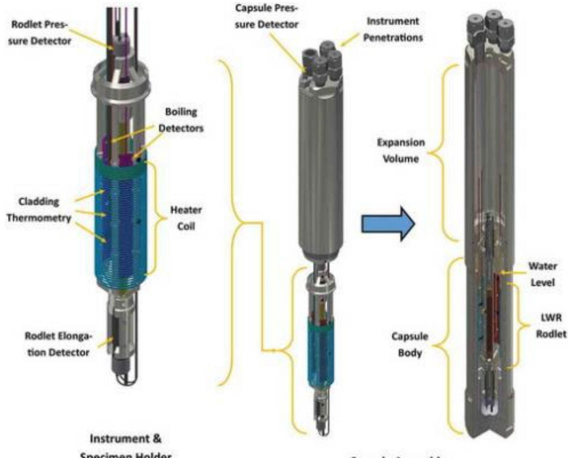
TWIST (LOCA Config)



TWERL

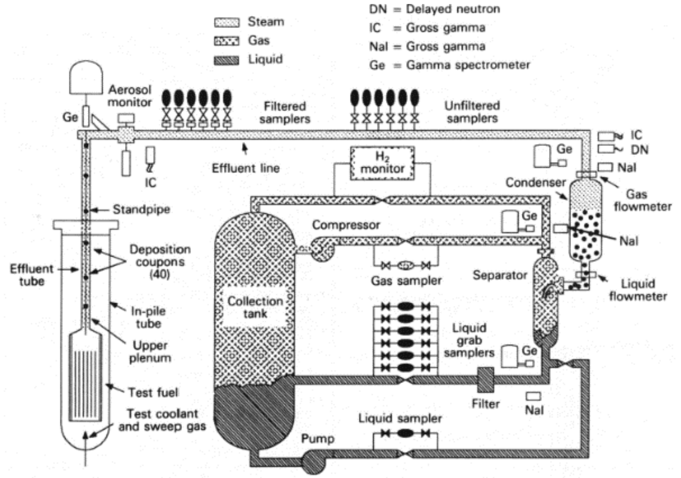


Sketch illustrating 9-rod potential in TWIST



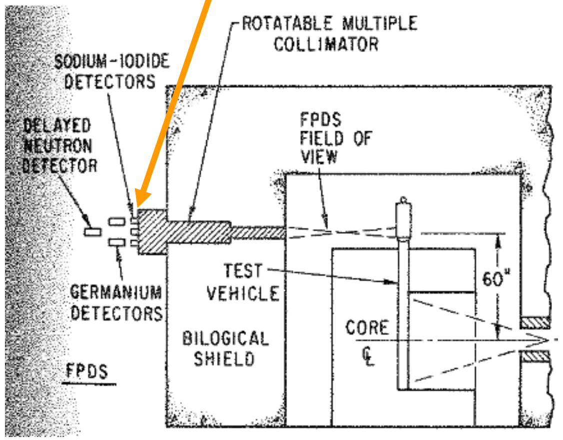
SERTTA

Thoughts on Real Time Fission Product Release Measurement



- TREAT's current steady state power limited to 120 kW (80 kW in practice)
  - Scoping calcs suggest 500 kW uprate viable
  - Could create short-lived isotopes (^{131}I) for subsequent transients for release fraction measurement

Fission Product Detection System for Sodium Loops in TREAT using the "porthole"



- Radioisotope release measurement to be determined, options under consideration:
- "Porthole" collimator to observe above-core part of flowing loops (hodoscope-like approach to fission product measurement)
  - Was attempted briefly just prior to TREAT's long shutdown, unclear whether it worked well or needed improvement
  - Signal to noise likely key consideration, limited to gamma/neutron emitting isotopes decay
  - Key benefit: Little impact on test vehicle design and radiologic hazard controls
- Ex-core plumbing and sampling system
  - Time and cost intensive engineering and installation evolutions (debris filtration, personnel shielding, and contamination control)
  - More advantageous in accessing the materials of interest with various analysis methods
- Best strategy to be determined, not presently under active pursuit within DOE programs

Part 2: A Crash Course in TREAT Experiment Design

A Boring Slide about Process

- All irradiation experiments, regardless of whether the work is performed internally or externally, will have an INL "Experiment Manager" assigned to help guide through the work acceptance, project management, engineering, and documentation processes
  - Much could be said here, a topic for a different presenter on a different day
- Projects typically proceed through the process summarized below:
- Conceptual design
  - To determine test requirements and which design concepts can meet them
  - End with an informal review, usually with the design team and experimenters
- Preliminary design
  - To mature the design, models, and prototypes (as needed) to ensure that all the requirements can be meet
  - Irradiation hardware manufacturing can often begin in the phase (acknowledging potential financial risks)
  - End with an informal review, usually with the design team, experimenters, and select facility/organization management
- Final design
  - To document, rigorously check, and approve all the engineering documents
  - End with a more formal review for engineering verification
  - Those with relaxed schedules (rare) and low tolerance for financial risk usually begin hardware manufacture after this phase
- Experiment Safety Analysis (ESA)
  - Qualified safety analysts assemble ESA package from the engineering documents
  - ESA is review by an internal independent safety committee

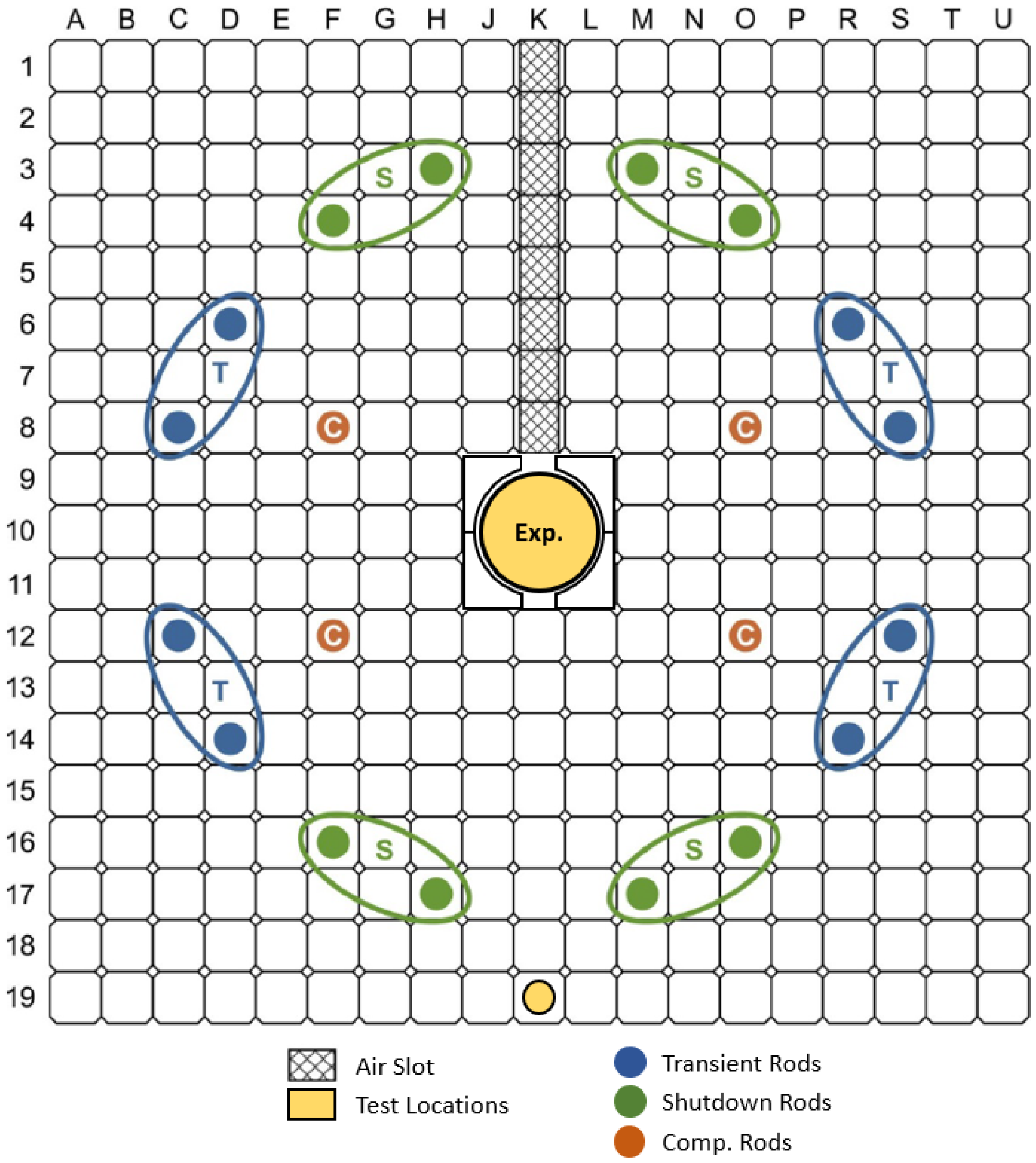
Safety Bases Requirements

- TREAT experiments chiefly governed by SAR-420, Ch 10, Mechanical Design Criteria 1-5, paraphrased below

No.	Requirement	Explanatory Notes
1	• Fresh fuel experiments (uranium only) require one containment layer, all other experiments require two. In either case, at least one layer must retain integrity in the accident transient (MURA)	• The layer credited with this surviving the MURA becomes the “safety containment”. In practice, almost all experiments are double contained with capsule/loop inside of Big-BUSTER where the latter is the safety containment. The practical implication is that the inner layer (i.e., capsule/loop) retains its integrity in the planned transient and does not explode in MURA (because shrapnel analysis would get complicated). Burst discs on the inner capsule/loop are often used for pressure relief into Big-BUSTER. • Retaining integrity essentially means not rupturing so that radioactive particulate is released. This requirement does not address things like finite leak rates of noble fission gas from mechanical seals.
2	• The experiment cannot interfere with other critical facility functions (e.g., control rods)	• The experiment is usually in the center of the core, far away from the control rods, and thus criterion 1 (to not rupture) makes this requirement easy to meet.
3	• The experiment must keep personnel radiation exposure to a minimum	• The use of self-contained experiments which are entirely handled in casks makes this requirement easy to meet. If experiments with significant radioisotopes and external fluid were to be performed again (they haven’t been since the 1980s), then meeting this requirement would take much effort. • Note: Sometimes additional shielding is needed for experiment installations.
4	• The experiment must not move, rearrange, or lose parts in a way that causes unanalyzed reactivity additions	• This requirement is met by securely affixing things like flux collars or by including reactivity changes (e.g., water blowdown) in the safety analysis.
5	• The safety containment must provide a level of protection equivalent to the ASME boiler and pressure vessel code	• The layer credited with criterion 1 must meet this requirement. Big-BUSTER, upper flange, and extender (if used) must meet this requirement.

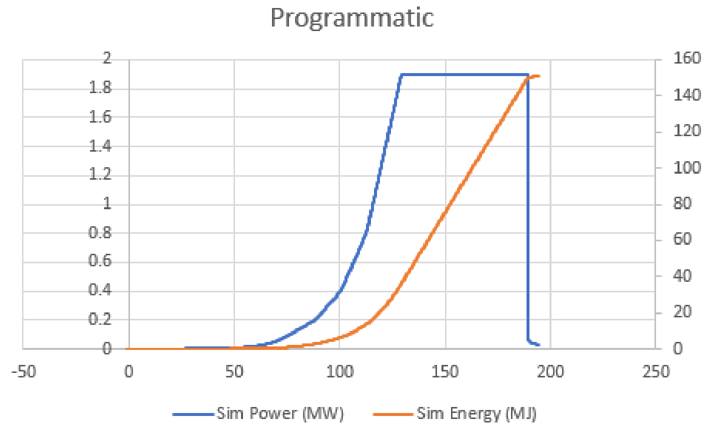
Transient Energy Capacity

- 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
  - Few experimenters want to study vaporized uranium, but many want large step insertions clipped early by transient control reinsertion for narrow pulse (<100 ms)
  - Only negative temperature feedback is credited for limiting energy release, thus the 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. Big-BUSTER core has as much driver fuel in it as possible.
  - Use of low neutron cross section hardware (Zry) extends energy capability. More affordable materials (SST) and flux suppression features reduce energy capability.
  - Graphite plugs in the experiment upper/lower reflector regions can extends energy capability.
  - Fuel specimens are usually small and have little effect, light water tends to significantly increase specimen heating, but also has a modest negative effect on reactivity worth.
  - Slow transients (> ~30 seconds) can benefit from "extended mode operations" where slower moving control/shutdown rods are manually withdrawn by operators during the transient.

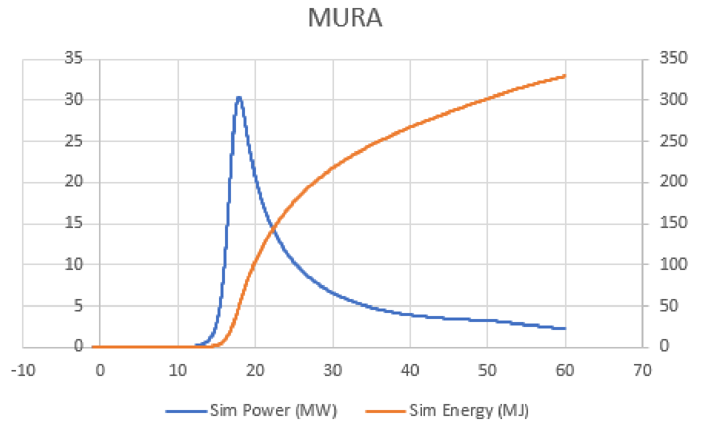


Transient Design and the MURA

- TREAT's Automatic Reactor Control System (ARCS) upgraded to LabView based software with point kinetics model
  - Standalone version exists to predict response of reactor to transient prescriptions and rod motion/feedback programing
  - Used to design transients for input to thermal experiment design
  - Used to derive MURA from planned transient parameters
- The MURA is essentially the design bases accident for experiment design, its formulation is older than most of the TREAT team and derives from SAR-420 Ch 10
  - Pulsed transients:
    - Planned step insertion +0.3% dk/k only limited by negative temperature feedback
  - Shaped transients:
    - Find largest planned step insertion at any point in the transient, add 0.3% dk/k
    - Find highest planned ramp rate at any point in the transient, multiply × 2
    - Start the step and ramp simultaneously, hold ramp until the +0.6% dk/k of the planned total reactivity
    - Shaped MURA derivation is nuanced, close coordination with TREAT reactor engineering needed
  - Experiment with the ability to cause positive reactivity insertion (water blowdown) must also include these terms in their MURA predictions



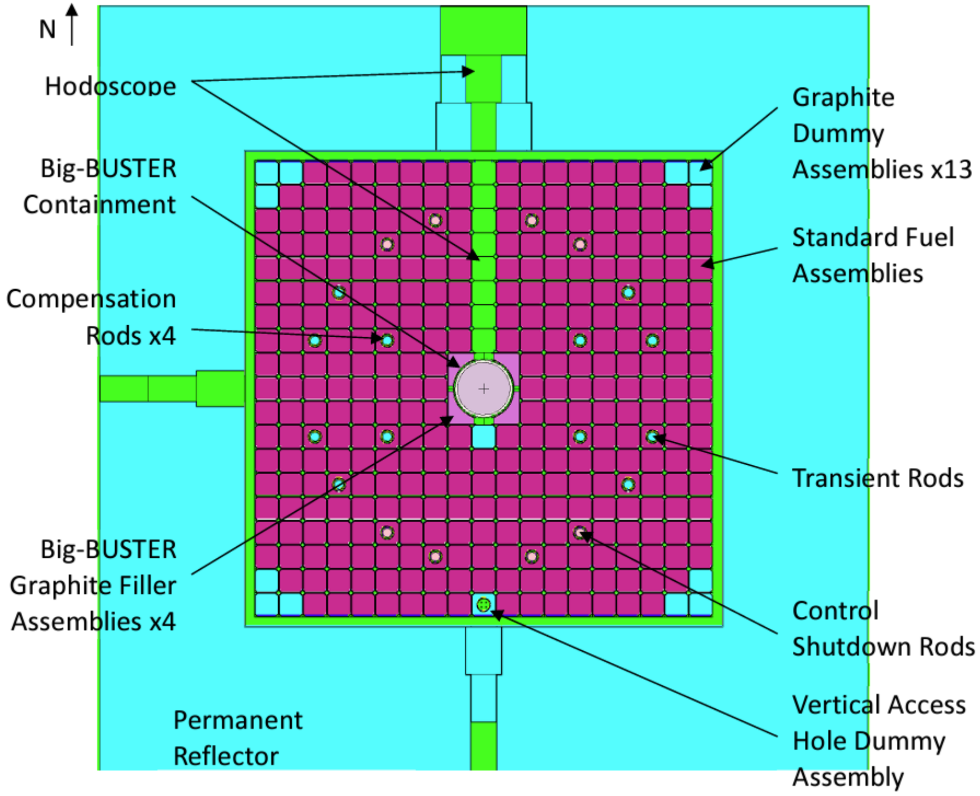
A Very Benign Shaped Transient



The Corresponding MURA

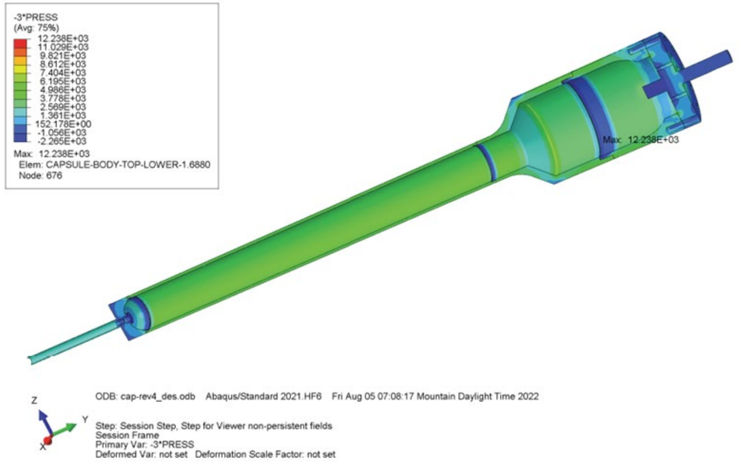
Neutronics Calculations

- After work begins, test concepts will be identified and sketched as needed (existing or new devices)
- Most often neutronic will then be performed to determine feasibility and refinements
- MCNP TREAT model used to compute the following throughout design iteration/phases:
  - Fission heating rates in specimens, n-alpha in certain absorbers (borated flux collars), and gamma heating in hardware can all be significant
  - Heating rate predictions often needed for hypothetical fuel relocation events (e.g., melt pool)
  - Excess reactivity available in control rods (important input to transient design and MURA derivation)
  - Reactivity worth of experiment hardware compared to past experiments
  - Sometime reactivity change predictions needed for certain events (e.g., water blowdown)
- INL MCNP model has been “adjusted” (e.g., graphite cross section treatment) to agree well with [small]-BUSTER data to date
  - Still accumulating Big-BUSTER data, uncertainties may be higher for a couple years yet
  - MCNP model can be shared externally
  - Others have built TREAT models in Serpent, OpenMC, Scale, etc., but the most trusted reference model right now is in MCNP



Thermo-Mechanical Calculations

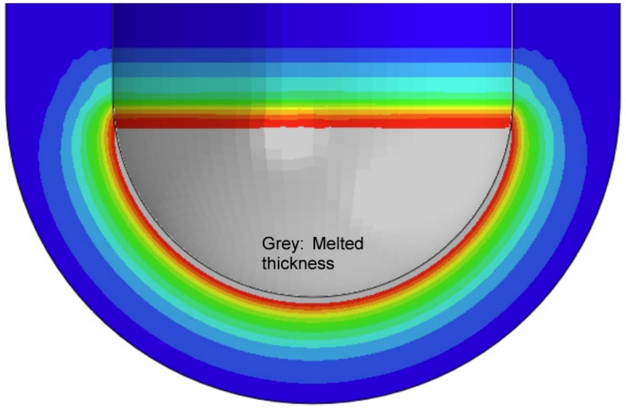
- Iterate with transient shapes (planned and MURA) predicted by standalone ARCS LabView simulator for power vs. time histories
  - Using heating rates predicted by neutronics codes
- Commercial FEA model (Abaqus, Comsol, Ansys), system codes (RELAP5-3D), fuel performance models (Bison), and CFD models (STAR) used as needed
  - Design the test to achieve desired conditions (fuel enthalpy, fuel/cladding temperature, cladding strain, etc.)
- Working closely with structural mechanics analysts to provide temperature and pressure predictions
  - Show that capsule/loop will perform as desired in planned transient (using ASME B&PV service level A acceptance criteria)
  - Show that Big-BUSTER will retain integrity in MURA (using ASME B&PV service level D acceptance criteria)
  - Capsules/loops often have burst discs to relieve into Big-BUSTER, but to date, all Big-BUSTER configurations have not had overpressure protection, thus design ratings are required to bound service level D)
    - So, the MURA could happen (it never does), and Big-BUSTER would theoretically be undamaged
  - Structural calculations also often performed for hoisting interfaces, horizontal to vertical up-righting, etc.



TWIST Capsule FEA Model

Melt Pools, Fuel Vaporization

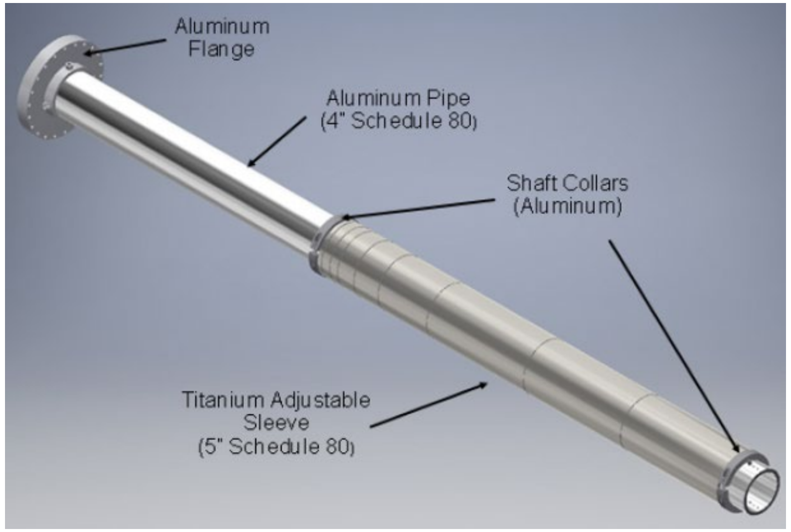
- Things can get rather imaginary in the MURA. Usually, calculations are taken in few state points
  - In the planned configuration (e.g., a fuel rod), energy deposited until geometry can not be guaranteed
    - Forced cooling not credited in this state (loop pump failure)
  - In a reconfigured state (e.g., fuel pool in a melt catcher)
  - Vaporization terms
    - Pressure from coolant vaporization, chemical interactions, fission gas, and fuel vaporization must be considered as applicable
    - Thermodynamics and simple ideal gas law calculations typically to show pressure in Big-BUSTER assuming capsule/loop relieves into it
  - Limits for rapid pressurization by fuel coolant interaction presently based on historic TREAT data



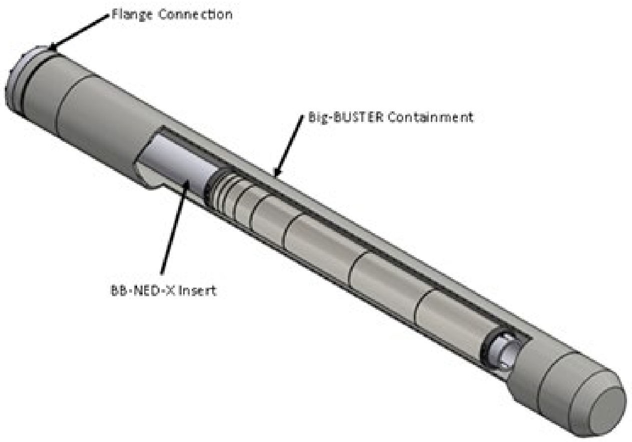
TWIST Melt Pool Prediction

Core Characterization

- TREAT reactor engineering is required to perform “core characterization” on new configurations
- Takes 2-3 weeks to measure
  - Control rods worth curves
  - Heat balance power calibration at 80 kW steady state power
  - Three progressively higher energy unclipped pulse transients to confirm temperature feedback and fuel assembly temperatures
- If a new experiment can be with ±0.05% dk/k of a past core characterization, then this work is not needed
  - Sometimes superfluous hardware (titanium slugs) have been added to capsule designs for this purpose
- Big-BUSTER’s Nuclear Equivalent Device (NED) is used for core characterizations and later trial transients
  - A series of stackable titanium rings that can be configured to match virtually any experiments’ reactivity worth
- One day in the future, we will have characterized every possible Big-BUSTER reactivity configurations
  - But core characterizations are a significant schedule consumer for the foreseeable future

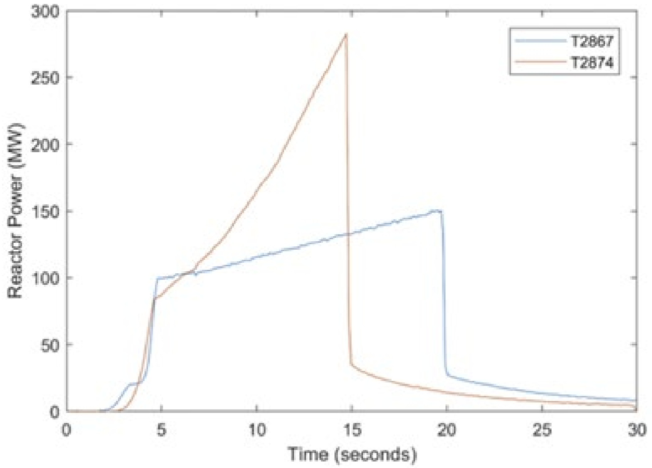


Big-BUSTER NED



Trial Transients

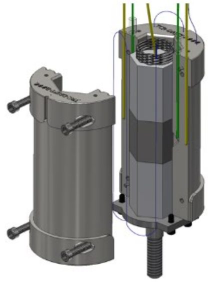
- All transient "prescriptions" must be rehearsed as follows:
  - Full simulation: ARCS using its internal point kinetics model in real time
  - Partial simulation: ARCS physically controlling the transient rods (but with the core subcritical) using its internal point kinetics model in real time
  - Trial Transients: Real nuclear transient controlled by ARCS
  - Sometimes the experimenter may wish to try again if the reactor power history did not come out as needed
- Then its time for the real fueled experiment
  - If needed, pre-transient neutron radiography can be performed with the experiment installed in the radiography stand
  - If needed, a steady state run can be performed with the experiment installed in the radiography stand to best align the hodoscope with the fuel specimen



Data from Trial Transients

Calibration Measurements

- MCNP predictions can be +/- 20% of measured power coupling factors (PCF)
- PCF measurement “calibration tests” required by the SAR prior to permission for high energy transients
  - Small transients can be performed based on predicted PCFs (SAR requires unclipped energy <25% of MURA energy)
  - In-situ thermometry to measure PCF by calorimetry
    - TC’s in fuel centerline water capsule pulse test
    - TC’s in heat sink capsule type pulse test
    - Coolant enthalpy rise in loop test
  - Alternate method: Post transient gamma spec on fuel specimens
    - Requires disassembly and shipping
  - Calibration experiments typically performed on fresh fuel specimens
    - Enrichment selected to be similar to predicted PCFs for irradiated specimens
    - Not perfect simulation of final test, some amount of correction factors often needed from neutronic calculations
  - If PCF is measured much different than predicted, it could be necessary to rerun new trial transient with Big-BUSTER NED (if they were already performed)
- And then, sometimes after years of preparation, the final transient(s) are performed



Specimen in heat sink exploded view

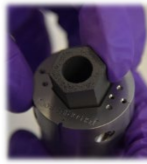
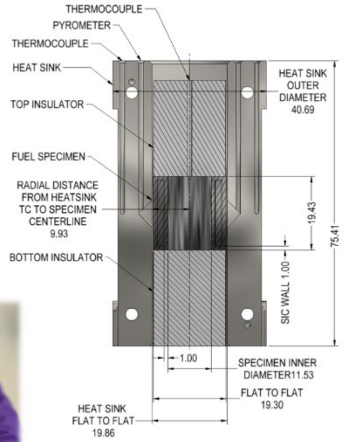
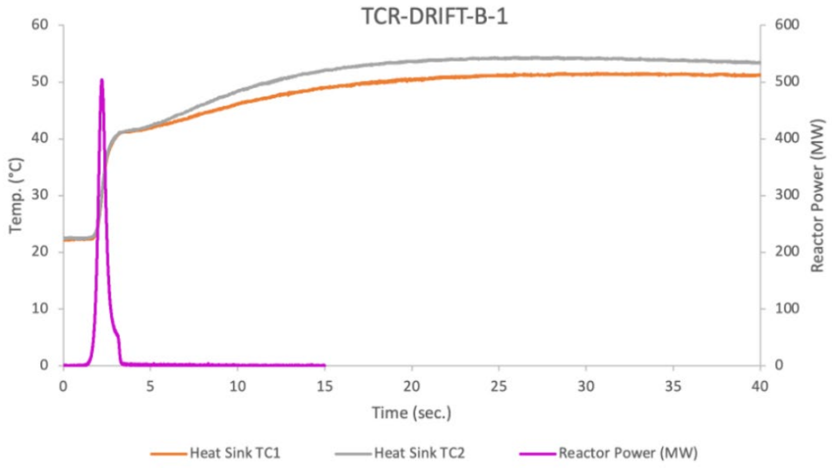


Image of fresh specimen being loaded into heat sink



Key Dimensions of Test Design (mm)

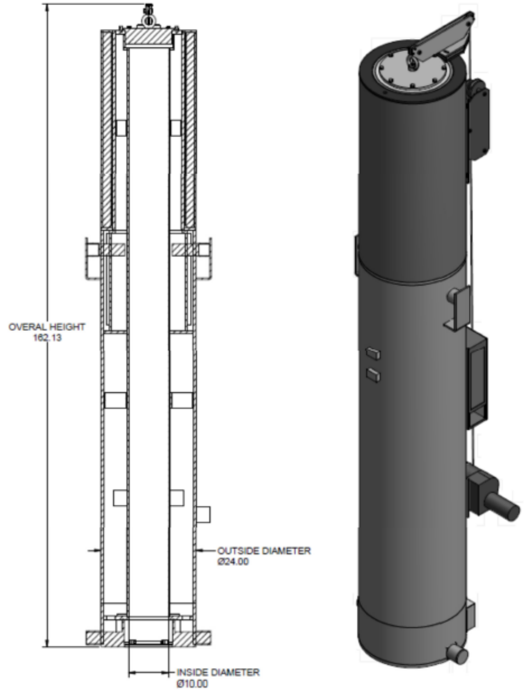


Heat sink capsule calibration test where prompt gamma heating appeared before fission heat conducted to the TCs, allowing both terms to be measured in one test. The final transient was performed just days later using the same capsule

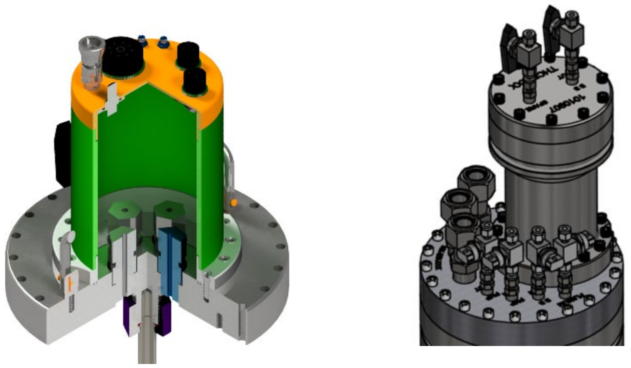
Transportation and Storage

- TREAT experiments go through multiple top-loading and bottom-loading evolutions on their way from HFEF to TREAT and back
- Big-BUSTER flanges can get crowded as they must provide all the useful interfaces during these evolutions
  - Penetrations/connectors for instrumentation and power lead
  - Hoisting interfaces, handling bails
  - Valves lines for evacuation and inert gas backfill
  - Screws for sealing flange to Big-BUSTER
  - Contamination covers

Loads from bottom	Loads from top	Goes thru a hole
TREAT loop cask	TREAT reactor itself	TREAT reactor top rotating shield plug
Lifting experiments into HFEF cell	Below-ground storage hole locations at TREAT	Floor between HFEF cask cart tunnel and hot cell
	TREAT neutron radiography stand	Transfer ring between TREAT loop cask and HFEF-15
	HFEF-15 Transport Cask	



Bottom-Loading TREAT Loop Cask


Example Big-BUSTER Flange Designs

Quality Levels

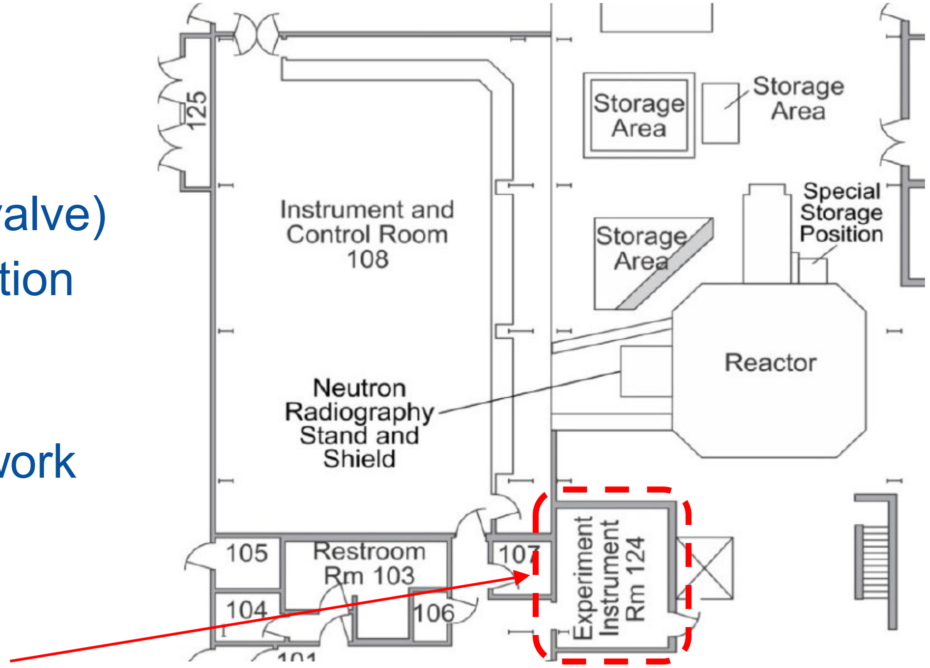
- INL has two "quality levels" for procured items
  - Nuclear grade: Procured from a supplier with an ASME NQA-1 quality assurance program (severely limits supplier options)
  - Commercial grade: Procured from a supplier with an applicable quality assurance program (e.g., ISO-9001, much more common)
  - Commercial grade items can be dedicated for nuclear grade with additional testing and/or oversight
- In TREAT experiments, only the reusable safety containment (Big-BUSTER, Extender, Flange) needs to be nuclear grade
  - Everything else can be commercial grade
  - In any case, all hardware must undergo receipt inspections, testing, examination as specified by the engineering documents (drawings, specifications)
- INL internal machining services can work to graded requirements to produce nuclear or commercial grade irradiation hardware
  - But INL's machining services are busy and expensive, other suppliers should be used to the extent possible

Leak Rates and Mechanical Seals

- Primary containment safety function is to retain integrity (to not rupture), this function belongs to the metal pieces in the weldments
  - Above function distinctly different than finite leak rates from mechanical seals, thus items like O-rings can be commercial grade
- Generally accepted fresh fuel tests and irradiated fuel tests are acceptable at 1E-4 and 1E-6 std cc/sec, respectively
  - Less stringent leak rates may be possible depending on experiment-specific source term
- Radiation tolerant elastomer O-ring seals have been reliable thus far sealing capsules and Big-BUSTER flanges
  - Big-BUSTER O-ring groove specified to accept metal c-ring seals if higher temperature service needed
- Grafoil sealant Conax compression seals most common method for sealing instrument leads, but occasionally struggled to meet leak rate limits until they are potted with epoxy
  - Radiant tolerant elastomer seals in Conax seals presently being pursued as a more reliably method (albeit with lower temperature tolerance)
  - Induction brazing would be the surefire but more costly option
- Pipe threads with grafoil sealant have been used on capsules, but ASME B&PV discourages use of pipe thread on Big-BUSTER flanges
- Fittings on Big-BUSTER flanges welded or connected with metal-metal compression (e.g., Swagelok)

EDACS and Data Acquisition

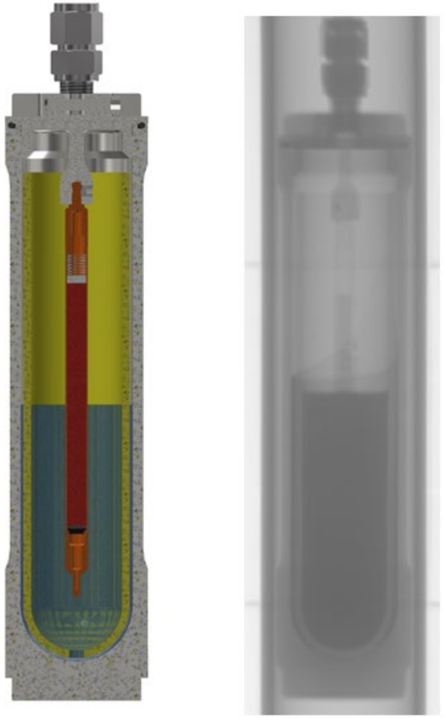
- Experiment Data Acquisition and Control System (EDACS), currently installed at TREAT with the following capabilities
  - LabView based control and data logging in I&C room
  - 1 ms logging rate, synchronized timestamps with ARCS
  - Numerous channels for TC's and other voltage input 4-20 mA instruments
  - Remote controlled relays for powering test devices (blowdown valve)
  - High current controllers for heaters with overtemperature protection
  - Test instruments trigger ARCS to advance to the next transient segment or terminate transient
  - Remote monitoring from TREAT control room through local network
  - Chassis have room to add other capabilities
- Wire trays to experimenter room adjacent to reactor allows for specialized/temporary instrument signal conditioning and logging
  - Signals from optical fiber instrumentation, high speed oscilloscope, and other special instruments (SPNDs) typically acquired here



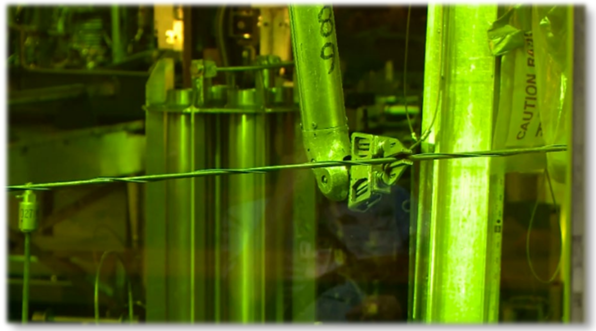
TREAT Facility Plan View

Miscellaneous Design Considerations

- Neutron radiography at TREAT can be severally hampered by the presence of moderators (water) or significant neutron absorbers surrounding the specimens (flux collar, thick metal heat sinks)
- TREAT also has on-site X-radiography equipment which is not hampered so much by water, but this equipment is not currently set up with adequate shielding for highly radioactive experiments
- Gamma dose from irradiated specimens and TREAT itself can degrade certain experiment components (polymers, electronics), materials should be selected carefully
- TREAT produces large amounts of gamma/neutron flux creating spurious results with some types of sensors, piezoelectric, strain gage, and diode devices have proven to be among the most sensitive
- Use of machinable tungsten-alloy shield plug installed just under Big-BUSTER flange is advised for limiting dose to personnel during the experiment installation
- Experiments with irradiated fuel specimens must be designed for remote assembly and manipulation in shielded hot cells, much could be said on this topic, not covered here



Neutron radiography image (right) of a capsule half-filled with water



Conclusions

- TREAT is a uniquely capable machine well-suited to various fuel safety and nuclear transient needs
- As the only surviving fuel safety research facility of its type in the United States, there is high demand to use TREAT for diverse testing needs
  - The facility design, and present demand, create unique design considerations for future experiments (e.g., easy-to-install package-type devices)
- Much has been learned since the reactor restarted, INL is now able to describe TREAT processes and constraints well enough to welcome external experimenters
  - The information herein is a high-level summary, close collaboration will be needed to succeed

For the Interested Reader

- Nicolas Woolstenhulme, “The Transient Reactor Test Facility,” Nuclear Reactors - Spacecraft Propulsion, Research Reactors, and Reactor Analysis Topics. IntechOpen, 2022. https://doi.org/10.5772/intechopen.95676
- Thomas Holschuh, Nicolas Woolstenhulme, Benjamin Baker, John Bess, Cliff Davis & James Parry (2019): Transient Reactor Test Facility Advanced Transient Shapes, Nuclear Technology
- John D. Bess, Nicolas E. Woolstenhulme, Colby B. Jensen, James R. Parry, Connie M. Hill, "Nuclear Characterization of a General-Purpose Instrumentation and Materials Testing Location in TREAT,” Annals of Nuclear Energy, 124 pp. 270-294, Oct 2018.
- Nicolas Woolstenhulme, Clint Baker, Colby Jensen, Daniel Chapman, Devin Imholte, Nate Oldham, Connie Hill, and Spencer Snow, Development of Irradiation Test Devices for Transient Testing, Nuclear Technology, February 28, 2019.