Overview of Transient Testing and TREAT Restart

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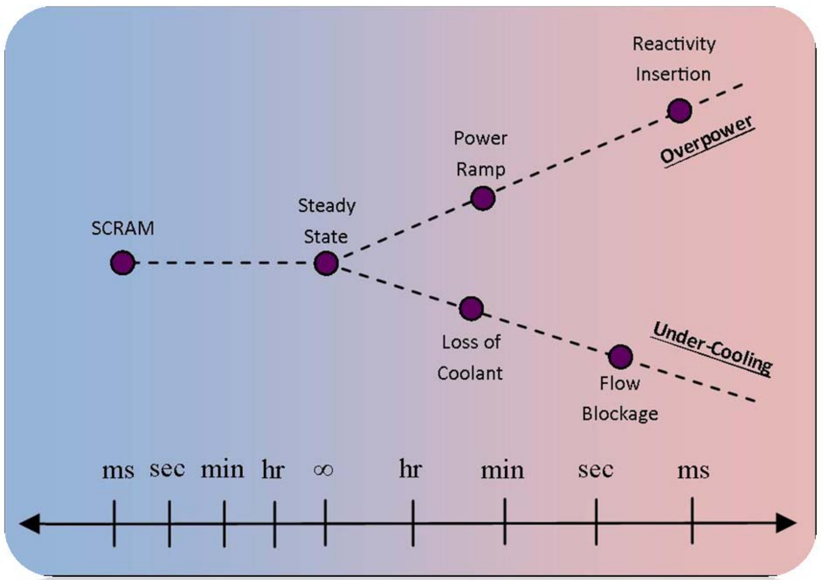
Idaho National Laboratory

What is Transient Testing?

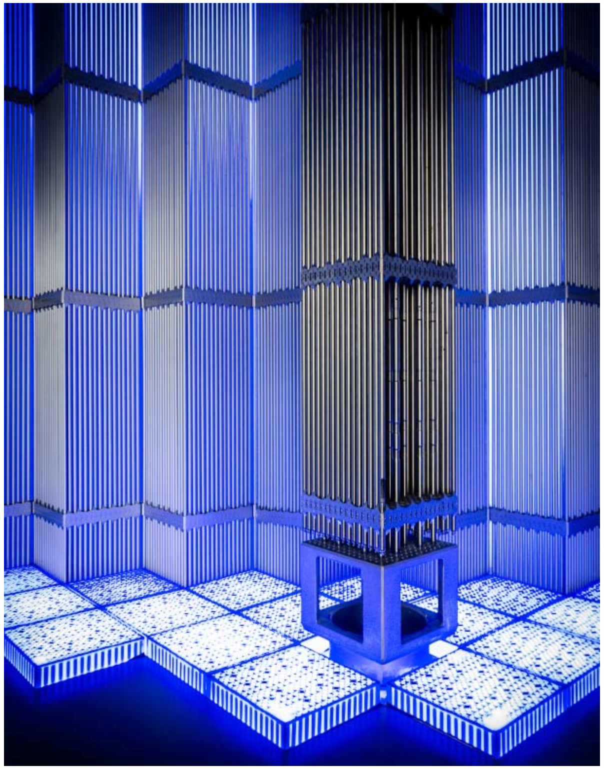
- Transient testing is like car crash testing for nuclear fuel
  - Demonstrate performance phenomena and limits for fuel development and reactor design
  - Show consequences of hypothetical accidents for licensing



- Transient testing is the study of fuel and fuel system behavior under power-cooling mismatch conditions
  - Slower event can be simulated out-of-pile or in steady state test reactors
  - Shorter events needed to be simulated with rapid nuclear heating

What is Nuclear Transient Testing?

- Nuclear transient testing is using fission heating, in part or in whole, to simulate power-cooling mismatch scenarios
- Electrically-heated non-nuclear transients tests are useful, but innately limited:
  - Lack of irradiation effects
  - Very difficult to achieve heating rates simulating rapid reactivity insertion accidents (RIA)
  - Heating “from the inside out” temperature profiles require fission heating
- Nuclear transient testing requires a transient test reactor



https://www.industryforum.co.uk/resources/articles/meeting-the-civil-nuclear-supply-chain-skills-challenge/

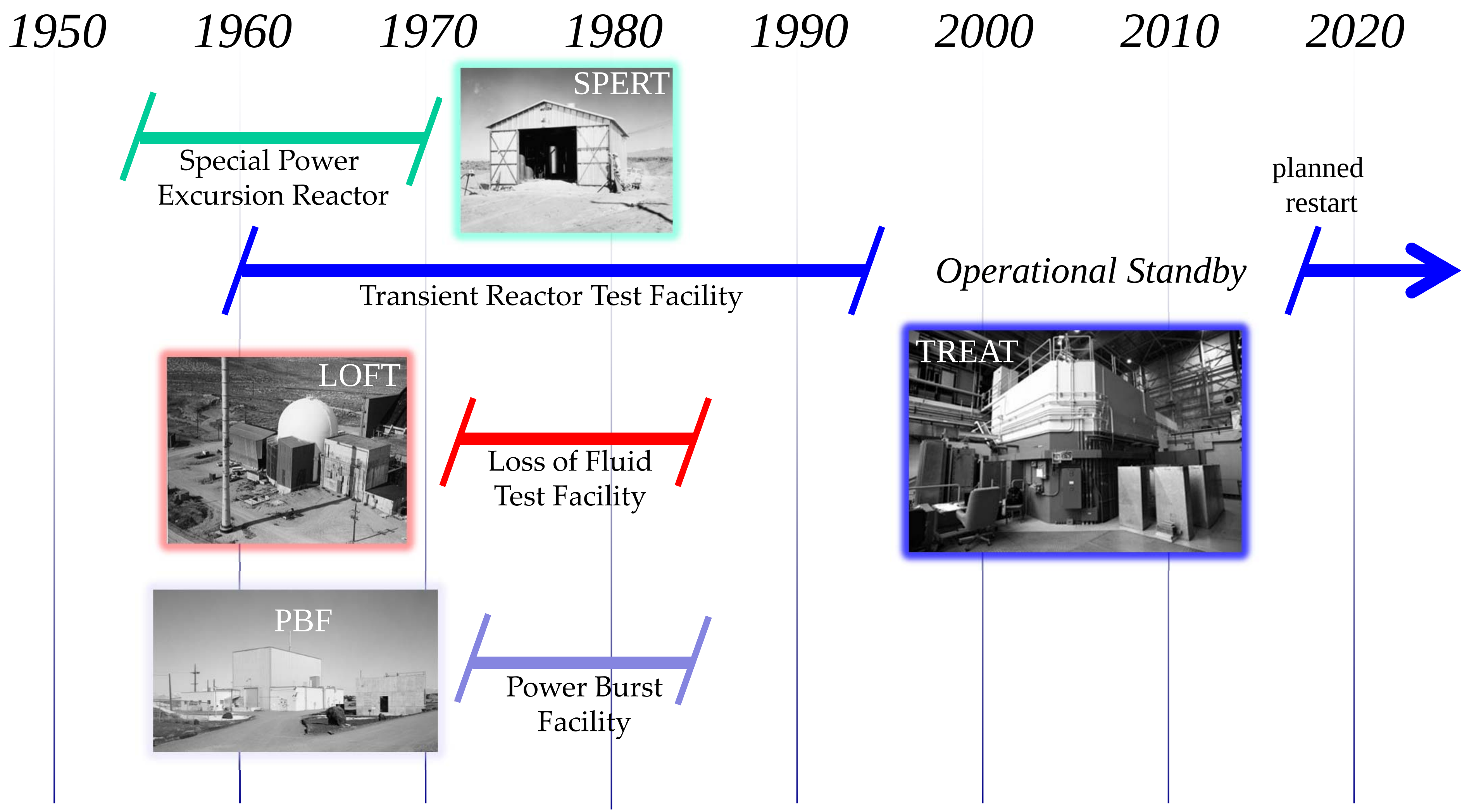
What is a Transient Test Reactor?

- Transient Test Reactors have special design features to enable accident simulation, for example:
  - Ability to safely insert large amount of reactivity:
    - Fast-acting transient control rods
    - Driver core tolerant of energy excursions
    - Strong negative temperature feedback (self limiting)
  - Ability to depressurize
    - Fast acting blowdown valves

Power Burst Facility

- Most of the time transient test reactors provide these conditions to an experiment position in the core
  - But sometimes the driver core itself was the subject of the test!
- The national reactor testing station (now INL) hub for nuclear transient testing

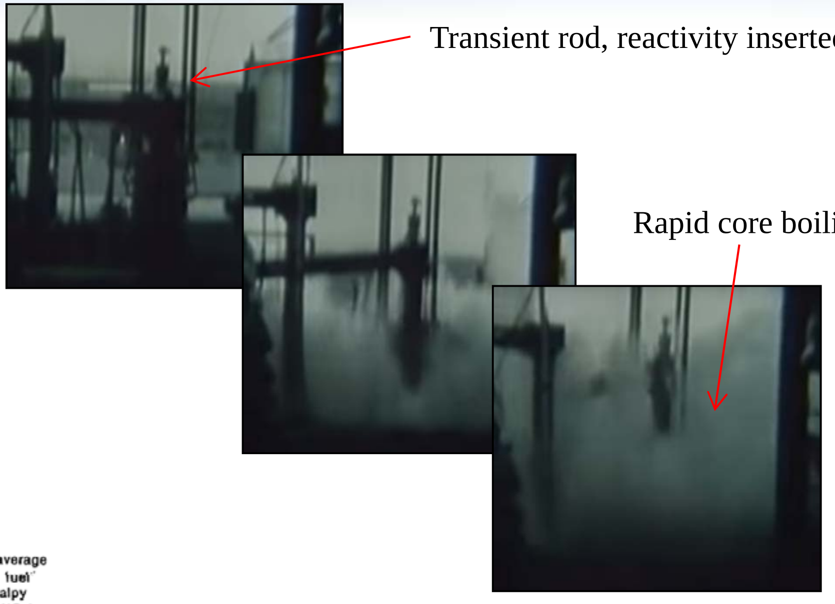
History of Transient Testing in Idaho



Slide courtesy of Dan Wachs

History of Transient Testing in Idaho

- The Special Power Excursion Reactor Test (SPERT) facilities was constructed in the 1950's
  - Actually several different core configurations, one of which was tested "destructively" under RIA conditions



https://www.youtube.com/watch?v=0FIhafVX_6I

Fig. 3 Posttest photographs of SPXM rods tested in the CDC.

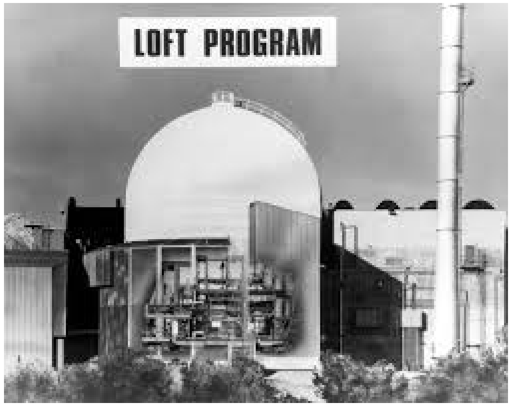
- SPERT Capsule Driver Core: Tested Light Water Reactor (LWR) fuels in water-filled capsules under RIA pulse-type transients
  - Set the stage for future PWR transient testing, the crux is maintaining rod-like geometry
- SPERT now decommissioned

History of Transient Testing in Idaho

- The Transient Reactor Test (TREAT) facility
  - Contemporary with SPERT, but primarily supported transient testing for sodium-cooled fast reactors
    - Also supported LWR and other reactor systems
  - Constructed in late 1950's, performed nearly 3000 transients
  - Placed in operational standby in 1994
  - More about TREAT later…

History of Transient Testing in Idaho

- The Loss of Fluid Test (LOFT) facility was a small PWR designed to test plant system response to Loss Of Coolant Accident (LOCA)
  - Fast acting valves simulated break of primary piping
  - Instrumental in validating computational codes and PWR licensing process
  - Constructed in the 1970's, now decommissioned



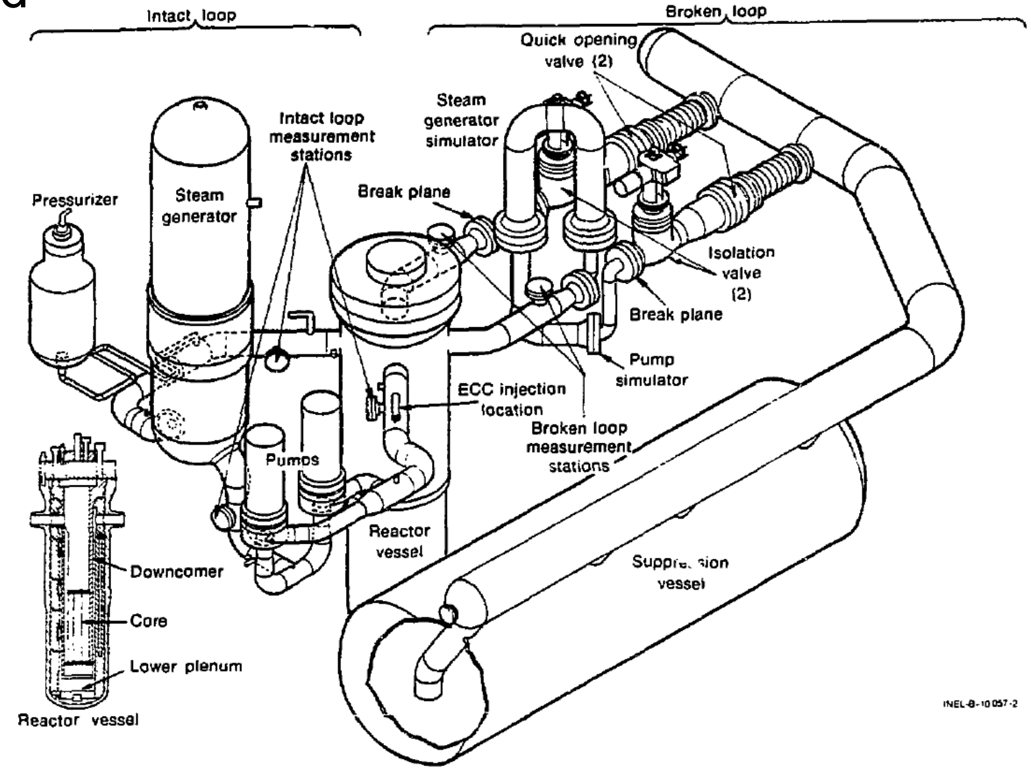
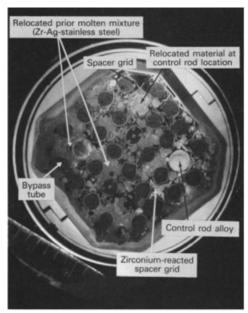


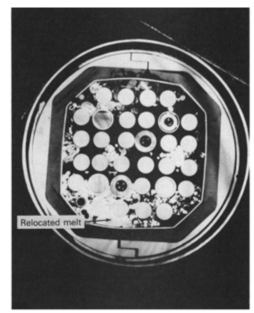
Fig. 1. - LOFT major components in cold leg break configuration

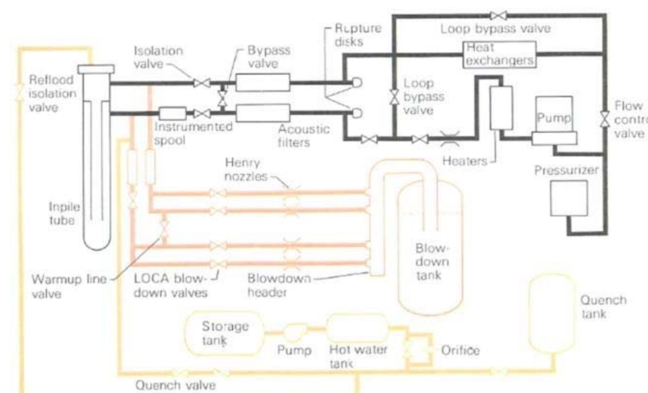
D.L. Reeder and V.T. Barta, "The Loss-of-Fluid (LOFT) Facility", EG&G Idaho, CONF-790803--13.

History of Transient Testing in Idaho

- The Power Burst Facility (PBF) facility was constructed in the 1970's
  - Contemporary to LOFT, but was designed to drive a central experiment position
  - Massive in-pile-tube, elaborate loop-system, and transient rods enabled sub-assembly testing of RIA and LOCA
  - Blowdown, reflood, and fission product transport measurements
- Post TMI: PBF tested 32-rod pre-irradiated PWR bundles in severe fuel damage tests
  - One of the most tremendous transient tests series in history
- Facility now decommissioned







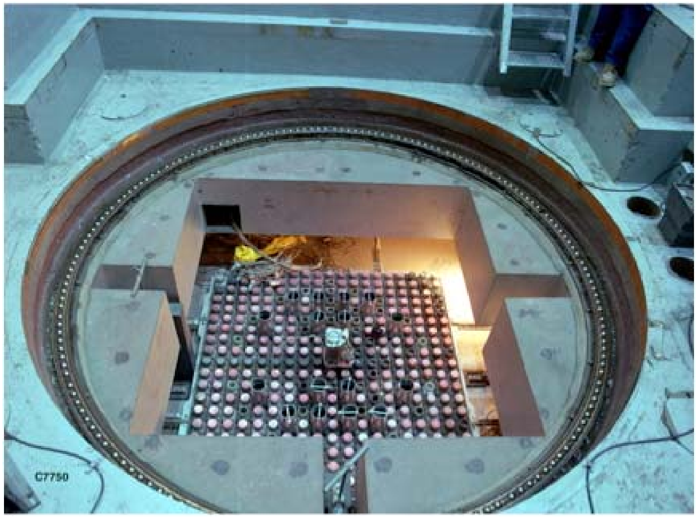
Fun Trivia: PBF's driver fuel was actually tested in TREAT to demonstrate resilience to power pulses

W.A. Spencer, A.M. Jensen, R.K. McCardell, "Capabilities of the Power Burst Facility", EGG-M-06582, International Topical Meeting on Irradiation Technology, Sep 28 – Oct 1, 1982.
F.K. Clements and E. Feinauer, "Analysis of Safety Considerations for Transient Testing of PBF Prototype Fuel Rods in TREAT", IDO-17056, Apr 1964.
David A. Petti, Zoel R. Martinson, Richard R. Hobbins, and Daniel J. Osetek, "Results from the Power Burst Facility Sever Fuel Damage Test 1-4: A Simulated Severe Fuel Damage Accident with Irradiation Fuel Rods and Control Rods", September 12, 1990, Nuclear Reactor Safety.

History of TREAT

- But TREAT outlived them all, why?
  - Contemporary to and collocated with the sodium-cooled fast reactor EBR-II
  - Water-free core design likely selected to simplify “what-if” scenarios for sodium-bearing tests
- Reduction in US fast reactor funding → TREAT went into operational standby in 1994
  - Dry and simple facility, little effort needed to maintain
  - So it sat hibernating for 20+ years
  - But more on that later….

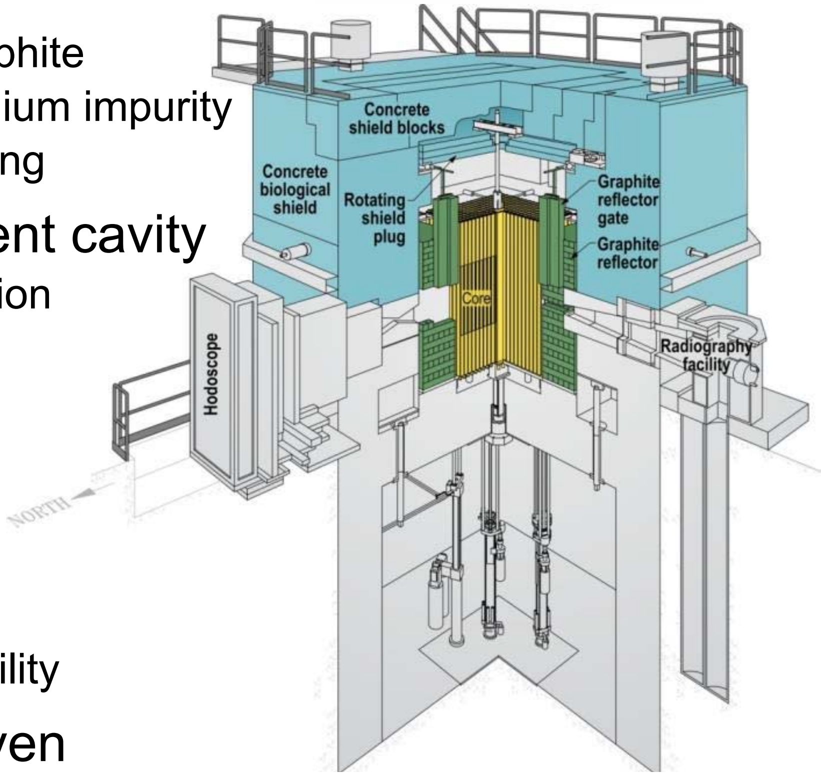
Water-Sodium Reaction

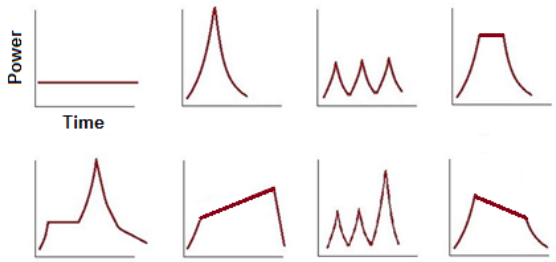


Top view of TREAT core, rare picture with shield plug removed

Introduction to TREAT

- TREAT core design:
  - Zircaloy-canned blocks of urania dispersed in graphite
  - Core is effectively a giant graphite block with uranium impurity
  - Strong negative temperature coefficient, self-limiting
- Displace fuel assemblies to create experiment cavity
  - Each fuel assembly is 10cm × 10cm in cross section
  - 1.2m of active core length
- Air cooling system
  - 100kW steady state
  - Not a required safety system
- 4 slots with view of core center, 2 in use
  - Fast neutron hodoscope, neutron radiography facility
- Fast-moving transient rods hydraulically driven
  - Allows for precise and flexible transient shaping
  - 2500MJ max core energy in prompt burst (<1 sec)
  - 2900MJ max core energy in shaped mode (up to ~5 min)
  - And practically anything in between





Example Transient Shapes

Bird’s Eye View of TREAT

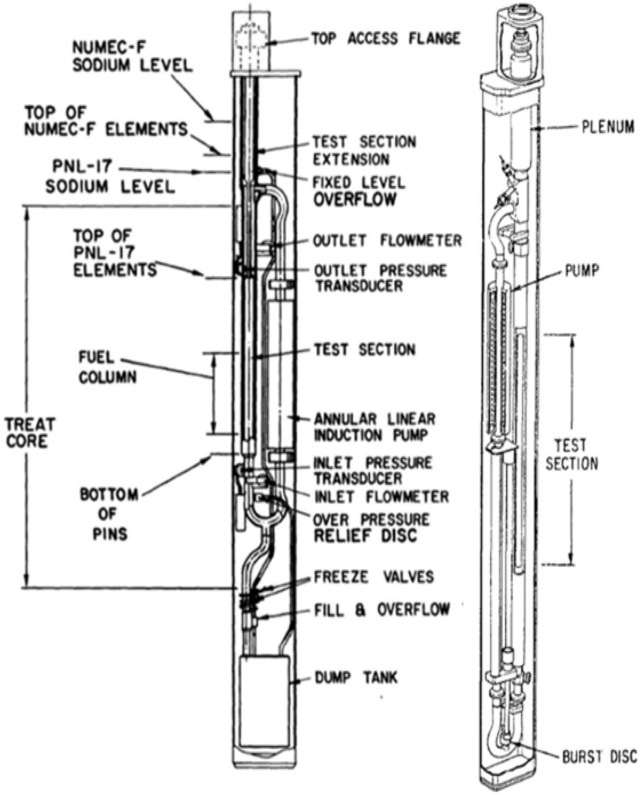
- 100 kW Steady-state power with 19 GW Peak Transient Power
- Core: ~1.2 m high x 2 m. dia.; surrounded by 0.25 m graphite reflector
- 19 x 19 array of 10 x 10-cm. fuel and reflector assemblies
- 12 steady-state and 8 transient control rods
- Immediate, large negative temperature coefficient
- 6604 reactor startups, 2884 transient irradiations

Fun Trivia: Some of TREAT’s reflector graphite came from CP-1, the world’s first nuclear reactor!

TREAT Experiment History

- TREAT is well suited to self-contained drop-in test devices
  - Installation, testing, and withdrawal in a matter of days
  - Enables support for different-environment test devices (e.g. water or sodium)
  - Assembly and disassembly in shielded hot cells
  - Device fits within shielded handling casks
    - Loop handling cask 25cm diameter X 387cm long

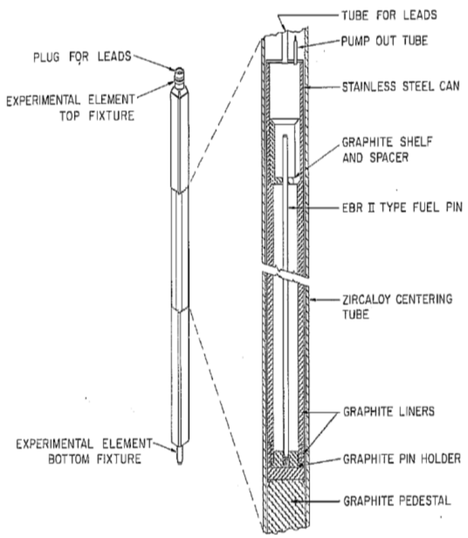
- TREAT's historic testing focused on sodium-cooled fast breeder reactor specimens
  - Highly successful with package-type loops and capsules
  - Robust piping primary containment, sheet metal leak-tight secondary enclosure
  - Pumps, heater, instrumentation, etc. all contained within enclosure
  - No contaminated coolant plumbing outside of shielding
  - Approach greatly facilitates testing of pre-irradiated fuel specimens

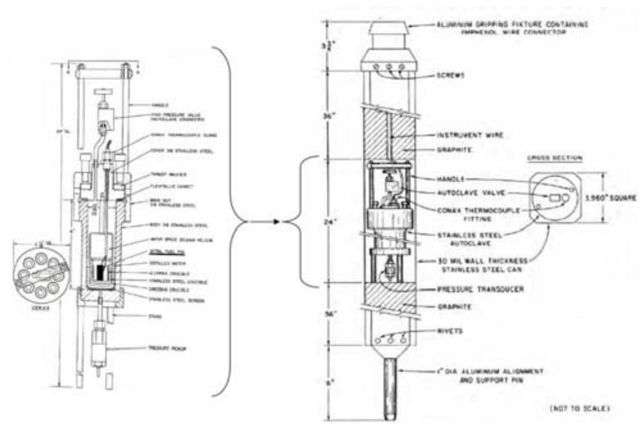


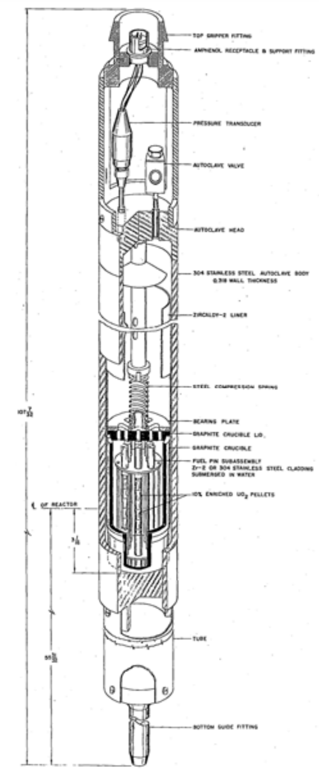
Historic Mk-series Sodium Loop

Static Capsule Testing

- TREAT has a rich history of transient testing in static capsules
  - Fast-reactor fuels, both dry and in sodium
  - PWR and research reactor fuels in water
  - Space nuclear propulsion fuels dry and in seawater





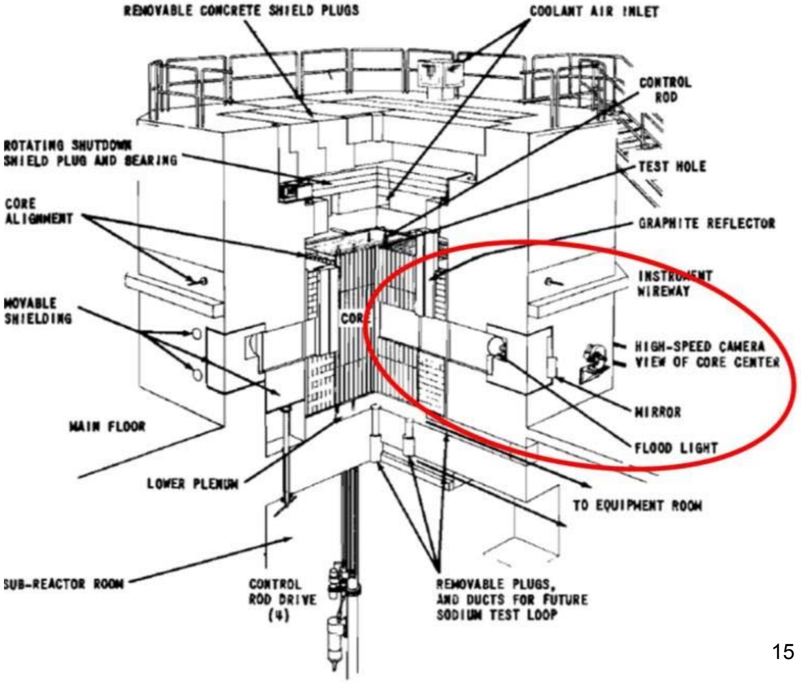


N.E. Woolstenhulme and J.D. Wiest, "ATF Transient Testing Pre-Conceptual Design and Engineering Considerations Summary", August 2013, INL/EXT-13-29898

- Almost every geometry imaginable
  - Rods, pins, bare pellets, plates, extrusions, bundles, clusters
  - Fresh and pre-irradiated

Fuel Visualization and Motion Monitoring

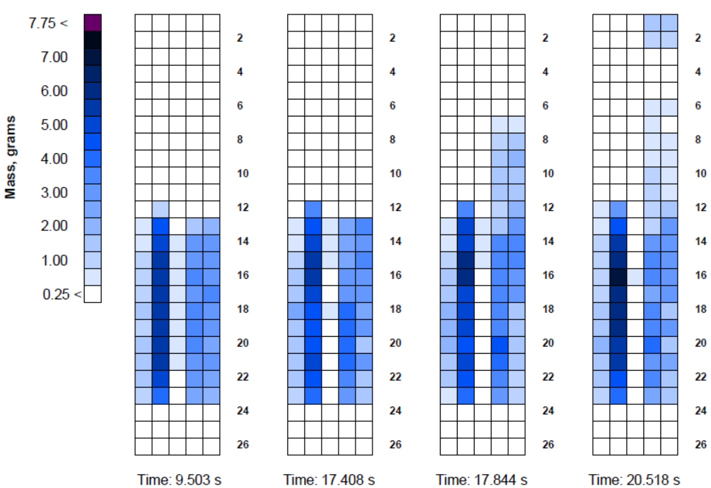
- TREAT's through-the-side access slots have been used to effectively watch the fuel in various ways
  - High-speed videography through transparent capsule with quartz windows (example videos on next slide)
    - Limited in providing pressurized water environments
    - Not terribly useful for testing in opaque sodium
    - But very useful in visualization basic phenomena
  - High-speed film-based camera (1960's)
  - Flood lamp and periscope
- Function later replaced by fast neutron hodoscope



Videos of Historic Transient Tests

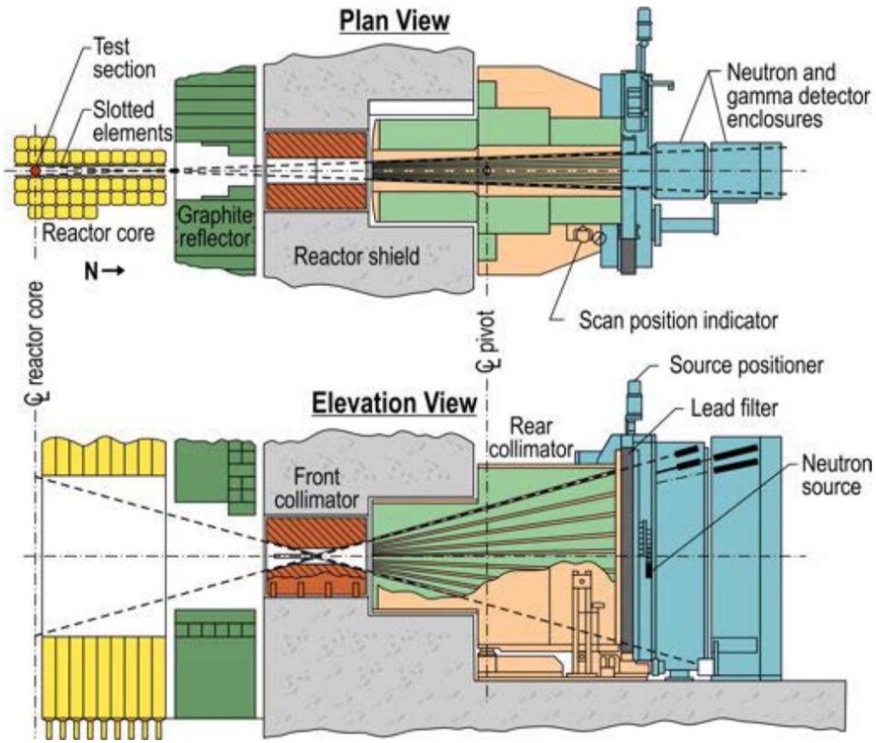
Fuel Visualization and Motion Monitoring

- Fast neutron hodoscope later became the key capability for monitoring fuel motion during the transient
- Fission-born fast neutrons emitted from specimen travel through vehicle's containment wall, through a collimator, and into detector array
- Provides pixelated view of fuel mass in each collimator slot



Snap-shot views of data from a Hodoscope experiment

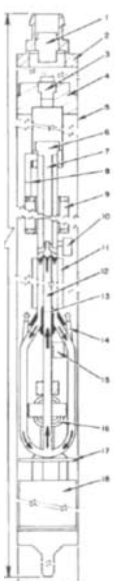
This data shows the simultaneous response of two fuel pins to a transient. The pin on the right shows significant axial fuel relocation has occurred at 17.844 seconds. This observation establishes the failure point and the progression of fuel movement after the breach.



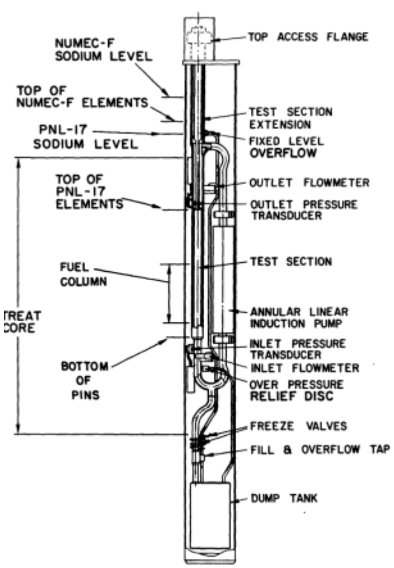
Slide Courtesy of David Chichester

Mk-Series Loops

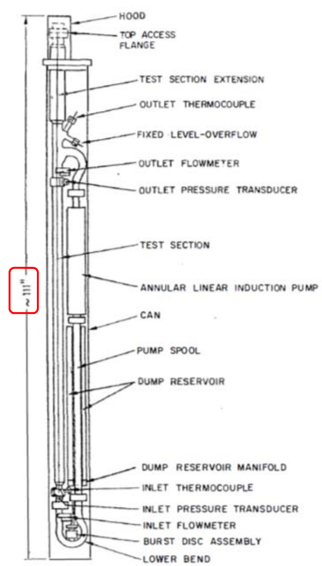
- Flagship fast reactor transient tests (1970’s-1980’s) occurred in Mk-series sodium loops
  - Very modular, could support test trains with 1, 2, 3, or 7 pins
  - 1 or 2 induction pumps depending on flowrate needed
  - Expansion tanks for additional pressure safety
  - Different axial configurations for upper or lower plenum pin designs



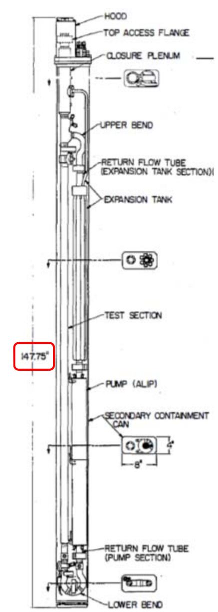
Mk-I



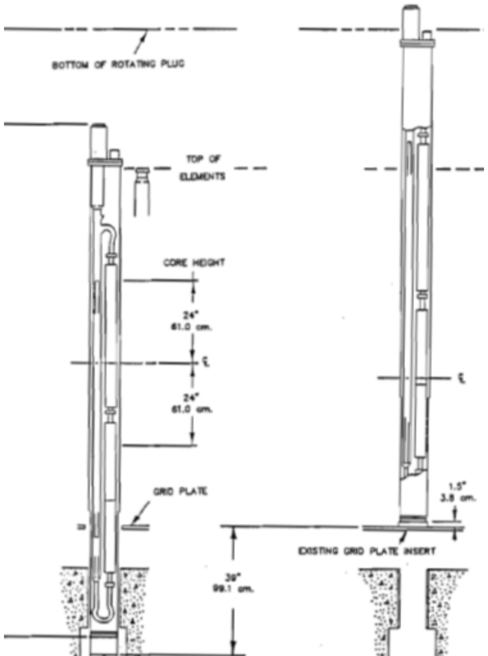
Mk-IIA



Mk-IIC



Mk-III



Axial Options

TREAT's Current Status

- DOE's accident tolerant fuels (ATF) program and other needs
  - Impetus for resuming transient testing in the US
  - TREAT selected, project is underway
- Other supporting infrastructure being revived
  - Hodoscope refurbishment
  - Hot cell equipment
  - Shielded handling casks

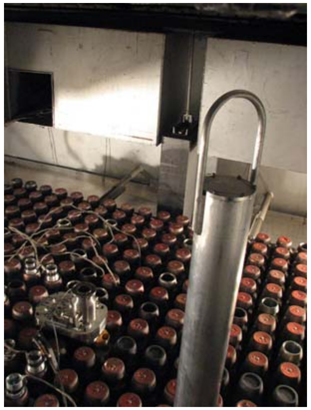
Resumption of Transient Testing Director John Bumgardner with TREAT in background, Published in Local Newspaper, Post Register "Bringing a nuclear test reactor back to life at INL", October 3, 2014.

Senator Ben Cardin and **Ernest Moniz** discuss the Transient Reactor Test Facility, commonly referred to as TREAT, with staff from the Energy Department's Office of Nuclear Energy at @COP21. | Energy Department photo by Matt Dozier.

Idaho National Laboratory's Transient Reactor Test Facility, commonly referred to as TREAT, is an air-cooled, thermal spectrum test facility designed to evaluate reactor fuels and structural materials. This 3D-printed model of the reactor shows a cutaway of its inner workings. | Energy Department photo by Matt Dozier.

TREAT Restart Status

- Fuel Evaluations Demonstrate Acceptability for Continued Use
  - Fuel assemblies inspected, some by removal from core, some by boroscope in-situ
  - Completed installation of 16 poison assemblies allowing for subcritical operations with removal of all control rods.
- Control Rod Drives Acceptable for Continued Use
  - Successfully refurbished existing drives (i.e. gears, hydraulics, snubbers, etc.)
  - Completed functional and SCRAM testing of all rod drives



Images courtesy of Resumption of Transient Testing Team

Transient Rod Video

- Video of one transient rod pair moving, 8 total rods exist

TREAT Restart Status

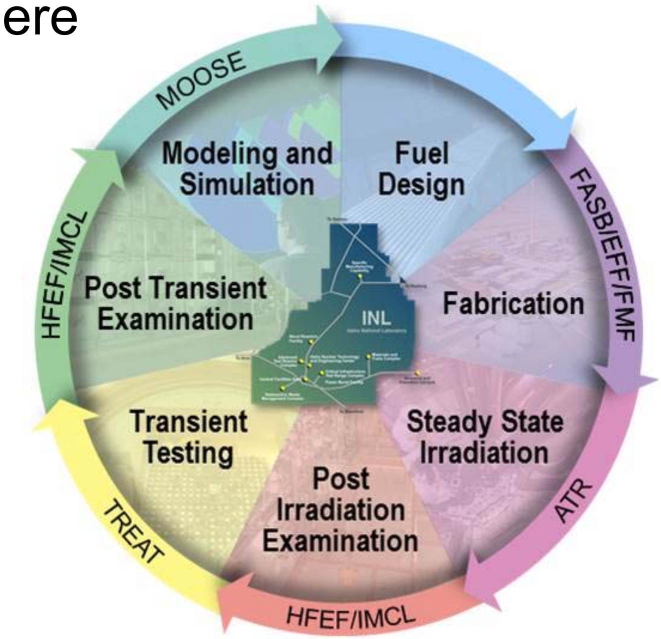
- Reactor control system testing to date indicates replacement not required
- Facility was left in remarkably good condition in 1994 and facility systems consistently maintained
- Current evaluations have affirmed functional plant system's conditions
- Updated Safety Basis To Current Requirements
  - Updated Safety Analysis Report (SAR) submitted to DOE for review
  - No issues anticipated with regulatory authorization to operate TREAT
- So what's left?
  - Primarily operator training
  - SAR review and approval
  - On schedule for operation in 2018, and maybe even sooner!

Images courtesy of Resumption of Transient Testing Team

No Test Reactor is an Island

- TREAT might look like its in the middle of nowhere
- But its actually right by much of what it needs

Advanced Test Reactor



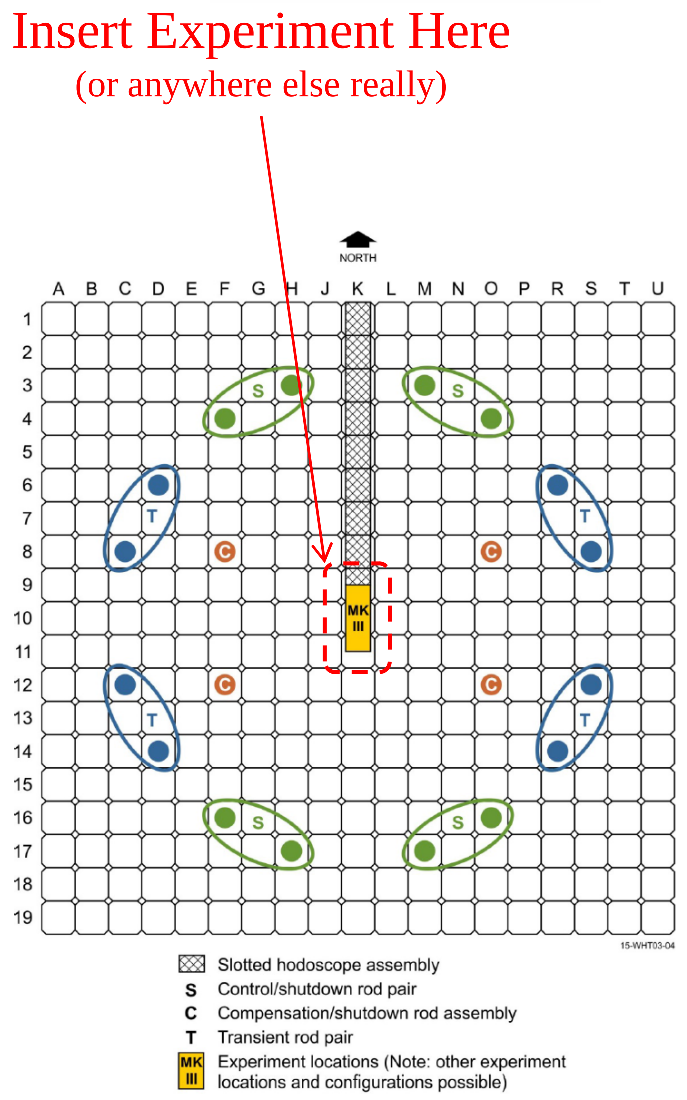
Fun Trivia: The Arco desert is actually green for a few weeks in spring

Materials and Fuels Complex

Hot Cells
Fuel Fabrication
Advanced Characterization

Experiment Design Status

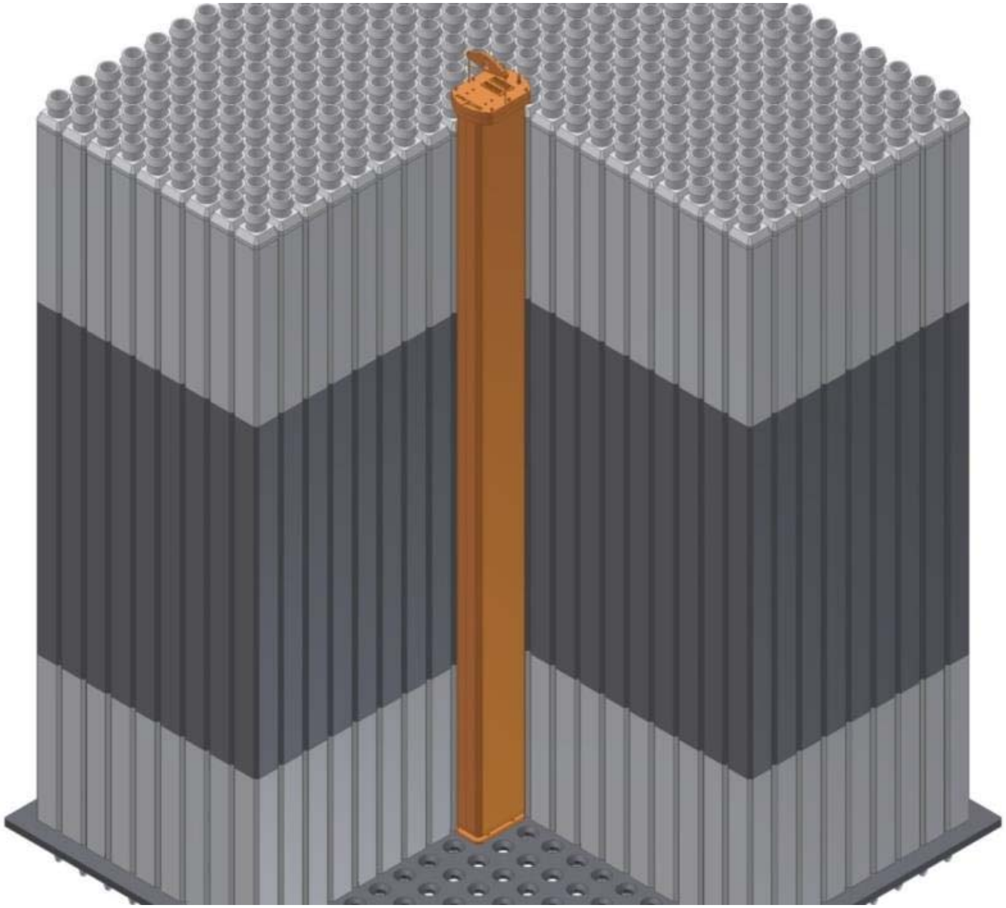
- TREAT is a brilliantly basic machine
  - But all it really does is provide neutrons
- The experiment vehicle (e.g. loop, capsule, etc.) does the other half of the work
  - Boundary conditions (heat transfer, coolant environment)
  - Instrumentation
- ATF transient tests likely to be the first transient tests
  - Support for congressional mandate to insert lead test rods in a commercial PWR
  - TREAT spent the last two decades of its prior operation (~1970-1990) largely supporting fast reactor tests
  - Transient testing experiment team developing pressurized water test capabilities for TREAT
- Revitalization of sodium-environment irradiation vehicles underway
- Development of vehicles for “science-based” specimens also underway



Static Environment Vehicles

Static Environment Rodlet Transient Test Apparatus (SERTTA)

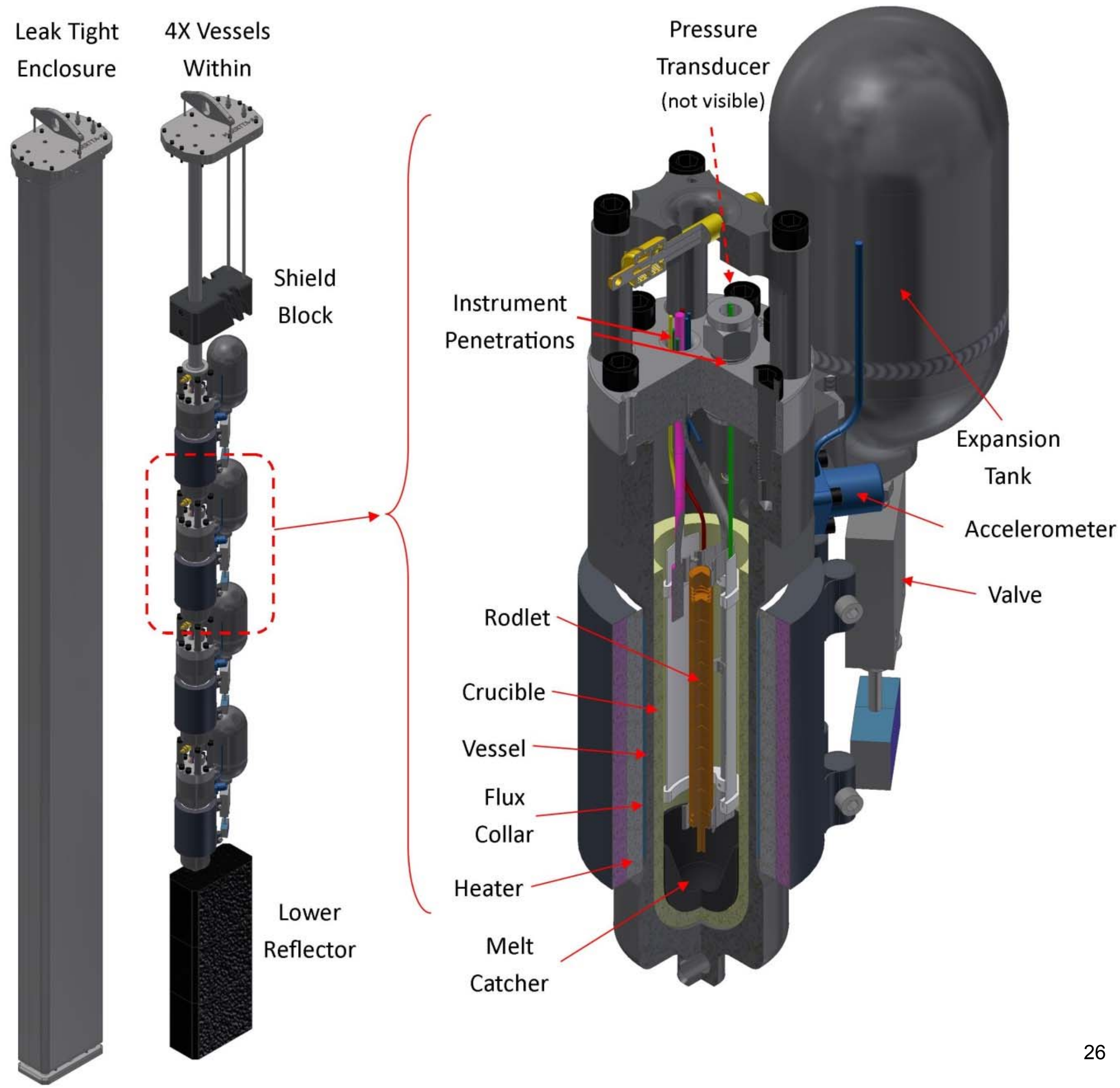
- General purpose devices without forced convection
- Pre-pressurized and electrically heated
  - Liquid water up to PWR condition (320C 16 MPa)
  - Inert gas or steam
  - Liquid sodium
- Vessels designed with tremendous safety margin
  - Nickel-based superalloy UNS N07718 enables thin vessel wall to minimize neutron absorption
- Two SERTTA's under development
  - 4X capsule "Multi-SERTTA"
  - 1X capsule "Super-SERTTA"



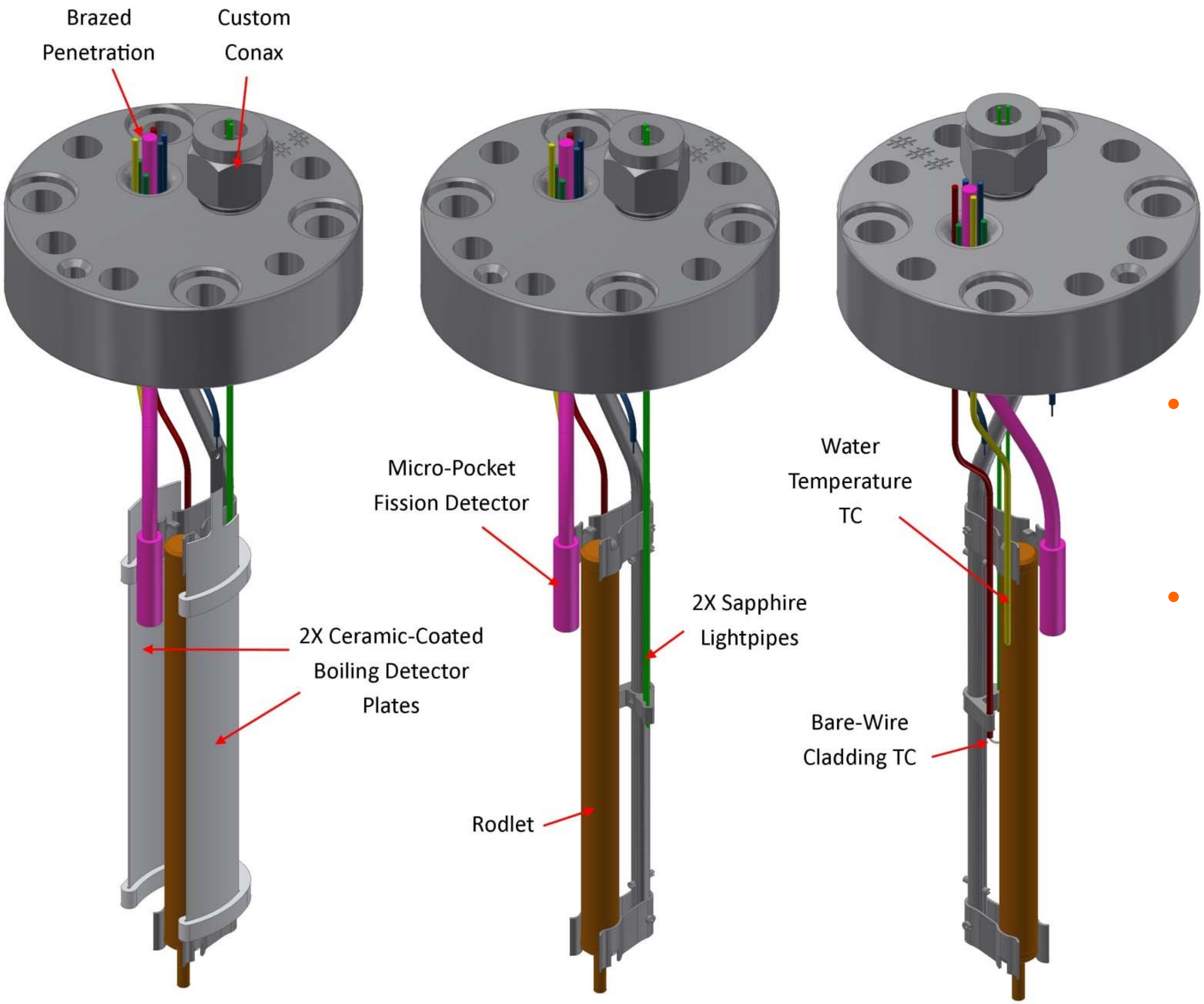
SERTTA shown in TREAT core ¾ section view
Secondary containment "can" visible

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



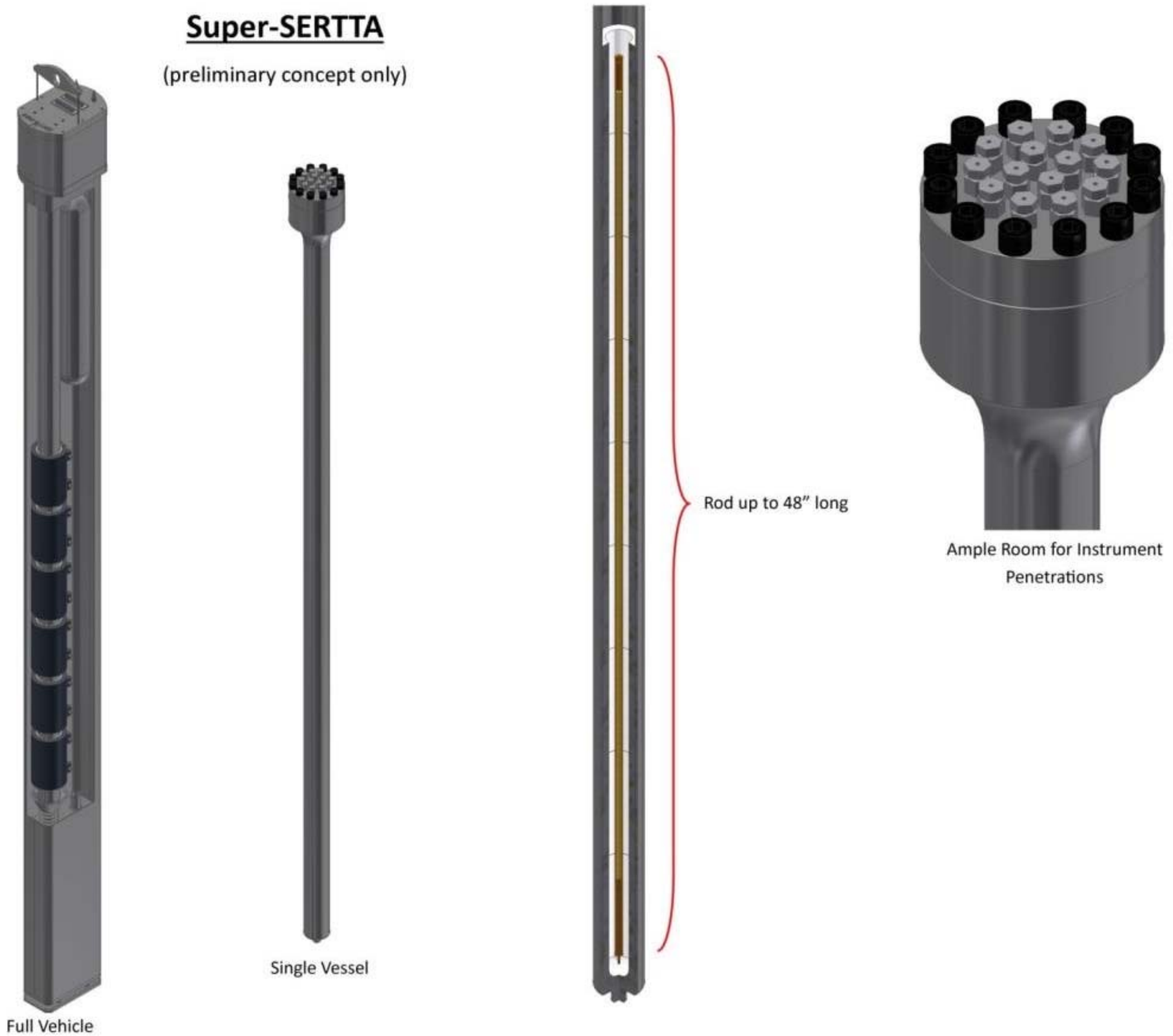
Multi-SERTTA



- Despite geometry limitations, has an impressive instrument array
- Modular, adaptable for other missions (version shown here is for PWR rodlets)

Super-SERTTA

- For larger specimens and/or bundles
- Higher energy capacity
- More geometry available for instrumentation



Flowing-Water Loop

- But static water will only get you so far
- Forced convection need to simulate LWR conditions (boiling response, etc.)
- Developing the TREAT Water Environment Recirculating Loop (TWERL)
- Based on MK-series concept
- Test train is modular:
  - One rod in a flow tube for highly instrumented test trains
  - Up to three rods in individual flow tubes for concurrent testing
  - Four-rod bundle Test-specific instrument designs

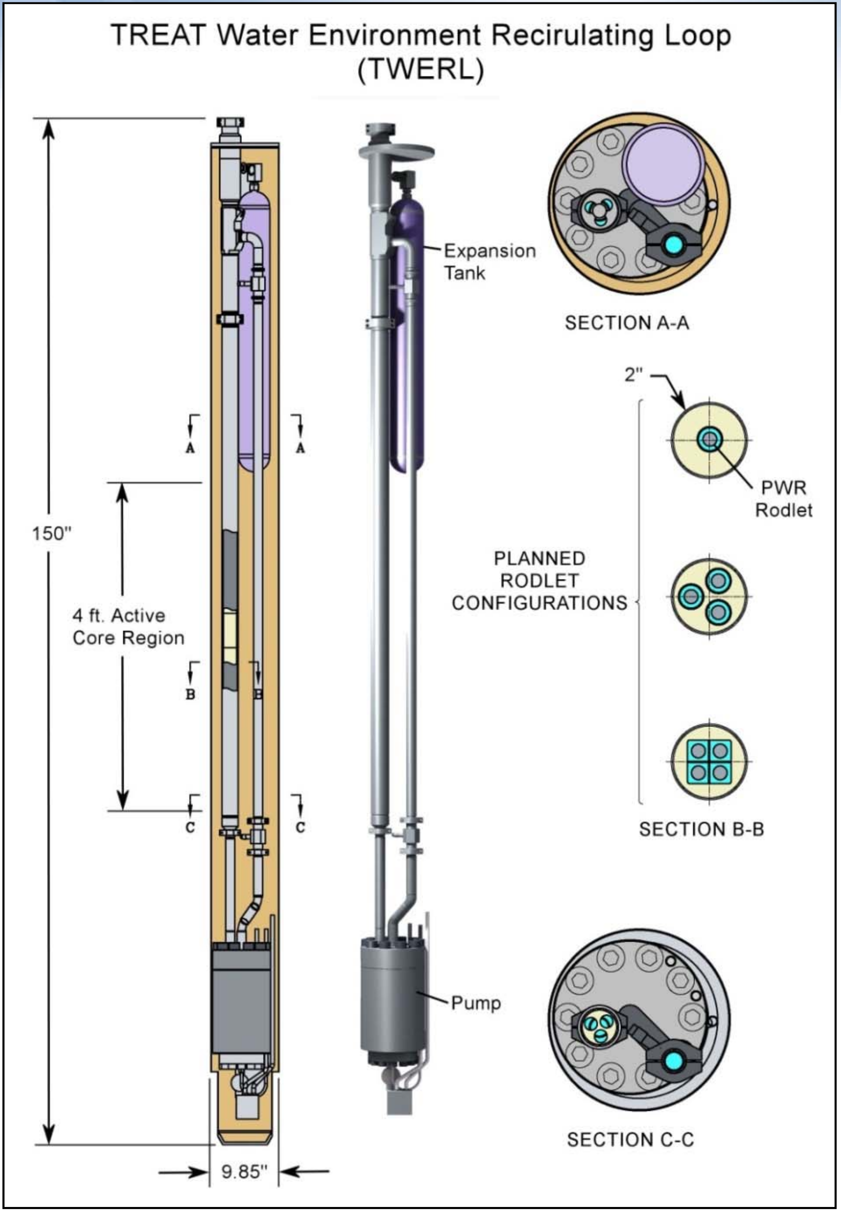
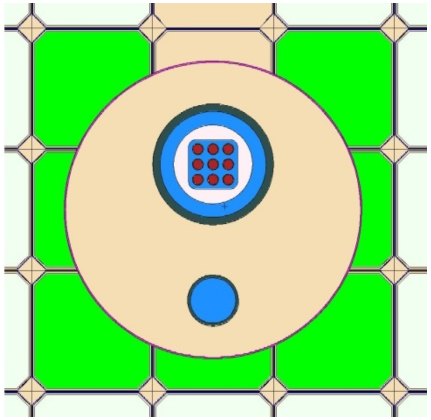


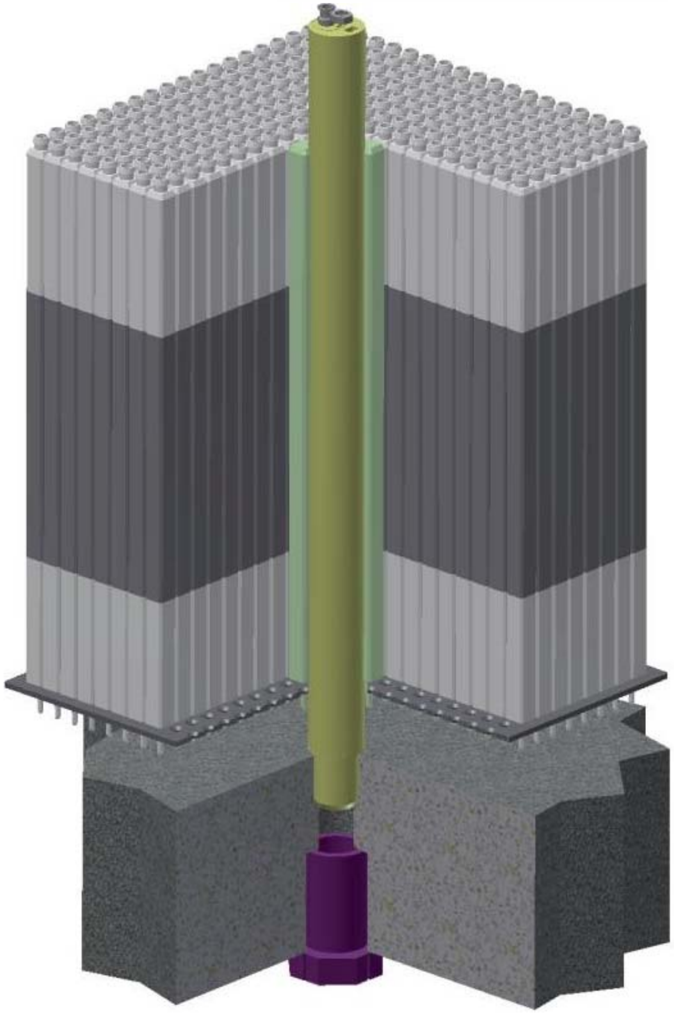
Image courtesy of Greg Housley

TWERL

- Larger cylindrical footprint in core
- Fits within existing shielded casks
- Further TWERL modules and evolutions envisioned
  - Blowdown valve and tank for LOCA simulation
  - 9-rod bundle “Super-TWERL” (nuclear analysis shows TREAT is capable)



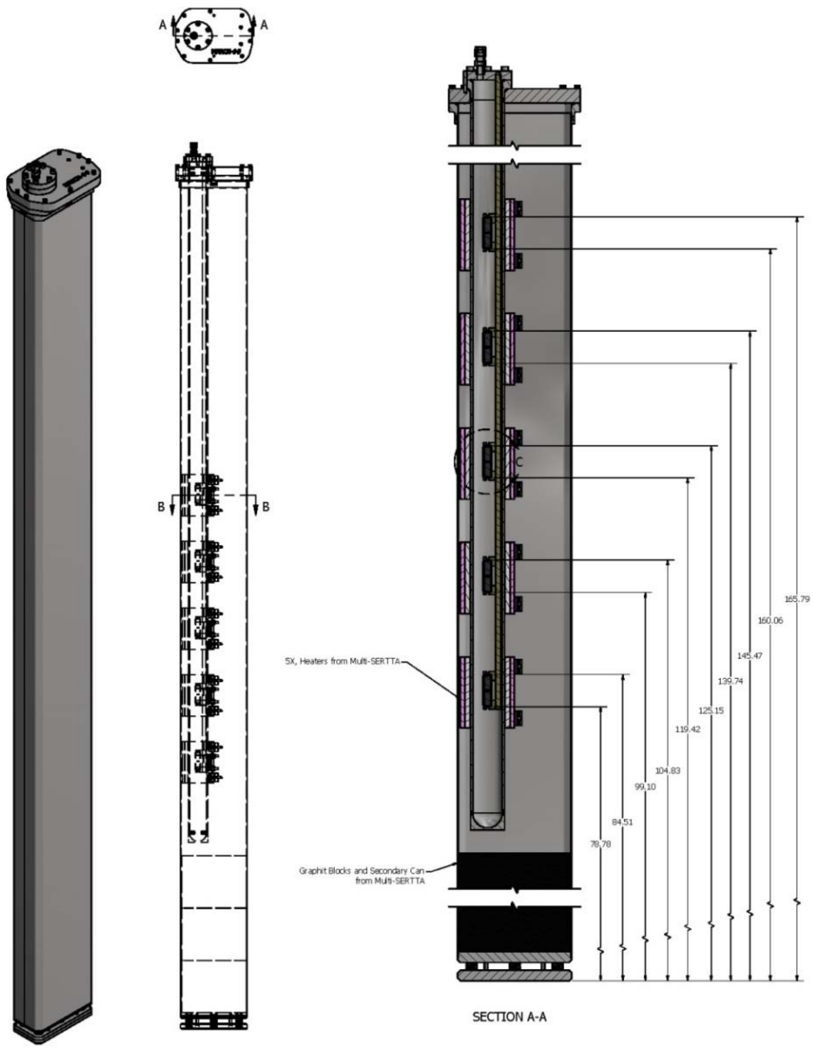
MCNP Rendering of 9-rod “Super-TWERL”
Image courtesy of Connie Hill



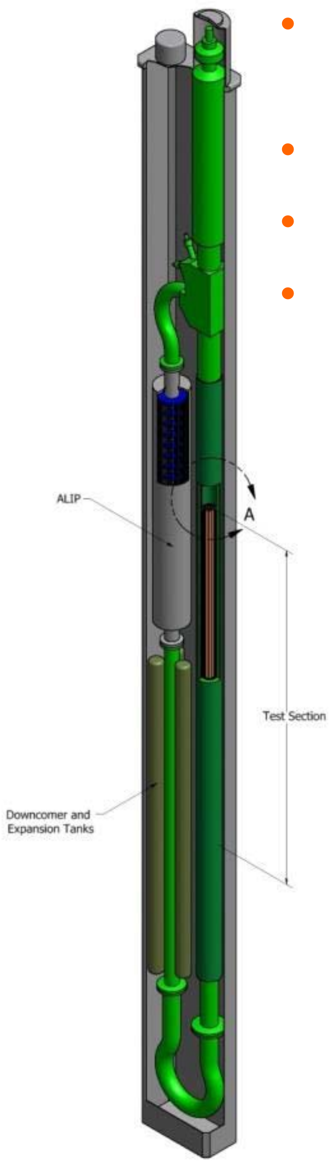
TWERL shown in TREAT ¾ section view
Image courtesy of Greg Housley

MARCH Vehicle

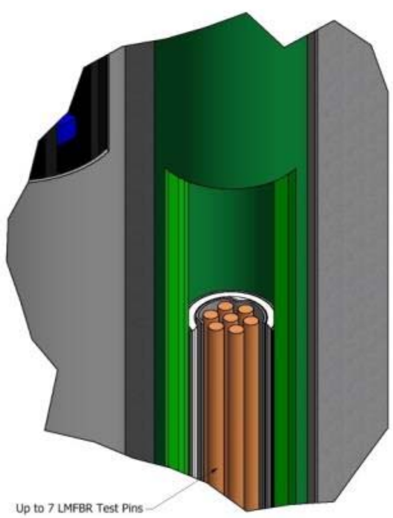
- Vehicle which enables small specimens to be irradiated at TREAT, extracted, and shipped for exams with little to no shielding
- Dubbed the Minimal Activation Retrievable Capsule Holder (MARCH)
  - Capability akin to hydraulic shuttle, (aka "rabbit"), but without the plumbing
  - Multiple small samples (fueled or unfueled) in low-activation capsules
  - Capsule-specific temperature control (heaters) and monitoring (thermocouples)
  - Small sample size greatly facilitates experiment safety analysis → the result is cheap and easy experiments
- Designed firstly for an LDRD that compares irradiation-induced microstructure changes to lower-length-scale performance models (MARMOT)
  - Many similar tests expected to follow
  - One could say it's designed to "Unify Theory and Experiments in the 21st Century"!



Mk-IV Sodium Loop



- Mk-series design concept is well-established
  - Some updates likely needed → "MK-IV" sodium loop
- Room for advancement – materials, instrumentation
- Modern fast reactor program needs to be incorporated
- Revitalization of induction pump capability



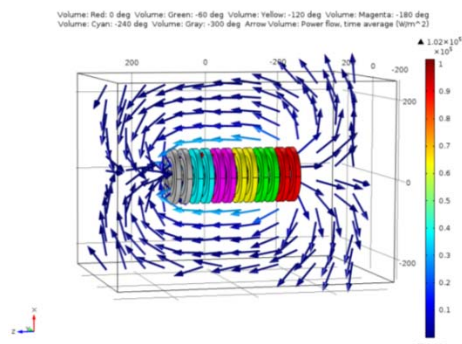
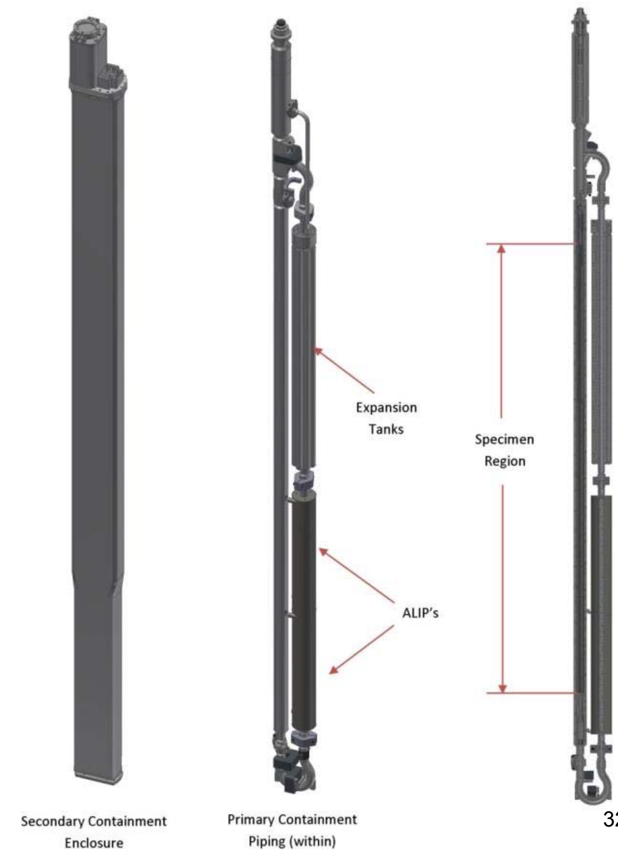


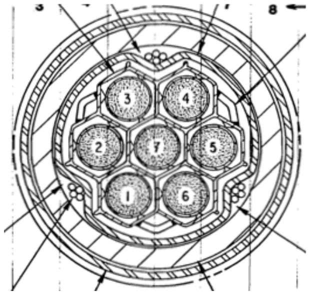
Figure 10. Vector simulation of 12 solenoids in a 2-pole electromagnetic pump.

Carlos O. Maidana and Juha E. Neiminen, "Multiphysics Analysis of Liquid Metal Annular Linear Induction Pumps: A Project Overview", Proceedings of NETS2016 meeting.

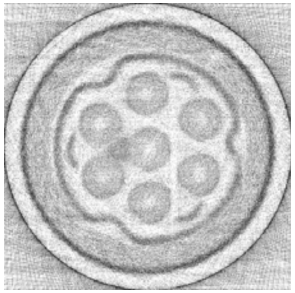


The Future

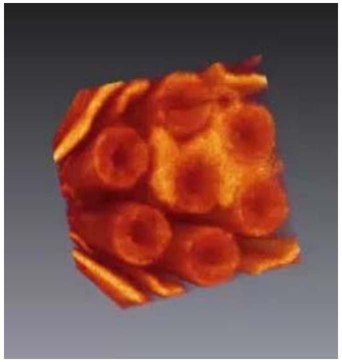
- 20 yrs of computational advances will set TREAT’s future apart from its past:
  - Multi-physics modelling of experiments (reactor, fuel performance)
  - Advanced post-transient exams (3D computed tomography)
- The future of transient testing “in Idaho” will reach far beyond INL’s border both domestic and abroad
  - Nuclear Science User Facilities (NSUF)
  - Industrial access through GAIN
  - Multiple university collaborations already, no doubt more to come
    - Instrument development, advanced hodoscope sensors, IRP led by UW Madison
    - Core/loop benchmarking, IRP led by OSU
  - Collaboration on in-pile advanced sensor development
  - International collaboration with other transient test reactors:
    - NSRR (Japan), CABRI (France), IGR (Kazakhstan)



Mk-series 7-pin test



Historic Neutron Tomograph



Modern 3D Reconstruction

Thank you for your attention