Overview of Transient Testing and TREAT Restart

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IRP Meeting at University of Michigan
May 24, 2016
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 \textit{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

• 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


- Special Power Excursion Reactor
- Transient Reactor Test Facility
- Loss of Fluid Test Facility
- Operational Standby
- Power Burst Facility
- Planned restart

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

- 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

**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

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…..
**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
• 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
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

- 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.

*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
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.
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
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!
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

Fun Trivia: The Arco desert is actually green for a few weeks in spring
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 Rodlet Transient Test Apparatus (SERTTA)

- General purpose devices without forced convection
- Pre-pressurized and electrically heated
  - Liquid water up to PWR condition (320°C 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”
**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
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”!

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**PHYSOR 2016**

Unifying 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

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)
Thank you for your attention