TREAT Restart and Transient Testing Program

Dr. Dan Wachs
National Technical Lead for Transient Testing

October 27, 2016
Why is TREAT so Important?

- Nuclear fuel technology development requires a comprehensive suite of testing infrastructure
- This infrastructure deteriorated significantly over the last several decades
- DOE is investing heavily in the recovery of the overall capability
History of Transient Testing at the INL

• Since its inception as the US Nuclear Reactor Testing Station (NRTS) in the 1950’s researchers at the INL have been conducting experimental programs to establish the limits of nuclear system performance

• These studies were critical to the development, design, and deployment of the nuclear technologies that form the basis of today’s nuclear energy industry
History of Transient Testing in Idaho


Special Power Excursion Reactor

Transient Reactor Test Facility

Loss of Fluid Test Facility

Power Burst Facility

Operational Standby

planned restart

Reliance on out-of-pile testing?
Transient Testing Program Schedule

- The TREAT Restart schedule is currently driven by the Accident Tolerant Fuels (ATF) program objectives
  - Insertion of lead test assembly in commercial power reactor by 2022
  - Transient testing must begin before the end of 2018 to support concept screening and safety criteria assessment/development
  - However, the possibility of early reactor restart has opened the opportunity for additional near-term experiments
## Resumption of Transient Testing Program (RTTP)

### Activity ID Activity Name

<table>
<thead>
<tr>
<th>Activity ID</th>
<th>Activity Name</th>
<th>Total Float</th>
<th>Start Date</th>
<th>Finish Date</th>
<th>% Complete</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td>Perform Fuel Inspections in Storage &amp; Core</td>
<td>0.00d</td>
<td>Jan-20-15</td>
<td>Apr-20-15</td>
<td>100%</td>
</tr>
<tr>
<td>1010</td>
<td>Re-establish Functionality of Fuel &amp; Fuel Storage Systems (#'s 1,2,3,4)</td>
<td>186.00d</td>
<td>Jan-20-15</td>
<td>Apr-20-15</td>
<td>100%</td>
</tr>
<tr>
<td>1020</td>
<td>Informal DOE Review &amp; Comment Resolution of DSA Update for Reactor Operations</td>
<td>0.00d</td>
<td>Jan-20-15</td>
<td>Apr-20-15</td>
<td>100%</td>
</tr>
<tr>
<td>1030</td>
<td>Start Up Reactor per TREAT Startup Plan (Aggressive - No Risk Realized)</td>
<td>0.00d</td>
<td>Jan-20-15</td>
<td>Apr-20-15</td>
<td>100%</td>
</tr>
<tr>
<td>1040</td>
<td>Simulated Operations</td>
<td>0.00d</td>
<td>Jan-20-15</td>
<td>Apr-20-15</td>
<td>100%</td>
</tr>
</tbody>
</table>

### Key Engineering Modifications

<table>
<thead>
<tr>
<th>Activity ID</th>
<th>Activity Name</th>
<th>Total Float</th>
<th>Start Date</th>
<th>Finish Date</th>
<th>% Complete</th>
</tr>
</thead>
<tbody>
<tr>
<td>1050</td>
<td>Design, Build, &amp; Install Fire Protection</td>
<td>100.00d</td>
<td>Jan-20-15</td>
<td>Apr-20-15</td>
<td>100%</td>
</tr>
<tr>
<td>1060</td>
<td>Plan, Design &amp; Perform Reactor Physics Analysis</td>
<td>100.00d</td>
<td>Jan-20-15</td>
<td>Apr-20-15</td>
<td>100%</td>
</tr>
<tr>
<td>1070</td>
<td>Computer Systems Readiness Determinations</td>
<td>100.00d</td>
<td>Jan-20-15</td>
<td>Apr-20-15</td>
<td>100%</td>
</tr>
<tr>
<td>1080</td>
<td>Program Management &amp; Integration</td>
<td>100.00d</td>
<td>Jan-20-15</td>
<td>Apr-20-15</td>
<td>100%</td>
</tr>
<tr>
<td>1090</td>
<td>Re-establish Functionality of Equipment Needed for Reactor Restart (#'s 8,9,10,11,12,13,14,15,16,17,18,20,25)</td>
<td>100.00d</td>
<td>Jan-20-15</td>
<td>Apr-20-15</td>
<td>100%</td>
</tr>
</tbody>
</table>

### Balance of Program

<table>
<thead>
<tr>
<th>Activity ID</th>
<th>Activity Name</th>
<th>Total Float</th>
<th>Start Date</th>
<th>Finish Date</th>
<th>% Complete</th>
</tr>
</thead>
<tbody>
<tr>
<td>1100</td>
<td>Re-establish Preventive Maintenance Program</td>
<td>100.00d</td>
<td>Jan-20-15</td>
<td>Apr-20-15</td>
<td>100%</td>
</tr>
<tr>
<td>1110</td>
<td>Re-establish Functionality of Reactivity Control Systems (#'s 5,6,7,21,22,23,24)</td>
<td>100.00d</td>
<td>Jan-20-15</td>
<td>Apr-20-15</td>
<td>100%</td>
</tr>
<tr>
<td>1120</td>
<td>Design, Build, &amp; Install Fire Protection Facilities</td>
<td>100.00d</td>
<td>Jan-20-15</td>
<td>Apr-20-15</td>
<td>100%</td>
</tr>
<tr>
<td>1130</td>
<td>Complete System Readiness Determinations</td>
<td>100.00d</td>
<td>Jan-20-15</td>
<td>Apr-20-15</td>
<td>100%</td>
</tr>
<tr>
<td>1140</td>
<td>Update FHA &amp; Reflect Updated Fire Protection Systems</td>
<td>100.00d</td>
<td>Jan-20-15</td>
<td>Apr-20-15</td>
<td>100%</td>
</tr>
</tbody>
</table>

### Nuclear Safety and Implementation

<table>
<thead>
<tr>
<th>Activity ID</th>
<th>Activity Name</th>
<th>Total Float</th>
<th>Start Date</th>
<th>Finish Date</th>
<th>% Complete</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000</td>
<td>Perform Reactor Physics Analysis</td>
<td>100.00d</td>
<td>Jan-20-15</td>
<td>Apr-20-15</td>
<td>100%</td>
</tr>
<tr>
<td>2010</td>
<td>Prepare DSA Full Update for Reactor Operations for DOE Informal Review</td>
<td>100.00d</td>
<td>Jan-20-15</td>
<td>Apr-20-15</td>
<td>100%</td>
</tr>
<tr>
<td>2020</td>
<td>Conduct MSA/CRA/RA for Readiness to Resume Reactor Operations</td>
<td>100.00d</td>
<td>Jan-20-15</td>
<td>Apr-20-15</td>
<td>100%</td>
</tr>
<tr>
<td>2030</td>
<td>DOE Formal Review &amp; Approve DSA Update for Reactor Operations &amp; Issue SER</td>
<td>100.00d</td>
<td>Jan-20-15</td>
<td>Apr-20-15</td>
<td>100%</td>
</tr>
<tr>
<td>2040</td>
<td>DOE Implementation for Reactor Operations (Including ISA)</td>
<td>100.00d</td>
<td>Jan-20-15</td>
<td>Apr-20-15</td>
<td>100%</td>
</tr>
</tbody>
</table>

### Reactor Startup Activities

<table>
<thead>
<tr>
<th>Activity ID</th>
<th>Activity Name</th>
<th>Total Float</th>
<th>Start Date</th>
<th>Finish Date</th>
<th>% Complete</th>
</tr>
</thead>
<tbody>
<tr>
<td>3000</td>
<td>Conduct Nuclear Instrument Technicians &amp; Operators for Fuel Inspections &amp; Initial Rod Drive Testing</td>
<td>100.00d</td>
<td>Jan-20-15</td>
<td>Apr-20-15</td>
<td>100%</td>
</tr>
<tr>
<td>3010</td>
<td>Training for Simulated Operations to Include Validation of Existing Training &amp; Procedures &amp; Delta Training</td>
<td>100.00d</td>
<td>Jan-20-15</td>
<td>Apr-20-15</td>
<td>100%</td>
</tr>
<tr>
<td>3020</td>
<td>Begin Reactor Startup Activities to Include Validation of Existing Training &amp; Procedures &amp; Delta Training</td>
<td>100.00d</td>
<td>Jan-20-15</td>
<td>Apr-20-15</td>
<td>100%</td>
</tr>
</tbody>
</table>

### Reactor Restart Schedule

<table>
<thead>
<tr>
<th>Activity ID</th>
<th>Activity Name</th>
<th>Total Float</th>
<th>Start Date</th>
<th>Finish Date</th>
<th>% Complete</th>
</tr>
</thead>
<tbody>
<tr>
<td>4000</td>
<td>Reactor Restart Risk</td>
<td>100.00d</td>
<td>Jan-20-15</td>
<td>Apr-20-15</td>
<td>100%</td>
</tr>
<tr>
<td>4010</td>
<td>Reactor Restart Risk</td>
<td>100.00d</td>
<td>Jan-20-15</td>
<td>Apr-20-15</td>
<td>100%</td>
</tr>
</tbody>
</table>

### Critical Remaining Work

<table>
<thead>
<tr>
<th>Activity ID</th>
<th>Activity Name</th>
<th>Total Float</th>
<th>Start Date</th>
<th>Finish Date</th>
<th>% Complete</th>
</tr>
</thead>
<tbody>
<tr>
<td>5000</td>
<td>Reactor Restart Risk</td>
<td>100.00d</td>
<td>Jan-20-15</td>
<td>Apr-20-15</td>
<td>100%</td>
</tr>
</tbody>
</table>

### Remaining Work

<table>
<thead>
<tr>
<th>Activity ID</th>
<th>Activity Name</th>
<th>Total Float</th>
<th>Start Date</th>
<th>Finish Date</th>
<th>% Complete</th>
</tr>
</thead>
<tbody>
<tr>
<td>6000</td>
<td>Reactor Restart Risk</td>
<td>100.00d</td>
<td>Jan-20-15</td>
<td>Apr-20-15</td>
<td>100%</td>
</tr>
</tbody>
</table>
### First Year of Operation

<table>
<thead>
<tr>
<th>Activity ID</th>
<th>Activity Name</th>
<th>Duration</th>
<th>Start</th>
<th>Finish</th>
<th>Physical Complete</th>
</tr>
</thead>
<tbody>
<tr>
<td>EXP001</td>
<td>Startup Testing</td>
<td>32.00d</td>
<td>Nov-13-17*</td>
<td>Jan-16-18</td>
<td>0%</td>
</tr>
<tr>
<td>EXP005</td>
<td>M8 Calibration</td>
<td>18.00d</td>
<td>Jan-17-18</td>
<td>Feb-15-18</td>
<td>0%</td>
</tr>
<tr>
<td>EXP010</td>
<td>Multi-SERTTA Calibration Phase I</td>
<td>8.00d</td>
<td>Feb-19-18</td>
<td>Mar-01-18</td>
<td>0%</td>
</tr>
<tr>
<td>EXP015</td>
<td>Ship Radio Chemistry for Multi-SERTTA Calibration Phase I Samples</td>
<td>41.00d</td>
<td>Mar-05-18</td>
<td>May-14-18</td>
<td>0%</td>
</tr>
<tr>
<td>EXP020</td>
<td>Configure Multi-SERTTA Phase II Vehicle</td>
<td>18.00d</td>
<td>May-15-18</td>
<td>Jun-14-18</td>
<td>0%</td>
</tr>
<tr>
<td>EXP025</td>
<td>Multi-SERTTA Calibration Phase II</td>
<td>12.00d</td>
<td>Jun-18-18</td>
<td>Jul-09-18</td>
<td>0%</td>
</tr>
<tr>
<td>EXP030</td>
<td>Ship Radio Chemistry for Multi-SERTTA Calibration Phase II Samples</td>
<td>30.00d</td>
<td>Jul-10-18</td>
<td>Aug-29-18</td>
<td>0%</td>
</tr>
<tr>
<td>EXP035</td>
<td>Analyze Results and Configure ATF-3-1-1</td>
<td>16.00d</td>
<td>Aug-30-18</td>
<td>Sep-27-18</td>
<td>0%</td>
</tr>
<tr>
<td>EXP040A</td>
<td>*Develop TREAT Core Temperature Profile/Negative Temperature Coefficient</td>
<td>32.00d</td>
<td>Mar-05-18</td>
<td>Apr-26-18</td>
<td>0%</td>
</tr>
<tr>
<td>EXP040B</td>
<td>*Develop Neutron Flux Map of the TREAT Core</td>
<td>32.00d</td>
<td>Apr-30-18</td>
<td>Jun-25-18</td>
<td>0%</td>
</tr>
<tr>
<td>EXP040C</td>
<td>*Build Transient Library/Characterize Transient Testing Capabilities of TREAT</td>
<td>16.00d</td>
<td>Jun-26-18</td>
<td>Jul-24-18</td>
<td>0%</td>
</tr>
<tr>
<td>EXP045A</td>
<td>*Perform Neutron Lifetime/Beta Measurements</td>
<td>32.00d</td>
<td>Jul-25-18</td>
<td>Sep-19-18</td>
<td>0%</td>
</tr>
<tr>
<td>EXP045B</td>
<td>*Perform Neutron Spectrum Characterization</td>
<td>32.00d</td>
<td>Sep-20-18</td>
<td>Nov-14-18</td>
<td>0%</td>
</tr>
<tr>
<td>EXP050</td>
<td>Complete Transient Testing of ATF-3-1-1</td>
<td>24.00d</td>
<td>Nov-15-18</td>
<td>Jan-07-19</td>
<td>0%</td>
</tr>
<tr>
<td>EXP055</td>
<td>Complete Transient Testing of ATF-3-1-2</td>
<td>24.00d</td>
<td>Jan-08-19</td>
<td>Feb-18-19</td>
<td>0%</td>
</tr>
<tr>
<td>EXP060</td>
<td>Complete Transient Testing of ATF-3-1-3</td>
<td>24.00d</td>
<td>Feb-19-19</td>
<td>Apr-01-19</td>
<td>0%</td>
</tr>
</tbody>
</table>

- **Startup Tests**
- **ATF-CAL tests**
- **Reactor Characterization, Mammoth Validation Tests & Transient Prescription Development**
- **ATF-3 Tests**
- **Potential New Separate Effects Test Program**

*Physics testing in TREAT core to support NW Ames computer model development.*

TREAT Reactor Characterization, Mammoth Validation Tests & Transient Prescription Development
Transient Testing Program Development

• The reactor must be complemented by cross-cutting and specific test infrastructure designed for a given experiment type
  – Experiment vehicle to provide the sample environment of interest
  – Instrumentation to measure the phenomena of interest
  – Infrastructure to assemble the experiment

• Infrastructure development investment has been prioritized based on current nuclear technology development objectives
  – Accident Tolerant Fuel (DOE) & LWR Burnup Extension (Industry)
    • Phase 1 - Static capsules with PWR coolant conditions
    • Phase 2 - Flowing water loop with PWR coolant conditions
  – Microstructural Evolution in Nuclear Materials under Irradiation
    • Capsule based system for small nuclear fuel samples in a controlled environment
  – Fast Reactor Fuel (fuel cycle, new fast test reactor, Gen IV reactor system)
    • Phase 1 - Static capsules with LMR coolant conditions
    • Phase 2 - Flowing sodium loop with LMR coolant conditions
  – … and more!
Transient Testing for ATF

- ATF-3 will provide DOE and Industry with initial nuclear transient performance screening of accident tolerant fuels concepts under PWR Reactivity Initiated Accident (RIA) conditions.
- PWR Hot Zero Power (HZP) temperature (280°C) and pressure (15.5 MPa) conditions will be initially established around specimens in static environment capsules.
- Under these conditions, a prototypical RIA energy deposition will be delivered. Fresh and Irradiated ATF specimens will be tested in accordance with NUREG RIA energy requirements.

The ATF-3 series of transient tests has motivated / driven the development of the Multi-SERTTA static capsule TREAT Irradiation Vehicle and conceptual designs of the Super-SERTTA capsule and TWERL water loop. Similarly, ATF-3 has determined in-pile instrumentation requirements for ATF-3-1 and ATF-3-2 series and has motivated instrument development activities at INL & industry.
The MAMMOTH Multi-physics reactor analysis software application is built on top of the MOOSE multi-physics framework. For this work, the MAMMOTH package includes Rattlesnake for time-dependent neutron transport, BISON for fuels performance, and RELAP-7 for thermal-fluids calculations. These applications co-exist within MAMMOTH and are able to directly share data. For this reason, MAMMOTH is uniquely suited to support time-dependent 3D simulation of TREAT core and experiments.

MAMMOTH is intended for use to support TREAT operations (including safety analysis, experiment and instrumentation design). It has been demonstrated to be able to reproduce transient power data from calibration measurements performed in the early 1990s. It is currently being used to support design of the Multi-SERTTA by performing transient simulations that cannot be completed by any other way.

Key to MAMMOTH deployment for various customers will be validation of the code against 3D steady state and transient data. We are coordinating with other stakeholders to ensure that the appropriate measurement campaign will be performed during restart testing.
Calibration Vehicle Design

- Nuclear-equivalent calibration
  - Fission wires at steady state (~50 kW)
  - Specimens at steady state (~50 kW)
  - Fission wires through planned transient

- Dosimeters extracted quickly enough for good gamma counting and/or radiochemistry
  - Drywell needed in CAL vehicle

- Compute power coupling factor (PCF) and transient correction factor (TCF) to show test is within safety analysis envelope

- Models indicate that PWR water dramatically influences PCF (not an issue for historic sodium tests)
  - Can’t be adequately simulated with solid moderators or water at ambient temperature
Static Capsule Test Vehicle for ATF

• Multi-Static Environment Reactor Transient Test Apparatus (Multi-SERTTA) being designed to support initial RIA testing in PWR coolant environment

• Device will accommodate up to 4 samples (fresh or pre-irradiated) with instrumentation packages tailored to the experiment objectives
**Instrumentation Package Development**

- **Instruments are required to monitor the:**
  - Experiment boundary conditions: Coolant temperature, vessel pressure, boiling
  - Fuel pin conditions: Cladding temperature, cladding elongation, cladding integrity, pin plenum pressure
  - Fuel motion monitoring

- **This requires the adaptation of existing instruments and the development and qualification of new instruments**

- **This is being enabled by several bilateral collaborations between leaders in the field including DOE-CEA, DOE-IRSN, and INL-Halden**
  - For example, IRSN to host a tri-lateral CEA/IRSN/INL meeting on in-pile instrumentation and the fast neutron hodoscope at CABRI in Cadarache in March
ATF In-Pile Instrumentation

- Fuel Pellet
  - Total energy deposition (neutron/gamma fluence) (internal and secondary containment dosimetry & micro-pocket fission detector (INL/IRP MPFD))
  - Fuel pellet axial expansion, movement or fragmentation (hodoscope, LVDT)
  - Rodlet internal pressure (LVDT)

- Cladding
  - Surface Temperature (fiber optic emissivity-corrected IR radiometry)
  - Cladding axial expansion (LVDT)

- Water Environment
  - Pressure (pressure transducers)
  - Temperature (TCs)
  - Boiling (void sensor, TCs, ultrasonics)
  - Water flow rate (turbine flow meter, LVDT)

- Event Timing
  - Boiling (TCs, accelerometers and microphones)
  - Cladding cracking (accelerometers and microphones)
Hodoscope Recovery

The TREAT Fuel Motion Monitoring System (FMMS) is used for measuring the location and movement of fuel during transient tests.

The FMMS employs a concrete front collimator and a steel, 360-slot rear collimator along with an array of fast-neutron detectors to record neutrons originating from fission in a test capsule under irradiation.

The FMMS data acquisition system (DAS) is capable of recording data in 1-ms increments, at rates >400,000 s⁻¹.

Collectively, the components of this system are referred to as the hodoscope.

Refurbishment Status

- **Detector Refurbishment**
  - All scintillator based detectors have been recovered (~99 of 327 detectors are candidates for refurbishment)
  - Scintillator refurbishment techniques developed
  - Identified, tested and selected replacement photomultiplier tube design
  - 16 detectors were assembled to support system level testing

- **Data Acquisition System Design**
  - A 16 channel DAS was designed, constructed, and is being used for system testing. The design is modular and components can be replicated to increase the number of channels.

- **Collimator Assessment**
  - An endoscope was procured to conduct collimator channel inspection (confirm there is no debris)

- **Electro-Mechanical System Recovery**
  - The Hodoscope collimator is maneuvered to optimize field of view for each experiment. The condition of the motor and control system is being assessed as a first step in returning to operation.

- **Hodoscope Modeling and Simulation**
  - Historic Hodoscope drawings were recovered and a 3D solid model was constructed. This model will be coupled to the reactor physics models to estimate signal strength as a function of experiment prescription.
  - Models of the scintillator were developed to study their physical response to estimate device performance and to support data processing software development
Modern M&S Driven Development

- A world-wide trend toward mechanistic treatment of nuclear fuel safety behavior and risk informed regulation is leading to reassessment of existing safety analysis codes.

- Benchmark studies conducted through this prism have revealed significant shortcomings in both the codes/models and the fuel safety criteria.

- For example,
  - RIA safety criteria is based on conservative fail/no-fail data extracted from a diverse set of integral tests (mostly conducted in the 1960’s and 70’s). All the required information to conduct mechanistic analysis is not available.
  - Benchmark studies conducted on the range of international analysis codes revealed that most phenomenological models are not consistently applied nor do they represent the ‘real’ behavior (e.g. transient boiling curves)
  - It is proposed that the integral behavior of fuel under these conditions be de-convoluted into a series of separate effects tests that will isolate the phenomena of interest as required to develop and validate new mechanistic models.
  - Specialized instrumentation and testing techniques developed to support these studies will then be applied to integral tests to validate the full function of the codes.
Collaboration

• Transient testing infrastructure around the world is becoming increasingly limited. Meeting the needs of advanced technology developers will require that all these resources be closely integrated.

• The US program has focused on developing collaborative relationships with several key international and industrial partners
  – CEA-DOE Bilateral Agreement: Transient testing of thermal and fast reactor fuel designs are included in the agreement
  – IRSN-DOE Bilateral Agreement: New agreement established to emphasis transient testing
  – NNC-INL MOU: New agreement to emphasize collaboration between IGR and TREAT
  – JAEA-DOE Bilateral Agreement: Tasks related to transient testing of both thermal and fast reactor fuels have been added to the agreement
  – Halden-INL MOU: New agreement includes collaboration on LOCA testing
  – SCKCEN-INL CRADA: New agreement including development of instrumentation and fuel pin re-fabrication
  – OECD Working Group for Fuel Safety: INL representative added to working group, will likely join the CABRI International Project (administered by WGFS)
  – EPRI Regulatory Technical Advisory Committee (Reg-TAC): INL participation in committee

• . . and University Partners. Transient testing related university projects include:
  – Three IRP awards (Wisconsin/Ohio State/Kansas State/Idaho State, Oregon State/Michigan/MIT, and Utah State/New Mexico/Florida)
  – Two NEUP awards (North Carolina State, Kansas State)
Summary

- Transient testing has played a central role in nuclear technology safety testing for over 60 years.

- Resumption of operations at TREAT is underway to continue that tradition and enable the development, design, and deployment of advanced fuel and reactor technology.

- The reactor restart schedule has been driven by the Accident Tolerant Fuels program objectives. The INL has committed to having the reactor restarted by the end of 2018. However, it is expected to begin operation as soon as March of 2018.

- Development of the irradiation devices and in-pile instrumentation required for the ATF program has been prioritized although infrastructure for a variety of technology types and users is planned.

- Broad international collaborations are being established to ensure optimal utilization of the existing safety testing infrastructure worldwide.
Questions?
Backup Slides