Fuel Cycle Research and Development

Advanced Fuels Campaign
In-reactor Instrumentation Overview

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Advanced Sensors and Instrumentation
2015 NE I&C Review Webinar
FCRD Advanced Fuels Campaign

- Develop near-term accident tolerant LWR fuel technology
- Perform research and development of long-term transmutation options

Advanced LWR Fuels with enhanced performance, safety, and reduced waste generation

Advanced reactor fuels with enhanced proliferation resistance and resource utilization

Capability Development for Science-based Approach to Fuel Development
- Advanced characterization and PIE techniques
- Advanced in-pile instrumentation
- Separate effects testing
- Transient testing infrastructure

Multi-scale, multi-physics fuel performance modeling and simulation

Advanced Fuels Campaign

NEAMS
Fuel Development Life Cycle

- Irradiation Testing
- Performance Assessment
- Advanced Fuel Design
- Feedstock Preparation & Characterization
- Ceramic & Metallic Fuel and Material Fabrication
- Fresh Fuel Characterization
- Multivariate Model Development & Simulation (Moose Bison Marmot)
- Out-of-Pile Testing
- Irradiation Testing
- In-reactor Instrumentation
- Transient Testing Potential
- Post-irradiation Examination

**Typically 3-5 years**

**Access to results sooner**

**Real-time data output**

**Intermediate data available**

**Longer for higher burnup experiments**

**Single data point at end of irradiation**

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**Single data point at end of irradiation**
Irradiation Experiment Goals

- Demonstrate new fuel behavior
- Measure bulk fuel behavior, integral fuel performance: macroscopic scale
- Collect smaller length-scale data for modeling and simulation: microscopic scale
- Compare new fuels to historic fuels database
- Identify life-limiting phenomena

In-reactor Instrumentation Goals

- “Observe” real-time fuel behavior
- Provide access to results before postirradiation examination (PIE)
- Inform decisions on continued irradiation or withdrawal based on performance data
- Generates intermediate fuel behavior data
Fuel Behavior is Complex

- Fission gas bubbles (Xe, Kr) cause fuel swelling
- Steep temperature gradient can lead to large difference in chemical potential and drive constituent migration
- Solid fission products cause fuel swelling, change in composition (oxygen potential in TRUO_x)
- Fuel-cladding mechanical interaction results from fuel swelling
- Fuel-cladding chemical interaction results from reaction between fuel and fission products
- Cladding: stainless steel or Zircaloy
- Gas pressurization of cladding tube
- ~100 MeV heavy fission fragments lead to very high defect densities, very fast diffusion
- Neutrons cause cladding damage
Key Fuel Performance Phenomena

- **Dimensional changes**
  - axial growth
  - radial swelling
- **Fission gas production and release (pin pressure)**
- **Fuel restructuring (zone formation)**
- **Constituent redistribution**
- **Fuel cladding chemical/mechanical interaction**

**Performance phenomena depend on**
- composition
- temperature
- burnup

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Transverse metallographic section from the high temperature region of a U-19Pu-10Zr element at 3 at.% burnup with superimposed microprobe scans, showing zone formation, cracking and Zr-U redistribution.


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Fission gas released to plenum above fuel for various metallic fuels as a function of burnup (EBR-II irradiation).
Desired Data

- Fuel temperature
- Cladding temperature
- Fuel dimensions
- Cladding dimensions
- Fuel pin internal gas pressure and composition
- Thermal conductivity
- Fuel-cladding chemical interaction depth
- Fuel microstructure
- Irradiation conditions
  - coolant temperature
  - neutron flux (fast, thermal)

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Types of Irradiation Experiments

**Steady State**
- Simulate normal operating conditions
- Supports long-term irradiation for high burnup demonstration (~1-5 years)

**Transient**
- Simulate accident conditions
- Short experiments (~ms-minutes)
- Fuel disruption and failure common

**Static (drop-in) capsule**
- simplest design
- no wires

**Instrumented Lead**
- more complicated design
- accommodates wired instruments

**Loop**
- most complicated design
- controlled environment
- accommodates wired instruments

**Integral**
- Bulk fuel pin behavior
- Prototypic irradiation conditions

**Separate Effects**
- Isolate specific phenomena
- Controlled conditions
In-reactor Instrumentation Constraints

Small experiments
- Irradiation experiments are usually representative of typical reactor fuel pins, dimensions ~5.8-9.5 mm (0.230-0.374 in.) outer diameter

Small in-reactor experiment locations
- Typical experiment positions 15-38 mm (0.62-1.5 in.) diameter

Stability and Survivability
- Instruments must survive irradiation and fuel environment with no (or known) drift
- Instruments must survive reactor conditions: high neutron flux, high temperature, high pressure, chemical environments
- Wired instruments must fit through reactor pressure vessel feedthroughs (leak tight)

Limited space (feedthroughs) for wired instrumentation

Total cost (fixed program budgets)
- Experiments with instrumented leads are more expensive to design, build, and operate

Deconvolution when instrumentation affects the experiment
- Example: fuel temperatures change fuel is removed and a thermocouple is inserted
- Modeling and simulation is needed to connect instrumentation data to other fuel phenomena and predict fuel behavior in absence of instrumentation
AFC Irradiation Experiments in ATR

**Design Features**
- Cd-shrouded baskets filter thermal flux
- Rodlet inside SS capsule (safety barrier)
- Gas gap provides prototypic cladding temperature
- LHGR < 500 W/cm  
  Target 350 W/cm
- PICT < 650°C  
  Target 500-550°C
- Capsule pressure <800 psi

**Outboard A (OA) Design**
- AFC-3, 4
- Rodlets in individual capsules (axial stack of 5)
AFC-OA Design

**Rodlet**
- HT-9 (SS 421) cladding
- height = 6 in. (15.2 cm)
- ID = 0.194 in. (4.93 mm)
- OD = 0.230 in. (5.84 mm)

**Capsule**
- SS 316L
- height = 8.5 in. (21.6 cm)
- ID = 0.234 in. (5.94 mm)
- OD = 0.274 in. (6.96 mm)
- 1 rodlet per capsule

**Capsules can be inserted and removed independently**

**Redesign in progress**
Experimental fuels and cladding concepts
- Teams from industry, national labs, IRPs

ATF-1 static capsule experiments
- Small I positions
- 3 channels per basket
- Each channel contains vertical stack of capsules (up to 7 x 6-in. / channel)

ATF-2 loop experiment for priority concepts
- Center flux trap
- Prototypic PWR conditions
- Instrumented pins
- Sensor qualification test (SQT) planned for early FY 2017
ATF-1 Design

- Double encapsulation (miniature pin in outer capsule)
- Outer capsule provides safety barrier
- Gas gap provides thermal resistance for cladding temperature
- 4 inch maximum fuel column height

[Diagram showing the inner and outer structures of the ATF-1 design, including dimensions and components like SST Capsule Body, Redlet OD, Aluminum Basket, and Flux Monitors.]

All Dimensions in inches. This is an example, see program specific drawings for all dimensions.
ATF-1 Basket

- 3 capsule channels
- 3 flux wire channels
- notch oriented toward ATR core

Flux wire holders
Current Instrumentation

- **Melt Wires**
  - ATF-1
  - inserted inside dU insulator pellets

- **Flux Monitors**
  - ATF-1 basket

- **SiC Temperature Monitors**
  - planned use in future ATF-1 experiments
### Sensor Qualification Test (SQT)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Sensor</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel Temperature</td>
<td>High Temperature Irradiation Resistant-Thermocouple (HTIR-TC)</td>
<td>INL</td>
</tr>
<tr>
<td>Fuel Temperature</td>
<td>Ultrasonic Thermometer</td>
<td>INL</td>
</tr>
<tr>
<td>Temperature</td>
<td>Thermoacoustic Sensor (TAC)</td>
<td>INL</td>
</tr>
<tr>
<td>Fuel Thermal Conductivity/ Temperature</td>
<td>Transient Hot Wire Method-Needle Probe</td>
<td>INL</td>
</tr>
<tr>
<td>Fast and Thermal Neutron Flux/Temperature</td>
<td>Micro Pocket Fission Detector (MPFD)</td>
<td>INL</td>
</tr>
<tr>
<td>Gas Pressure</td>
<td>Linear Variable Differential Transformer (LVDT)/Bellows</td>
<td>Halden</td>
</tr>
<tr>
<td>Gas Pressure</td>
<td>Fiber Optic Pressure Transducer</td>
<td>Luna</td>
</tr>
<tr>
<td>Elongation</td>
<td>LVDT</td>
<td>Halden</td>
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</tbody>
</table>

### Fuel Test (Planned)

<table>
<thead>
<tr>
<th>Parameter</th>
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<tbody>
<tr>
<td>Fuel Temperature</td>
<td>HTIR-TC</td>
<td>INL</td>
</tr>
<tr>
<td>Gas Pressure</td>
<td>LVDT/Bellows</td>
<td>Halden</td>
</tr>
<tr>
<td>Fuel Elongation</td>
<td>LVDT</td>
<td>Halden</td>
</tr>
<tr>
<td>Cladding Elongation</td>
<td>LVDT</td>
<td>Halden</td>
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</tbody>
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Sensors to be evaluated have potential advantages, but have not been demonstrated previously in-core

- Developmental sensors may be used in ATF-2 fueled experiment if performance is exceptional
Conservative sensor selection:
- Sensors with prior irradiation demonstration preferred
- Additional sensors tested in ATR SQT will be evaluated for ATF-2

Several un-instrumented rodlets will include multiple LVDT cores
- Allows for intermittent measurements in ATR canal
- Can be utilized for ATF-3 transient tests
Transient Testing

- TREAT experiments planned in 2018
- Transient experiments are short, ~100 ms
  - Rapid instrument response required
  - Short term neutron exposure
- Experiments include fresh and irradiated fuel
  - Irradiated fuel experiments require remote fabrication/assembly
- Initial static capsule design has limited instrumentation space
  - Boiling detectors
  - Water temperature TC
  - Cladding surface pyrometer
  - Cladding temperature TC
  - Micro pocket fission detector
- Future experiment designs will include additional instrumentation space
Ex-Core Fuel-Motion Monitoring

TREAT Hodoscope
- Ex-core detectors measure fast neutrons from in-core fuel experiments to infer fuel location and density during transient test
- ZnS-based proton-recoil detectors with photomultiplier-tube light sensors
- Methane-filled proportional counters
- Large shield array with 360 pencil-beam collimators

Advanced Fast-Neutron Detector Goals
- Improved fast-neutron detector efficiency
- Improved gamma-ray insensitivity/rejection
- Increased throughput
- Improved high-end linearity
- Detector simplification (e.g., elimination of need for external high-voltage power supplies)

Advanced Fast-Neutron Detector

Nuclear Energy

■ Desired Functional Capabilities
  – Fission-spectrum neutron intrinsic detection efficiency: 1% or greater
  – Fission-spectrum photon intrinsic detection efficiency: 0.01% or less
  – High-rate capability: 500,000 neutron events per second or greater
  – Linearity: linear response of 4 decades of event rates or more
  – Stability: stable without calibration or adjustment for 100 hours or more
  – Output: either direct digital output (preferred) or easily-digitized/analyzed analog output
  – Power: no specific requirement: an internal high-voltage power supply is preferred, if needed, but not required (elimination of the need for an external high-voltage power supply is desired)

■ Form Requirements
  – Detectors will be placed within a light-tight enclosure
  – A single detector must fit within a circular tube with 2.54 cm (1 in.) inner diameter; length must not exceed 30 cm (11.8 in.)
Advanced Fuels Campaign is currently using flux wires and melt wires in ATF-1 experiments.

Wireless thermoacoustic sensor demonstrated in Breazeale Reactor September 2015.

ATF-2 loop experiment will use demonstrated in-reactor instruments to measure:
- fuel temperature
- fuel pin internal gas pressure
- fuel stack elongation
- fuel pin elongation

Sensor qualification test will demonstrate existing and new instruments in ATR conditions.

Transient testing requires instrumentation with rapid response times and remote experiment assembly.
Acknowledgments

ATF-1 Melt Wires
- Jason Harp

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- Brian Durtschi

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- Josh Daw
- Jim Smith

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- Nic Woolstenhulme

TREAT Ex-Core Fast Neutron Monitoring
- David Chichester