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Fuel Cycle Research and Development

Advanced Fuels Campaign In-reactor Instrumentation Overview

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Advanced Sensors and Instrumentation
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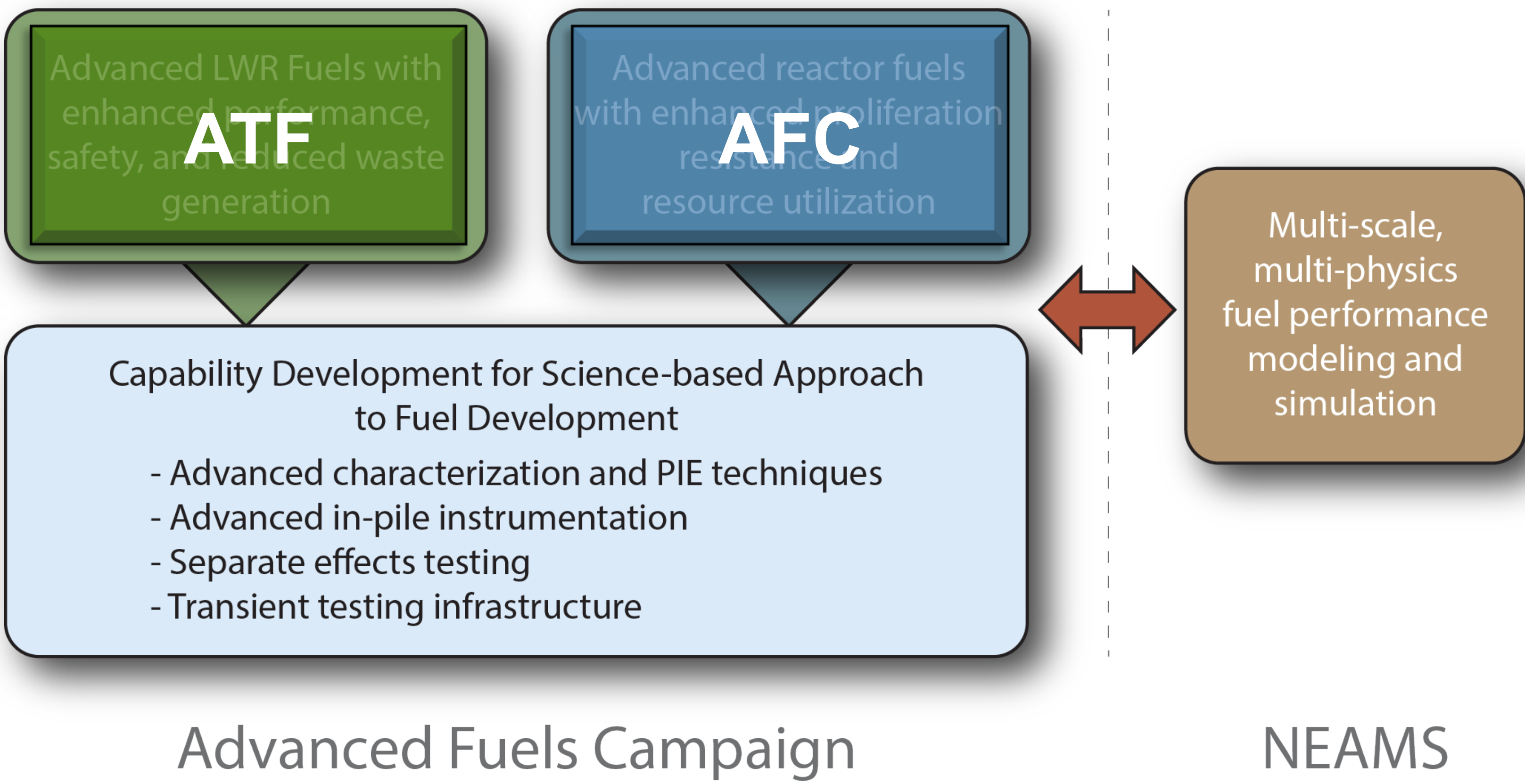
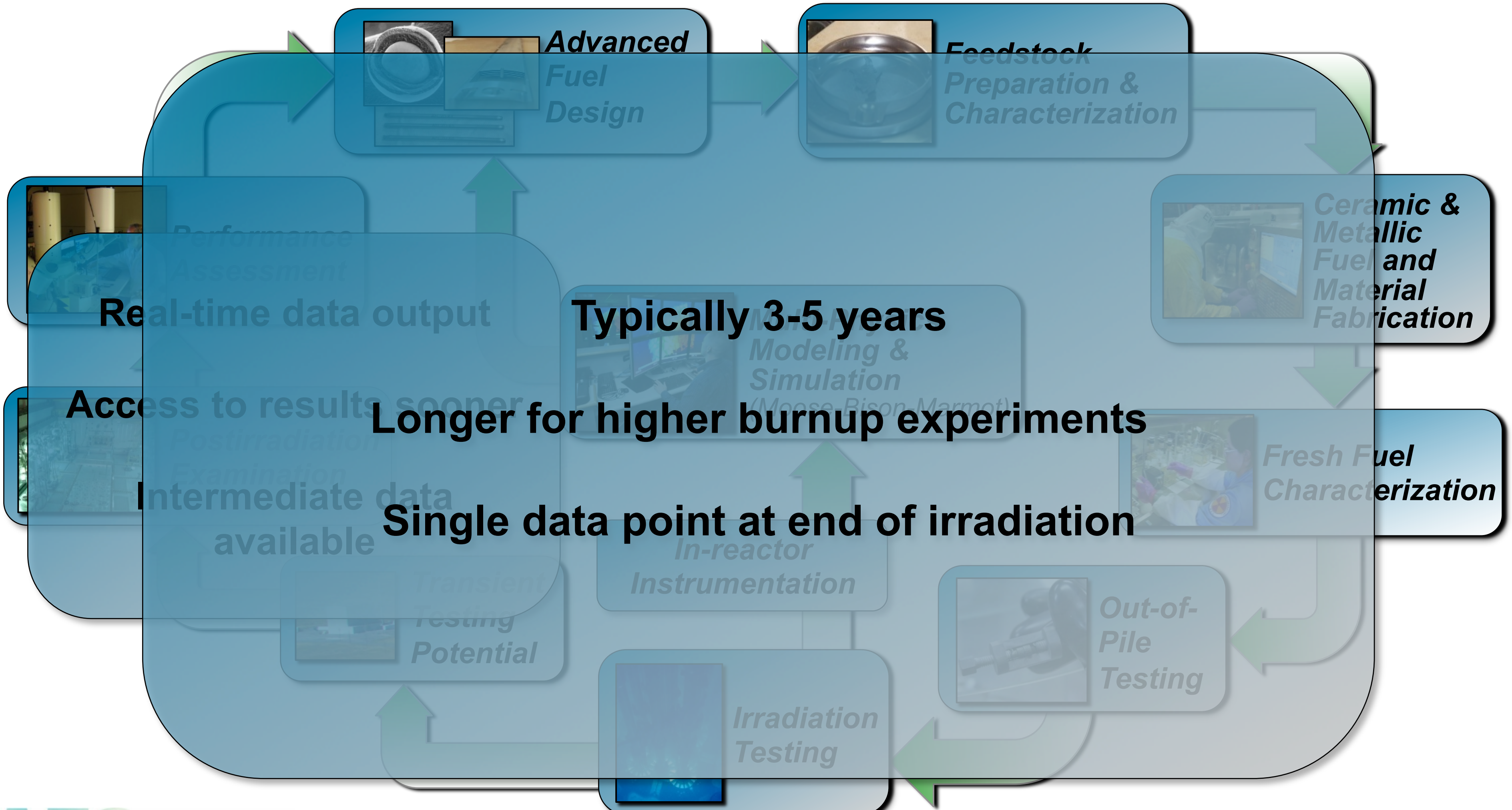
FCRD Advanced Fuels Campaign

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



Fuel Development Life Cycle



Goals

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

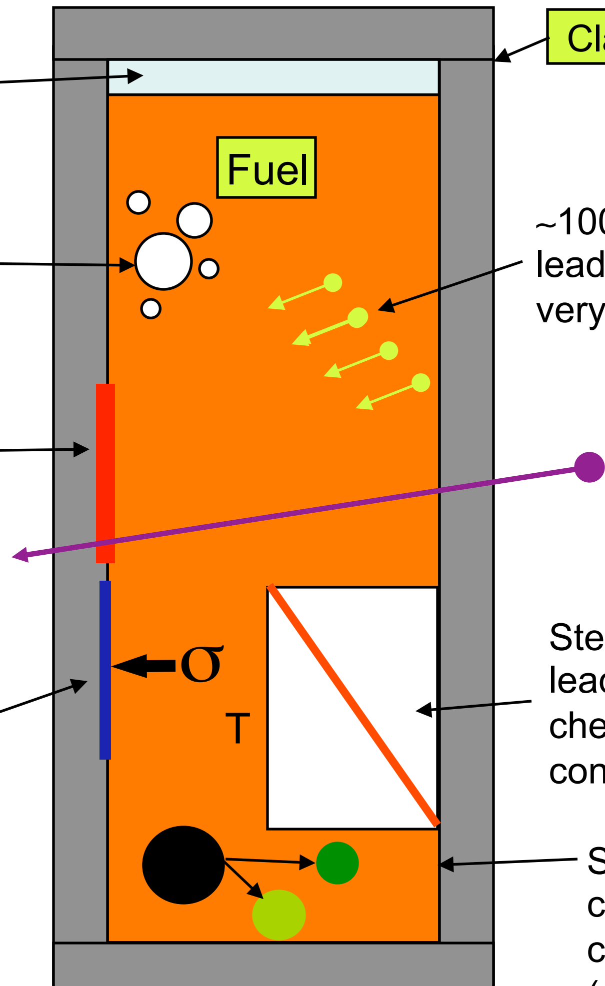
In-reactor Instrumentation Goals

- "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

Cladding: stainless steel or Zircaloy

Gas pressurization of cladding tube



Fission gas bubbles (Xe, Kr) cause fuel swelling

~100 MeV heavy fission fragments lead to very high defect densities, very fast diffusion

Fuel-cladding chemical interaction results from reaction between fuel and fission products

Neutrons cause cladding damage

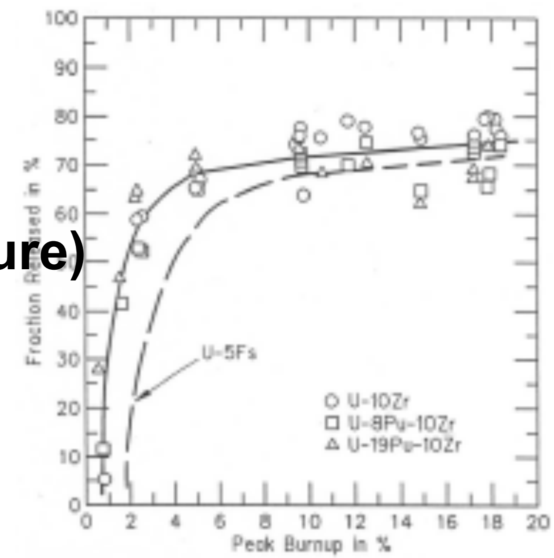
Fuel-cladding mechanical interaction results from fuel swelling

Steep temperature gradient can lead to large difference in chemical potential and drive constituent migration

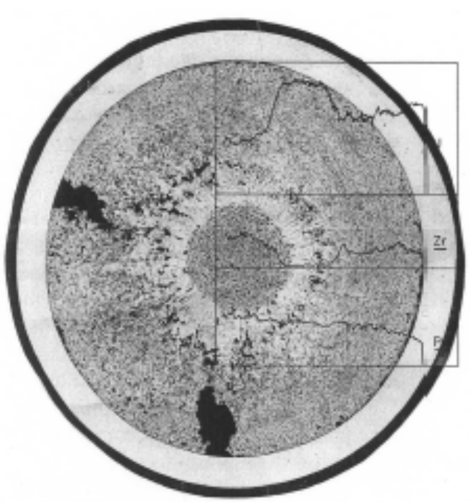
Solid fission products cause fuel swelling, change in composition (oxygen potential in $TRUO_x$)

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



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

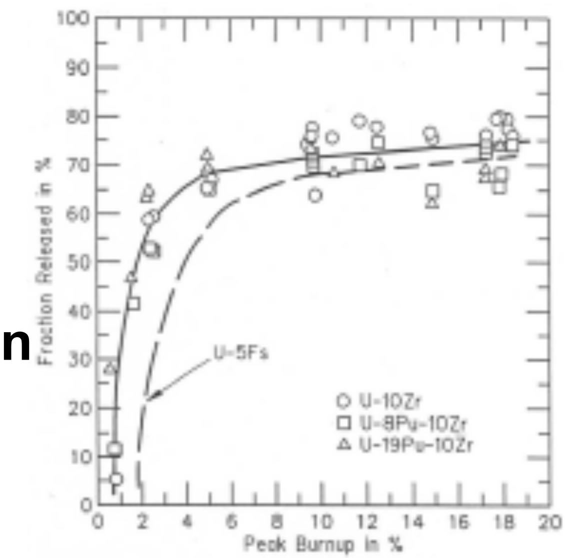


Transverse metallographic section from the high temperature region of a U-19Pu-10Zr element at 3 at.% burnup with superimposed microprobe scans, showing zone formation, cracking and Zr-U redistribution.

G.L Hofman and L. C. Walters, "Metallic Fast Reactor Fuels," Materials Science and Technology Vol. 10A, 1994.

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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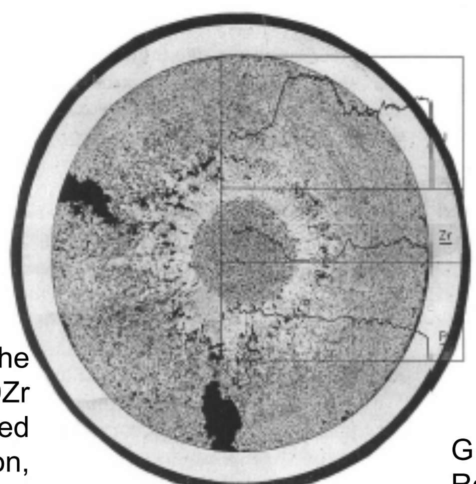

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Types of Irradiation Experiments

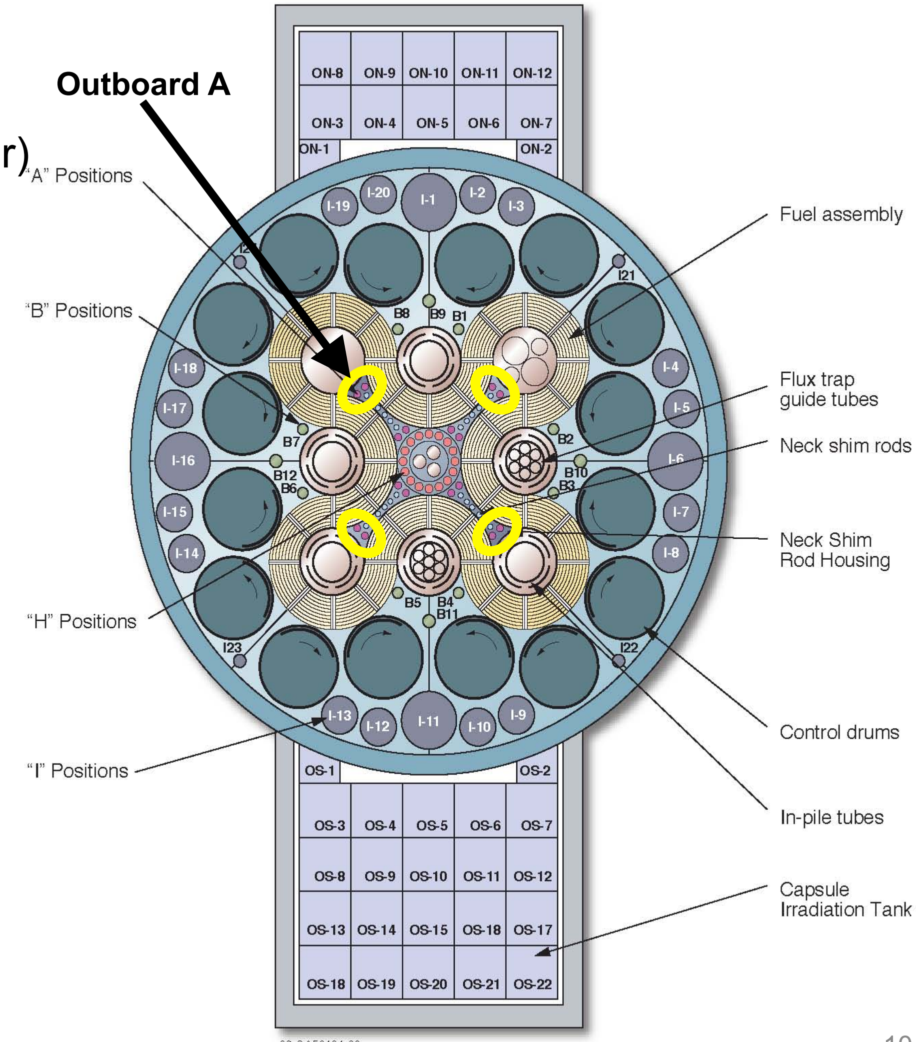
- **Steady State**
  - Simulate normal operating conditions
  - Supports long-term irradiation for high burnup demonstration (~1-5 years)
- **Transient**
  - Simulate accident conditions
  - Short experiments (~ms-minutes)
  - Fuel disruption and failure common
- **Static (drop-in) capsule**
  - simplest 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

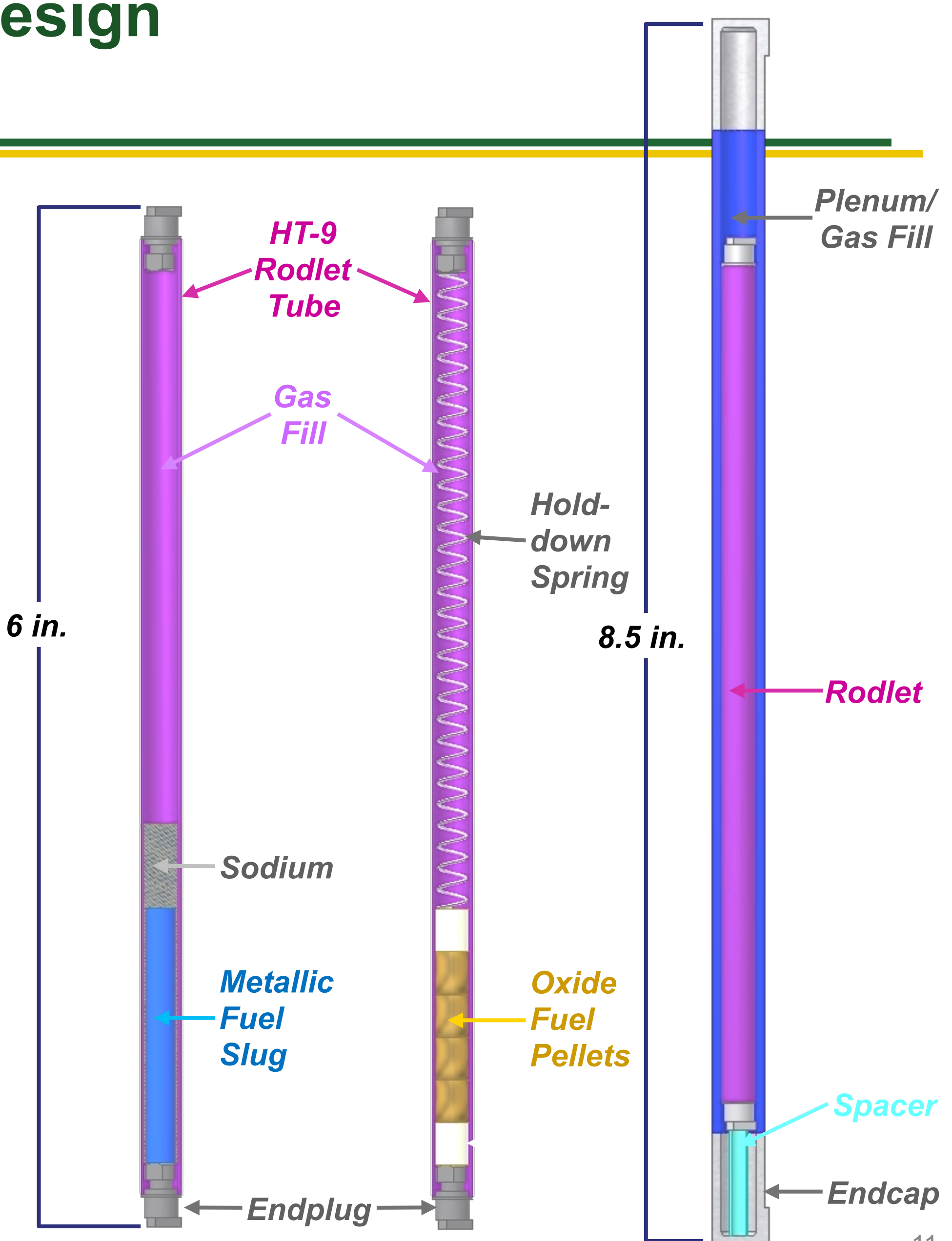
AFC Irradiation Experiments in ATR

- **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)



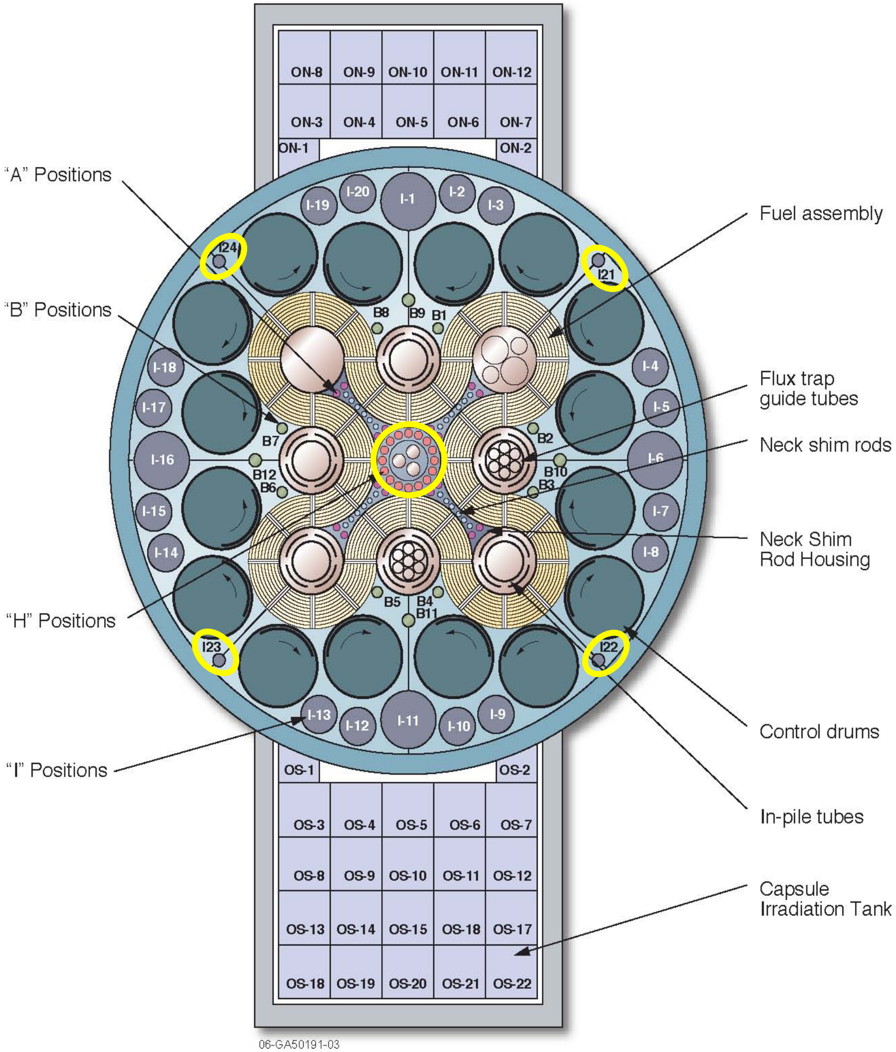
AFC-OA Design

- **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**



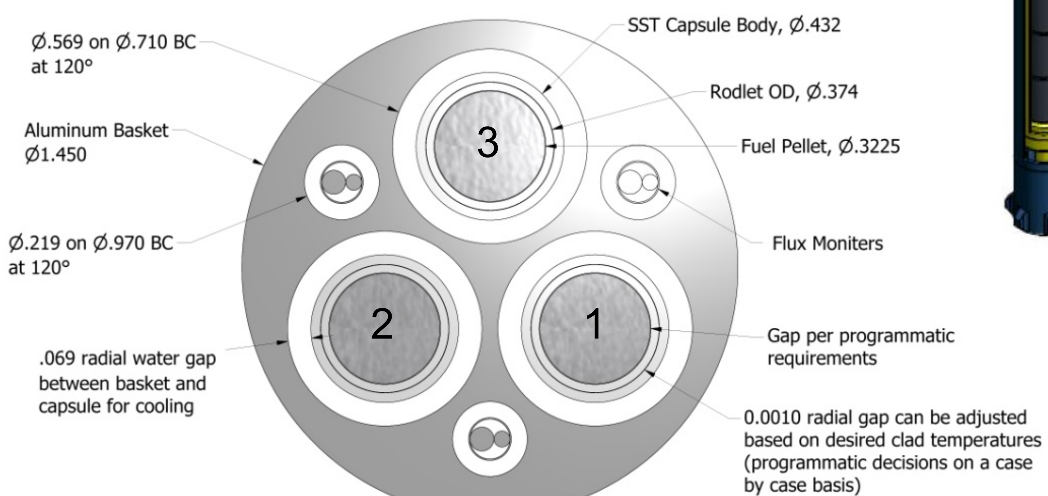
ATF Irradiation Experiments in ATR

- **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

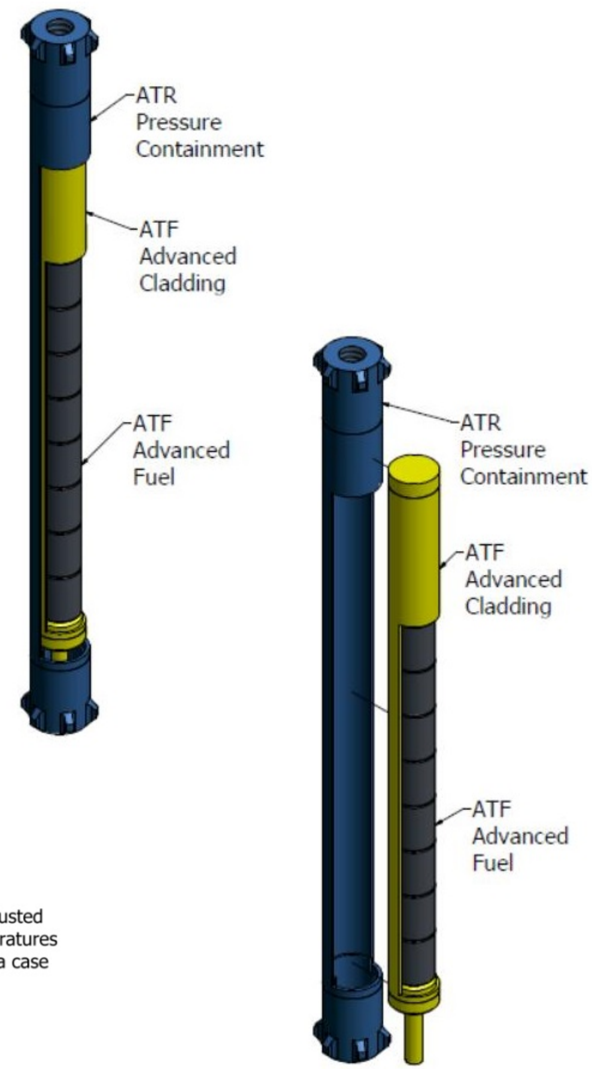


ATF-1 Design

- 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



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

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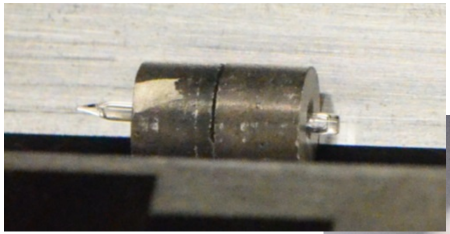
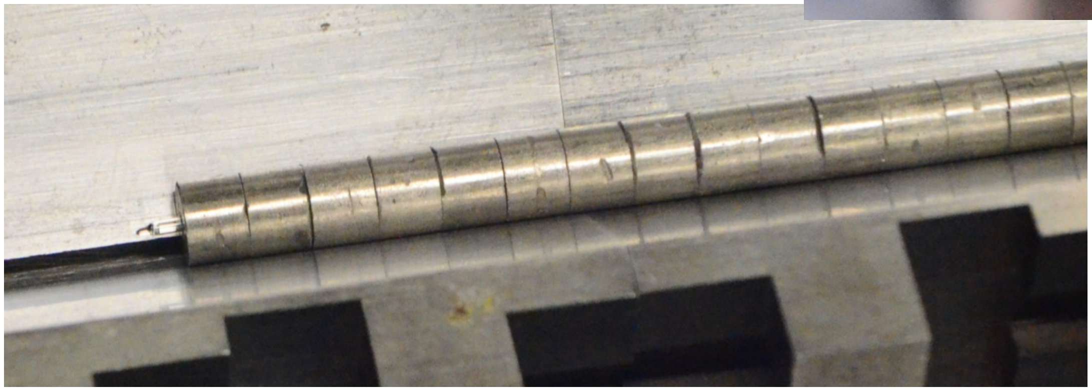
Current Instrumentation

- **Melt Wires**
  - ATF-1
  - inserted inside dU insulator pellets
- **Flux Monitors**
  - ATF-1 basket
- **SiC Temperature Monitors**
  - planned use in future ATF-1 experiments





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ATF Loop Planned Instrumentation

Sensor Qualification Test (SQT)

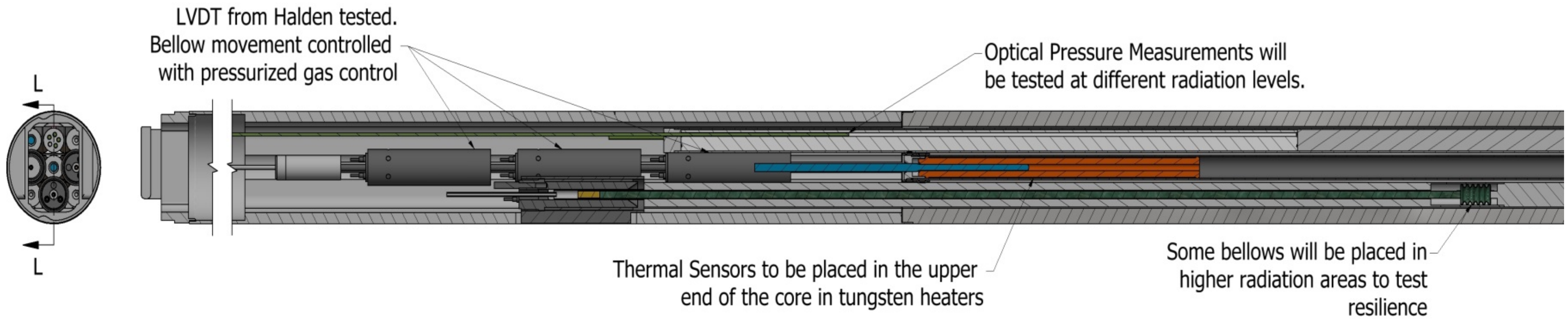
Parameter	Sensor	Source
Fuel Temperature	High Temperature Irradiation Resistant-Thermocouple (HTIR-TC)	INL
Fuel Temperature	Ultrasonic Thermometer	INL
Temperature	Thermoacoustic Sensor (TAC)	INL
Fuel Thermal Conductivity/ Temperature	Transient Hot Wire Method-Needle Probe	INL
Fast and Thermal Neutron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

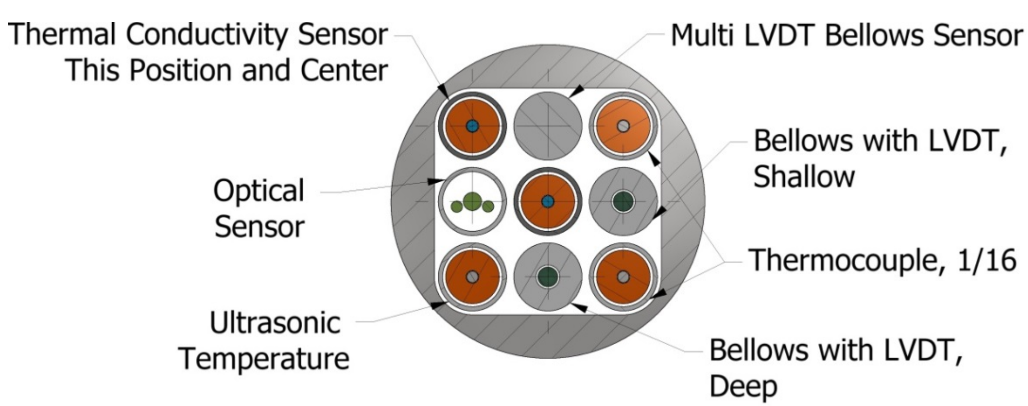
Fuel Test (Planned)

Parameter	Sensor	Source
Fuel Temperature	HTIR-TC	INL
Gas Pressure	LVDT/ Bellows	Halden
Fuel Elongation	LVDT	Halden
Cladding Elongation	LVDT	Halden

SQT Instrumentation (Top Tier)

- **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





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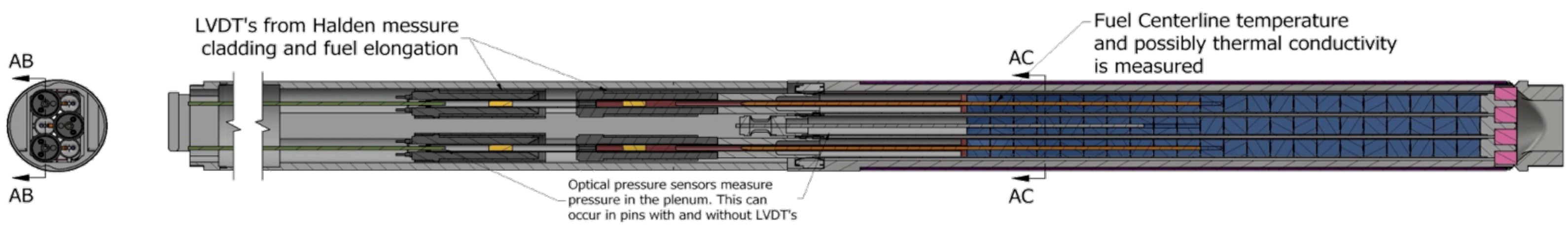
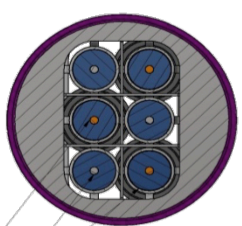
ATF-2 Instrumentation (Top Tier)

- **Conservative sensor selection:**
  - Sensors with prior irradiation demonstration preferred
  - Additional sensors tested in ATR SQT will be evaluated for ATF-2





Fuel Centerline Temperature to be measured via thermocouple type or ultrasonic type measurement. Thermal conductivity may also be measured in rodlets without LVDT's.

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

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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

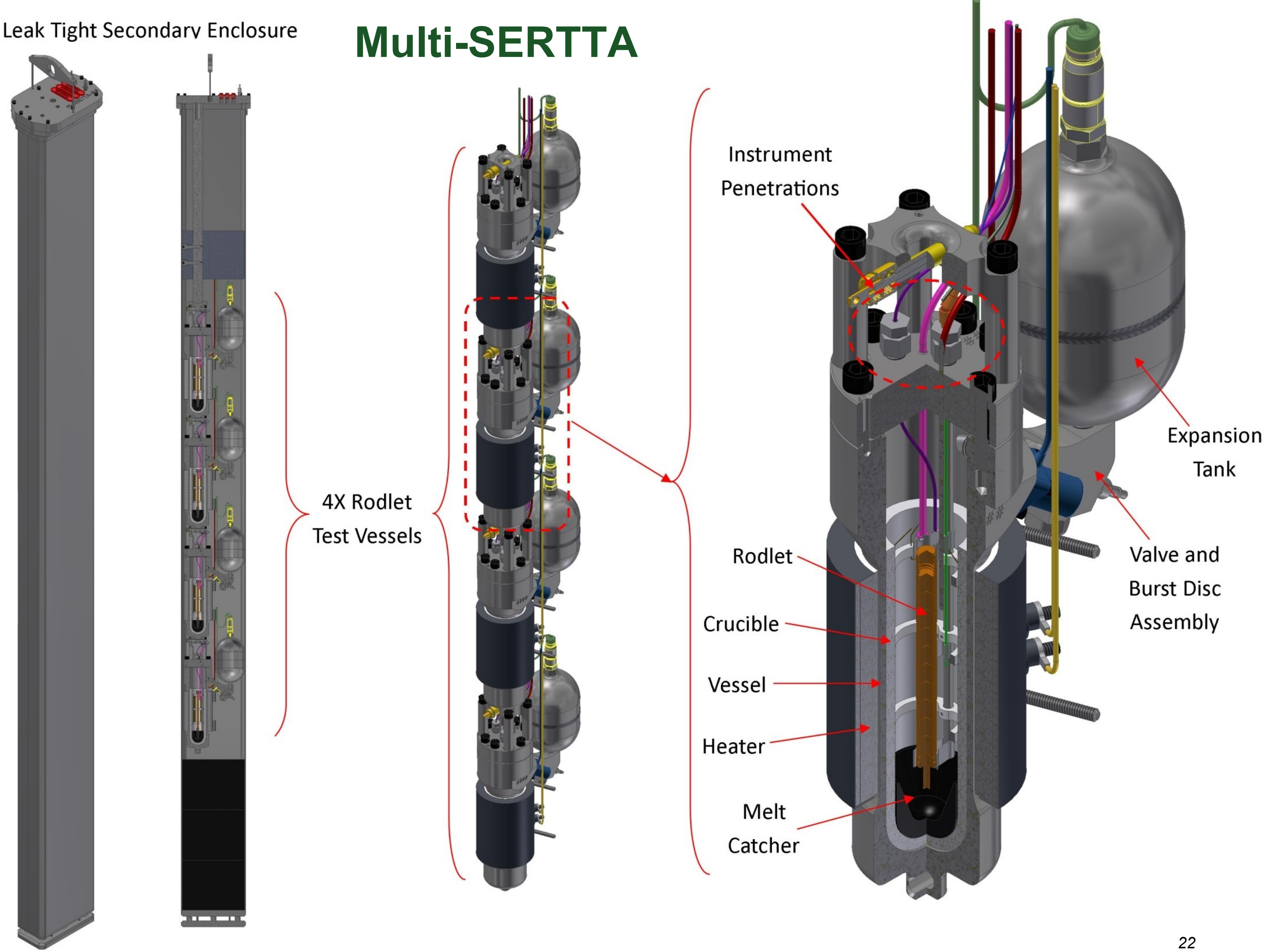
- **Advanced Fast-Neutron Detector Goals**
  - Improved fast-neutron detector efficiency
  - Improved gamma-ray insensitivity/ rejection
  - Increased throughput
  - Improved high-end linearity
  - Detector simplification (e.g., elimination of need for external high-voltage power supplies)

Reference: Fink, C. L., Boyar, R. E., Eichholz, J. J., and DeVolpi, A., "Improvement in TREAT Hodoscope Fuel-Motion Capabilities," CONF-820406--3, Argonne National Laboratory, Argonne, Ill. (1982)

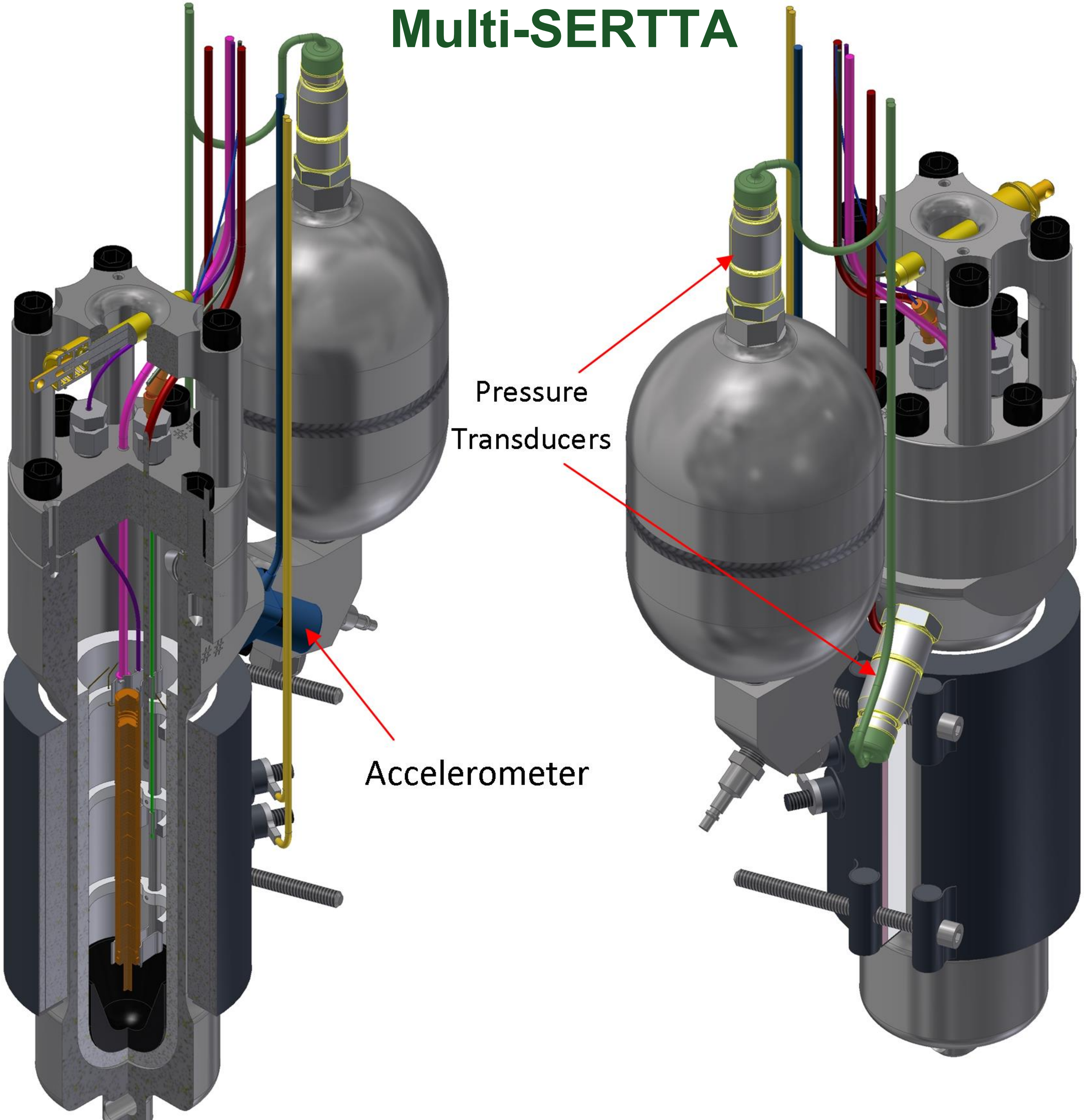
Advanced Fast-Neutron Detector

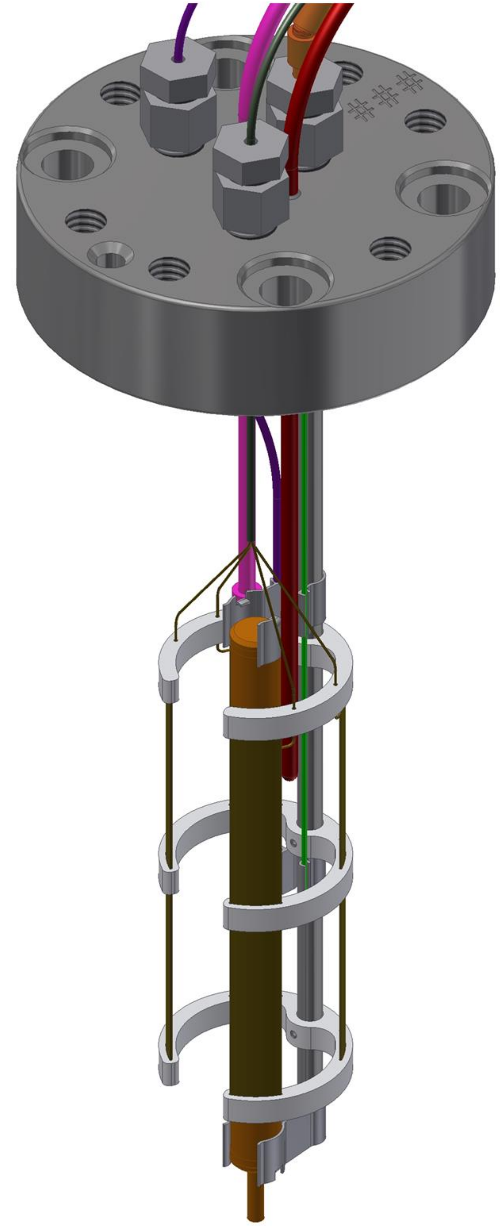
- **Desired Functional Capabilities**
  - Fission-spectrum neutron intrinsic detection efficiency: 1% or greater
  - Fission-spectrum photon intrinsic detection efficiency: 0.01% or less
  - High-rate capability: 500,000 neutron events per second or greater
  - Linearity: linear response of 4 decades 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.)

Multi-SERTTA



Multi-SERTTA





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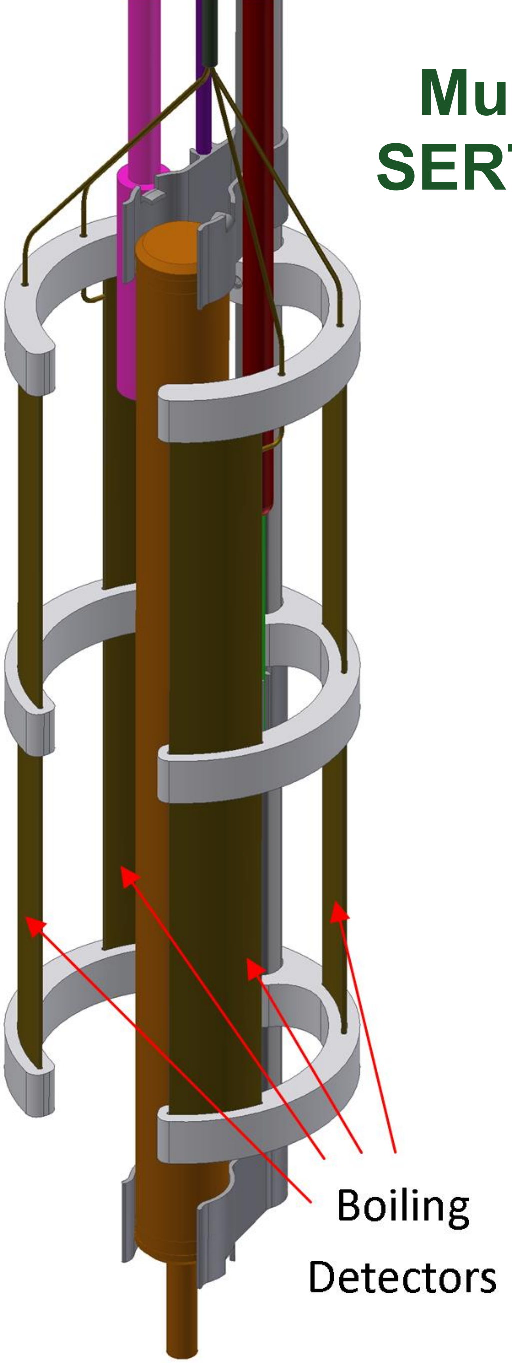

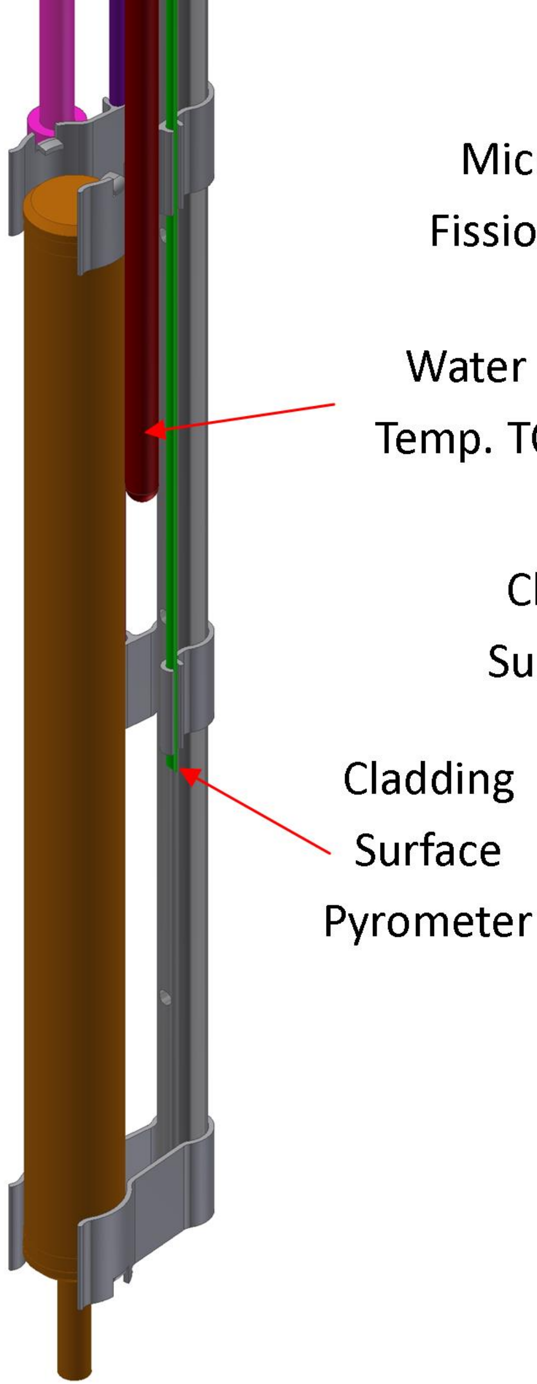

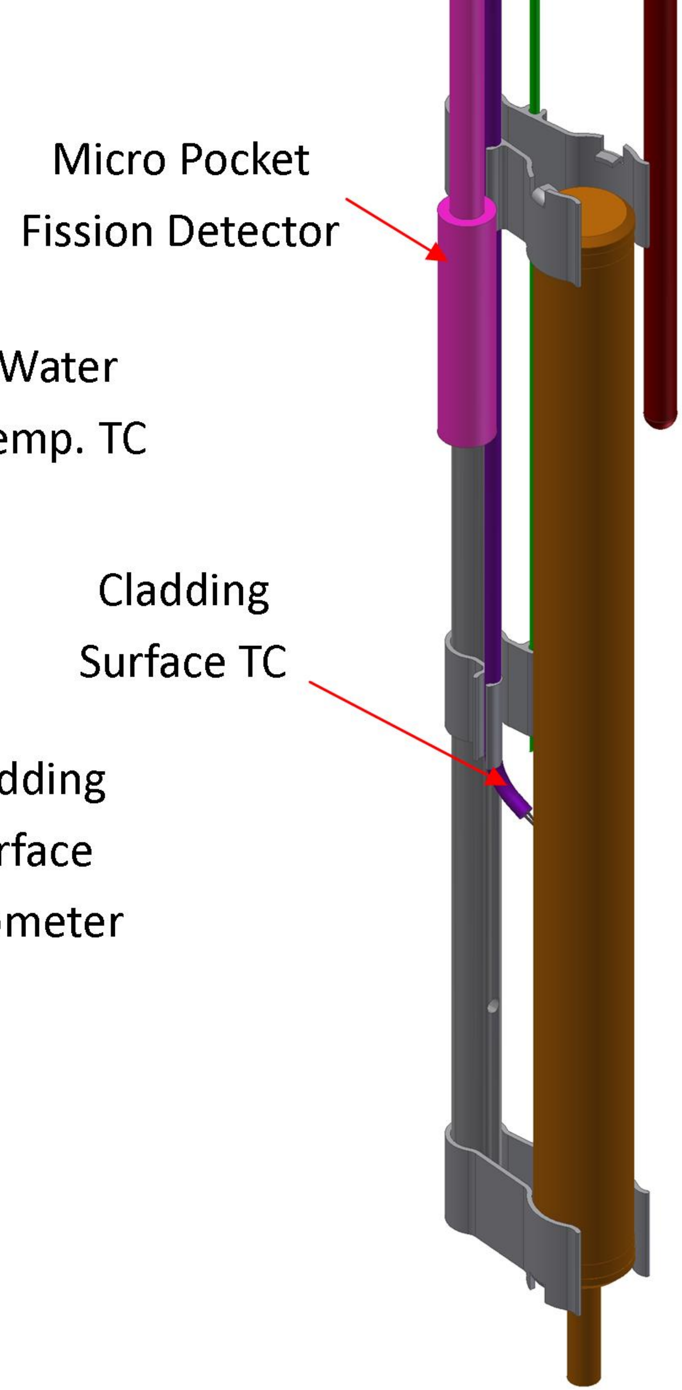

Summary

- **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
- **SQT and ATF-2 Loop Experiment and Design**
  - Kristine Barrett
  - Brian Durtschi
- **SQT and ATF-2 Loop Instrumentation**
  - Troy Unruh
  - Josh Daw
  - Jim Smith
- **TREAT Experiment Vehicles**
  - Nic Woolstenhulme
- **TREAT Ex-Core Fast Neutron Monitoring**
  - David Chichester