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Fuel Cycle Research and Development

Advanced Fuels Campaign In-reactor Instrumentation Overview

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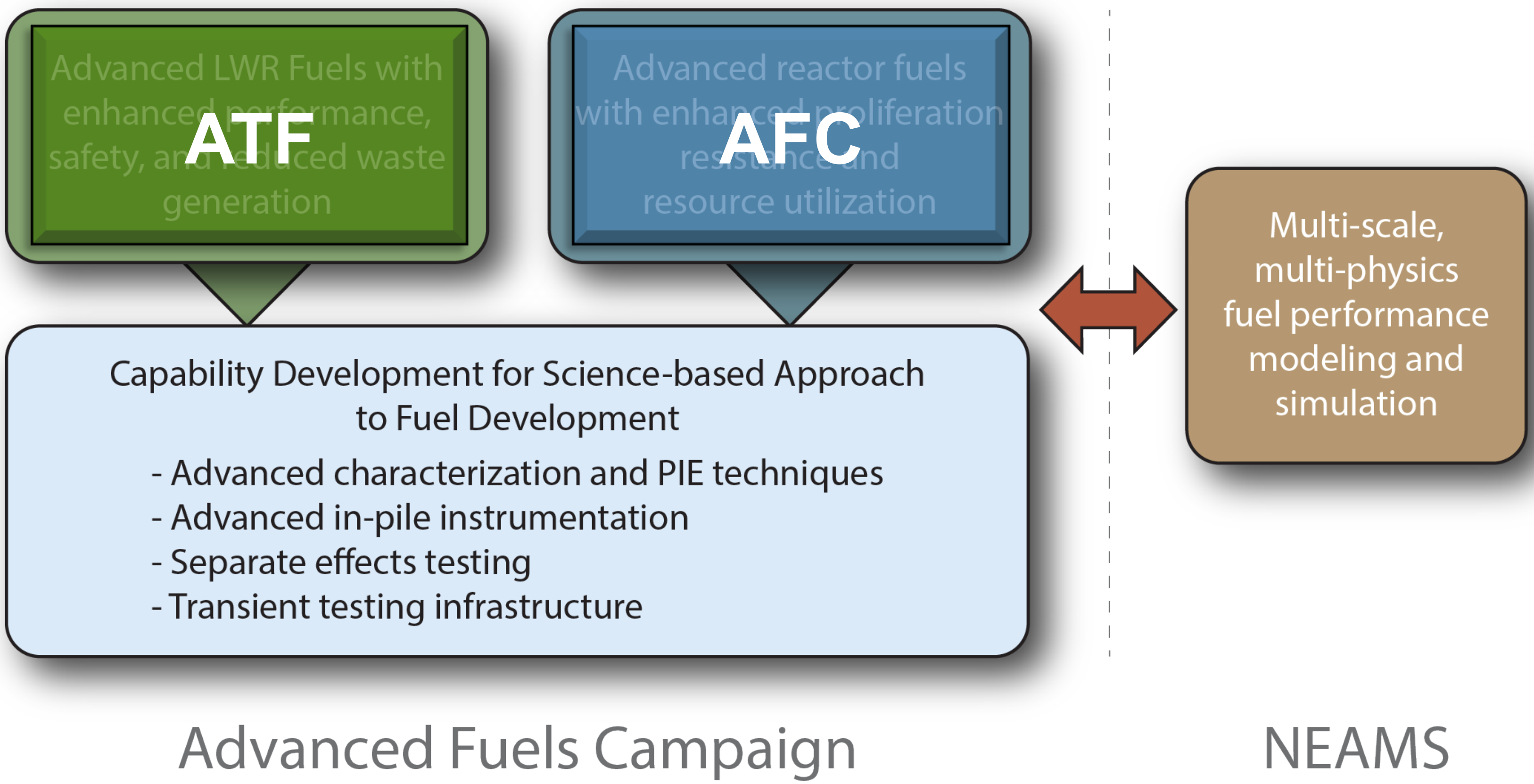
Advanced Sensors and Instrumentation
2016 NE I&C Review Webinar

Advanced Fuels Campaign

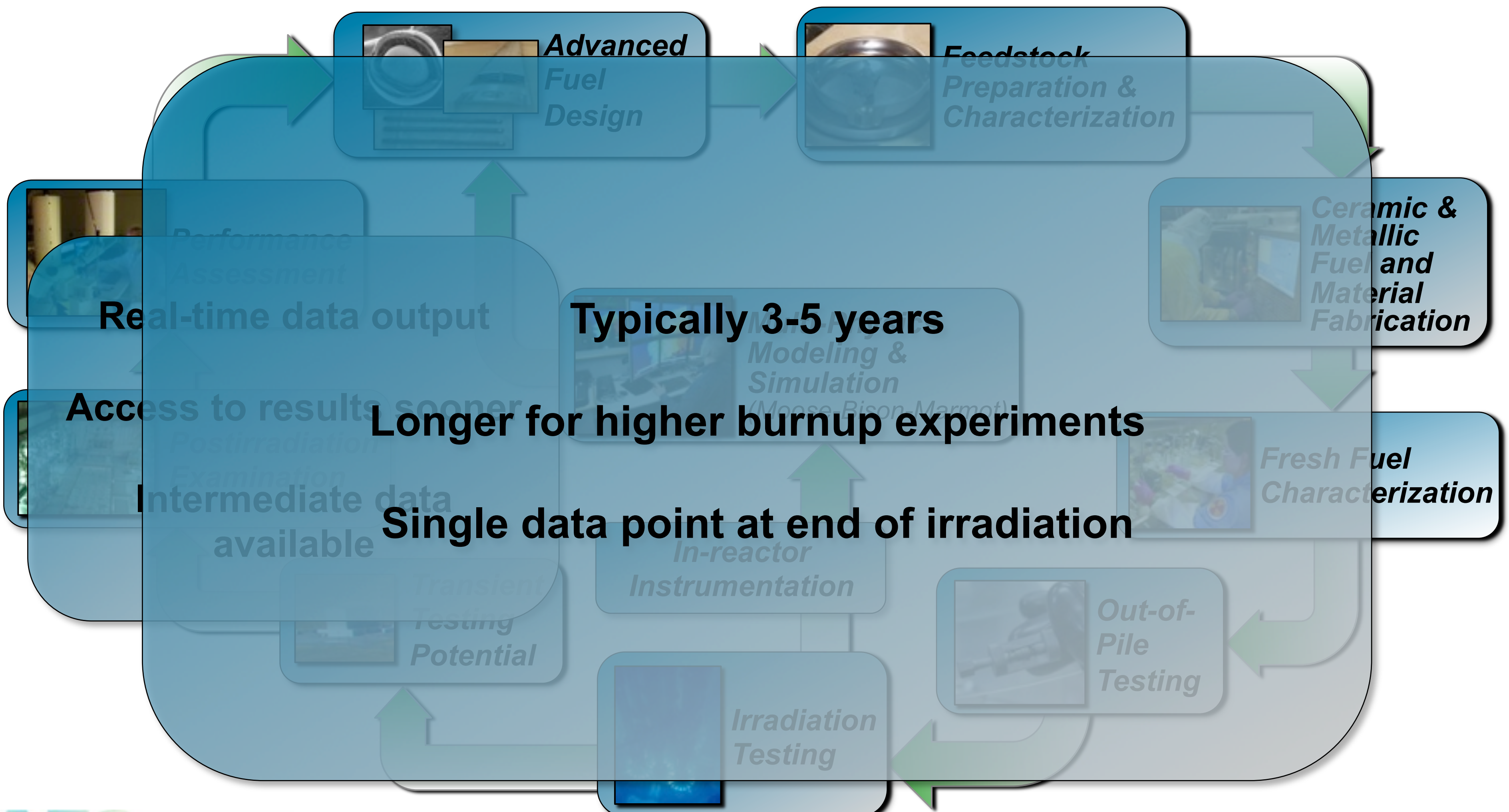
INL/MIS-15-37102

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



Typically 3-5 years

Longer for higher burnup experiments

Single data point at end of irradiation

Real-time data output

Access to results sooner

Intermediate data available

In-Reactor Test 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

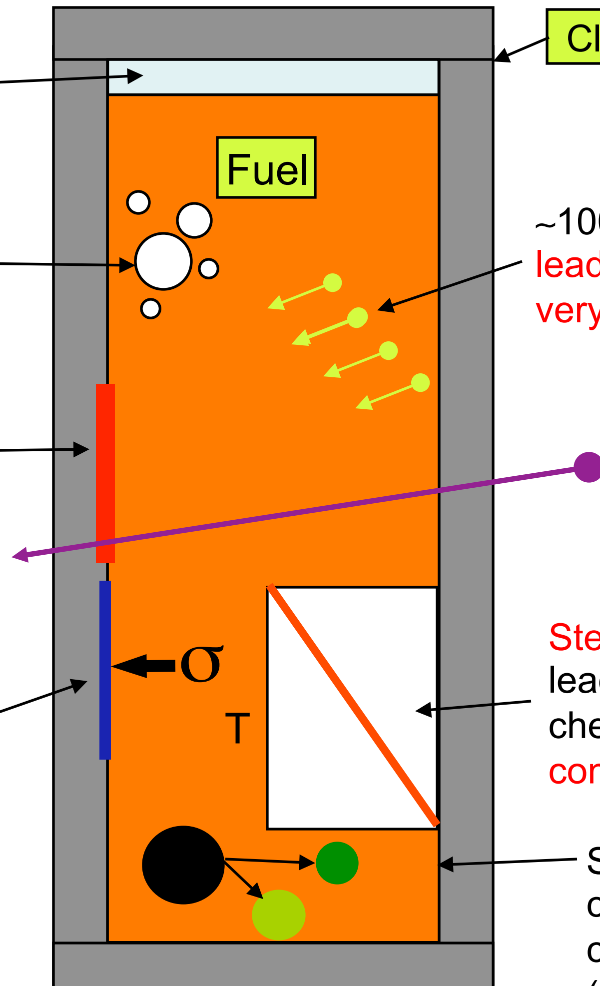
Cladding: stainless steel or Zircaloy

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

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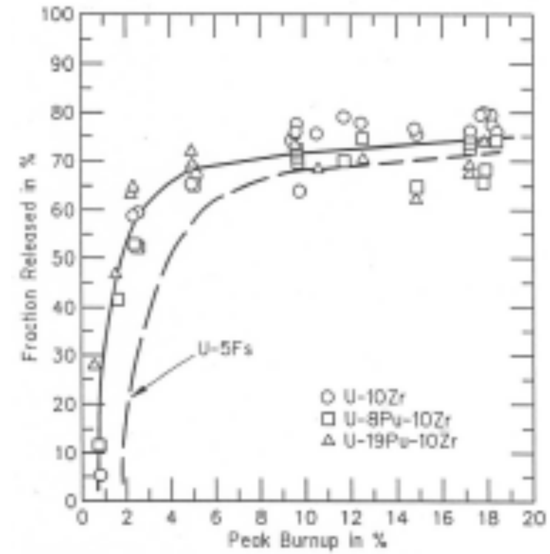
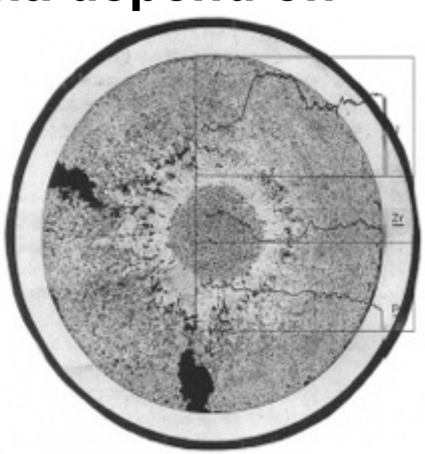
- **Dimensional changes**
  - axial growth
  - radial swelling
- **Fission gas production and release**
  - In-pin pressure
- **Fuel restructuring (zone formation)**
- **Constituent redistribution**
- **Fuel cladding chemical/mechanical interaction**
- **Performance phenomena depend on**
  - composition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

In-Situ Instrumentation Considerations

Experiment Types

- **Static Capsules**
  - simplest design
  - most cost-effective
  - accommodate wireless instruments
- **Instrumented Lead**
  - extensive design and handling
  - accommodate wired instruments
- **Loop Experiments**
  - coolant environment controlled independent of ATR coolant
  - accommodate wireless or wired instruments

Instrument Types

- **Wired**
  - only in instrumented leads and loops
  - handling concerns
- **Wireless**
  - applicable to any experiment type

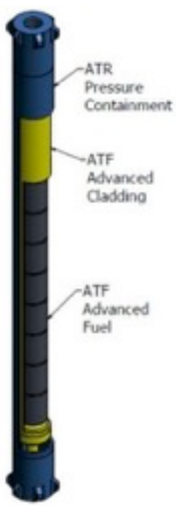
Measurement Types

- **State Point**
  - end of irradiation
  - supplemental data, but limited
- **Real Time**
  - provides more data
  - detailed history of long experiments

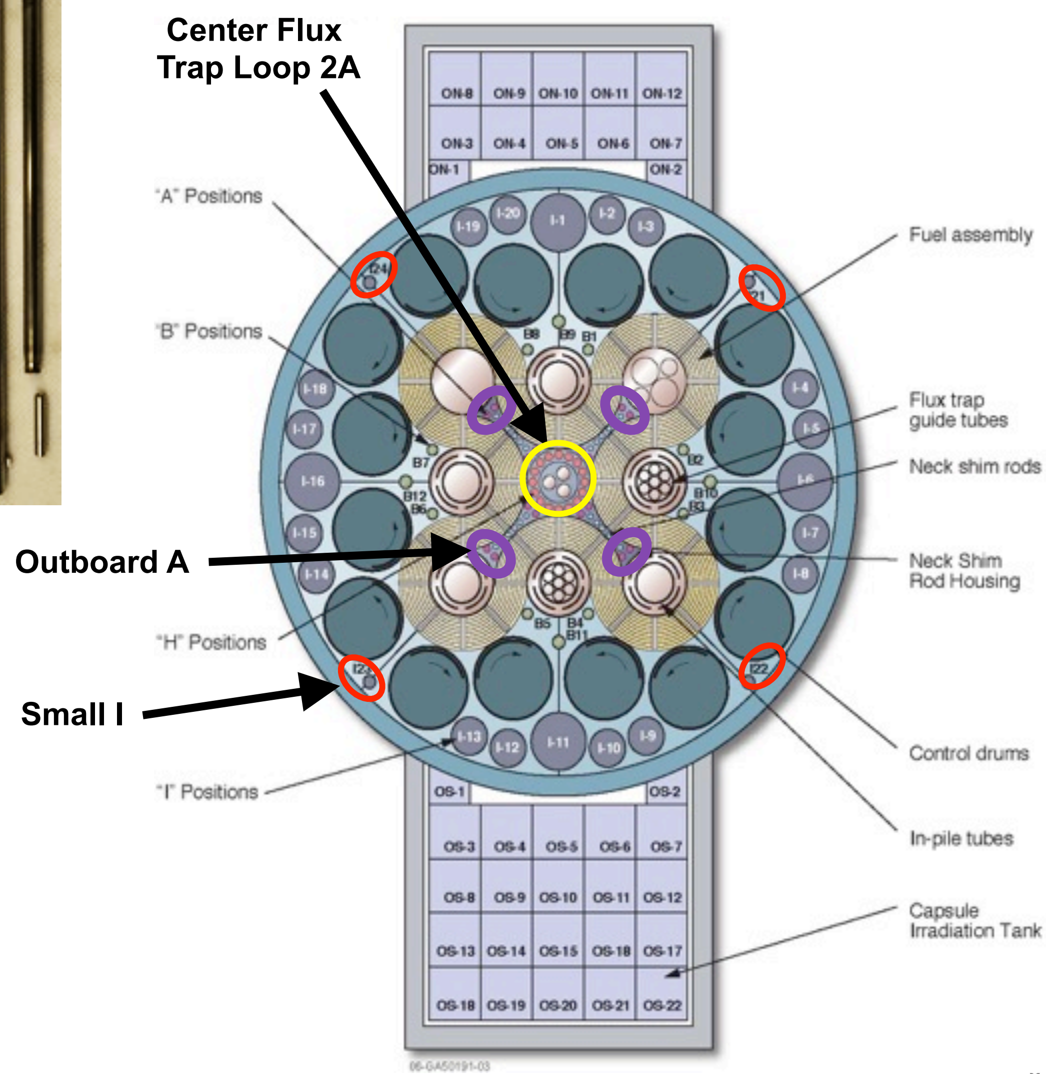
In-reactor Instrumentation Constraints

- **Small diameter experiments**
  - Irradiation experiments are usually representative of prototypic reactor fuel pin dimensions ~5.8-9.5 mm (0.230-0.374 in.) OD
- **Small in-reactor experiment locations**
  - Typical ATR experiment positions 15-38 mm (0.62-1.5 in.) ID
- **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**
  - ATR loops are limited to 24 leads (5-6 instrumented rods per test train)
- **Total cost (fixed program budgets)**
  - Experiments with instrumented leads are more expensive to design, build, and operate

AFC Irradiation Experiments in ATR



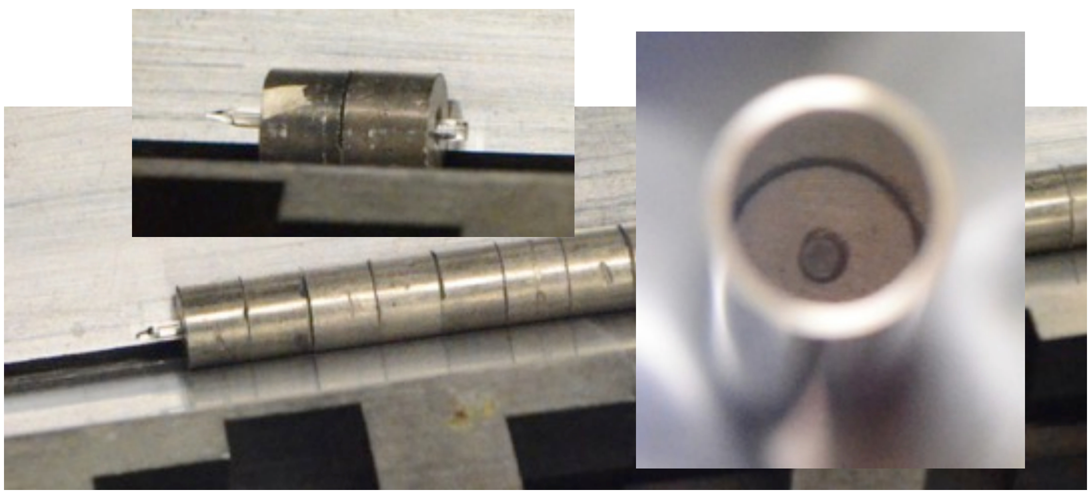
- **Drop-In Capsule**
  - ***Outboard A Positions***
  - Metallic transmutation fuel experiments
  - Cd-shrouded baskets filter thermal flux
  - Rodlet inside SS capsule (safety barrier)
  - Gas gap provides prototypic cladding temperature
  - **Small I positions**
  - ATF-1 feasibility test
  - Rodlets in individual capsules (axial stack of 5)
- **Instrumented Lead**
  - ***CFT Water Loop 2A***
  - ATF-2 demonstration test
  - Prototypic PWR conditions
  - Test Train w/Instrumented leads
  - A-priori Sensor Qualification Test (SQT)



Current Irradiation Test Instrumentation

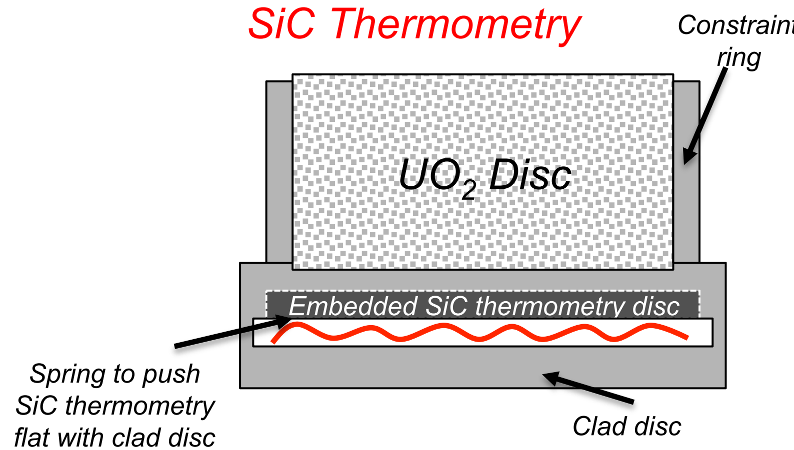
- **Melt Wires**
  - ATF-1
  - inserted inside dU insulator pellets
- **Flux Monitors**
  - ATF-1 basket
- **SiC Temperature Monitors**
  - ATF-1 and ATF-2 experiments

In-basket Flux Wires



In-Pellet Melt Wires

SiC Thermometry



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ATF Loop Planned Instrumentation

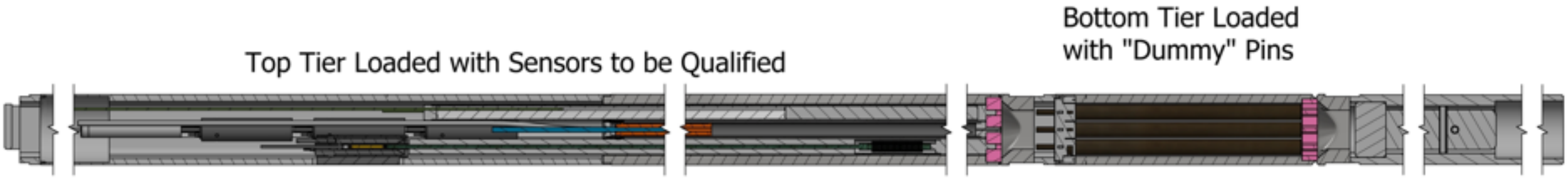
SQ Test Lead Arrangement				
Top Tier				
Lead Sheath Diameter (inches)	0.039	0.063	0.125	
Multiple LVDT Single Bellows	6 (2 Per LVDT)	1		
LVDT Single Bellows	2 (2 Per LVDT)	1		
LVDT Single Bellows	2 (2 Per LVDT)	1		
Optical Pressure		5		
HTIR TC		2		
Type N TC		1		
Type N TC with TAC		1		
Ultrasonic Multipoint Temp		1		
MPFD Neutron Detector			1	
Lead Size	0.039	0.063	0.125	Total
Total Leads	10	13	1	24

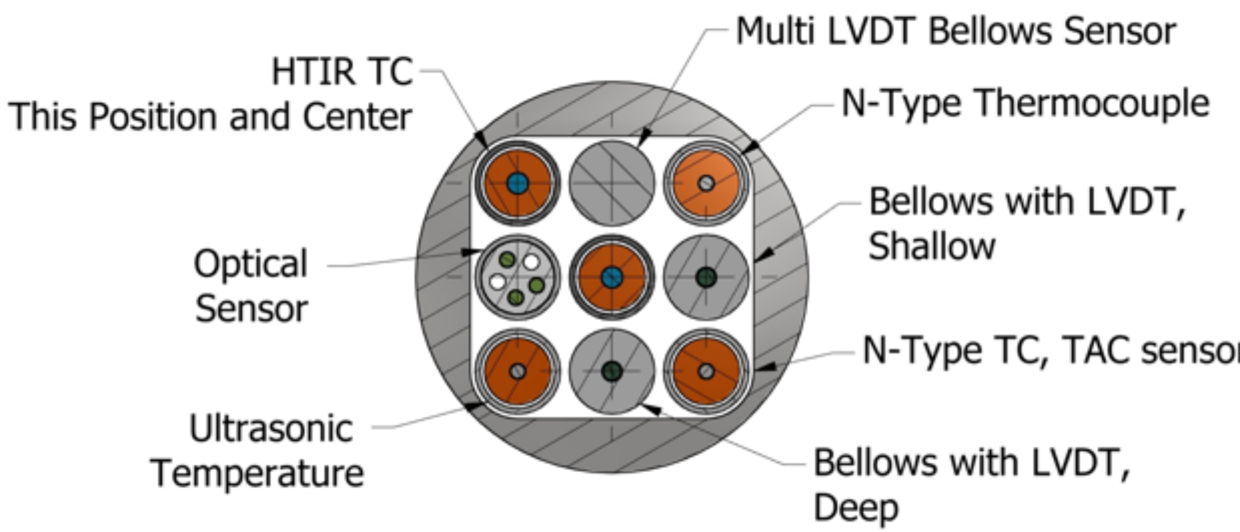
Fuel Test (Planned)

Parameter	Sensor	Source
Fuel Temperature	HTIR-TC	INL
Gas Pressure	LVDT/ Bellows	Halden
Fuel Elongation	LVDT	Halden
Cladding Elongation	LVDT	Halden
Coolant Water Electro-chemical Potential	ECP	Halden
Neutron Flux	Flux Wire	INL
Coolant Water Temp – Core Region	TC	INL

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

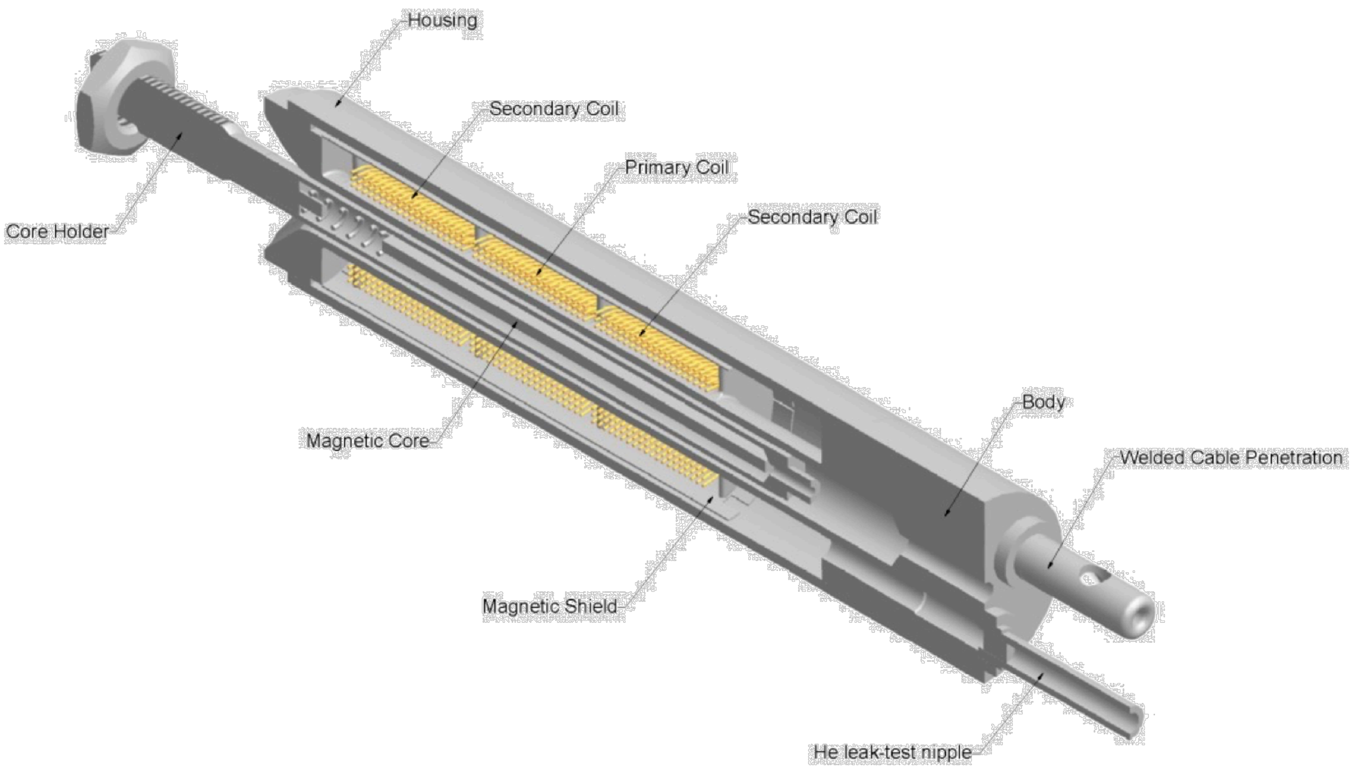




Flowing Autoclave Test – Mock-up of SQT Prior to ATR Insertion

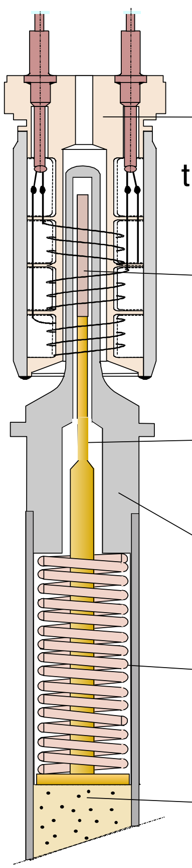
- **Westinghouse Electric Research Laboratory – Churchill, PA**
- **Collaboration with IFE / Halden**
- **Assemble mock-up test train at INL and ship to Westinghouse**
- **ATR / PWR Prototypic Operating Conditions**
- **Evaluate durability of sensors under high flow/water Temp conditions**
- **Examine Chemical Interactions**
  - Crud buildup
  - Clad corrosion
  - Formation of dissolved solids
  - Plating on clad surfaces

Halden LVDT Based Instruments

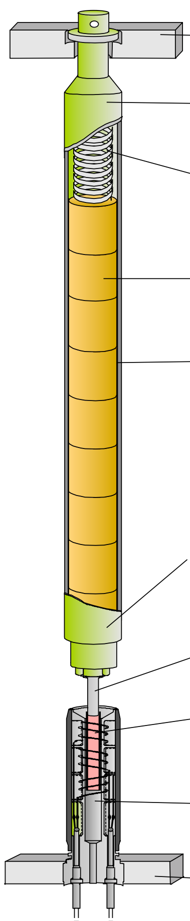


- **Performance and robustness demonstrated over several years and irradiations**
- **Used in test reactors worldwide**
- **Not previously demonstrated in ATR – minor modifications are being implemented for fuel and clad elongation measurements**

Fuel Extensometer: Pellet Stack Growth
Cladding Extensometer: Pin Growth



Fuel Extensometer

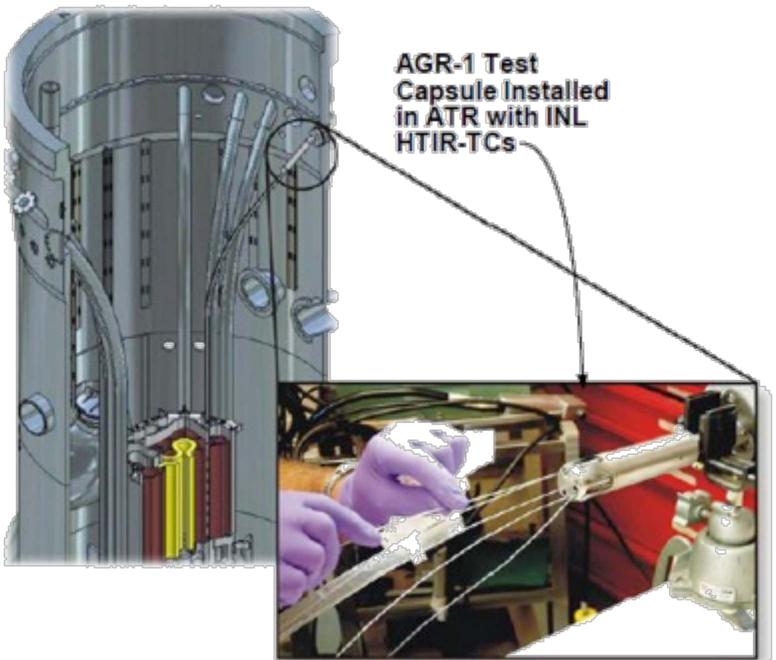


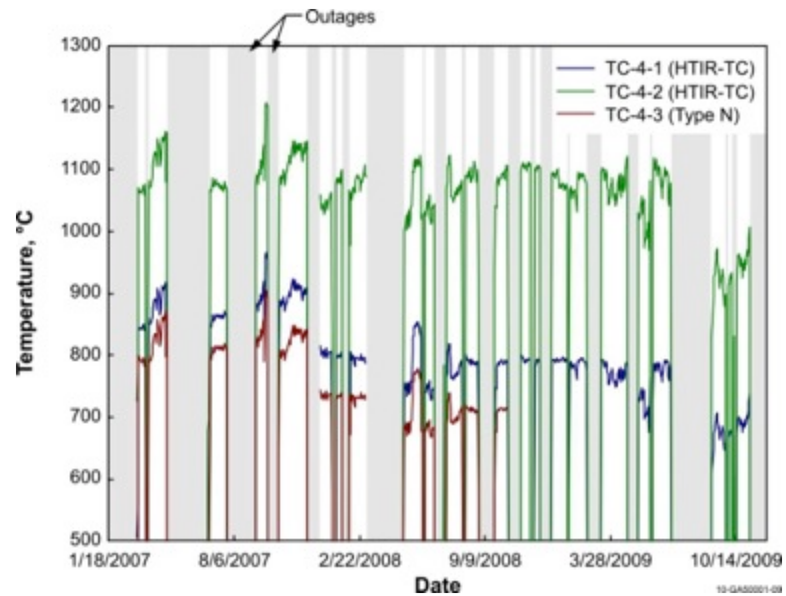
Cladding Extensometer

- **Potential issues to be evaluated:**
  - Irradiation/temperature response of LVDT
  - Water ingress and vibration damage in MIMS cables
  - Sensitivity of LVDT/Core combinations
- **Changes from Halden design for ATR application:**
  - Fuel Extensometer:
    - Type-10 LVDT fits around fuel rod
    - Core placed on end of fuel stack/no pushrod

High-Temperature Irradiation Resistant Thermocouple: Fuel Centerline Temperature

Initial evaluations suggested doped Mo/Nb-1%Zr thermoelements with HfO_2 insulation and Nb1%Zr sheaths most suitable combination for HTIR-TCs.





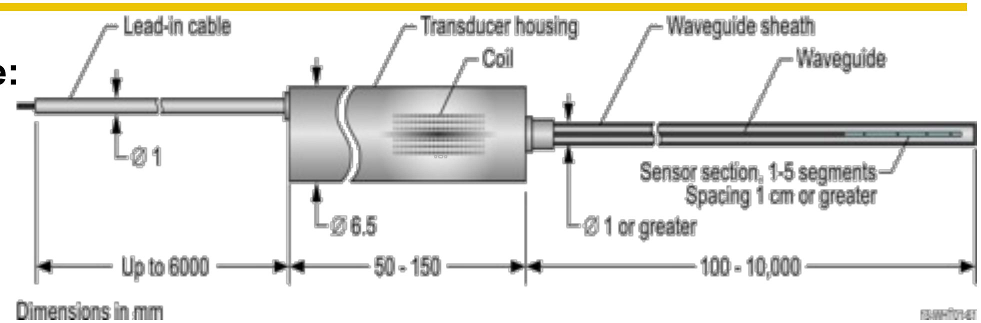
HTIR-TCs performed well throughout AGR-1 irradiations (while commercial TCs failed)

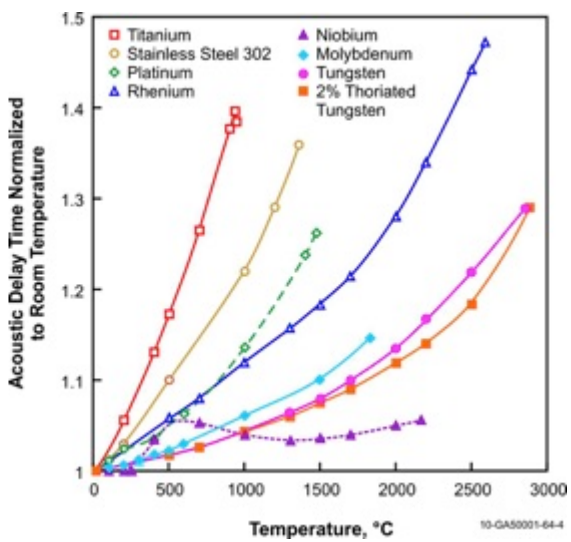
HTIR-TCs patented by BEA and deployed

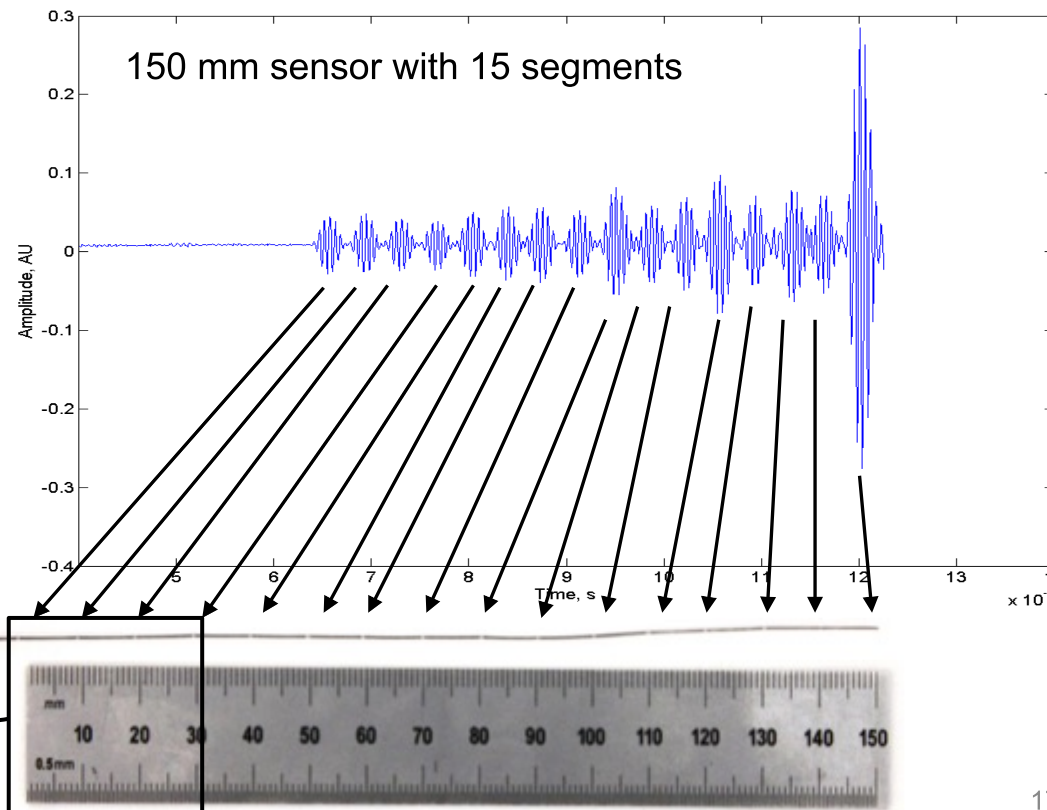
- **Near term development to address existing limitations:**
  - Lack of Nb-1%Zr availability
  - Activation of hafnia and availability of newer insulation materials
  - Current effort to improve HTIR-TC with newer materials (Doped Nb, Yttria)

Ultrasonic Thermometer: Fuel Centerline Temperature

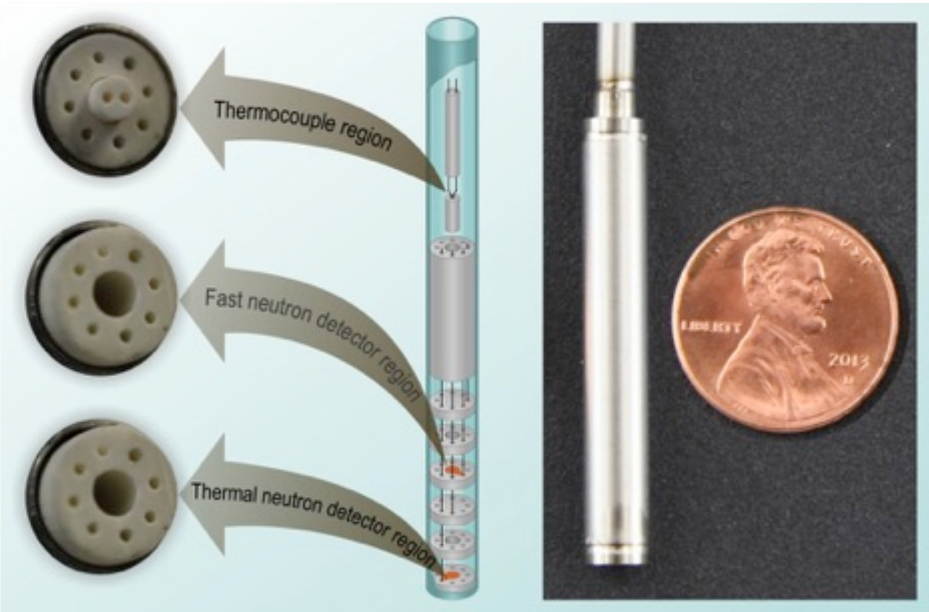
- **Potential improvements over thermocouple:**
  - Very high temperature capability
  - Multi-point measurement
  - Sensor material selectable for environment and temperature range
  - SQT UT may have single segment

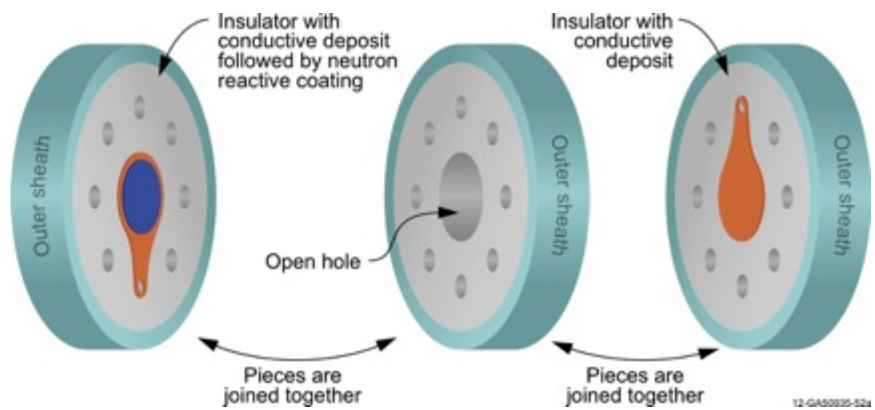






Micro Pocket Fission Detector (MPFD): Environmental Temperature and Neutron Flux

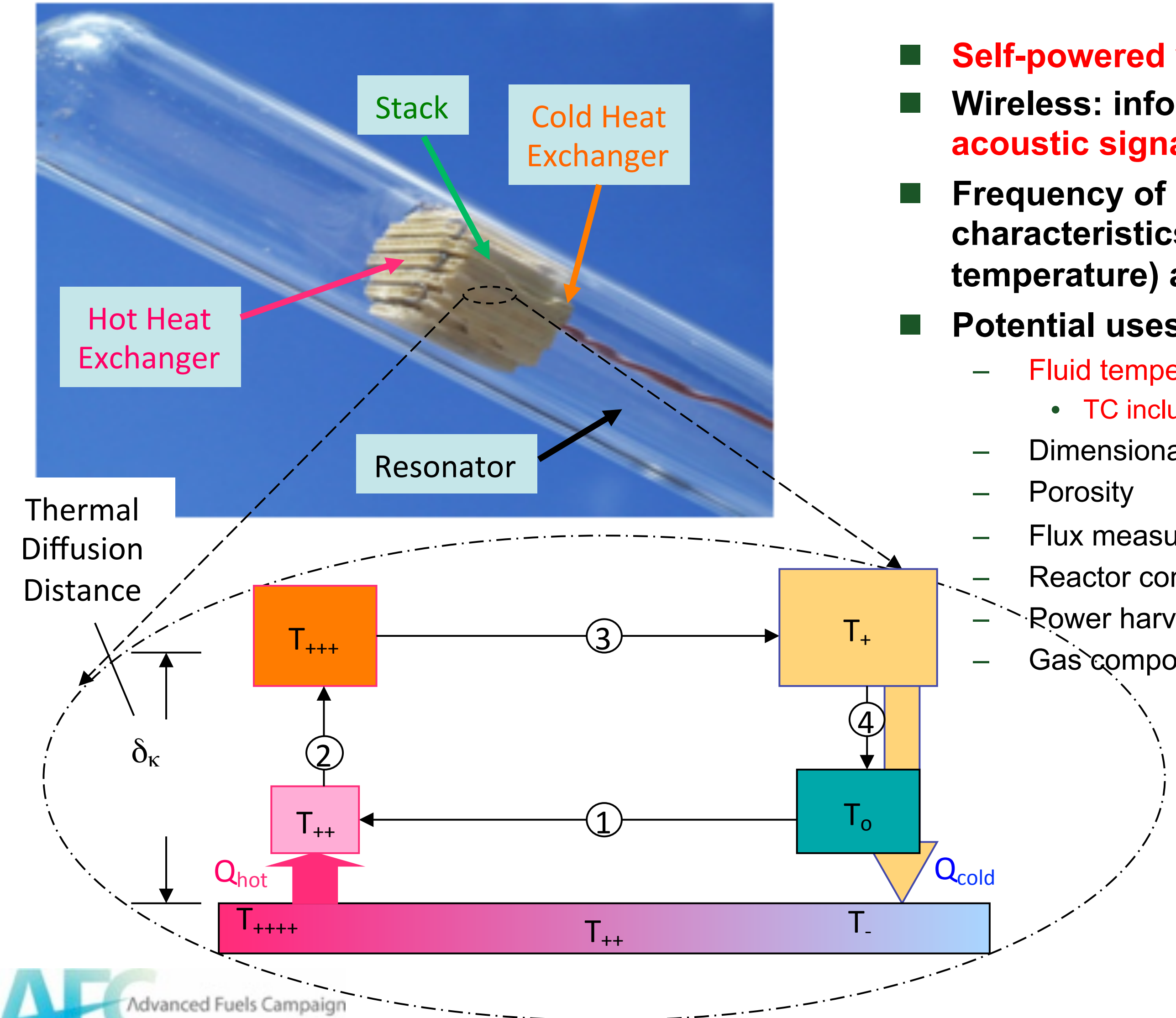




- **Three sensors in a single, compact package:**
  - Thermal neutron detector
  - Fast neutron detector
  - Temperature detector
  - Modular design may allow more chambers

- **MPFDs use parallel plate fission chamber design**
  - Neutron signal not based on full energy deposited
  - Small size
  - Fast response
  - Inherent background radiation discrimination
- **Prototype evaluated in HTTL furnaces and KSU TRIGA reactor**
  - Tested to 500ºC for 1000 hours
  - Tested in a TRIGA at 10^{13} n/cm^2-s
- **Current effort to design for temperatures to 800ºC**

Thermoacoustic (TAC) Sensor: Fluid Temperature

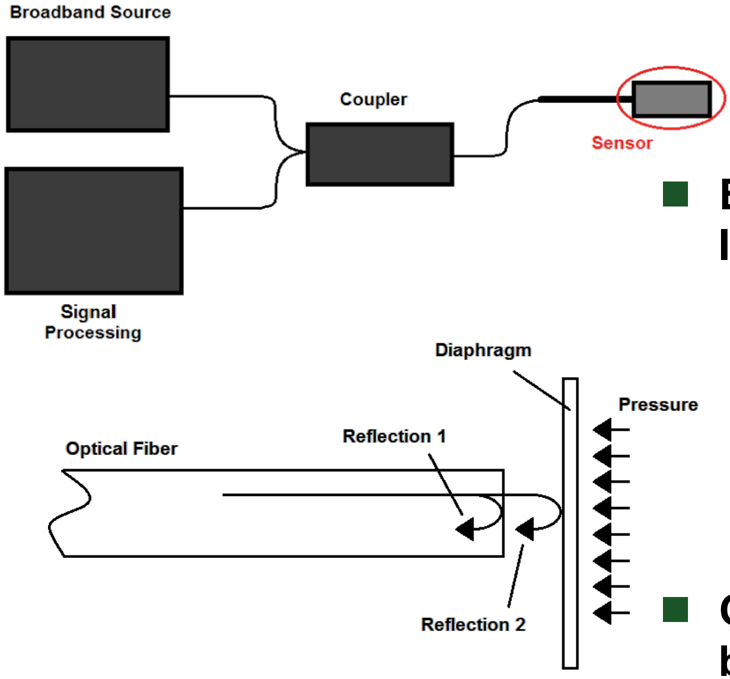


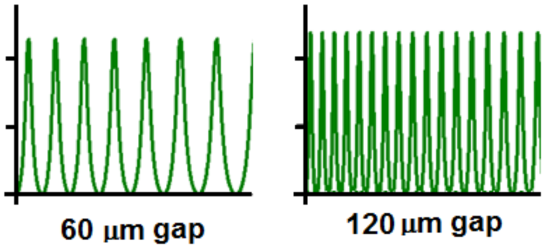
- **Self-powered via temperature differential**
- **Wireless: information carried by pure tone acoustic signal**
- **Frequency of signal function of gas characteristics (composition and temperature) and geometry of resonator**
- **Potential uses:**
  - Fluid temperature measurement
    - TC included for temperature verification
  - Dimensional changes
  - Porosity
  - Flux measurement
  - Reactor condition monitoring
  - Power harvesting
  - Gas composition

Successfully demonstrated at Penn State Breazeale Reactor Sept. 2015

Luna Innovations Fiber Optic Sensor: Pin Gas Pressure

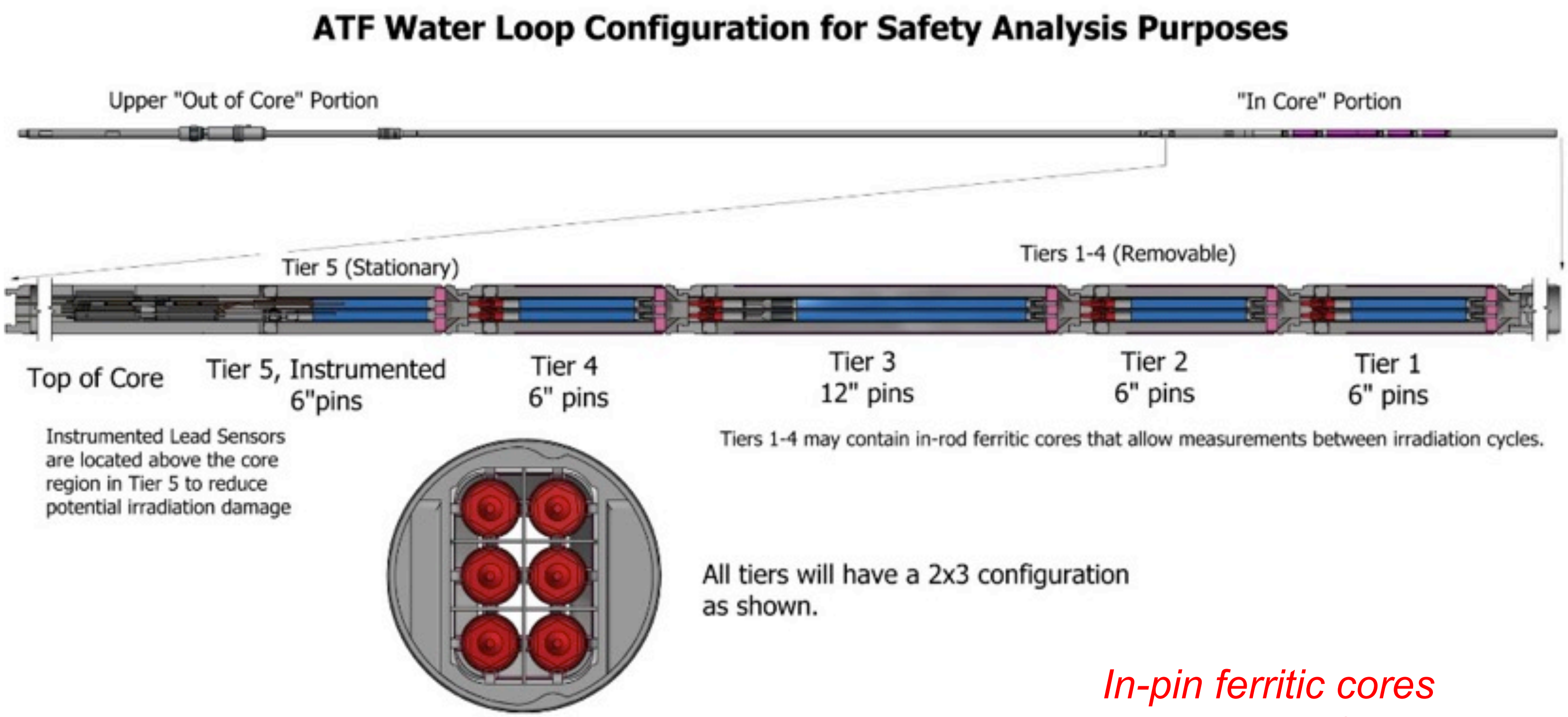
- **Fiber optic pressure sensor significantly smaller than LVDT based system**
- **Fiber optics known to degrade – outside core region for ATR application**





- **Extrinsic Fabry-Perot Interferometry**
  - 1/16 inch diameter
  - 1.5 inch length
  - Demonstrated to 16000 psi
  - Response time down to 13 µs
- **Other sensors possible based on method:**
  - Temperature
  - Dimensional changes

ATF-2 Test Train Conceptual Design



In-pin ferritic cores can be used for periodic in-canal measurements of clad and fuel elongation Tiers 1-4

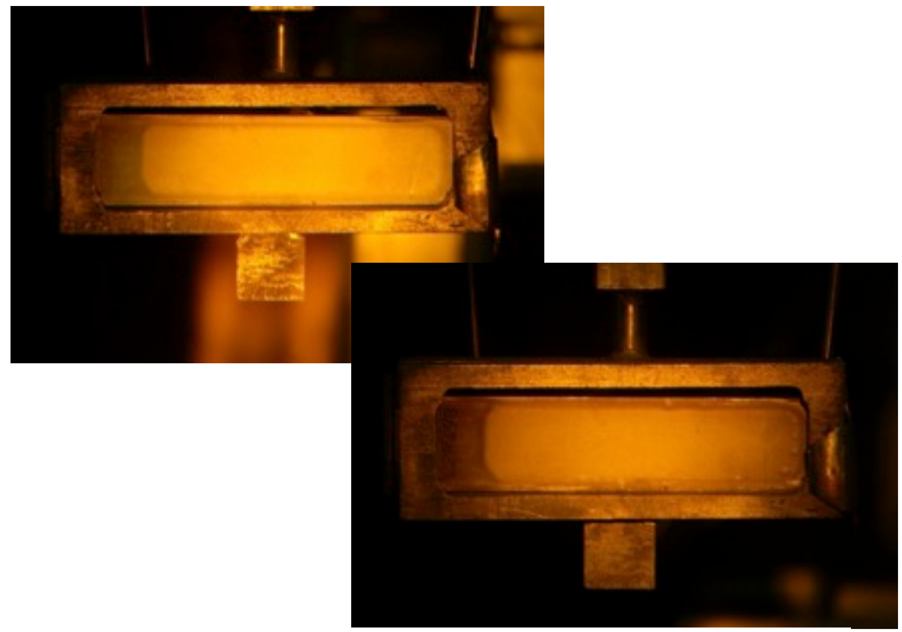
ATR Loop Condition Sensors/Controls

- **Thermo-couples (TCs) to measure inlet and outlet temperatures**
  - can adjust water temperature “on the fly” during irradiation testing as needed
- **Flow meters to measure loop flow rates**
  - can adjust water flow rate “on the fly” during irradiation testing as needed
- **In-line Chemical sensors**
  - H2, Conductivity, pH
- **Water “grab sample” collected daily**
  - Boron measurement daily; dissolved metal constituents measured weekly
- **Electro-chemical Potential (ECP)**
  - Measures concentrations of dissolved oxidants in loop coolant water
  - Will be used to monitor formation/dissolution of clad corrosion
  - Halden reactor has developed a reference electrode that is capable of withstanding in-core conditions – has been successfully used in Halden Reactor
- **Core region Thermo-Couple**
  - Measures coolant water temperature in the core region (included in the ATF-2 test train)
  - ATR measures loop inlet and outlet water temperatures only
- **Test Train Flux wire**
  - Measure neutron flux in the test train region
  - Used to refine neutronics calculations to support burnup predictions
    - center flux trap flux is not controlled directly (4 corner lobes) and fluctuates during the cycle duration

ATR In-Canal Measurements

- **Change Detection Software (CDS) has the potential to identify changes in fuel rod surface features "in-canal" between cycles**
  - Couple CDS to camera output for intuitive real-time change information
    - Fracture formation / propagation
    - Clad corrosion / oxidation
    - IR images - fuel changes (swelling, cracking, growth)
  - Uncertainty reduction in fuel performance models by providing multiple data points for a single fuel rod
- **In-Pin Ferritic Core / LVDT**
  - Fuel / clad elongation

Before and After Fuel Plate Blister Images Using DCS



Summary

- **Advanced Fuels Campaign is currently using flux wires and melt wires in ATF-1 experiments**
- **Wireless thermoacoustic (TAC) sensor demonstrated in Breazeale Reactor at Penn State September 2015**
- **Sensor qualification test will demonstrate existing and new instruments in ATR conditions**
  - Out-of-pile SQT mock-up test in flowing autoclave prior to ATR insertion
- **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
- **In-Canal measurement will provide fuel performance data between cycles**
  - Fuel/clad elongation
  - Clad surface feature changes
  - Fuel growth, swelling, cracking

Acknowledgments

- **ATF-1 Melt Wires**
  - Jason Harp
  - Kurt Davis
- **SQT and ATF-2 Loop Experiment and Design**
  - Kristine Barrett
  - Brian Durtschi
- **SQT, Autoclave, and ATF-2 Loop Instrumentation**
  - Troy Unruh
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  - Jim Smith
  - Kurt Davis
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