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Nuclear Technology Research & Development

Advanced Fuels Campaign: Instrumentation Needs

Advanced Fuels Campaign

Steven L. Hayes
National Technical Director

Advanced Sensors and Instrumentation
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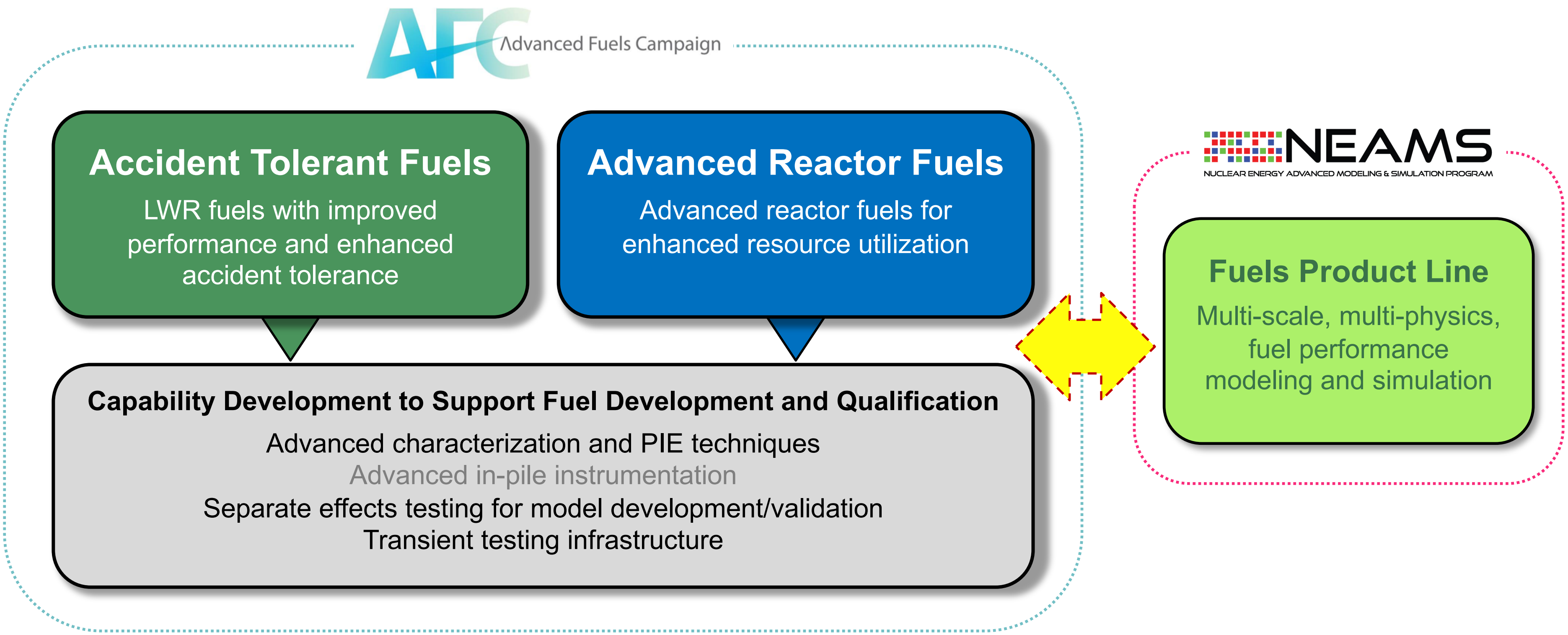
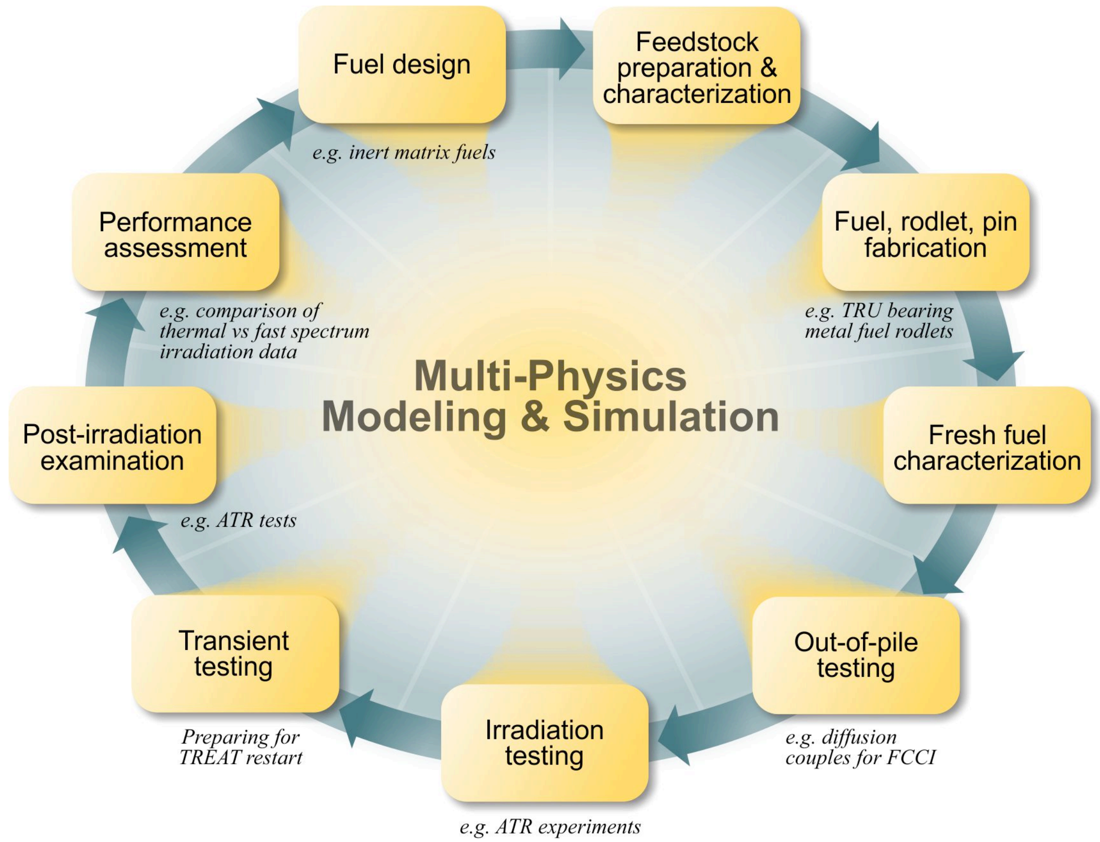
Advanced Fuels Campaign: Structure and Mission

- **Mission:**
  1) Support development of near-term **Accident Tolerant Fuel** (LWR) technologies
  2) Perform research and development on longer-term **Advanced Reactor Fuel** technologies



Fuel Development R&D Life Cycle



In-Reactor Test Objectives

Irradiation Experiment Goals:

- Investigate new fuel behavior, or demonstrate mature fuel behavior
- Measure fuel behavior, integral fuel performance: macroscopic scale
- Quantify microstructure-scale data for modeling and simulation: microscopic scale
- Compare performance of new fuels to historic fuels database
- Identify life-limiting phenomena

In-reactor Instrumentation Goals:

- Measure in-reactor conditions (e.g., power, flux, temperature)
- Observe “real-time” fuel behavior
- Provide rapid access to results before postirradiation examination (PIE)
- Inform decisions on continued irradiation or discharge based on performance or conditions
- Provide intermediate fuel behavior data

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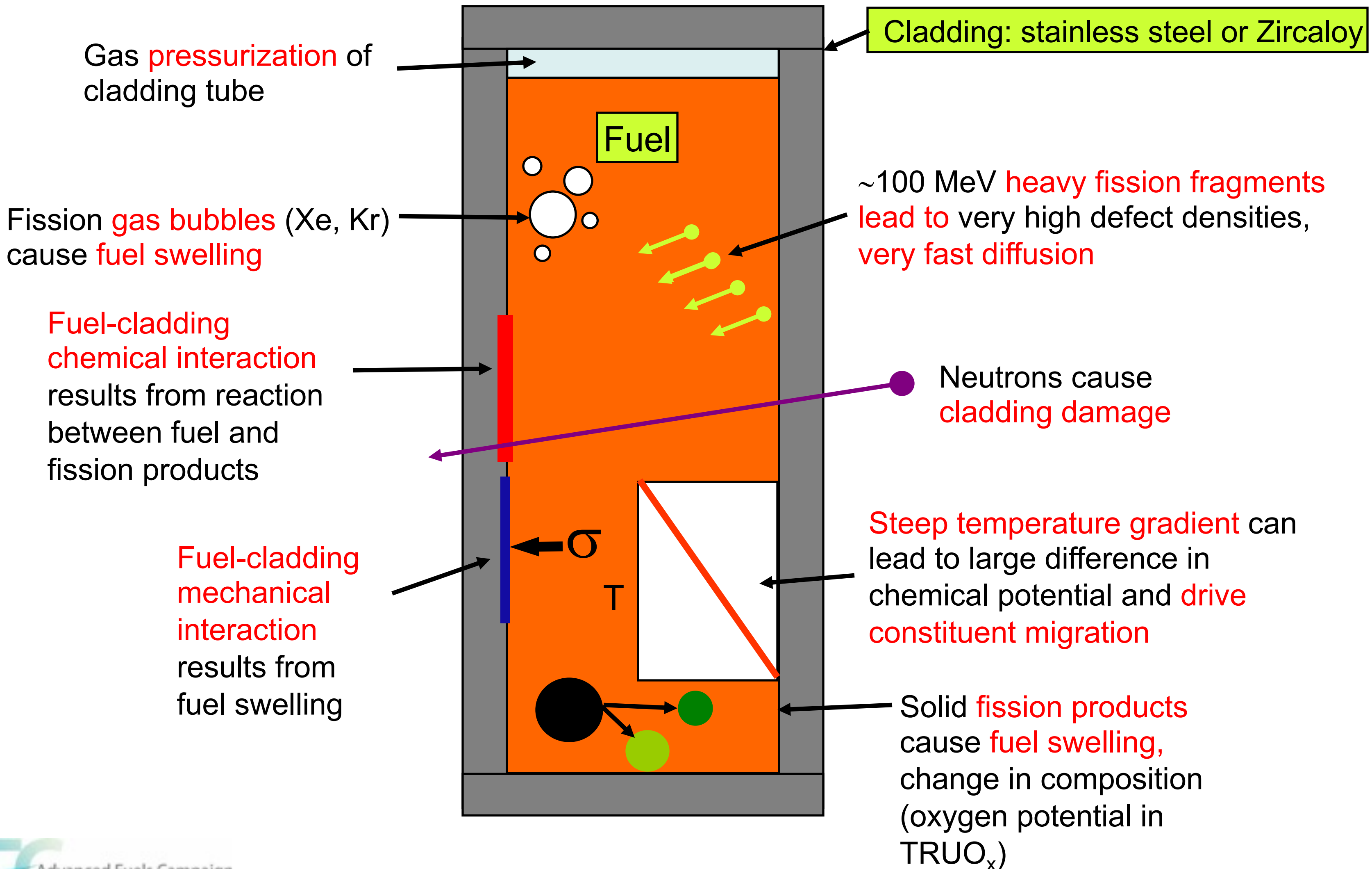
Fuel Behavior is Complex



In-Situ Instrumentation Considerations

Experiment Types

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

Instrument Types

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

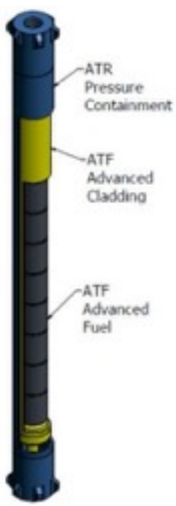
Measurement Types

- **State Point (PIE)**
  - end of irradiation
  - supplemental data, but limited
- **Real Time (*in situ*)**
  - provides much more data
  - detailed history for long experiments

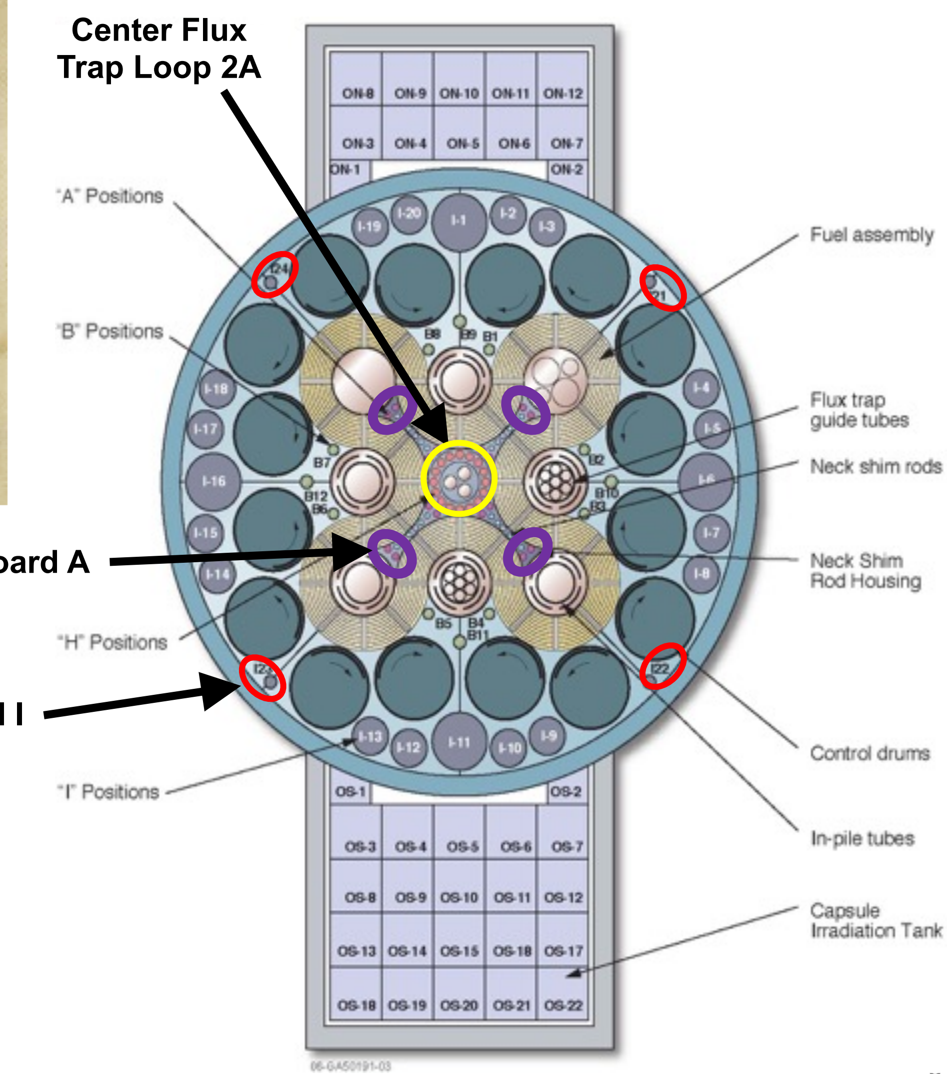
In-reactor Instrumentation Constraints

- **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 much more expensive to design, build, and operate

AFC Irradiation Experiments in ATR



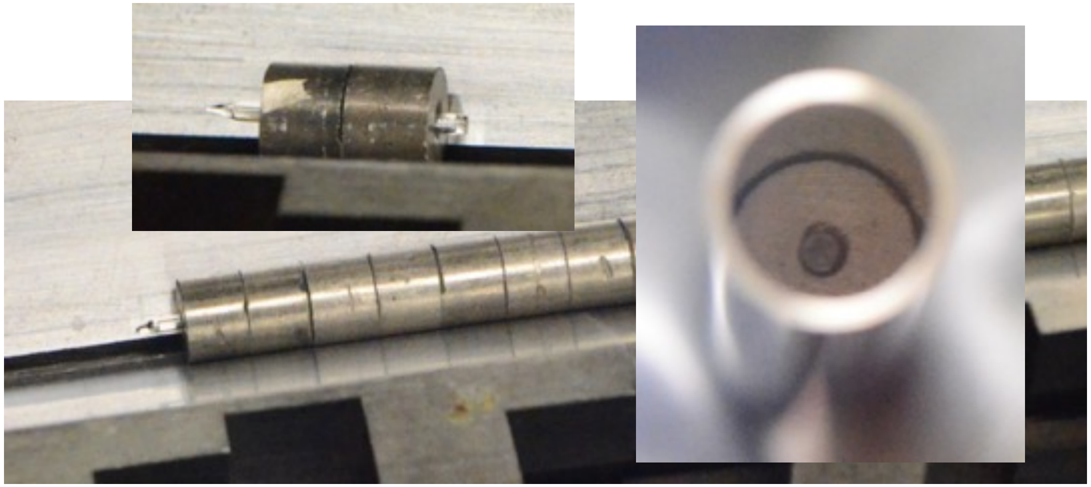
- **Drop-In Capsules**
  - ***Outboard A Positions***
  - Metallic fuel experiments
  - Cd-shrouded baskets filter thermal flux
  - Rodlet inside SS capsule (safety barrier)
  - Gas gap provides prototypic cladding temperature
  - ***Small I positions***
  - ATF-1 feasibility testing
  - Rodlets in individual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



Current Irradiation Test Instrumentation

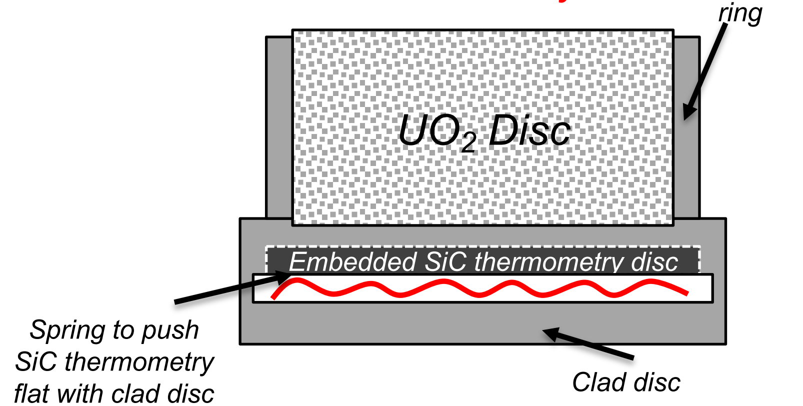
- **Melt Wires**
  - ATF-1
  - inserted inside DU insulator pellets
- **Flux Monitors**
  - ATF-1 baskets
- **SiC Temperature Monitors**
  - ATF-1 and ATF-2 experiments

In-basket Flux Wires



In-Pellet Melt Wires

SiC Thermometry



ATF-2 Loop Instrumentation

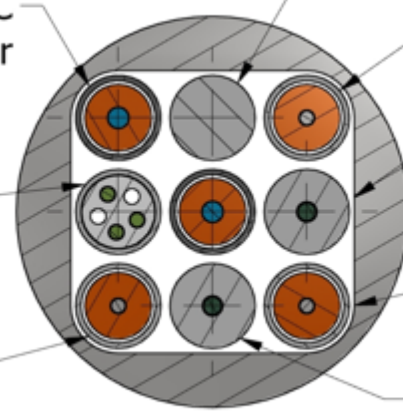
SQ Test Lead Arrangement				
Top Tier				
Lead Sheath Diameter (inches)	0.039	0.063	0.125	
Multiple LVDT Single Bellows	6 (2 Per LVDT)	1		
LVDT Single Bellows	2 (2 Per LVDT)	1		
LVDT Single Bellows	2 (2 Per LVDT)	1		
Optical Pressure		5		
HTIR TC		2		
Type N TC		1		
Type N TC with TAC		1		
Ultrasonic 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)

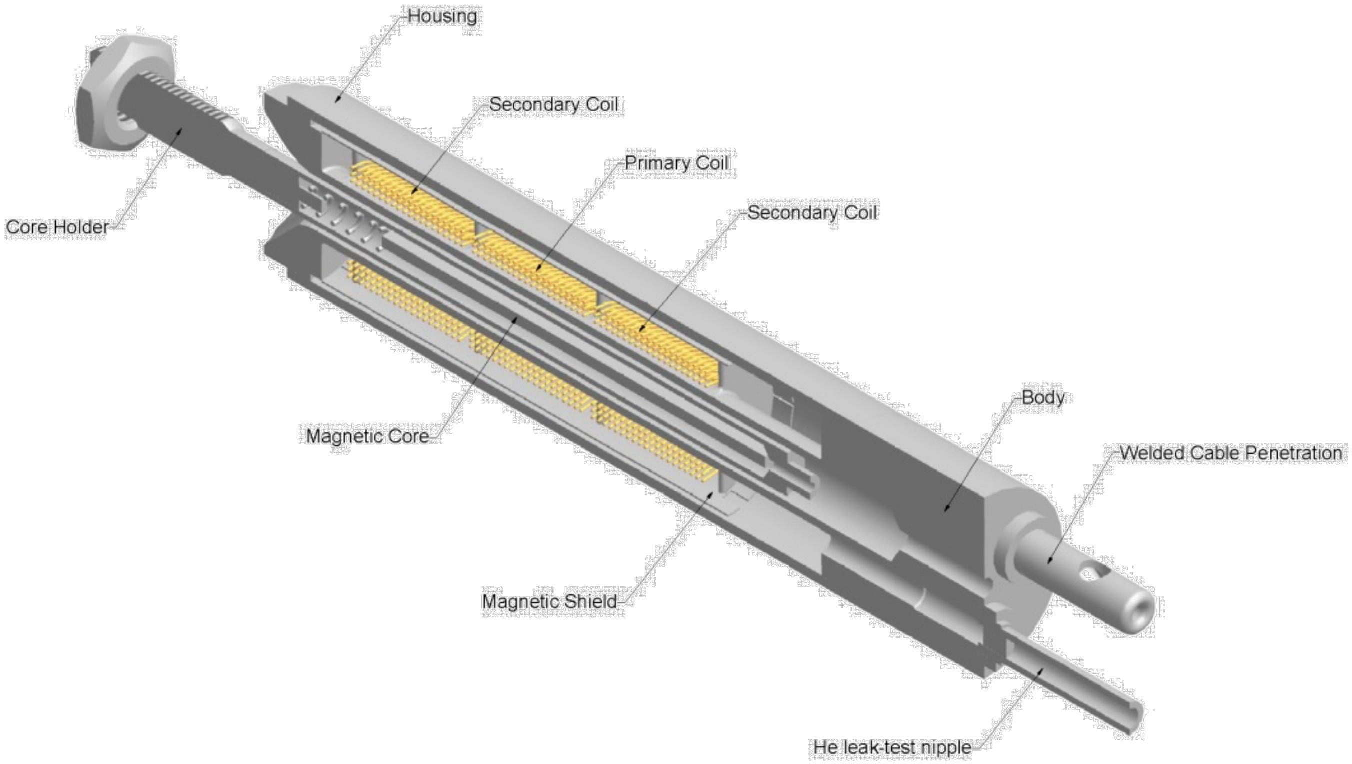
- **Sensors to be evaluated have potential advantages, but have not been demonstrated previously in a high flux environment**
  - Developmental sensors may be used in ATF-2 fueled experiment if performance is exceptional



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

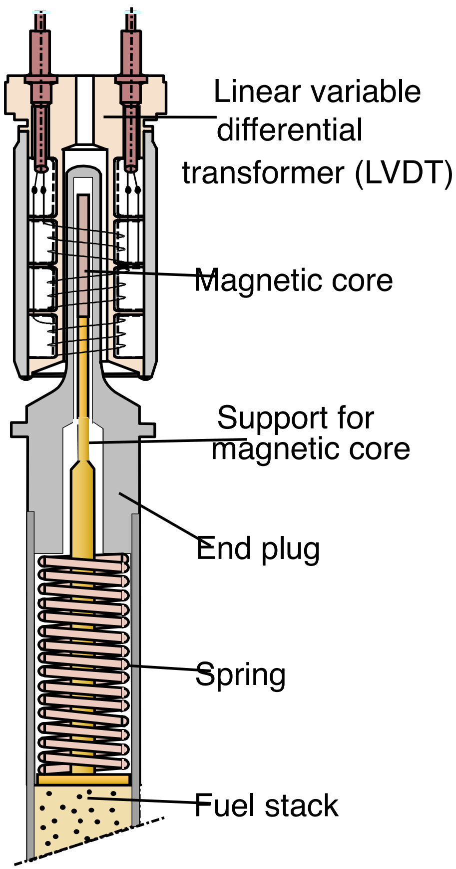
- **Westinghouse Electric Research Laboratory – Churchill, PA**
- **Collaboration with IFE / Halden**
- **Assemble mock-up test train at INL and ship to Westinghouse**
- **ATR / PWR prototypic operating conditions**
- **Evaluate durability of sensors under high flow/water, temperature conditions**
- **Assess chemical interactions**
  - Crud buildup
  - Cladding corrosion
  - Formation of dissolved solids
  - Plating on cladding surfaces

Halden LVDT-based Instruments

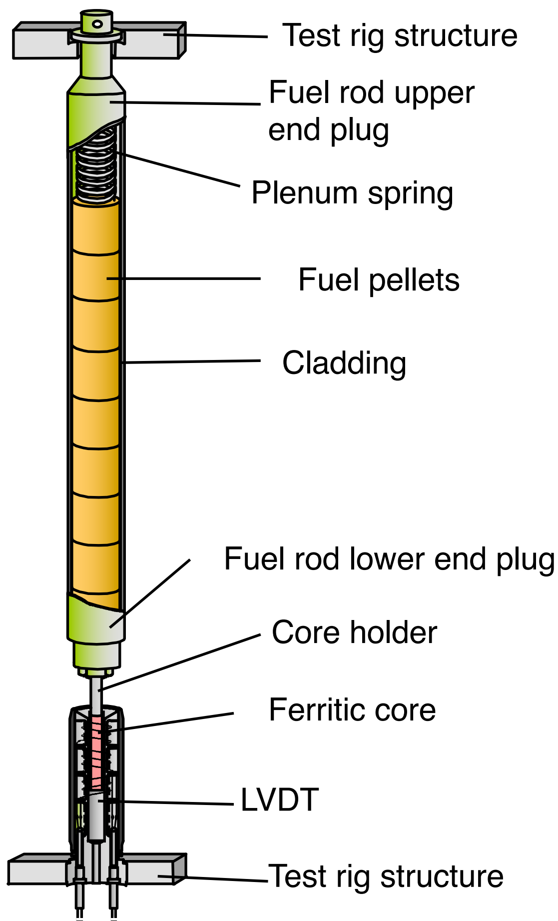


- **Performance and robustness demonstrated over several years and irradiations**
- **Used in test reactors worldwide**
- **Not previously demonstrated in ATR – minor modifications are being implemented for fuel and cladding elongation measurements**

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
- **Modifications of 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

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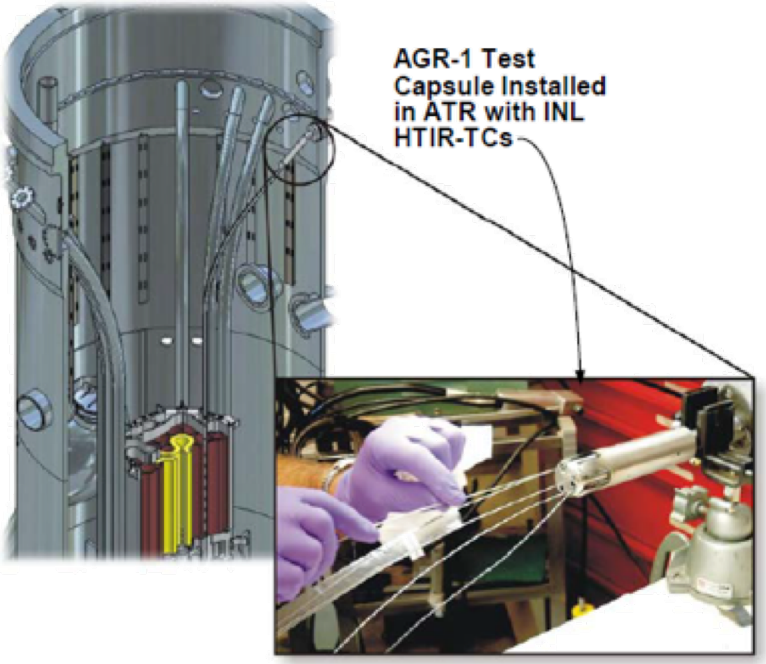
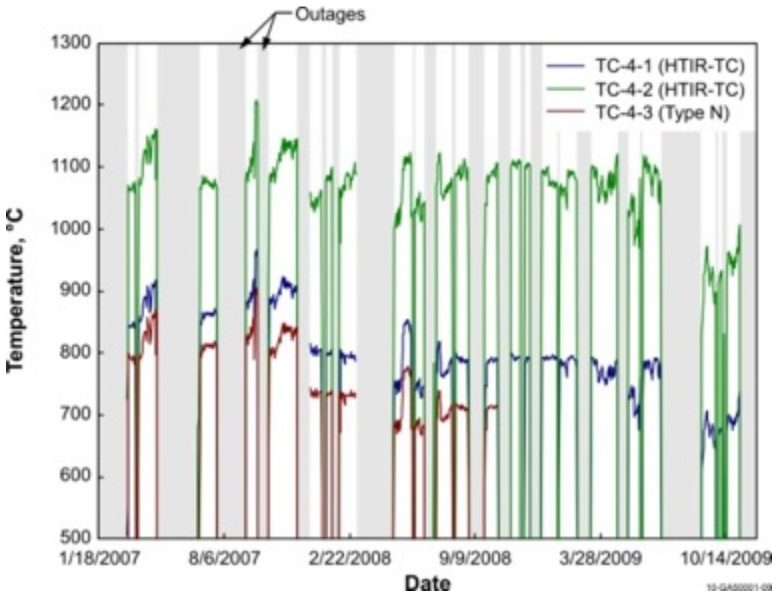
Initial evaluations suggested doped Mo/Nb-1%Zr thermoelements with HfO_2 insulation and Nb1%Zr sheaths most suitable combination for HTIR-TCs.





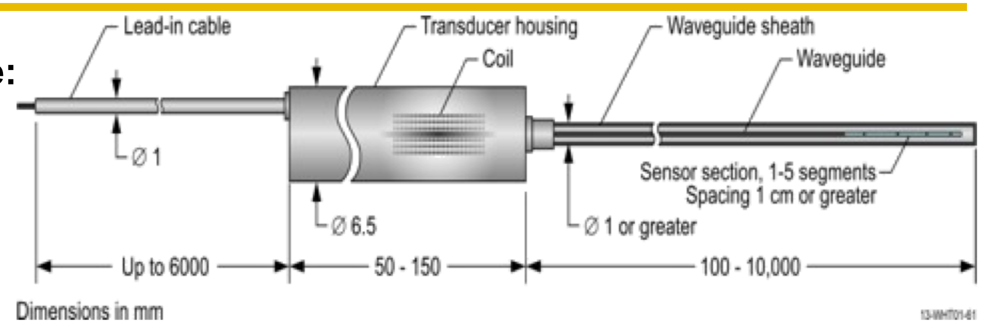
HTIR-TCs performed well throughout AGR-1 irradiations (while commercial TCs failed)

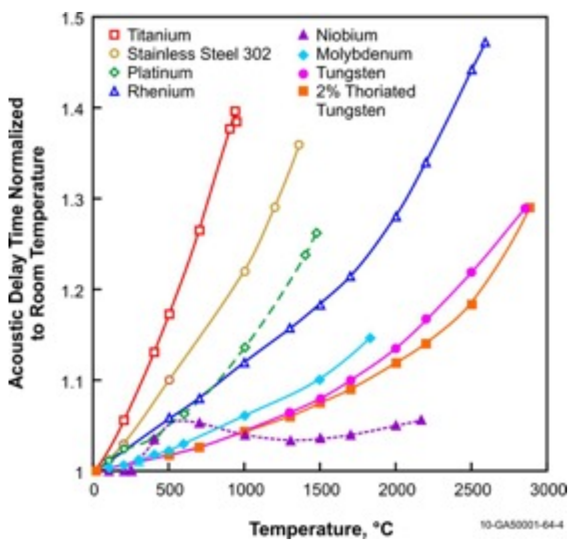
HTIR-TCs patented by BEA and deployed

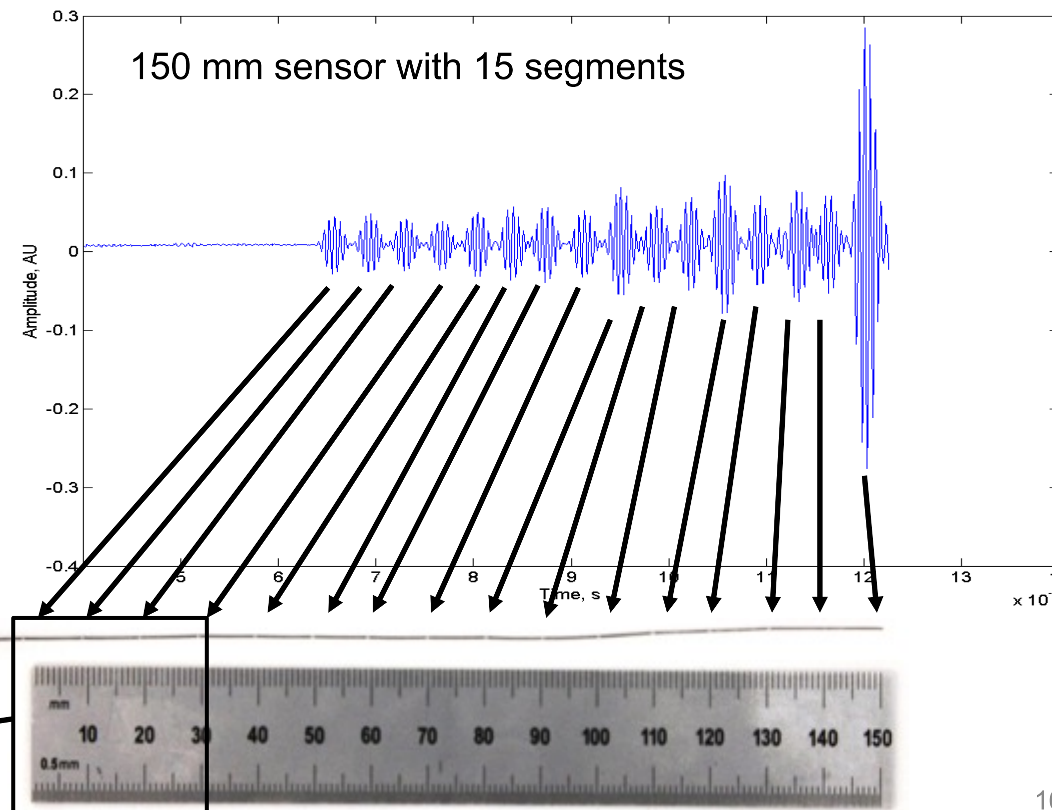
- **Near term development to address existing limitations:**
  - Lack of Nb-1%Zr availability
  - Activation of hafnia and availability of newer insulation materials
  - Current effort to improve HTIR-TC with newer materials (Doped Nb, Yttria)

Ultrasonic Thermometer: Fuel Centerline Temperature

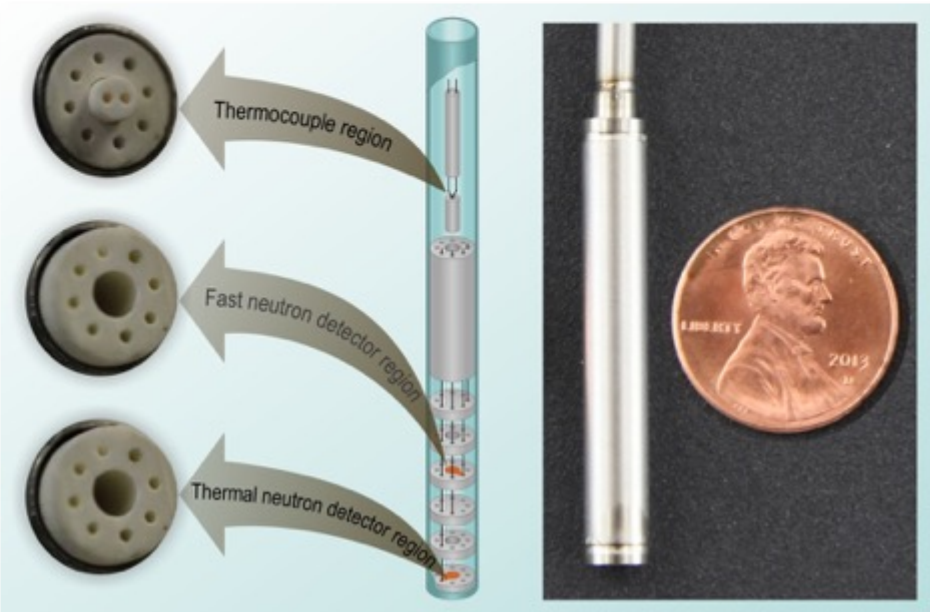
- **Potential improvements over thermocouple:**
  - Very high temperature capability
  - Multi-point measurement
  - Sensor material selectable for environment and temperature range
  - SQT UT may have single segment

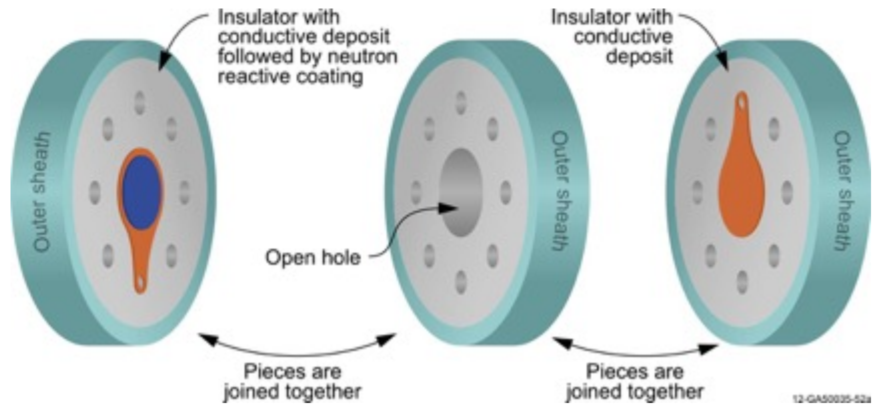






Micro Pocket Fission Detector (MPFD):
Environmental Temperature and Neutron Flux

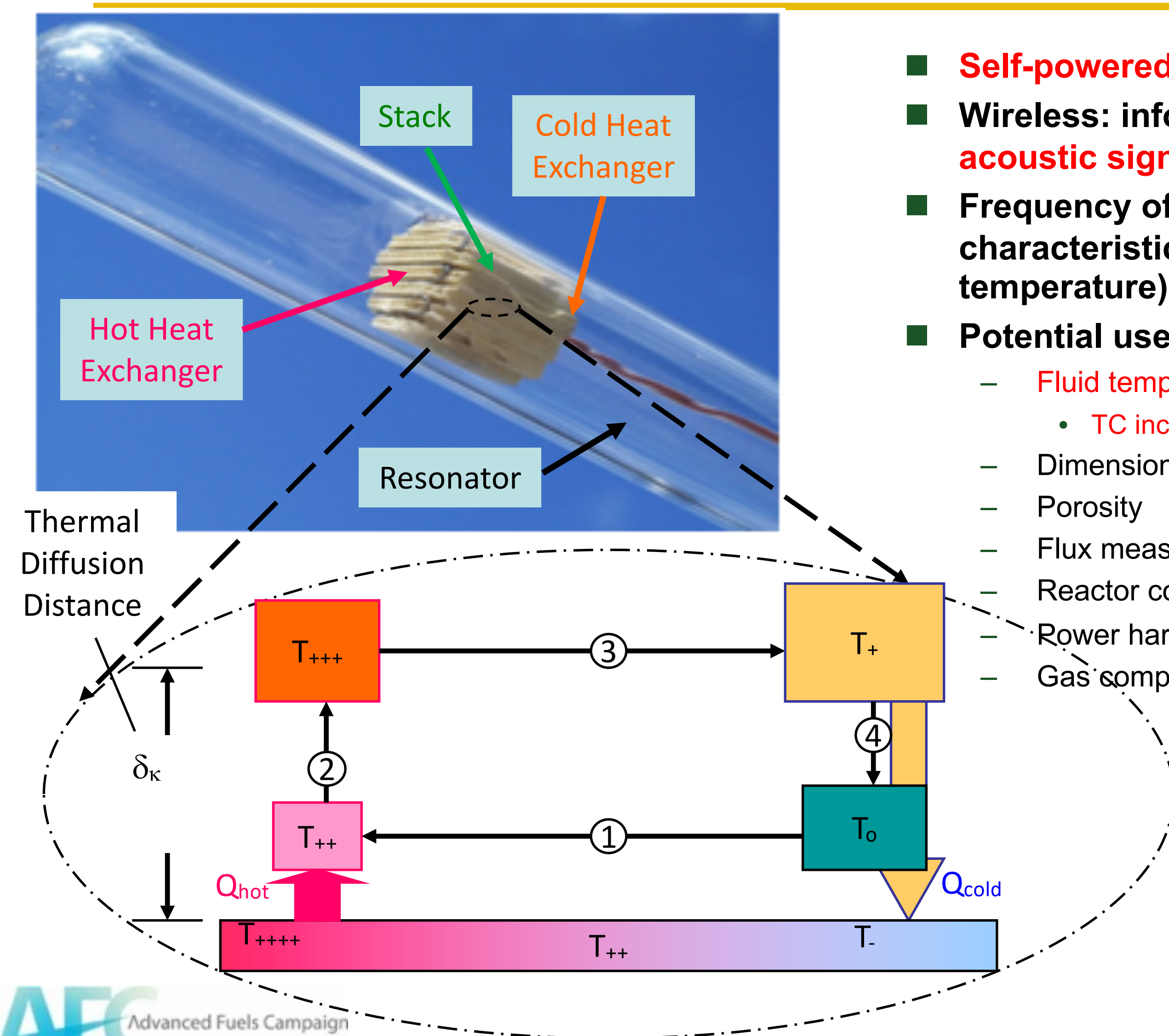




- **Three sensors in a single, compact package:**
  - Thermal neutron detector
  - Fast neutron detector
  - Temperature detector
  - Modular design may allow more chambers

- **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

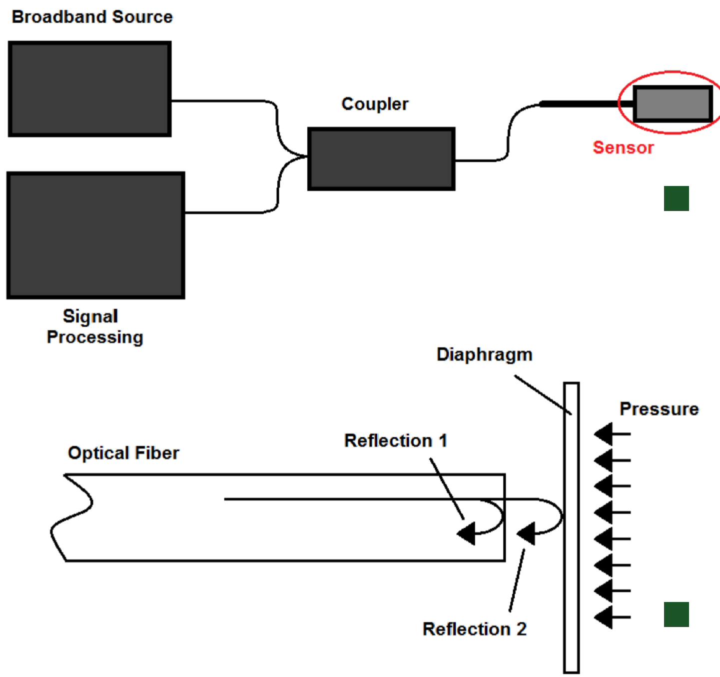


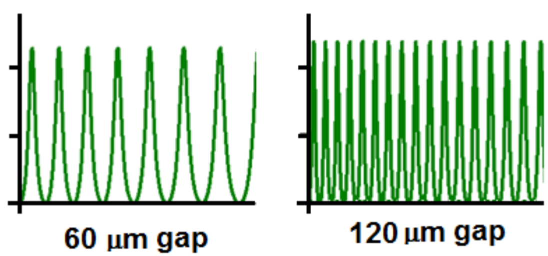
- **Self-powered via temperature differential**
- **Wireless: information carried by pure tone acoustic signal**
- **Frequency of signal function of gas characteristics (composition and temperature) and geometry of resonator**
- **Potential uses:**
  - Fluid temperature measurement
    - TC included 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

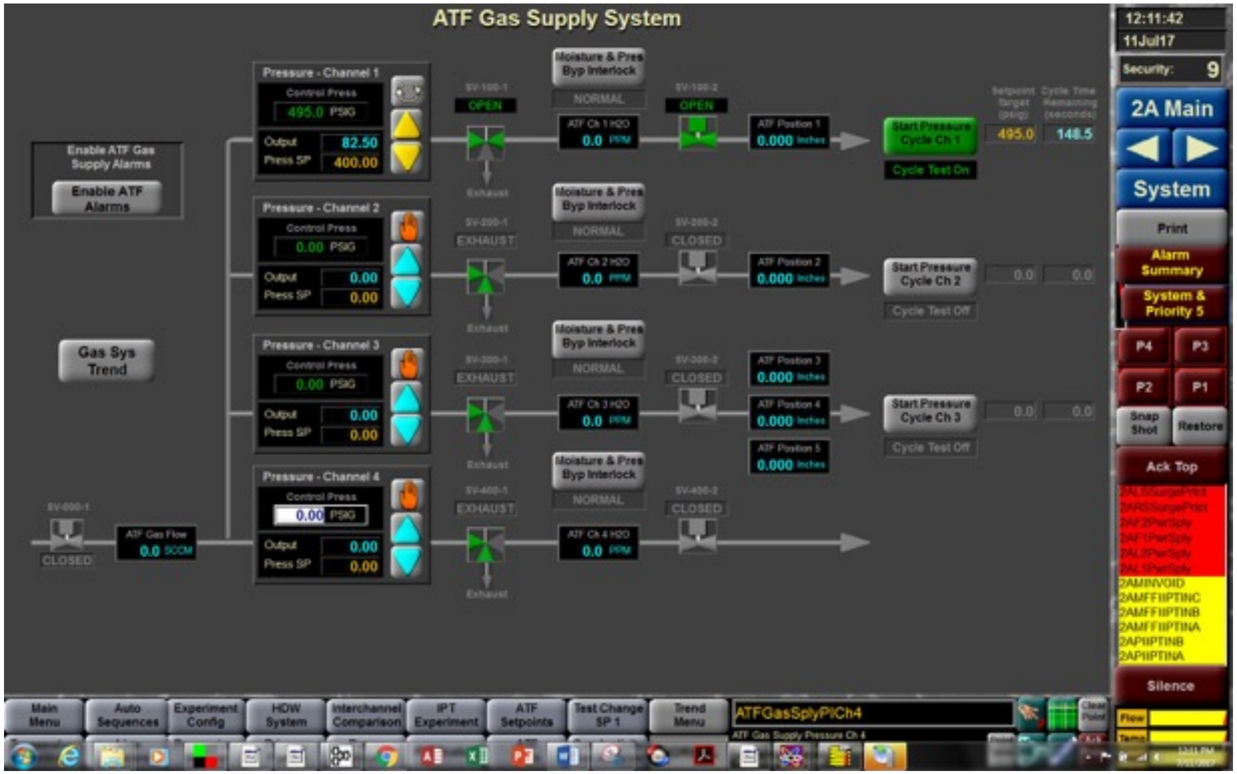
- **Fiber optic pressure sensor significantly smaller than LVDT based system**
- **Fiber optics known to degrade – outside core region for ATR application**

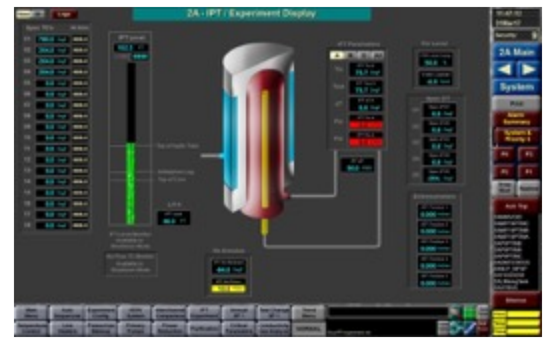


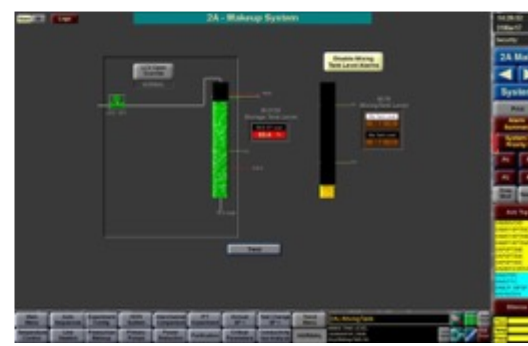


- **Extrinsic Fabry-Perot Interferometry**
  - 1/16 inch diameter
  - 1.5 inch length
  - Demonstrated to 16000 psi
  - Response time down to 13 µs
- **Other sensors possible based on method:**
  - Temperature
  - Dimensional changes

SQT Distributed Control System (DCS)

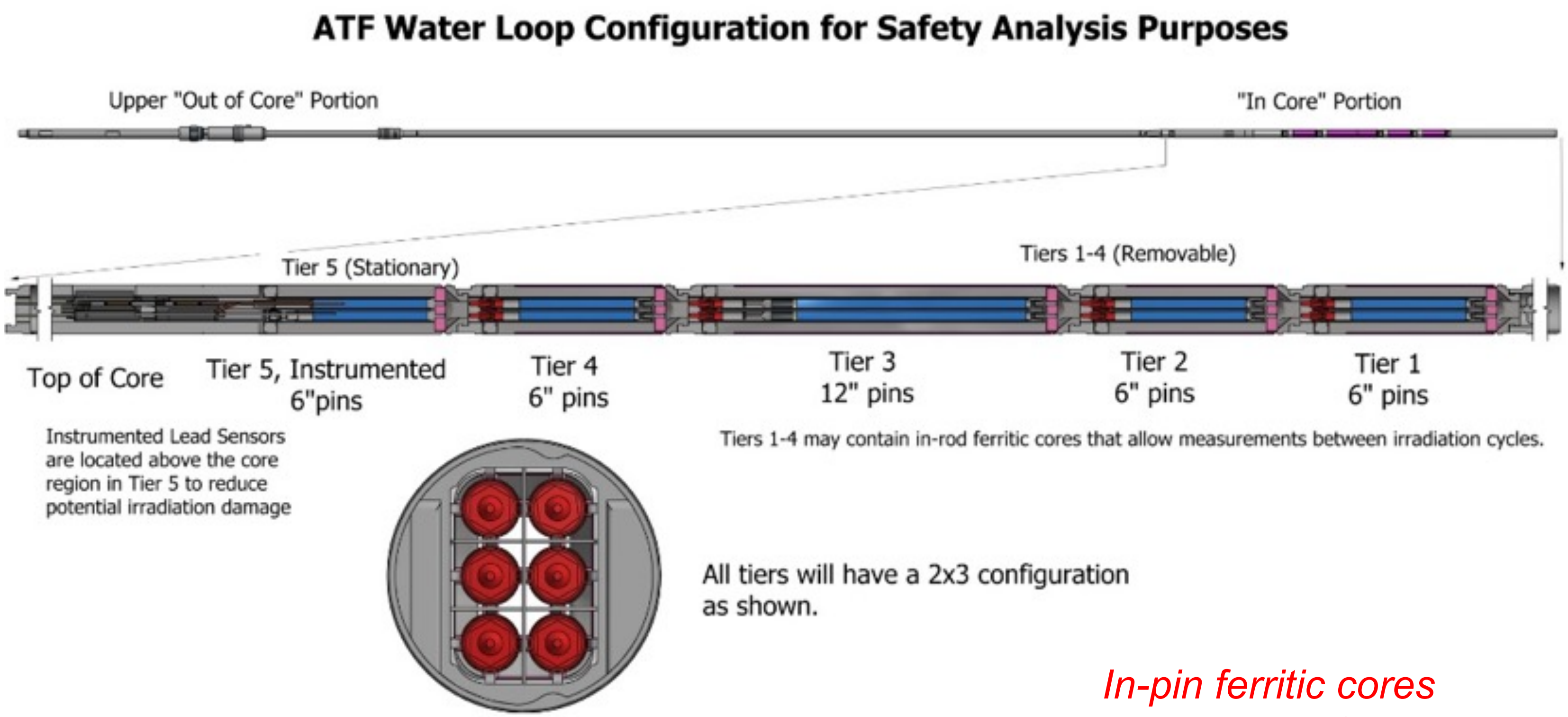






The DCS provides data acquisition and control capabilities associated with the ATF-2 SQT gas panel and experiment as well as the 2A experiment loop.

ATF-2 Test Train 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 evaluations
    - center flux trap flux is not controlled directly (4 corner lobes) and fluctuates during the cycle duration

Summary

- **Advanced Fuels Campaign is currently using flux wires and melt wires in ATF-1 experiments, expect to use LVDTs and thermocouples in loop experiments.**
- **Wireless thermoacoustic (TAC) sensor demonstrated in Breazeale Reactor at Penn State (09/2015)**
- **Sensor qualification test evaluated existing and new instruments in ATR conditions**
  - Out-of-pile SQT mock-up test in flowing autoclave tested prior to ATR insertion
  - TC drift and water ingress at pin penetration were observed
- **ATF-2 loop experiment will (eventually) use demonstrated in-reactor instruments to measure:**
  - fuel temperature
  - fuel pin internal gas pressure
  - fuel stack elongation
  - fuel pin elongation

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Contacts for Detailed Information

- **ATF-1 Melt Wires**
  - Jason Harp
  - Kurt Davis
- **SQT and ATF-2 Loop Experiment and Design**
  - Brian Durtschi
  - Nate Oldham
  - Doug Crawford
- **SQT, Autoclave, and ATF-2 Loop Instrumentation**
  - Troy Unruh
  - Josh Daw
  - Jim Smith
  - Kurt Davis
  - Steinar Solstad – IFE/Halden (steinar.solstad@ife.no)