Advanced Temperature Instrumentation for Transient Reactor Testing

WISCONSIN
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Outline

- Distributed optical fibers (UW, OSU)
- HTIR-TC (INL)
- Thermal conductivity Probe (INL)
- Ultrasonic temperature sensor (INL)
- Diamond thermistor (UW)
- Radiation testing
- Path forward

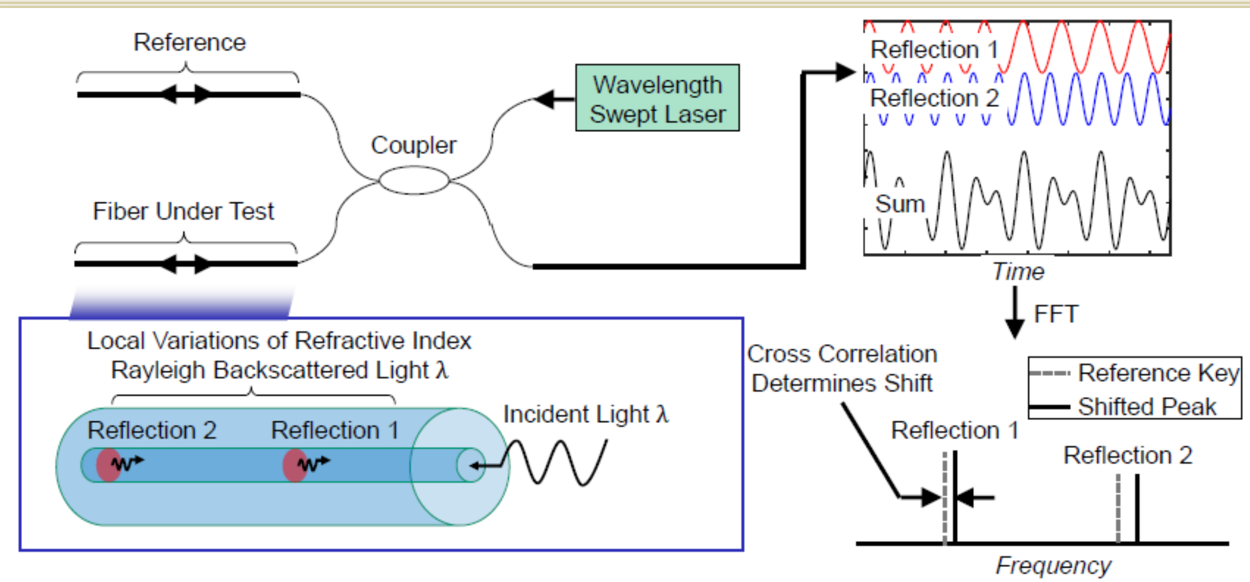
Distributed Optical Fiber Temperature Sensors

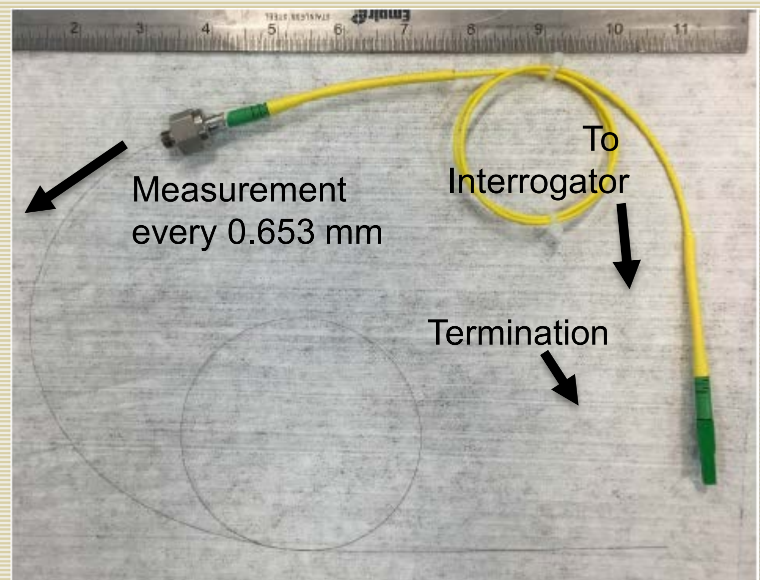
- Rayleigh backscatter based fiber optic temperature sensors provide quasi-continuous, high resolution 1D temperature measurements
- Optical Frequency Domain Reflectometry (OFDR)

1. Near infrared laser shines down single mode optical fiber
2. Intrinsic defects in fiber core produce Rayleigh backscatter
3. The sum of these Rayleigh backscatter reflections produce a distinct profile at reference temperature, which will shift at high temperature in a predictable manner as scatter sites migrate apart from one another
4. FFT taken of Rayleigh backscatter profile which is cross correlated to reference. Amount of frequency shift can then be converted to temperature shift
5. High spatial temperature measurements ~1500 discrete temperature measurements/meter along the length of a 125μm silica fiber.

Specification for Luna's ODiSI-B (Optical Distributed Sensor Interrogator)

Operation Mode	Standard	High-Speed	High-Resolution	Extended Length	
Maximum Sensing Length	10	2	10	20	[m]
Acquisition Rate	100	250	23.8	50	[Hz]
Sensor Spacing	2.56	2.56	0.64	2.56	[mm]
Gage Length	5.12	5.12	1.28	5.12	[mm]
Temperature Repeatability	0.4	0.4	1.6	0.8	[C]





Distributed Optical T-sensors

Area of Inquiry	**Updated Matrix showing current status of Fiber testing**			
Spatial Limit	Fiber Length [2-20 m]	Bend Radius (signal) [> 5 cm]	Strain Sensitivity	-
Temporal Limit	Acquisition Rate [0.2 - 250 Hz]	Labview Limiting [Currently ~5 Hz displayed]	Sheathing Impact [100ms time delay]	-
Resolution Limit	Software Limit [0.64 - 2.56 mm]	-	-	-
Accuracy & Precision	Luna Quoted Specs [± 0.4-1.6 °C]	Check Luna Specs	-	-
Mechanical Failure	Handling/Ben Limit	Tension Limit	Coating Removal	-
Thermal Failure	Temp Gradient [30°C/cm - 500°C/cm]	Molecular Mobility [Temp > 700-800°C Initial Anneal]	Melting Point [1713°C]	Broadband H sites [Initial T > 900°C, Con't T > 850°C]
Chemical Failure	Coating Influence	Gaseous Influence	Carbon Coating	-
Radiation Failure	Gamma Site Creation [Minimal to null]	Gamma Excitement [300-500 nm absoption band]	Neutronic Damage [Damage increases 300-500 nm bands]	Fluence Limit [No observed impact on sensor signal strength]

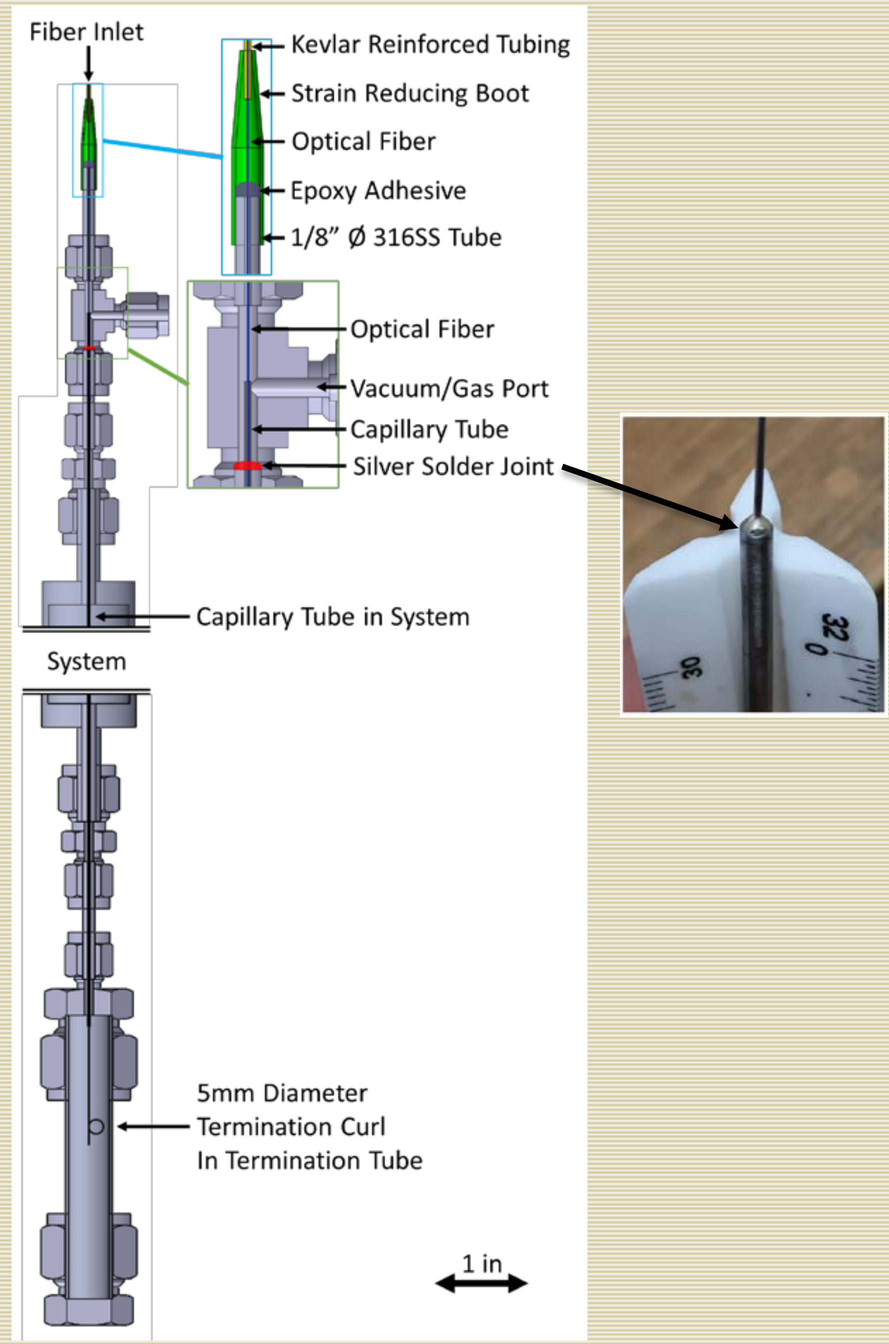
Green	Red
Claim made before IRP began work	Work completed by IRP

Main concerns:

- Insertion into test vehicle
- Calibration
- Temperature limits
- Temperature gradient limits
- Long term stability
- Temperature response time
- Robustness for measurements
- Effects of radiation on fibers

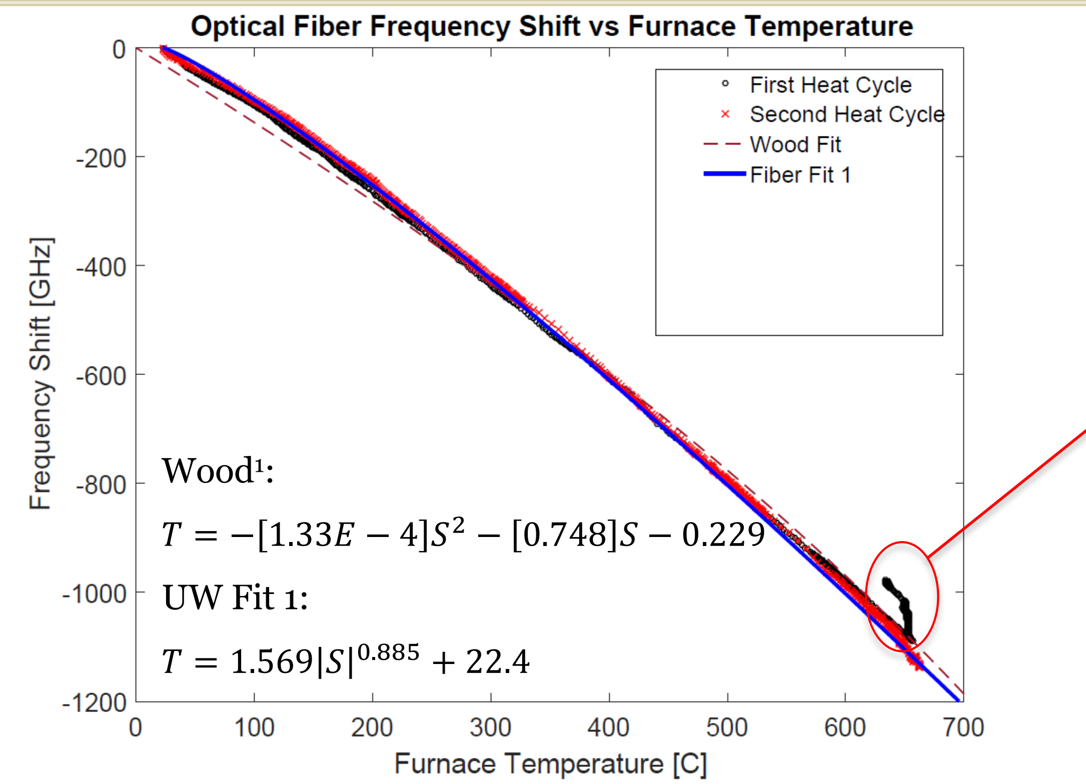
Optical Fiber in Capillary Setup

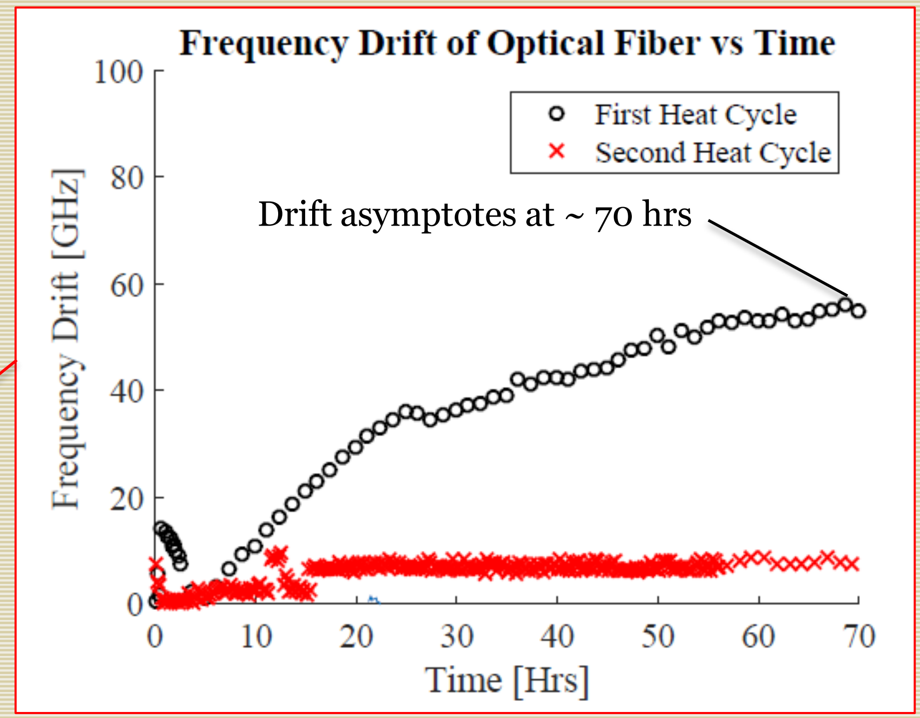
- Optical fiber can be installed (free hanging) in capillary tube to protect and eliminate mechanical stress
    - 1/32" OD – 0.020" ID SS316 capillary tube used works well
- Can purge and seal with cover gas
    - Protects fiber from moisture in environment and allows for use of high thermal diffusivity gas such as helium
- Fiber exits heated area and needs to be terminated
    - Small coil
    - Coreless fiber
    - Need to reduce back reflection



Calibration

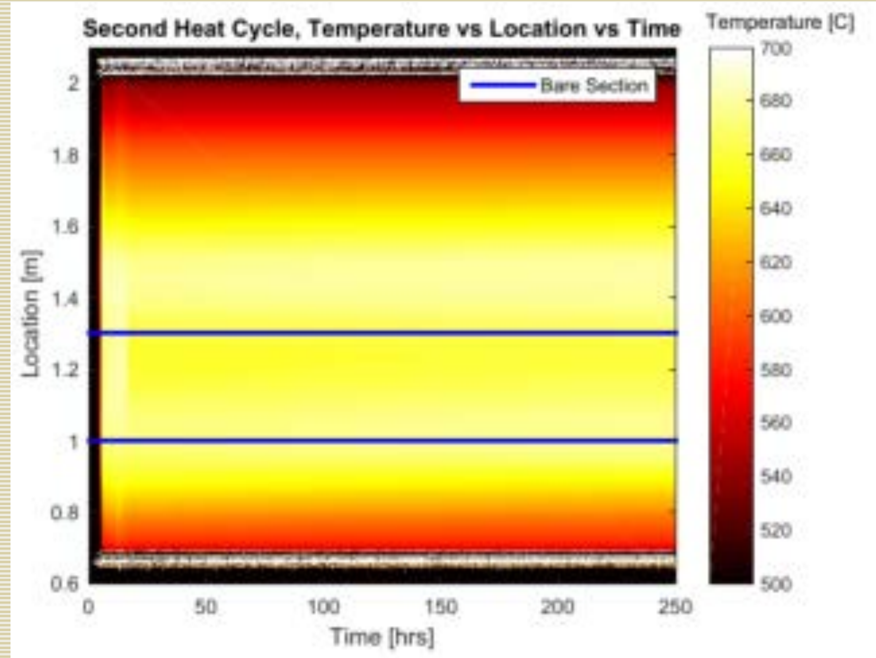
- Calibration curves have been established for fibers and seem to be consistent amongst different fibers.
- Calibration does change slightly after heating.
  - Recommended to bring up to temperature above what is going to be tested at and then “key” fiber back at room temperature.



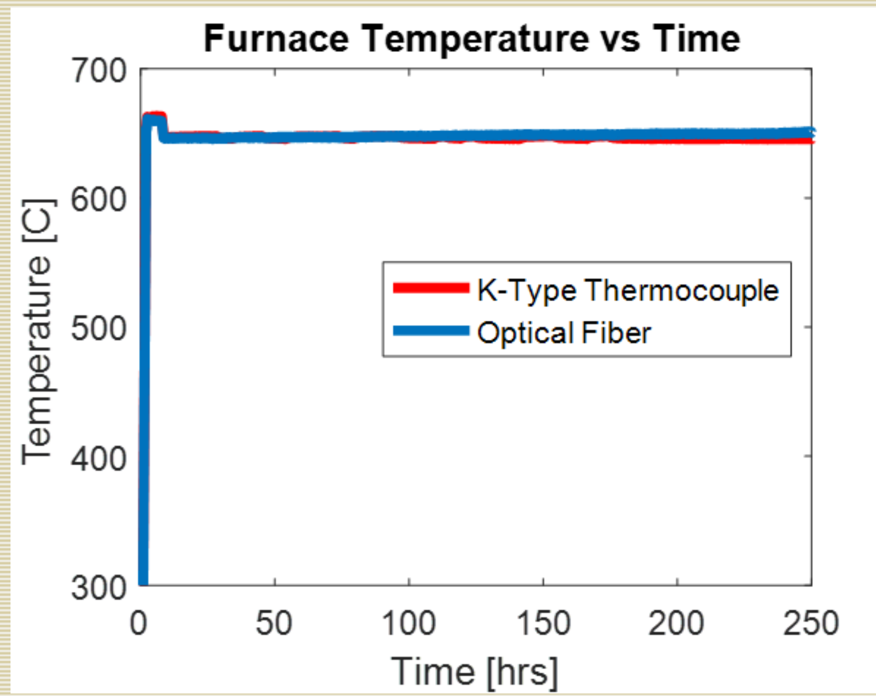


1. Wood, Blake, et. Al, Evaluation of the Performance of Distributed Temperature Measurements with Single-Mode Fiber using Rayleigh Backscatter up to 1000 C. IEEE Sensors Journal

Long Term Stability Tests

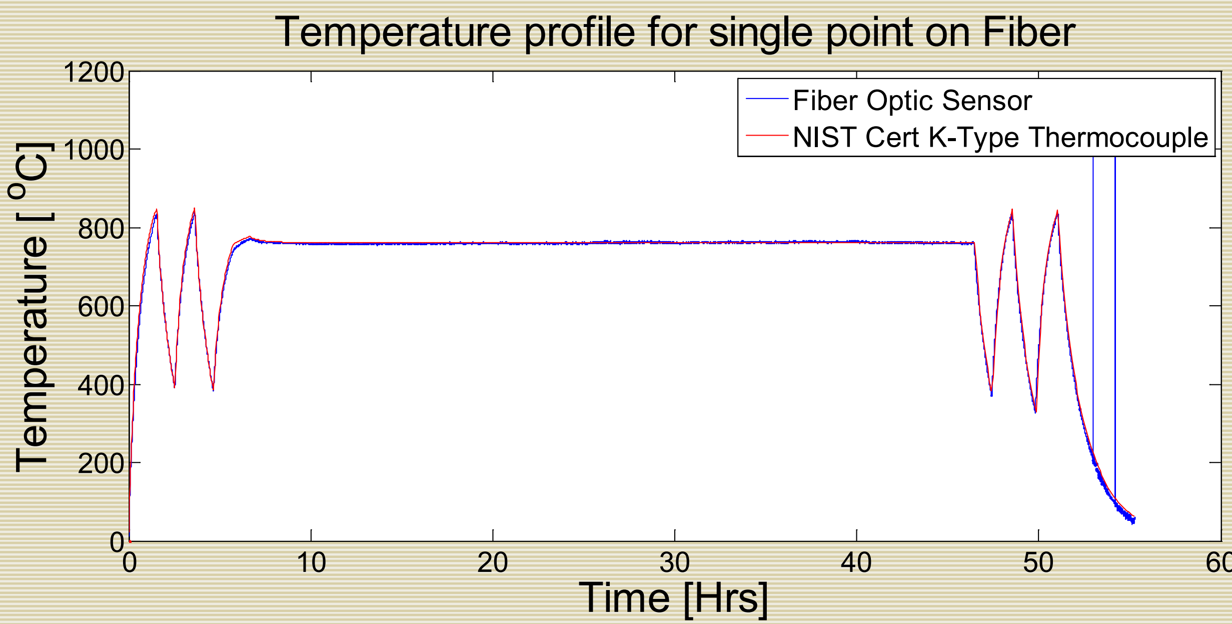


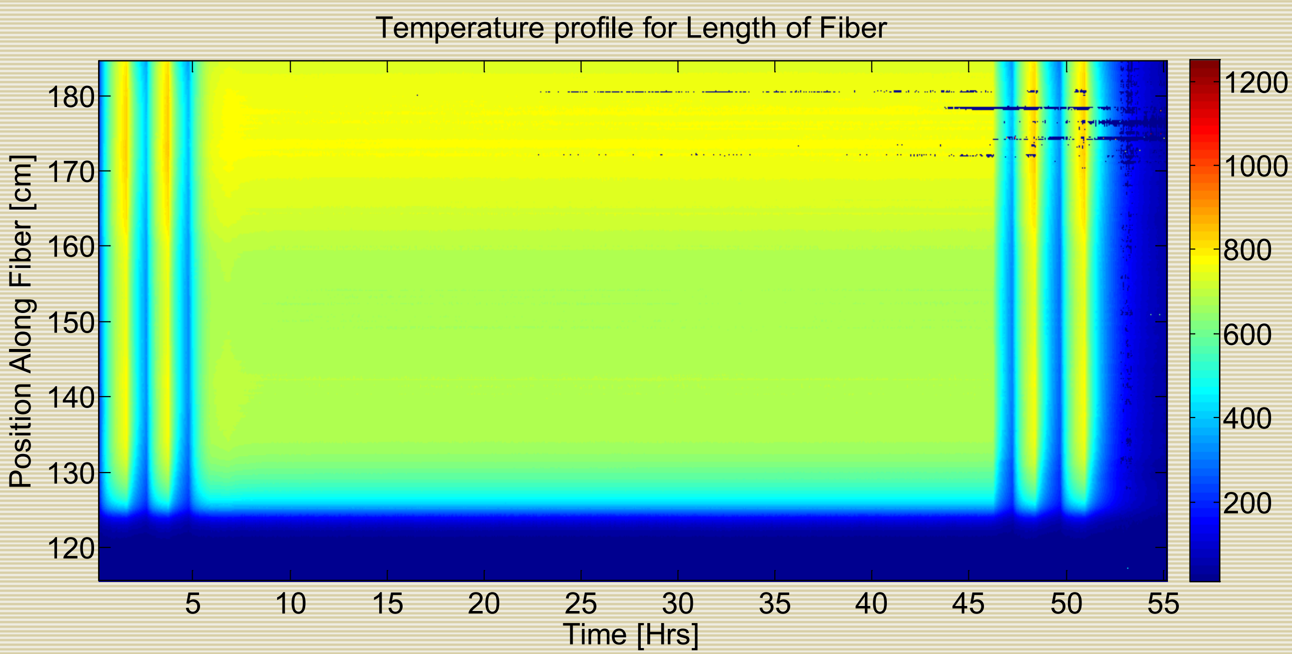
- 250 hour constant temperature stability test at 650°C
- Fiber passed through tube furnace graph shows temperature verses location along fiber as a function of time.



High temperature stability test

Improvement in fabrication and design has increased maximum short term measurements (minutes) to +900°C and long term measurements to ~800°C (days)





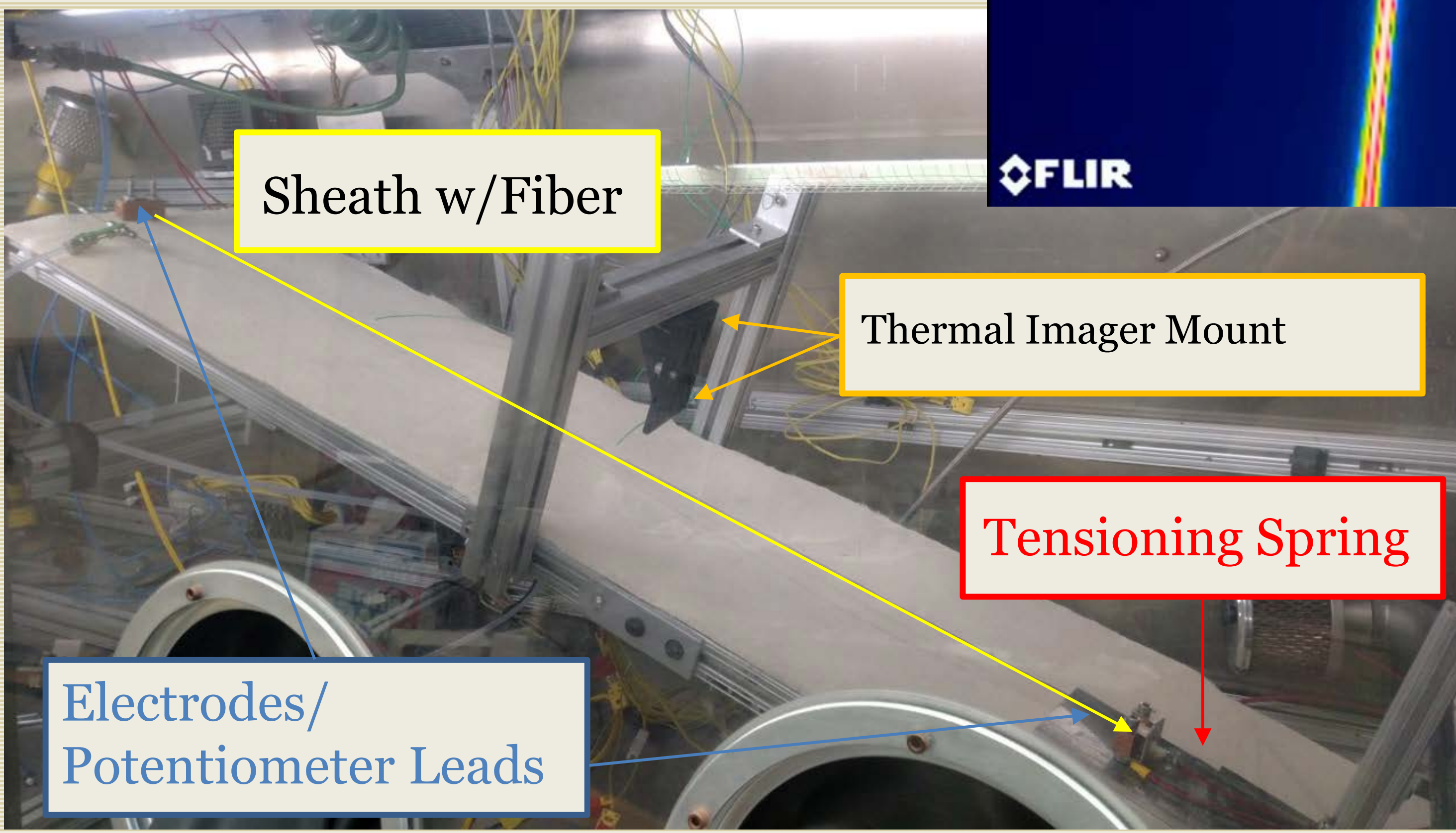
Standard Deviation:

±5°C

±0.66%

Time Response Experiment

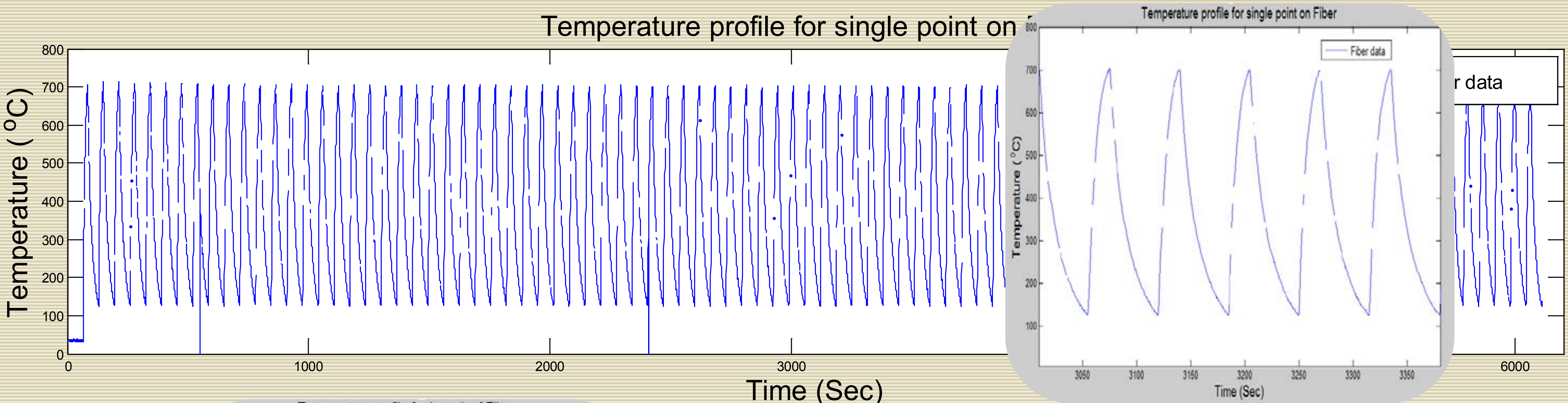
Drive current through the sheath itself and measure the voltage drop across it

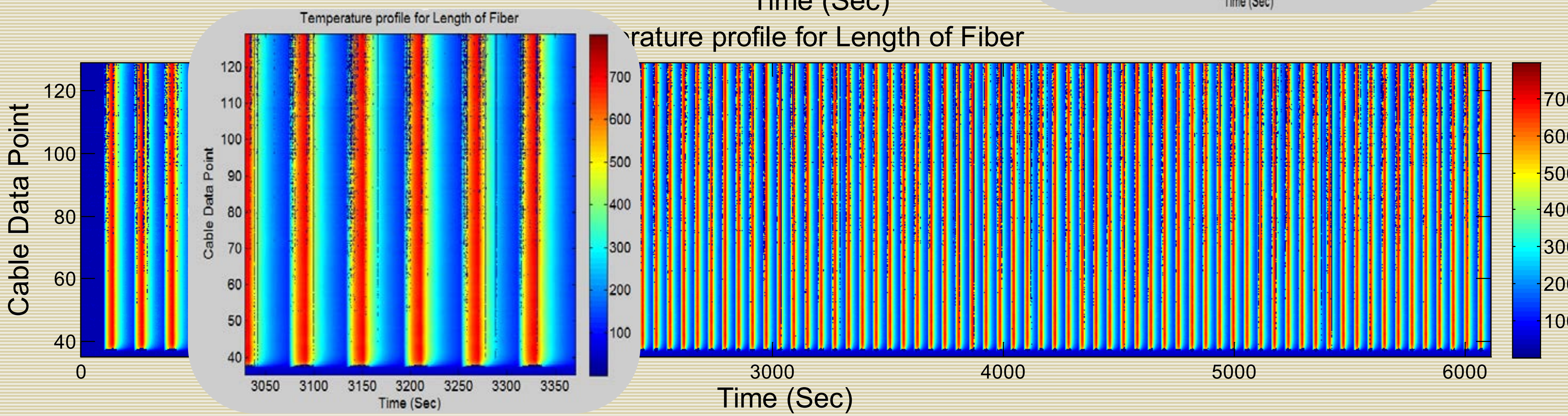


– Voltage is used to calculate the resistivity change and from that the temperature

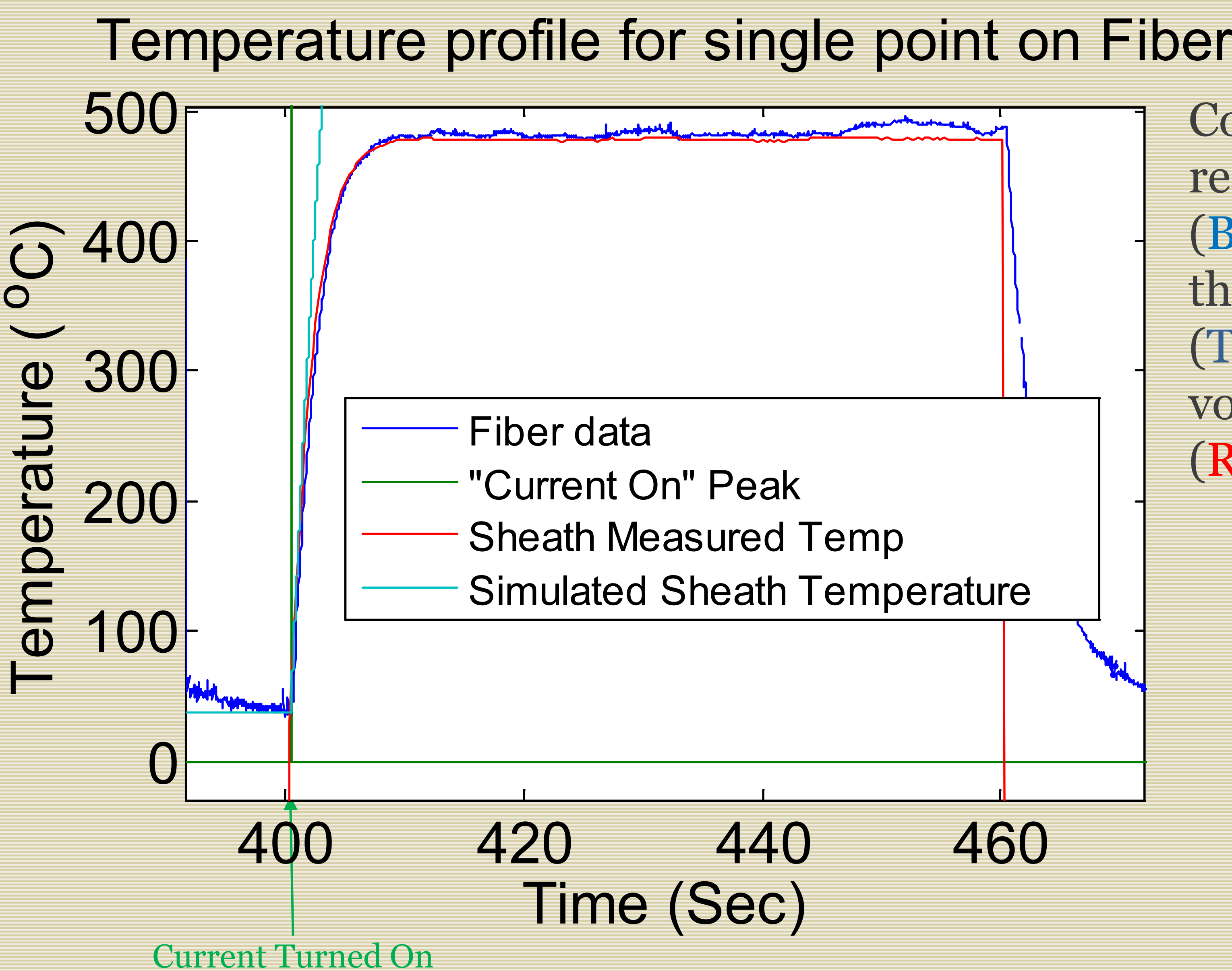
Resistive Heating Data

Cyclic testing from 100C to 700 C for up to 100 hours shows good reproducibility





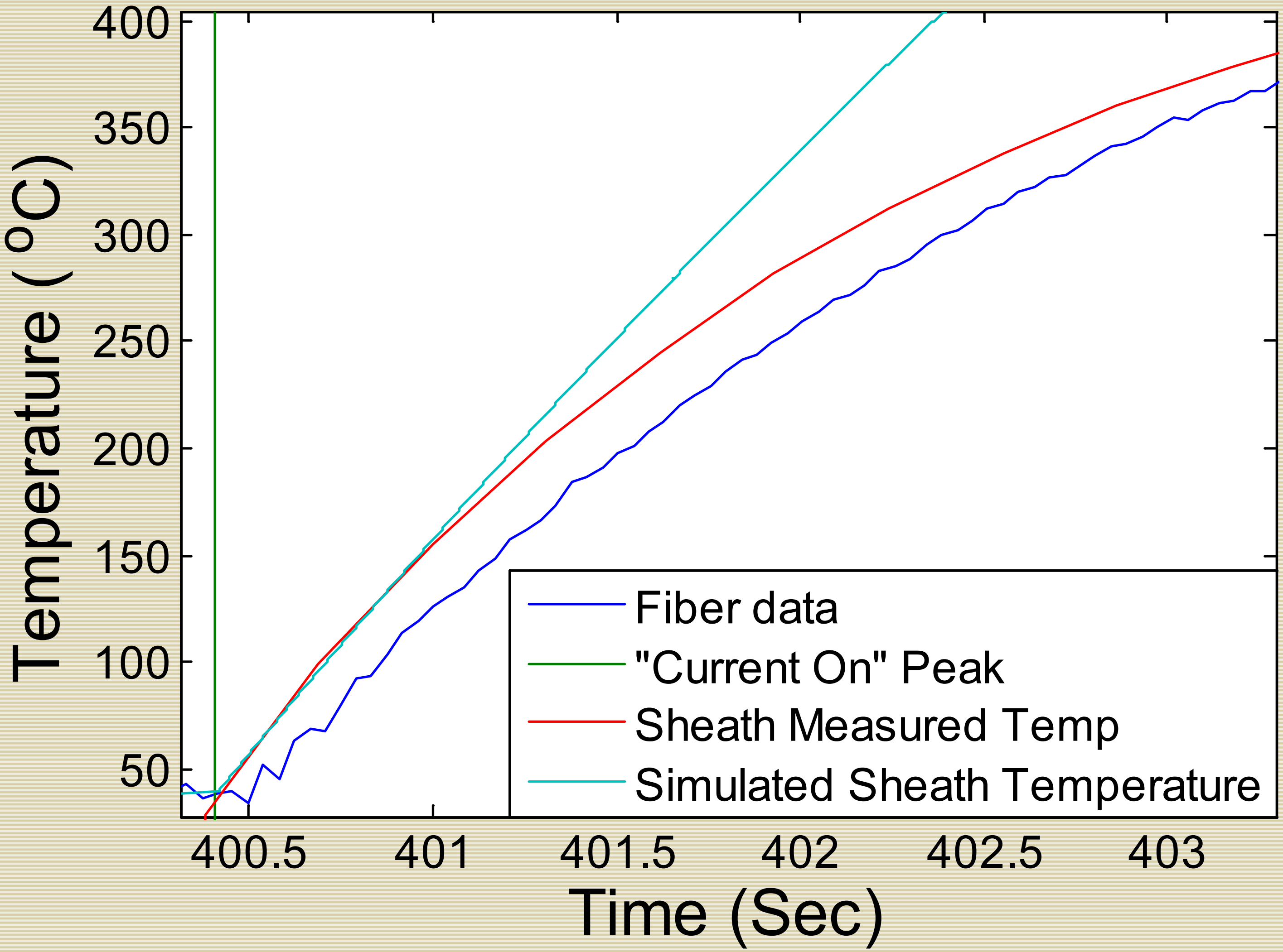
Time response measurements



Compare temperature reading of fiber sensor (Blue) with adiabatic theoretical heat up (Teal) and resistivity voltage measurement (Red)

Time Response

Temperature profile for single point on Fiber



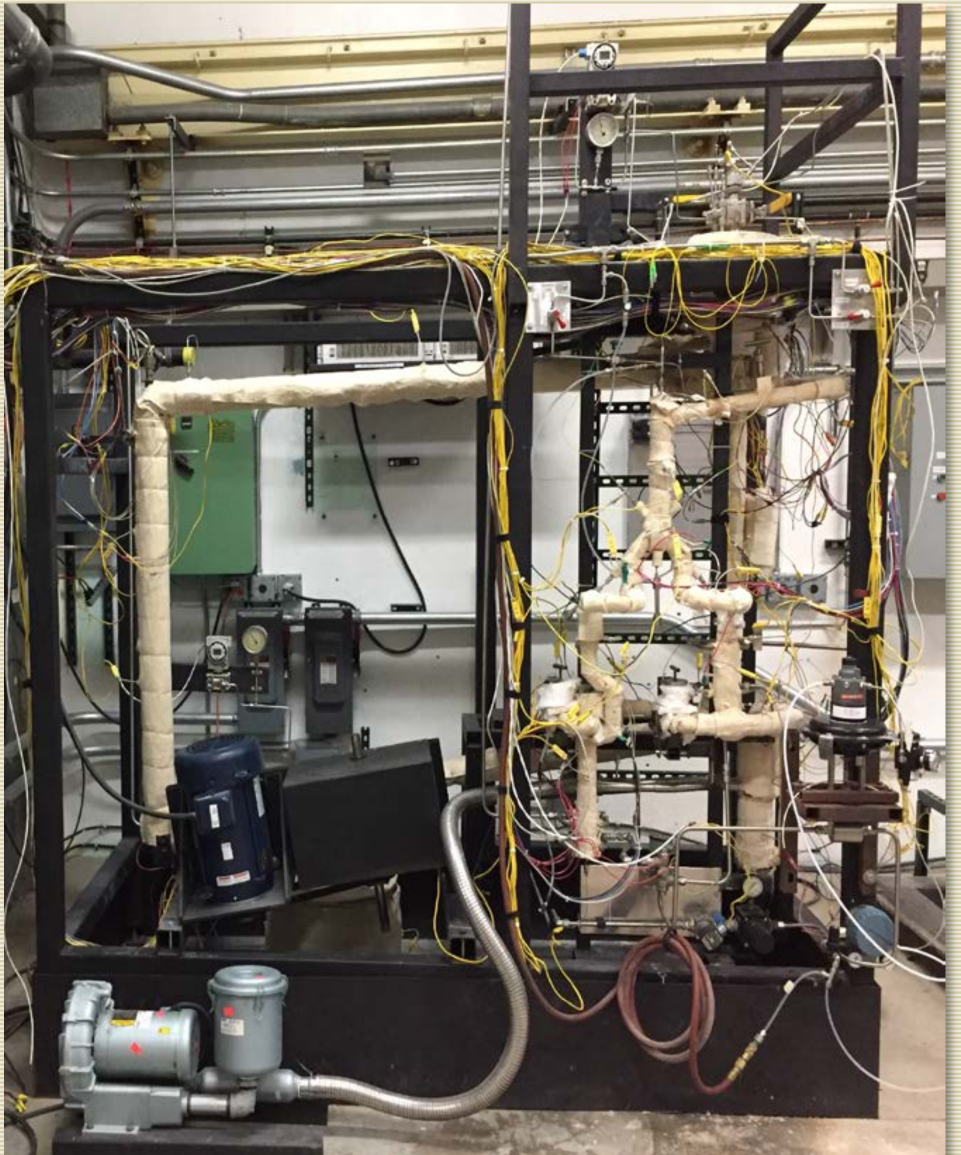
Data for .013" OD X 0.007" ID

Time Lag: τ~0.1-0.2 s for this particular sheath

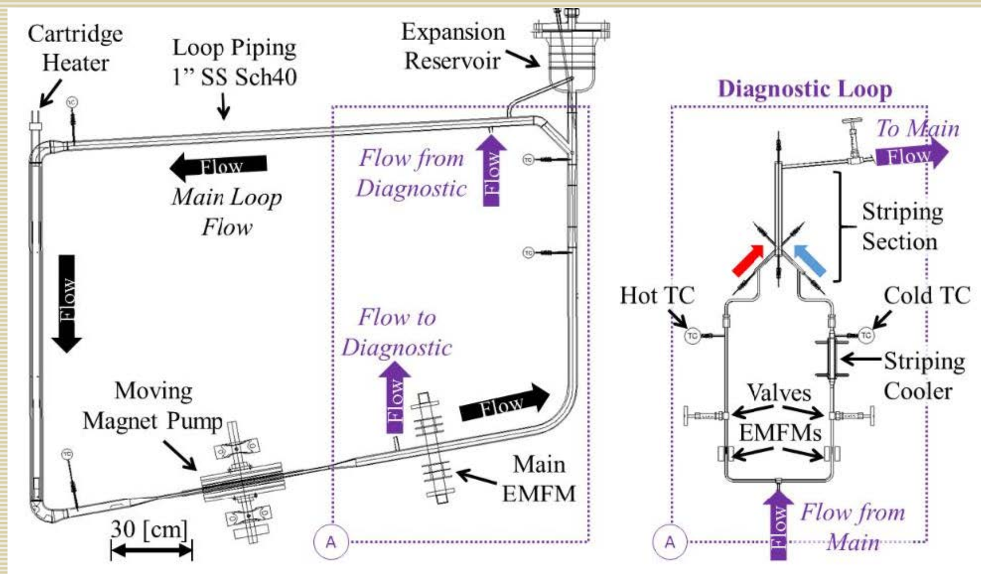
Sodium work done at the UW has shown τ~0.025 s

Robustness in sodium loop testing

Fibers installed in sodium loop to measure mixing of cold/hot streams of sodium

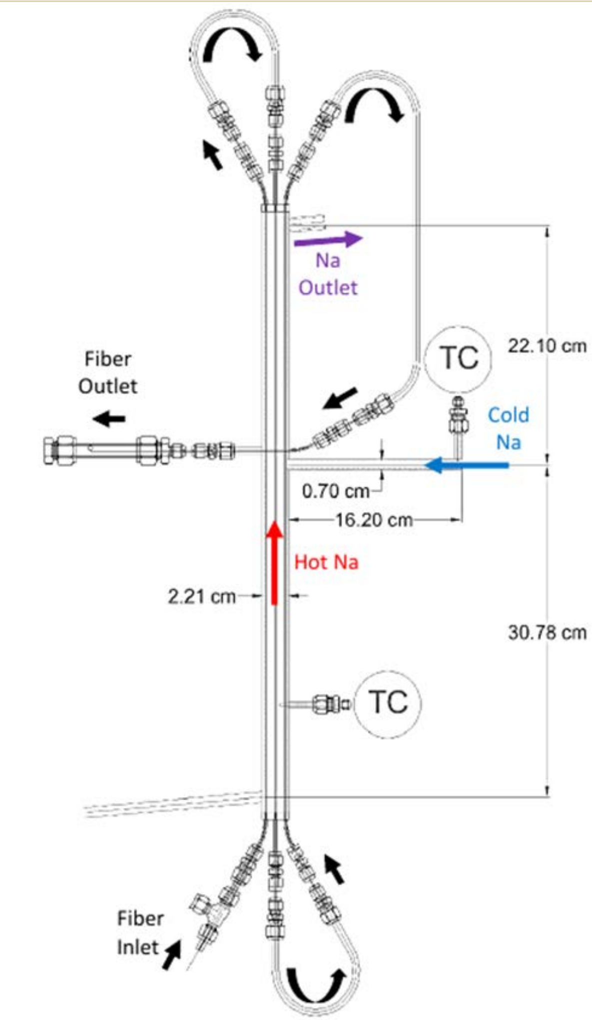


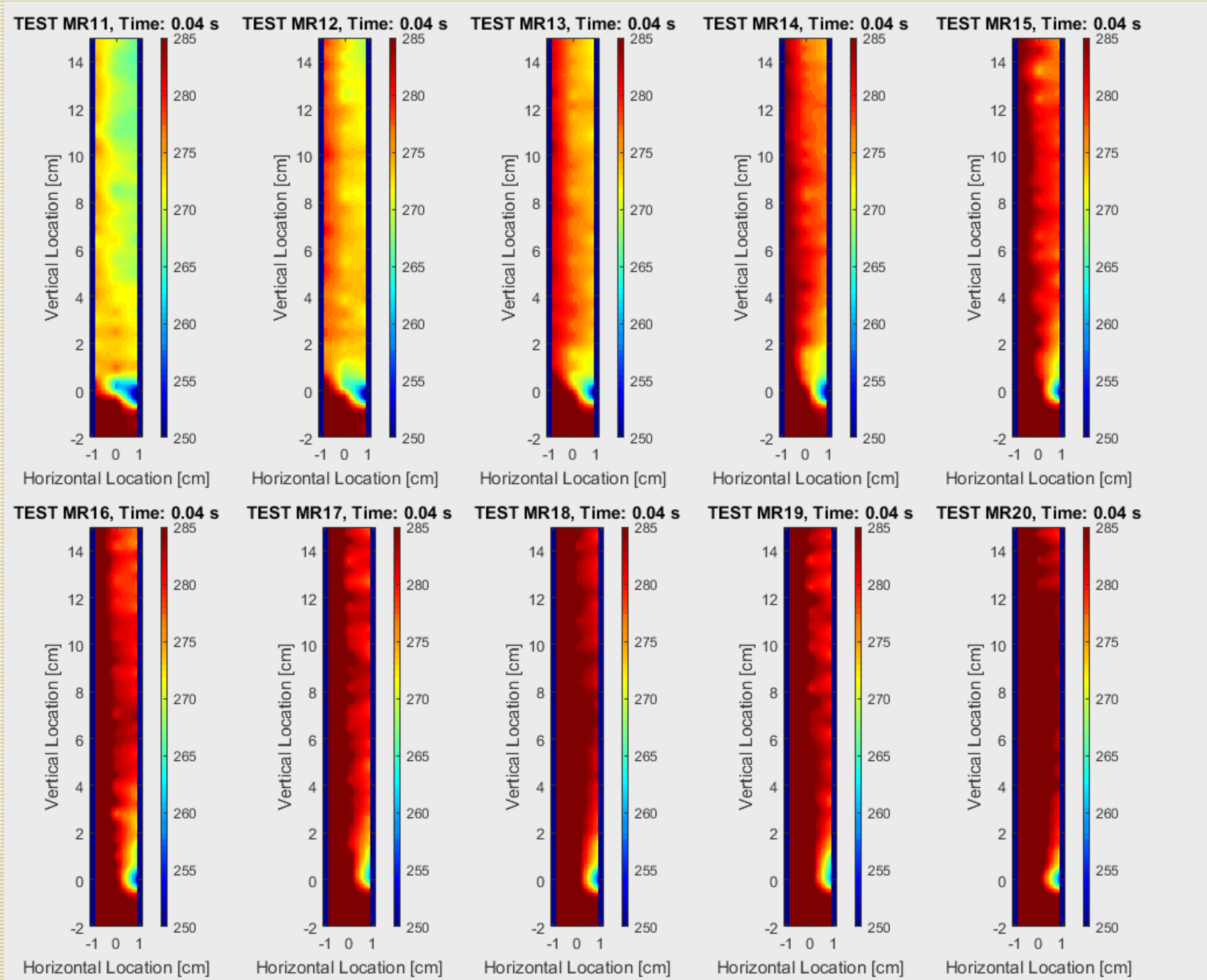
Loop Parameter	Value
Construction Material	316 Stainless Steel
Temperature Range	100-700 [°C]
Sodium in Loop	7 [L] from MSSA (France)
Maximum Flow Rate	150 [L/min]
Oxide Control	0.82 [L] Cold Trap
Oxide Level Reading	RDT Spec. Plugging Meter
Pump Type	Moving 24x SmCo Magnets
Heater Types	4 [kW] AC Cartridge 1 [kW] AC Tape Heaters DC Nichrome Heaters
Data Acquisition	National Instruments (NI) CompactRIO 9024
Sodium Flowmeters	3x Permanent Magnet Type Voltage Read w/ NI 9219
Temperature Acquisition	K Type TCs, NI 9212



Fiber tests in mixing sodium

- T-junction geometry facilitates mixing of two non-isothermal streams of sodium to create transient temperature oscillations. Transient fiber temperature measurements are shown below



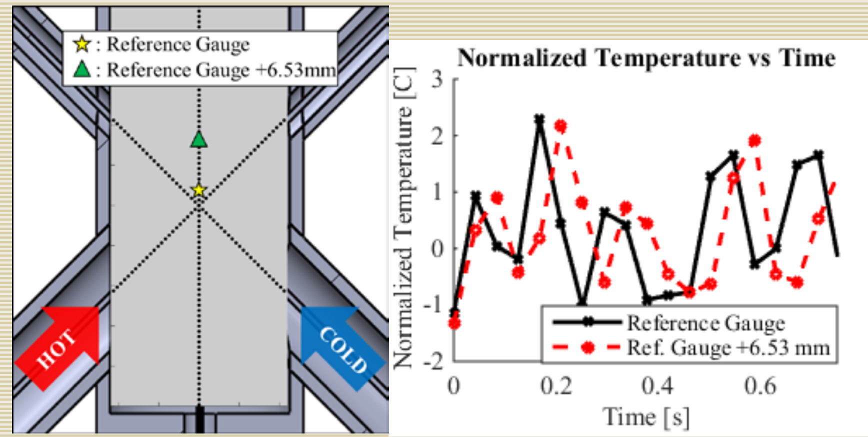


Other ancillary uses of the fibers

Fluid velocity measurements

1. Choose a reference gauge and acquire temperature data at reference gauge and at gauges downstream
2. Calculate cross correlation at downstream temperature gauges with respect to reference gauge
3. Find gauge location with maximum correlation at particular time lag values
4. Calculate velocity with known gauge distance and calculated time lag value

1.

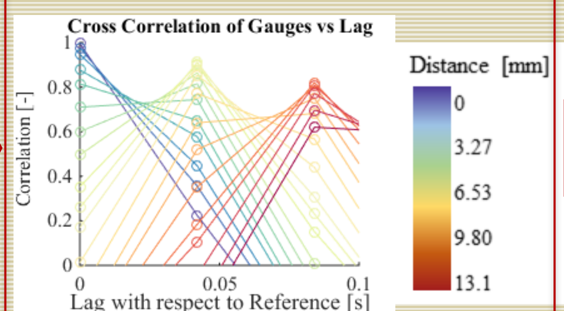


2.

$$C_{12}(\tau) = \frac{1}{P-\tau}\sum_{n=1}^{P-\tau} G1_n G2_{n+\tau}$$

C_{12} ≡ Cross correlation of gauge 1 to 2
P ≡ Measurement time period
τ ≡ Lag
$G1, G2$ ≡ Temperature at gauge 1 and 2

3.



4.

$$V = \frac{D}{\tau_{CCV}}$$

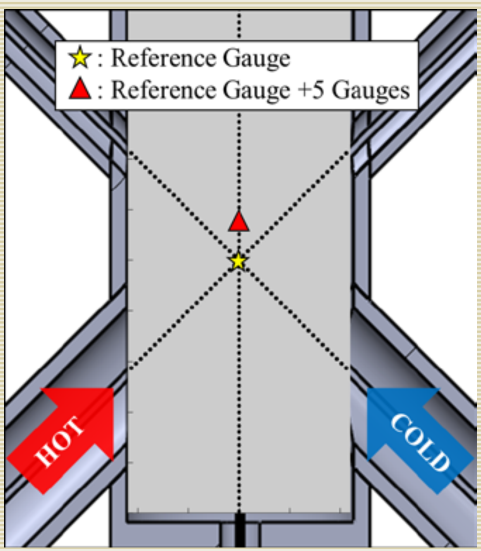
V ≡ Calculated Velocity
D ≡ Distance b/t gauges
τ_{CCV} ≡ Calculated lag b/t gauges

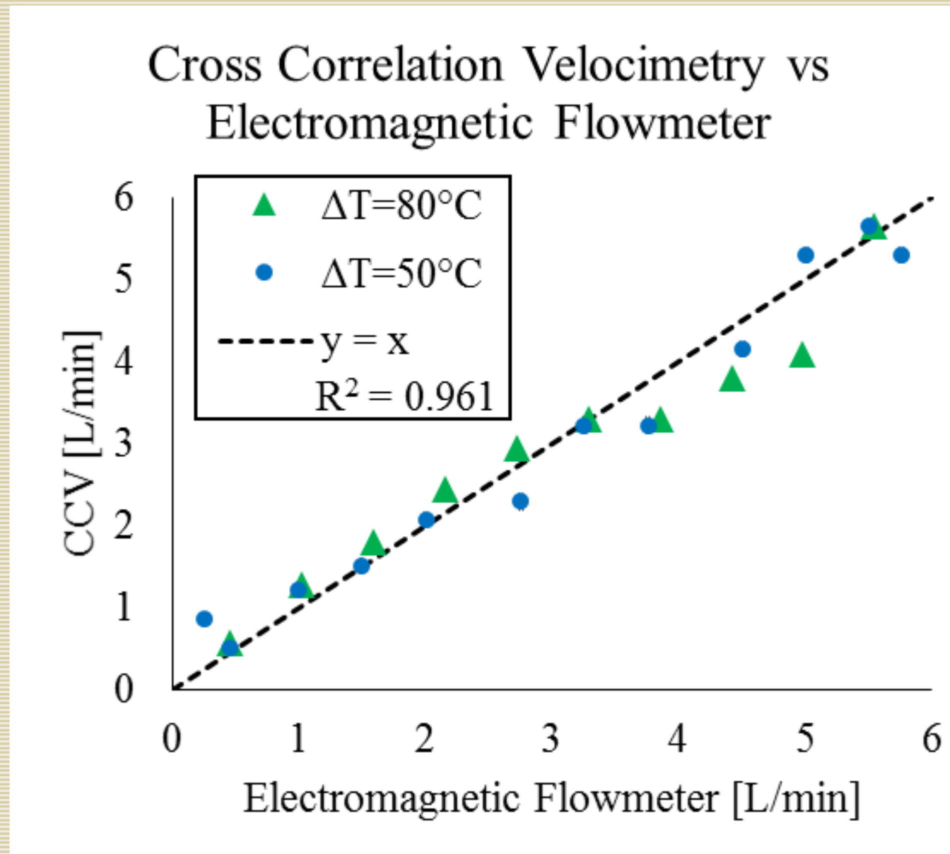
Optical Fiber Cross Correlation Velocimetry

- Cross correlation velocimetry (CCV) performed for a constant momentum ratio of 0.7 at a temperature gradient of 80C and 50C between the two flow streams for flow rates between ~0.25-5.8 L/min.
- A reference gauge at the crossing point was chosen and the cross correlation was performed with a fiber gauge 5 gauges down stream from reference.
- The momentum ratio of 0.7 was experimentally found to give steady and consistent oscillations at the center of the mixing tube.
- Data acquisition period of 60 [sec] for each flow rate
- Good correlation found between CCV and calibrated electromagnetic flowmeters

System Parameters:

	T_{hot} [°C]	T_{cold} [°C]	M_R
ΔT=80°	500	420	0.7
ΔT=50°	500	450	0.7



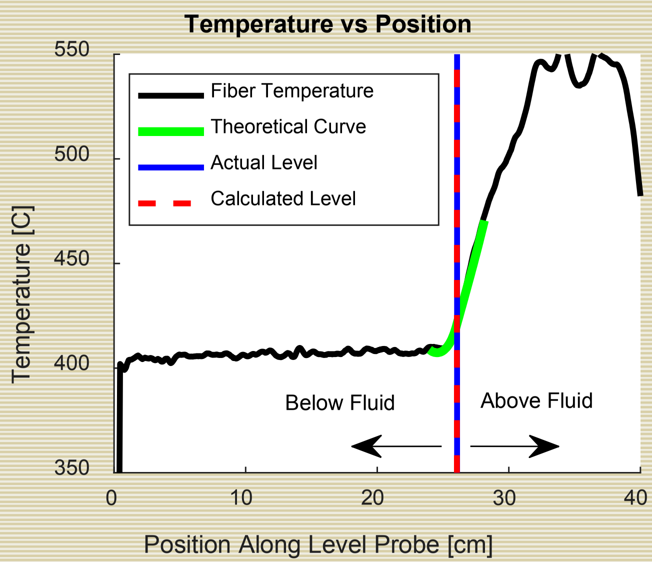


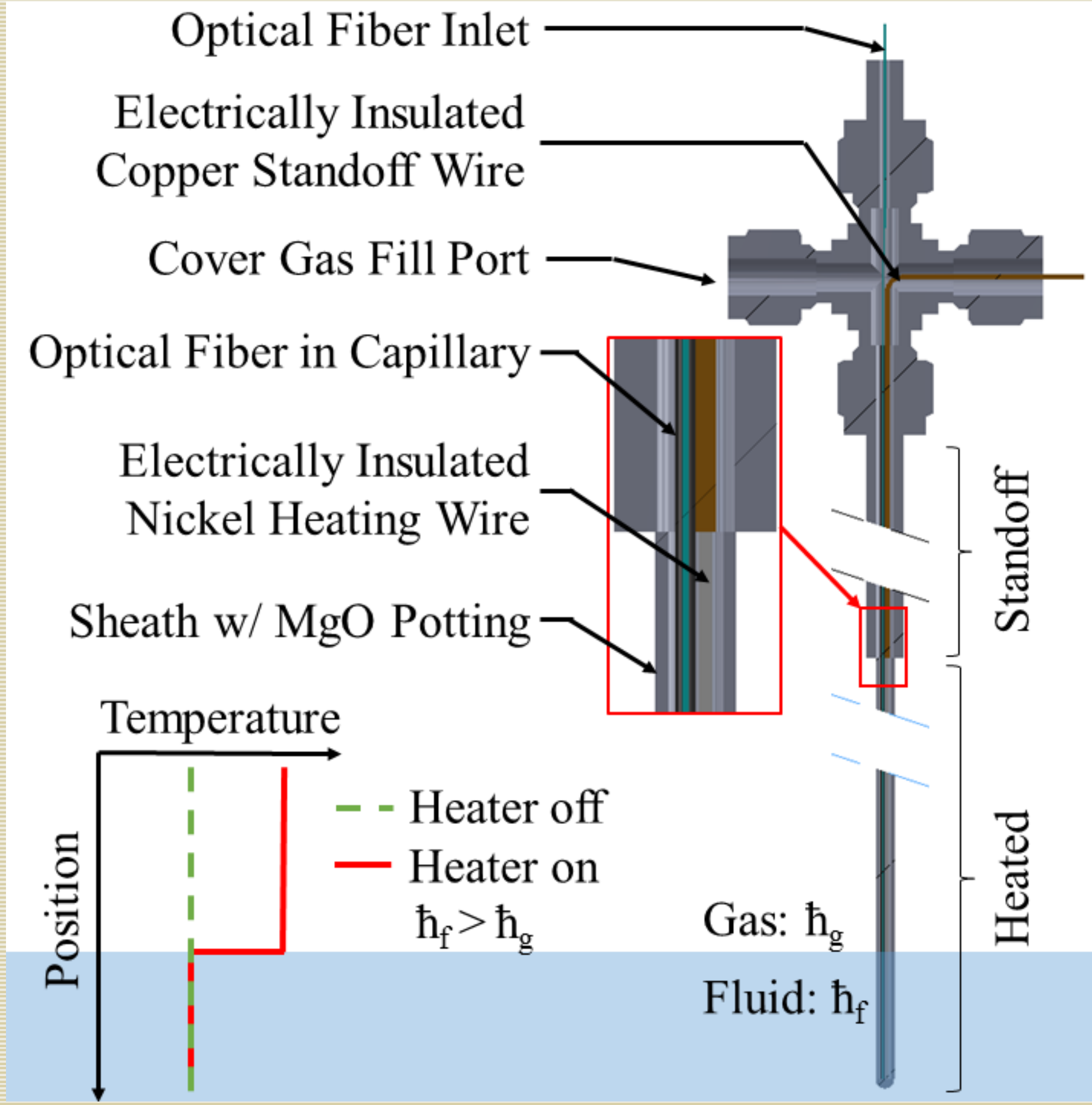
Continuous precision level sensing

- Continuous level sensing or thermal conductivity in high temperature fluid/solid use of optical fiber level sensor
- Optical fiber temperature sensor running tangential to heating wire may diagnose convection coefficient at level sensor surface.
- Free convection coefficient may be theoretically determined by calculating Rayleigh number and using correlations provided in literature to find Nusselt number[1]

$$Ra = \frac{gL^3\beta(T_s - T_\infty)}{\nu \cdot \alpha} \qquad Nu = \frac{\bar{h}L}{k}$$

- Using heater power and calculated free convection coefficient a theoretical temperature profile may be determined numerically and fit to actual fiber data to determine level position





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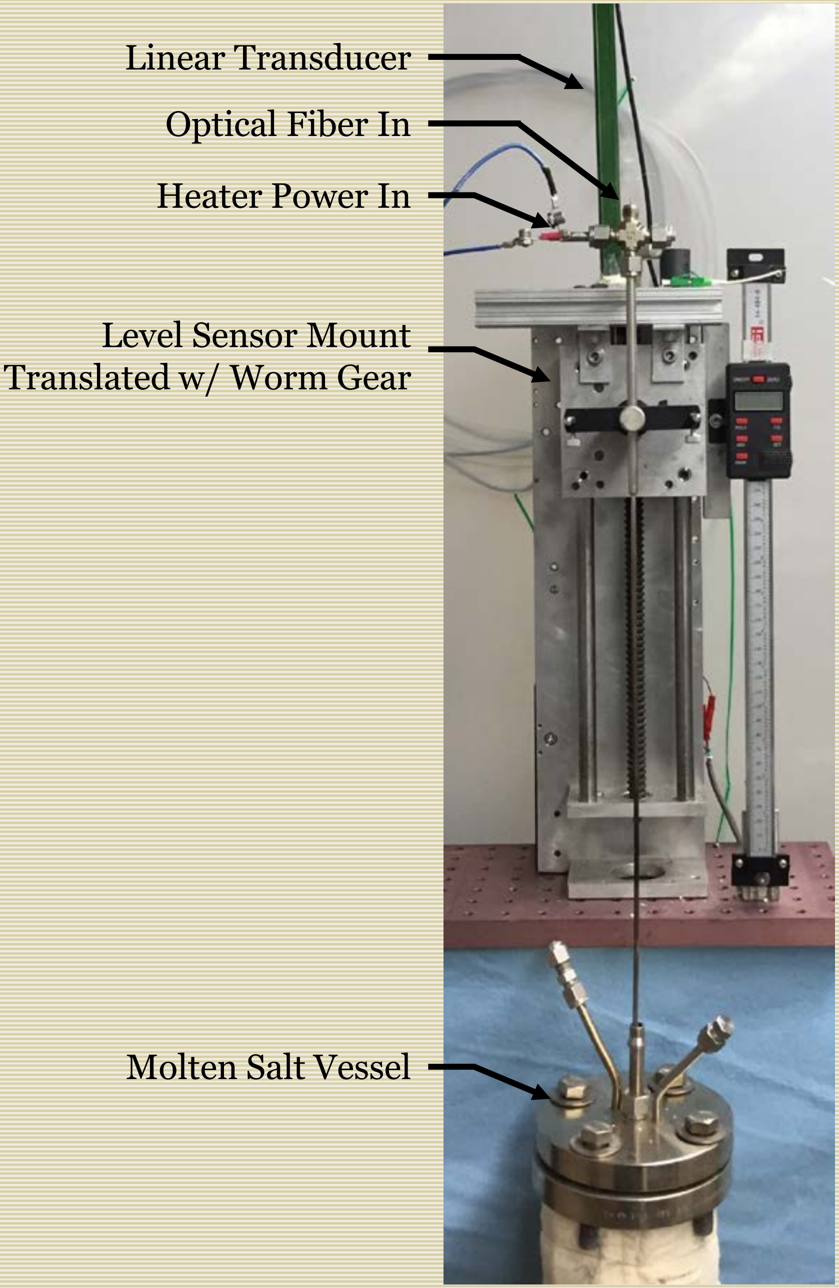
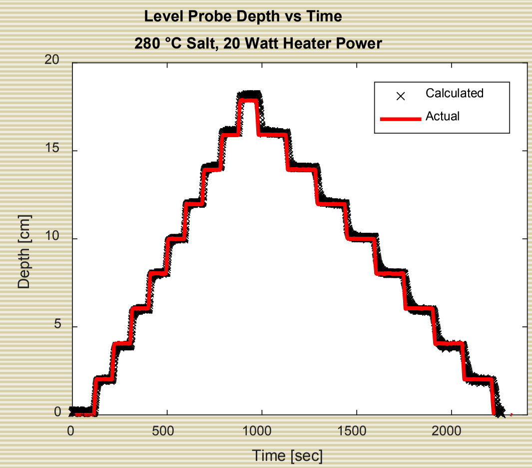
UTILITY PATENT APPLICATION TRANSMITTAL (Only for new nonprovisional applications under 37 CFR 1.53(b))	Attorney Docket No.	1512.582 (P170028US02)
	First Named Inventor	Mark Harlan Anderson
	Title	Optical Fiber Thermal Property Probe
	Express Mail Label No.	EFS-WEB

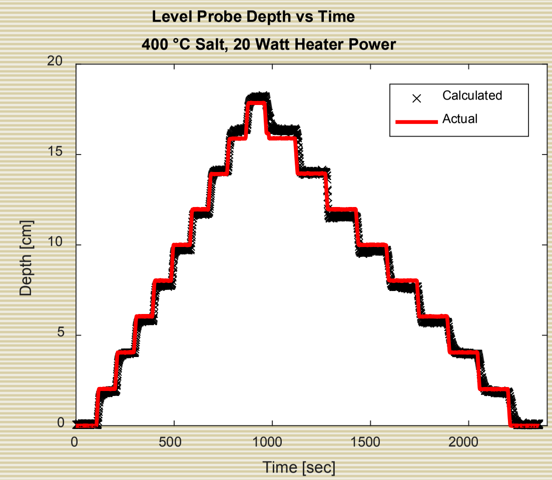
worked with WARF to file patent

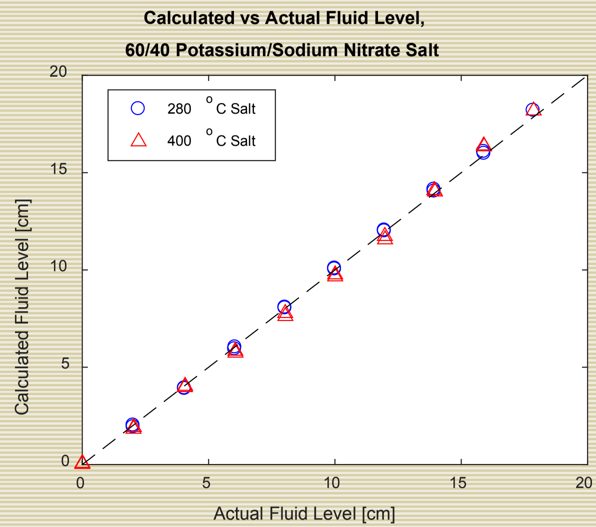
1. Nellis, Klein, Heat Transfer, 2009

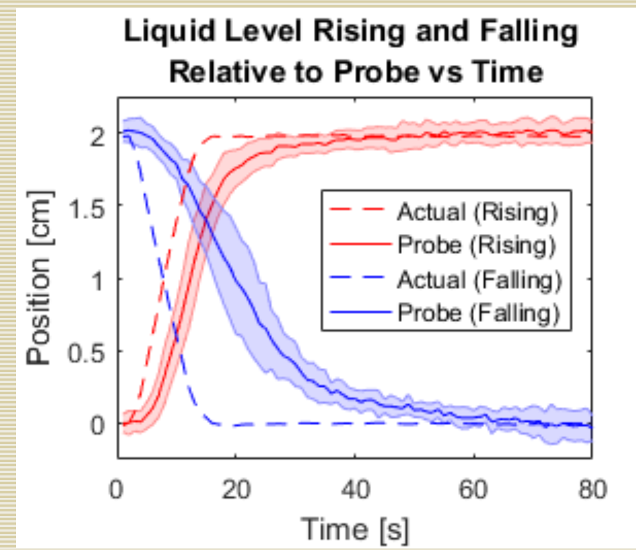
Optical Fiber Level Sensor, Results in Molten Salt





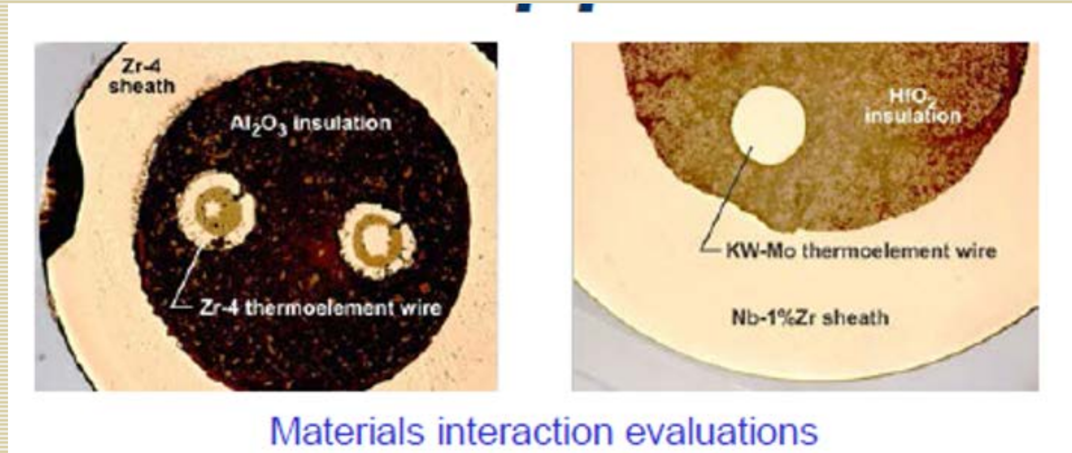


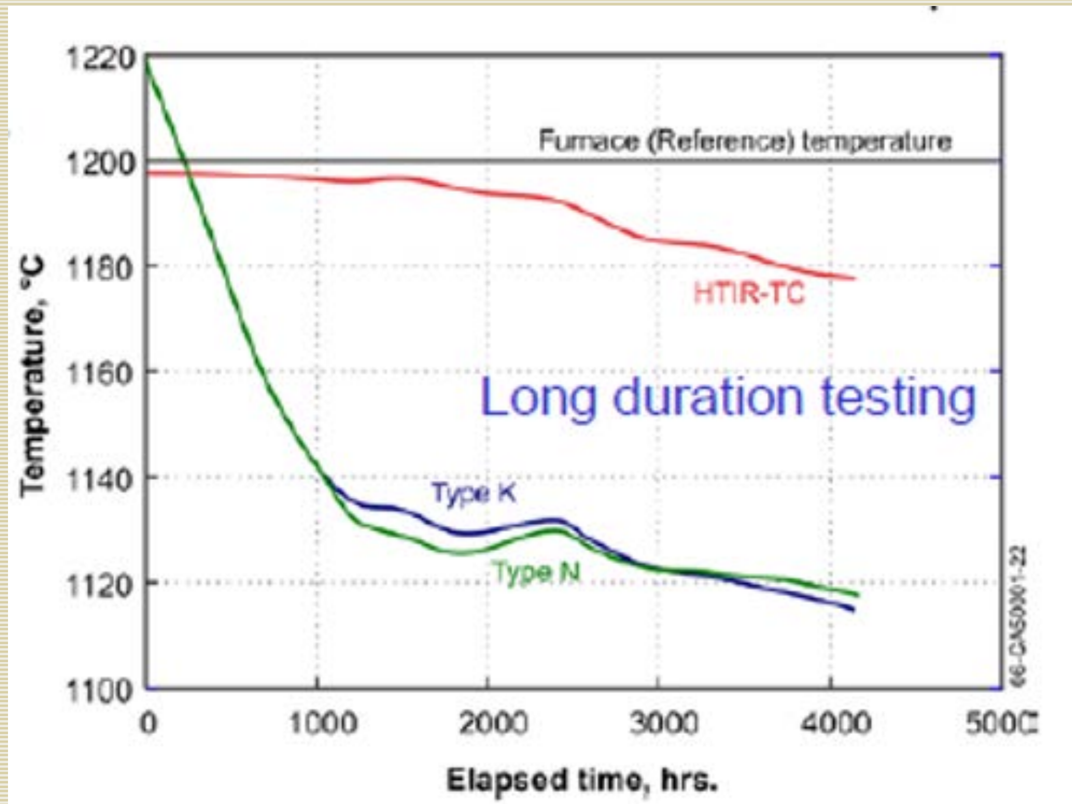




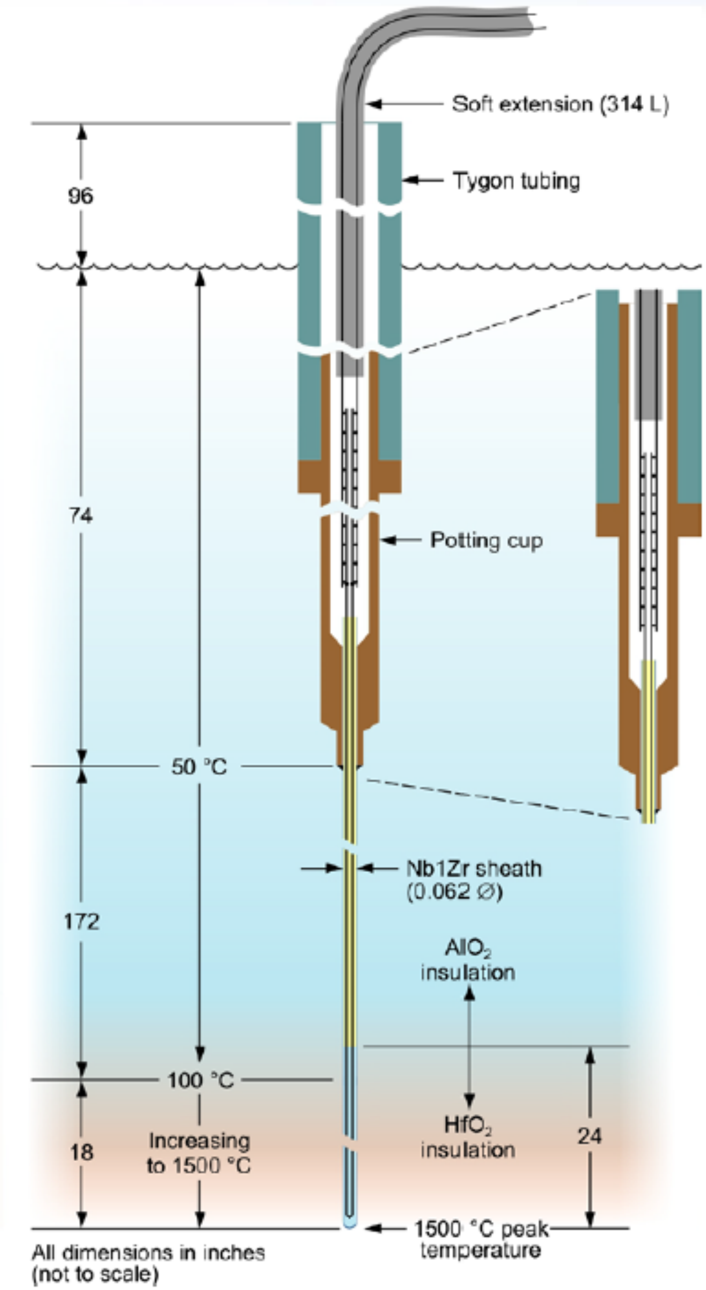
HTIR-TC

- HTIR-TC uses Nb-1%Zr and Mo thermocouple elements for stability at high temperature in radiation environment
- Temperature range 800-1800C
- Nb-1%Zr sheath for high temperature service
- More stable than commercially available Tungsten, Rhenium, Platinum and Rhodium elements that can decalibrate due to transmutation. The elements used in the HTIR-TC are more stable
- HfO2 insulation for high thermal resistance at temperature.





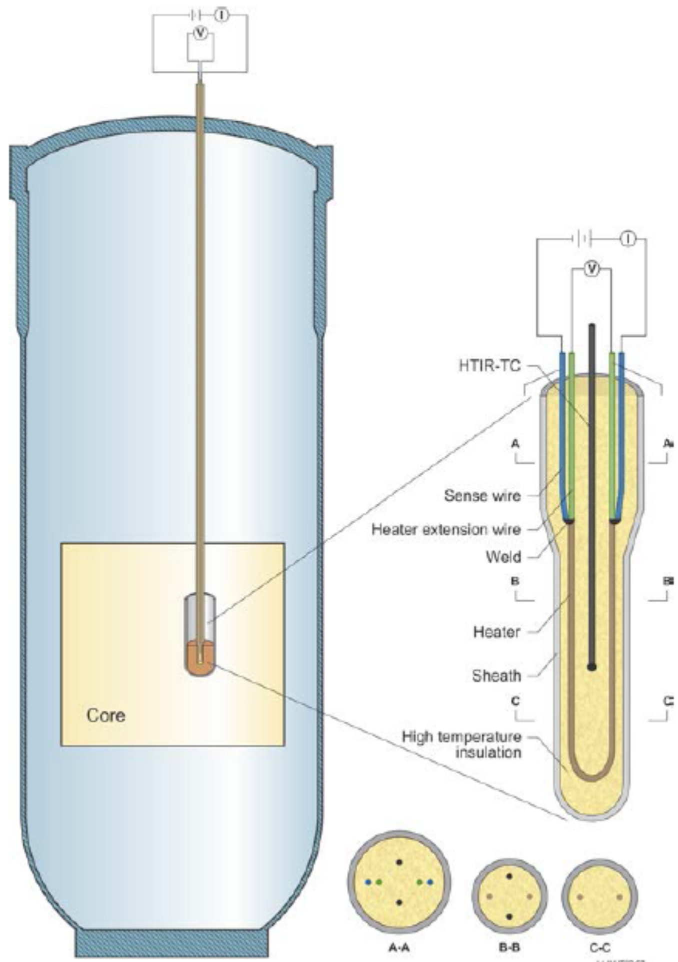
HTIR-TCs Designed for Experiments at UW-Madison



- HfO_2 insulation required in high temperature region – Al_2O_3 elsewhere
- Transition to soft extension in pool via custom potting cup
- Transition to soft extension protected by Tygon tubing

Thermal Conductivity Sensor

TCNP Overcomes Obstacles Associated with In-pile Thermal Conductivity Measurement



Dual diameter heater

- Smaller diameter heater wire in specimen
- Heater wire / lead materials and diameters selected to minimize heating in leads
- Transition to 4 wires for power detection located in cool location

Dual diameter probe

- Smaller diameter minimizes probe influence on specimen being measured
- Larger diameter accommodates larger diameter heater leads

Irradiation resistant high temperature fabrication

- TC-like construction with high temperature materials that resist interactions and transmutation
- Specialized welding techniques join small diameter heater to larger diameter leads
- Can include INL-developed HTIR-TCs for detection in high temperature irradiation conditions
- Specialized swaging techniques provide a dual diameter leak-tight sheath

Current issues with thermal conductivity sensor

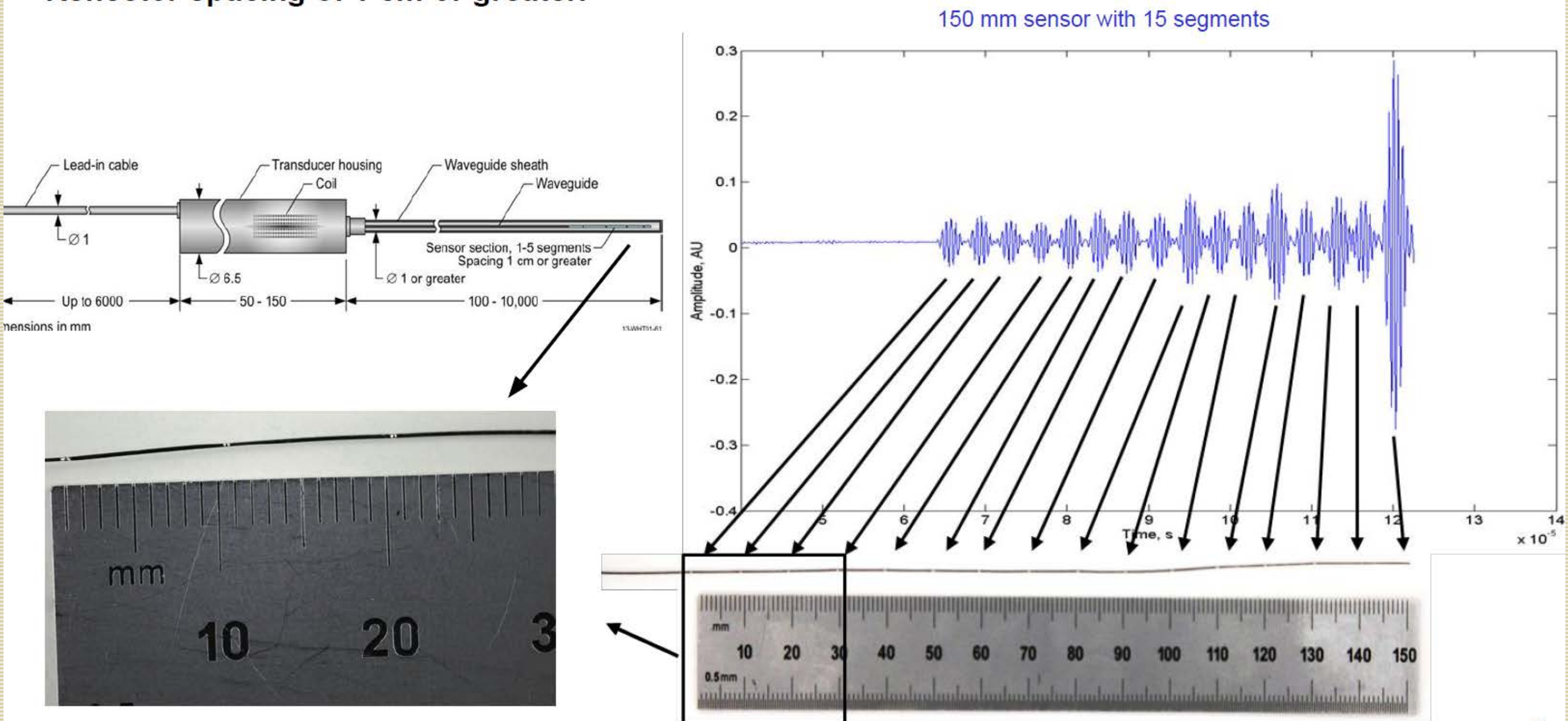
- The Thermal Conductivity sensor requires a thermal contact with the medium it is measuring such that the thermal resistance is low enough so as not to be the limiting factor in observing the temperature decay inside the probe.
- Currently, finely machined ceramics are being tested in the hopes that a tight fit will produce a low resistance junction between the sensor sheath and the medium under test
- This is proving troublesome and results are indicate that a new method pot the sensor into the medium maybe necessary.

Ultrasonic temperature sensor

Idaho National Laboratory

UT Development Allows Gradient Measurement

- Multiple sensor segments allow temperature profiling along probe length.
- Sensor material selected for optimum performance in various environments and temperature ranges.
- Temperature resolution dependent on reflector spacing and sensor material.
- Reflector spacing of 1 cm or greater.



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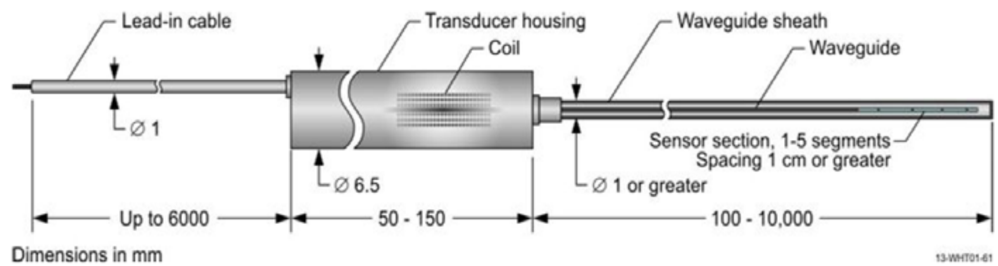
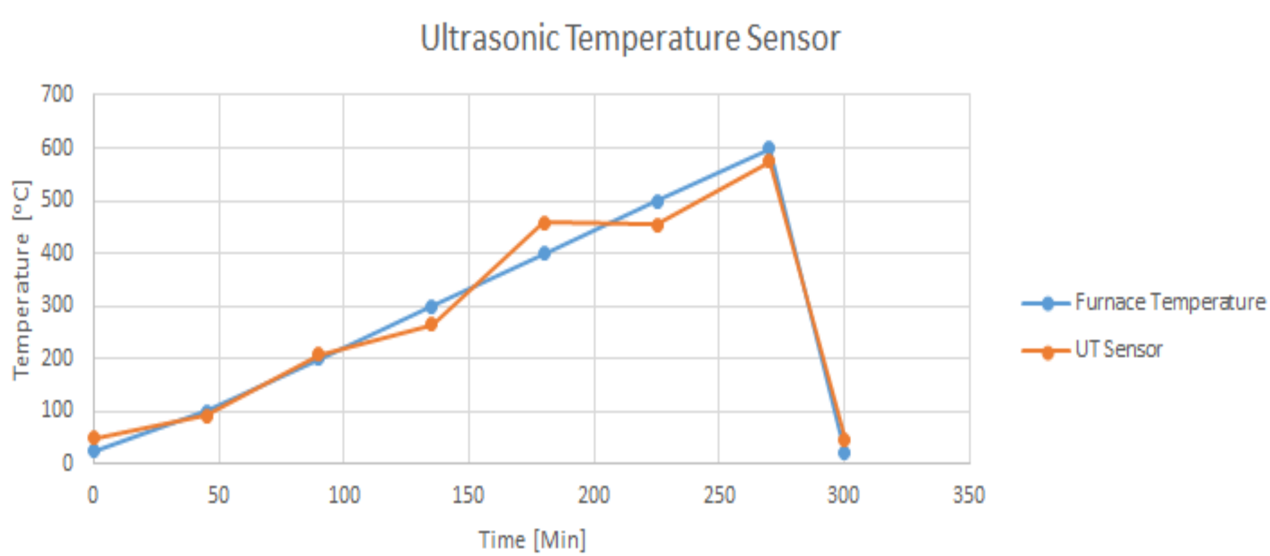
Sensors tested

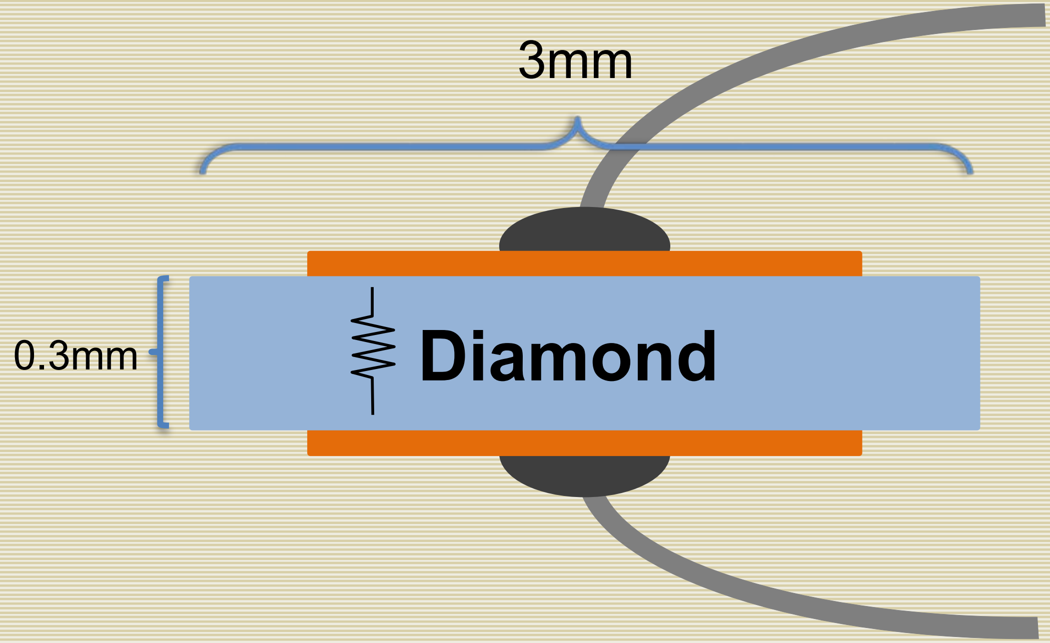
Sensor	Configuration	Max. Temperature
Molybdenum	Single sensor	1500 °C
Inconel 606-1	Single sensor	900 °C
Inconel 606-2	Four sensors	900 °C

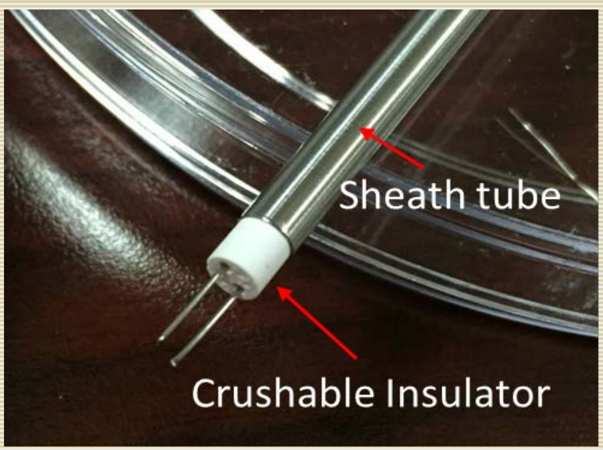


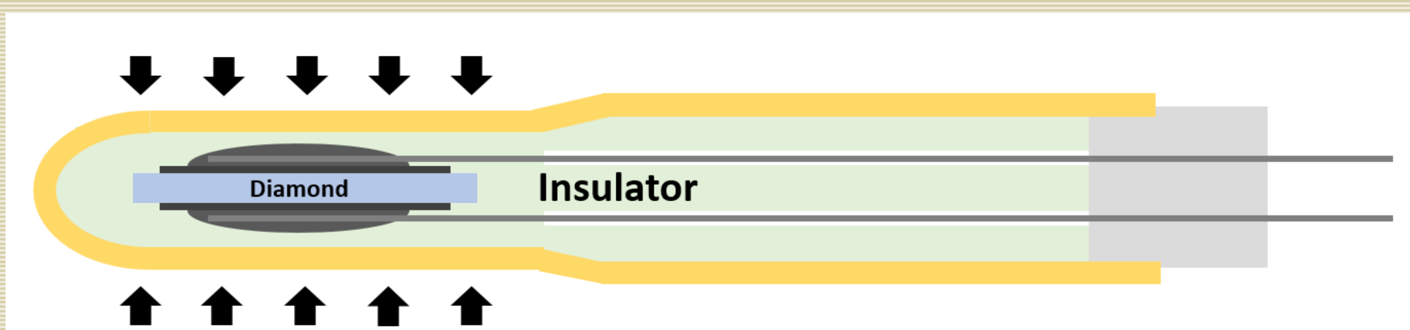


Prototype Diamond Thermistor

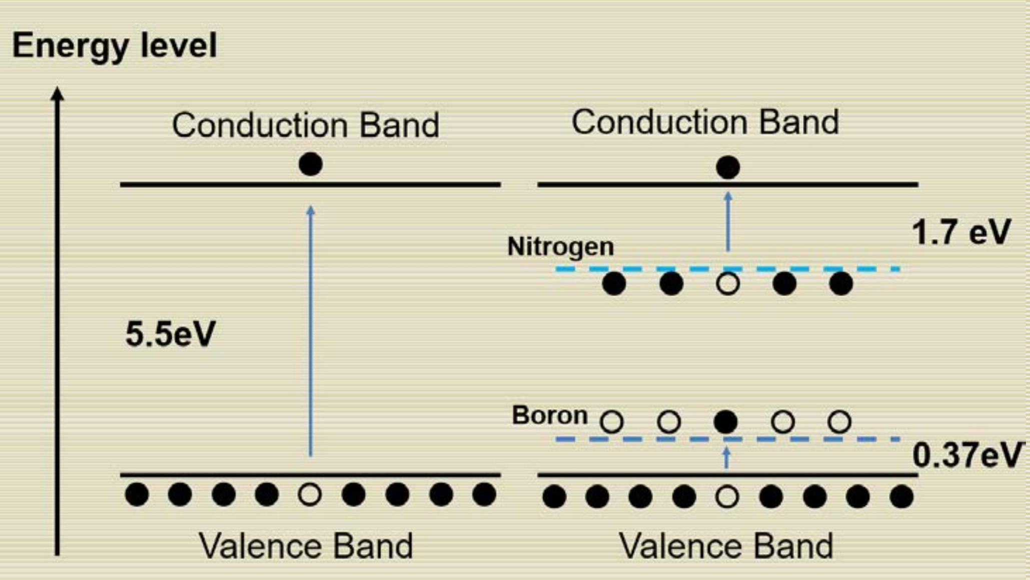
Mo=50nm
Pt=150nm
Ni = 50μm







Properties of the Diamond

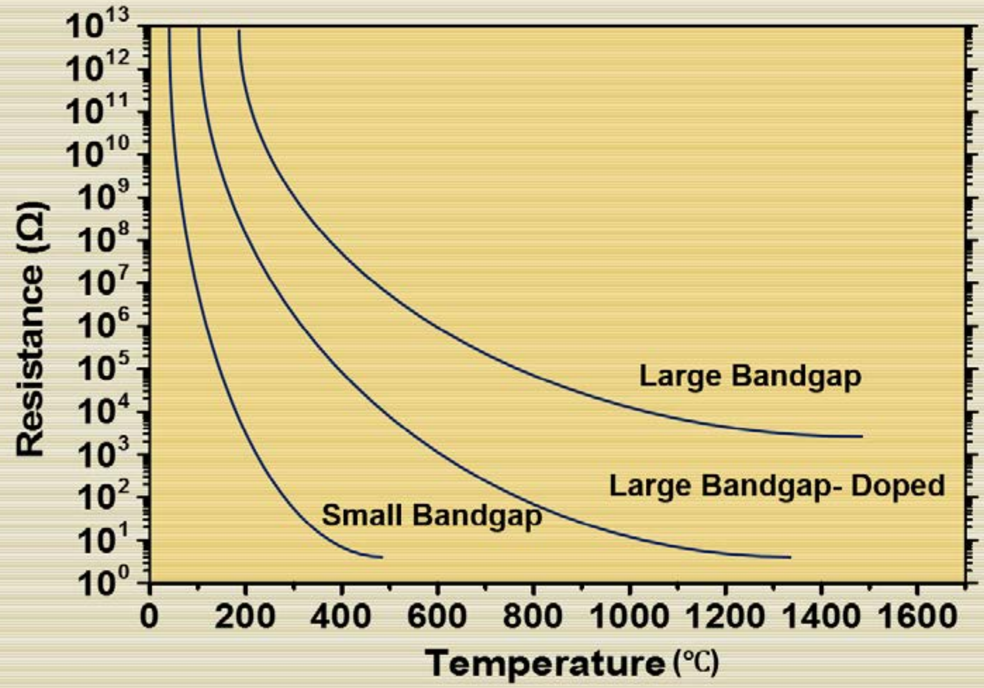


CVD Diamond

Boron: <0.05 ppm
Nitrogen: < 1 ppm

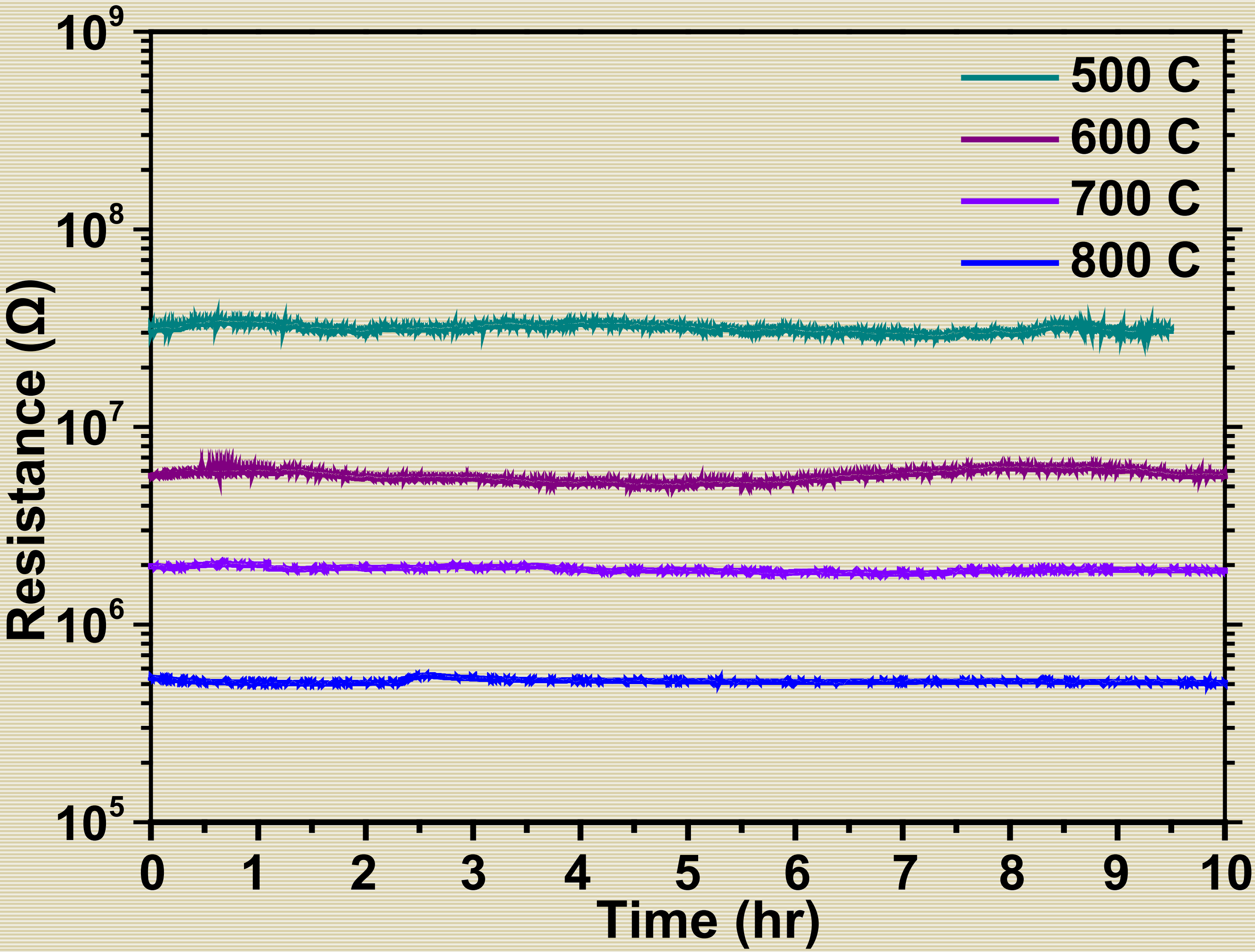
HPHT Diamond

Boron: <0.1 ppm
Nitrogen: < 200 ppm



- As dopants are added we can change the band gap and change the resistance as a function of temperature curve
- Allows optimization on sensor temperature sensitivity

Stability Test of CVD diamond



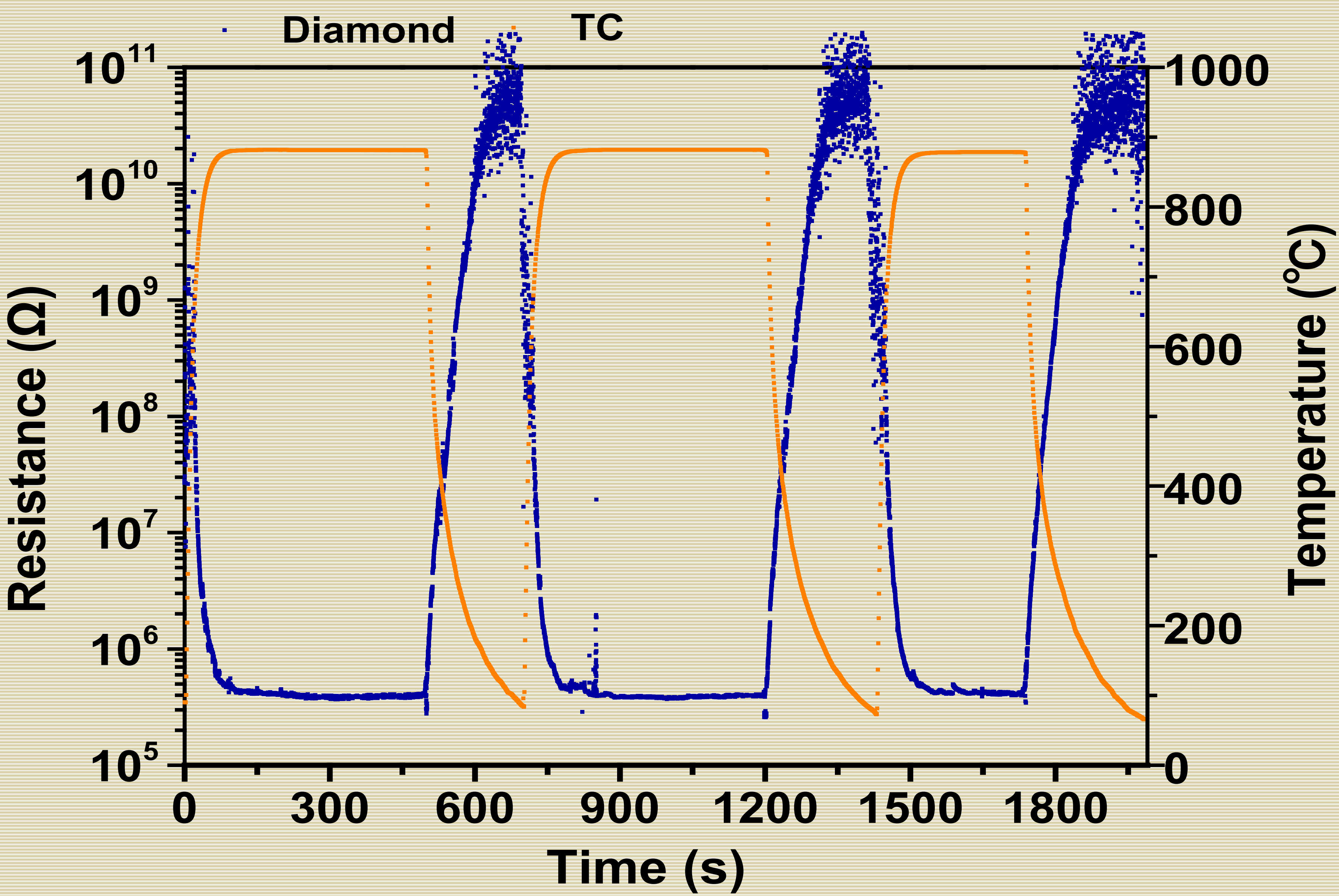
Deviation

Temp	Min(%)	Max(%)
500°C	-4.9	6.7
600°C	-5.3	4.4
700°C	-1	1.4
800°C	-0.8	0.8

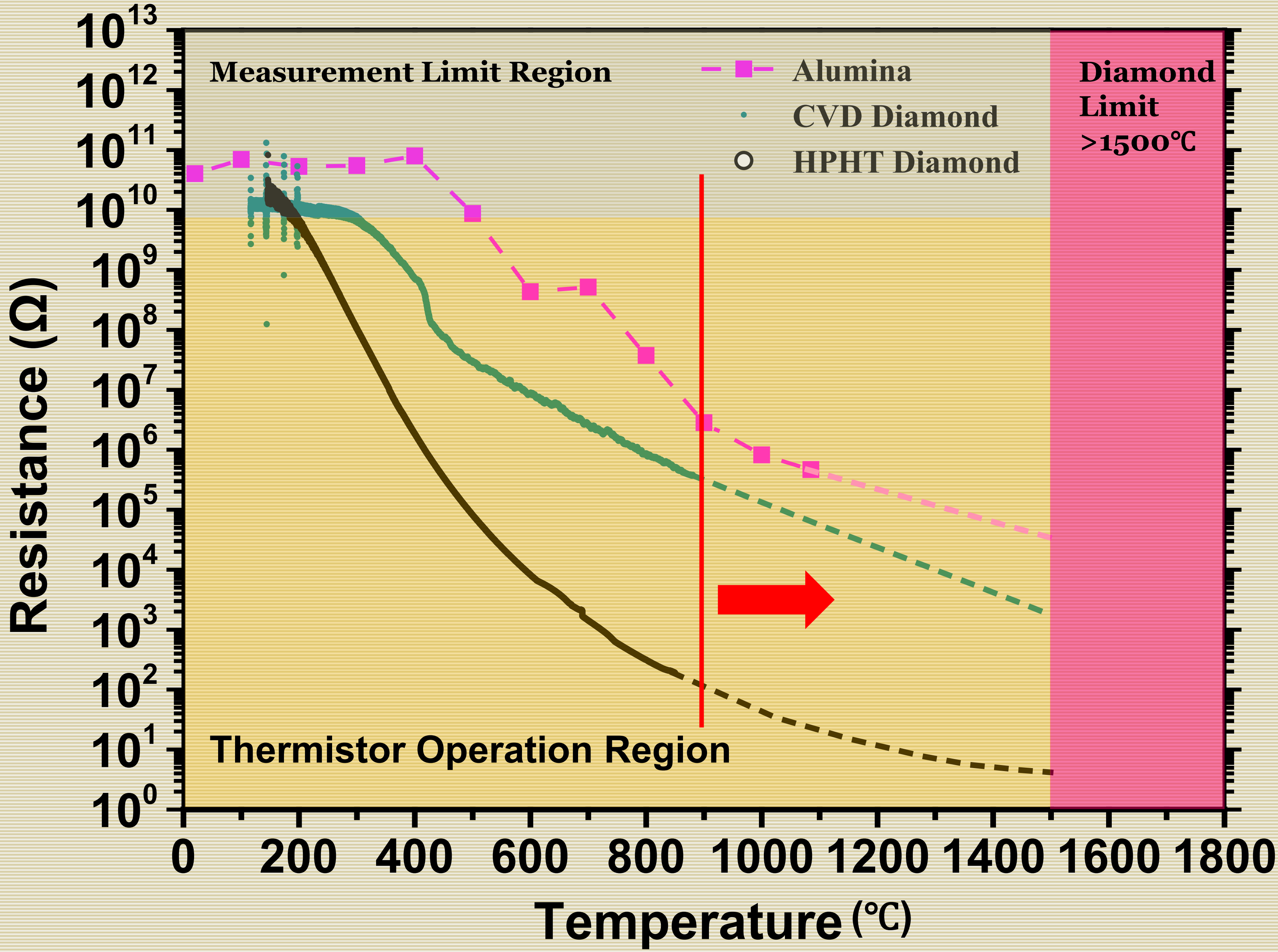
Drift

Temp	**% per Hr**
700°C	-0.29
800°C	-0.45

Cycling Test (CVD, 880 °C)



Resistance as function of temperature

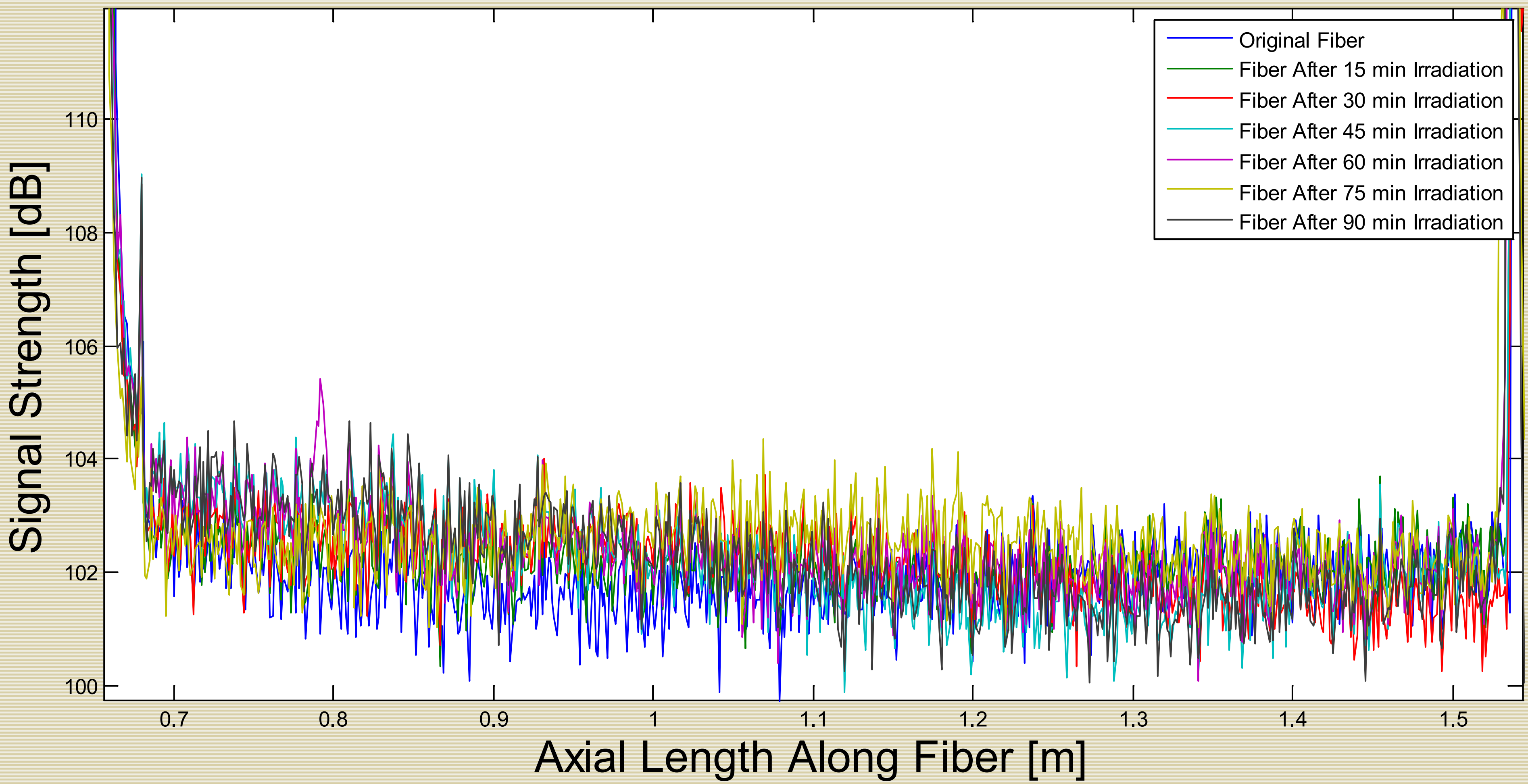


Fiber Radiation Testing

Irradiated fibers in UW-Madison reactor facility

Even after 90 min in core (Total fluence of 4.58 E16 Thermal/1.91E16 Fast) No appreciable change in backscatter signal was detected via the Luna system

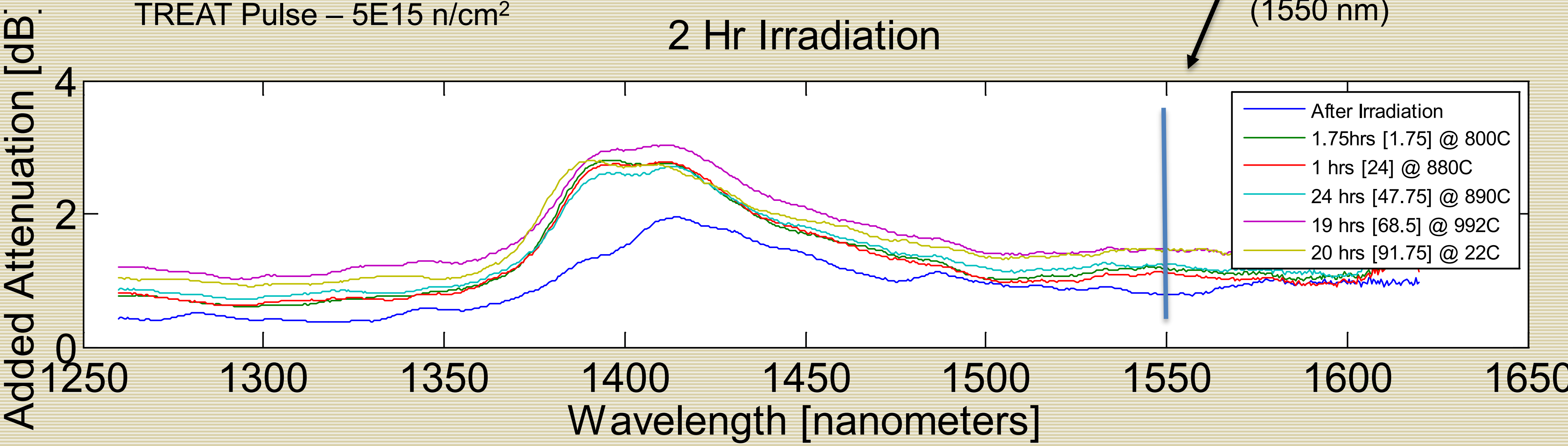
Fiber 4 "key" signal

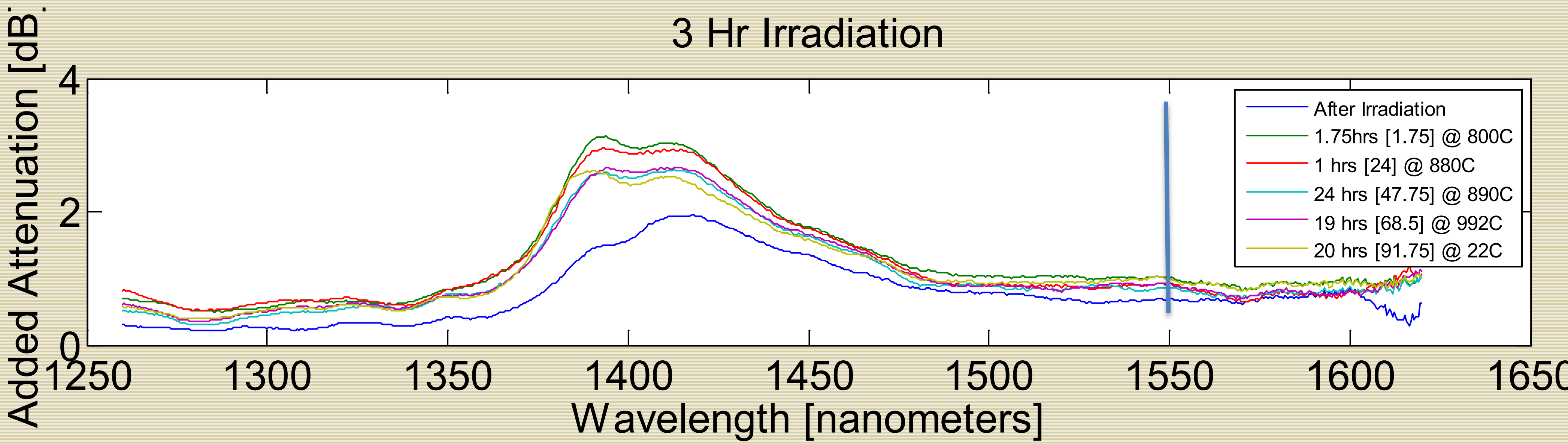


Attenuation Testing Results

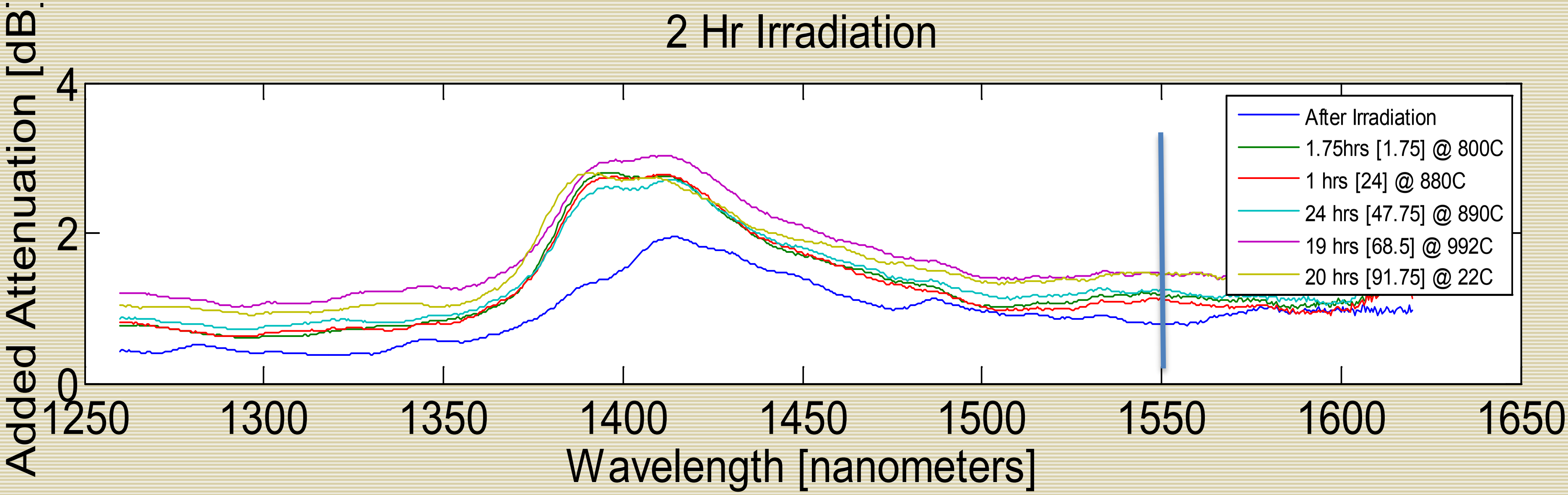
Fluences:
1 hour - 1.27E16 n/cm^2 fast
2 hours - 2.54E16 n/cm^2 fast
3 hours - 3.81E16 n/cm^2 fast
TREAT Pulse – 5E15 n/cm^2

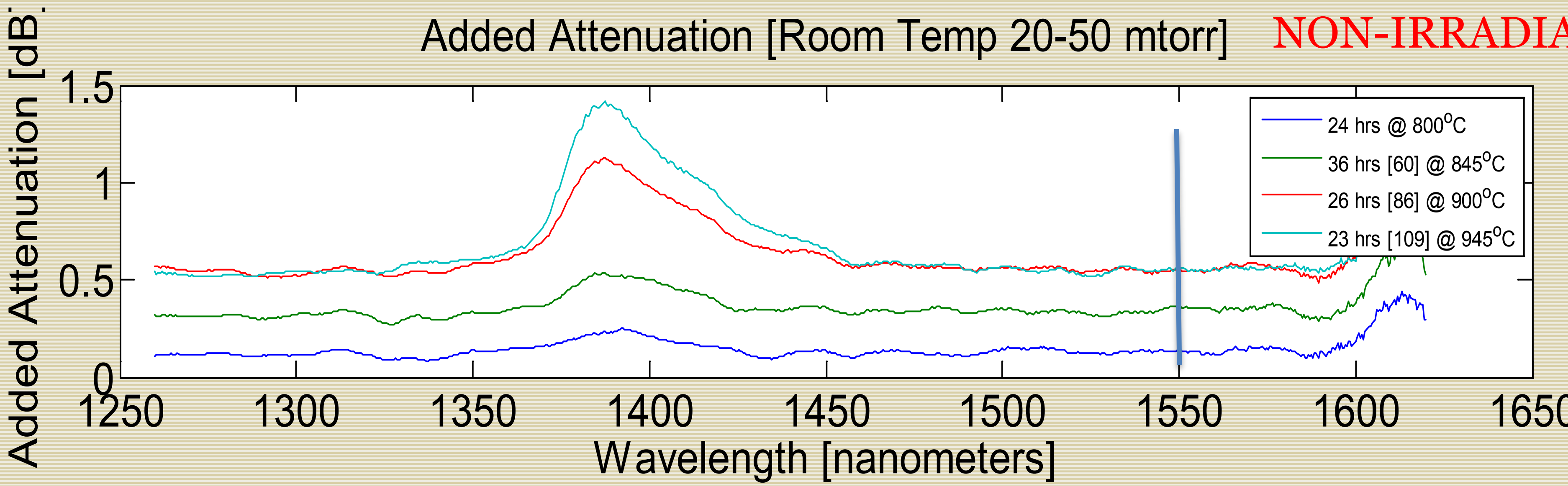
Wavelength used for temperature measurement (1550 nm)





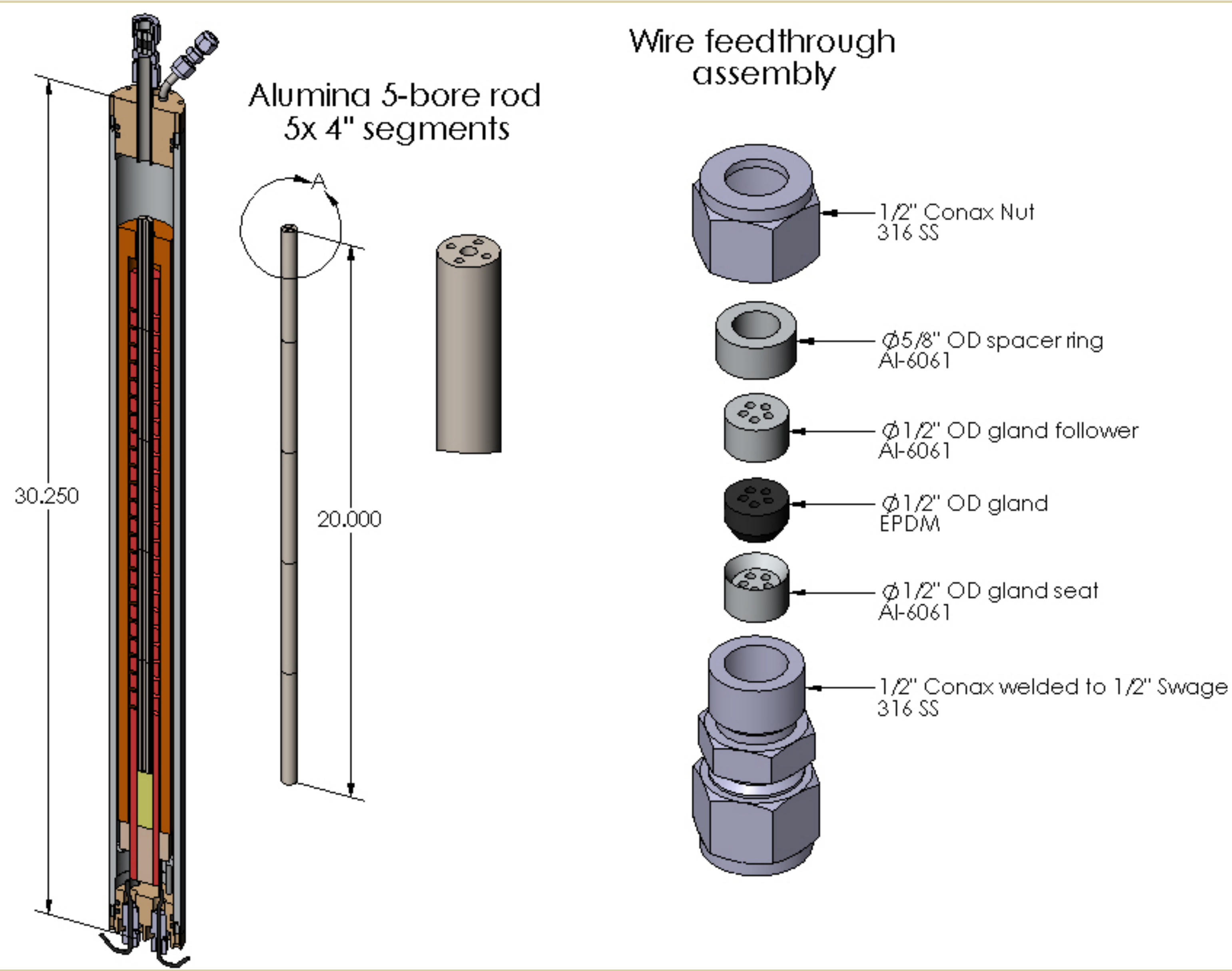
Comparison with Non-Irradiated



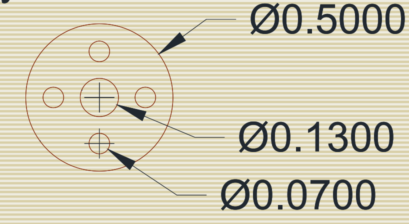


NON-IRRADIATED

Test vehicle for in-pile testing of sensors (radiation testing)



Custom Zirconia Cylindrical Core



Fiber, HTIR-TC, Ultrasonic Temperature sensor tested in UWNR reactor pool under a series of temperature and radiation pulses

Reactor test vehicle

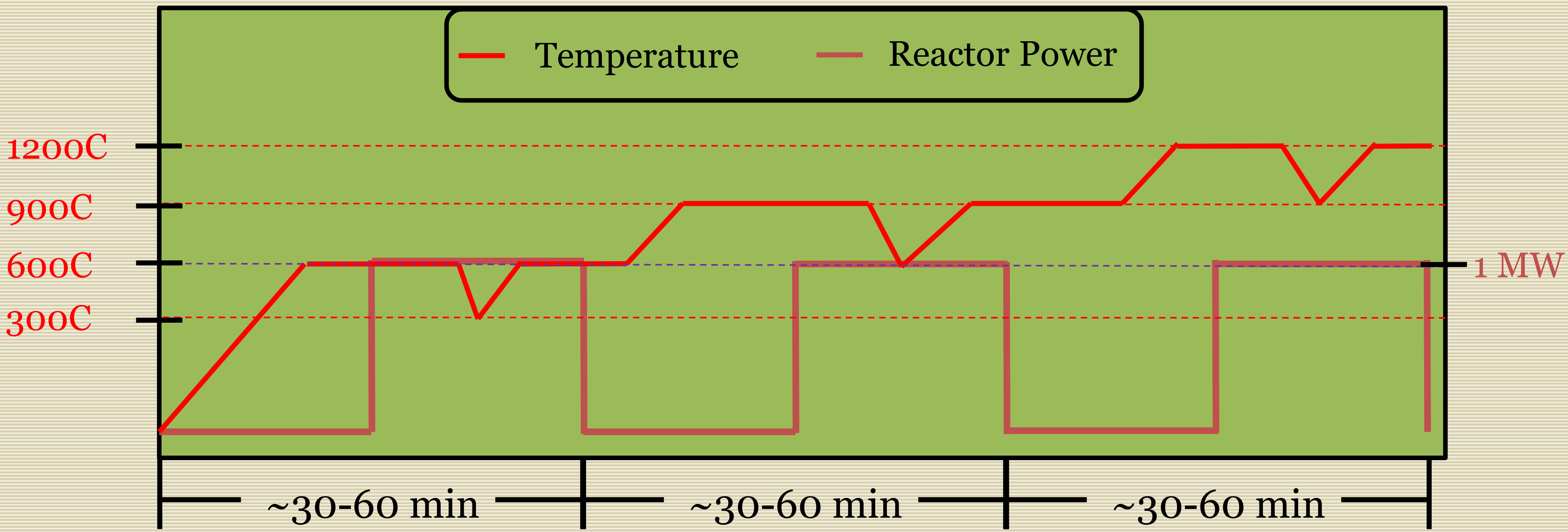
Test Section with Reservoir in background

Current Top Cap

Bottom Cap w/ Heater Leads

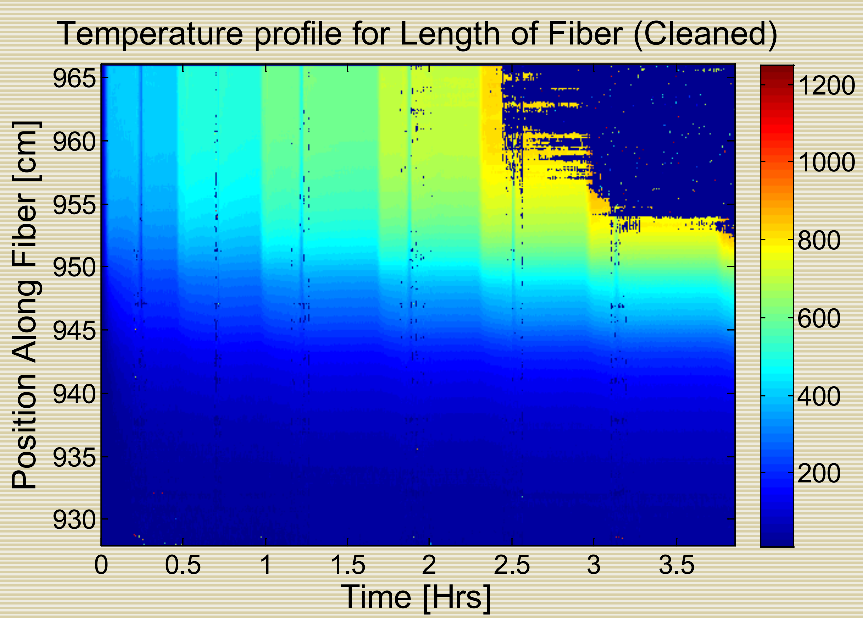
Reactor testing

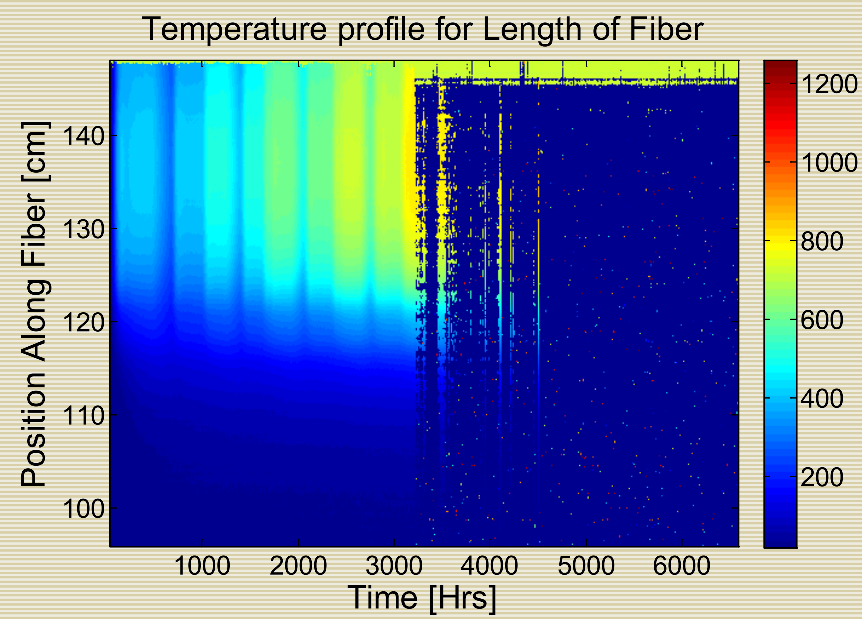
Heat from 400 – 1200°C following the general schedule as shown below to allow for steady state in temperature and power as well as transients of both

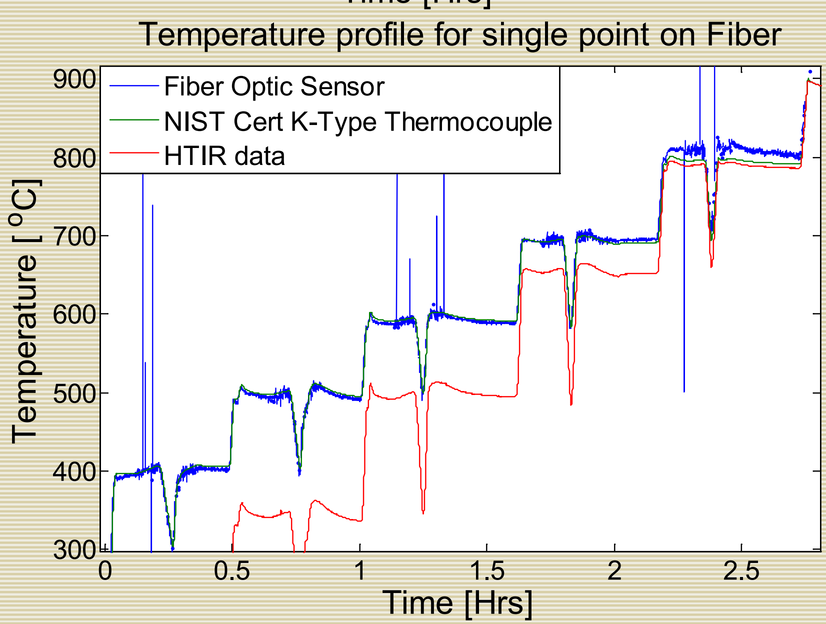


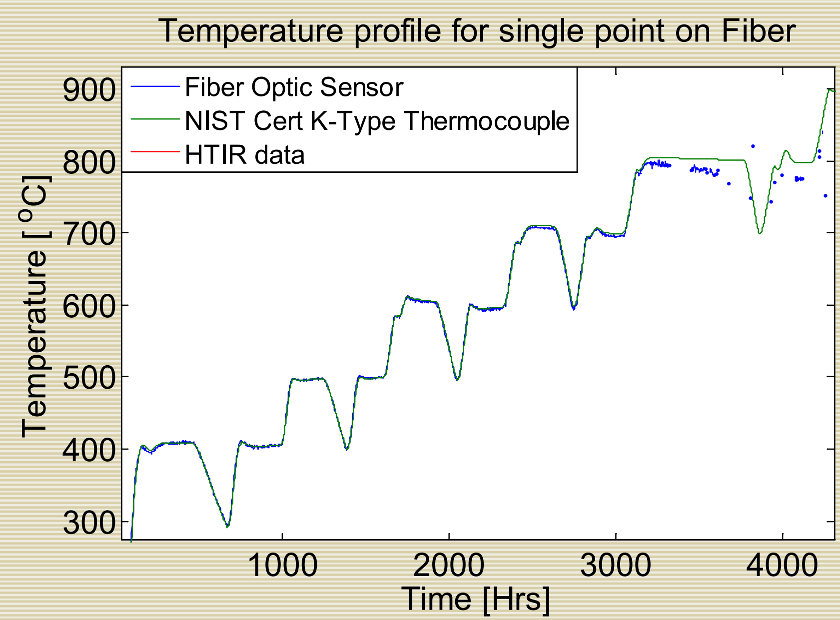
Out-of-Pile vs In-Pile Fiber Performance

High temp testing both inside and outside a radiation environment



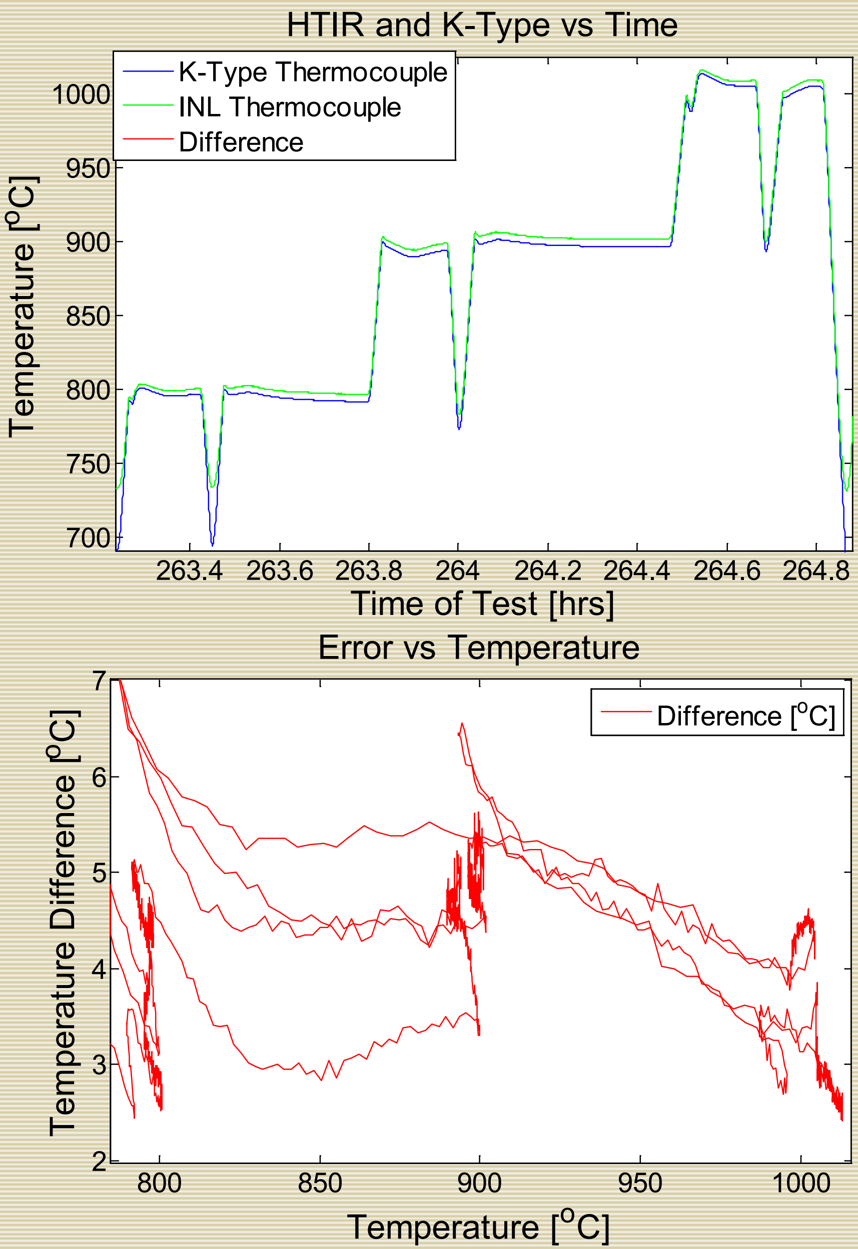


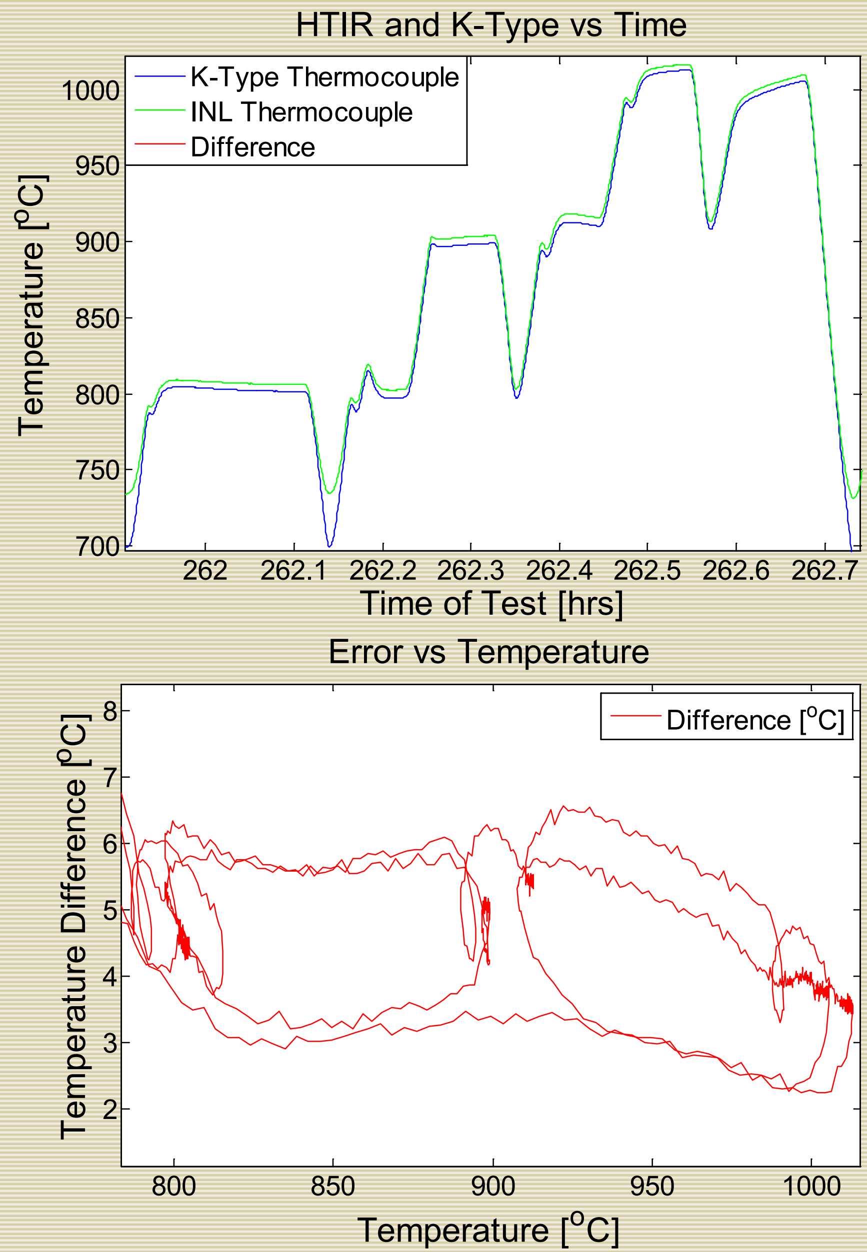




HTIR-TC Radiation Impact

High temp testing both inside and outside a radiation environment





Path forward

- Distributed Optical Temperatures sensors have high potential for use in TREAT
  - Good operation up to 900C for short durations (hours) 800C for long durations (days-weeks)
  - Need high temperature annealing
  - Fibers are fragile when coating removed.
  - Potential for temperature limit improvement with sapphire (long development path)
  - Good radiation stability
- HTIR-TC works well
  - Some concerns about oxidation, need to run in ultra pure oxygen free environment
  - Good radiation stability
- Thermal conductivity sensor
  - Issues with calibration and coupling to material
  - Needs additional work
- Ultrasonic temperature sensor
  - Needs further development
- Diamond Thermistor
  - Works up to 800C – further development to push to higher temperatures
  - Needs work on probe fabrication and bonding to diamond pad
  - Potential for temperatures up to 1500C and small dimensions

Acknowledgement

U.S. DEPARTMENT OF ENERGY

Fed. Manager : S.Schupner(DOE)

TPOC: C.Jensen (INL)

Project Number: 2014-7353

Advanced Instrumentation For Transient Reactor Testing

Contract Number: DOE-NE0008305

U.S. DEPARTMENT OF ENERGY

Sodium thermal striping work

Fed. Manager : T. Sowinski (DOE)

TPOC: T. Sofu (ANL)

Project Number: 16-10268

Sodium Cooled Fast Reactor Key Modeling and Analysis for Commercial Deployment

Contract Number: DOE-NE0008548