U.S. DEPARTMENT OF ENERGY | Office of NUCLEAR ENERGY

ASI Advanced Sensors and Instrumentation

Non-Contact Strain and Displacement Monitoring via Optical Fiber Based Interferometry

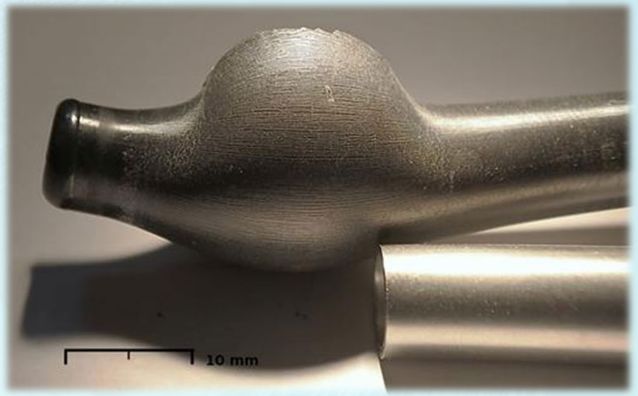
Advanced Sensors and Instrumentation (ASI) Annual Program Webinar
October 24 – 27, 2022

Dan Homa, Gary Pickrell, Anbo Wang, Ruixuan Wang, Zach Dejneka

Center for Photonics Technology, Virginia Tech

Project Overview

- Research Objective
  - Develop a non-contact “burst detection” system to monitor the structural health of the fuel cladding under high fluence and elevated temperatures
- Research Approach
  - Design and construct an optical fiber based interferometric sensing system capable of measuring the displacement and radial strain of the fuel cladding in real-time
  - Demonstrate the performance of a prototype sensing system in a simulated laboratory environment
- Research Scope
  - Determine sensor operating requirements and specifications
    - Virginia Tech will work with INL to ensure the sensing system is fit for use
  - Perform theoretical analyses and modeling of the Fabry Perot sensor response
  - Design and construct laboratory scale test facilities
  - Design, construct, and characterize the displacement sensor
  - Design, construct, and characterize the strain sensor
  - Perform test the prototype sensing system in a laboratory setting
  - Prepare for testing of prototype sensing in selected test reactor (TREAT)



Project Overview

- Participants
  - Center for Photonics Technology (CPT) at Virginia Tech
  - PI: Gary Pickrell, Co-PI: Anbo Wang, Key Personnel: Dan Homa
  - GRAs: Ruixuan Wang (ECE), Zach Dejneka (MSE)
  - Active collaboration with Idaho National Laboratory (INL)
- Schedule
  - Start Date: 5/3/2023 , End Date: 6/1/2023
  - Potential 6 month extension to construct a fully integrated sensing system for deployment and testing at the TREAT, ATR or HFIR

GANTT CHART		Project Year 1											
Task #	Task Name	M1	M2	M3	M4	M5	Q6	Q7	Q8	Q9	Q10	Q11	Q12
1	Project Management and Planning												
2	Development of Sensing System Specifications and Requirements												
3	Construction of Simulated Laboratory Test Facilities												
4	Perform Theoretical Analyses and Develop Sensor Algorithms												
4.1	Peform Theoretical Analysis of Sensor Response												
4.2	Develop Displacement and Strain Sensing Algorithms												
M1	**MILESTONE 1 / DECISION POINT 1**												
5	Design, Construction and Testing of Displacement Sensing System												
5.1	Design and Fabrication of the Sapphire Sensor Element(s)												
5.2	Construction of Sensor Interrogation and Demodulation System												
M2	**MILESTONE 5 / DECISION POINT 2**												
6	Design and Construction of Strain Sensing System												
6.1	Design and Fabrication of the Sapphire Sensor Element(s)												
6.2	Construction of Sensor Interrogation and Demodulation System												
M3	**MILESTONE 5 / DECISION POINT 2**												
7	Demonstrate Performance of Prototype Sensing System												
7.1	Conduct Full Scale Integration of Prototype Sensing System												
7.2	Conduct Performance Assessment of Prototype Sensing System												
7.3	Develop Deployment/Field Trial Test Plan for Prototype Sensing System												

Technology Impact

- Fuel cladding integrity is a primary focus of safety testing and remains a significant research priority for the Advanced Fuels Campaign [1, 2]
  - Performance of accident-tolerant fuel (ATF) candidates must be evaluated under simulated loss-of coolant accident (LOCA) conditions to support licensing of these materials
  - An understanding of high-burnup fuel fragmentation, relocation, and dispersal (FFRD) in the event of cladding failure under LOCA conditions is necessary for licensing to extend the peak rod average burnup
- Fuel cladding swells ("balloons"); under some conditions it can rupture during LOCA
  - Reactor coolant pressure drops below the internal fuel rod gas pressure
  - Core behavior depends on the type of accident, the time at which swelling and rupture occurred, the magnitude of swelling, and the resulting coolant flow blockage (i.e., reduction in flow area)
- Displacement, strain, and creep measurements of standard specimens under irradiation is a prevailing interest of the nuclear community from a scientific and engineering perspective
  - Linear variable differential transformers (LVDTs) and strain gauges require mechanical contact of the specimen
  - Contact with the surface of cladding will significantly impact the thermal behavior thereby negating the value of the data
- Recent success of fiber optic-based instruments for in-pile applications provides a basis for the contactless fiber optic-based measurement of mechanical behavior

[1] Garrison, Ben E., Patrick A. Champlin, Michael Howell, Mahmut N. Cinbiz, Maxim N. Gussev, Christian M. Petrie, and Kory D. Linton. *Length Dependence of Severe Accident Test Station Integral Testing*. No. ORNL/SPR-2019/1324. Oak Ridge National Lab.(ORNL), Oak Ridge, TN (United States), 2019.

[2] S. J. Zinkle, K. A. Terrani, J. C. Gehin, L. J. Ott, and L. L. Snead, 2014. Accident Tolerant Fuels for LWRs: A Perspective, J. Nucl. Mater. 448, 374–379.

Results and Accomplishments: Requirements & Specifications

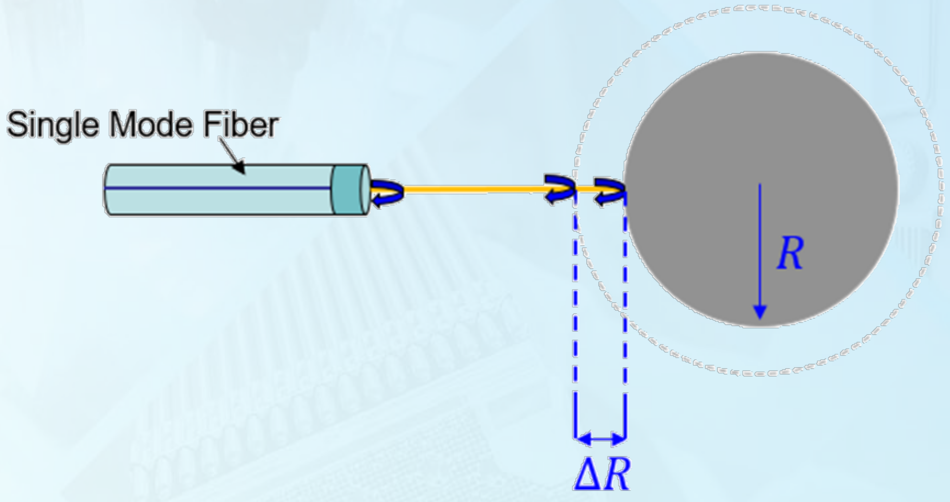
- Conducted a technical survey of the operating conditions and performance requirements
  - Leveraged expertise at INL
  - Ensure prototype is fit-for-use
- Sensor packaging and design is dictated by the specific experiment
- Identified significant technical challenges that must be addressed
  - Variable refractive index of environment
  - Vibrations
  - Minimum allowable standoff distance
- Intimate collaboration with INL to ensure sensing system will provide value to the nuclear community

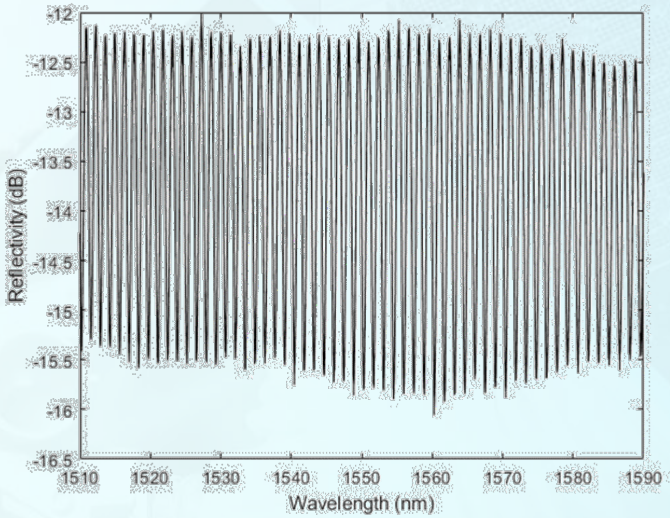
Property	SPECIFICATIONS	
	Required	Desired
Environmental/Operating Conditions		
Sensor: Max. Temperature	100 °C	300 °C
Viewing: Max. Temperature	200 °C	800-1200 °C ***
Viewing: Temperature Range	-----	200-1200 °C
Sensor Operating Environment	Inert (Helium/Argon) *	Inert (Helium/Argon), Water, Steam
Interrogator Operating Environment	Ambient	Ambient
Sensor Stand-Off Distance**	5-25mm	5-25 mm
Interrogator Stand-Off Distance	10 m	20 m
Sensor Performance		
Fuel Cladding Diameter	~ 10mm	~ 10mm
Fuel Cladding Material		SS-316, Zirc-2, Zirc-4, Zirlo
Fuel Cladding Length	Not a strong requirement	100 mm
Length of Interest	<50 mm; not a strong requirement	50-75 mm
Containment to Cladding Distance	15-40 mm; can be changed	15-40 mm
Maximum Change in Diameter	30% (13 mm)	100% (20mm) ****
Max. Rate of Diameter Change	1-2 seconds.	250 ms (40mm/s rate).
Min. Displacement Resolution	1 mm on the radius	≤ 0.5 mm
Minimum Strain Resolution	10^{-3}	10^{-4}
Linear Coverage	Not a strong requirement	-----

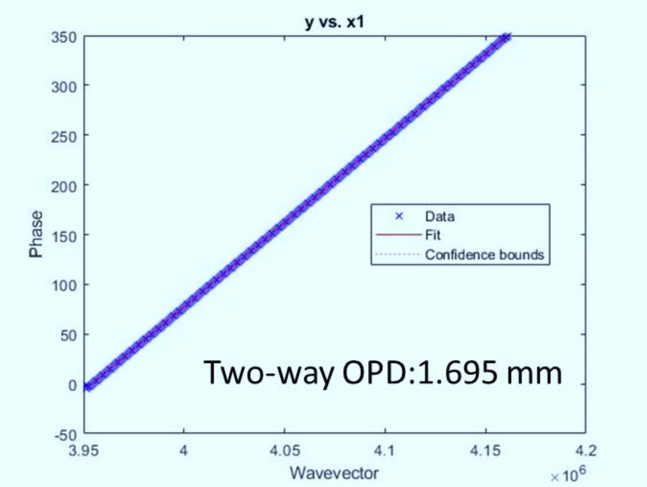
** Capability of varying composition or pressure to change RI*
***In-Vessel vs. On-Vessel*
****Highly dependent on experiment*
*****Highly variable*

Results and Accomplishments: Approach

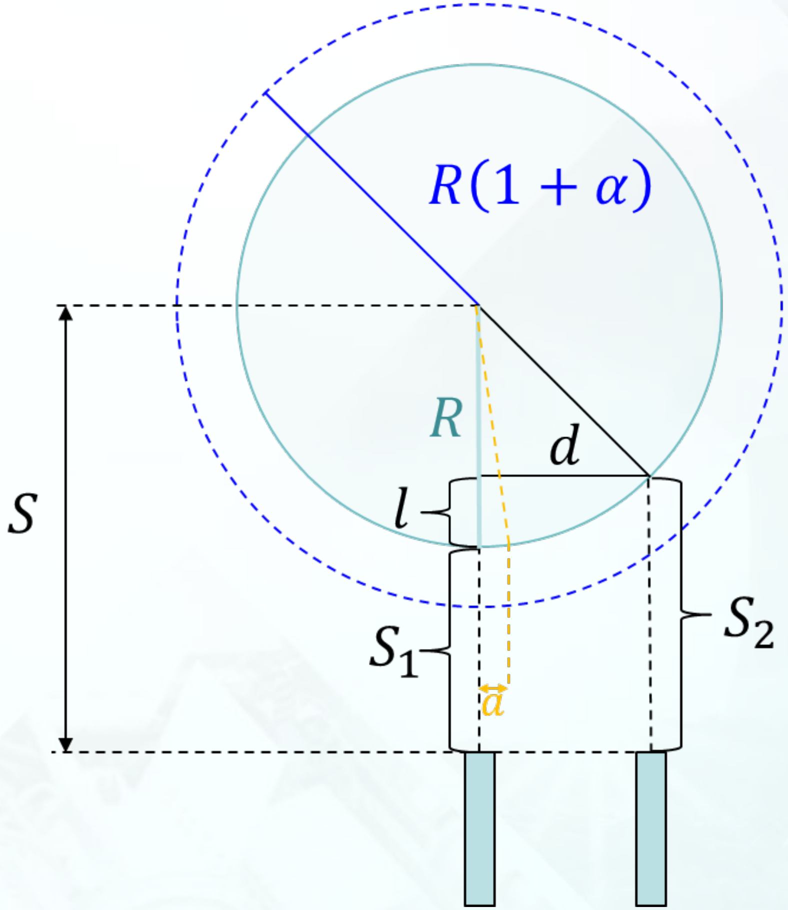
- Proposed sensor is an optical fiber based Fabry-Perot Interferometer (FPI)
  - Sensing element is a 90° polished single mode fiber that is parallel to the tangent surface of the test substrate
  - Interrogation system based on a tunable laser (Micron Optics SM125)
- Demodulation via white light interferometry
  - Allows for absolute measurements
- Optical path difference (OPD) is the distance between the probe and the metal surface.
  - Fit the periodicity of the interference pattern,
  - Obtain the demodulated OPD via linear interpolation, zero phase filtering, linear regression, or Fourier Transform.
  - Minimum detectable displacement using Type I demodulation: 2.5 μm







Results and Accomplishments: “Dual Probe” Sensor



α: “swelling” expansion coefficient
S: distance between fuel rod center and probe surface
s_1, s_2: distance between fuel cladding and probe surfaces

R: radius of the fuel rod (~1.5”)
d: lateral distance between probes
a: lateral vibration (“mode II”)
l: the difference between s_1, s_2

Displacement

$$s_1 = S - R$$

$$s_2 = S - \sqrt{R^2 - d^2}$$

$$s_{1,2} \approx 0.03\ mm$$

Radial Strain

$$\Delta s_1 = \alpha R$$

$$\Delta s_2 = \sqrt{[(1+\alpha)R]^2 - d^2} - \sqrt{R^2 - d^2}$$

$$\epsilon_{radial} \approx 66\ ppm$$

Axial Strain

$$\frac{R'\theta' - R\theta}{R\theta} = \alpha$$

$$\theta = suface\ arc$$

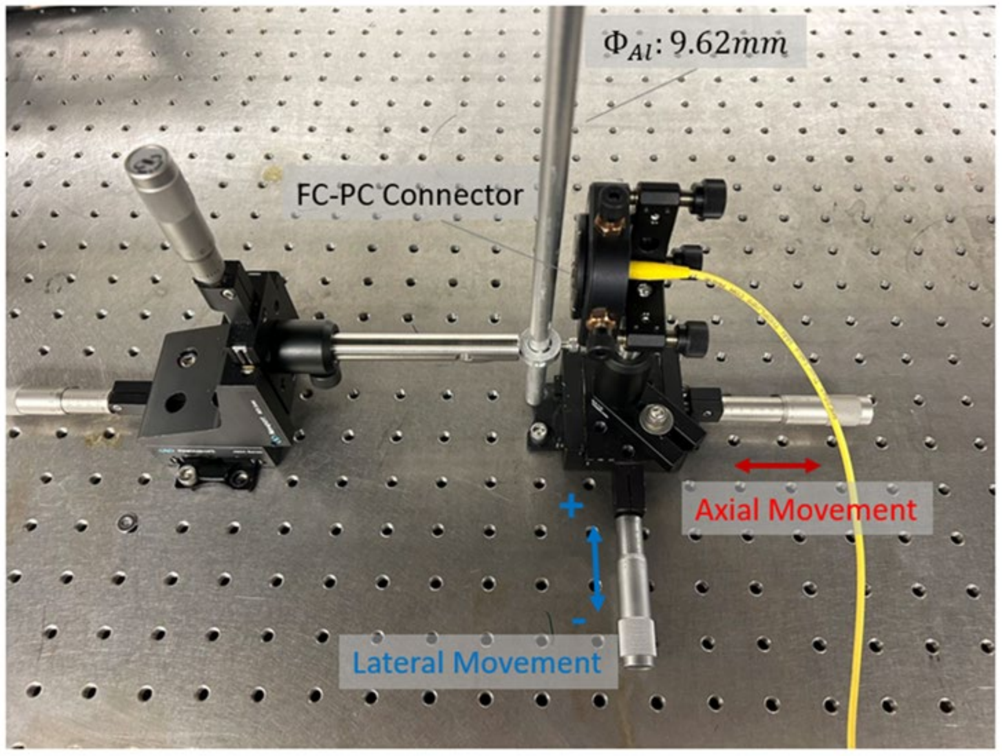
$$\epsilon_{axial} = \frac{\epsilon_{transverse}}{\nu}$$

$$\epsilon_{axial} = \frac{66\ ppm}{0.30}$$

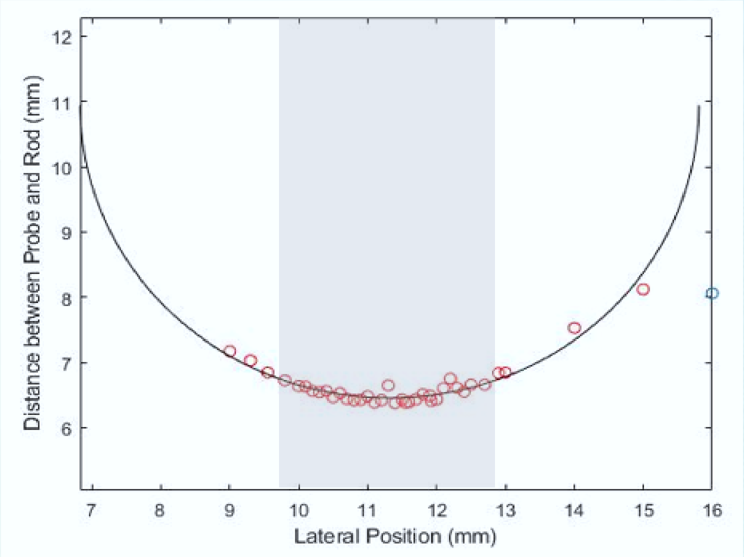
$$\epsilon_{axial} \approx 220\ ppm$$

Results and Accomplishments: Sensor Parameters Study

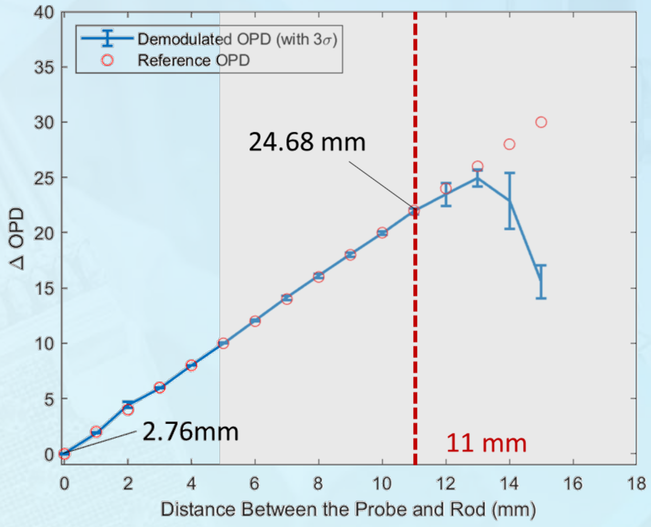
Laboratory Test Setup

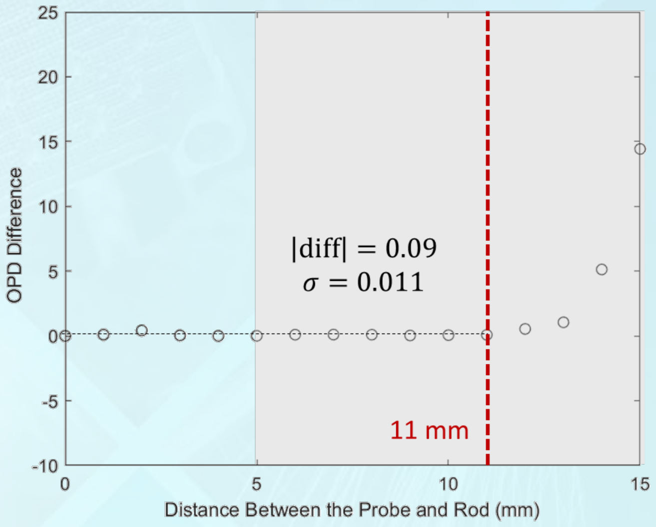


Lateral Movement



Radial Movement





Max Standoff Distance: 11 mm (center probe)

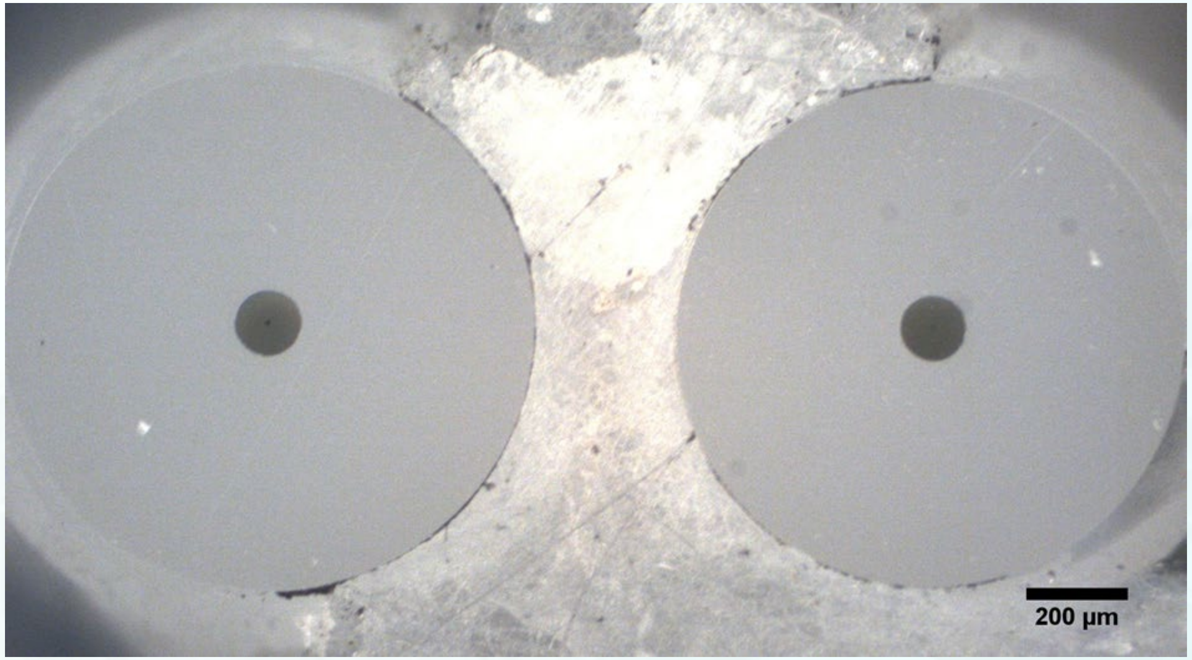
Max Sensor Spacing: 1.5 mm

Results and Accomplishments: Preliminary Demonstration

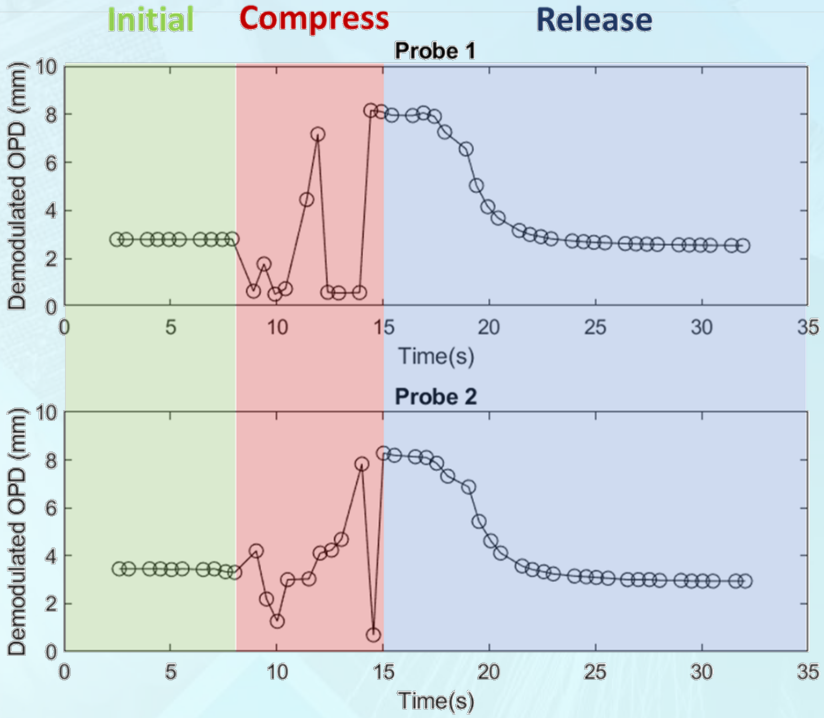
- Fabricated "dual-probe" sensor
  - Attached two 1.25 mm ceramic ferrules with cyanoacrylate.
  - Inserted bare SMF 28 fibers into the ceramic ferrules
  - Polished sensor end face

- Demonstrated feasibility via bench-top test
  - Plastic pipette was coated with silver paint to increase the surface reflections
  - Pipette diameter changed by applying negative pressure and then releasing it

"Dual-Probe" Sensor



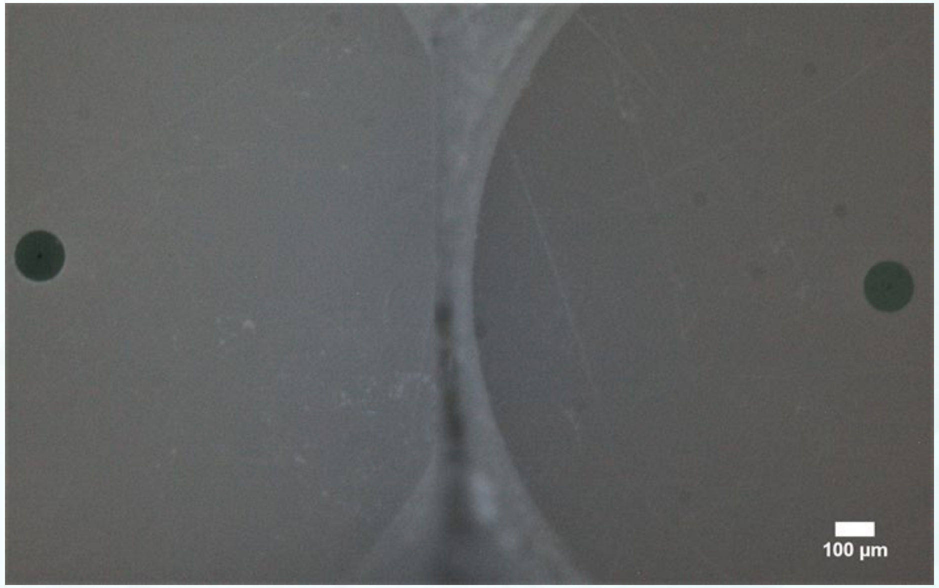
"Pipette" Test and Sensor Response



Results and Accomplishments: “Laboratory Standard” Dual Probe

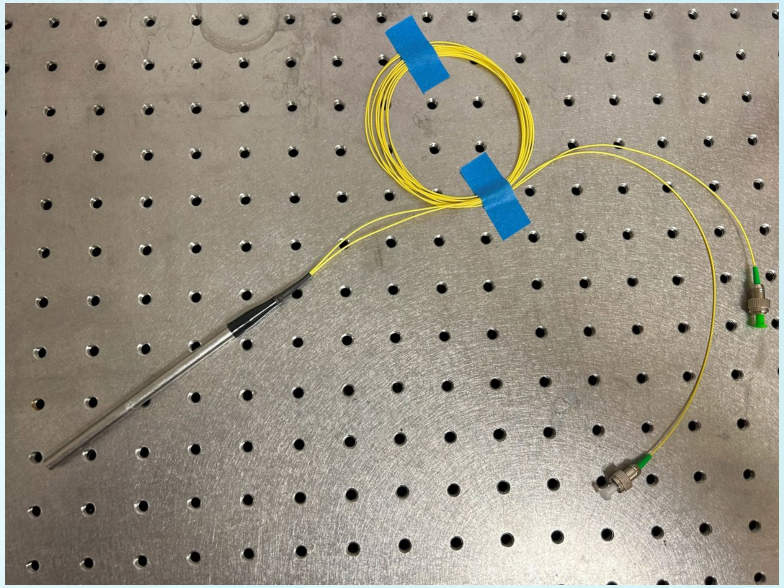
- Designed and fabricated “laboratory standard” dual probe sensor
  - Attached two 1.25 mm ceramic ferrules with cyanoacrylate.
  - Inserted bare SMF 28 fibers into the ceramic ferrules
  - Housed in stainless steel ¼” tubing with fiber strain relief
  - Polished sensor end face
- Successfully used to monitor pressurized tube expansion

SMF28 in Ceramic Ferrules



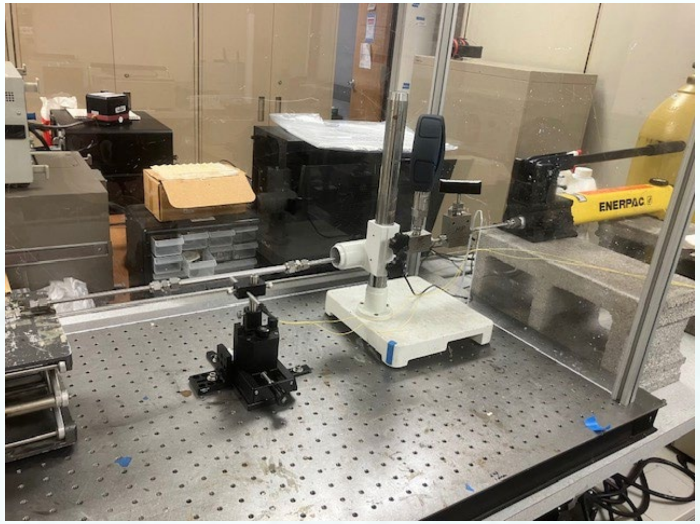
Dual Probe Housed in SS316 Tube

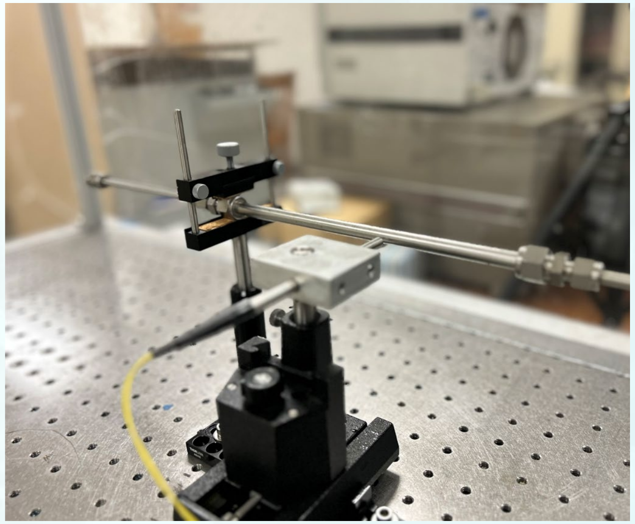
“Laboratory Standard” Sensor

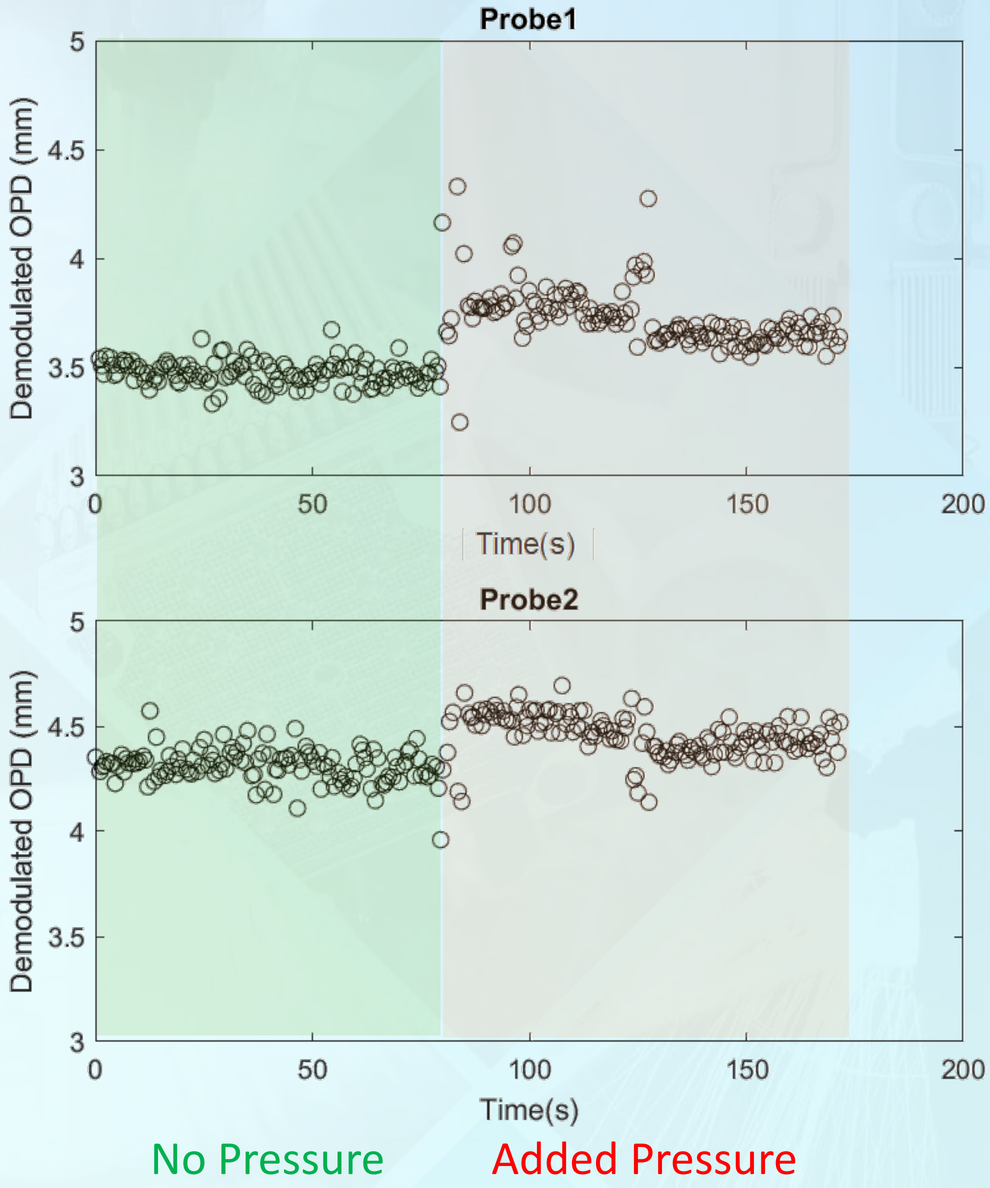


Results and Accomplishments: Preliminary Performance Test

- Designed and constructed bench-top pressurized tube burst test setup
  - Enerpac P2282 Ultra-High Pressure Hydraulic Hand Pump
  - High pressure hydraulic stainless steel tubing (1/4")
  - Thin wall "burst tubing" (3/8")
  - Full plexiglass enclosure
- Successfully demonstrated displacement sensor
  - Did not "burst" the tube in the test

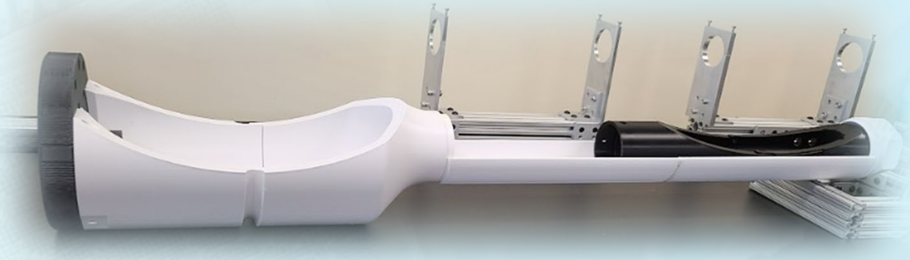






Concluding Remarks

- Project Status and Accomplishments
  - Determined sensor operating requirements and specifications
  - Performed theoretical analyses and modeling of the Fabry Perot sensor response
  - Designed and constructed laboratory scale test facilities
  - Successfully demonstrated the displacement sensor
- Near-Term Work Plan
  - Optimize sensor design and sensing algorithms
  - Demonstrate strain measurements
  - Design and construct laboratory scale, relevant environment test facilities (refractive index variations, vibrations, elevated temperatures)
    - Demonstrate performance necessary for field testing
  - Collaborate with INL to prepare for testing in selected test reactor
- Intellectual property disclosure for the dual probe sensor design filed with Virginia Tech Intellectual Properties (VTIP)



Dan Homa
Research Assistant Professor
dan24@vt.edu
C (410)-262-4775

Thank You