DE-FE0031786
Oil & Gas Project Review Meeting
Hydraulic Fracturing Technologies
University Lead: Virginia Tech
Industrial Partner: Sentek Instrument LLC
October 14, 2020

FULLY DISTRIBUTED ACOUSTIC AND MAGNETIC FIELD MONITORING VIA A SINGLE FIBER LINE FOR OPTIMIZED PRODUCTION OF UNCONVENTIONAL RESOURCE PLAYS

DE-FE0031786

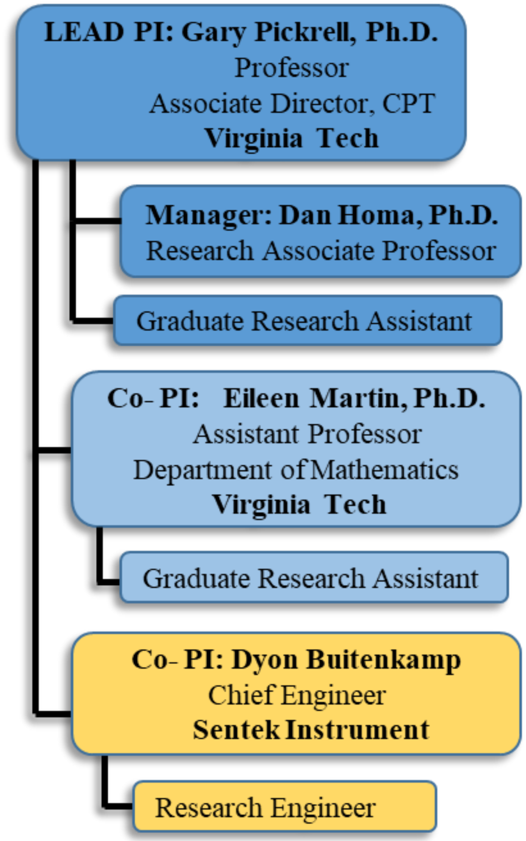
Gary Pickrell, Daniel Homa
Virginia Tech
Center for Photonics Technology
Blacksburg, VA 24061
pickrell@vt.edu, dan24@vt.edu

Eileen Martin
Virginia Tech
Department of Mathematics
Blacksburg, VA 24061
eileenrmartin@vt.edu

Dyon Buitenkamp
Sentek Instrument LLC
Blacksburg, VA 24061
dbuitenkamp@sentekinstrument.com

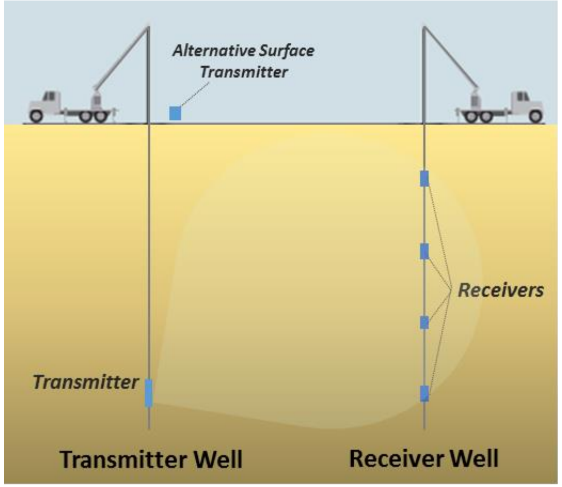
Project Team

- Lead PI : Dr. Gary Pickrell
  - Provide executive management for all phases of the project, and oversee the design, fabrication, and characterization of the sensing fibers
- Co-PI : Dr. Eileen Martin
  - Support all phases of the project and provide technical expertise as in pertains to sensor response, data analysis, optimization of the sensing fiber design and applicability for subsurface imaging applications.
- Co-PI: Dyon Buitenkamp
  - Provide technical and project management for the sensor interrogation system development, as well as support optimization of the sensing fiber
- Technical Manager: Dr. Daniel Homa
  - Daily project management, to include technical insights, under the guidance of the PI and Co-PI(s)



Overview

- General Information
  - Goals/Objectives
  - Anticipated Outcomes/Impact
  - Research Approach
- Project Management Plan
  - Tasks, Milestones, Success Criteria
- Project Update
  - Development and Dissemination
  - Execution of Tasks (5-8)
- Progress and Near-Term Plan



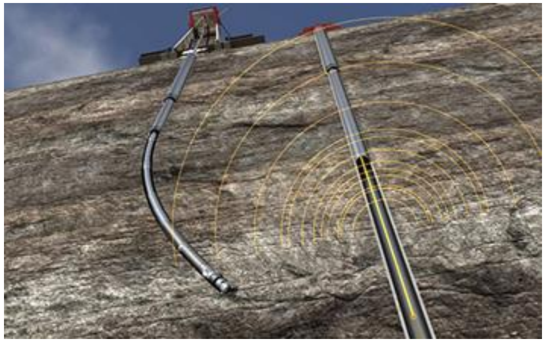


Image from Halliburton website

GENERAL INFORMATION

Goals/Objectives

- **Objective:** Develop a fiber-optic sensing system capable of real-time simultaneous and distributed measurements of multiple subsurface parameters via a first-of-its-kind optical fiber with an electromagnetic field sensing capability over an unprecedented sensing length
- **Goal:** Design and fabricate a multi-material sensing fiber for distributed magnetic field and acoustic measurements
- **Goal:** Design and construct an optical interrogation system and develop the sensing algorithms for distributed magnetic field and acoustic measurements with ultra-high sensitivity via a single sensing fiber
- **Goal:** Demonstrate the performance of a fully integrated multi-parameter sensing system in a simulated laboratory environment

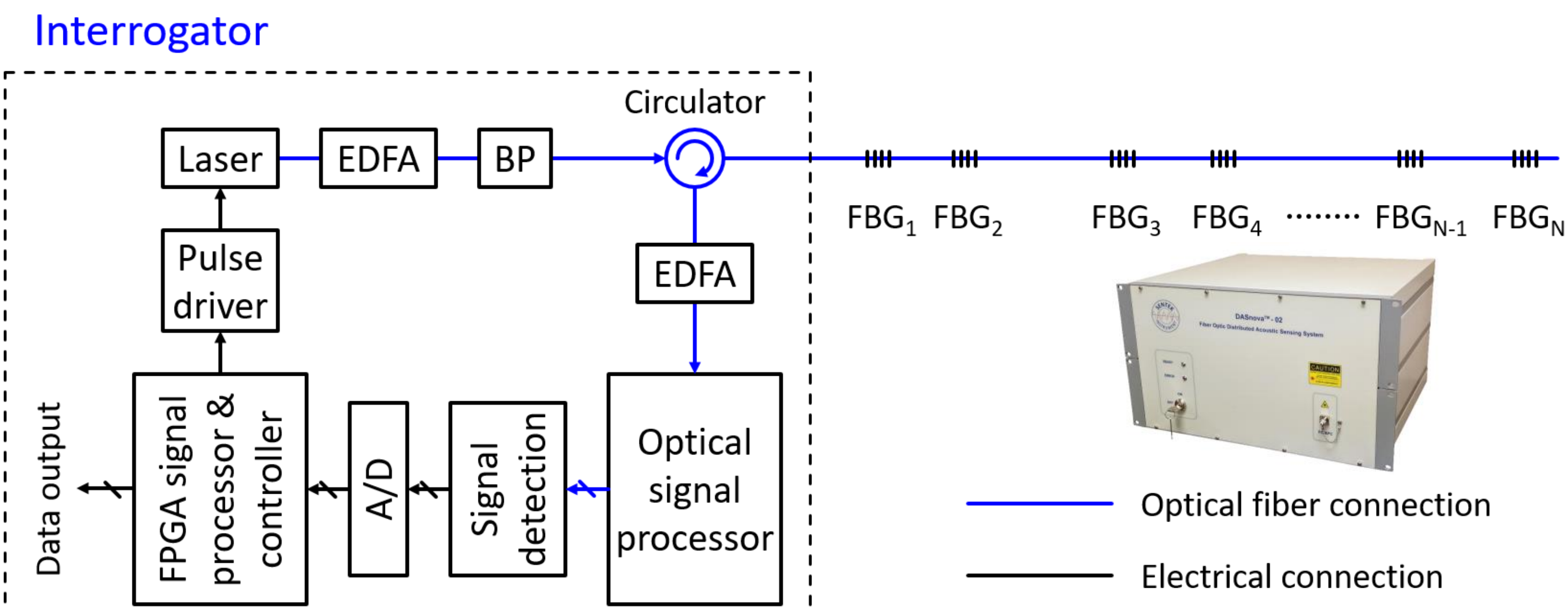
Anticipated Outcomes/Impact

- High resolution sensing and imaging of the subsurface will provide operators with more clarity of the subsurface and provide real-time information for optimized drilling and production
  - Cross-Well Imaging Techniques
  - Passive/Active Magnetic Ranging
  - Position Monitoring for Downhole Completion Devices
  - Monitoring while Drilling (MWD)/Logging while Drilling (LWD)
  - Permanent Well Monitoring
- Reliability and performance capabilities of the fiber optic sensing system will assure that the operators have the most reliable and accurate information necessary to make critical decisions

Research Approach

DASNova™ Fiber Optic Sensing Technology

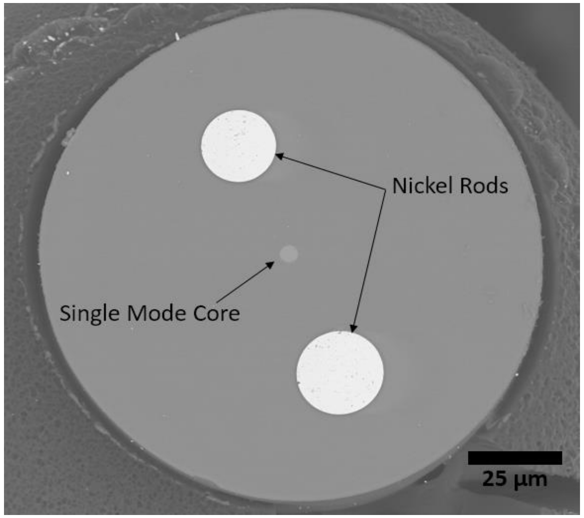
- Relies on an elegant marriage between a special type of FBG device and a time-division-multiplexing (TDM) signal processing scheme
- Superior performance
  - 100 times more sensitive than traditional DAS systems
  - Uniform sensitivity distribution across entire sensing range
  - Capable of multi-parameter measurements.



Research Approach

Multi-Material Magnetic Sensing Fiber

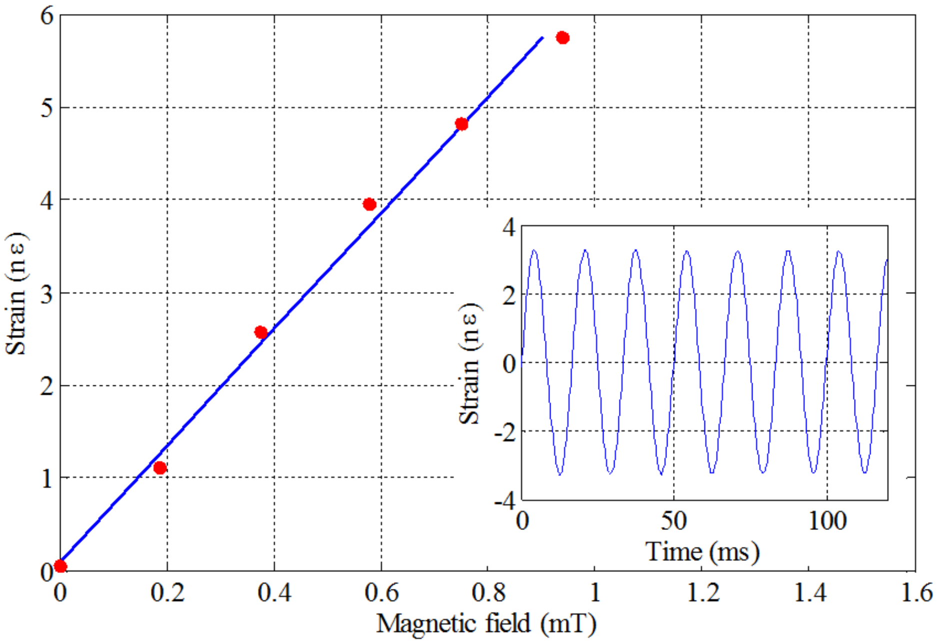
- Single mode optical fiber core with a magnetostrictive material in the cladding
  - The magnetostrictive material expands or contracts upon exposure to a magnetic field, inducing a strain on the FBG based interferometers in the optical fiber
- Stack-and-draw technique utilized to incorporate dissimilar materials in the fiber via optical fiber draw
- Magnetostrictive materials
  - Galfenol, Metglas 2605®, Nickel
- All other sensing schemes require bonding of the magnetostrictive material to the fiber, including it in the coating, and/or utilizing other post-processing schemes),



Research Approach

Preliminary Demonstration of Magnetic Field Sensor

- Response of a prototype sensing fiber to a magnetic field generated by the alternating current of an air solenoid
  - Small wire diameter (~20 µm)
  - Poor mechanical coupling
  - Limited magnetostriction (30 ppm)
- Significant performance improvement anticipated
  - Improved mechanical coupling via fiber twist during draw
  - Use of materials that exhibit larger magnetostriction
  - Increase the surface area of the magnetostrictive material in the sensing fiber
  - Utilize composite magnetostrictive structures



SENTEK INSTRUMENT CPT CENTER FOR PHOTONICS TECHNOLOGY VirginiaTech Invent the Future

PROJECT MANAGEMENT PLAN

Project Tasks

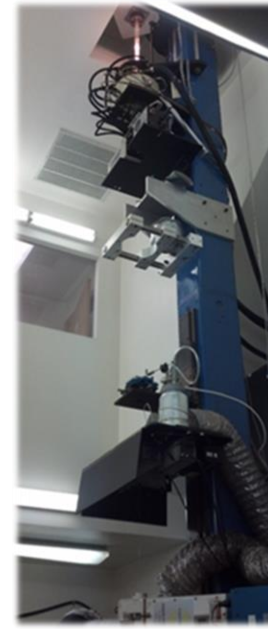
Year 1

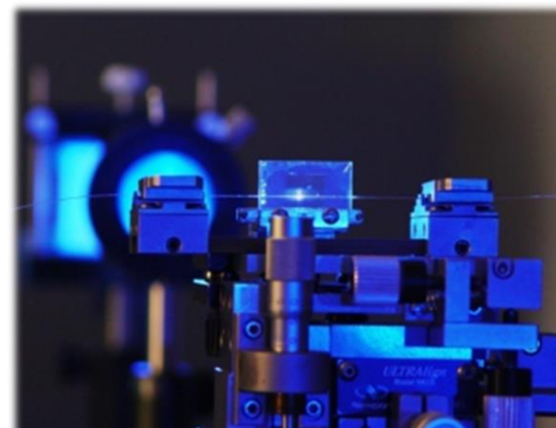
- Task 1.0 – Project Management and Planning (VT)
- Task 2.0 – Workforce Readiness Plan (VT)
- Task 3.0 – Data Management Plan (VT)
- Task 4.0 – Technology Maturation Plan (VT)
- Task 5.0 – Theoretical Modeling and Analyses (VT)
  - Evaluate design parameters for the sensing fiber
  - Evaluate design parameters for the interrogation system
  - Determine anticipated strain, acoustic, and magnetic field response
- Task 6.0 – Design and Construction of the Simulated Subsurface Test Facilities (VT)
  - Theoretical modeling and computational data analysis of shale oil and gas reserves will guide the design of the facilities
  - Testing will provide an accurate assessment of the performance

Project Tasks

YEAR 2

- Task 7.0 – Multi-Parameter Sensing Fiber Fabrication (VT)
  - Preform and fiber fabrication
  - Fiber Bragg grating array fabrication
- Task 8.0 – Demonstration of Distributed Sensing System
  - Interrogation Design and Implementation
  - Distributed Sensing System Construction
  - Demonstration with Commercial Fibers
- Task 9.0 – Fabrication and Characterization of Prototype High Temperature DAS Fiber
  - Short length (<10 meter) prototype high temperature (~$300^{\circ}C$) DAS sensing fiber





Project Tasks

Year 3

- Task 10.0 – Integration of Distributed Multi-Parameter Sensing Fiber and System
  - Fabrication of Distributed Magnetic Sensing Fiber
  - Demonstrate Distributed Multi-Parameter Sensing with Magnetic Sensing Fiber
  - Perform Sensor Calibration and Verification
- Task 11.0 – Prototype Sensing System Testing
  - Fabrication of Prototype Distributed Magnetic Sensing Fiber
  - Construct Multi-Parameter Sensing System with Magnetic Sensing Fiber
  - Test Sensing System and Evaluate Performance
- Task 12.0 – Prepare and Submit Final Report
  - Develop and propose a field trial test plan for the deployment of the prototype sensing system

Project Milestones

- "Year 1" Activities
  - Project Management Plan
  - Theoretical Modeling and Analyses
  - Commissioned Test Facilities
- "Year 2" Activities
  - Distributed Magnetic Sensing Fiber
  - Prototype Acoustic Sensing System

Task/ Subtask	Milestone Title & Description	Planned Completion Date	Completion Date (% Completion)
1.0	Project Management Plan	8/1/19	10/15/19
5.0	Theoretical Modeling and Analyses	9/30/20	9/30/20
6.0	Commissioned Test Facilities	9/30/20	9/30/20
7.0	Distributed Magnetic Sensing Fiber	9/30/21	35%
8.2	Prototype Acoustic Sensing System	9/30/21	40%
9.0	High Temperature Sensing Fiber	9/30/21	---
11.0	Multi-Parameter Performance Test	6/30/23	---
12.0	Final Report	9/30/23	---

Project is ON SCHEDULE and ON BUDGET

Milestone Success Criteria

- "Year 1" Activities
  - Theoretical Evaluation
    - Demonstrate technical feasibility
  - Test Facilities
    - Design and construct the necessary facilities for performance testing
- "Year 2" Activities
  - Distributed Magnetic Sensing Fiber
    - Demonstrate experimental feasibility
  - Prototype DAS System
    - Demonstrate performance capabilities

ID	Title	Description	Decision Point	Date
SC1	Theoretical Evaluation	1. Minimum Sensitivity: 10 millitesla (mT)	D1	9/30/20
SC2	Test Facilities	1. Maximum Exposure Temperature: ≥ 150ºC 2. Minimum Magnetic Field Exposure: 1mT	D1	9/30/20
SC3	Fabrication of Distributed Magnetic Sensing Fiber	1. Minimum Fiber Length: 50 m 2. Minimum Tensile Strength of 50 kpsi	D2	9/30/21
SC4	Distributed Acoustic and Strain Sensing System	1. Minimum Spatial Resolution: 2m 2. Minimum Strain Sensitivity: 0.5 nanostrain	D2	9/30/21
SC5	Distributed Magnetic Sensing System	1. Sensing Length: > 1 km 2. Minimum Spatial Resolution: 5m 3. Minimum Magnetic Field Sensitivity: 2 mT	--	9/30/22

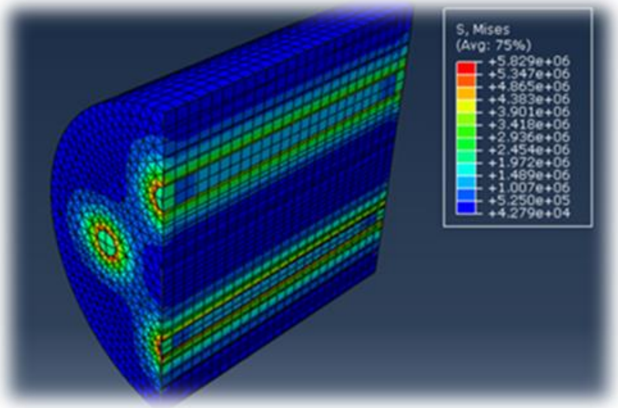
PROJECT UPDATE

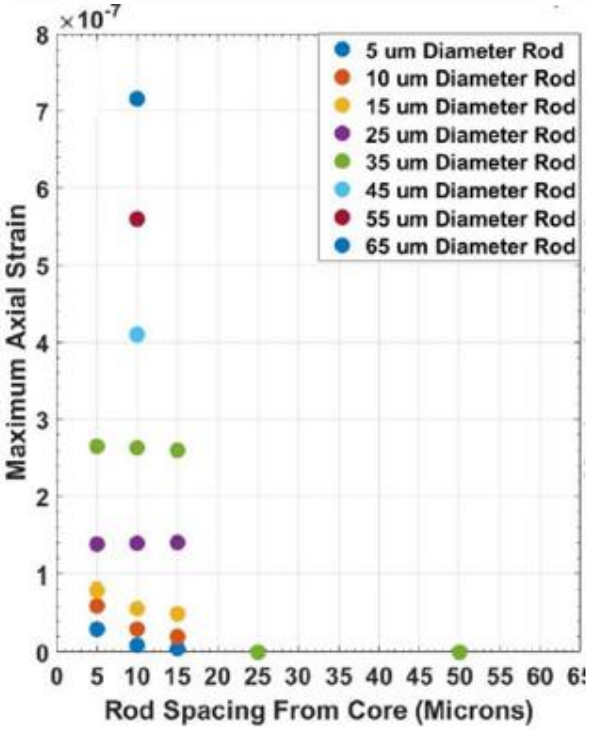
Development and Dissemination

- Proactive adjustments and progress made during pandemic
  - University closed from April 3, 2020 to June 9, 2020
  - Bi-weekly meetings continued via Zoom
  - Efforts focused on theoretical modeling, design and construction of test facilities, sensing fiber fabrication development, and design and construction of sensor interrogation systems (Tasks 5-8)
- Graduate student development
  - MSE Ph.D. candidate (Pickrell)
  - Mathematics M.S. candidate (Martin)
- Publications (2) – plan to submit
  - “Footstep Detection in Urban Seismic Data with a Convolutional Neural Network” (Martin)
  - “Magnetic Field Sensing via Multi-Material Optical Fibers” (Pickrell)

Task 5.0 – Theoretical Modeling

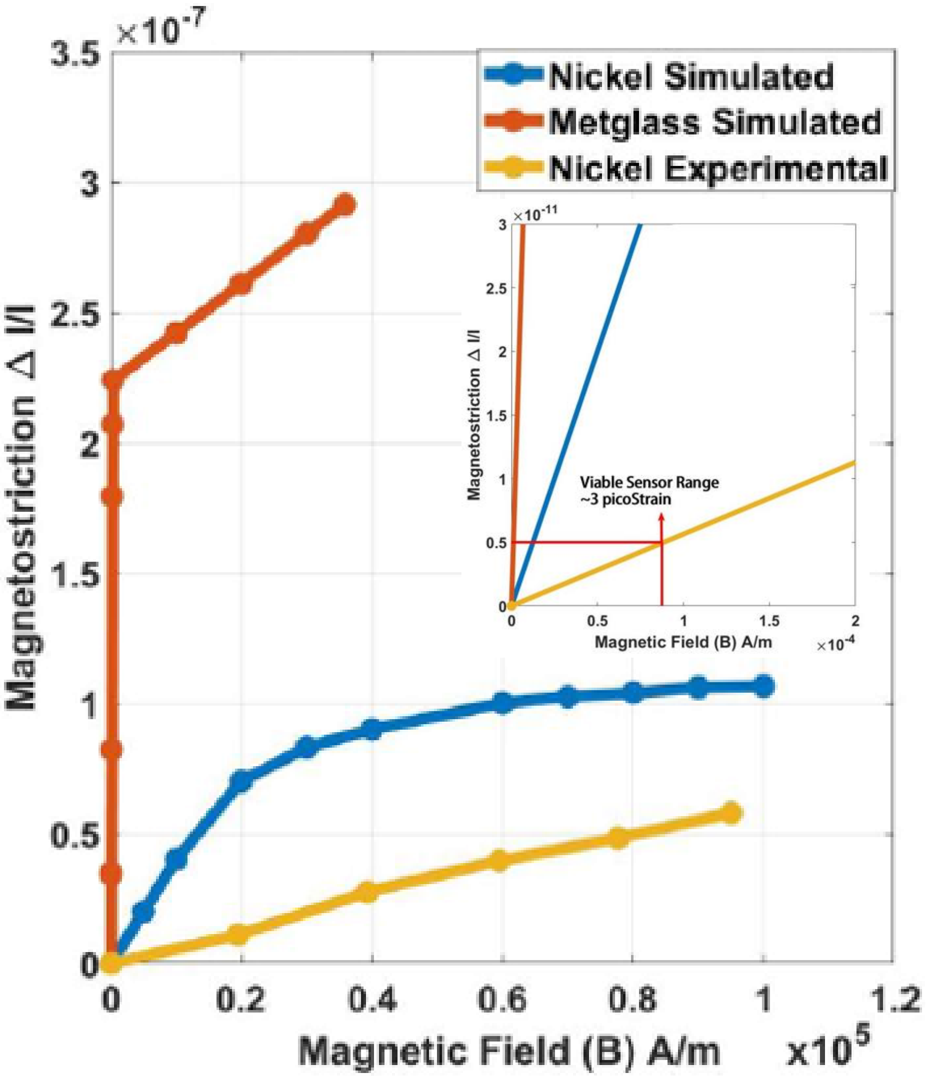
- Developed theoretical models and techniques necessary to optimize magnetic sensing fiber performance
  - Finite Element Analysis (FEA)
  - COMSOL V4.2a
- Evaluate response to magnetic field
  - Geometry (size, number and position of magnetostrictive rods)
  - Magnetostrictive material (Ni, Galfenol, FeBSi)
- Comprehensive model for sensing fiber
  - Incorporate optical, acoustic, and magnetic response
  - Validate and refine model per experimental results
- All work performed by MSE Graduate Student (Zach Hileman)





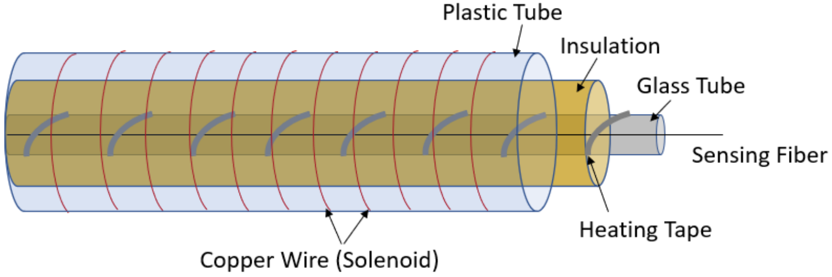
Theoretical Modeling

- "Basic" sensing fiber with one magnetostrictive rod
  - Single mode GeO_2-SiO_2 core
  - One magnetostrictive rod
- Study parameters that directly affecting optical sensing outputs
- Selected magnetostrictive materials
  - Nickel, Galfenol, FeBSi
- Met Success Criteria for Milestone 6
  - Minimum Sensitivity: 10 mT



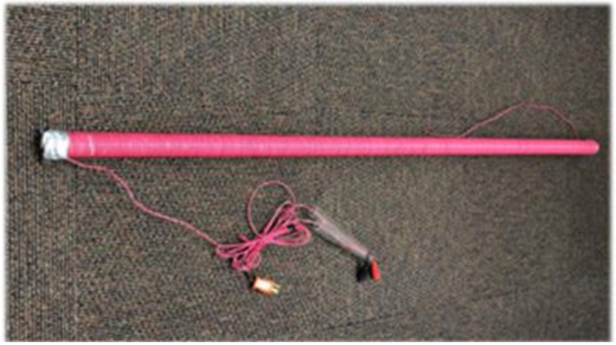
Task 6.0 – Testing Facilities

- Constructed test stands (2) to evaluate magnetic response of sensing fiber
  - Air-core solenoid
  - Length = 2 meters, 5 meters
- Design and construction of soil test bed(s) for simulated environmental testing
  - Uniform earth material
  - Controlled magnetic and acoustic sources
  - Bare sensing fiber/Cemented in metal tubing
- High temperature testing (>150ºC)
  - Air Core Solenoid(s)
  - Soil Test Bed(s)



Testing Facilities

- Completed construction of Test Bed #1
  - Vibration isolation of soil test bed on optical table with air mounts/rigid kinematic supports
  - Dimensions: 2m (l) x 0.9m (w) x 0.6m (h)
- Completed construction of Test Bed #2
  - Dimensions: 5m (l) x 0.6m (w) x 0.6m (h)
- Magnetic/Acoustic/Thermal Response
  - Air Core Solenoid / Low Field Point Sensor
  - Tactile Transducer/ Accelerometer
  - Heating Cartridges/ Thermocouples
- Status update for Milestone 7
  - Met Success Criteria #2
    - Minimum Magnetic Field Exposure: 1mT
  - Met Success Criteria #1
    - Maximum Exposure Temperature: ≥ 150ºC

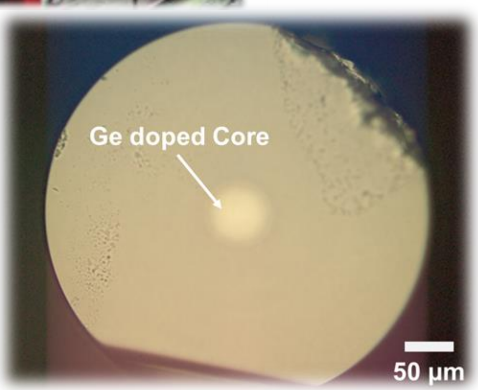


SENTEK INSTRUMENT CPT CENTER FOR PHOTONICS TECHNOLOGY VirginiaTech Invent the Future

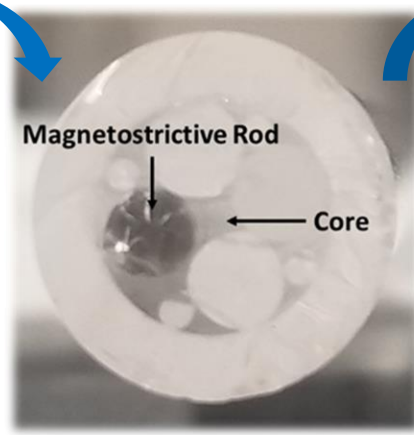
Task 7.0 –Fiber Fabrication

- Developed multi-material preform and fiber fabrication process
- Novel and extremely cost-effective single mode core rod fabrication
  - Precision overcladding of large core (360 µm) Ge-doped step-index fiber
  - Improved research efficiencies and path to process up-scaling
- Completed evaluation of precursors for magnetostrictive materials
  - Powder fill / Wire fill / Cane draw

Core Rod Fabrication



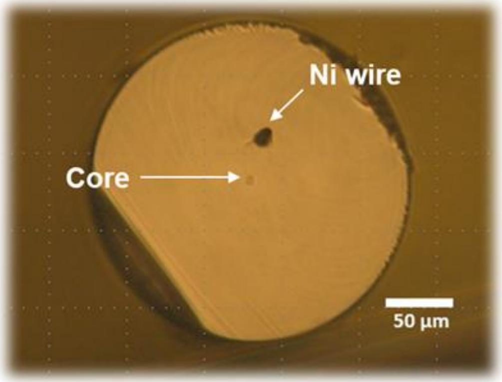
Tube Fill and Prep Preform Stacking

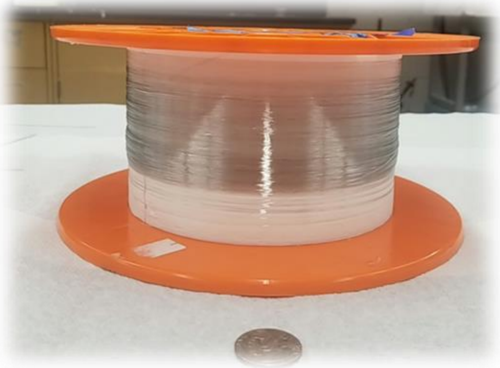


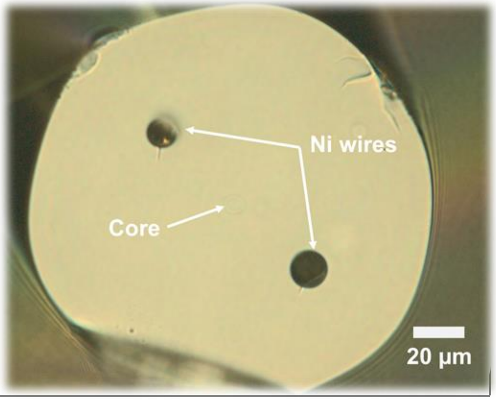
Multi-Material Fiber Draw

Task 7.0 –Fiber Fabrication

- Successfully demonstrated stack and draw technique for the fabrication of sensing fibers
  - Vacuum-assisted draw
- Demonstrated ability to produce multi-material sensing fiber via VT draw tower
  - Magnetostrictive materials: Galfenol, Ni, FeBSi
  - Multiple number of magnetostrictive rods: 1-3
  - Relatively long and continuous lengths (>500 m)
  - High strength (>100 kpsi) via bend test (d<10 mm)
- Status update for Milestone 9
  - On Schedule to meet Success Criteria #1
    - Minimum Fiber Length: 50 m
  - On Schedule to meet Success Criteria #2
    - Minimum Tensile Strength of 50 kpsi





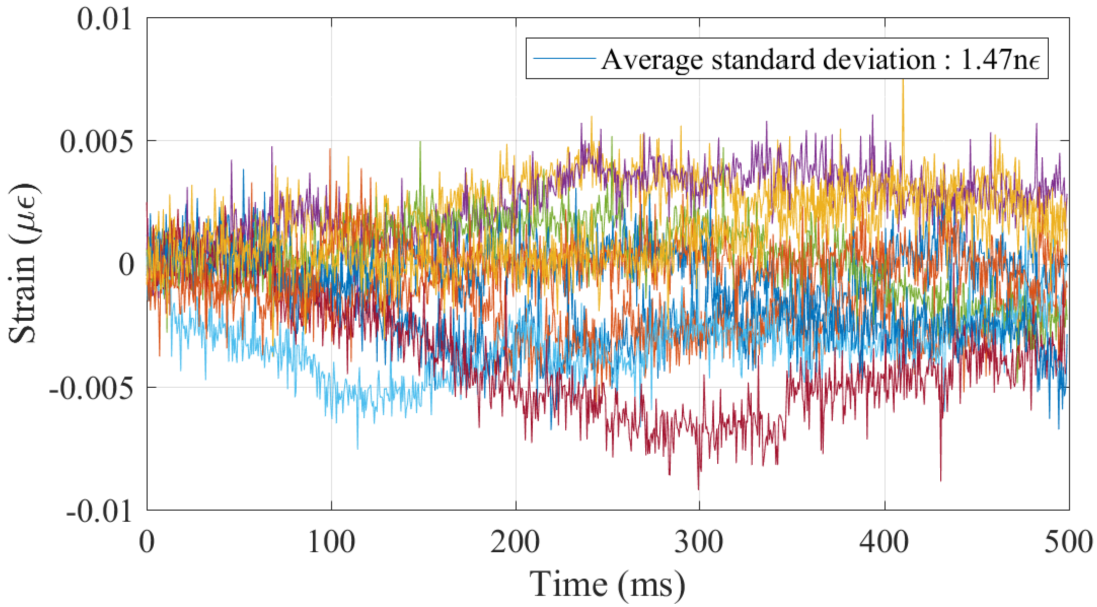


Task 8.0 – Sensing System

- Manufactured a DASNova™ interrogator
  - Spatial resolution of 5 meters
  - Available for the testing of sensing fiber samples (VT)
- DASNova™ with 2 m spatial resolution under construction
  - All the components have been purchased and received.
  - Critical components that require special assembling and adjustment have been manufactured and have been fully tested
- Status update for Milestone 9
  - On Schedule to meet Success Criteria #1
    - Minimum Spatial Resolution: 2m
  - On schedule to meet Success Criteria #2
    - Minimum Strain Sensitivity: 0.5 nanostrain

Sensing System

- Successful demonstration of "FBG-less" DAS system
  - Does not require inscription of FBGs in multi-material sensing fiber
  - Very significant technological development
    - Improve efficiencies specific to sensing fiber development



- Test facilities to evaluate response of DAS system

Progress Review and Near-Term Plan

- Theoretical Modeling (Task 6)
  - Successfully demonstrated magnetic sensing capabilities
  - Incorporate additional functions (acoustic & optical response)
  - Verify and refine models based on experimental results
- Test Facilities (Task 7)
  - Successfully constructed sensing fiber test stands(2) and soil test beds(2)
    - Magnetic, acoustic, and temperature response
    - Spectral attenuation, time domain reflectometry, and SM cutoff
  - Add additionally functionality and control, as necessary
- Sensing Fiber Fabrication (Task 8)
  - Optimize design and processing parameters
  - Fabricate and characterize magnetic sensing fiber samples
- Sensing System (Task 9)
  - Optimization of “FBG-less” sensing system
  - Manufacture DASNova™ with 2m spatial resolution

Acknowledgements

Department of Energy

National Energy Technology Laboratory
Project Manager: Gary L. Covatch
Project Manager: Skip Pratt

Halliburton

Industrial Support: Dorothy Wang, Ph.D.

Prysmian Group

Industrial Support: Brian Risch, Ph.D.

Weatherford

Industrial Support: Zhuang Wang, Ph.D.

THANK YOU FOR YOUR TIME

Questions?