Single-crystal sapphire optical fiber sensor

(DE-FC26-99FT40685)

NETL Cross Cutting Review Meeting

Anbo Wang, Gary Pickrell, Zhihao Yu, Brian Scott

Center for Photonics Technology

Virginia Tech, Blacksburg, VA 24061

awang@vt.edu

Outline

- Phase I and Phase II
  - Background
  - Sensing principle candidates
  - Laboratory tests
  - Field tests
- Phase III
  - Study on the property of sapphire fibers
  - Finalizing of the sensor structure
  - Silica-sapphire splicing technique
  - Optimization of optical system and data acquisition
  - Materials Selection
  - Probe Design
  - Field Testing

Motivation

- Temperature sensor for harsh-environments:
  - Coal gasifier
  - Gas turbine
- Temperature measurement is critical for:
  - Gasifier start-up
  - Process optimization
    - Insulation wear vs. coal slag transition.
  - Event/failure detection
- **Help make gasification cost-competitive**
  - Reduce down-time
  - Improve operational efficiency

Objective

- Objective:

  To demonstrate the capability of an integrated sapphire optical temperature sensor through the development of sapphire based sensor assemblies and performance evaluation of the sensor on a full scale coal gasifier and a bench scale aero thermal turbine combustion rig.

Background: challenges

- Coal gasifiers - challenging harsh environment:
  - High temperatures: between 1100-1500^{o}C.
  - Extreme corrosion:
    - coal slag
    - alkali vapors
    - transition metals

P1&P2: Background

- Industrial need in high temperature measurement
- Review on existing technique
  - Non-optical: high temperature thermocouple, acoustic methods and gas-viscosity thermometry
  - Optical: remote pyrometry, thermal expansion thermometers, thermoluminescence thermometers and Rayleigh scattering thermometers
- Advantage of single crystal sapphire
  - Optical properties
  - Thermal-optic effects
  - Mechanical properties
  - Chemical inertness

P1&P2: Sensing principle candidates

- Principles:
  - Extrinsic Fabry-Pérot Interferometric (EFPI)
  - Polarized-light interferometric sensor (PLIS)
  - Broadband Polarimetric Differential Interferometry (BPDI)
  - EFPI sapphire wafer sensor
- Possible sensor designs
- Algorithm principles
- Estimation on the affect of harsh environment
  - Blackbody Radiation
  - Corrosion

P1&P2: Laboratory tests

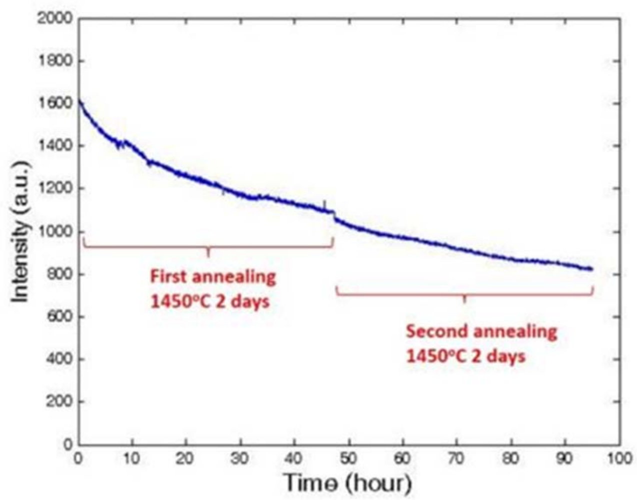
- Sapphire fiber EFPI sensor
  - Too complicated to fabricate
  - Not suitable for industrial deployment
- Intensity based PLIS sensor
  - Structure not practical for industrial deployment
- Sapphire BPDI sensor
  - Free space structure has a high requirement for testing environment and low robustness
- Sapphire wafer EFPI sensor (chosen)
  - Compact, simple, robust and stable.

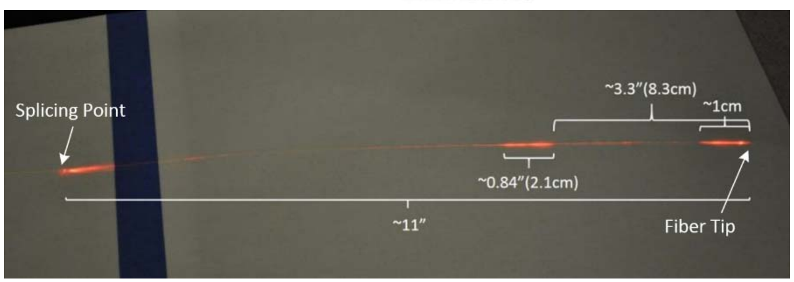
P1&P2: Field tests

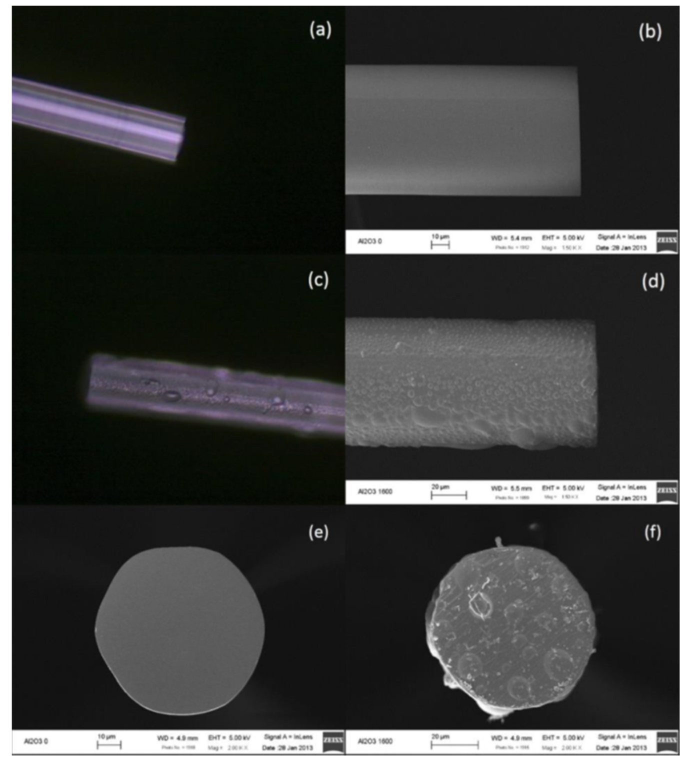
- Wabash field test of BPDI sensor
  - No test were performed due to numerous logistical problems
- TECO field tests of sapphire wafer EFPI sensor
  - First (2006-2007): ~210 days of sensor lifetime demonstrated
  - Second (2006): ~20 days of sensor survival
  - Third (2007-2008): ~9 days of sensor survival
- Issues addressed: packaging and sensor long-term stability

P3: Study on the property of sapphire fibers

- Study on contamination and decay of sapphire fiber

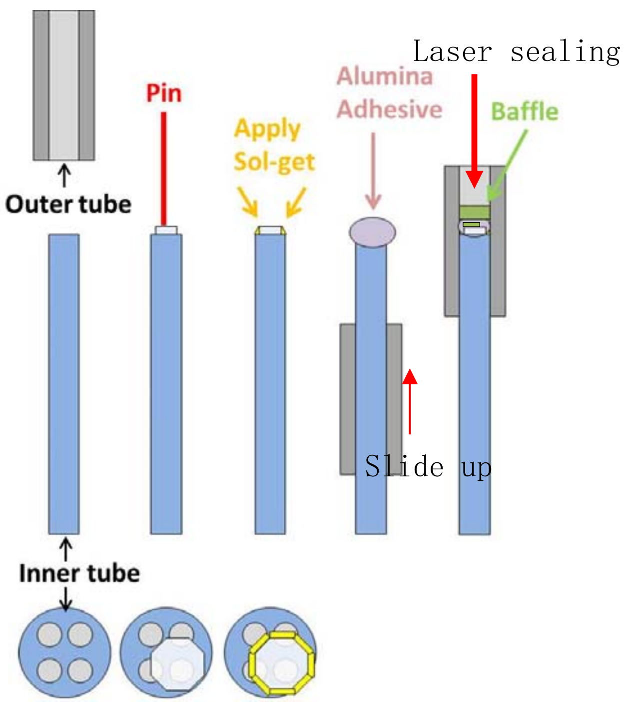


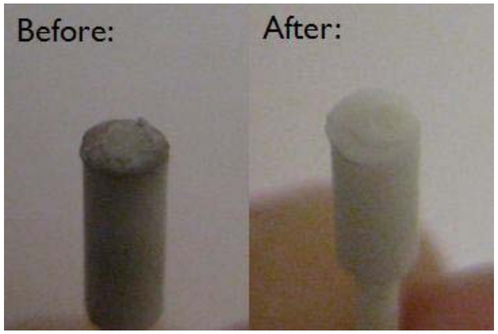


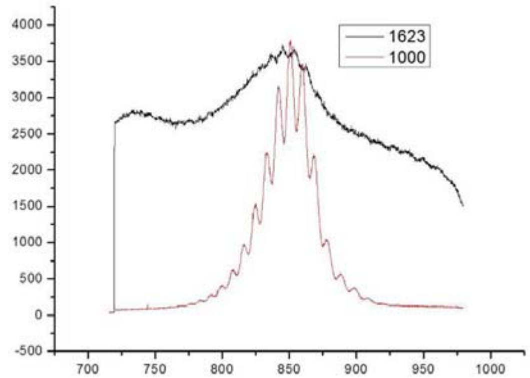


P3: Finalizing of the sensor structure

- Thermal fusion cap sealing technique

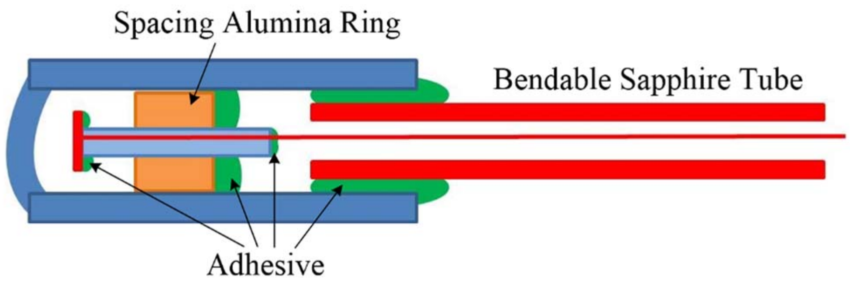


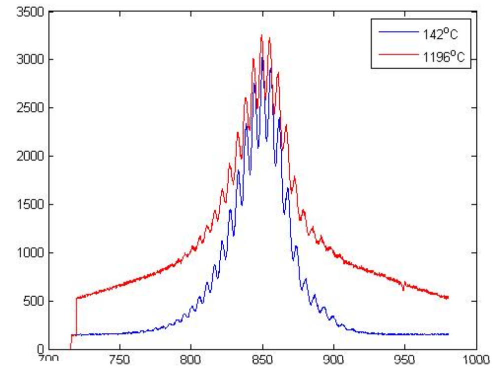


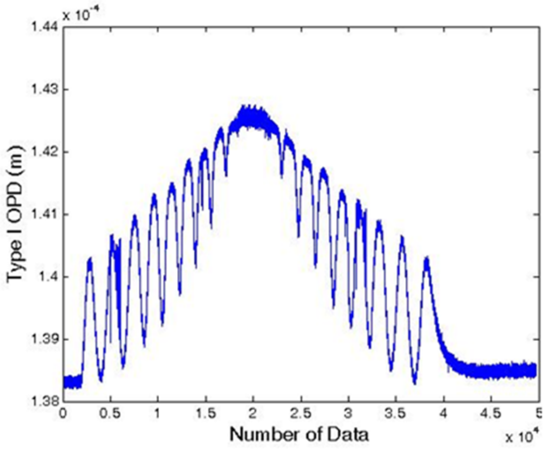


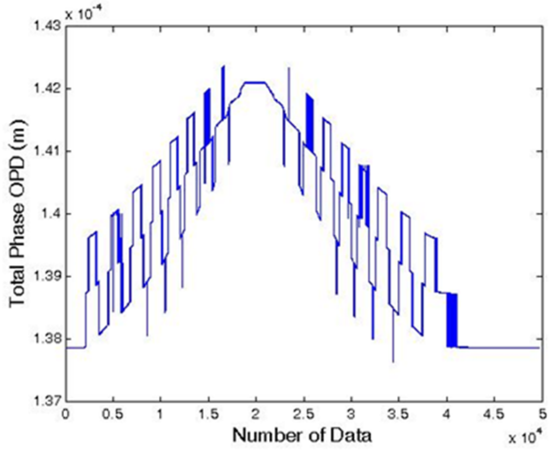
P3: Finalizing of the sensor structure

- Tube sealing sensor



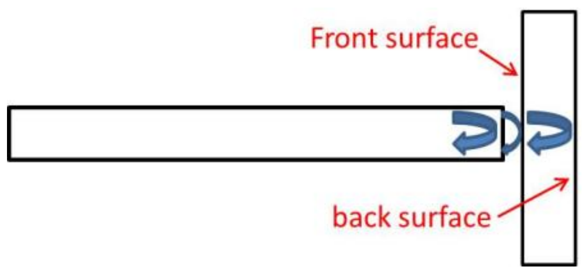


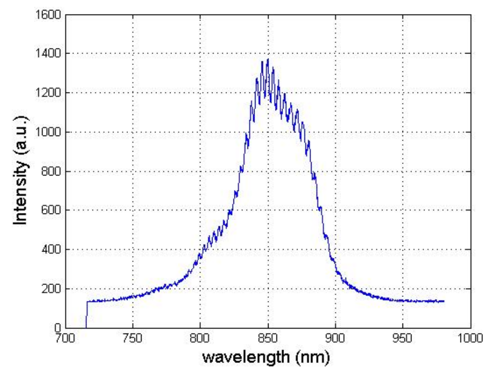


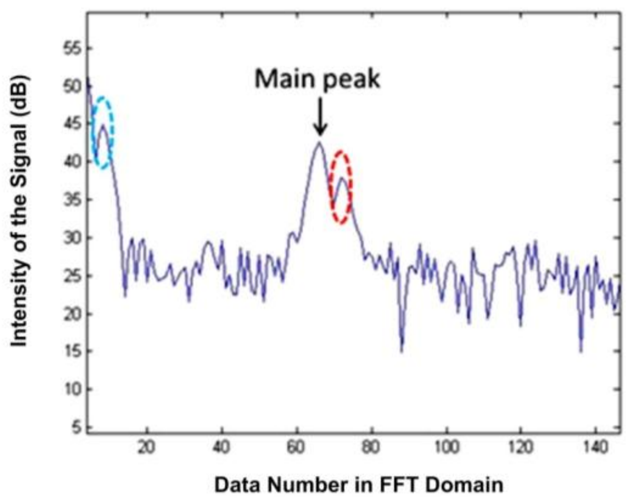


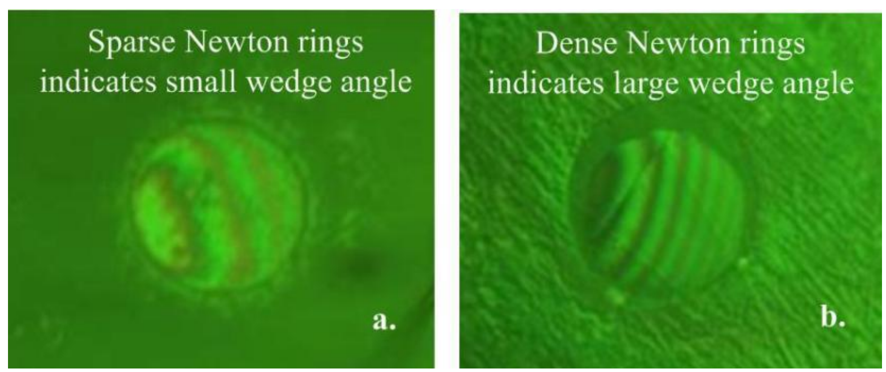
P3: Finalizing of the sensor structure

- Addressing of multi-surface interference issue





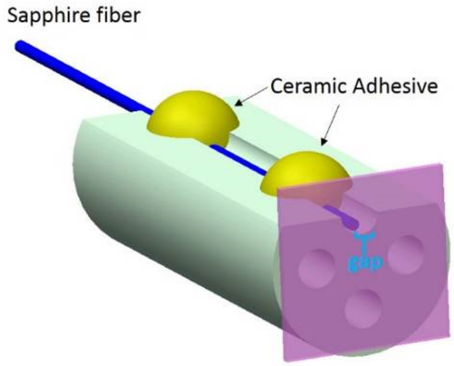


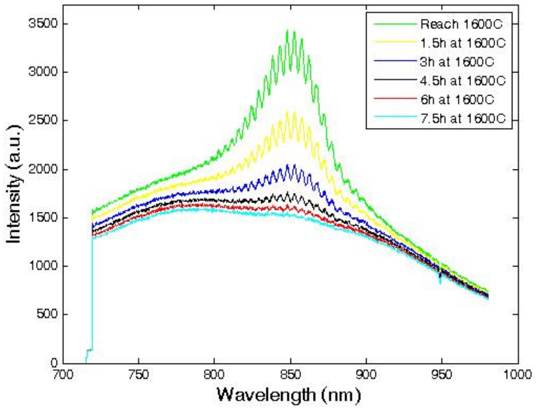


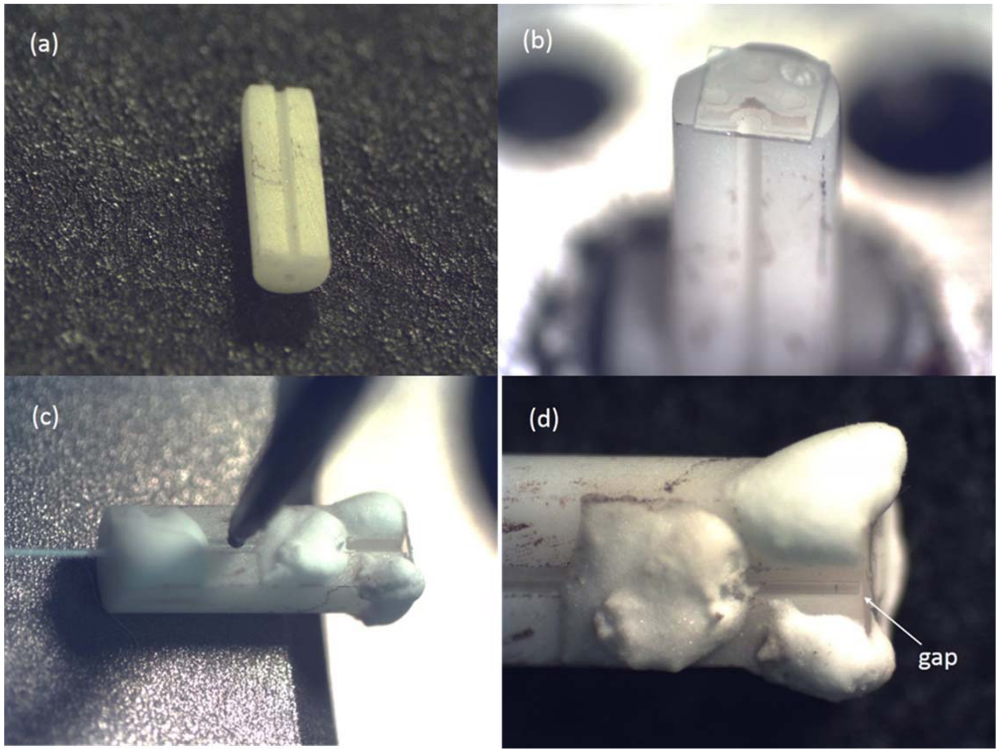
Angled polishing of fiber tip

P3: Finalizing of the sensor structure

- Side polished sensor design

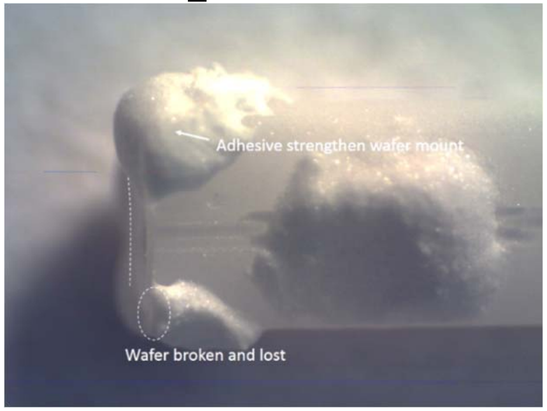


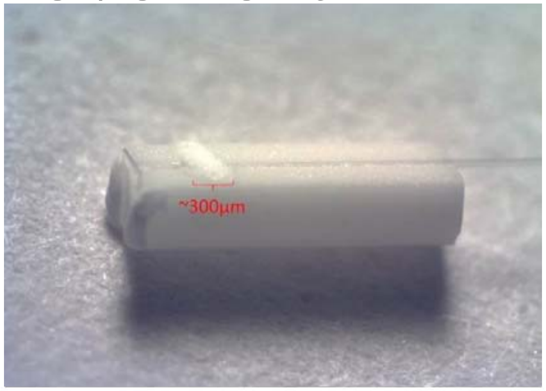


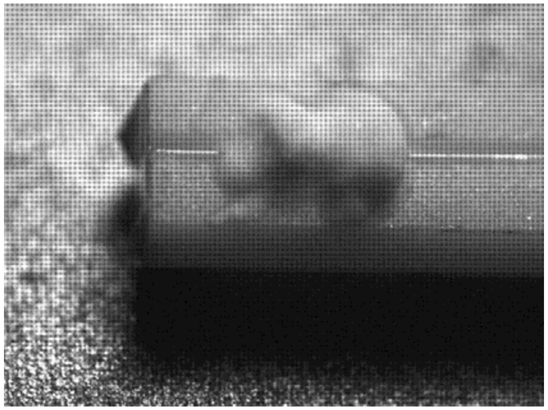


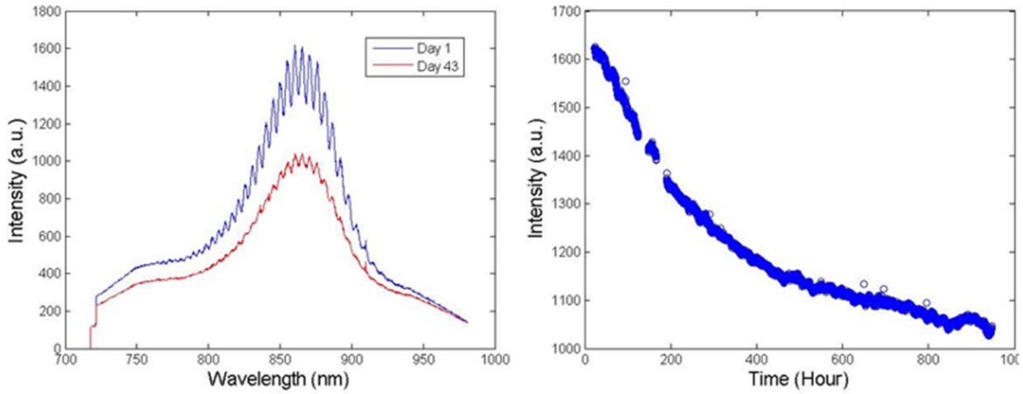
P3: Finalizing of the sensor structure

- Side polished sensor improvement





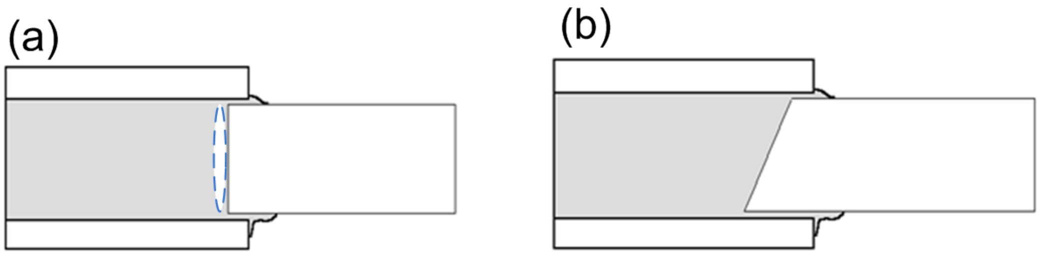




43 days lab test passed

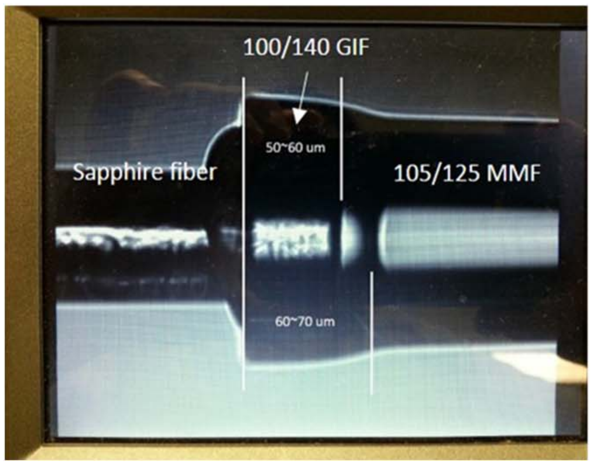
P3: Silica-sapphire splicing technique

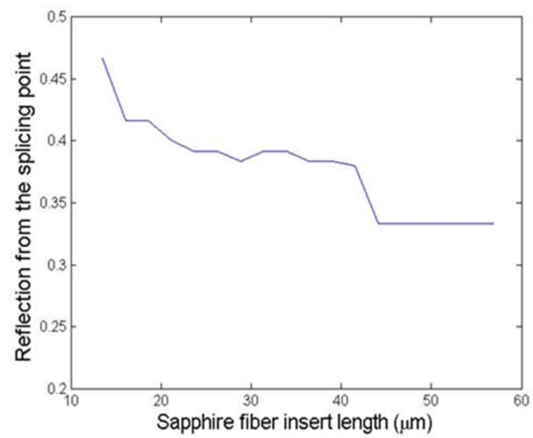
- Choosing the right multimode fiber:
  - Nufern 100/140 MMF
  - OFS 105/125 MMF
- Attempt of angle-polished design to remove void in fiber core



P3: Silica-sapphire splicing technique

- Sapphire-100/140 MMF-105/125 MMF splicing scheme

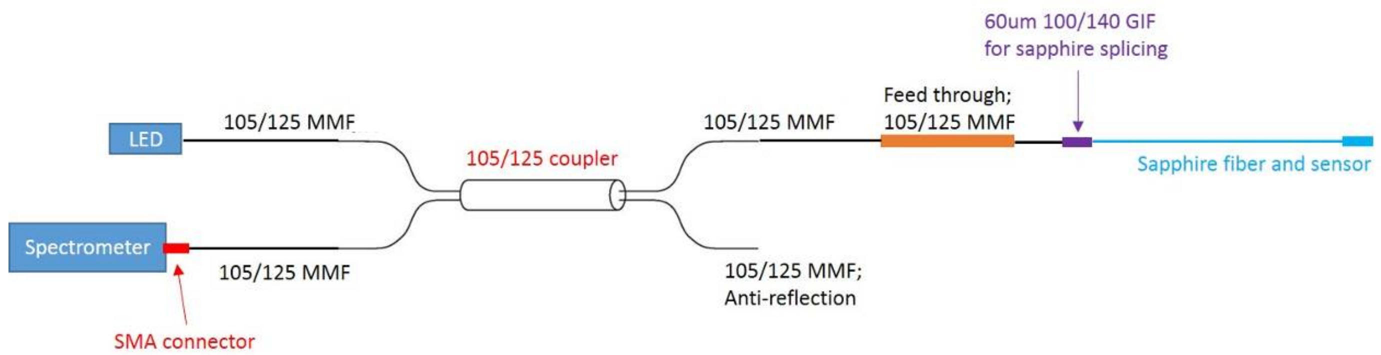




- Splicing point thermal endurance characterization
  - 600°C as the maximum surviving temperature
  - 400°C as the suggested working temperature

P3: Optimization of optical system and data acquisition

- Fiber system optimization



105/125 MMF for all system, including coupler and feedthrough. Effectively reduced loss and extended lifetime of sensors.

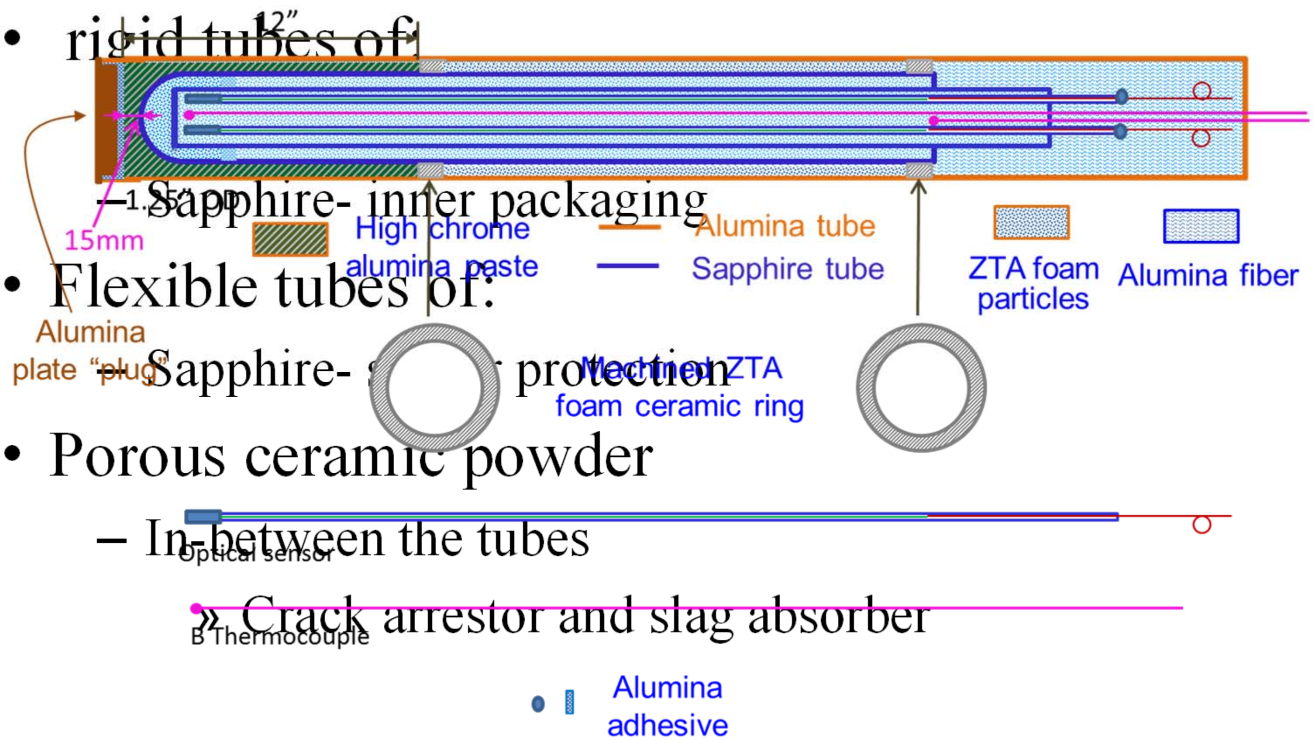
P3: Optimization of optical system and data acquisition

- Data Acquisition Software

Totally rewritten and fully tested. Now more stable, more flexible, more robust, jumping free in demodulation, and field-communication ready.

P3: Probe packaging design

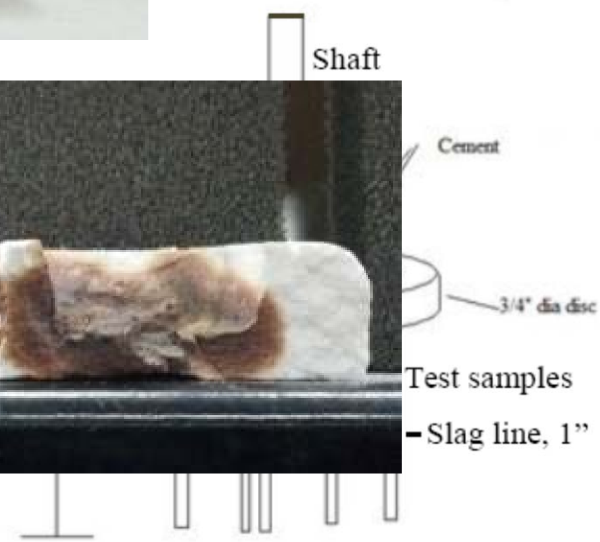
- Based on the corrosion testing
  - Design utilized:
    - rigid tubes of:
      - Sapphire- inner packaging
    - Flexible tubes of:
      - Sapphire- s[illegible] protection
    - Porous ceramic powder
      - In-between the tubes
        - » Crack arrestor and slag absorber



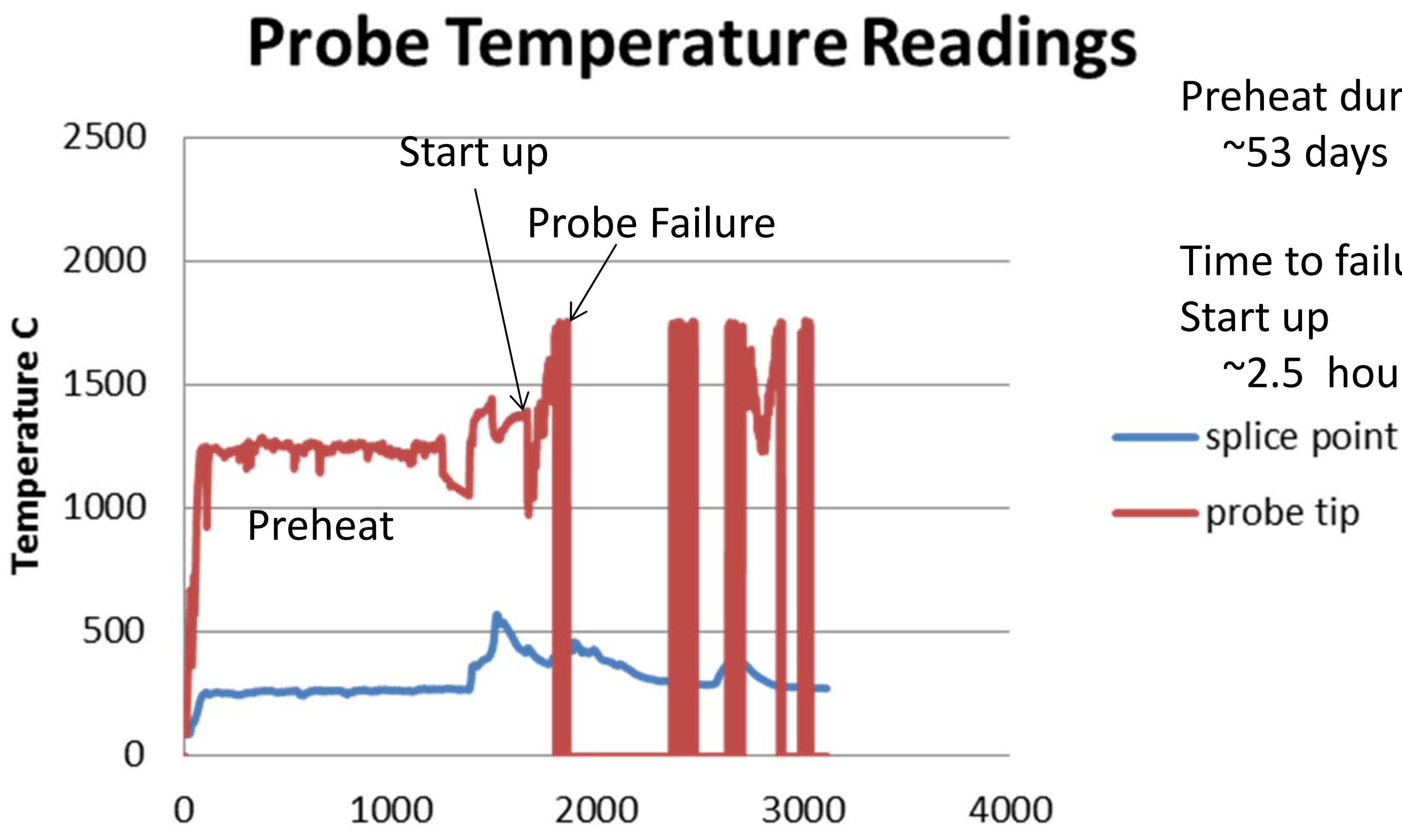
P3: Materials Testing and selection

- Materials testing for corrosion from coal slag

ide, hafnium



First blank probe results



Preheat duration
~53 days

Time to failure after Start up
~2.5 hours

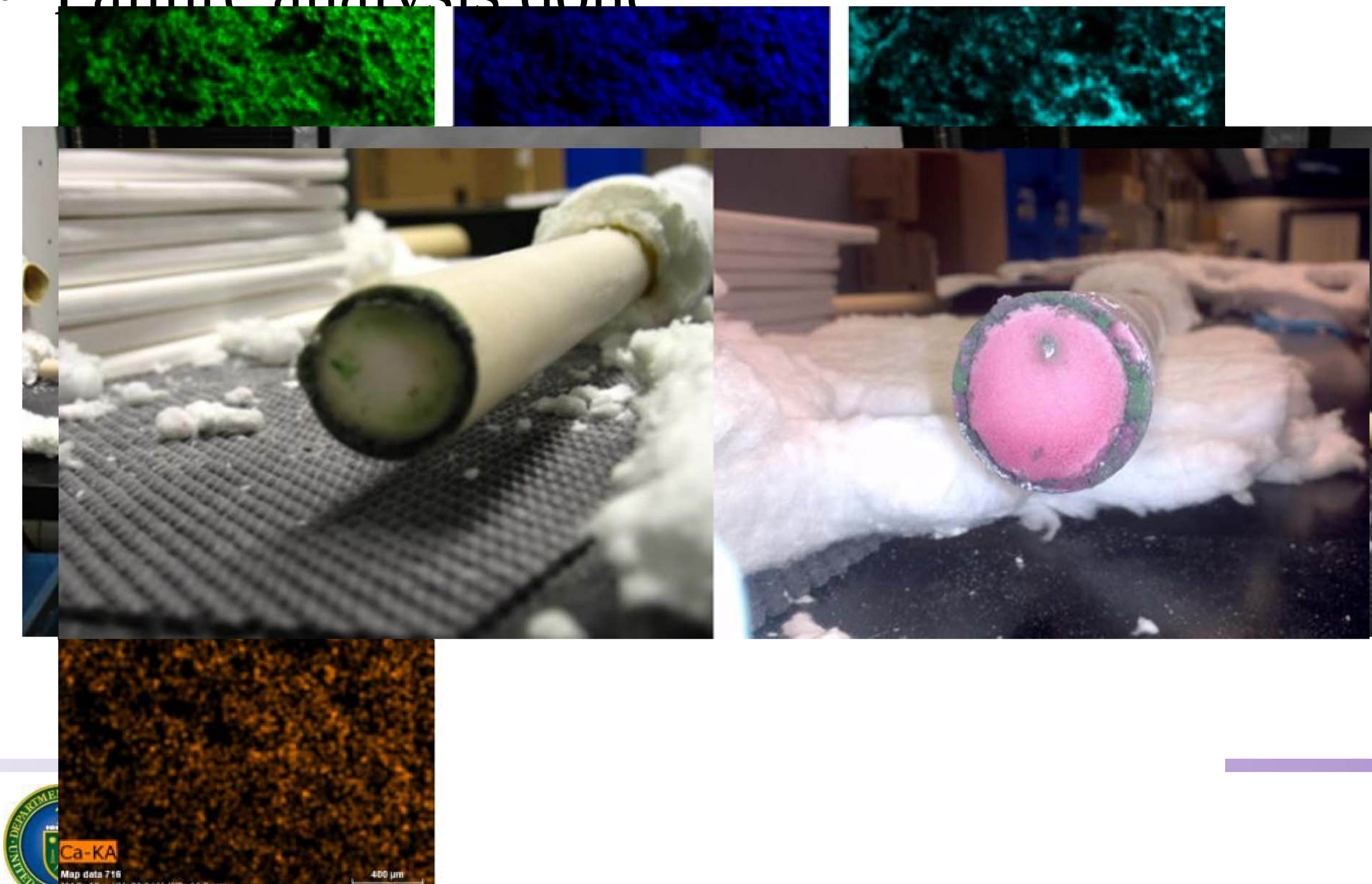
P3: Blank probe field test #1 results

- Probe installed at Eastman Chemical on 2/0
  - I

fa

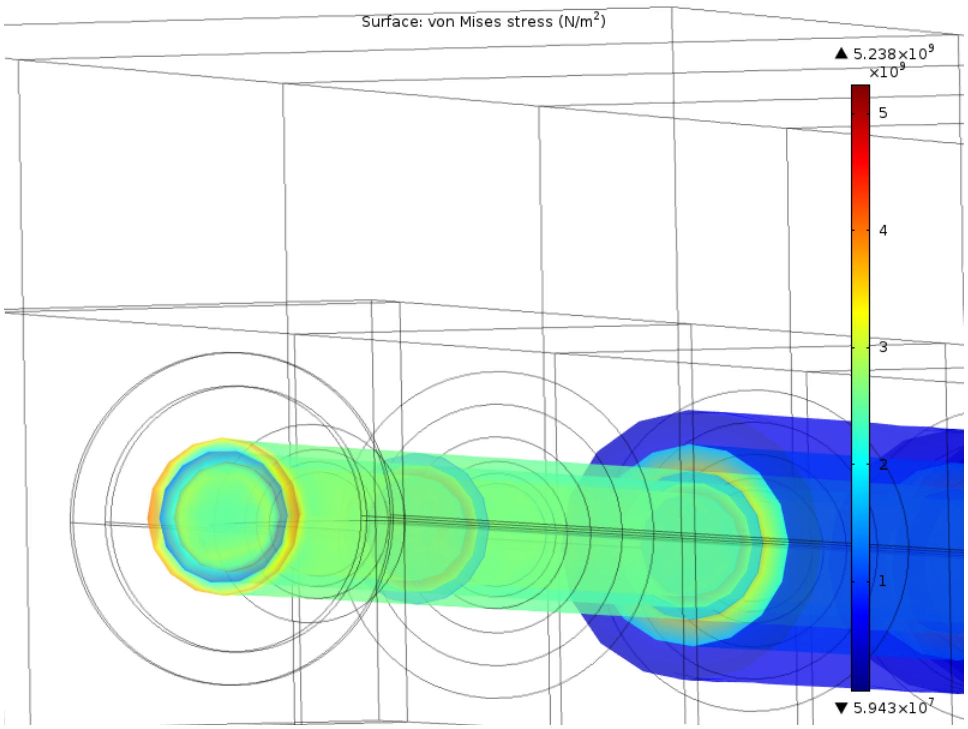
P3: Blank probe field test #1

- Failure analysis done



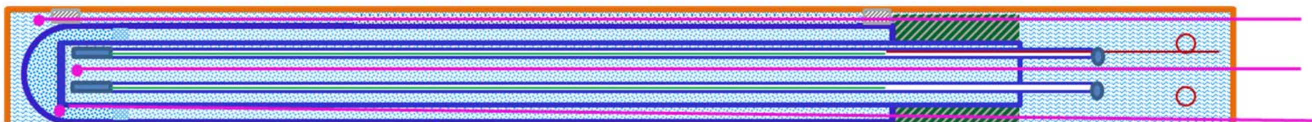
Progress updates: blank probe thermal modeling

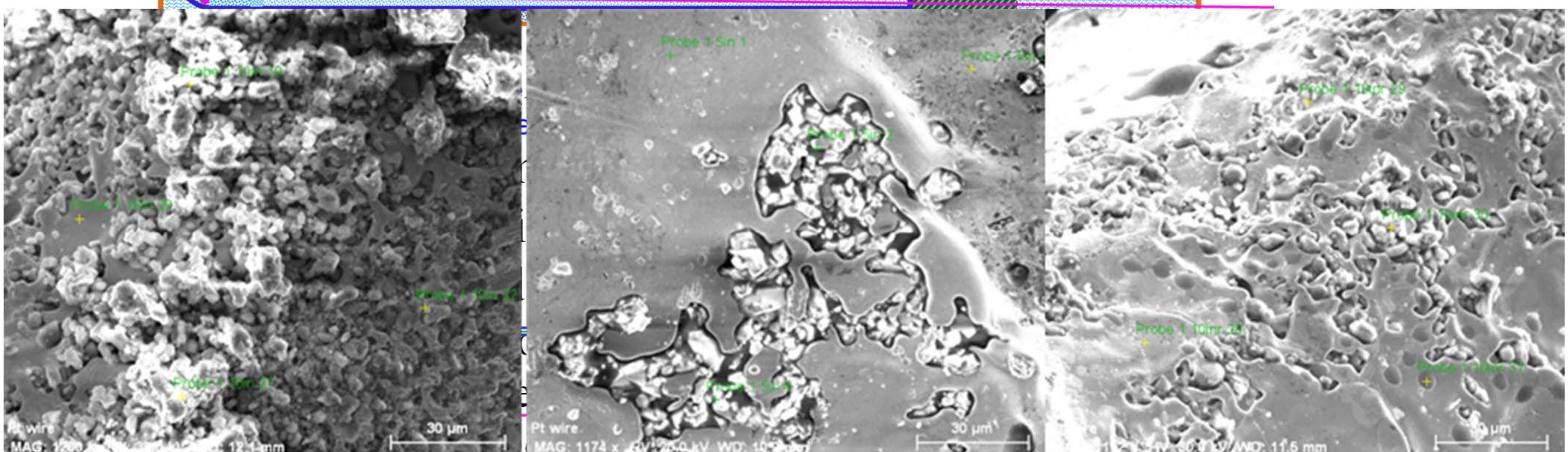
- Sapphire tube surrounded by high chrome paste experienced stresses ranging from 1.5GPa-5GPa (220ksi-725ksi).
- Highest stress concentrations in corners.
- Yield strength of sapphire at room temperature is around 400MPa (58ksi).
- Yield strength drops to 325MPa (47ksi) at 1000°C.



P3: Blank probe field test #2

- Redesigned based on field test #1
  - Moved chrome paste to cold area



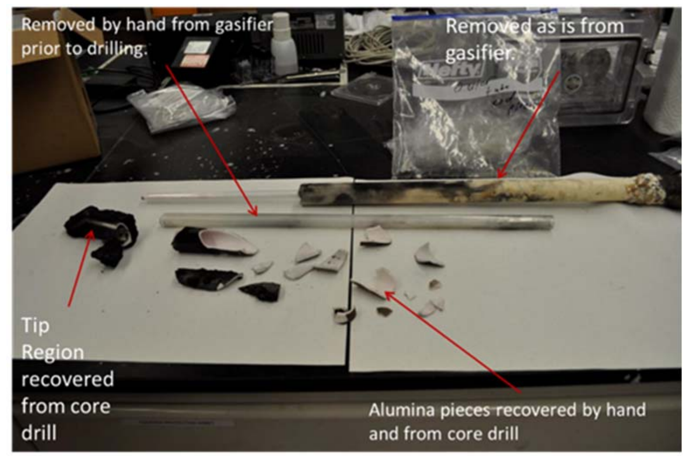


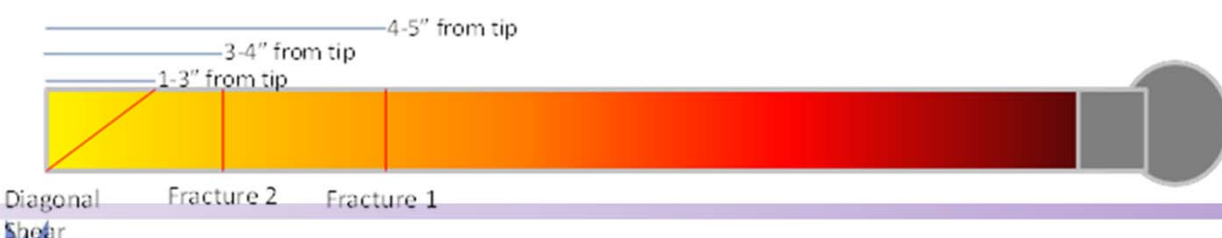
–

Alumina adhesive

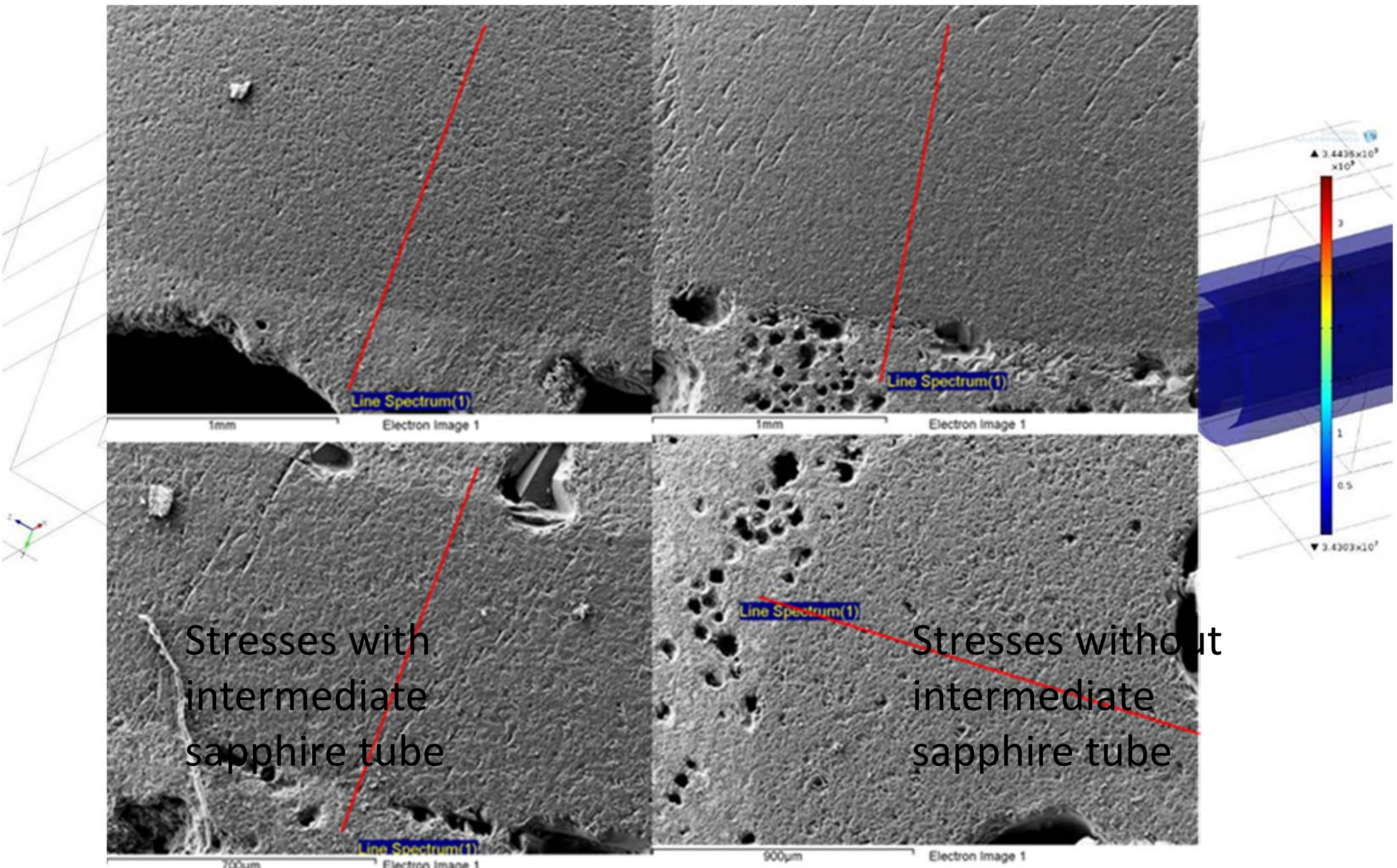
P3: Blank probe field test #2 results

- Probe installed at Eastman on

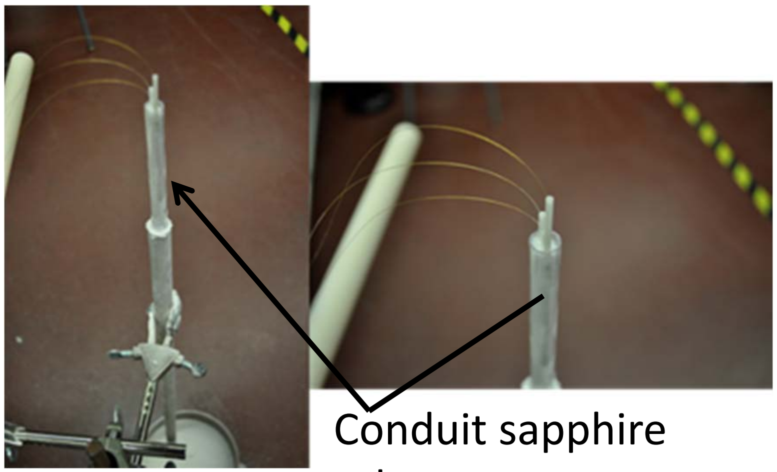




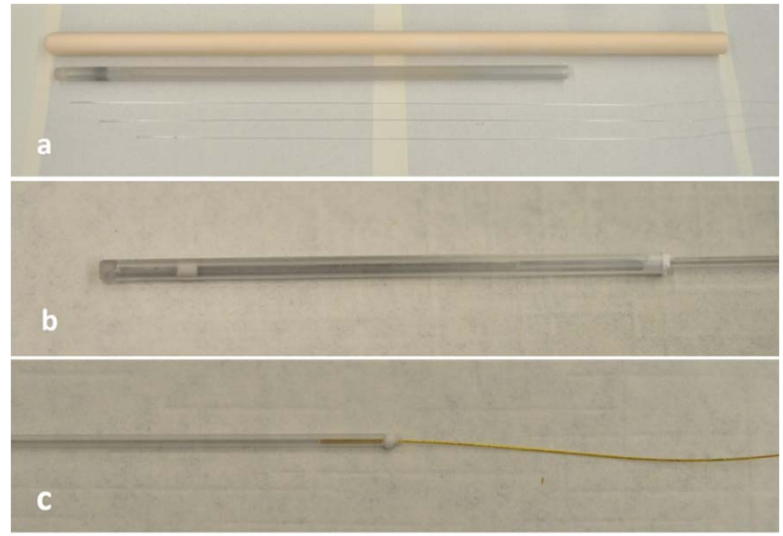
P3: Blank probe field test #2 results



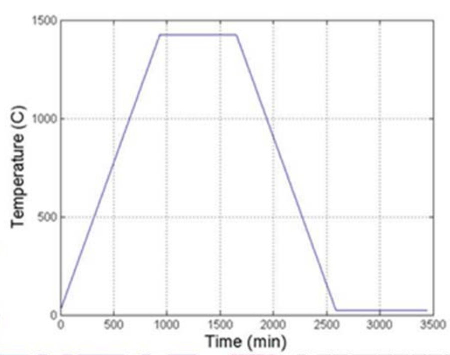
P3: Final Field test probe assembly

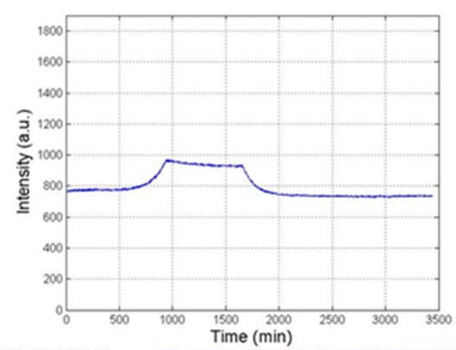


Conduit sapphire tube



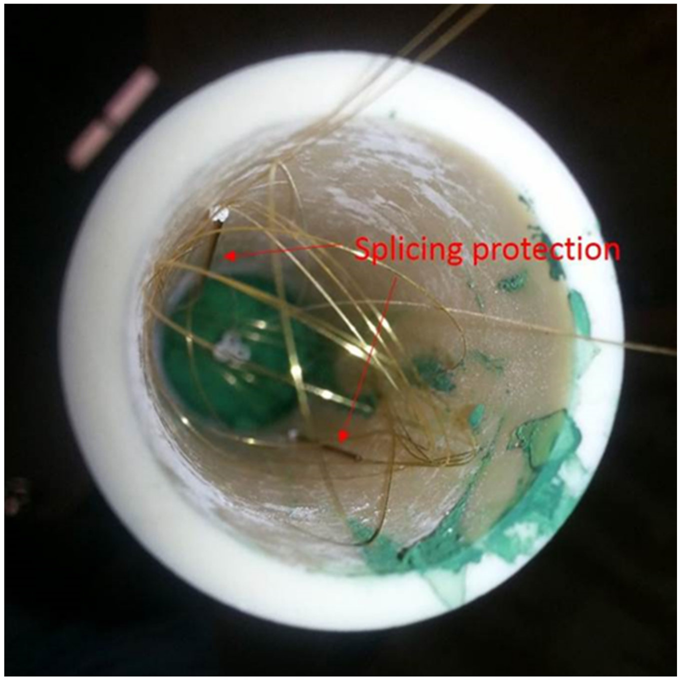
Probe packaging components





Sensor signal during final laboratory test

P3: Final field test probe testing



Final packaging prior to flange attachment

Sensor #	S10	S11	S14	S15	S16	S18
Original total intensity (a.u.)	3193	3277	1789	3233	2377	3120
Total intensity after annealing	36%	65%	40%	62%	52%	57%
Original fringe contrast	0.232	0.192	0.204	0.184	0.193	0.221
Fringe contrast after annealing	85%	100%	80%	97%	85%	91%

Sensor stability

Summary

- Difficult environment to operate and experiment in:
  - Developments achieved
    - Long term sensor stability
      - Elevated T
    - Accurate & stable High T measurement
      - Harsh environment
    - Environment-material interaction understanding
      - Coal slag
      - Packaging
      - Temperature
    - Sapphire temperature instrumentation packing
      - High T
      - High T & corrosive environment

Thank you

- Questions?