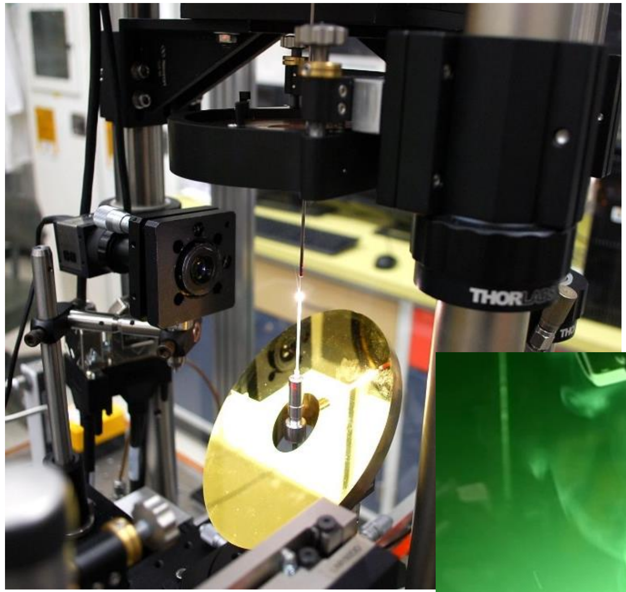
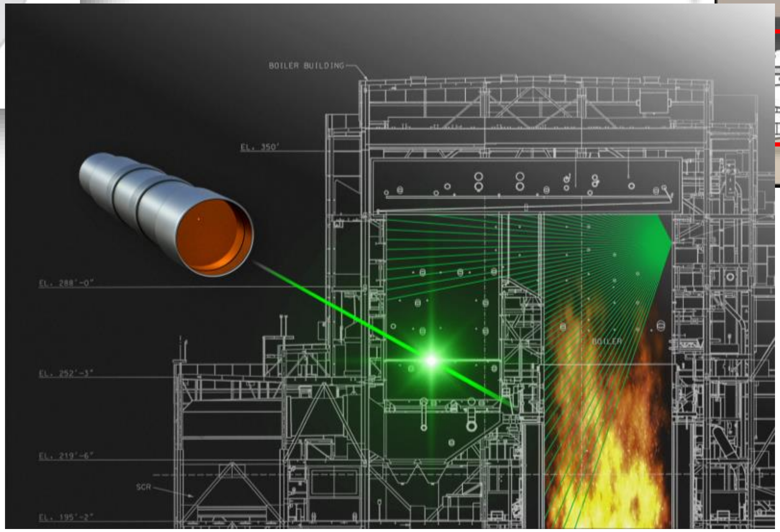
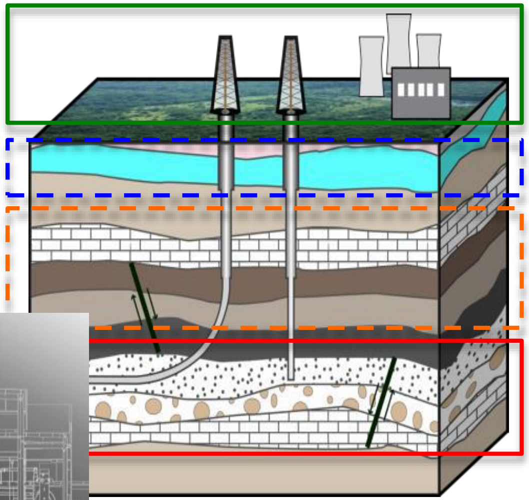
RIC Advanced Sensors & Controls FWP

Novel Sensors for Boilers

Dustin McIntyre, Dan Haynes, Joe Yip, Dan Hartzler, Chet Bhatt, Juddha Thapa, Nari Soundarrajan, Yan Zhou, Swarom Kanitkar, Steve Richardson, Jennie Stoffa

Presenter: Benjamin Chorpening, Ph.D.
Technology Portfolio Lead
Benjamin.Chorpening@netl.doe.gov



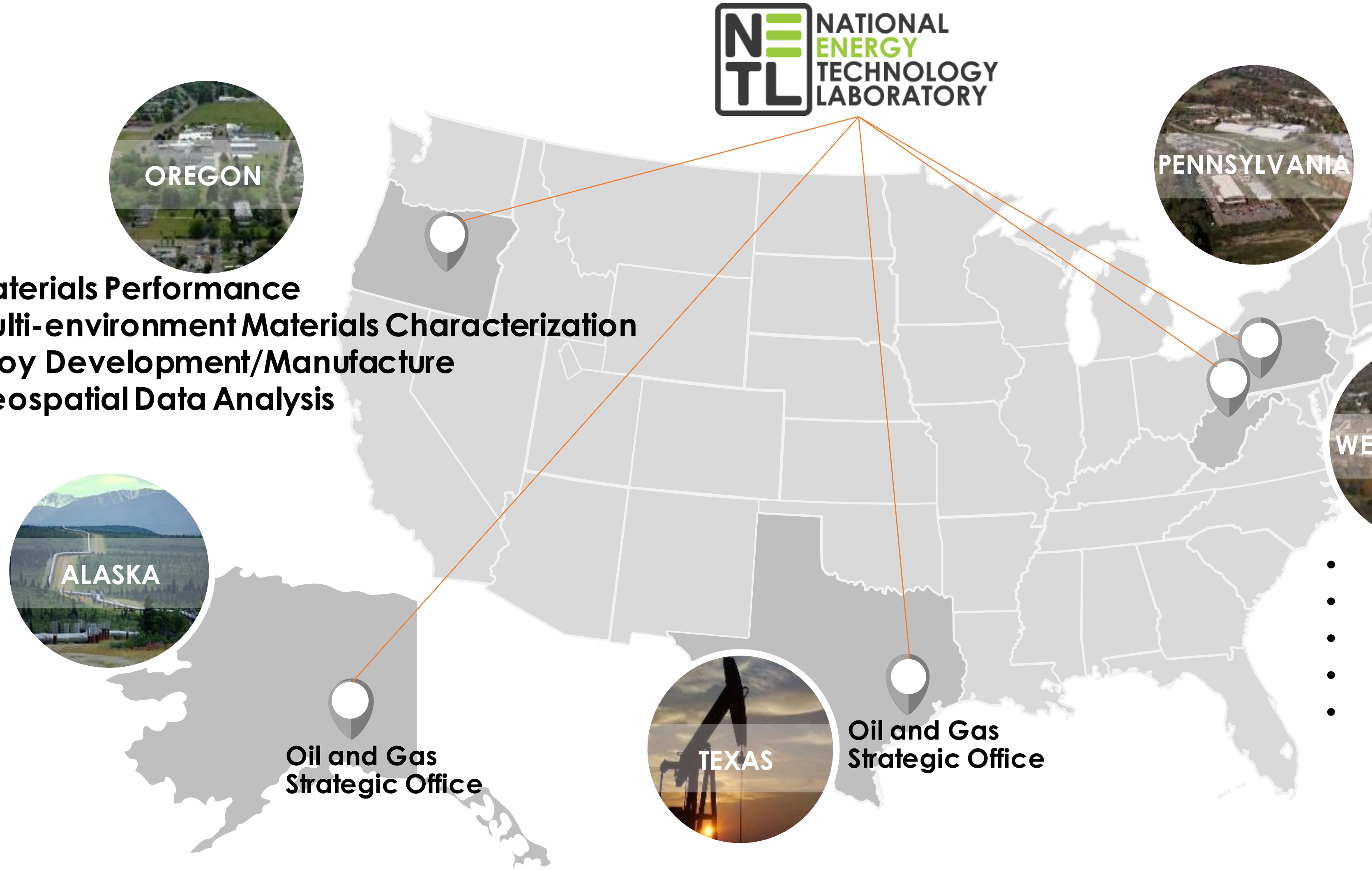
Crosscutting Research and Advanced Energy Systems Annual Project Review Meeting, May 20, 2021

Introduction

First a little about the Research & Innovation Center…

Research Focus by Site

Multiple Sites Operating as One Lab System



Oregon

- Materials Performance
- Multi-environment Materials Characterization
- Alloy Development/Manufacture
- Geospatial Data Analysis

Pennsylvania

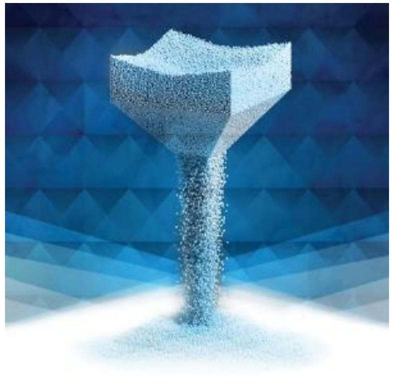
- Process Systems Engineering
- Decision Science
- Functional Materials
- Environmental Sciences
- Energy Systems Optimization

West Virginia

- Energy Conversion Devices
- Simulation-Based Engineering
- *In-Situ* Materials Characterization
- Supercomputer Infrastructure
- Diagnostics, Sensors, and Controls

NETL Core Competencies

Effective Resource Development • Efficient Energy Conversion • Environmental Sustainability

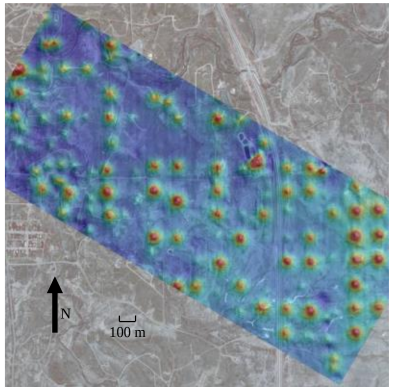


Computational Science & Engineering

- High Performance Computing
- Multi-Scale Modeling Atomistic to Device
- Artificial Intelligence & Machine Learning

Materials Engineering & Manufacturing

- Structural & Functional Materials
- Design, Synthesis, & Performance
- Characterization



Geological & Environmental Systems

- Geo-Analysis & Monitoring
- Reservoir Engineering
- Geochemistry

Energy Conversion Engineering

- Reaction Engineering
- Design & Validation
- Thermal Sciences
- Advanced System Engineering

Strategic Systems Analysis & Engineering

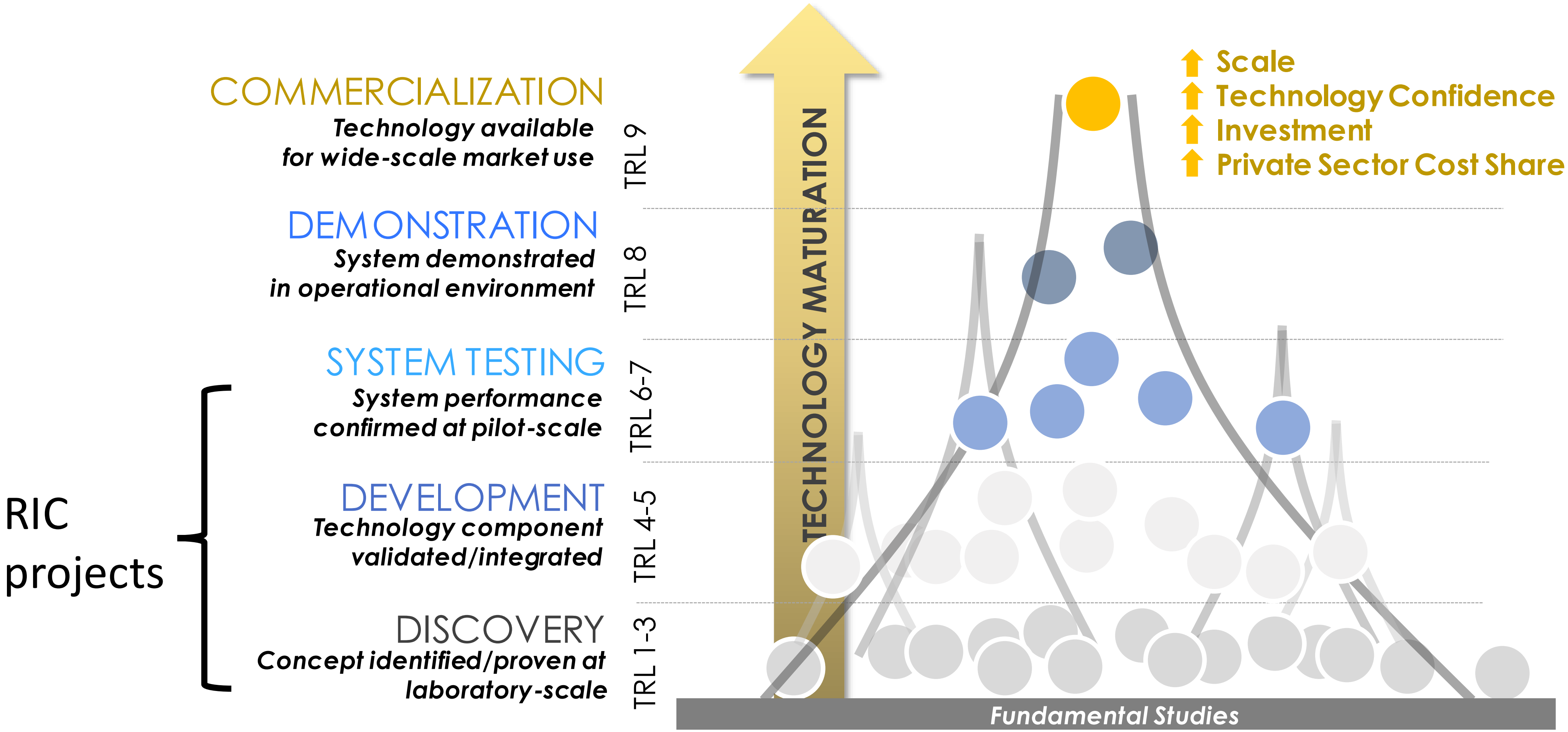
- Energy Process & System Engineering
- Multi-scale Modeling, Simulations & Optimization
- Energy Markets Analysis

Research Planning & Delivery

- Technical Project Management
- Business Management & Agreements

Technology Development Pathway

An Active Portfolio from Concept to Market Readiness



Changing Requirements for Fossil Energy Power

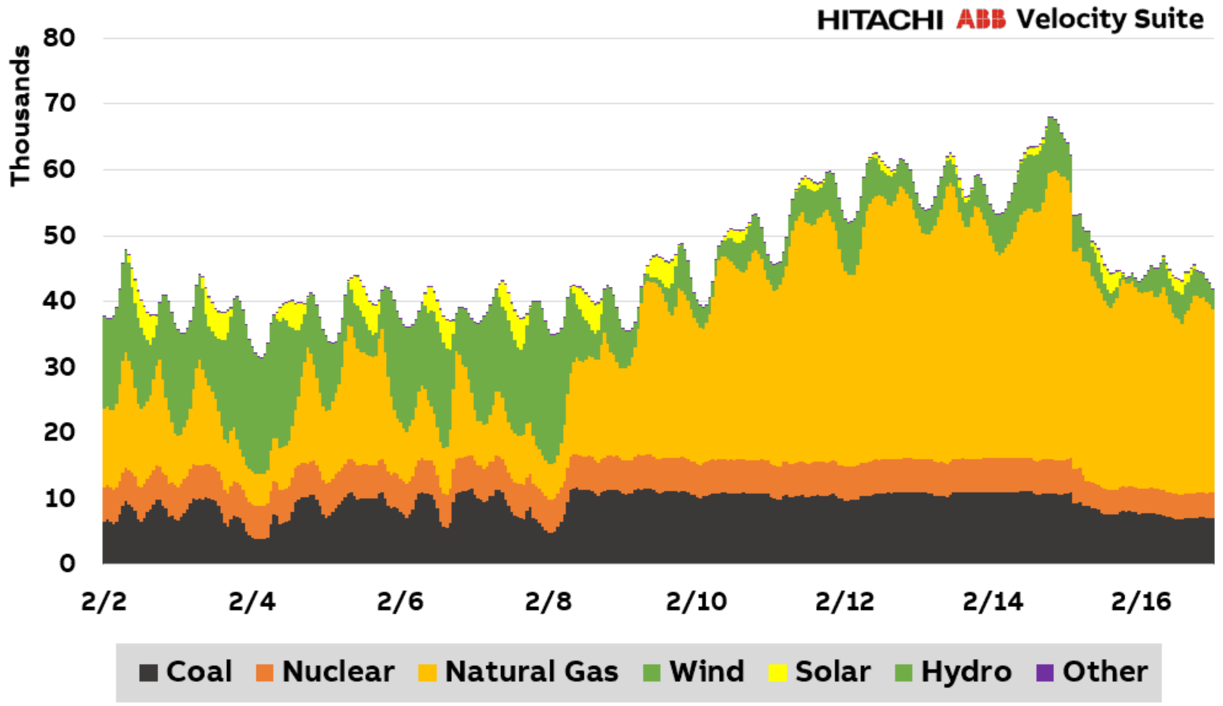
Increase Flexibility, Reduce CO_2 Emissions

Executive Order 14008 includes a goal of a carbon pollution-free electricity sector by 2035

How do we get there?

Fossil power plants
- Improve dispatchable power flexibility
- Integrate operation with **energy storage**
- Integrate with **carbon capture**

This will require development of
- Sensors to increase actionable plant information
- Optimized plant and grid control strategies
- Integrated system dynamic controls
- Sensors to assure environmental safety of carbon storage



ERCOT hourly electricity by fuel, Feb. 3-16, 2021, MWh. Source: Hitachi ABB Power Grids (Power Magazine, 2/19/2021)

Dispatchable power generation must flex better to coordinate with renewables to meet power demand while reducing CO_2 emissions.

Overview of Adv Sensors & Controls FWP (EY21)

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Sensors & Instruments

- High temperature optical fiber sensors
  - Crystalline fiber
  - Sensing materials
  - Interrogation
- Real-time gas composition analysis
- LIBS for subterranean chemical sensing
- In-boiler temperature field measurements

Controls

- Testing online system identification for detecting equipment problems
- Cyber-physical systems as a hybrid power plant development acceleration tool

Cybersecurity and Novel Concepts

- VLC – Alternative to WiFi
- Strengthening Cybersecurity with Fast Proxy Models in High Fidelity Digital Twins
- AI for screening and design of functional materials
- Quantum sensors for fossil energy applications

Ultrafast Laser Measurements for Power Generation (Task 48)

Dan Hartzler, Chet Bhatt, Nari Soundarrajan, Dustin McIntyre, B. Chorpening

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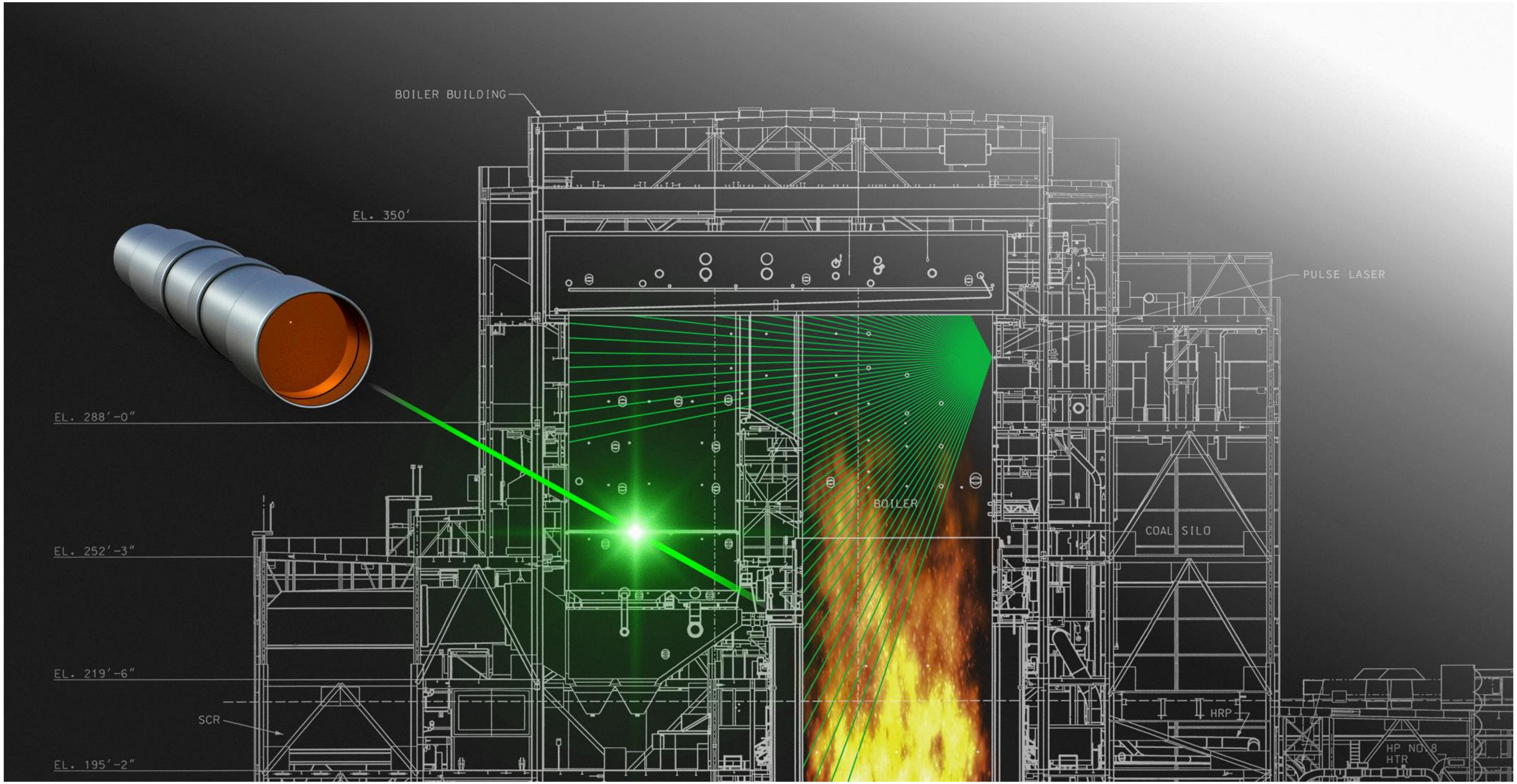


Project Objective and Approach

- **Objective**

Provide a laser based time domain measurement of species and temperature inside a boiler along a single line of sight

- **Benefits**

Extreme environment non-invasive non-contact measurement that can provide information on combustion and Thermodynamic processes that would potentially allow tuning of input parameters to improve operation and efficiency

- **Challenges**

Need a better understanding of the time domain scattering processes in the extreme environment and whether the Measurement can be adequately made with nanosecond or picosecond pulsed laser systems.

- **Approach**
    - Ambient Measurements

      Measurements in lab air with available lasers and spectrometer/camera systems
    - Gas Cell Measurements

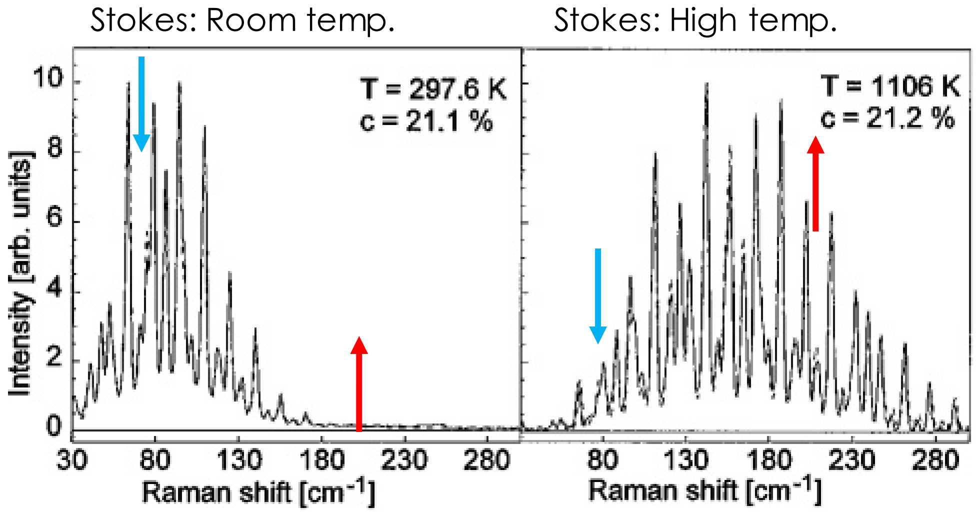
      Measurements in low pressure optically accessible gas cell to determine calibration characteristics
    - Tube Furnace Measurements

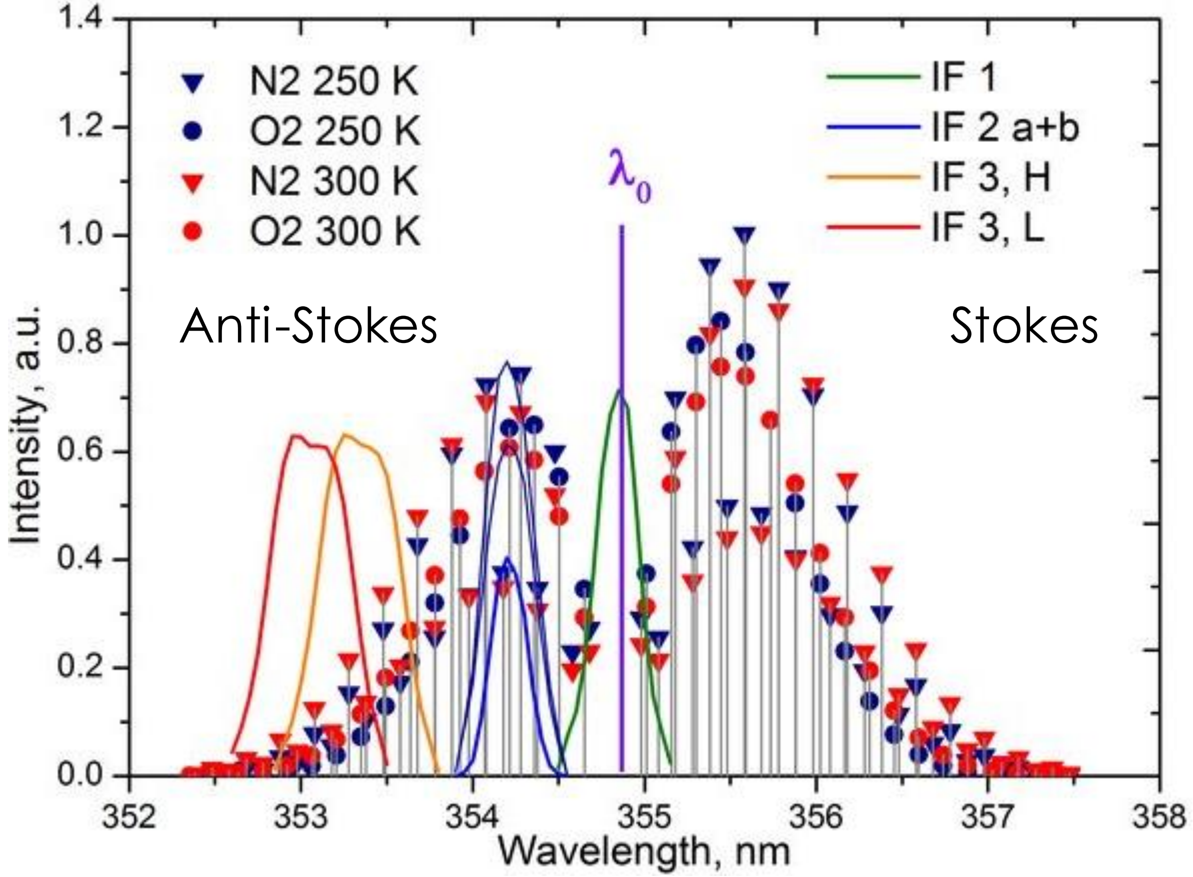
      Measurements in optically accessible high temperature gas cell with optical access to understand measurement Characteristics in a more relevant environmental conditions

Rotational Raman Scattering

Temperature sensitivity of pure RRS bands is in the:

- Stokes/anti-Stokes ratio (RIGHT)
- Relative intensities of the high and low frequency RRS bands (BELOW)





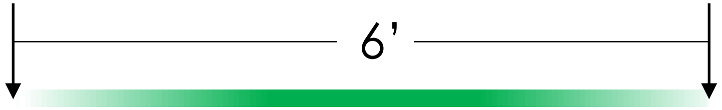
Hammann 2015 - "Temperature profiling of the atmospheric boundary layer with rotational Raman lidar during the HD(CP)^2 Observational Prototype Experiment
Seeger 1996 – "Experimental comparison of single-shot broadband vibrational and dual-broadband pure rotational coherent anti-Stokes Raman scattering in hot air"

Testing the Concept

The Raman measurement at room T/P using the 2' long gas cell.

Laser: 532 nm @ ~100 mJ/pulse, beam diameter ~ 9mm

Detector window was set to 6 ns (6' length) →

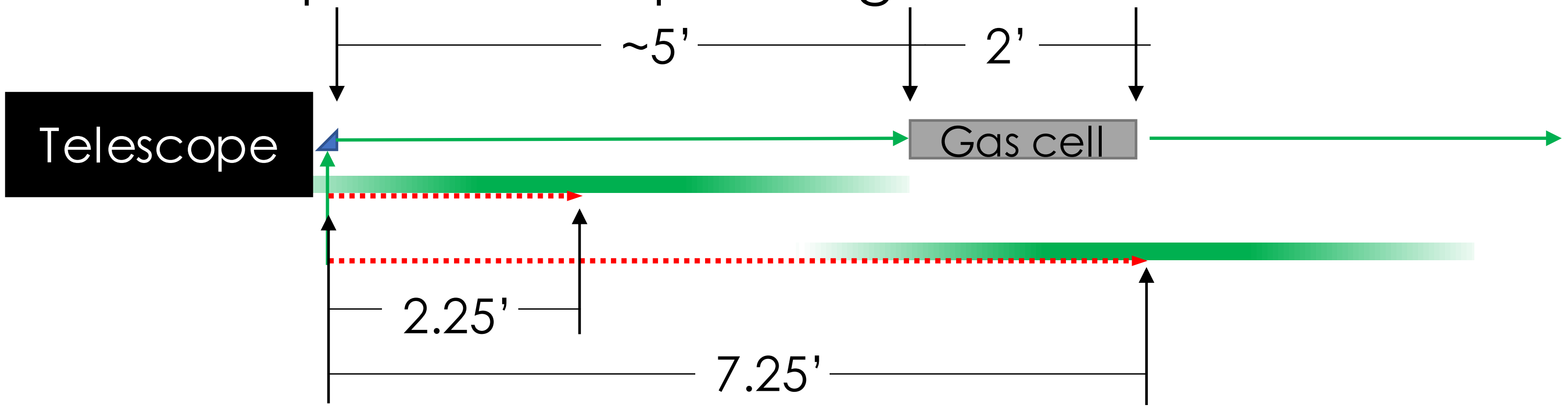


High resolution spectrometer setting used in order to resolve the N2 and O2 rotational bands (high res. = Low bandwidth)

- Thus, the vibrational bands can't be observed at the same time as the rotational bands

Air was diluted with nitrogen so that the O2 concentration = 21% and 12%

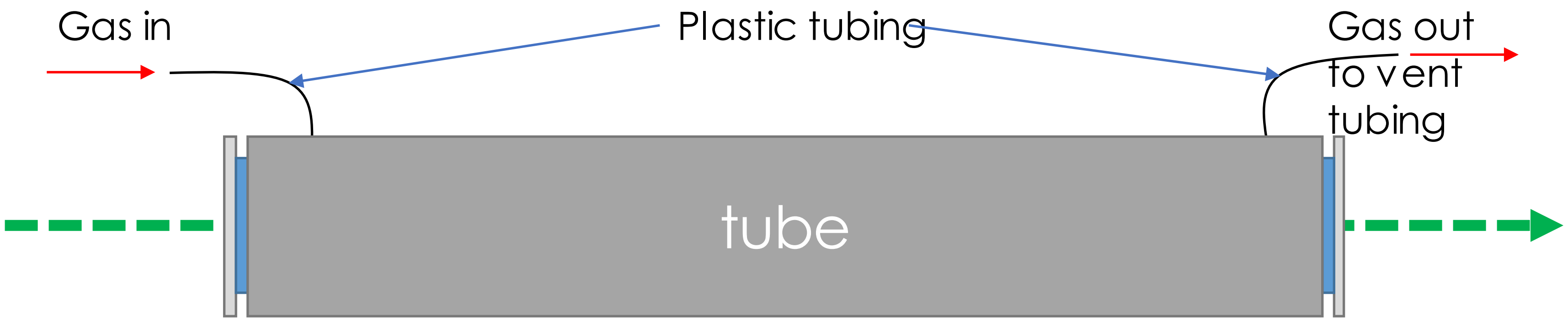
The cell was located about 5' from the telescope as shown below, data was measured at two points corresponding to ~2-2.5' and 7-7.5' from the telescope

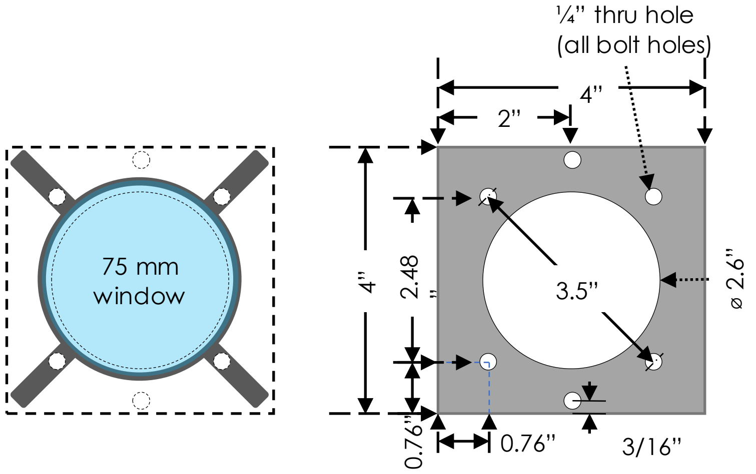


Ambient Temperature Testing

Description

- Dimensions: 71 mm (2.8") ID tube x 61 cm (24") long (2.41 L)
- Windows: ⌀ 75 mm, Fused Silica, MgF_2 AR coating (R < 1.5% @ 532 nm)
- Gasket sealed, gas tight (low pressures only)





Concentration Calibration

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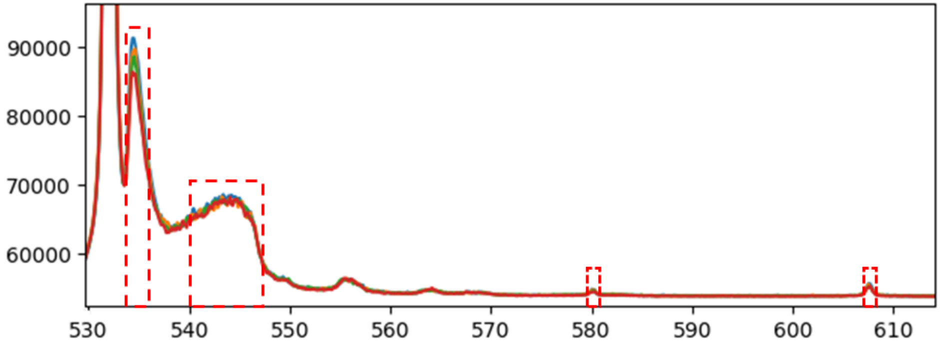
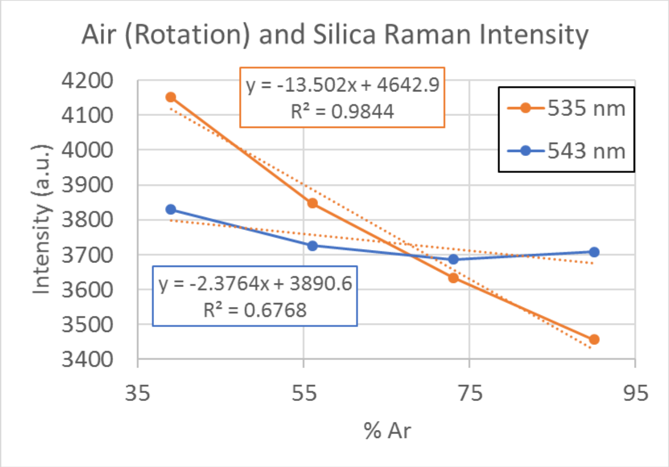
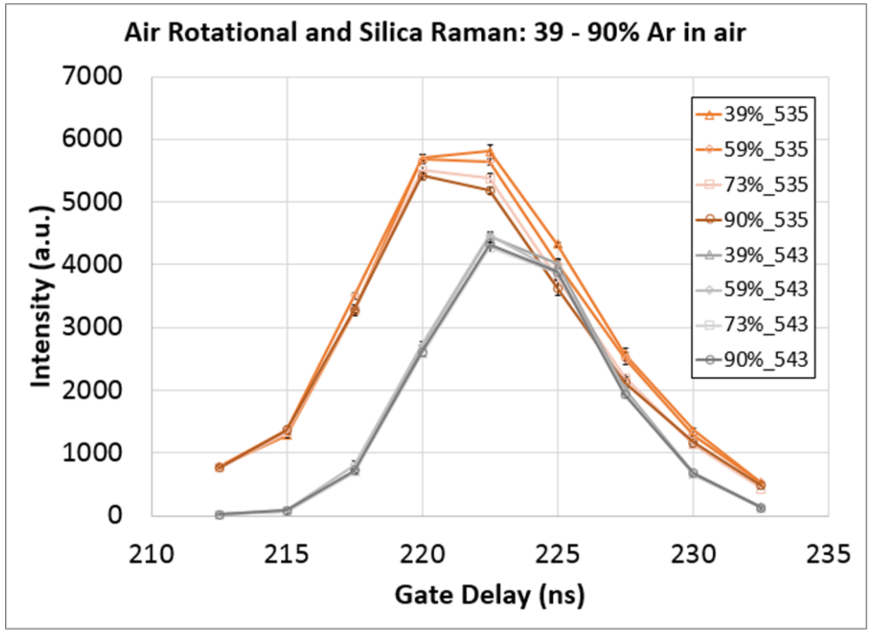
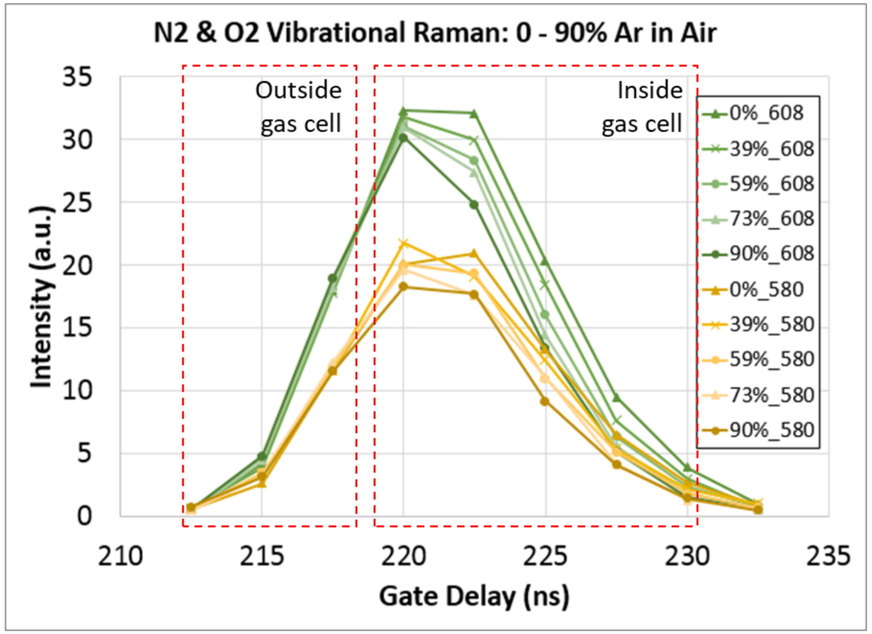


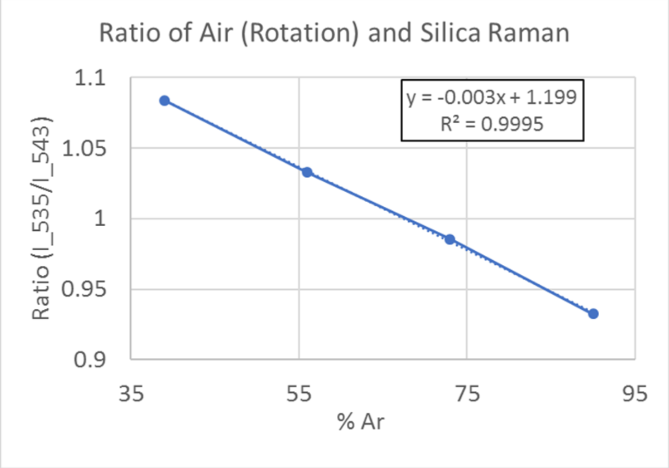
Silica Raman originates from the gas cell windows. It can be used to normalize the gas Raman signal.



Raw calibration curve







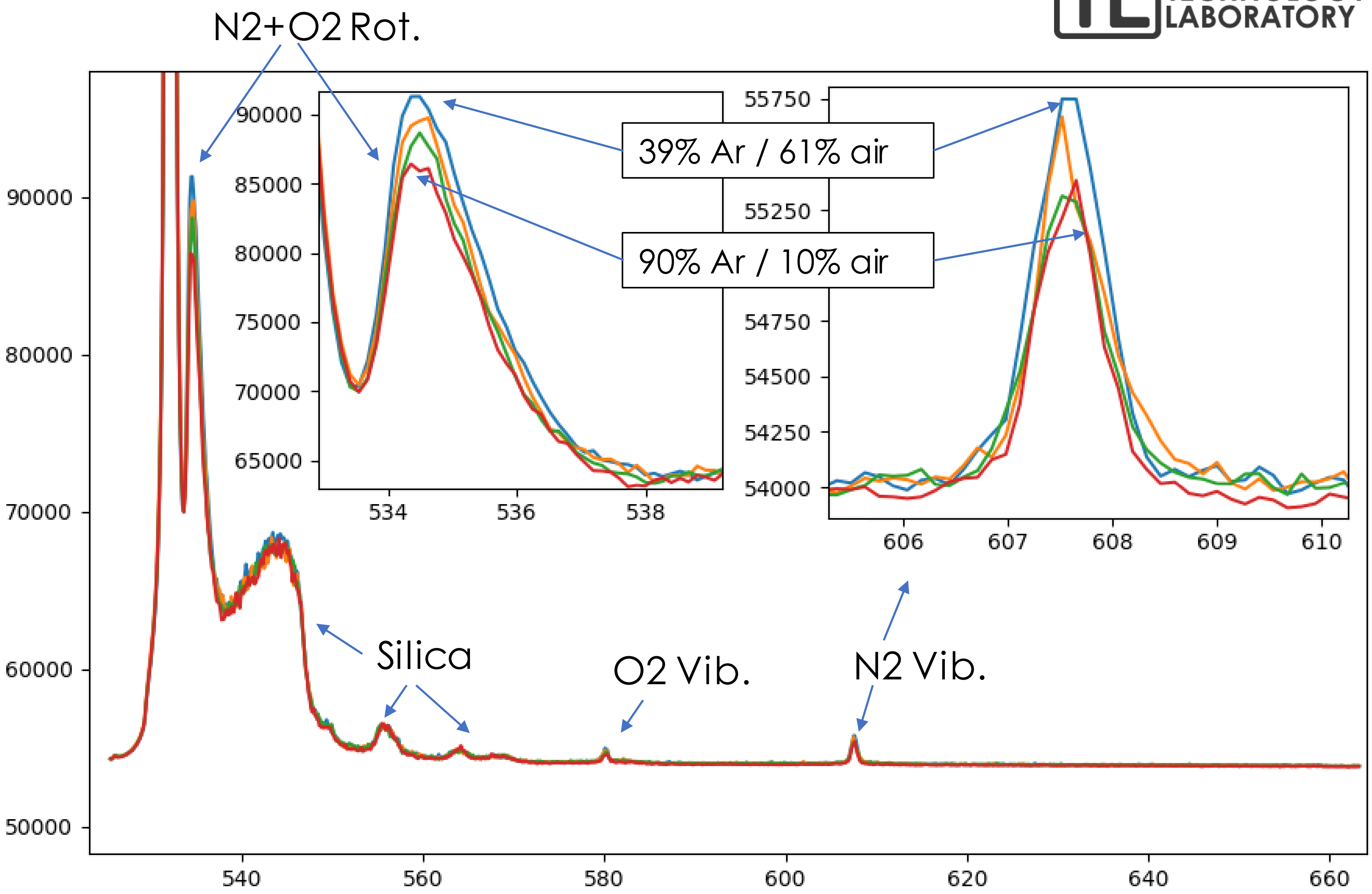
Silica normalized calibration curve

Concentration Calibration

Raman spectrum of 39, 56, 73 and 90% Ar in air

Peaks

- ~535 nm – N2+O2 rotational
- ~543 nm – Silica
- 580 nm – O2 vibrational
- 608 nm – N2 vibrational



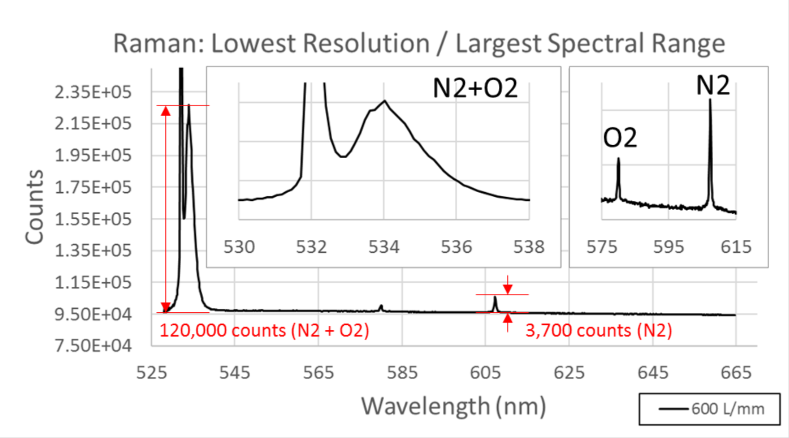
Next Steps for Laser Measurements

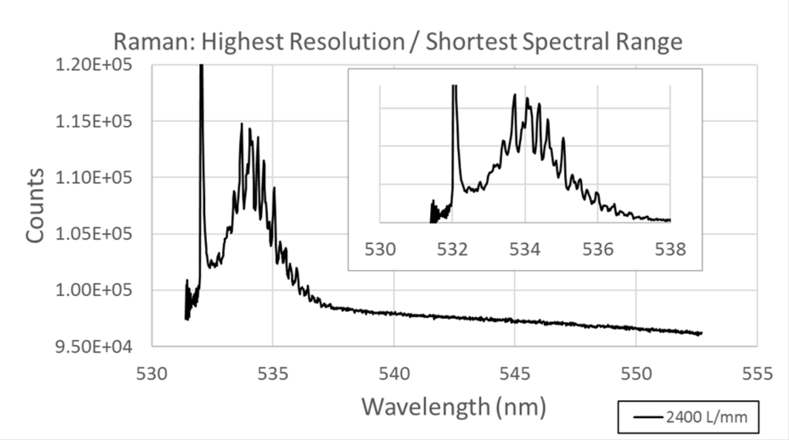
EY20 Progress Highlights

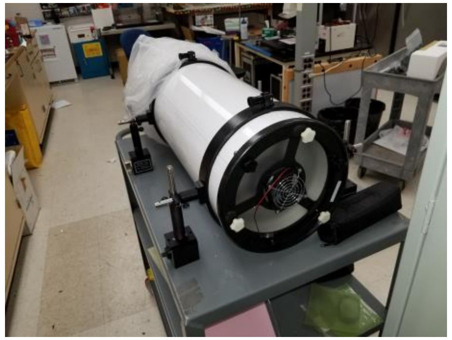
- Safety analysis performed and infrastructure installed
- Installation of tube furnace in to B25 212
- Initial measurements in unheated seal tube completed successfully

Upcoming Milestones

- Optical testing in tube furnace with various gas concentrations and elevated temperature
- Installation of telescope optics equipment in lab for validation and signal enhancement







Technical Challenges and COVID Impacts

- Vendor issues have caused delays with fabrication efforts
- Time resolution limitations of existing laser and spectrometer

Temperature Measurements via Reactive Particles (Task 47)

Dan Haynes, Yan Zhou, Swarom Kanitkar, Nari Soundarrajan, B. Chorpening

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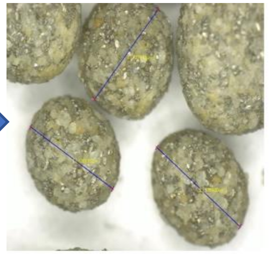
Goal: To understand boiler temperature to optimize thermal performance

- Accurate temperature data will validate combustion models for more efficient designs
- Aid in improving operation and reducing damage to the boiler from localized hot spots at part load conditions

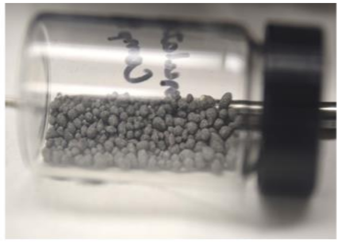
Approach:

Design and develop green light emitting pyrotechnic particles with 2 protective layers that are shed from thermal stresses due to heating and cooling

Optimization of green-light pyrotechnic formulation development

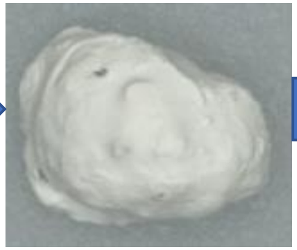


(a)

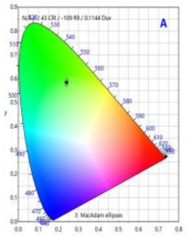


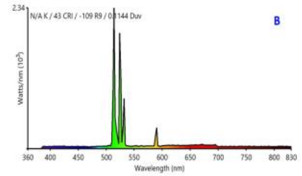
(b)

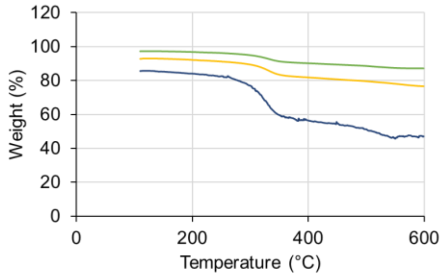
Granulation of formulations into particles sizes similar to coal (<500 µm)



Coating of ZrO2 and Al2O3 layers







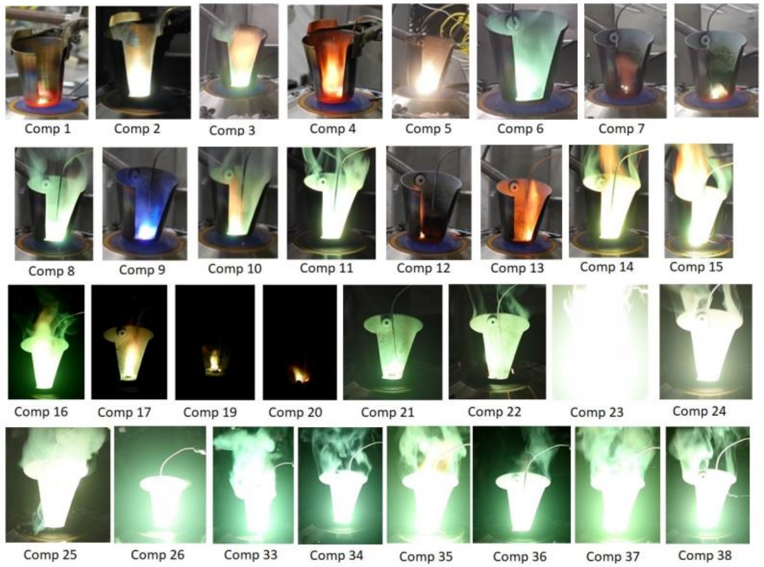
Performance Validation

Reactive Core Development

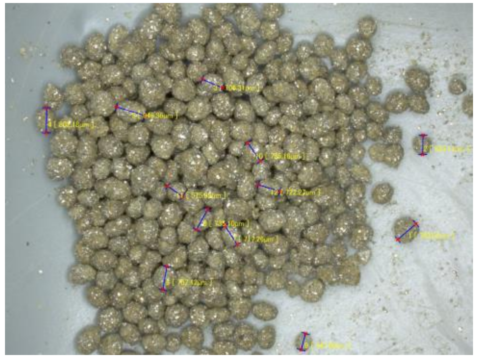
Key Results and Highlights

- Development of the reactive core
  - Examined over 30 mixtures of green light emitting formulations and identified key components for metallic fuel, oxidizer, binder, and colorant
  - 5 compositions have been selected as candidates for further study to be refined and optimized for coating
  - Compositions selected can be tuned by the type of components or their amount to facilitated granulation and coating while minimizing impact to green light emission.

- Granulation of the reactive core
  - Developed a procedure to generate the desired size of granules (420 μm < size < 840 μm)
  - Working to improve method since yield is low (<10%) and a secondary treatment is needed to smooth into spherical shape for coating



a. Light emission studies

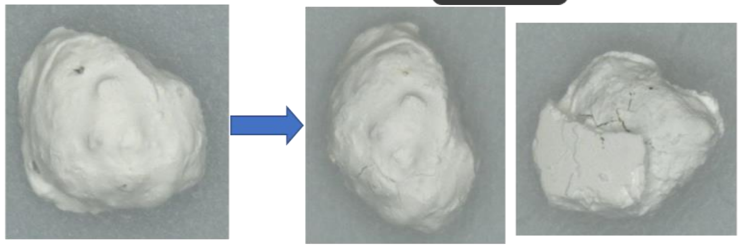


b. Granulated core material

Particle Coating Progress

Key Results, and Highlights

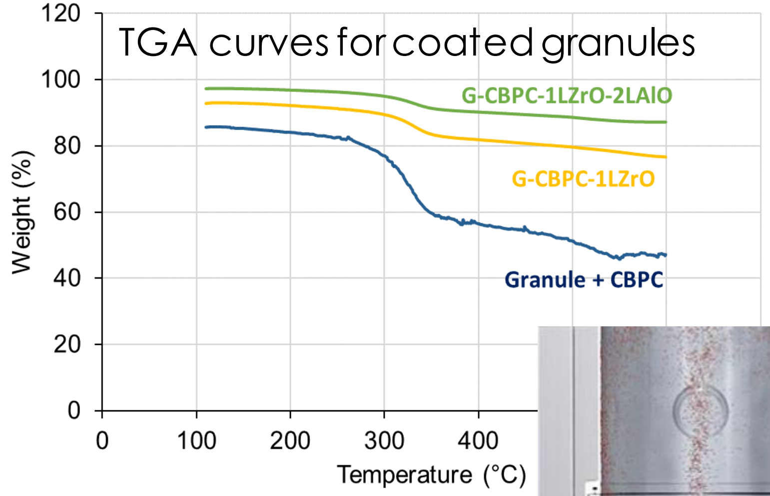
- <u>Coating of the fine granulated core materials</u>
  - A representative particle made with core Mg and multilayer ZrO_2/Al_2O_3 coatings showed to protect metal from oxidation at elevated temperatures (>600°C).
  - Developed method to normalize pyrotechnic surface with phosphates to improve adhesion of ZrO2 middle layer
  - Demonstrated coating of multiple layers onto fine pyrotechnic particles
  - Continuing work will focus on improving adhesion and uniformity of the layers to improve thermal protection
- *Fluidized spouted bed under development to enable more uniform coating of the small particles*
- <u>Modeling of the reactive particle</u>
  - Constructing an analytical model for multi-layered composite particles with pyrotechnic core to predict optimized thickness, and breakage time curves during thermal shock in a simulated boiler environment



(tg22m-CBPC-BZ1L-AlO2L)

After TGA (tg22m-CBPC-BZ1L-AlO2L)-front

After TGA (tg22m-CBPC-BZ1L-AlO2L)-back



Progress and Challenges

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Challenges

Identifying best green light emitting compositions → Granulation of best composition (-20 +40 mesh, 420 – 840 μm) → *Tumbling* → Coating 1st layer (ZrO_2) → Coating 2nd layer (Al_2O_3)

Identifying best green light emitting compositions

- Oxidant: $KClO_4$
- Fuel: Sn/Co/Mg
- Colorant: $Ba(NO_3)_2$, $BaCl_2.2H_2O$
- Binder: Ethyl Cellulose/Shellac
- Chlorine source: PVC/Parlon

Challenges:

- Highly heterogeneous system
- As high as 5/6 components with varying properties

Granulation of best composition (-20 +40 mesh, 420 – 840 μm)

- Best results so far:
- Ethyl Cellulose (5w%), Ethanol (75wt%), Water (20wt%)
- Instrument: High shear mixer

Challenges:

- Granules are not smooth (requires additional steps – ex. tumbling)
- Complexity of binder/solvent involvement in multiple stages
- Homogeneity in granules at the desired scale (400-800 μm)

Coating 1st layer (ZrO_2)

- Binder: Boehmite/E.C.
- Solvent: Ethanol

Coating 2nd layer (Al_2O_3)

- Binder: Boehmite/E.C.
- Solvent: Ethanol

Challenges:

- Coating single particles without avoiding contact
- Static – very small particles
- Possibility of redissolution of binder compromising granule integrity

Temperature Measurement via Reactive Particles Milestones

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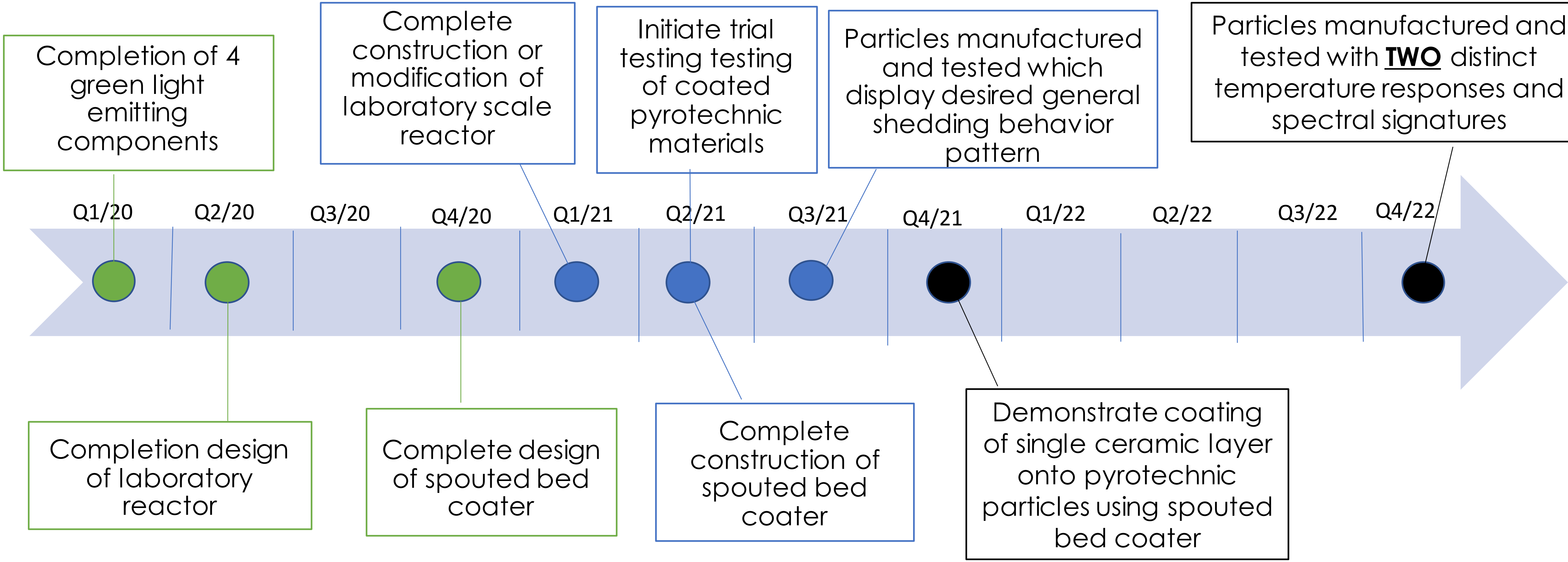
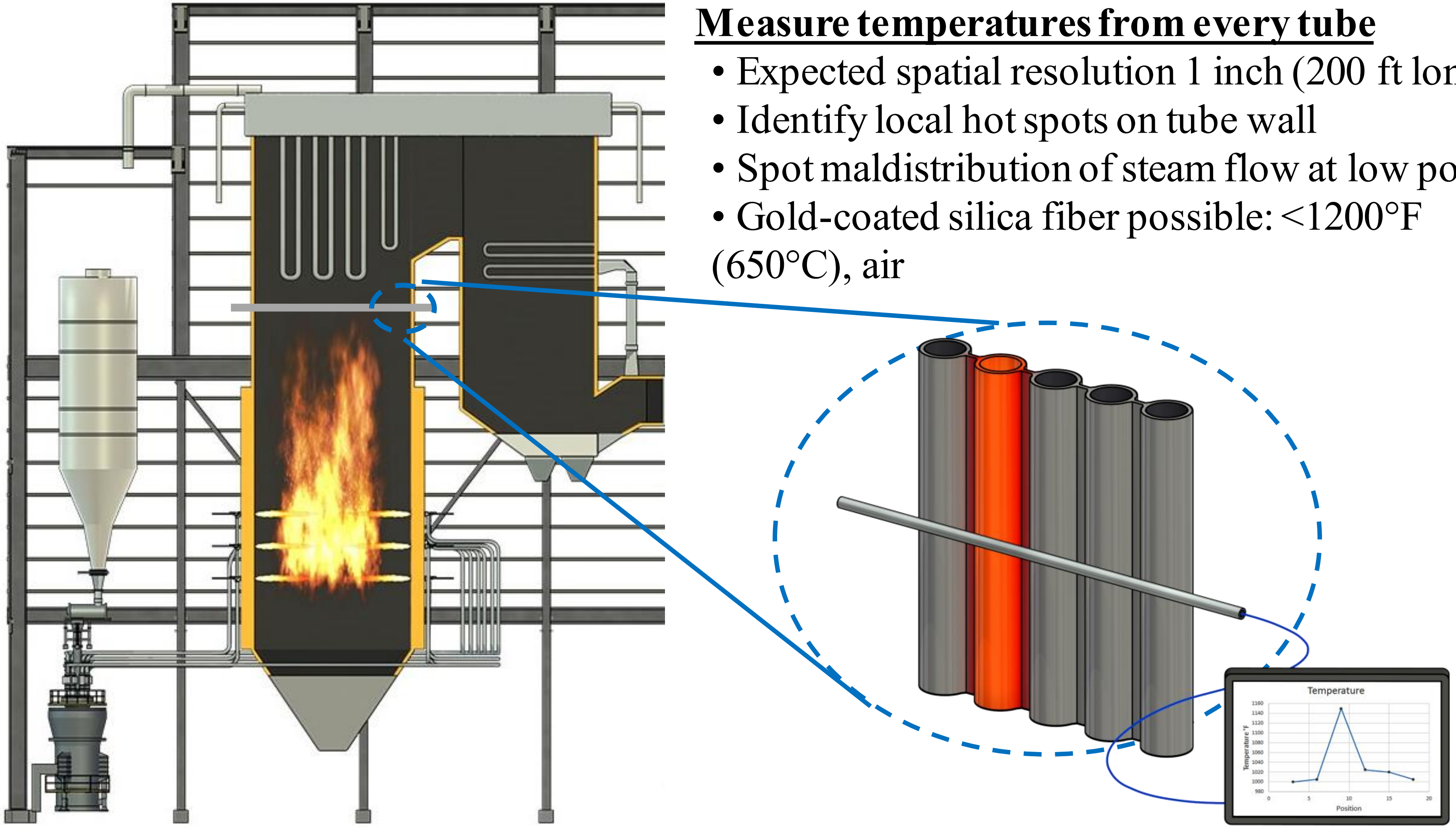
Milestones



Completed, In progress, Not initiated

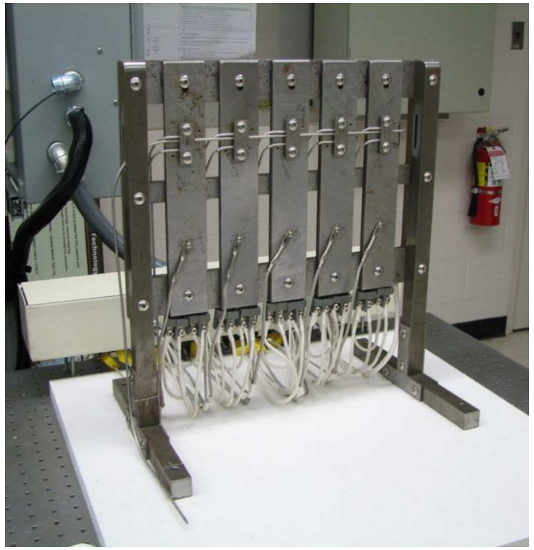
Multipoint Boiler Tube Temperature Monitoring (Task 32)

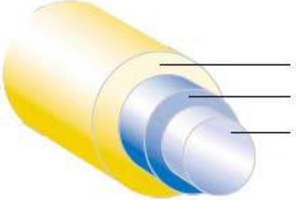
Juddha Thapa, Jared Charley, Benjamin Chorpening



Measure temperatures from every tube

- Expected spatial resolution 1 inch (200 ft long)
- Identify local hot spots on tube wall
- Spot maldistribution of steam flow at low power
- Gold-coated silica fiber possible: <1200°F (650°C), air





Distributed Temperature Sensing

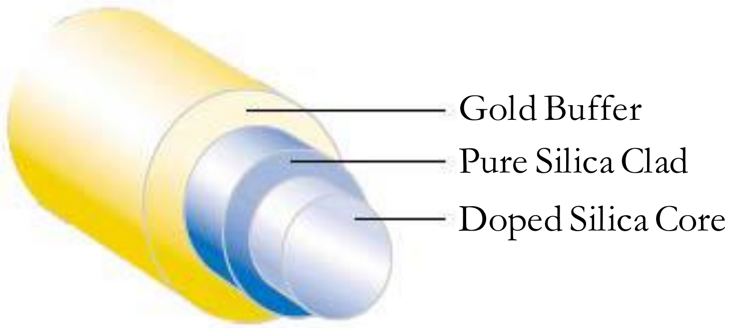
Measuring temperature at multiple points along the optical fiber

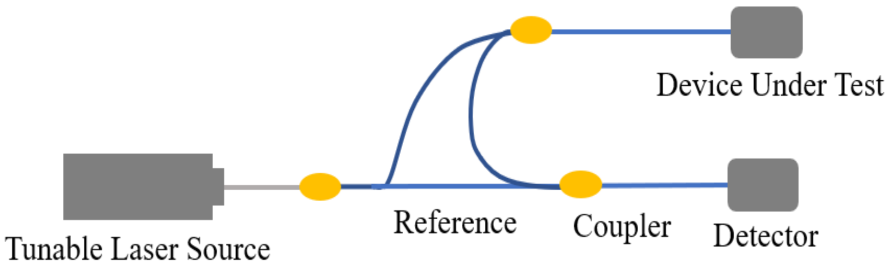
Optical Fiber

e.g., Variable temperature zone and mm, cm or more sensor spacing

Luna OBR 4600

Rayleigh Scattering





Gold-coated fiber

Singlemode, up to 700°C

OFDR: high resolution and distributed temperature measurements

Plate Heater Apparatus in the Laboratory

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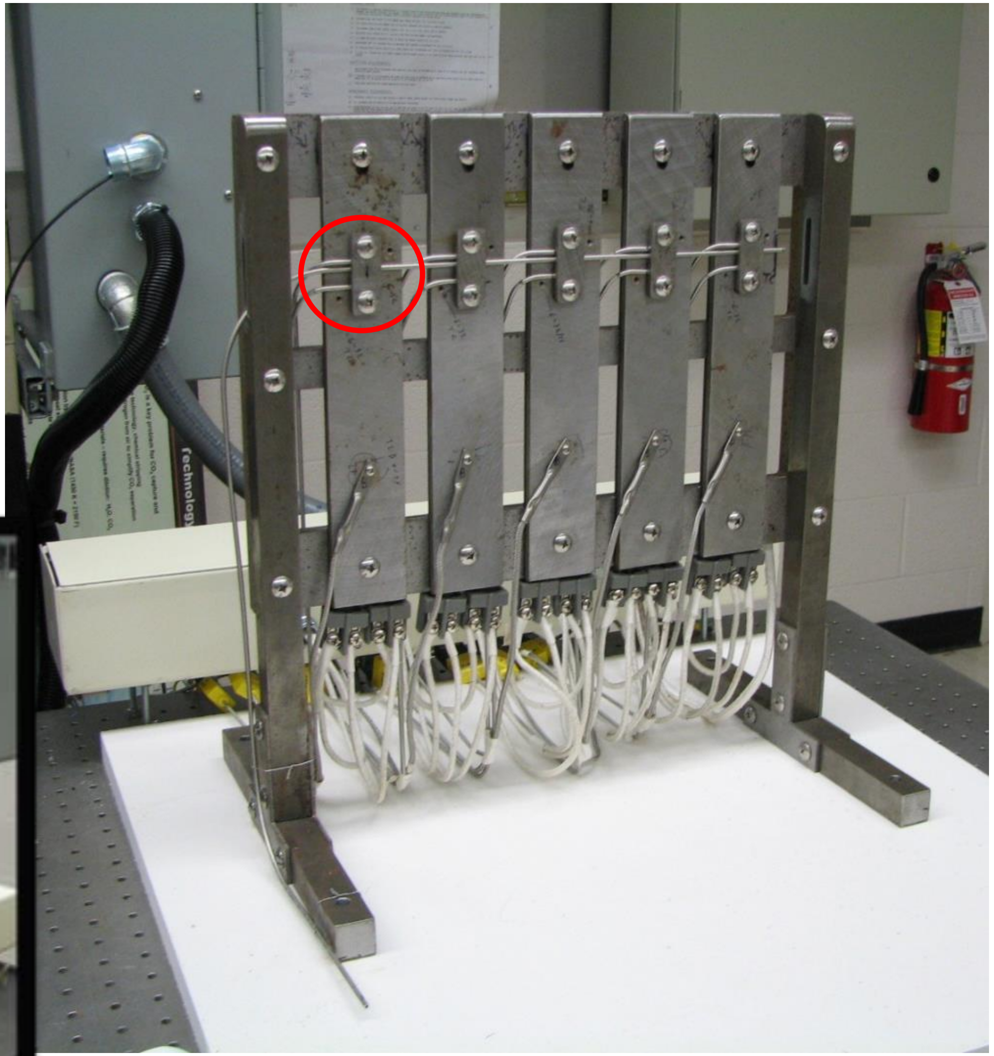
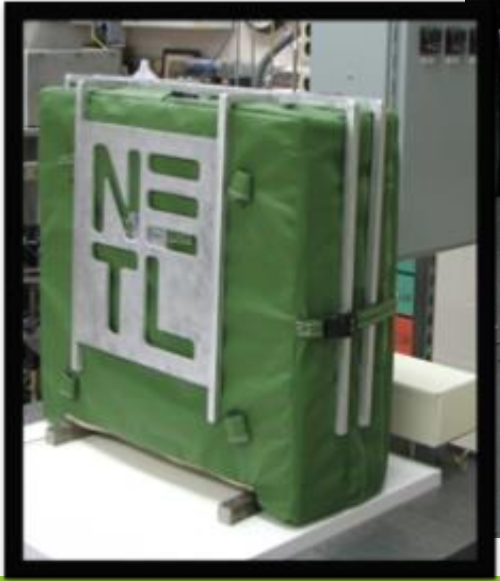
- For testing distributed temperature measurement up to 700°C
- Electrically heated steel plates, 5 cm (2 inches) wide
- Thermocouples for temperature comparison, 2 on each plate near fiber
- Also for testing optical fiber installation approaches

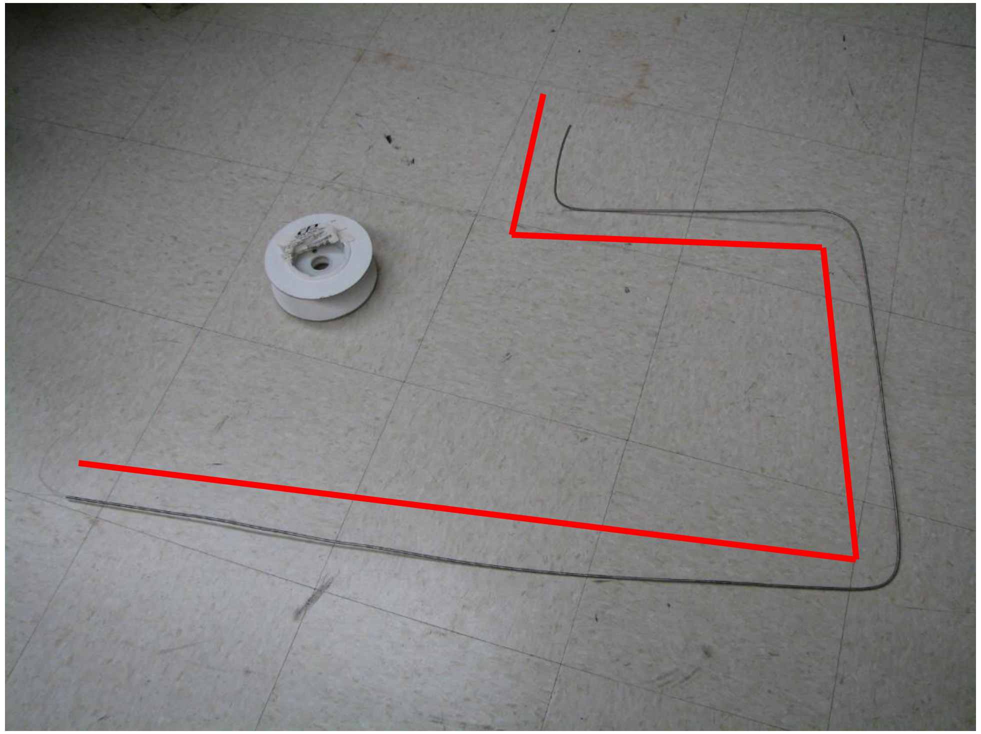




Gold-coated Fiber Inside SS Tubing

Gold-coated fiber is flexible and fragile → Put it inside the stainless steel tubing to protect.

Inserting 125μm diameter, flexible gold-coated fiber inside the 1/8th inch SS tubing is difficult → Insert Teflon tubing inside the SS tubing, use it to pull the fiber into the tube

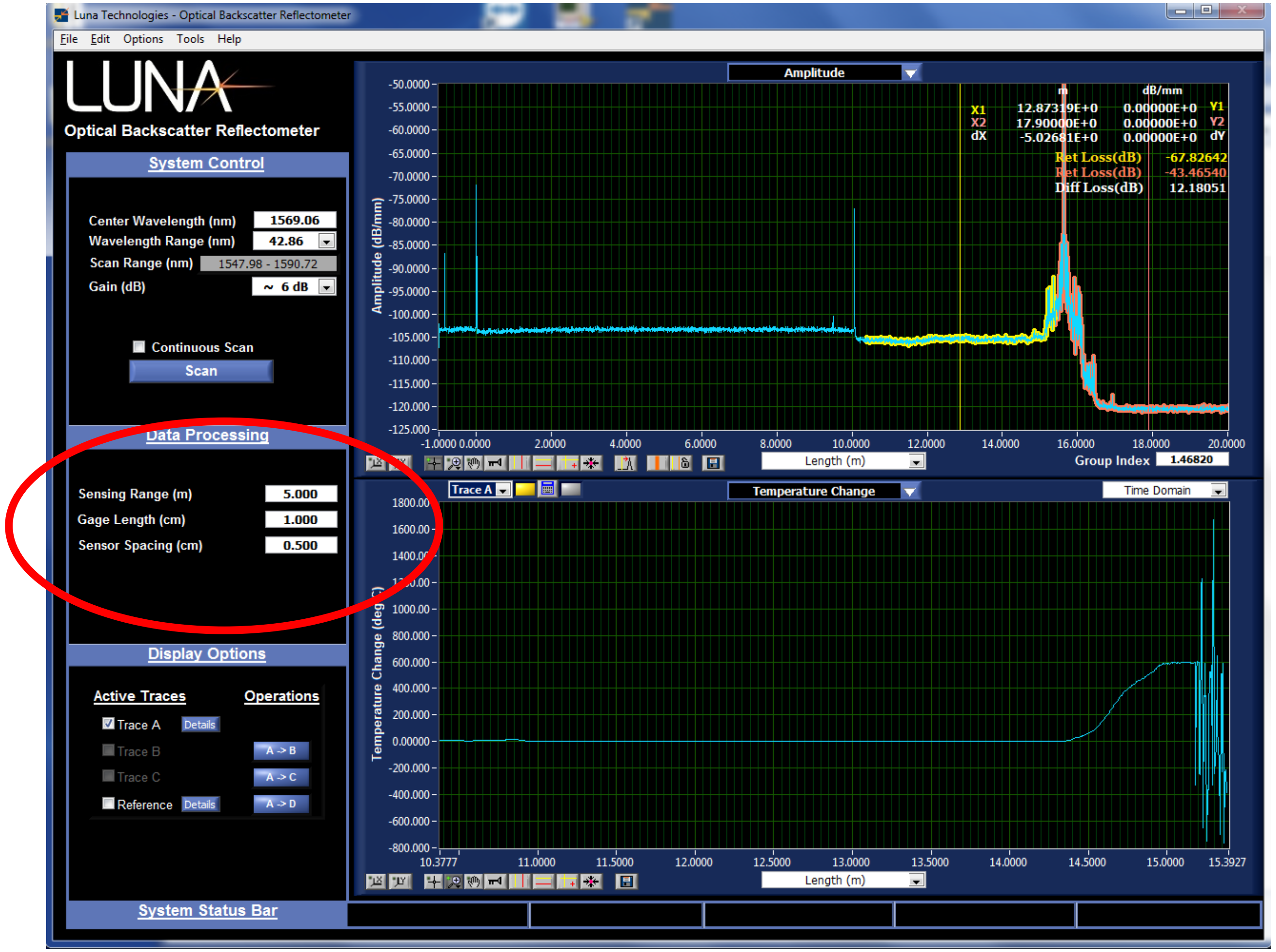


Minimum bend radius of about 1.5 inches at 3 locations

Gold-Coated Fiber Test

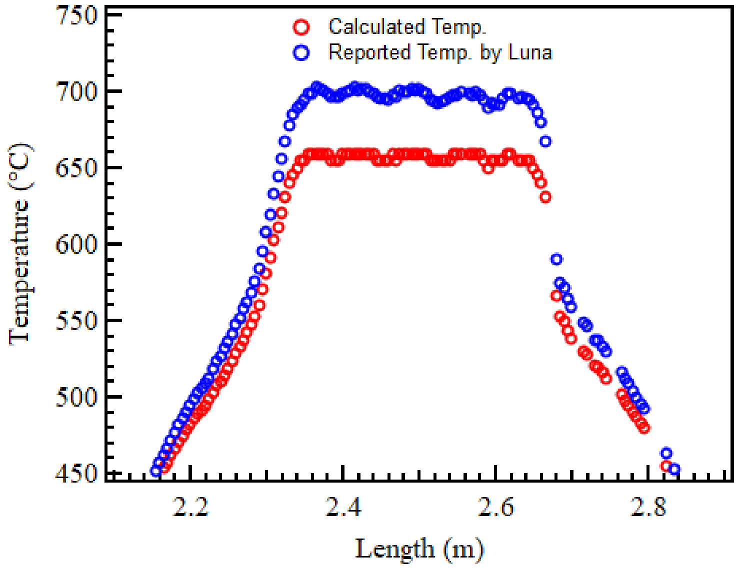
Length of the gold fiber=5m

First cycle
Sensing Range (m)=5.000
Gage Length (cm)=1.000
Sensor Spacing (cm)=0.500



Temperature Calibration

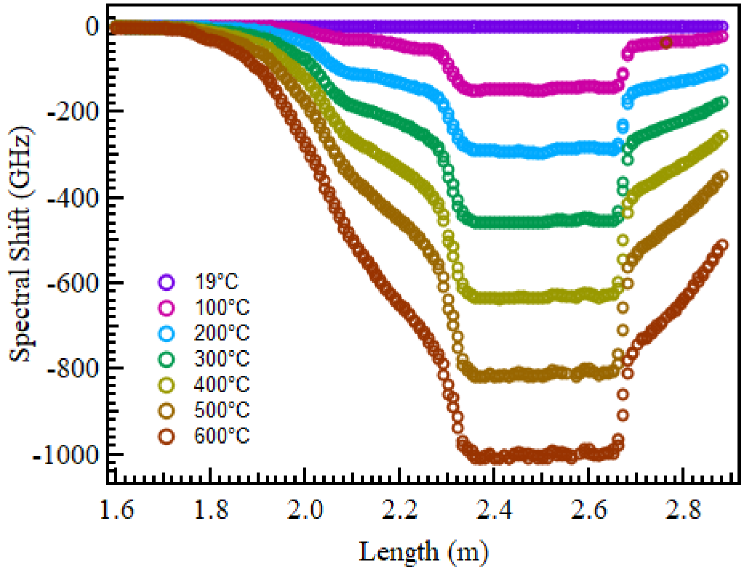
Temperature reported by Luna software has larger difference to that of measured temperatures



Calculated temperatures (red circles)

Temperatures reported by Luna device (blue circles)
Set temperature 650°C

Generate a temperature calibration equation and post process the data. LabView program has been written to post process the temperature data.

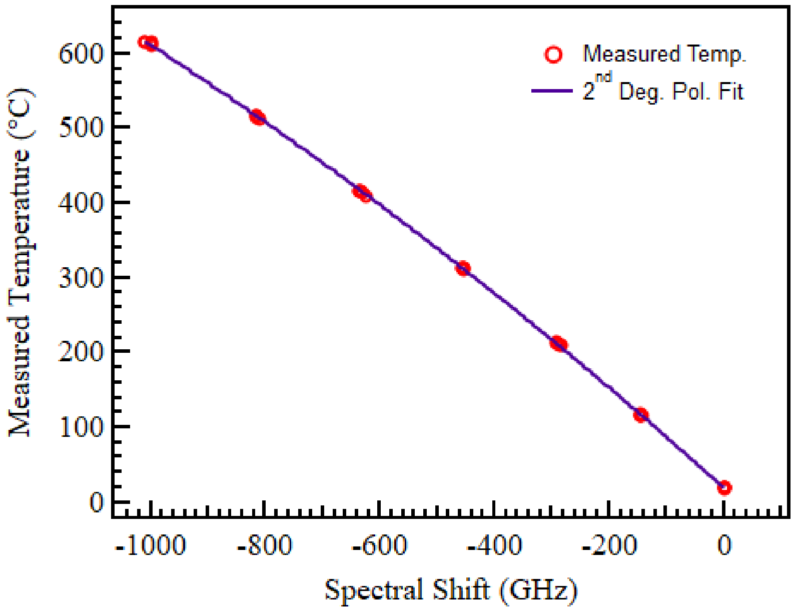


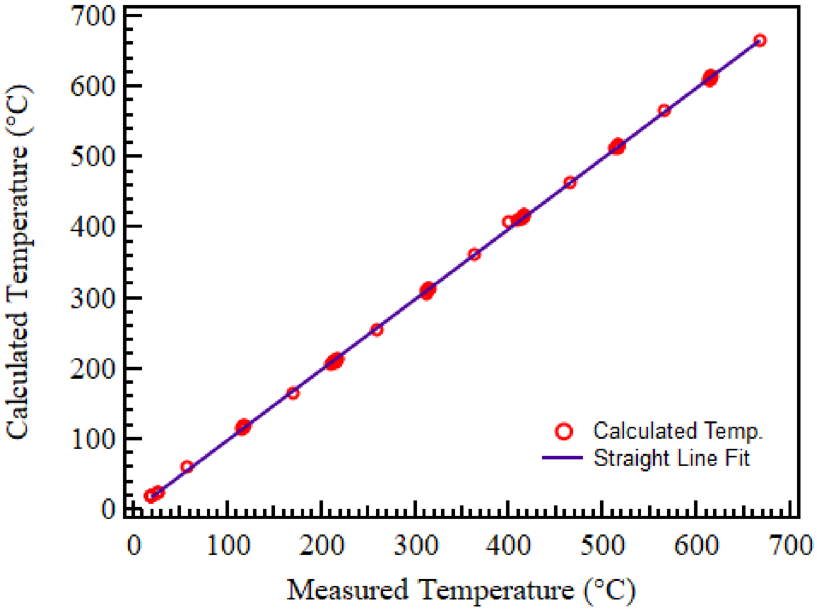
Spectral shift along the length of the gold-coated fiber from: 19°C to 600°C.

Temperatures inside the graph are the set values.

J. Thapa, J. Charley, B. Chorpening, "Evaluation of High Temperature Distributed Sensing Using Gold-Coated Optical Fiber and OFDR Technique," 2020 Pittsburgh Coal Conference

Temperature Calibration



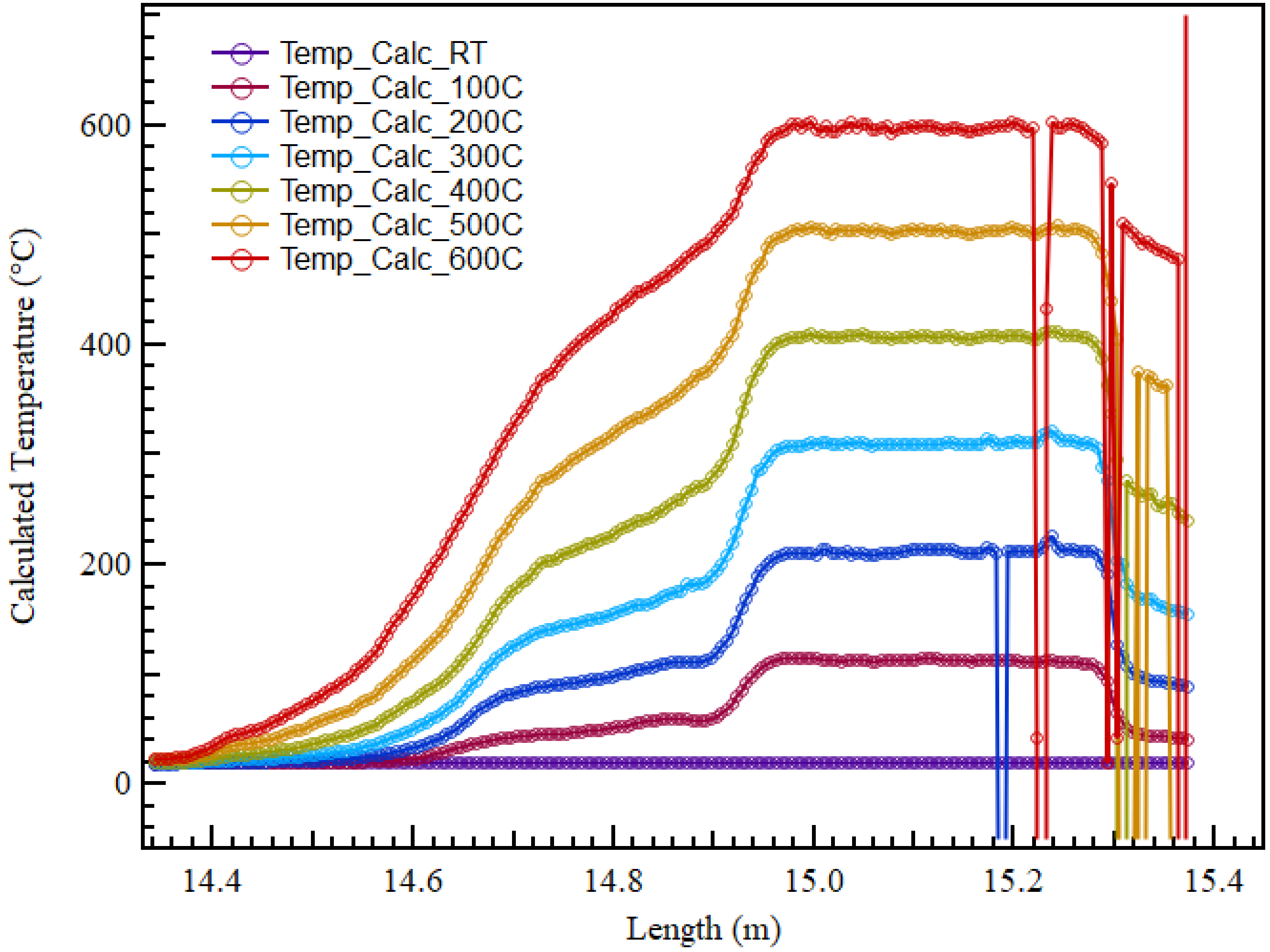


Where T is temperature in °C and SS is the spectral shift in GHz

Difference between the calculated and measured temperatures less than 8°C

Postprocessed Temperature vs Length

First Cycle



RT=22°C

After postprocessing, Error > ±10°C at higher temperatures (500 and 600°C)

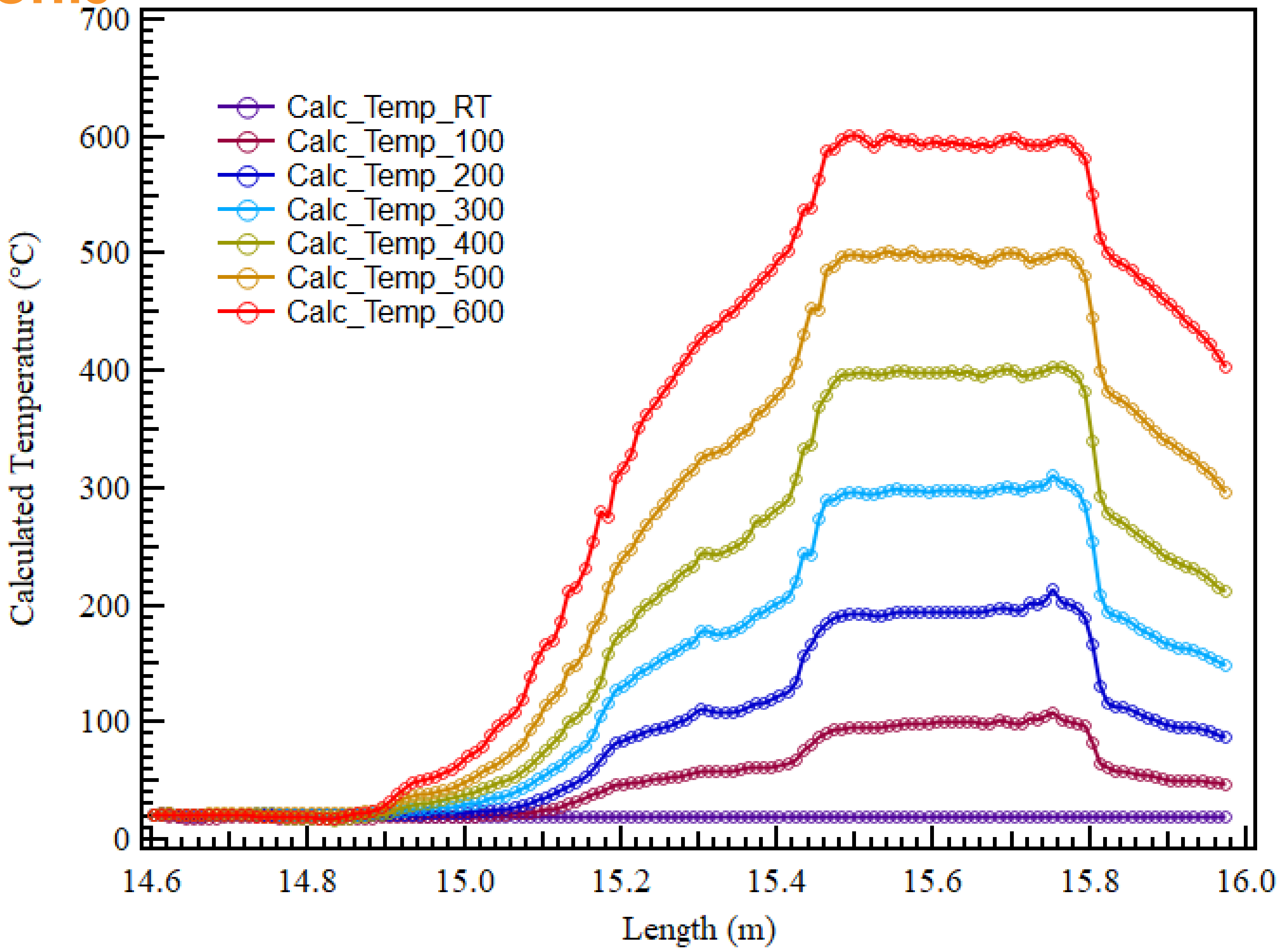
Spikes result of bad data points

Postprocessed Temperature vs Length

After adjustments

- Increased gauge length
- Annealed the gold-coated fiber up to 600°C

RT=22°C



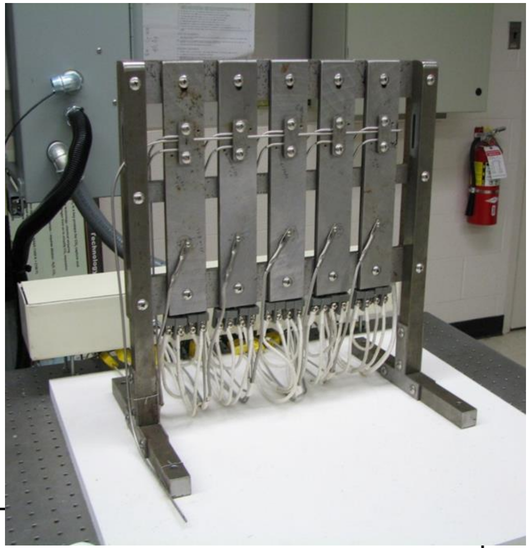
After Postprocessing, Error < ±10°C vs thermocouples

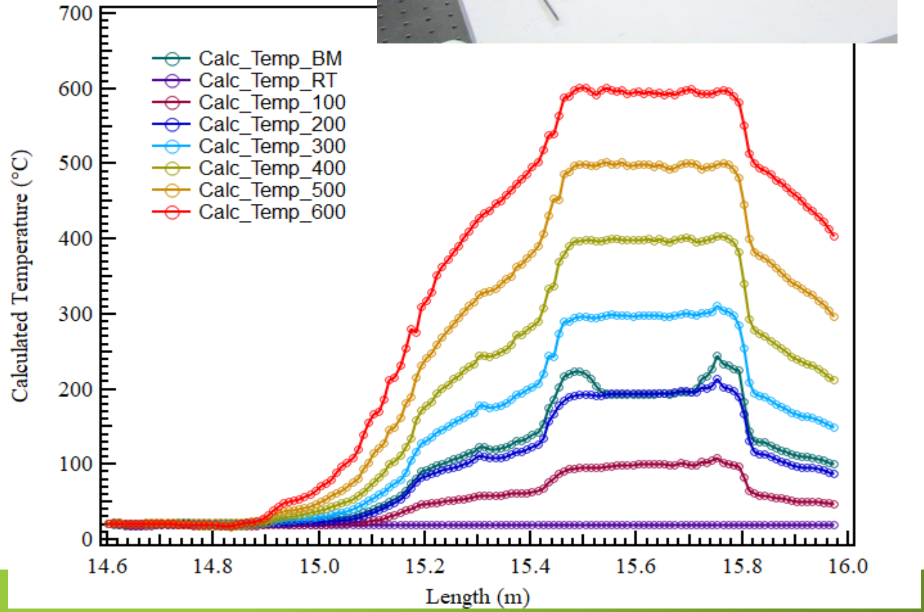
The gold-coated fiber could be used for the distributed high temperature measurements in the boiler tube environment.

Status and Future Work

- Lab-bench testing successful
  - Adjusted measurement settings
  - Anneal fiber
  - Temperature accuracy and resolution checked
- Dry run of installation and testing in NETL laboratory to prepare for pilot-scale test at UNDEERC
  - Installation of the gold-coated fiber into a 1/8 inch stainless steel tube for protection
  - Included mechanical connection to a 30 meter section of ordinary silica fiber (lead-in)
  - Tested through several temperature cycles up to 600°C using the plate heater apparatus
  - Custom postprocessing of data necessary to obtain accurate temperature readings across the temperature range (within 10°C)
- Pilot scale test put on hold in March 2020 due to COVID-19, expected to move forward in 2021
- Power plant field test

2-inch wide heated bars approximate boiler tubes





Questions

Benjamin.Chorpening@netl.doe.gov

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