Tunable Diode Laser Sensors to Monitor Temperature and Gas Composition in High Temperature Coal Gasifiers

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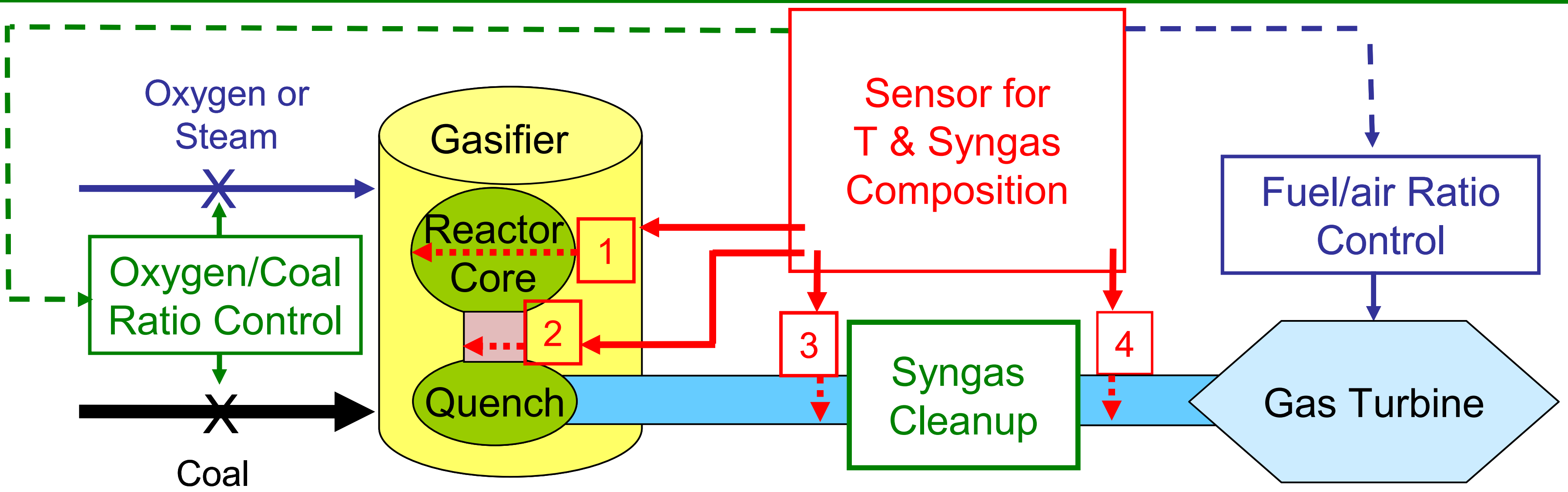
STANFORD MECHANICAL ENGINEERING

THE UNIVERSITY OF UTAH

- Vision for tunable diode laser (TDL) sensors
- Goals
- Challenges
- University of Utah sensor test bed
- Stanford sensor concept
  - TDL fundamentals
  - Prior measurements reduce risk
- Proposed work plan
- Current status

Vision and Goals for TDL Sensing in IGCC



Vision: Sensor for control signals to optimize gasifier output and gas turbine input

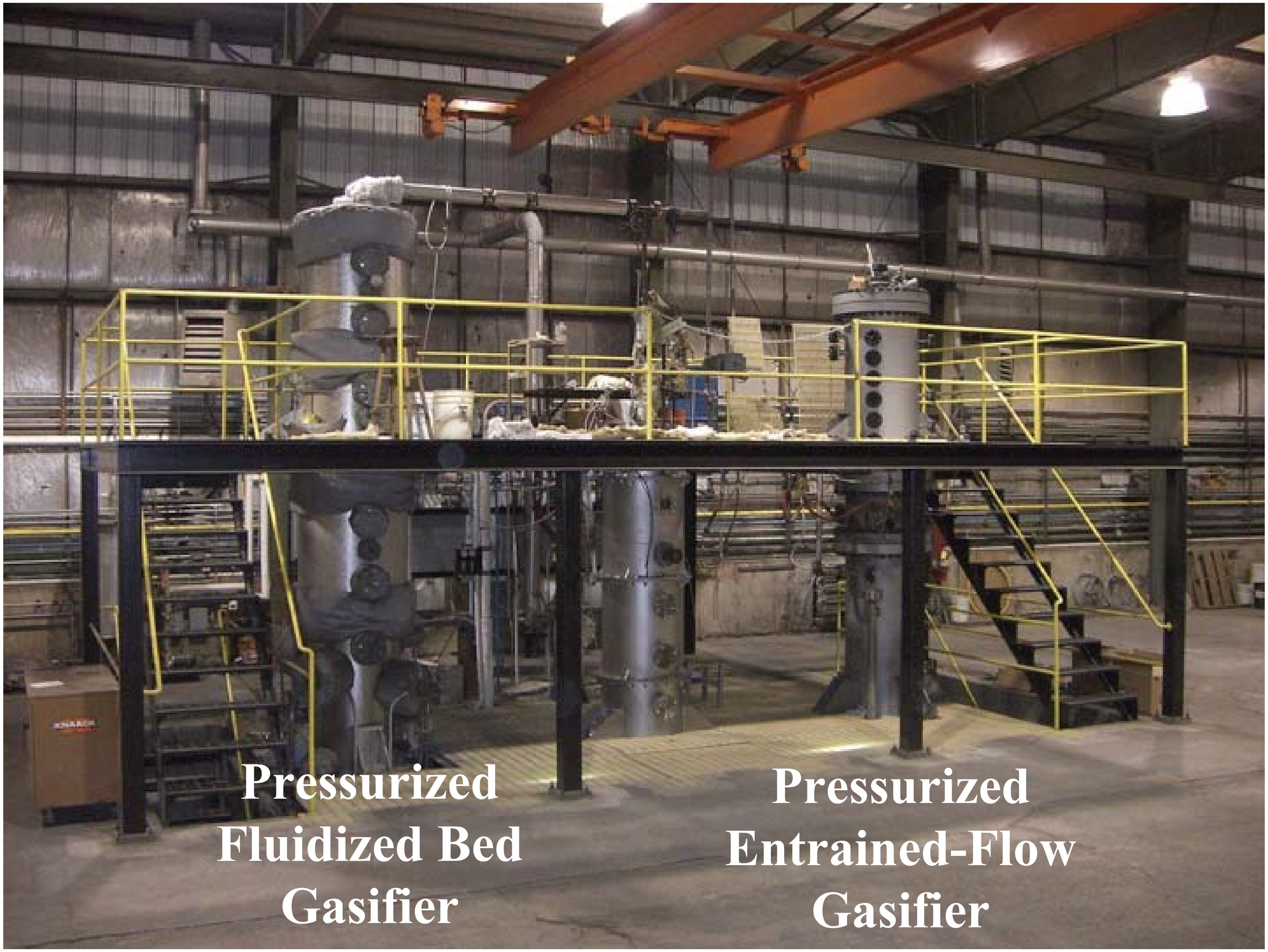
Goals:
- Two control signals investigated: gas temperature and heating value
  - Measurements of CO, CH_4, CO_2, and H_2O provide heating value
    - H_2 determined by gas balance and H_2S ignored
  - Gas temperature determined by ratio of H_2O measurements
- Four sensor locations investigated: (1) reactor core, (2) pre-quench, (3) post-quench, and (4) post-particulate clean-up
  - Locations 1 & 2 yield faster control, but have the biggest challenges

Challenges to TDL Sensing in Coal Gasification

- Gasifier pressure, temperature, particulate, and slag present window difficulties
  - Successful preliminary measurements in Utah fluidized bed reactor provide guidance for next generation window design
  - Fiber-coupled lasers require modest clear aperture
  - Stanford modulation schemes can accommodate time varying window transmission
- High pressure broadens spectral features making absorption difficult
  - Prior success for high-pressure measurements in IC engines, laboratory gas cells, and behind shock waves provides design criteria for modulation schemes (reduces risk)
- Particulate scattering attenuates laser transmission making absorption difficult
  - Prior success in Utah fluidized-bed reactor provides proof-of-concept

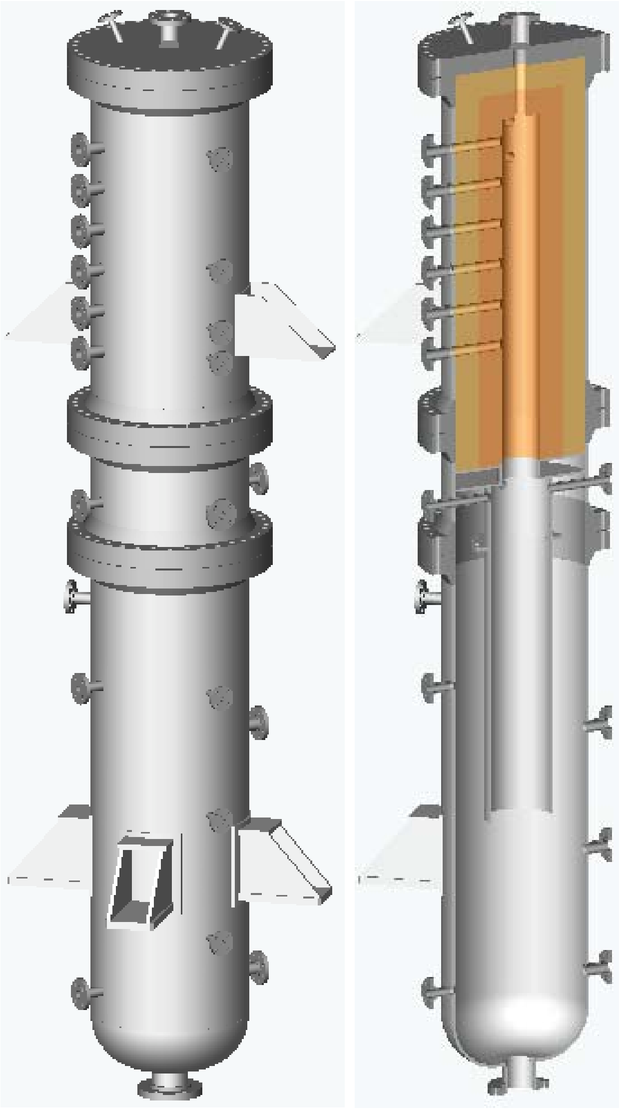
Prior work reduces risk, but gasifier has a unique environment: Hence demonstration measurements in large-scale gasifier at Utah are crucial to research effort

University of Utah Gasification Facility



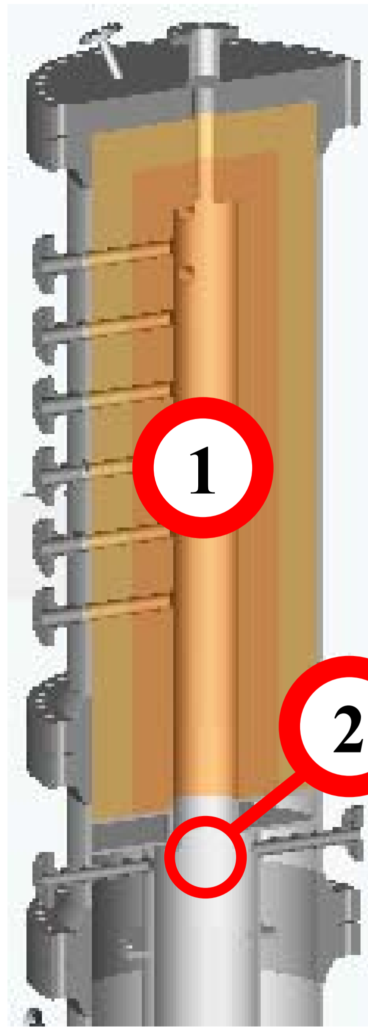
University of Utah Entrained-Flow Gasifier

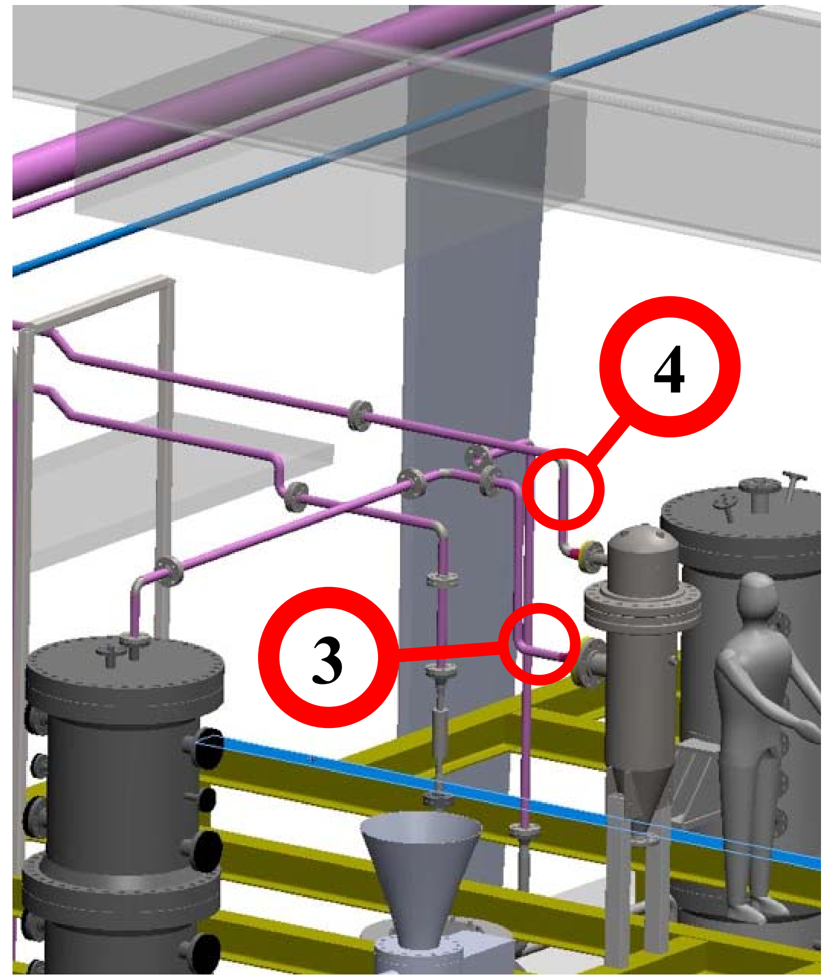
- Max. 450 psi
- Max. 3100 °F
- Throughput (coal)
  - 1 ton/day
  - 0.4 MW
- Overall dimensions
  - 17 feet tall
  - 30 inch vessel
- Reactor dimensions
  - 8 inch ID
  - 60 inch length
- Analytical
  - Continuous analyzer for $H_2/CO/CO_2/CH_4$
  - GC for 18 gases



Sensor Locations

- Location 1
  - Reactor "core"
  - ~2600°F / 250 psi
  - Molten slag
- Location 2
  - Pre-quench
  - ~2000°F / 250 psi
  - No slag blockage
- Location 3
  - Post-quench
  - ~250°F / 250 psi
  - Possible particles
- Location 4
  - Post filter
  - ~200°F / 250 psi
  - Particle-free

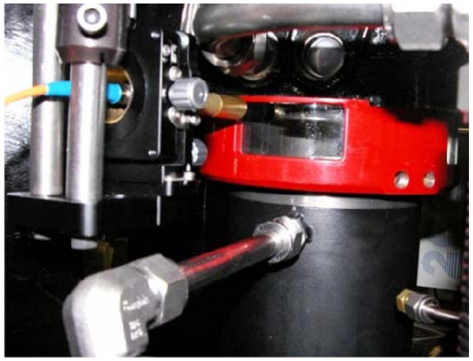




Stanford Has Long History of Successful TDL Measurements in Harsh Environments

- Utilizes cheap, robust and portable TDL light sources and fiber optics
- Can yield multiple properties: species, T, P, V, & $\dot{m}$ in real-time over wide conditions
  - T to 8000K, P to 50 atm, V to 15km/sec, multiphase flows, overcoming strong emission, scattering, vibration, and electrical interference
- Proven in harsh environments and large-scale systems:
  - Aero-engine inlets, scramjets, pulse detonation engines, IC engines, arcjets, gas turbine combustors, shock tunnels, coal-fired combustors, rocket motors,….
- Potential use in control of practical systems

IC-Engines @ Sandia NLL



Mattison et al., *Proc. Comb Symposium* **31** (2007)

SCRAMJET @ WPAFB

Rieker et al., *Applied Optics* **48** (2009)

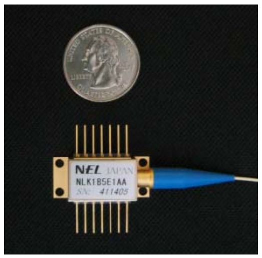
PDE at NPS

Brophy et al. *J Propulsion & Power* **22** (2006)

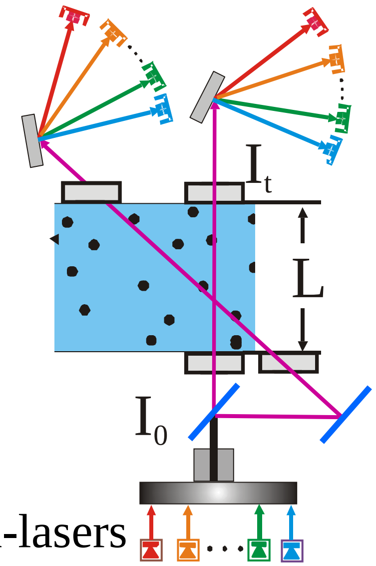
Absorption Fundamentals: The Basics

- TDL absorption: non-intrusive, time-resolved *line-of-sight* measurements

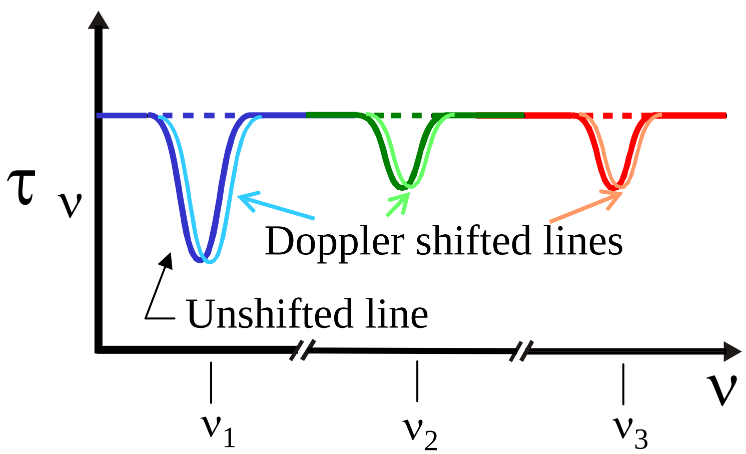
Fiber-coupled lasers are small and robust



Visible & near-IR λ's



Multiplexed-lasers



- Beer-Lambert relation

$$\tau_\nu \equiv \frac{I_t}{I_o} = \exp(\underbrace{-k_\nu \cdot L}_{\text{absorbance}}) = \exp\left(-n_i \cdot \sigma_\nu \cdot L\right)$$

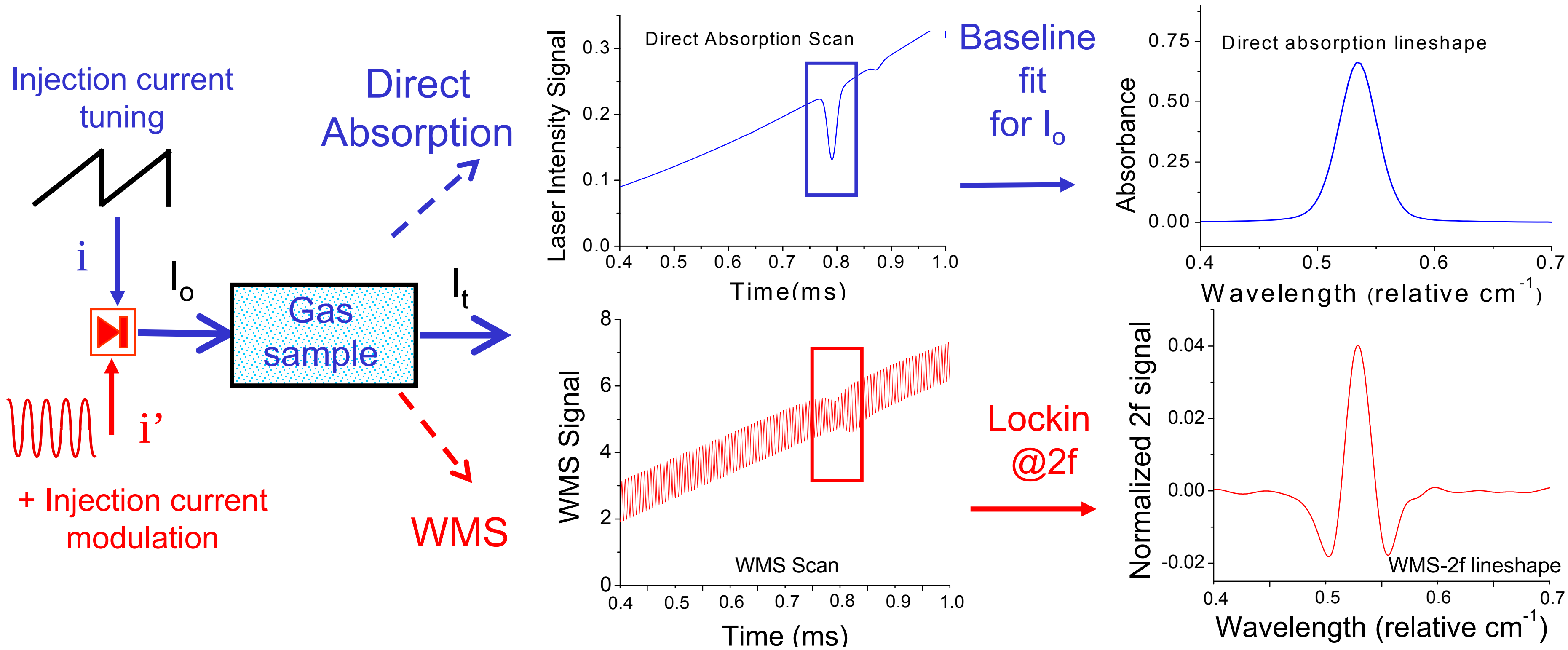
- Spectral absorption coefficient

$$k_\nu = S(T) \cdot \Phi(T, P, \chi_i) \cdot \chi_i \cdot P$$

- Wavelength-multiplexing for *multi-parameters*
- Ratios of two (or more) lines yield T
- T and τ_ν yield χ_i (mole fraction) or n_i or ρ
- V from Doppler shift of spectra
- Mass and momentum flux from ρ and V
- *Many-line* data for non-uniform $T(x)$, $X_i(x)$…

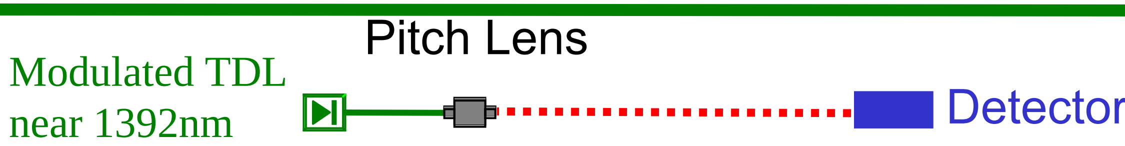
- Approaches: fixed λ and scanned λ
  - Direct absorption
  - WMS with harmonic detection

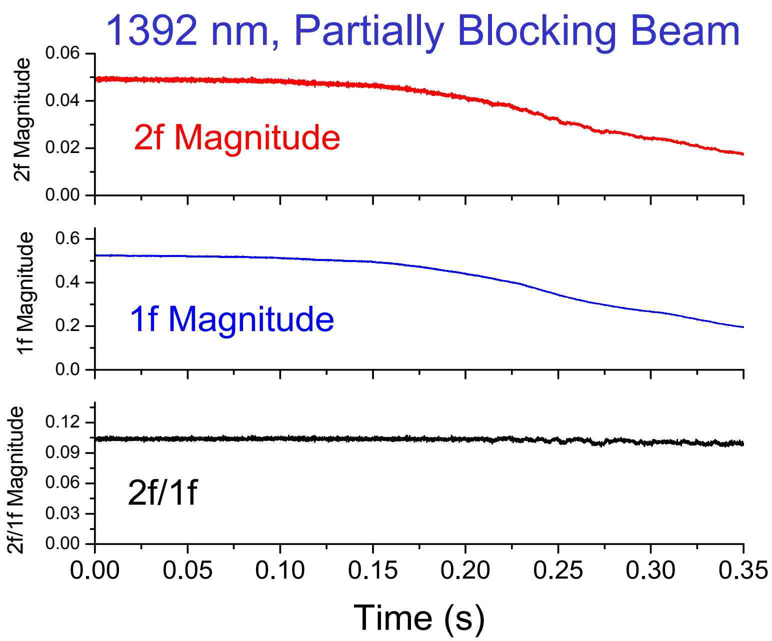
Absorption Fundamentals:
Direct Absorption & Wavelength Modulation Spectroscopy

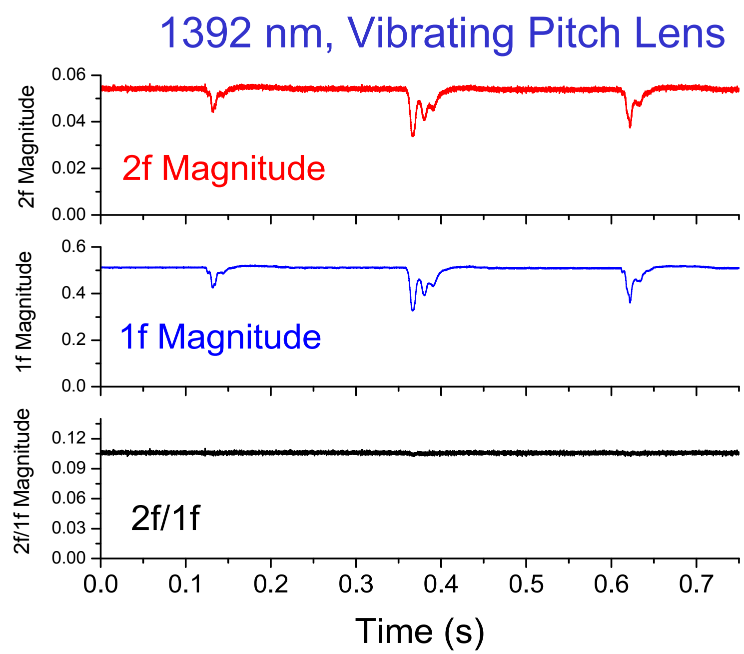


- Direct absorption: Simpler, if absorption is strong enough
- WMS: More sensitive (x10 or more); better noise rejection
  - WMS-2*f* signal approximates 2nd derivative of line shape at small modulation amplitude
  - Ratio of two WMS-2*f* signals provides T
  - Injection current FM produces intensity modulation @*1f* → enables normalization

Experiments Demonstrate WMS Normalization







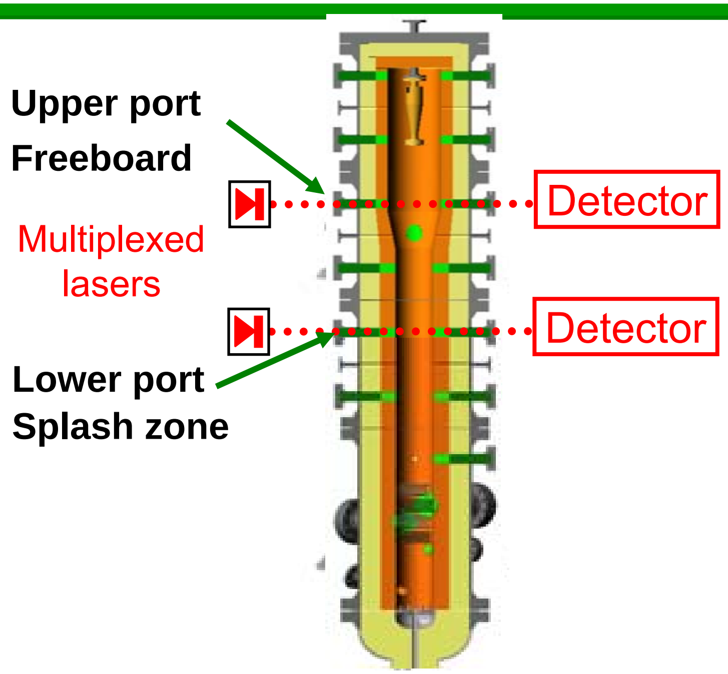
- Measure ambient H_2O (T=296 K, 60% RH, L=29.5 cm, ~6% absorbance)
- Attenuate the beam by partial blocking: Normalized *2f/1f* signal constant
- Attenuate the beam by mechanical vibration: Normalized signal constant
- Expect strategy to provide immunity from window fouling and particulate loading

Examples of Stanford TDL Sensing in Harsh, High-P, High-T Environments

- IC-Engines
  - Crank-angle-resolved measurements of temperature and EGR
    - T-sensing for HCCI research with Sandia National Labs
    - Development of WMS-based T-sensor for production engines
  - Crank-angle-resolved measurements of gasoline

- Fluidized-bed gasification of black liquor (funded by EPRI)
  - TDL absorption measurements in the presence of particulate
    - Successful measurements with 92% beam attenuation
    - Provides proof-of-concept for gasification application
  - TDL in the Utah fluidized-bed rig discussed below

TDL Experiments in Fluidized Bed Gasifier @ Utah in 2009

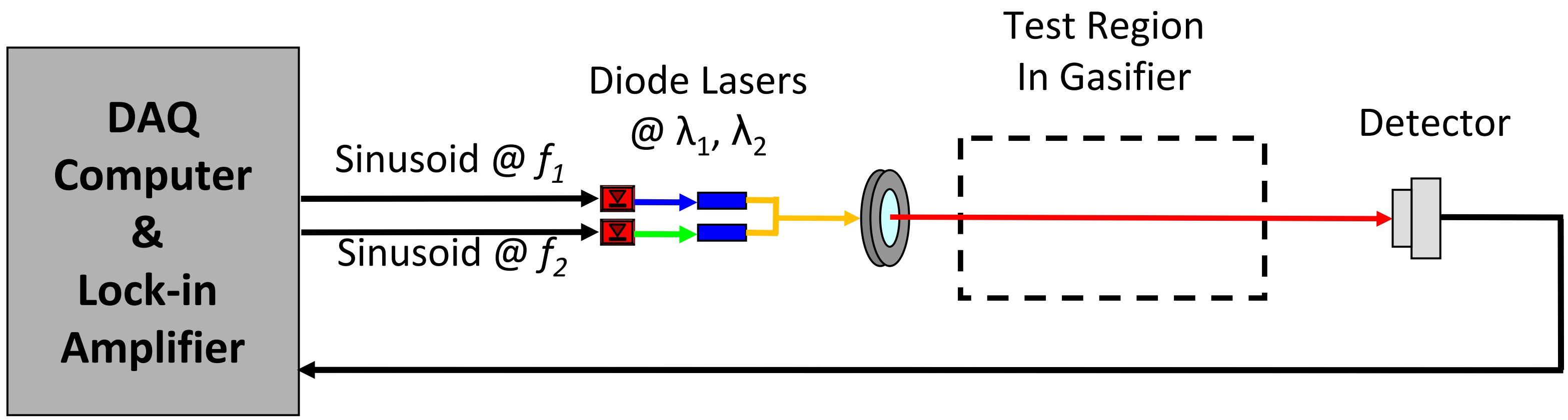


- Measurements in two ports investigated different types of particulate interference for the laser-absorption measurements
  - Lower port views the "splash zone" where optical transmission experiences time-varying interference as bed particulate (~ 200µm) splashes up and down in the beam
  - Upper port views the gasifier products where transmission is obscured by char particulate (~10µm)

EPRI funded proof-of-concept demonstration experiment

Sensor Concept for Fluidized-Bed Gasifier Measurements

Two-color TDL sensor for T and X_{H2O}

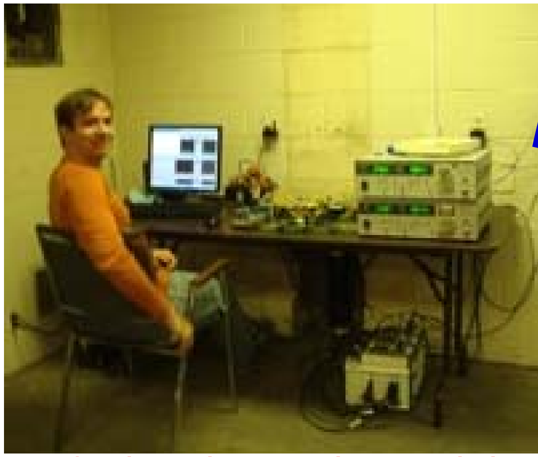


- Two lasers (λ_1 & λ_2) wavelength-modulated at 40 and 60 kHz respectively
- Signals detected @ 2f and 1f for each laser scanned at 2 kHz across H_2O absorption line
- Normalization of 2f by the 1f signal corrects each laser for scattering losses
- Temperature from the ratio of 2f/1f signals @ λ_1 & λ_2
- Concept tested with EPRI support in U Utah fluidized-bed gasifier

EPRI funded proof-of-concept demonstration experiment

Optical Fibers Enable Remote Location of Lasers

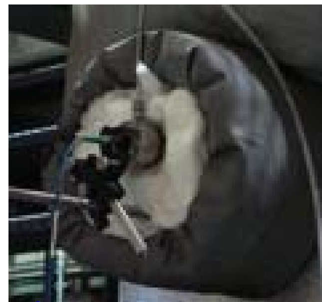
Lasers and electronics

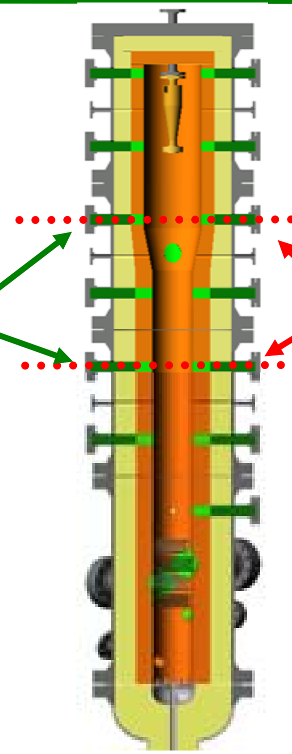


Stanford student Andrew Fahrland in gasifier control room

Optical fiber 30m long

Fiber launch of laser beam





Fiber collection transmitted light

Remote detector

- Fiber-coupled lasers and electronics located in the control room
  - Transmitted light collected onto a fiber to allow remote location of detector
- Two different diode laser detection strategies tested
  - Wavelength-scanned direct absorption
  - Normalized (1f) wavelength-modulation spectroscopy with 2f detection (WMS-2f/1f)

Just looking at the raw signals shows potential of TDL sensing

EPRI funded proof-of-concept demonstration experiment

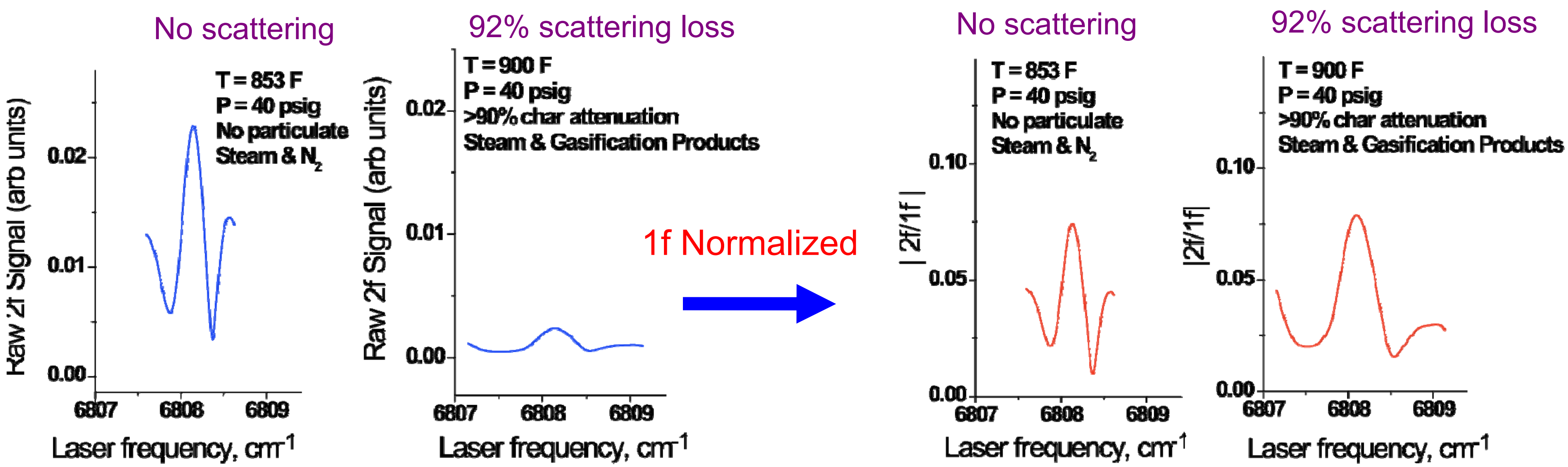
1f Normalized WMS-2f Accounts for Scattering Losses

Measurements in reactor core to test influence of char particle scattering on WMS

Single-scan data at 2kHz (measurement time = 0.5ms)

Raw 2f signals

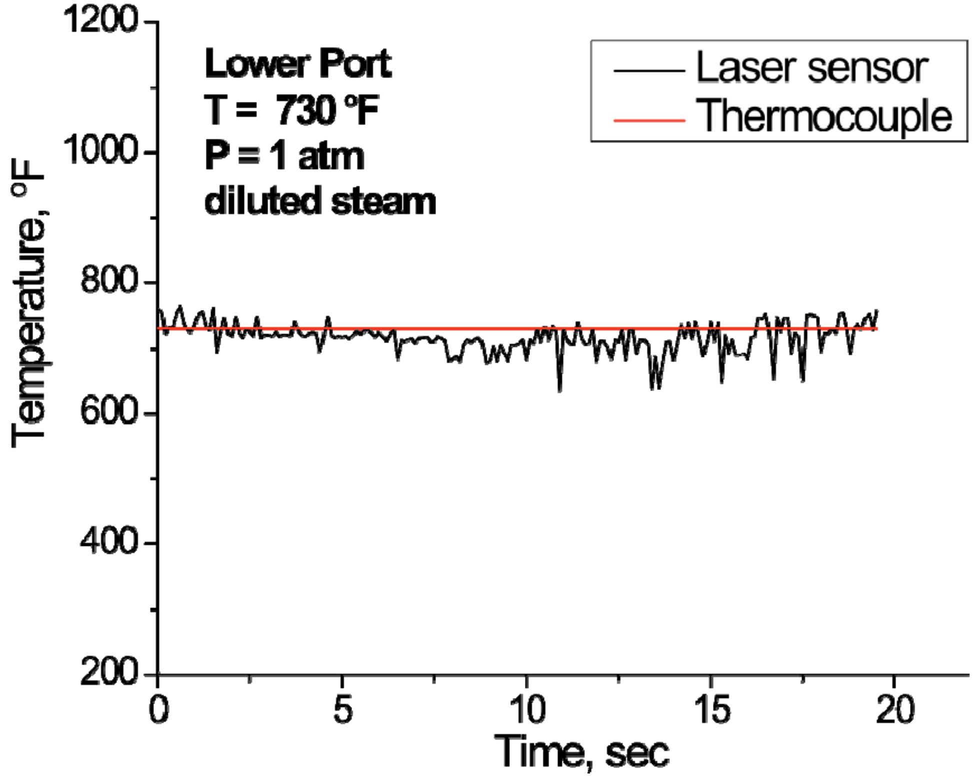
1f Normalized 2f signals



- Char particles made during gasification attenuate the transmitted signals by 92%
- Normalization of 2f by 1f signals recovers a quantitative WMS-2f signal
- Excellent SNR provides proof-of-concept for TDL sensing in highly scattering reactor environments

EPRI funded proof-of-concept demonstration experiment

Temperature Versus Time Without Particulate



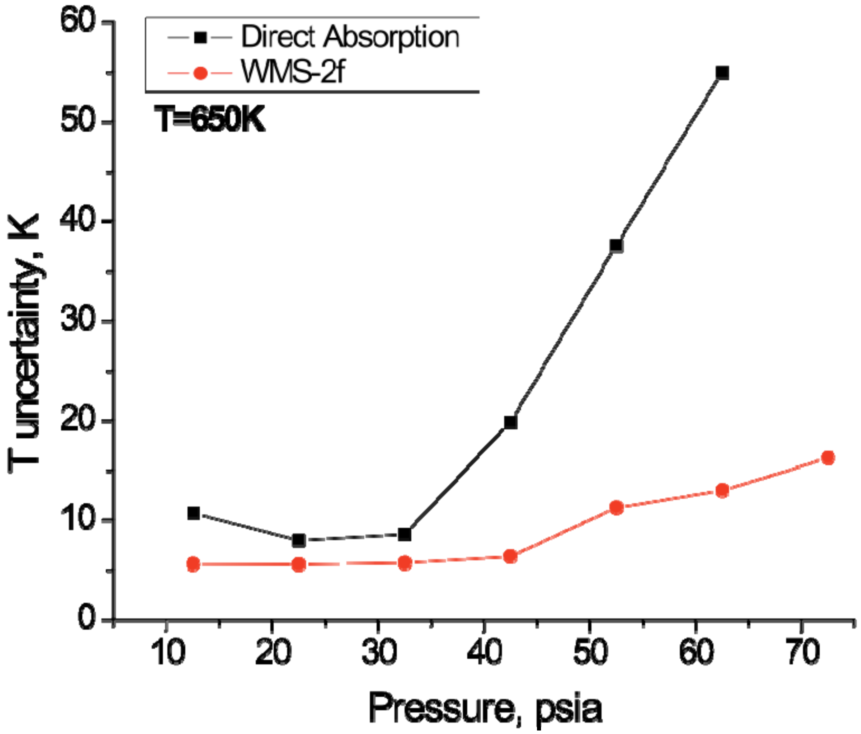
TDL measurements on lower port without bed in nitrogen-diluted steam

Single-scan data at 2kHz (measurement time = 0.5ms)

- Time record of temperature agrees well with facility thermocouple
- Statistical temperature uncertainty used to characterize precision of sensor

EPRI funded proof-of-concept demonstration experiment

Temperature Uncertainty Versus Pressure



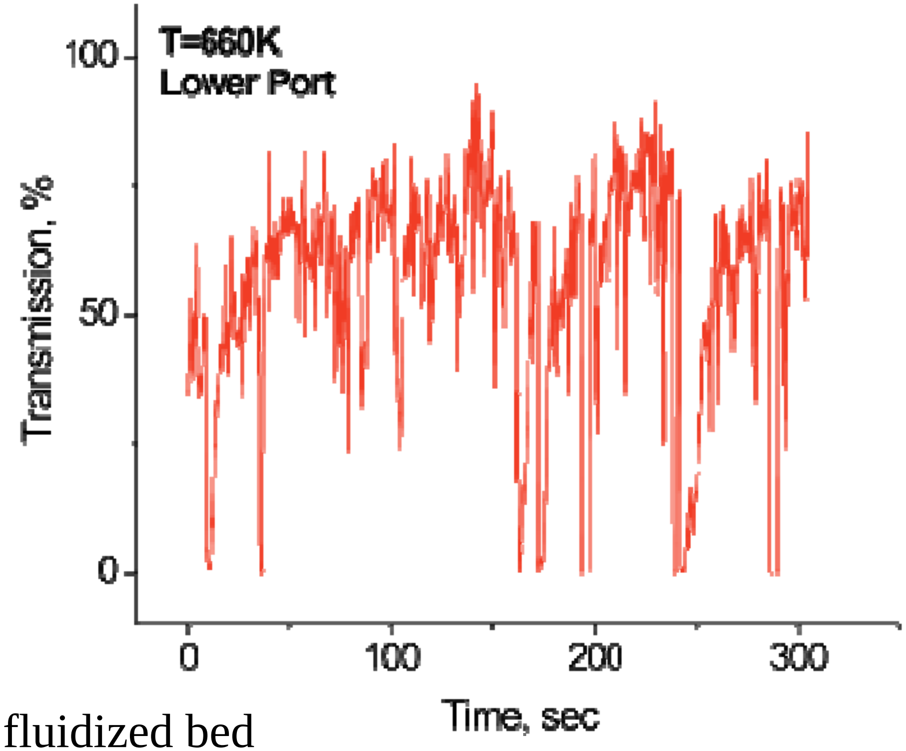
TDL measurements on lower port without bed in nitrogen-diluted steam

Single-scan data at 2kHz (measurement time = 0.5ms)

- Temperature uncertainty increases with pressure for direct absorption
  - Less than 15K uncertainty at 2kHz for all pressures available with WMS-2f/1f
  - Wavelength modulation signal significantly less sensitive to pressure increase
- Potential to further increase signal-to-noise ratio by averaging (reducing bandwidth)

EPRI funded proof-of-concept demonstration experiment

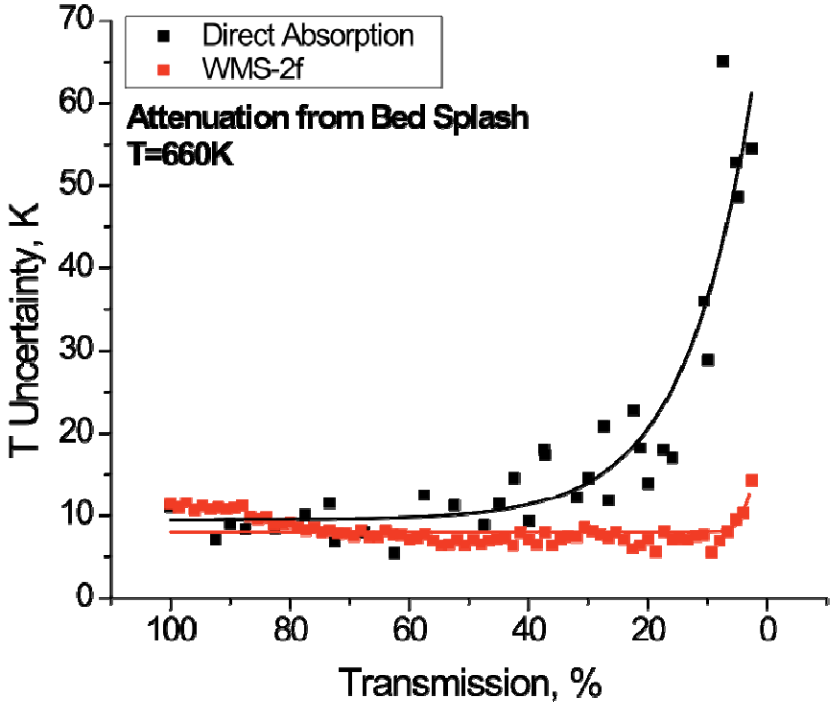
Splash Zone Transmission Time-Varying



- Picture/movie shows cold flow model of fluidized bed
  - Large bed particles (200 μm) are splashing in the bed of the reactor
- This particulate bounces up and down through the beam, sometimes completely blocking the beam
- TDL data taken in actual fluidized bed reactor and 300 seconds of data is binned by transmission for analysis of T vs transmission

EPRI funded proof-of-concept demonstration experiment

Temperature Uncertainty With Particulate



Splash Zone

TDL measurements on lower port with bed fluidized by steam flow

Beam attenuated by scattering from bed particle splash

Single-scan data at 2kHz (measurement time = 0.5ms)

- Bed particle splash produces time-varying transmission (2kHz data rate)
- Wavelength modulation less sensitive to signal attenuation
- Signal binned by transmission, analyzed for temperature uncertainty
- Less than 15K uncertainty at 2kHz for >5% transmission with WMS-2f/1f
- Illustrates potential for WMS-2f/1f strategy for DoE gasifier measurements

EPRI funded proof-of-concept demonstration experiment

Proposed DoE Work Plan

- 2010
  - Design TDL sensors for H_2O and CO (SU)
  - Design and fabricate optical access for pre-quench, post-quench, clean output (Utah)
  - Validate H_2O and CO spectroscopic database (SU)
  - Controlled environment sensor tests (SU)
  - Field measurements at Utah with SU sensor for H_2O and CO (SU & Utah)
  - Designs to extend the TDL sensor for methane and carbon dioxide begin (SU)
- 2011
  - Validate CO_2 and CH_4 spectroscopic database (SU)
  - Laboratory tests of gas composition (H_2O, CO, CO_2, and CH_4) (SU)
  - Optical access for the reactor core will be designed and tested (Utah)
  - The water and temperature sensor design will be finalized (SU)
  - Initial field measurements for gas composition (H_2O, CO, CH_4, CO_2) (SU & Utah)
- 2012
  - Optical access to the reactor core will be completed (Utah)
  - Sensor design will be finalized (SU)
  - Final field measurements of gas composition (heating value) & T (SU & Utah)

Progress & Current Status: Sensor Design

location	1. Reactor	2. Pre-quench	3. Post-quench	4. Output
T	1500K	1200K	500K	500K
P	7-18 atm	7-18 atm	7-18 atm	6-17 atm
Path Length	20 cm	34 cm	5 cm	5 cm
CO	34%	34%	44%	44%
CH_4	1.6%	1.6%	2%	2%
H_2	20%	20%	26%	26%
H_2S	1.3%	1.3%	1.6%	1.6%
CO_2	17%	17%	21%	21%
H_2O	26%	26%	6%	6%

Estimate gas composition, temperature, pressure and pathlength @ Utah

- Use this data to estimate relative contributions to lower heating value
- Use this data to simulate absorption spectra for sensor design

Progress & Current Status: Contributions to Lower Heating Value

Test locations 1& 2

Species	LHV (MJ/$kg_{mixture}$)	Percent
CH_4	0.556	7.7%
H_2O	0	0%
CO_2	0	0%
CO	4.247	58.6%
H_2	2.162	29.8%
H_2S	0.288	3.9%

Mixture LHV(MJ/kg): 7.253MJ/kg

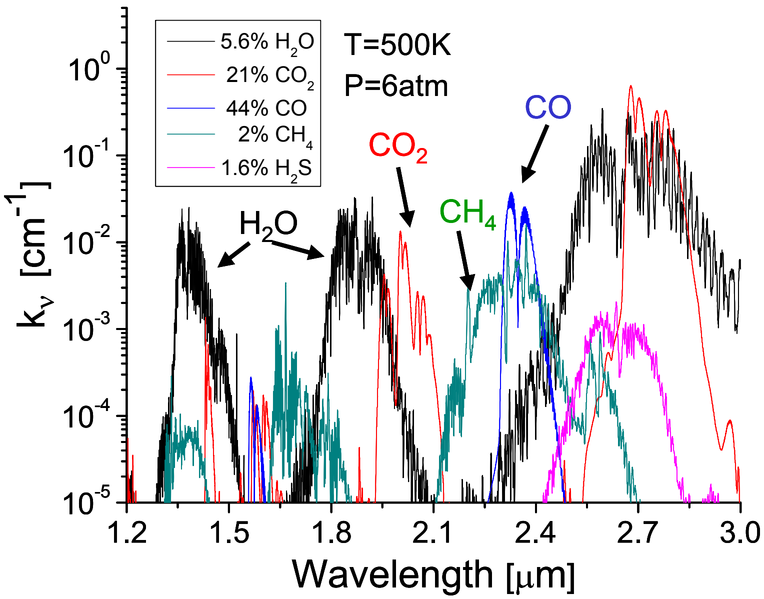
Test locations 3 & 4

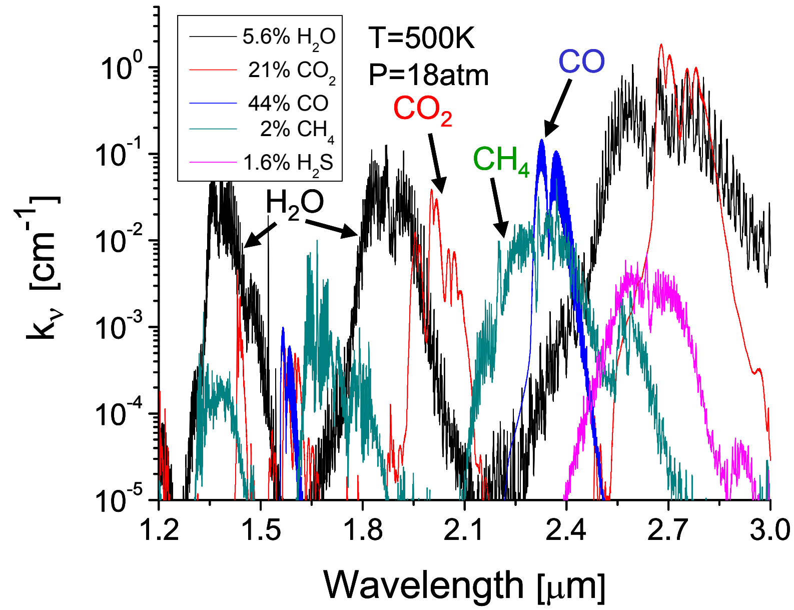
Species	LHV (MJ/$kg_{mixture}$)	Percent
CH_4	0.673	7.7%
H_2O	0	0%
CO_2	0	0%
CO	5.140	58.6%
H_2	2.616	29.8%
H_2S	0.350	3.9%

- TDL sensor measures CH_4, H_2O, CO_2, and CO and assumes that H_2 is the balance of the gas (ignoring H_2S and N_2)
  - Although H_2S has 4% of the LHV assuming “balance” as H_2 results in an error for the gas mixture of only 0.3%
  - If N_2 is approximately known, similar errors in the LHV result
- Model calculations show that heating value can be monitored with TDL measurements of CH_4, H_2O, CO_2, and CO

Progress & Current Status: Sensor Design

- Use HITRAN database to simulate the expected absorption signals

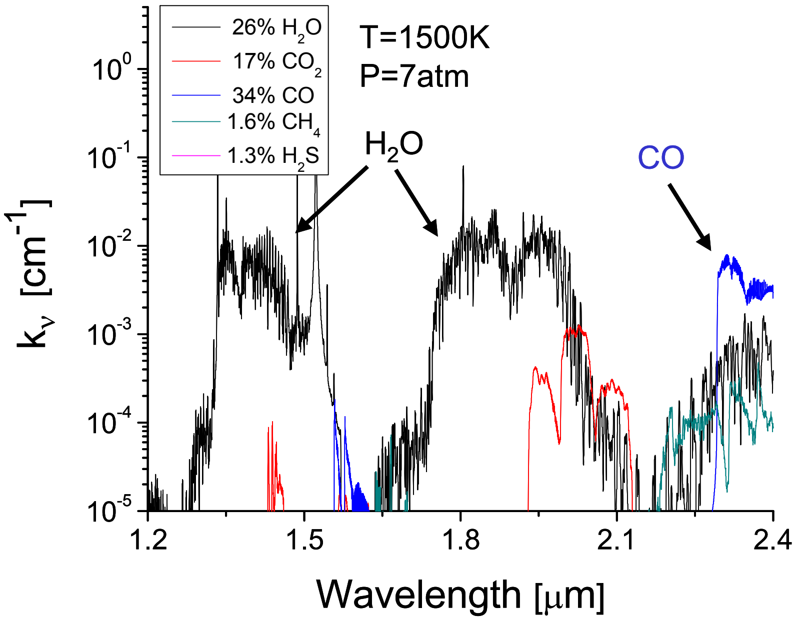


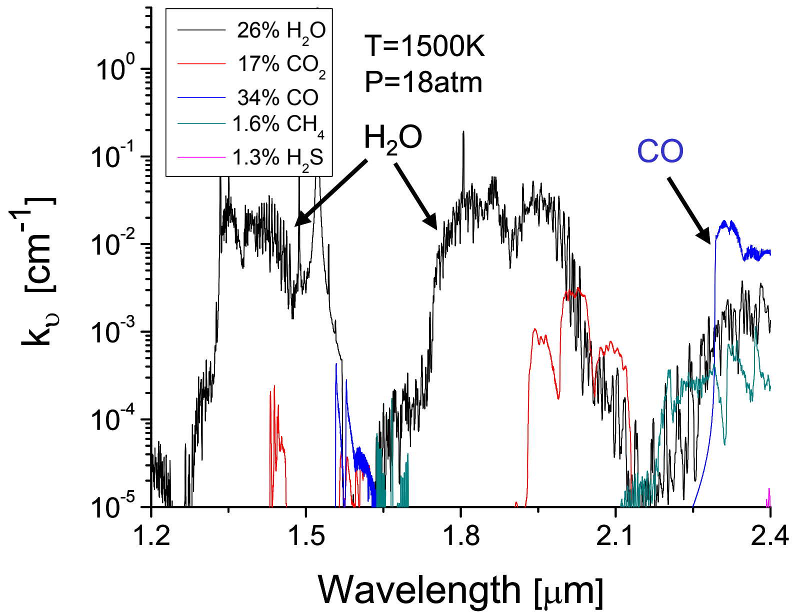


- At 500K there are many laser wavelengths where H_2O, CO, CO_2, and CH_4 can be detected with minimal interference
- Increase in pressure broadens the transitions, but still good separation between the different species

Progress & Current Status: Sensor Design

- Use HITRAN database to simulate the expected absorption signals

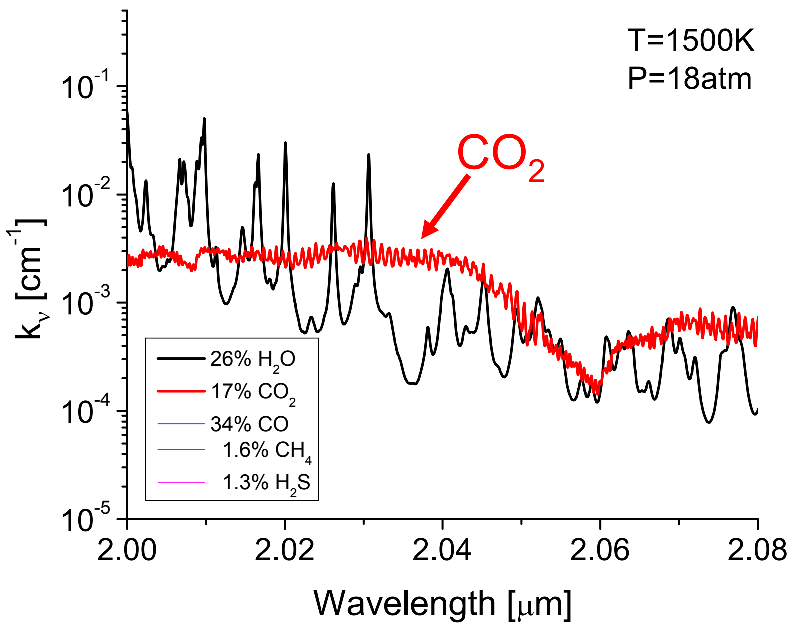


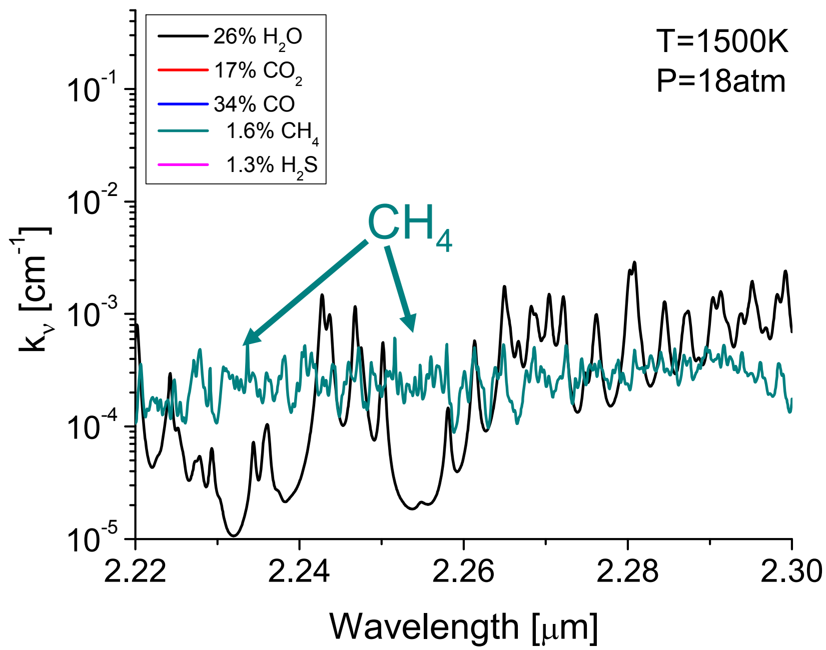


- At 1500K, H_2O and CO can be detected with minimal interference
  - H_2O in the bands near 1.4 μm and the bands near 1.8 μm
  - CO in the first overtone band near 2.3 μm
- Selection of laser wavelength for CO_2 and CH_4 must carefully avoid interferences

Progress & Current Status: Sensor Design

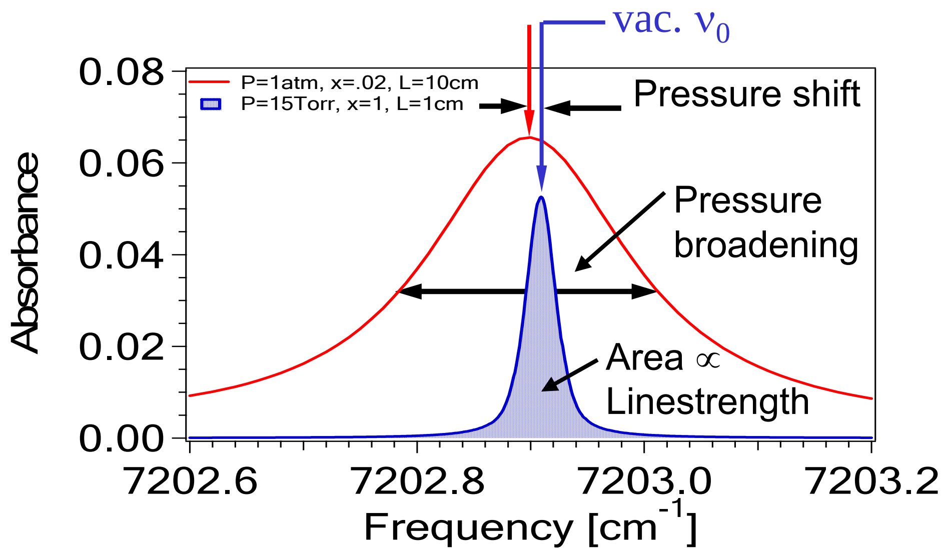
- Use HITRAN database to simulate the expected absorption signals

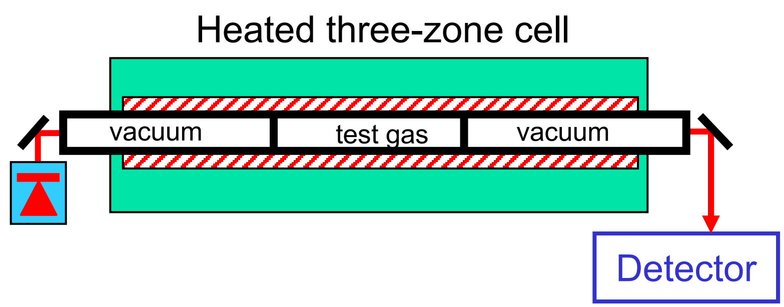




- Simulations show, H_2O is the major interference species
- There are gaps or "windows" in the H_2O where CO_2 and CH_4 detection should be possible
- Careful validation of the spectroscopic database is required (especially for H_2O in the region for CO_2 and CH_4 detection)

Progress & Current Status: Spectroscopic Database

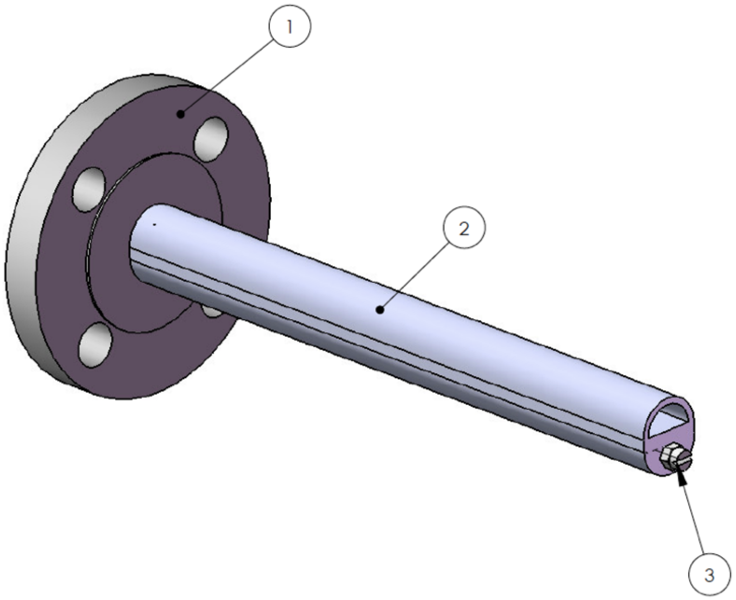




- Laboratory measurements to validate spectral database
  - Three-zone furnace with quartz cell for measurements to 1500K
  - Measurements versus pressure (at low values) to determine spectral data
- Current status:
  - Lasers for H_2O and CO purchased and on-hand
  - Initial line selection for CH_4 and CO_2 complete

Progress & Current Status: Optical Access

- Sensor locations 3 and 4 (post-quench in piping)
  - Assessing optimum optical pathlength
  - Either "tee" (across pipe) or along length of pipe
  - Nitrogen purged sapphire window
    - Purge provides air curtain to avoid fouling
  - Developed technology – minimum fabrication time
- Sensor location 2 (pre-quench below reactor)
  - Use existing quench spray ports (two opposing)
  - Axially split spray lance to allow optical access in upper half and quench spray in bottom half
  - Optical pathlength (14" or 35.5cm)
  - Requires fabrication and testing
- Sensor location 1 (gasification reactor)
  - Modeling work planned to assess options to keep slag layer from blocking windows (fiber technology can minimize needed aperture)
  - Plan reactor modifications for opposing ports on the completion of the window design
  - Required for Year 3 experiments



Critical Milestones: TDL Measurements in Gasifier

Field measurements using Stanford sensor technology in Utah gasifier facilities

- 2010: Field measurements for H_2O and CO concentrations
- 2011: Initial field measurements for gas composition (H_2O, CO, CH_4, CO_2)
- 2012: Final field measurements of gas composition (heating value) & T