Tunable Diode Laser Sensors for Monitoring Combustion and Gasification Systems

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1. Fundamentals of TDL absorption sensing
2. TDL sensing for coal gasification
   - T and H_2O sensing*
   - CO, CO_2, CH_4, H_2O sensing**
3. Monitor of syngas heating value

*Sponsored by EPRI (Jose Marasigan & Jeff Phillips)
**Sponsored by DoE NETL (Susan Maley)

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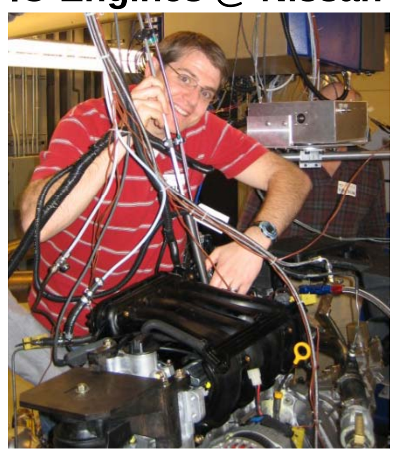
My main message today is that:
TDL Absorption is Practical in Harsh Environments

- Utilizes economical, 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
- Demonstrated in harsh environments and large-scale systems:
  - Aero-engine inlets, scramjets, pulse detonation engines, IC engines, gas turbines arcjets, shock tunnels, coal-fired combustors, rocket motors, furnaces….
- Potential use in control of practical energy systems

Coal-fired Utility Boiler

Chao, *Proc Comb Inst*, 2011

IC-Engines @ Nissan



Jeffries, *SAE J. Eng*, 2010

Coal Gasifier @ U of Utah

Jeffries, *Pittsburgh Coal Conf,* 2011

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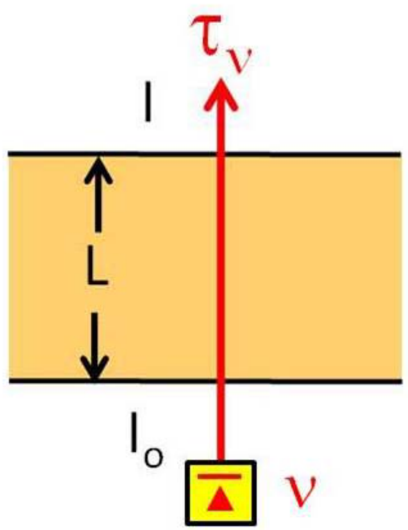
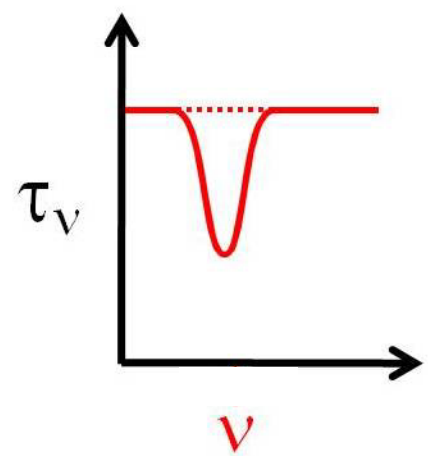
Absorption Fundamentals: Species

Absorption of monochromatic light





- **Scanned-wavelength *line-of-sight* direct absorption**
  - **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** $k_\nu = S(T) \cdot \Phi(T, P, \chi_i) \cdot \chi_i \cdot P$

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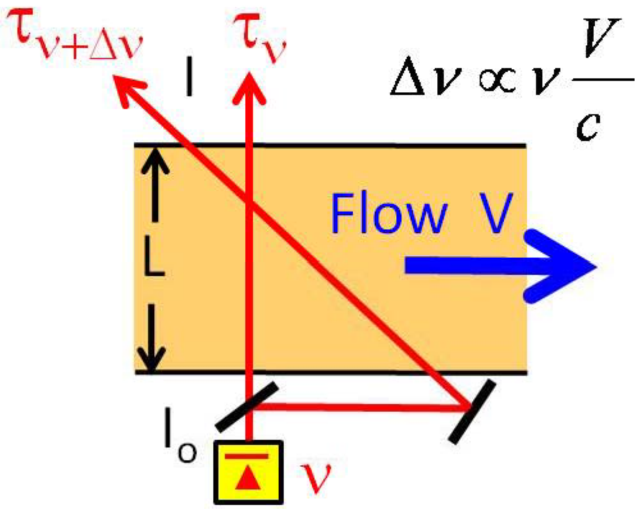
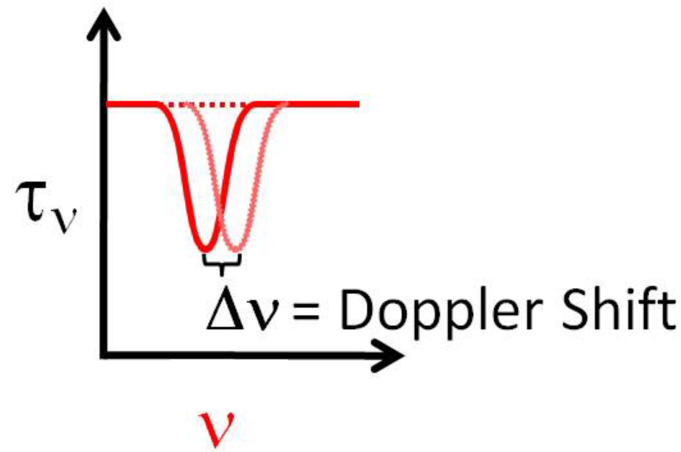
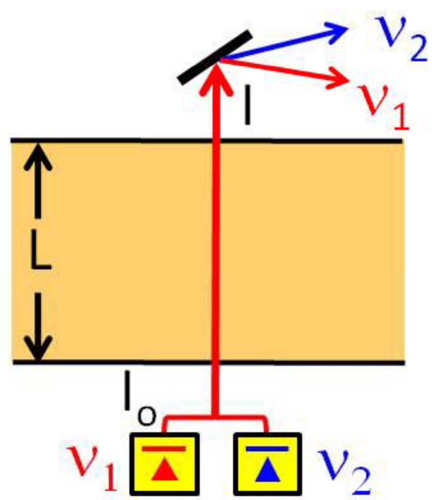
Absorption Fundamentals: Velocity

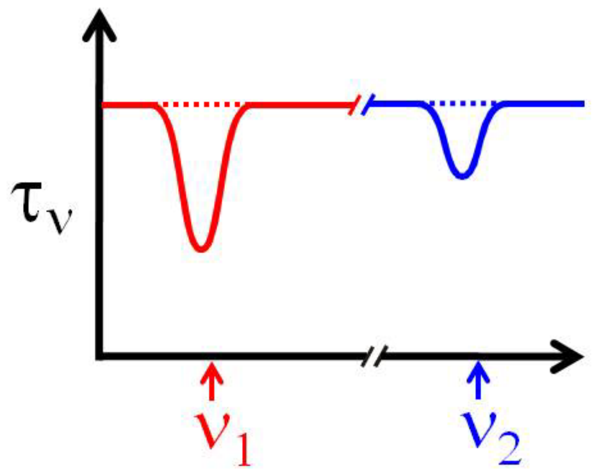




- **Shifts & shape of Φ contain information (T,V,P,χ_i)**

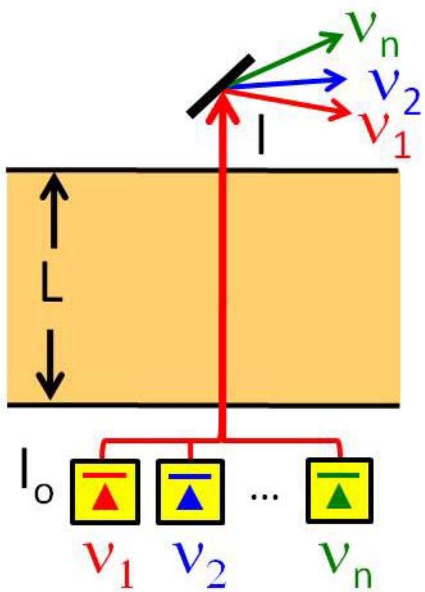
Absorption Fundamentals: Temperature

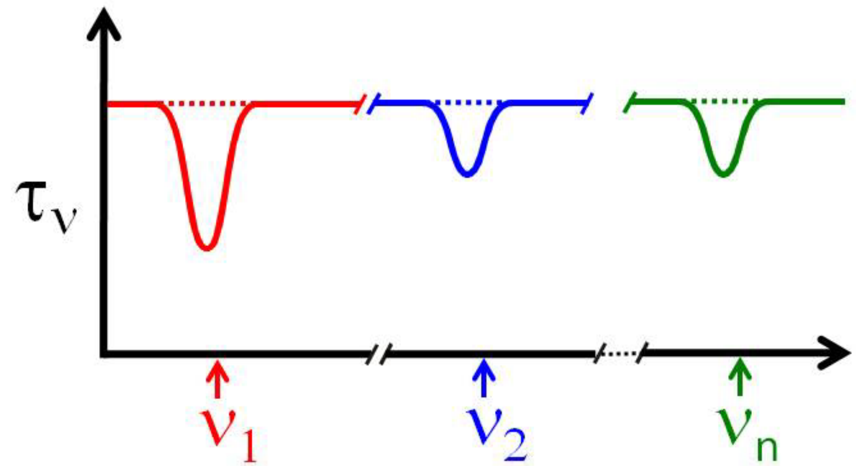




- **T from ratio of absorption at two wavelengths**

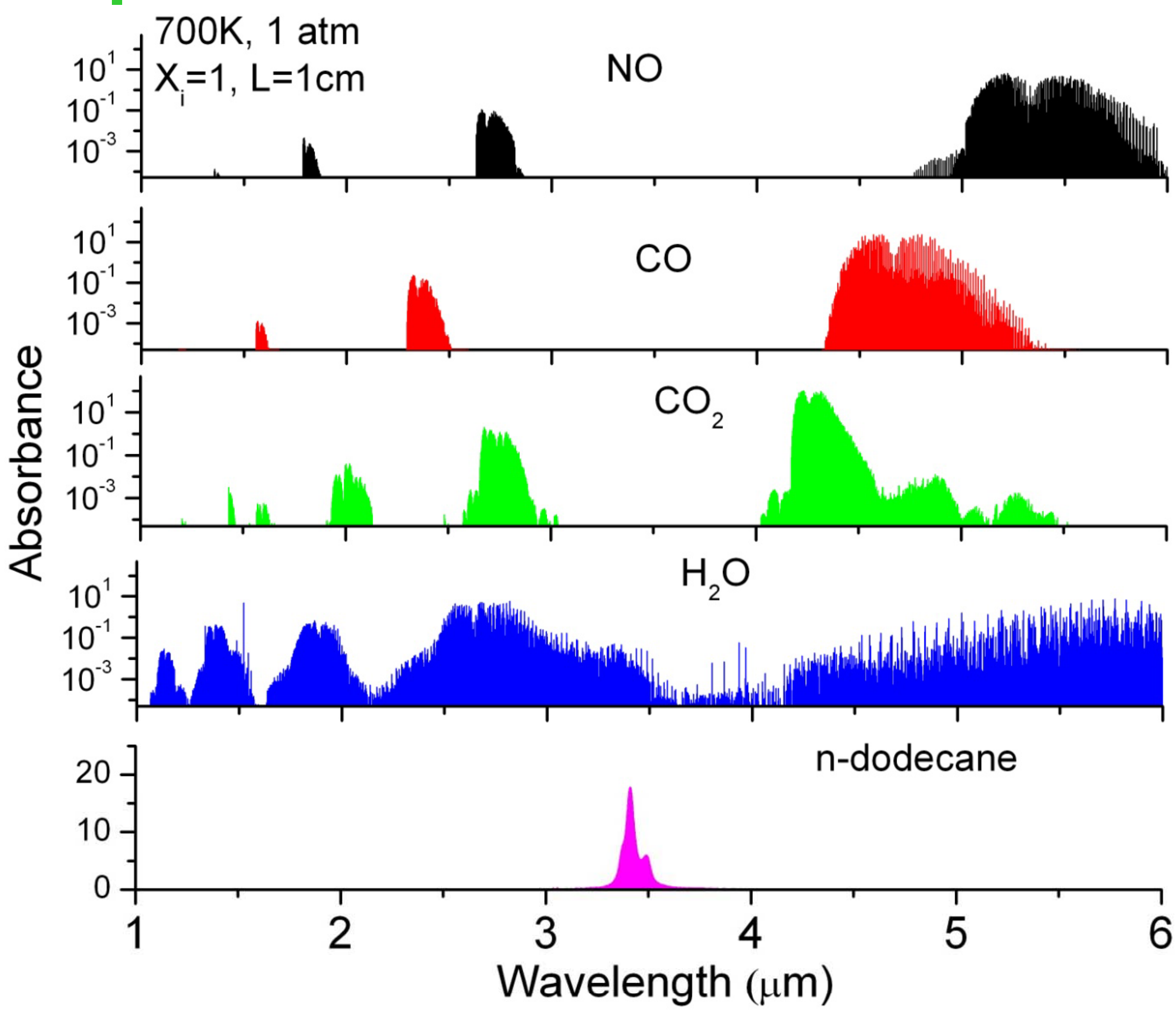
Absorption Fundamentals: Multiplexed





- **Wavelength multiplexing is often utilized**
  - **To monitor multiple parameters or species**
  - **To assess non-uniformity along line-of-sight**

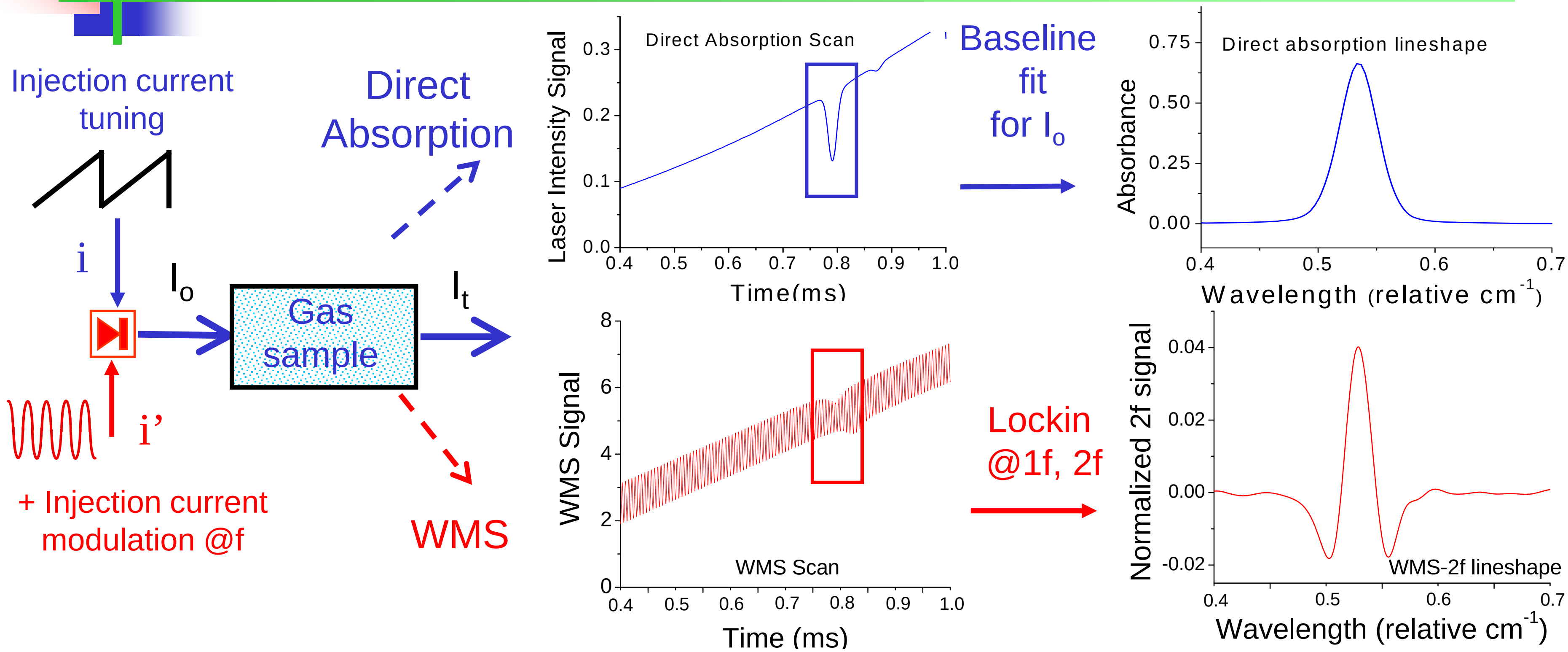
TDL Sensors Provide Access to a Wide Range of Combustion Species/Applications



- Small species such as NO, CO, CO_2, and H_2O have discrete rotational transitions in the vibrational bands
- Larger molecules, e.g., hydrocarbon fuels, have blended features

Two primary TDLAS sensor strategies

Two Absorption Measurement Techniques:
Direct Absorption (DA) & Wavelength Modulation Spectroscopy (WMS)



- **Direct absorption: Method of choice when applicable**
- **WMS: More sensitive especially for small signals (near zero baseline)**
  - **WMS with TDLs improves noise rejection**
  - ***1f-Normalized WMS-2f/1f:* Provides I_o without a baseline**

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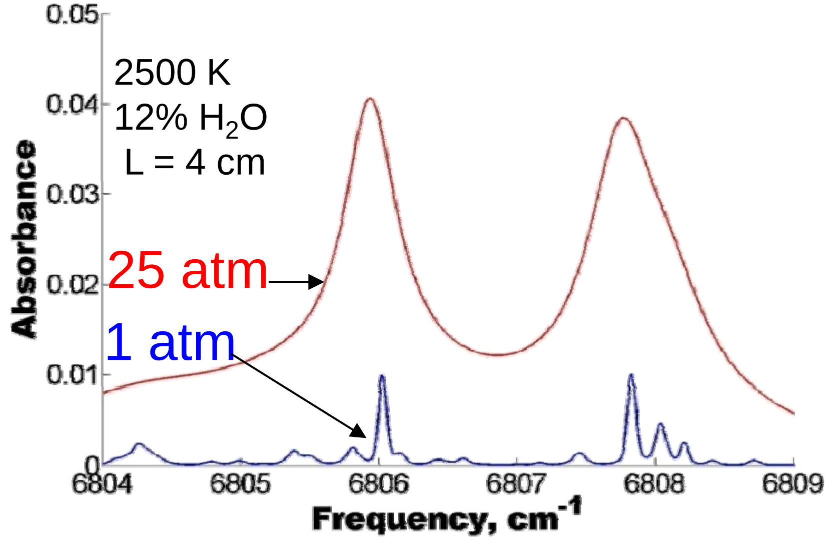
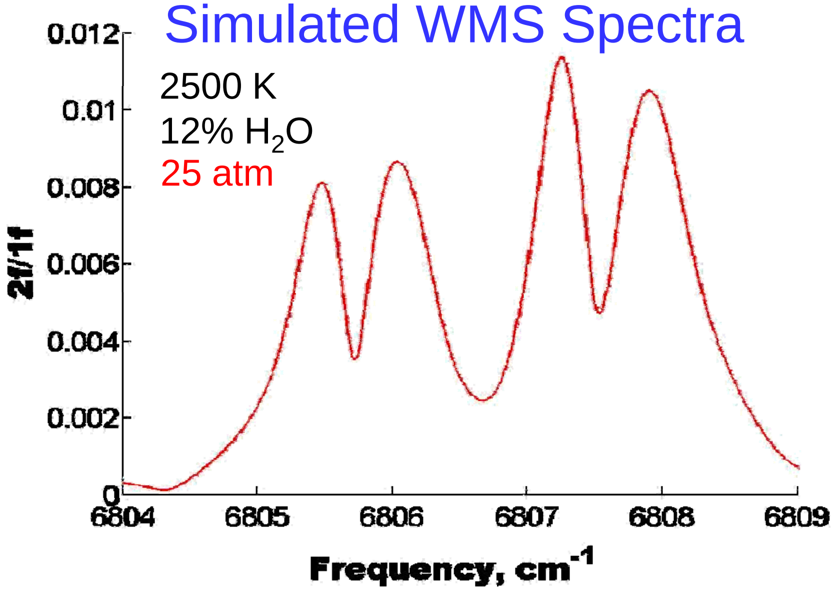
High P,T Sensing Enabled by WMS

- **High P, T challenges**
  - Broad and blended spectra at high P
  - Decreased absorbance at high T

Simulated Absorbance Spectra



Simulated WMS Spectra



- **Solution**
- ***1f*-Normalized WMS-*2f***
  - Recovers strong peaks
  - No baseline I_o needed!
  - Also suppresses noise and transmission losses

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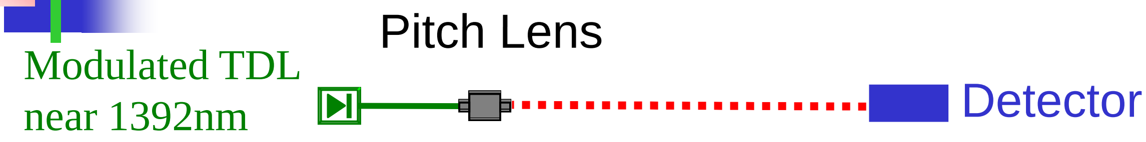
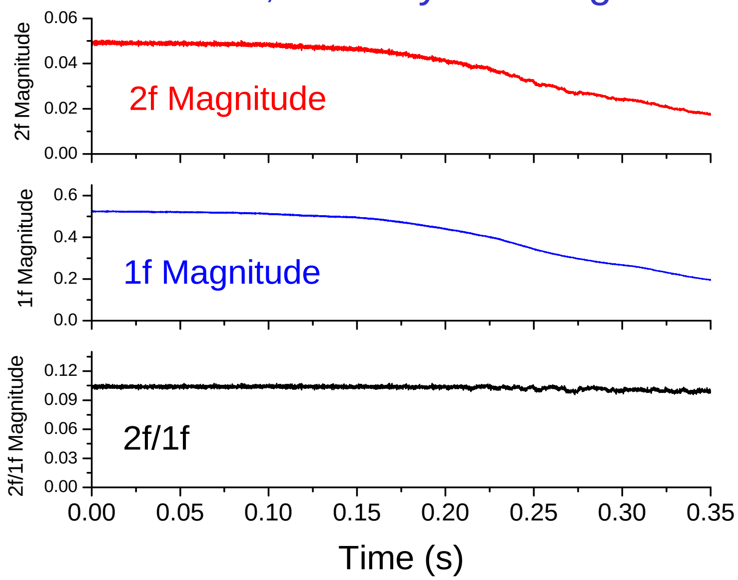
WMS-2f/1f Accounts for Non-Absorption Losses

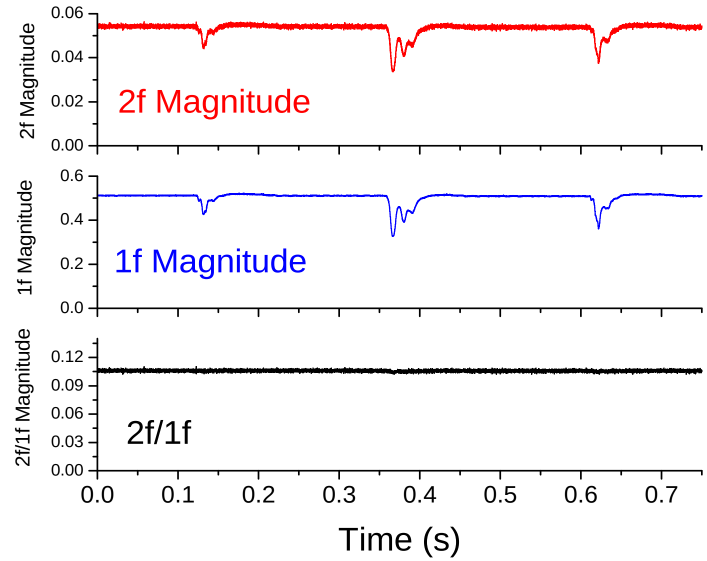


- Fixed λ WMS-*2f/1f*
- Ambient H_2O (T=296 K, 60% RH)
- L=29.5 cm, ~6% absorbance)

1392 nm, Partially Blocking Beam



1392 nm, Vibrating Pitch Lens



- **Demonstrate normalized WMS-*2f/1f* in laboratory air**
  - **2f/1f unchanged when beam attenuated (e.g., scattering losses)**
  - **2f/1f unchanged when optical alignment is spoiled by vibration**

WMS-*2f/1f* signals free of window fouling or particulate scattering

WMS has other advantages too

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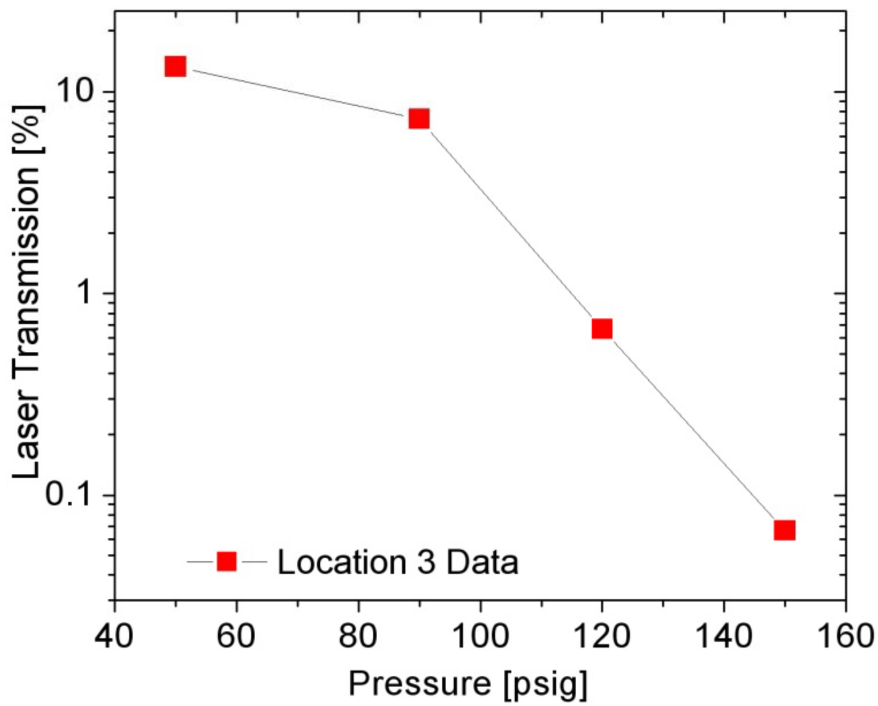
Sensing with Large Transmission Losses from Scattering Enabled by WMS

Transmission of laser light at non-absorption wavelengths



- Measurement in syngas product line before particulate filtering
  - Particulate loading increases with pressure (99.9% loss at 150psig)
- Varies with gasifier performance, fuel, temperature, etc.

<u>Solution:</u> Stanford's 1f-normalized WMS-2f scheme

What might we measure in syngas?

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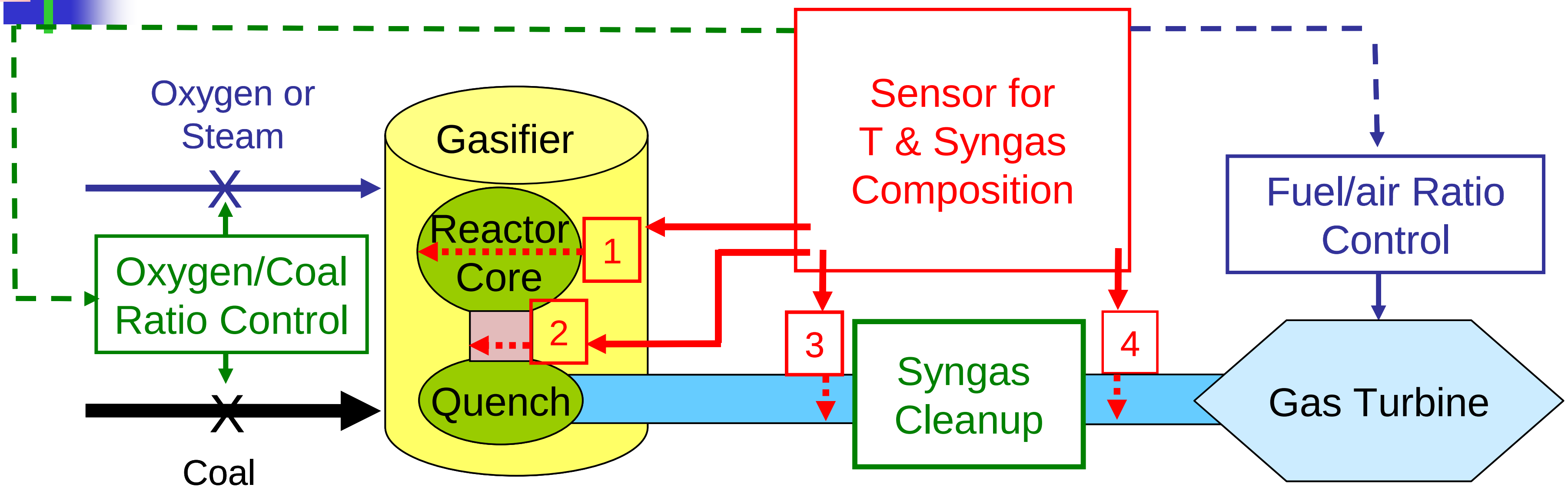
Vision and Goals for TDL Sensing in IGCC



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

Goals:

- Two flow parameters considered: gas temperature and heating value
  - Gas temperature determined by ratio of H_2O measurements
  - Measurements of CO, CH_4, CO_2, and H_2O provide heating value
    - H_2 determined by gas balance as other species ignored
- Four measurement stations considered: spanning reactor core to products

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Oxygen-blown, Down-fired, Entrained-flow Coal Gasification Facility at the University of Utah

Pilot scale gasifier

- Rated to 450 psig
  - current data to 200 psig
- Rated to 3100 °F
- Coal throughput: 1 ton/day
- Overall dimensions
  5.1 m (17') tall
  0.76 m (30'') OD
- Reactor dimensions
  1.5 m (60'') long
  0.20 m (8'') ID

- **Four measurement campaigns to test Stanford TDL sensors:**
  - Aug. 2010, Dec. 2010, Aug. 2011, May 2012
- **Ideal facility for instrumentation testing:**
  - **Rapid transition from 1 atm flame to 20 atm gasification conditions**
  - **Reactor kept hot with 1 atm natural gas flame between runs**

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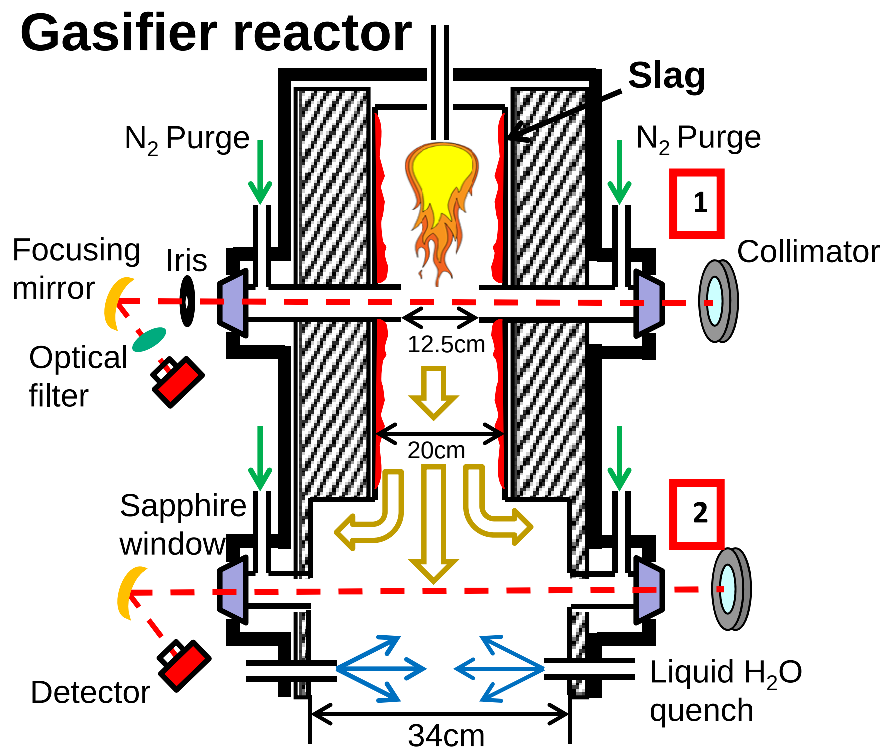
Sensor Setup in Utah Gasifier: T and H_2O

Two reactor locations tested

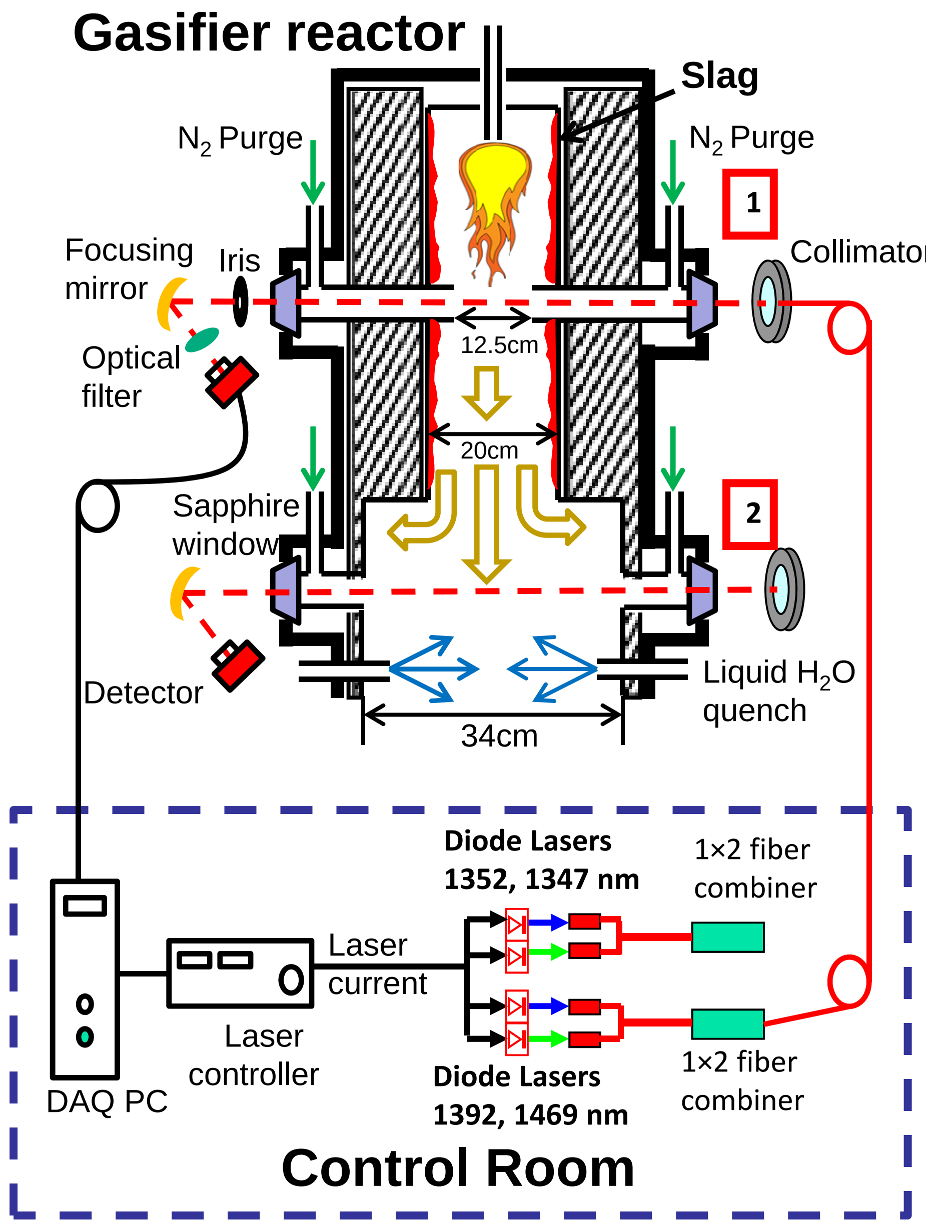
- Position 1: Reactor core
- Position 2: Quench location



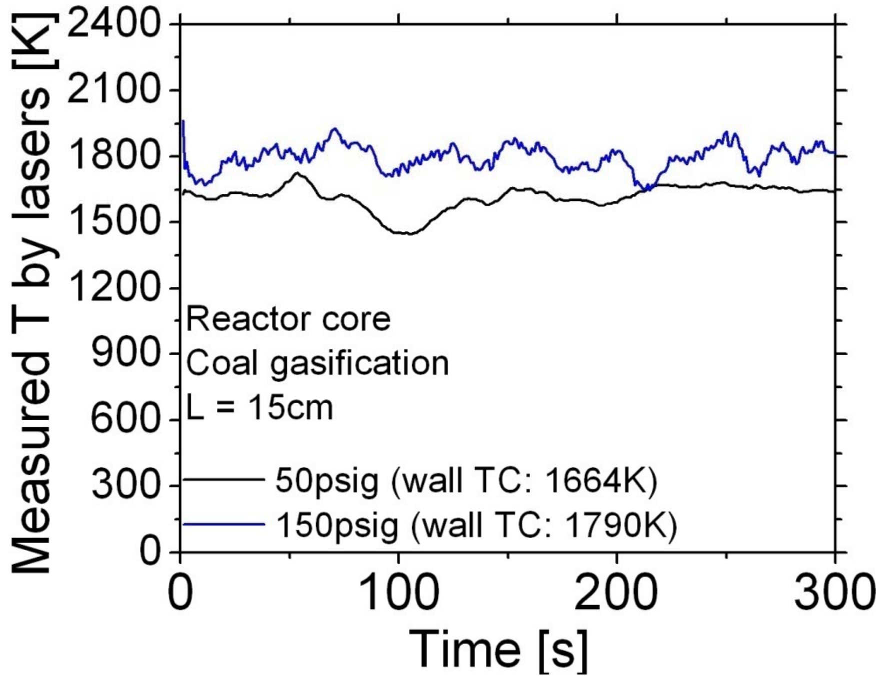
Sensor Setup in Utah Gasifier: T and H_2O

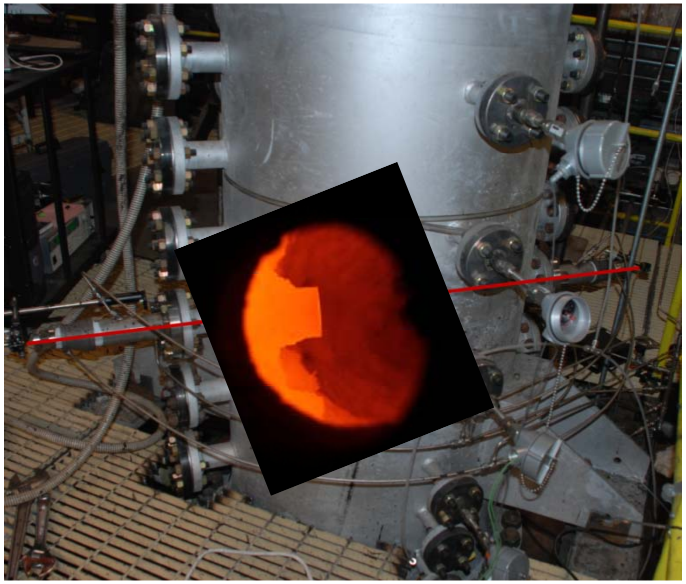
Two reactor locations tested

- Position 1: Reactor core
  - Highest T
  - Largest scattering losses
  - Emission interference
  - Time limited by slag flow
  - Successful measurements demonstrated



Temperature in Reactor Core





- Transmission at 50 psig 0.13% dropping to 0.02% at 150 psig
  - Normalization scheme successful
  - Very strong optical emission - optical filtering scheme successful
- Optical access tube successfully stayed open in presence of flowing slag'
  - Later unsuccessful with different coal (and different atomizer)

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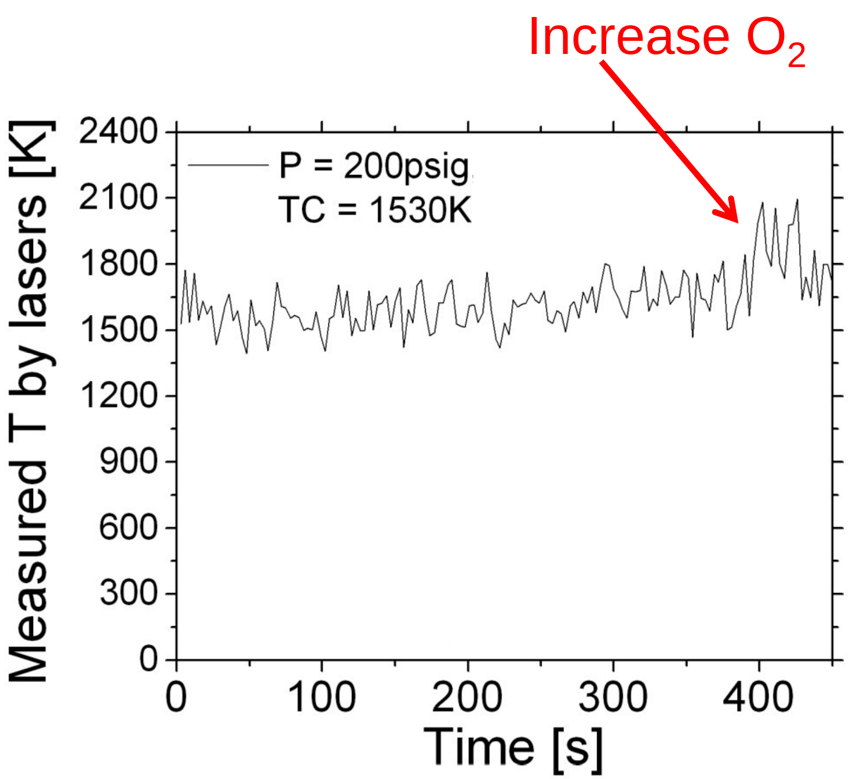
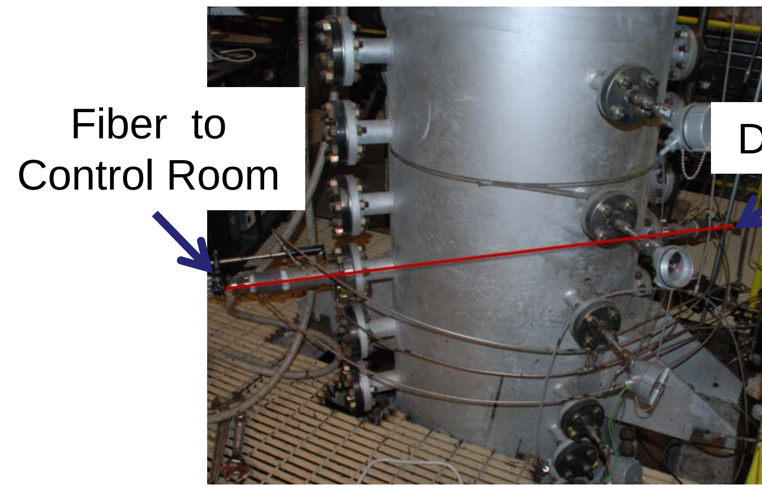
Temperature in Reactor Core



Reactor Core

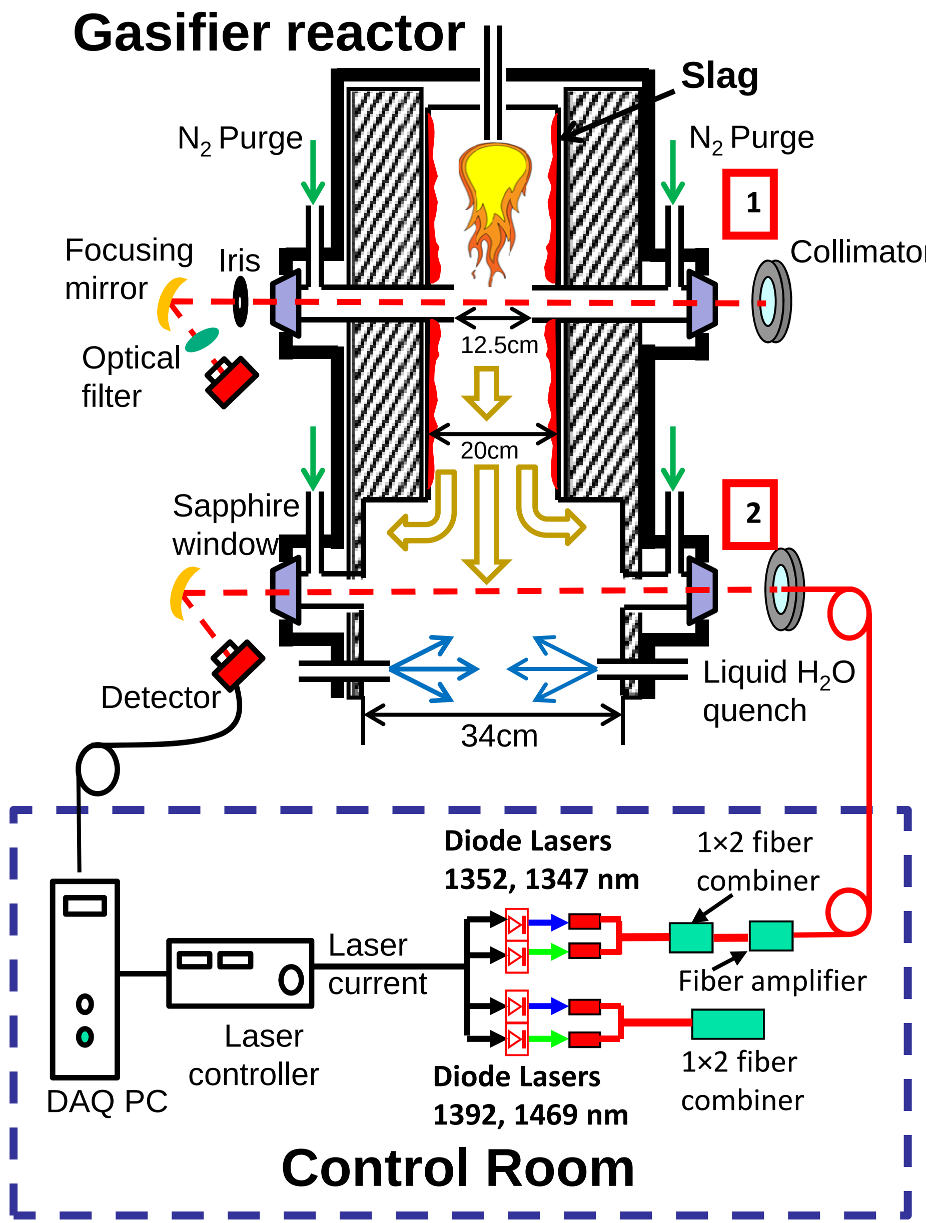


- **Normalization scheme successful with low transmission (< 0.02%)**
- **TDL sensor time response can capture flow changes**

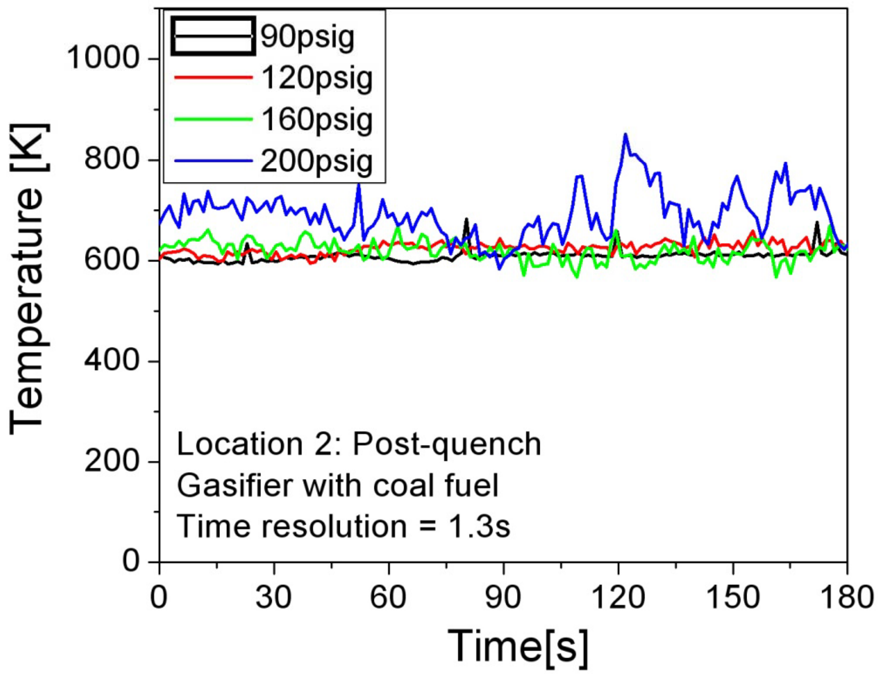
Sensor Setup in Utah Gasifier: T and H_2O

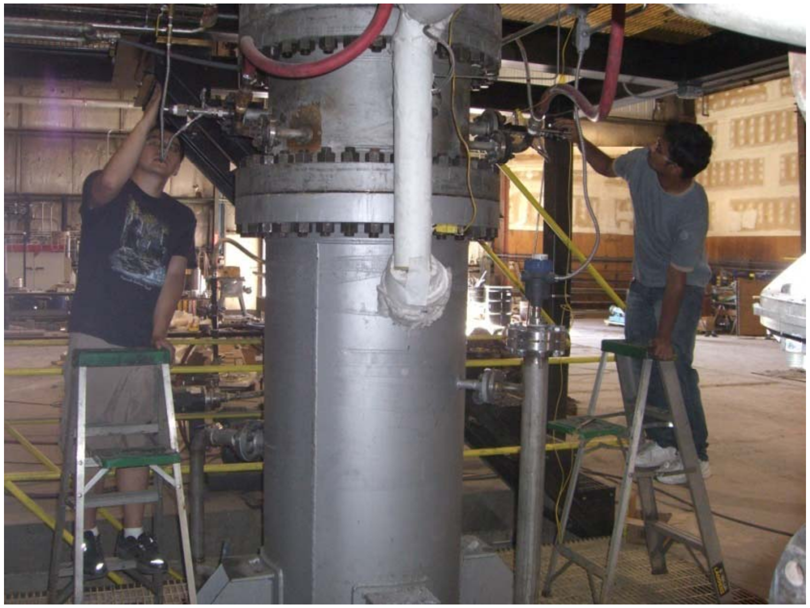
Two reactor locations tested

- Position 2: Quench location
  - Modest purge flow keeps windows clean
  - Lower T – different line pair
    - Amplifier available
    - Increase power x10
  - Successful measurements even with 10^{-5} attenuation



Temperature @ Quench Location





- Normalized WMS accounts for varying transmission (10^{-3} at 160 psig)
- Measured T at reactor pressures of 90, 120 and 160 psig stable
- Measured T at 200 psig identifies potential fuel/O_2 input instabilities

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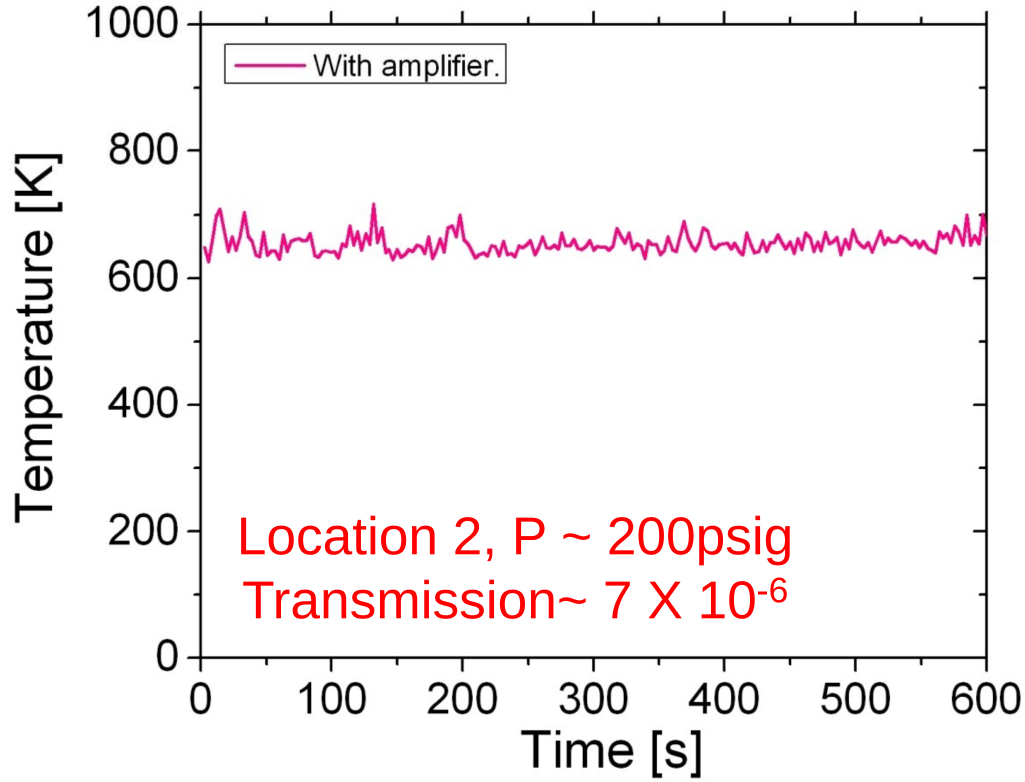
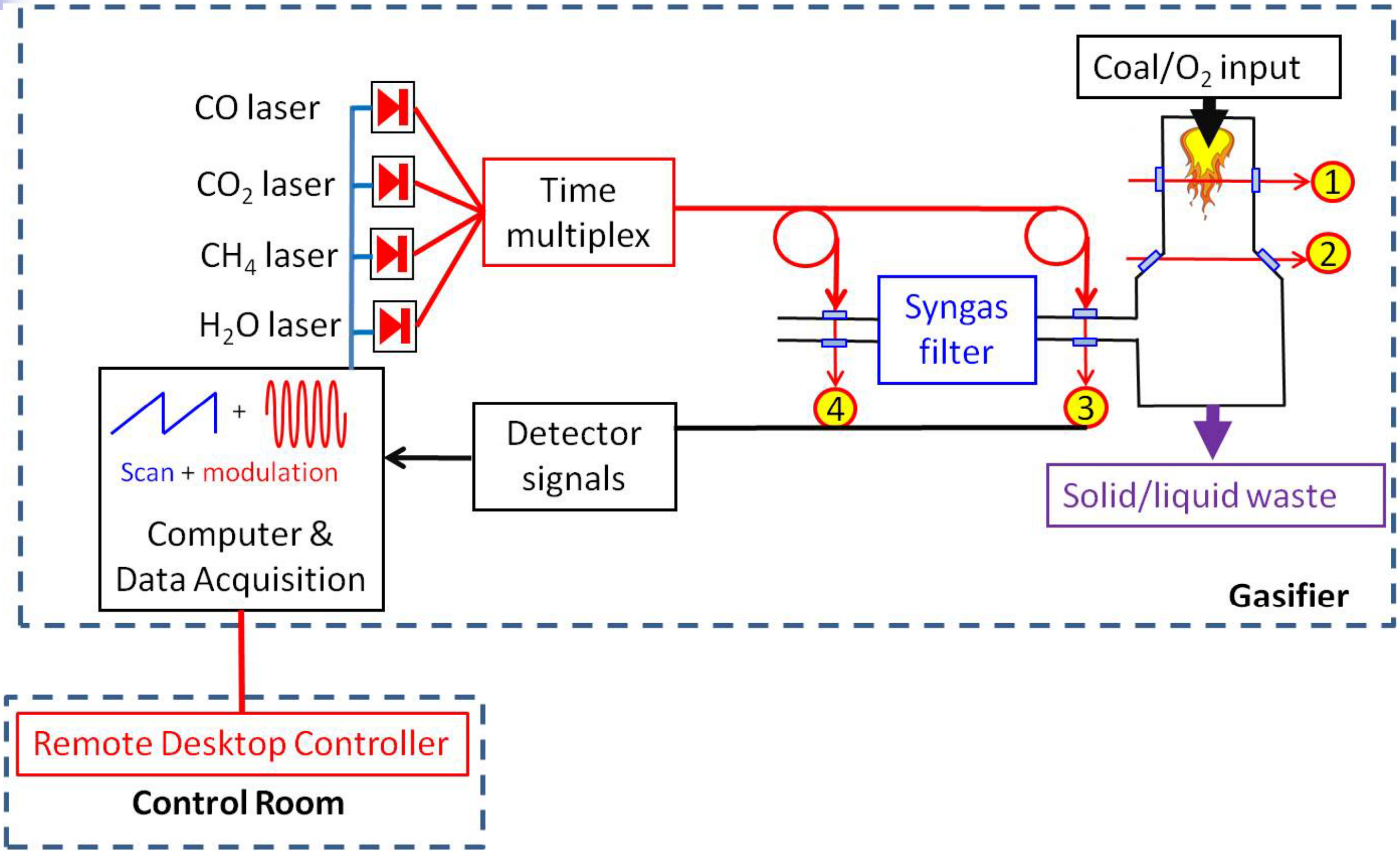
Temperature @ Quench Location



- Different gasifier conditions, different coal, more particulate scattering
- High SNR, time-resolved measurements of T using fiber amplifier
  - Less than 10^{-5} of the laser light transmitted

Sensor Setup in Utah Gasifier: Syngas Composition



- CO, CO_2, and CH_4 lasers use lasers 2-2.3 μm
  - Fiber technology less available
  - TDLs controlled remotely but located near measurement

Sensor Setup in Utah Gasifier: Syngas Composition

- Syngas can by-pass sensor location for window maintenance
- Similar setup before and after particulate filter (similar results)
- Multiple-lasers directed through one window
  - Rapid (10 Hz) switching from one species to another
  - Time-resolution ~1/3 second

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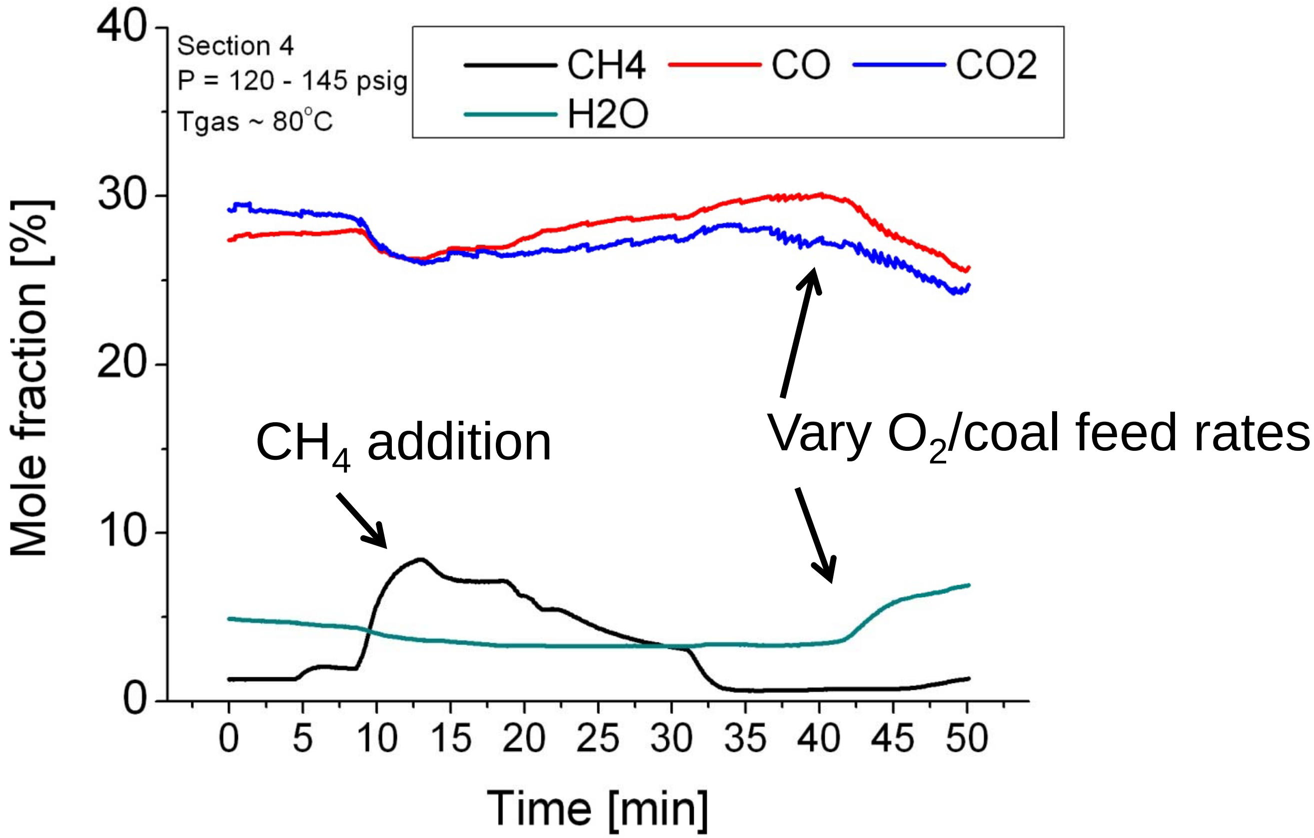
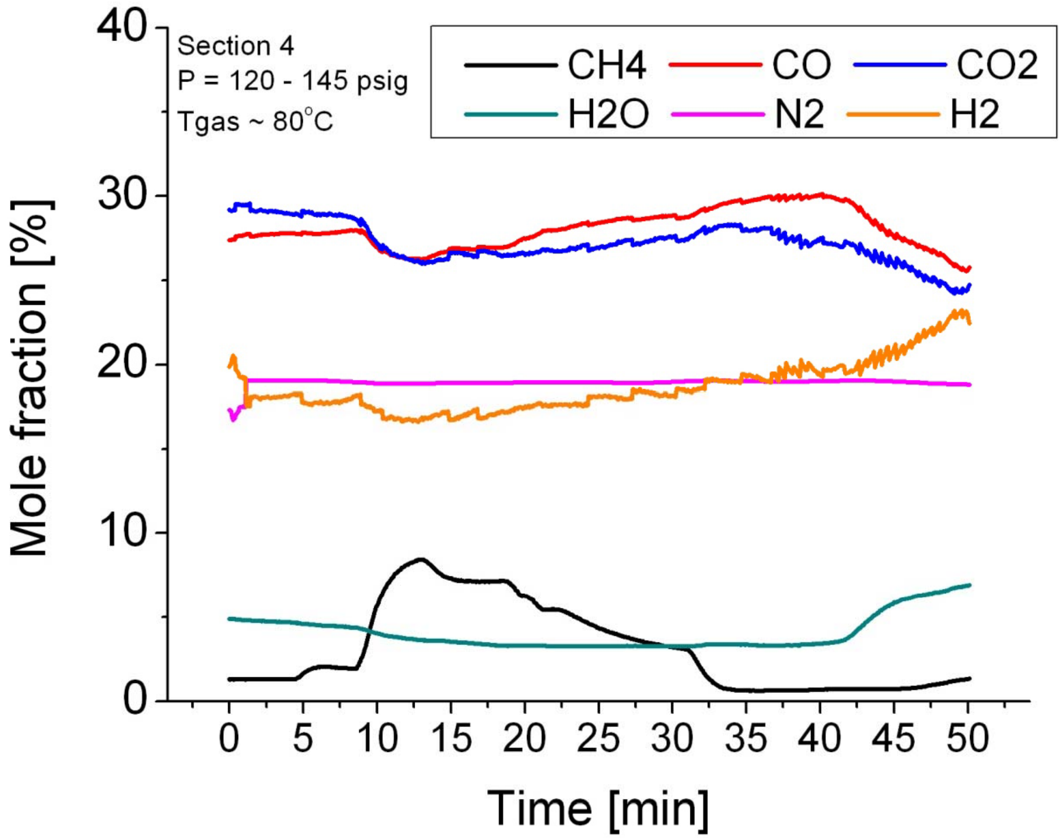
TDL Sensor Measured Syngas Composition



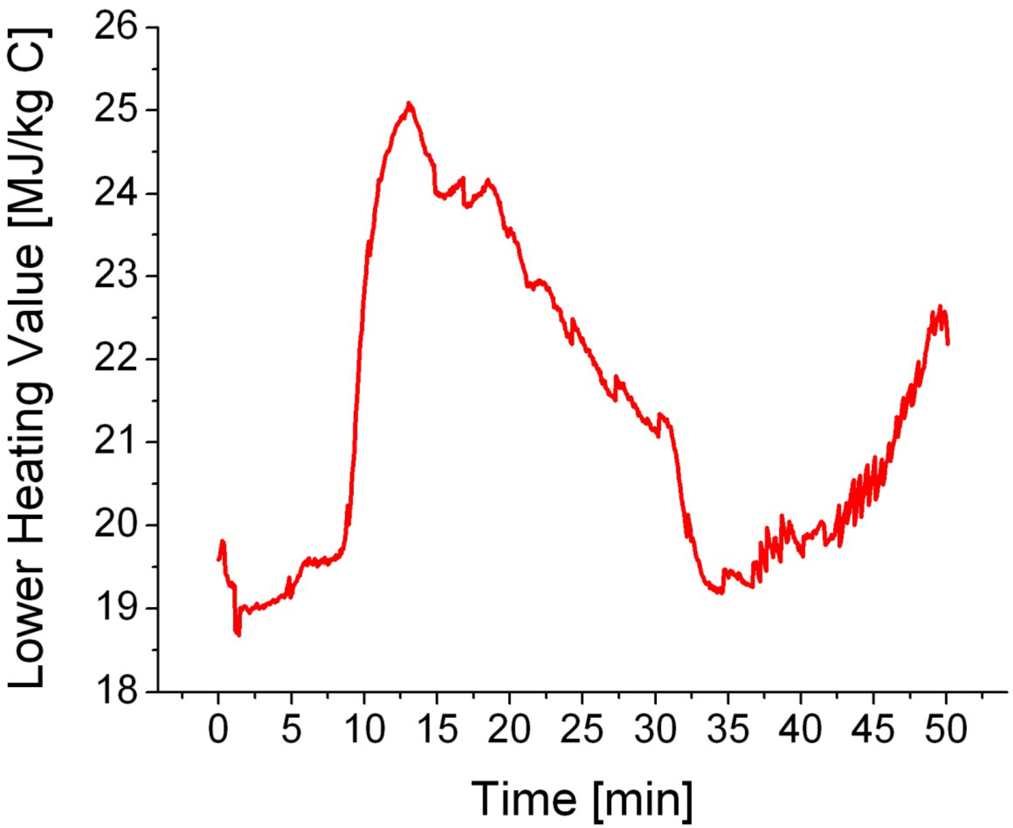
- Laser absorption measurements of CO, CO_2, H_2O and CH_4 over 1 hour
- CH_4 added to syngas to test sensor response and vary gas composition
- Gasifier feed rates changed to test sensor response

Syngas Composition Including N_2 and H_2



- N_2 in flow from gas purges – determined by metering and GC data
- Assume the rest of the syngas is H_2
  - Enables determination of lower heating value (LHV)

Time-Resolved Monitor of Syngas LHV



- One hour time record of syngas lower heating value (LHV)
  - CO, CO_2, CH_4 and H_2O from TDL sensor and N_2 from facility data
- Assume balance of syngas H_2
  - LHV contribution of small concentrations of H_2S and NH_3 are estimated to be less than 2% (accounted as H_2)

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Summary

- A novel modulation strategy enables measurements in high pressure environments with extinction by scattering
  - Scheme validated for extinction as large as 10^5
- Sensor demonstration measurements made in four locations of a pilot-scale, entrained-flow, coal gasifier
  - Time-resolved measurements capture small changes in gasifier operating conditions
- Current work focused on sensor validation and demonstration

Next Steps:

- Transition sensor to real-time for continuous unattended monitoring
- Add H_2S and NH_3 to sensor suite
- Package next-generation sensor for industrial-scale applications (test Utah?)
- Find suitable industrial-scale demonstration opportunities

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