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DOE Sensors & Automation 2005 Annual Portfolio Review

Tunable Diode Laser for Harsh Combustion Environments

William Von Drasek & Anna Pubill Melsio
American Air Liquide, 5230 S. East Ave.
Countryside, Il 60525

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Tunable Diode Laser for Combustion Process Monitoring

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Goal: Develop and test an industrial multiple gas near-IR diode laser sensor for **O_2**, **CO**, **H_2O** and **T**emperature monitoring targeted for harsh process monitoring.

Challenge: Demonstration of the technology measurement accuracy and reliability with minimum maintenance for dynamic high temperature and high particle density processes

Benefits: Cross-cutting technology supporting all industrial processes requiring combustion atmosphere monitoring and control.

Diode laser Electronics and Data Acquisition System

Key Project Deliverables:

- Sensor development and characterization
  - →Pilot furnace testing
- Industrial Demonstration Tests
  - →Steel reheat furnace
  - →Aluminum reverberatory furnace
  - →Electric arc furnace
    - ✓ System hardening
    - ✓ On-Demand Laser Power Control

Development Partner: PSI Physical Sciences Inc.

Industrial Host-site Partners:

Charter Steel

IMCO Recycling Inc.

GERDAU AMERISTEEL

Tunable Diode Laser for Combustion Process Monitoring

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- Cross-cutting technology supporting all industries requiring combustion atmosphere monitoring and control

Barrier → Pathway → Metrics

Barrier

- Lack of sensor technology suitable *in-situ* process monitoring at high temperatures and high particle densities
- Lack of real-time sensors
- Lack of low maintenance sensors

Pathway

- Develop multiple species *in-situ* non-intrusive laser-based measurement system
- Identify high temperature spectral region
- Multiple wavelength capability
- Fabricate hardened system adaptable for a variety of industrial monitoring applications
- Industrial evaluation for optimization

Metrics

- Long-term measurement demonstration
- Large dynamic range
  - →Concentration (0-70%)
  - →Temperature (1000-1800 °C)
- Evaluate frequency and level of maintenance
- Measurement reliability

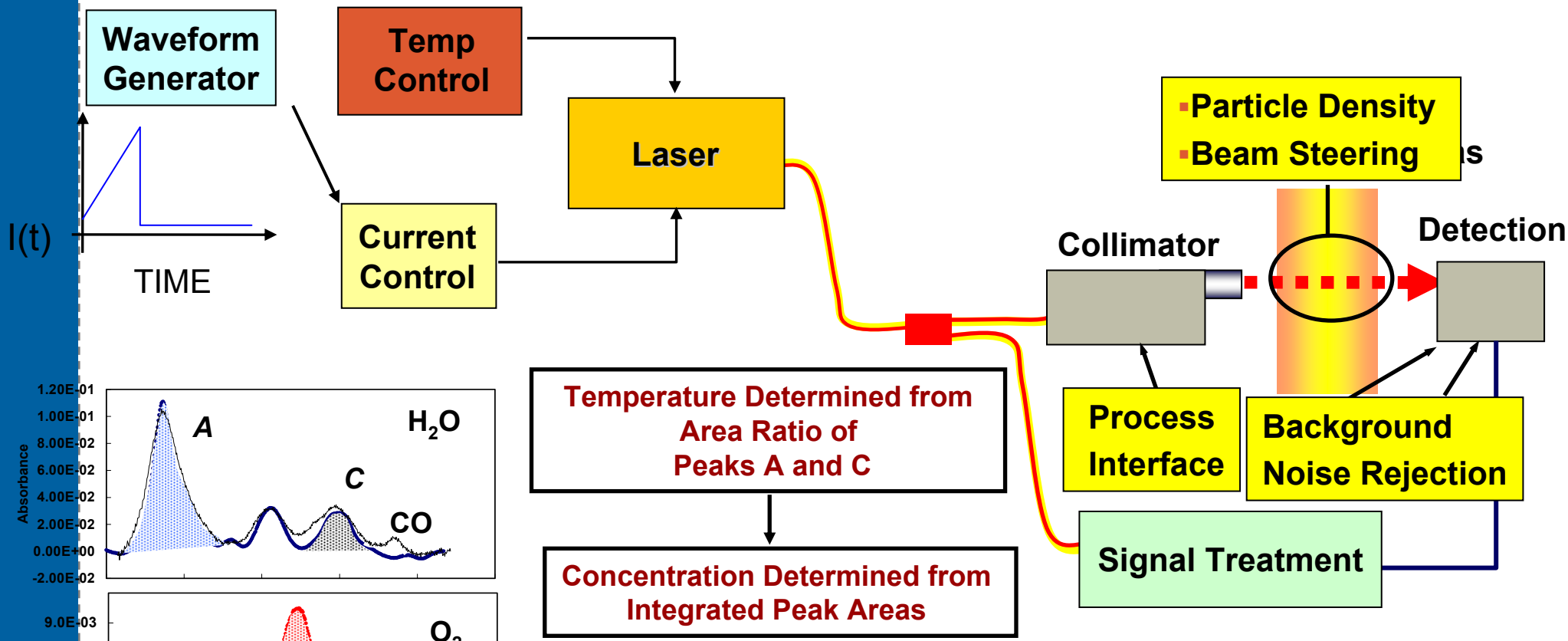
Aluminum Furnace

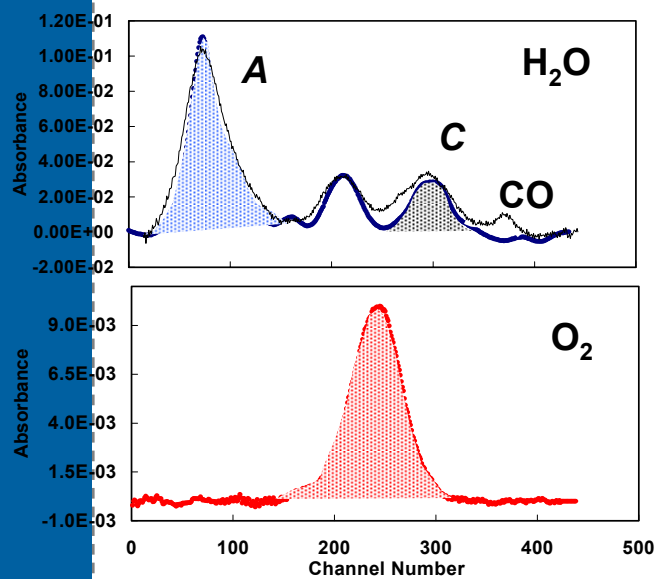
Electric Arc Furnace

Incinerator

- ✓Dynamic Processes
- ✓High Temperature & Particle Density
- ✓Limited Process Control & Automation

Technology Concept





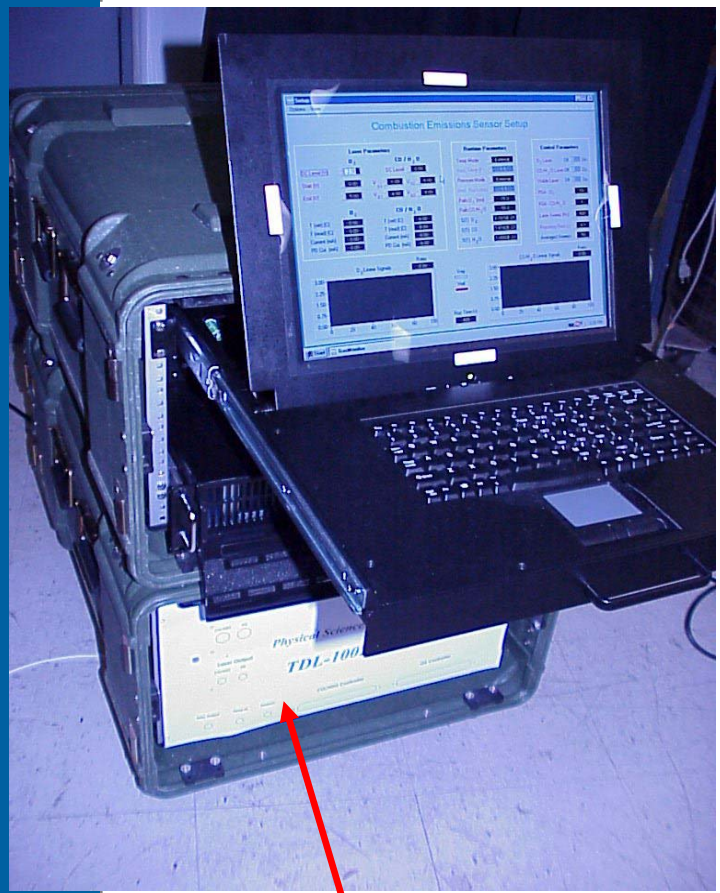
Resonant absorption (Beer-Lambert):

$$I_v = I_{v,o} \exp\left[-\underbrace{S(T)}_{\text{Linestrength}}\underbrace{g(v - v_o)}_{\text{Lineshape}}\underbrace{Nl}_{\text{Number Density X Pathlength}}\right]$$

Industrial Prototype System

Multiple Gas Sensor (MGS) System (CO, O_2, H_2O & Temperature)

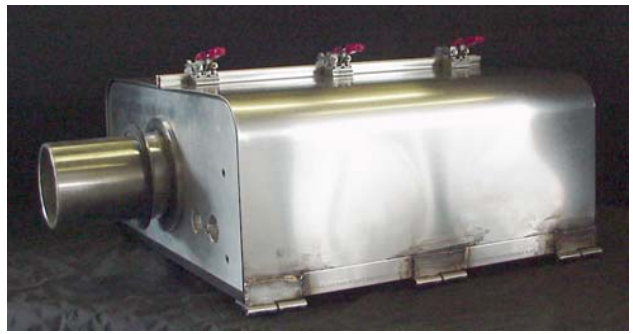
•Semi-Harsh Process Monitoring



Lasers & Associated Electronics

Launch Module

Receiver Module



<u>Features</u>

Lasers & associated electronics

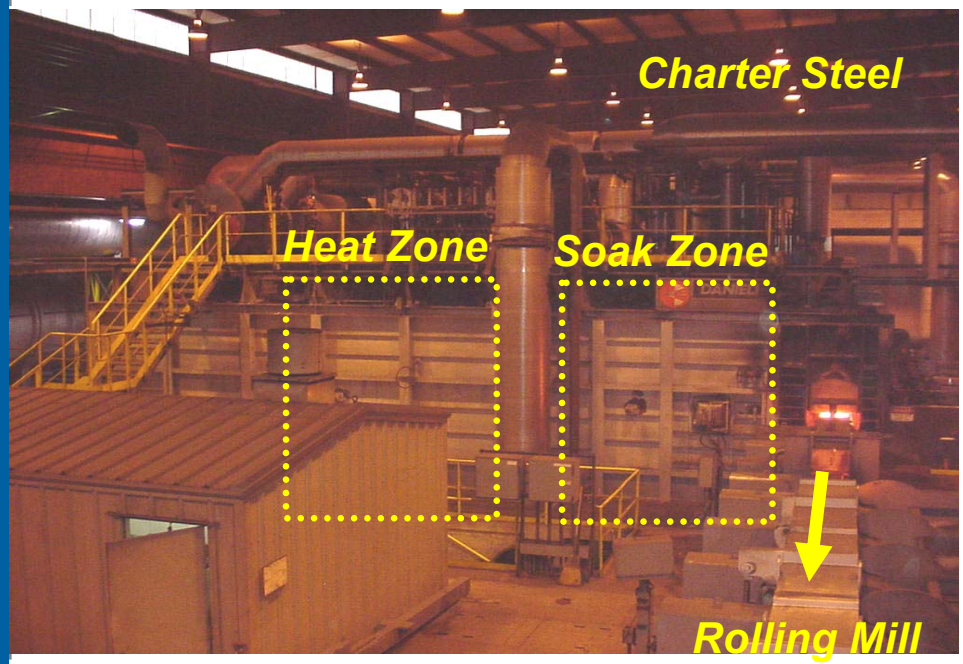
- •Modular Design
- •Multiple Laser System
- •Fiber Optic Beam Transport

Process interface modules

- •Multiple Wavelengths Launched and Received
- •Alignment Hub Process Interface
- •Background Radiation Rejection
- •Gas Purged

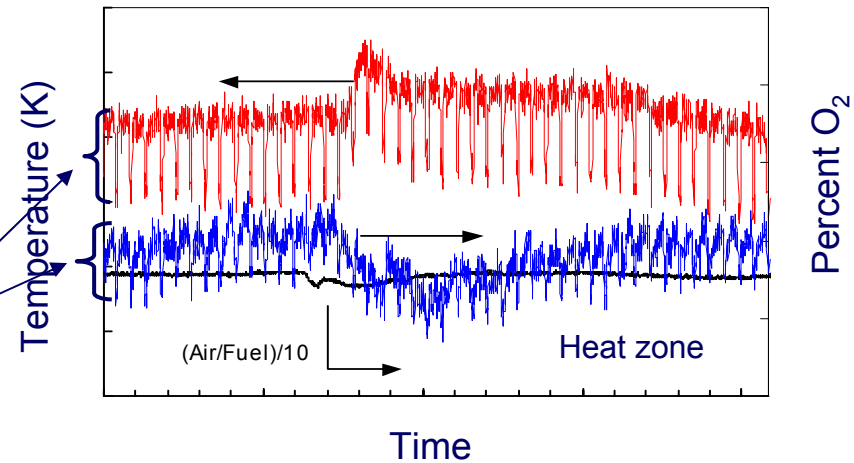
Steel Reheat Furnace (1st Industrial Trail)

- **Furnace Characteristics**
  - 30 MW
  - 100 ton/hr
  - 56 burners



- **Industry Needs**
  - Fuel Efficiency
  - NOx Reduction
  - Productivity Limits
  - Product Quality
    - Scale Formation
    - Decarburization
- **Measurement**
  - Near billet surface

Simultaneous T & O_2 Monitoring



Variations in temperature and concentration relative to measurement position

Secondary Aluminum Melting (2nd Industrial Trial)

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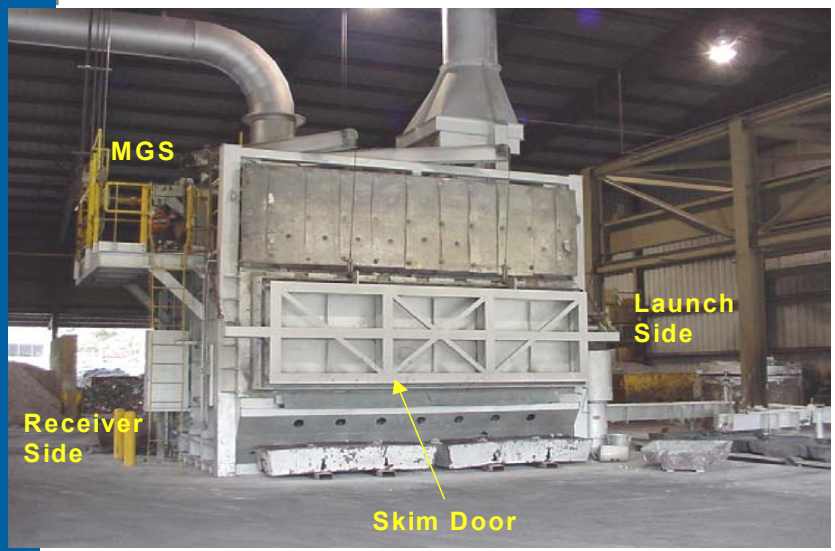
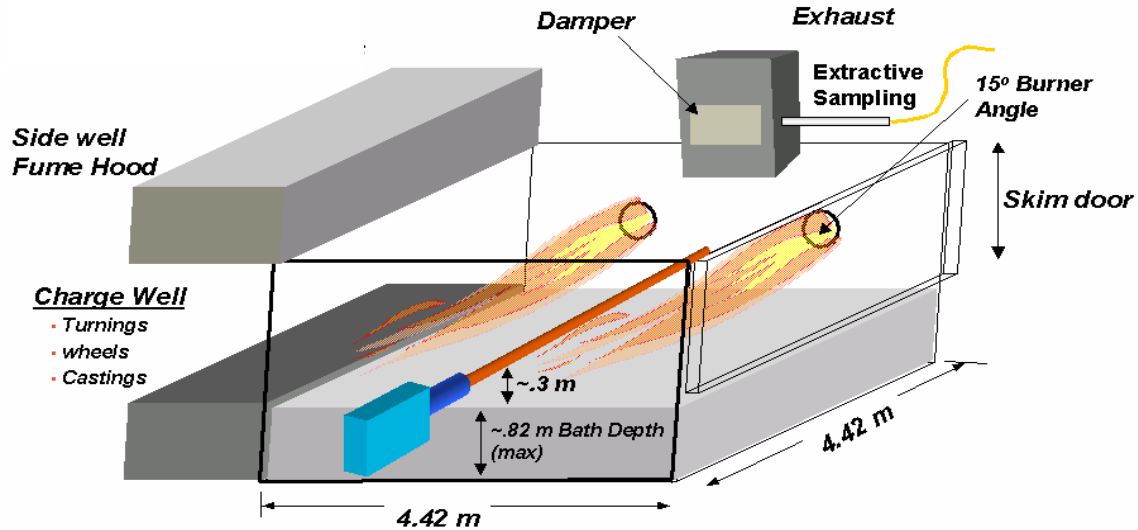
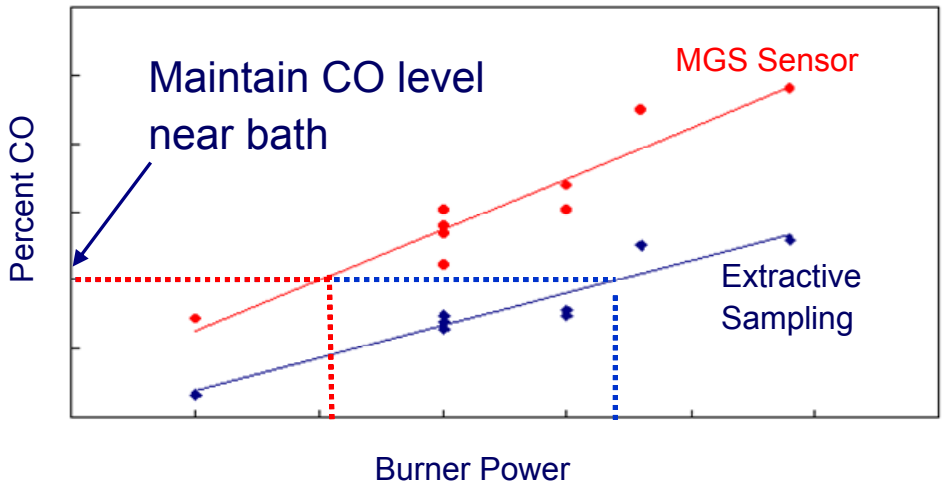
IMCO RECYCLING REVERBERATORY FURNACE TRIALS





Note: Typical Bath Depth .56-.71 m



- Key Results
  - Installation on hot furnace (optical access & sensor)
  - 8-days continuous operation
  - No maintenance
  - Process dynamics captured
  - Fuel Savings > 5%

EAF off-gas Monitoring (3rd Industrial test)

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Motivation for EAF Monitoring

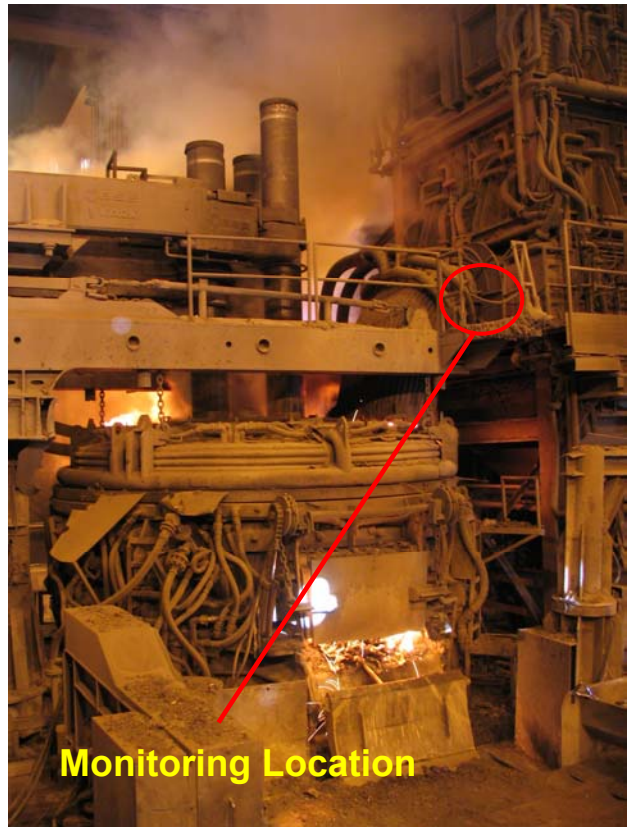
- **In-situ Measurement Advantages**
  - ✓Low maintenance
  - ✓Fast-time response
- **Coupling with Post-combustion Control**

	Theoretical real time oxygen injection	Control by set-points	Extractive Sampling	Real-time MGS
Savings	9.5-12.7 kWh/t	50-80 %	60-70 %	100 %

Potential US EAF Energy Savings → 640,000,000 KWh ($19MM)

Gerdau Ameristeel (Wilton Iowa)

- 80 ton furnace
- Power consumption of 450 kWh/t
- O2 consumption 1200 scf/t

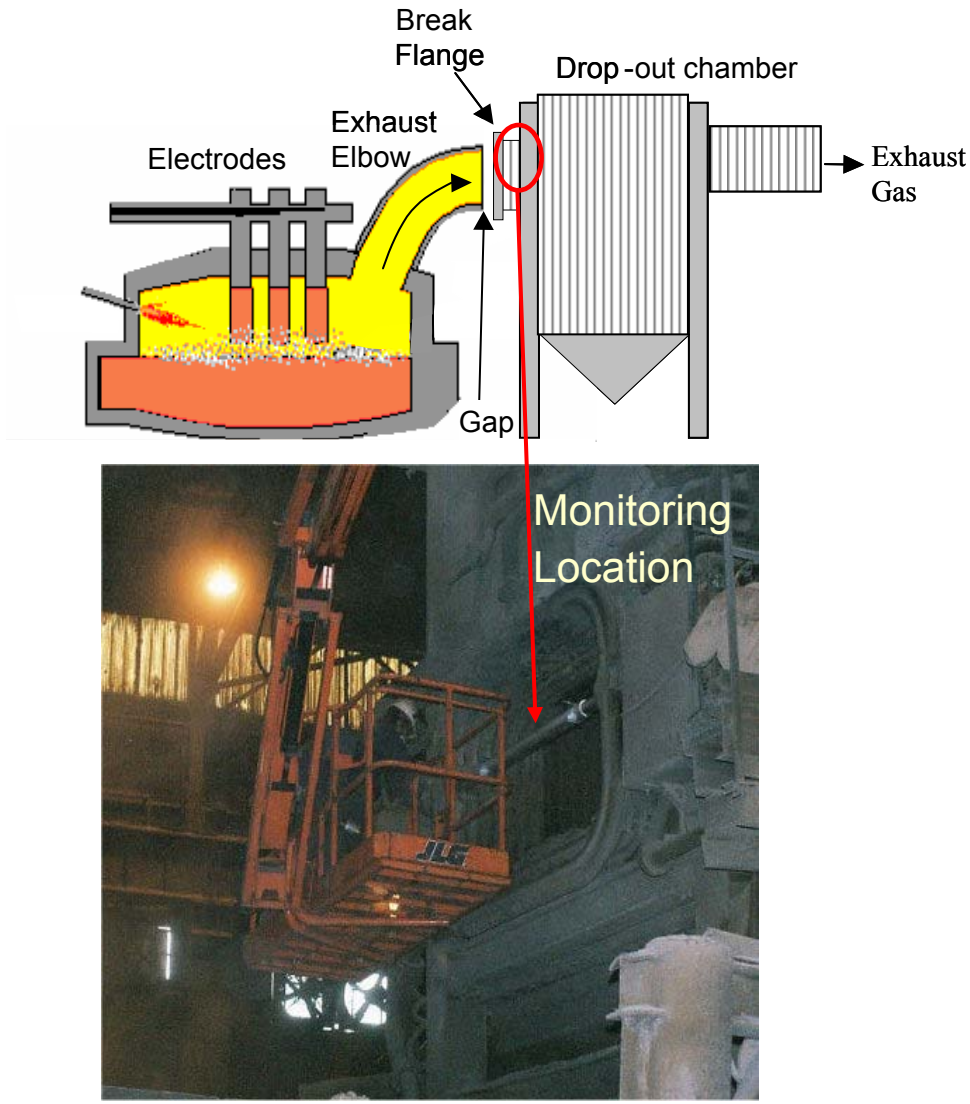


Typical EAF Conditions

- ✓Batch Process (60-90 minutes)
- ✓CO Profile (0-50%)
- ✓Temperature (1000-1600 °C)
- ✓Particle Density –> 150 g/Nm^3

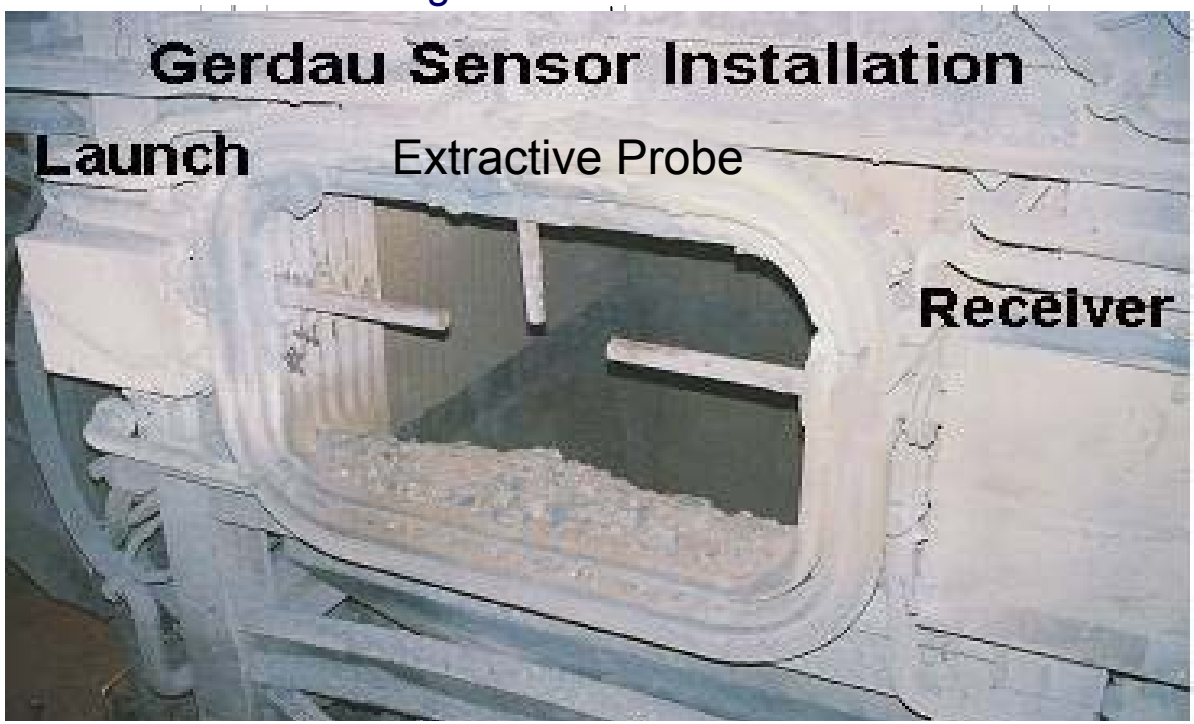
Process & Sensor Modifications

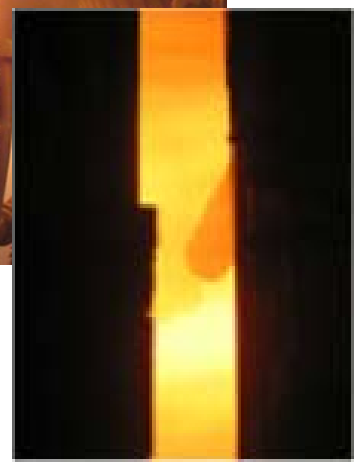
- **Installation Requirements**
  - ✓Line-of-sight access
    - →Design & install new exhaust duct
  - ✓Rigid module mounting
  - ✓Cooling water supply
  - ✓Purge gas supply
  - ✓Fiber optic cable installation
- **MGS System Modifications**
  - ✓Overall system hardening
  - ✓Remote alignment capability
  - ✓Fiber optic communication
    - →Long distance
    - →Bi-directional
  - ✓Electro-optic component packaging
  - ✓On-Demand laser power control
    - →Improved transmission in high particle process streams
- **Installation complications**
  - ✓Limited access time
  - ✓Access by manlift required



Module Design and Process Interface

Pathlength Controlled Measurement Zone





- **Module support on main I-beam structure**
- **Design incorporates alignment adjustment**
- **Water-cooled Faraday cage module for electro-optic components**
  - Water-cooling shields against intense radiation load
  - Heat-sink for multiple electronic modules and power supplies
  - Dual box design will guard against EMI and EMF
  - Protection against flying debris

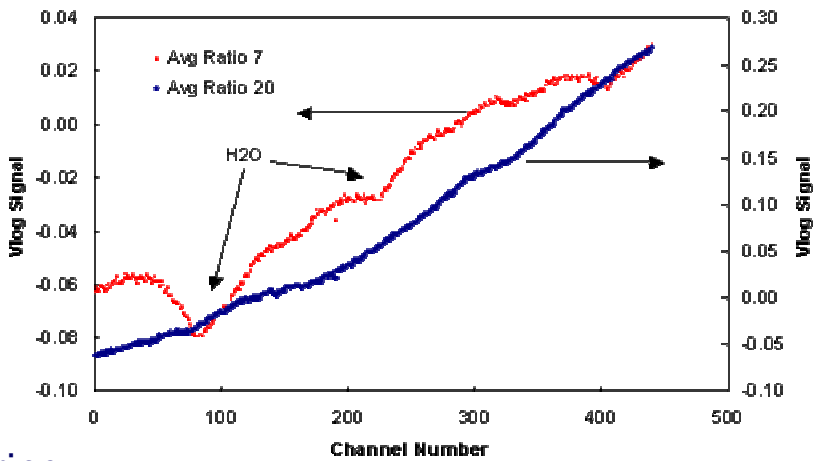
EAF

EAF Test Results

- Phase I
  - Basic configuration (Laser system)
  - Hardened modules
  - Fiber optic communication
  - Remote alignment

→ Sensor platform used in Steel reheat and aluminum reverberatory furnace tests

- Conclusions from Phase I tests
  - O_2 Monitoring
    - → Launch laser power is too low
    - → Suffered from additional losses with fusion spliced 5 μm dia. fiber
  - CO/H_2O Monitoring
    - → Measurements obtained only during low particle loading
    - → Laser power too low for continuous monitoring



- Phase II
  - On-demand power control
  - Focus on CO/H_2O monitoring
  - Enhancements based on Phase I results

On-demand Laser Power Control

- **Add-on modules**

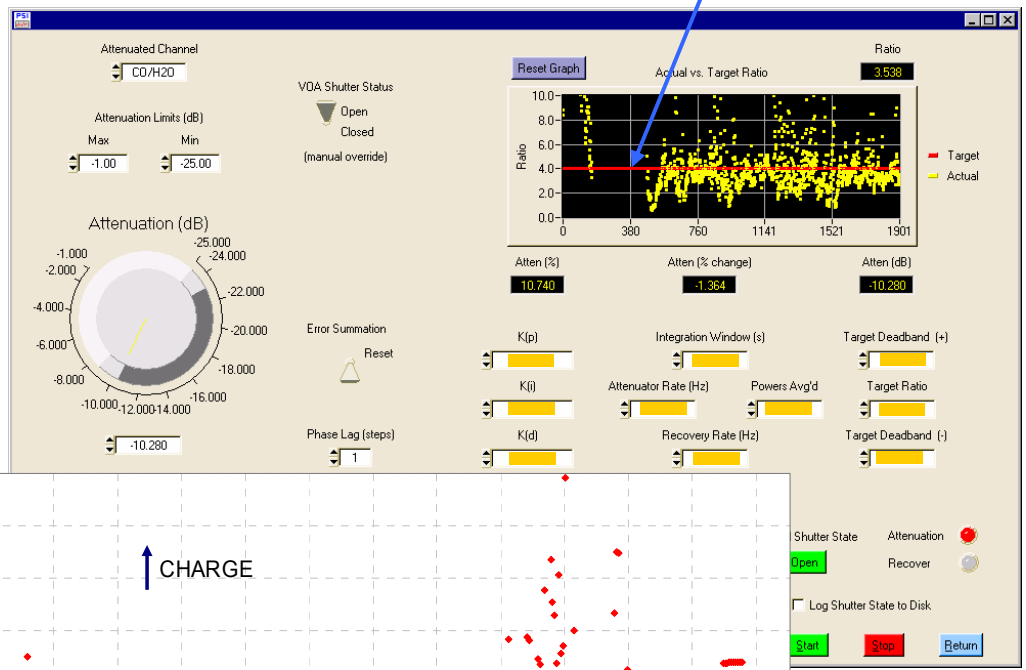
On-Demand Power Control

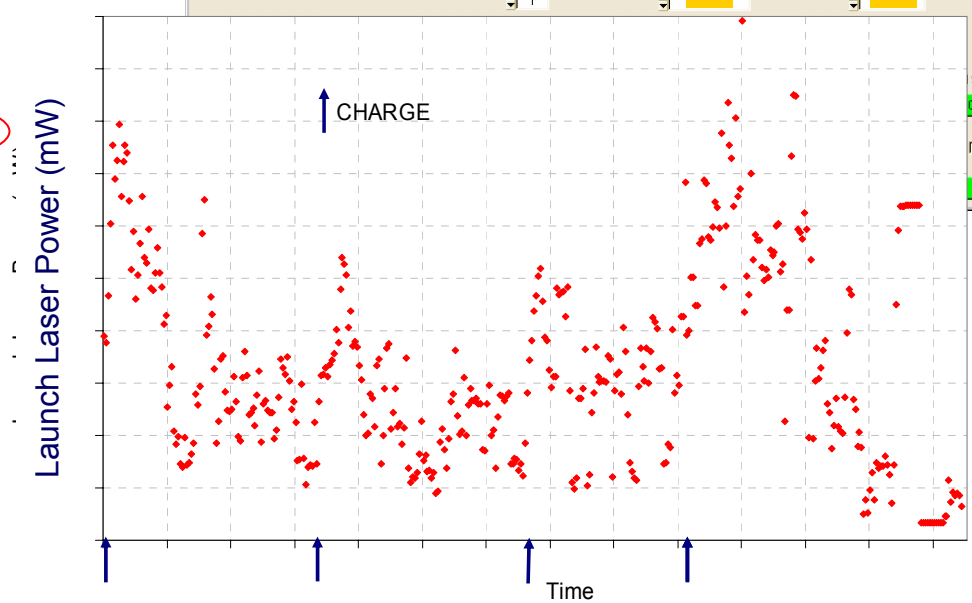
Fiber Link & Remote Alignment

Never Used

- **PID laser power control**
  - **Set-point → ref/sig ratio**

Set-point





Measured Absorption Spectra from EAF

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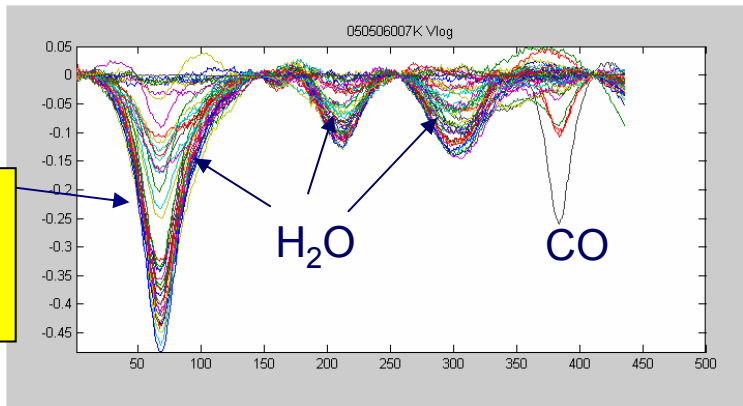
Measurement Results

- **Time response**
  - **Long-term (24/7) tests have been (and on-going) conducted at 5,10, and 20 second acquisition rates**
  - **Averaging is required due to baseline variation**
    - Background radiation
    - Particle-light interaction from non-homogenous particle distribution (temporal response of detection system)
    - Mechanical vibration
- **Absorption features of H_2O and CO clearly observed**

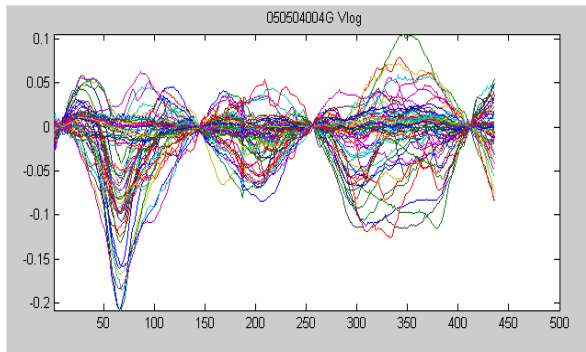
Peak Height variation results from Concentration and temperature changes



Spectra Quality

Dependent on EAF operating conditions

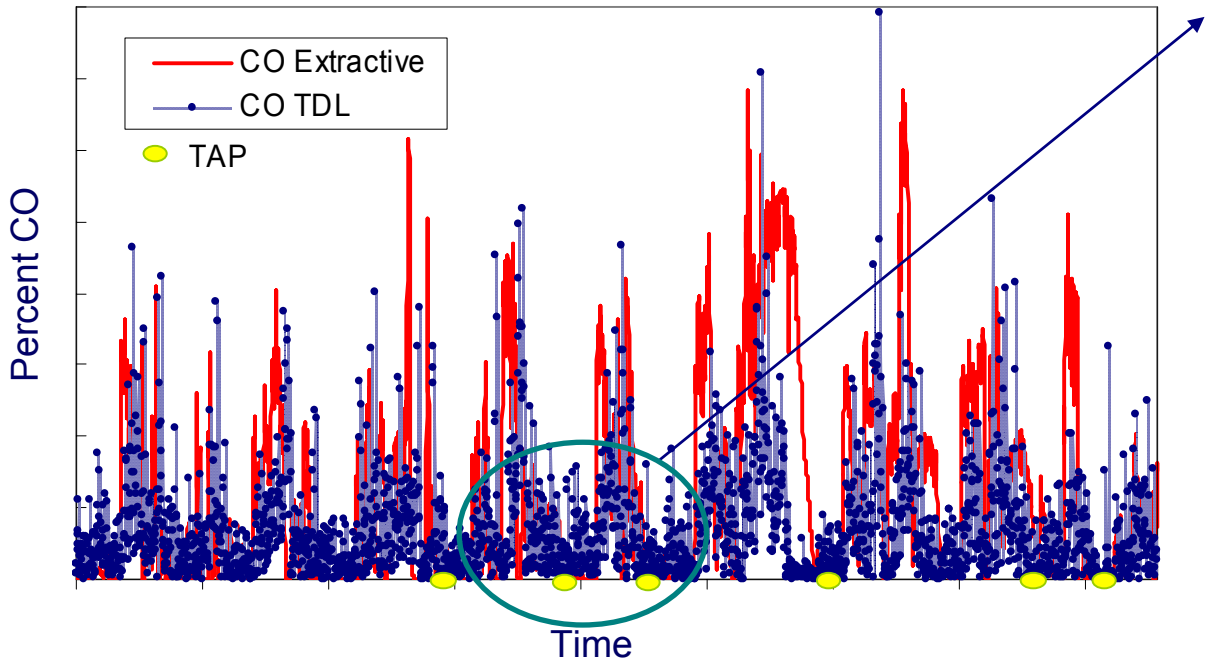
- **EAF Off**
- **Particle loading**

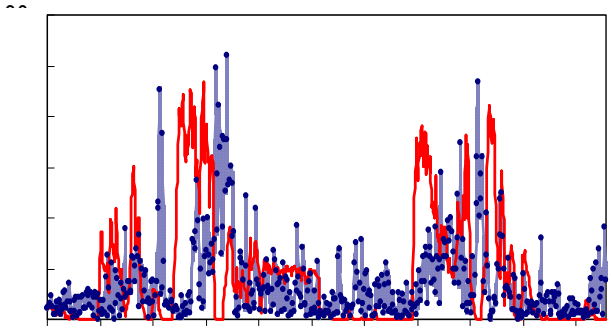


- **60 spectra collected over 1 hour (randomly selected 1/min)**
- **10 sec averaging**

EAF CO Monitoring Results

- **Measurement Comparison with Extractive Sampling**
  - ✓Point vs. path averaged measurement
  - ✓Measurements not at same location

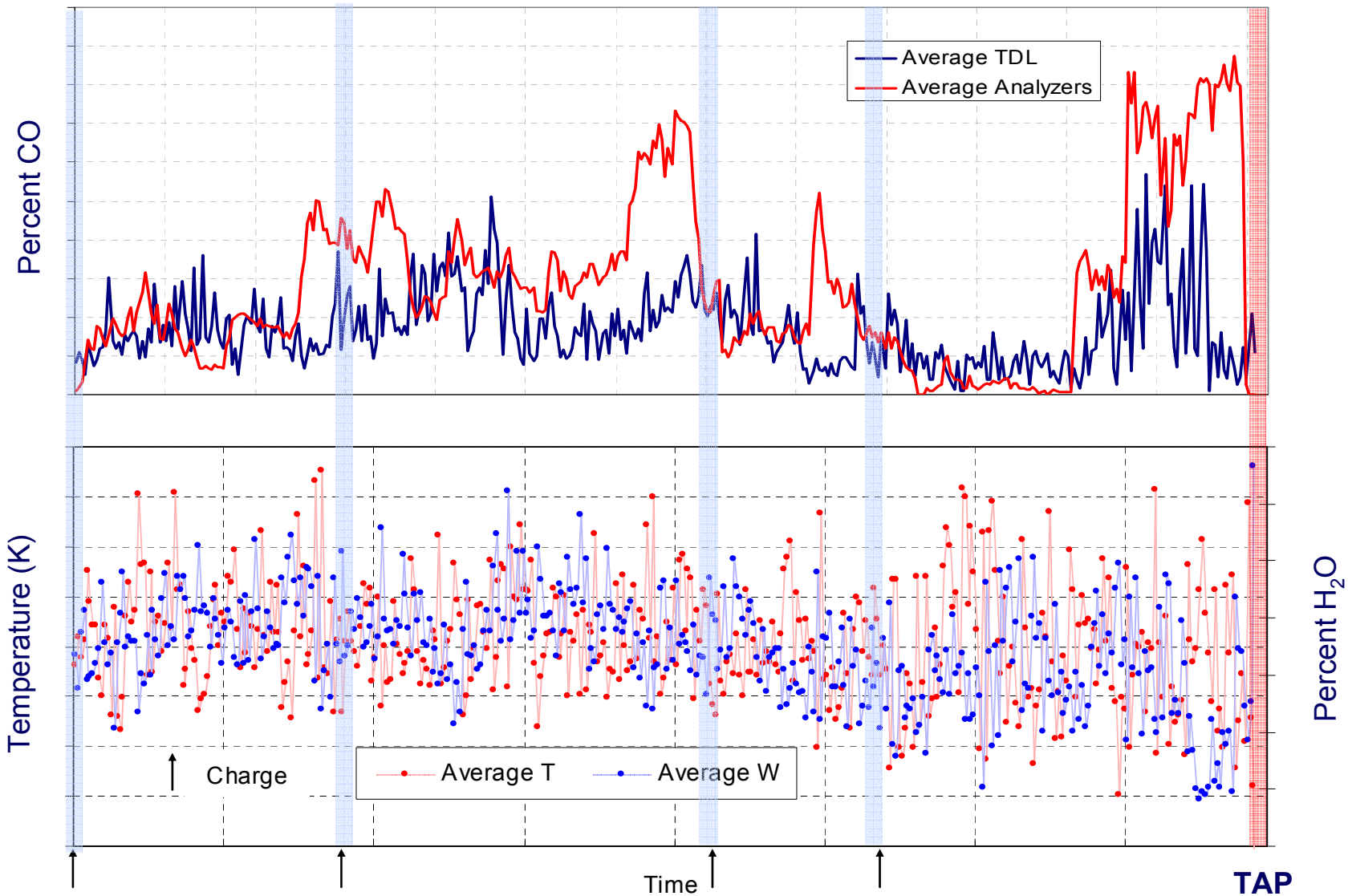




- **10 sec data acquisition rate**
- **TDL data filtered to remove erroneous measurements**

EAF Monitoring Results

- Average values for 7 heats



Observed Maintenance

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Maintenance and repairs performed

- **System alignment and transmission maintained (no intervention) over 5-week period**
  - *Continuous N_2 purge*
  - *High pressure N_2 purge is used every 30 minutes*
- **Windows have not required cleaning since initial installation (>6 months)**
- **Preventive maintenance performed on plant shutdown days (1/wk) "if AL personnel are present"**
  - *6 inch section of probe cleaned with brush*
  - *No special equipment or access needed*
  - *Total task time <5 minutes (both probes)*
- **Pin-hole water leak in receiver probe (December 2004)**
  - *Area welded with probe in place*
  - *Leak fixed*
- **Additional cooling added to receiver module**
  - *Vortex cooling purge added with purge directed on sensitive electronic components*

Probes Installed July 2004

Program Summary

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- Industrial Sensor Development
  - High temperature spectral region identified
  - Single-point access multiple wavelength launch and receive design (.76 μm & 1.5 μm)
  - On-Demand Power Control system
  - Process interface designs developed for different monitoring applications
- Industrial Process Monitoring
  - Steel reheat furnace monitoring (2001-2002)
    - Detected dynamic process conditions for T & O_2
    - Measurements near billet surface
    - Hot installation for sensor
  - Reverberatory aluminum melter (2002-2003)
    - *In-situ* monitoring near bath
    - Performed low-level process adjustments → >5% fuel savings
    - Hot installation for optical access and sensor
  - EAF testing currently on-going and will continue
    - Less maintenance than anticipated
    - >100 heats of data
    - CO trends detected
- Intellectual Property/Publications
  - 6 patent applications filed
  - 7 conference papers presented

Market Potential

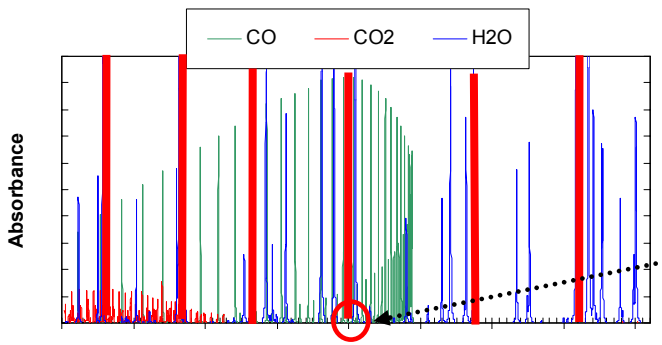
- **Commercialization plan**
  - Develop Commercial Offer
    - Sensor technology/process control
    - Selected markets
    - System tailored to process needs

Variety of System Configurations

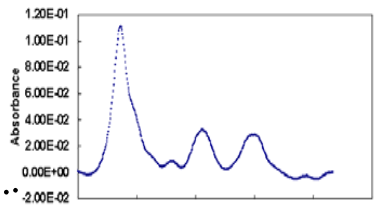
- Species selection, e.g., O_2, CO, H_2O
- Hardening and process interface options
- Fiber optic communication → long distance
- On-demand power control
- Remote alignment control

- **Continued Development Post-ITP**
  - Continue test campaign at Gerdau
  - Synergy with manufacturing partner
  - Technology evaluation and integration
    - Multiplexed systems
    - Emerging laser technology
  - Explore new applications

Multi-section Laser



40 nm tuning range



2nd System Manufactured in 2003

- Used in 2004 on other industrial tests

Commercial/Technical Risks Remaining

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- Continue Evaluation at Gerdau
  - Comparison with extractive measurement
  - Measurement reliability
  - Correlate with process variables
    - Process control (?)
  - Long-term maintenance
- Improve Measurement Quality
  - Higher power amplifier
  - Increase the scanning rate
    - *Improve signal averaging & reduce acquisition rate*
  - Spectra quality filter → Average only spectra that satisfy a defined quality indicator
- Economic Evaluation
  - Next-generation system configuration

Acknowledgements

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- CHARTER STEEL, SAUKVILLE WI: Chuck O'Connell and Rick Gaskill
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- Physical Sciences, INC., Andover MA: Shawn Wehe, Phil Mulhall, and Mark Allen
- American Air Liquide: Ken Mulderink