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Tunable Diode Laser Sensors for Monitoring and Control of Harsh Combustion Environments

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1. Executive Summary

This work represents the collaborative effort between American Air Liquide and Physical Sciences Inc., to develop a sensor based on near-IR tunable diode lasers (TDL) for *in-situ* industrial furnace monitoring. The sensor simultaneously monitors CO, O₂, and H₂O concentration as well as measuring gas temperature. The chemical species targeted are fundamental for combustion space control to improve energy efficiency, reduce pollutants, and improve product quality. The nonintrusive nature of the technique is well suited for harsh high temperature environments with corrosive gases and high levels of particulate matter. Therefore, many of the problems suffered by traditional gas extractive sampling technology such as probe plugging and corrosion are avoided with the TDL sensor. Furthermore, the *in-situ* measurement provides real-time information on the combustion space unlike conventional extractive sampling that suffers from delays associated with sampling line lengths and analyzer electronics.

The sensor is based on advanced telecommunication fiber optic components and rapidly tunable diode lasers. The tuning range for these lasers is typically too short to provide multiple species detection. However, this problem was solved by identifying a spectral region where simultaneous detection of CO and H₂O is possible at high temperatures. Therefore, the sensor only uses two lasers for O₂ (.76 μ m) and CO/H₂O (1.5 μ m) monitoring. For gas temperature monitoring an empirical calibration was developed based on the ratio of two H₂O lines.

Simultaneously monitoring O₂ and CO/H₂O is a challenging problem because the difference in laser wavelengths used requires dedicated detectors for each species. This problem was addressed using an innovative optical design that separates the wavelengths in the receiver module allowing simultaneous detection of both O₂ and CO/H₂O. This approach reduces installation complexity since only one set of modules and optic ports is needed and allows nearly identical monitoring along the optic path the beam transverses. The combination using the standard launch and receiver modules with the TDL sensor control unit and acquisition system represents the basic sensor platform. This configuration is well suited for semi-harsh industrial process monitoring applications such as, steel reheat furnaces, secondary aluminum furnaces, annealing furnaces, and glass melting furnaces, as just a few examples.

To expand the flexibility of the sensor technology several add-on modules were developed. For example, an On-Demand Power Control system for the 1.5 μ m laser was developed for boosting the laser power to maintain the desired transmission level through the process. This is useful for processes with high and varying particle density such as electric arc furnaces (EAF) for steel melting or coal-fired boilers. In addition, a fiber optic communication system was integrated into the system to transfer measurement data overlong distances immune to interferences. Both of these options are passive to the sensor and can be considered plug-and-play devices. Other options include hardened modules to withstand high ambient temperatures, electrical noise shielding, protection against flying debris, and remote alignment capability. The modules can be coupled to

pathlength control laser beam probes that were also developed and tested. The probes help in setting a fixed pathlength and measurement location useful in high temperature particle laden exhaust stream as found on the EAF process.

Demonstration of these different system configurations were conducted on Charter Steel's reheat furnace, Imco Recycling, Inc. (now Aleris International, Inc.) aluminum reverberatory furnace, and Gerdau Ameristeel's EAF steel melting furnace. The basic module and sensor configuration was used at Charter steel and Imco Recycling, since the severity of these process conditions is not bad. For both of these tests the measurement was conducted as close as possible to the manufactured product. For Charter steel's reheat furnace the measurements were made at different zones in the process and near the steel billet surface. These results captured the dynamics of the process for O₂ and temperature monitoring as well as detecting gradients in temperature and O₂ at different heights above the billet surface. For Imco Recycling the measurements were made ~ 20 inches above the aluminum bath. Measurements of CO, O₂, H₂O and temperature captured the process dynamics when compared with extractive sample measurements from the stack. However, the laser measurement near the bath indicated higher CO levels suggesting a difference between the measurements based on location. From these findings, the laser measurement was used for low level process adjustment to optimize the furnace. A conservative approach was taken for the process optimization resulting in 5% fuel savings, but the measurements indicated a higher reduction could be achieved given >10% fuel savings.

The success of the technology demonstration at Charter and Imco set the groundwork for transitioning to harsh monitoring conditions as found on the Gerdau Amersiteel EAF. Because of the harsher conditions of the EAF environment, this can be considered as one of the most demanding tests for a sensor to endure. Hardened modules with pathlength control laser beam shielding probes were installed to provide a well defined 60 cm measurement path. The On-demand power control (ODPC) unit provided the added boost in laser power needed to transmit across the high particle density exhaust gas stream. Without the ODPC measurement success was limited to only sparse times when particle levels were low. For this reason O₂ monitoring was aborted, since the O₂ laser has limited output power and is not compatible with the ODPC. Following several troubleshooting steps of the sensor when first installed, measurements have been conducted over a 6-month period with minimal maintenance. The only maintenance performed has been periodic cleaning of the pathlength control shielding probes that are exposed to the exhaust gas. Alignment has been stable with no need for remote adjustment.

Comparative measurements between the TDL sensor and conventional extractive sampling showed good agreement for CO monitoring when the extractive measurements are corrected for wet-values and delay time. The trends in CO concentration are clearly captured by the TDL sensor, but shows scatter in the measurements because of baseline variations from the non-homogenous particle loading. To address this issue several iterative steps have been made that reduced the baseline noise. This led to an overall improvement in the measurement quality that is usable for process control. The TDL

sensor is still in operation at Gerdau and the next-step under investigation is coupling the measurement to their process control system. The objective is to use the TDL sensor measurement for O₂ injection control to recover the potential chemical energy from CO (and H₂) that would otherwise be exhausted.

1.1 Program Planning

The tasks and planning over the course of this project changed significantly. The original program planning for the major tasks and timing is shown in Figure 1. Under this plan the major tasks involved upgrading a tunable diode laser (TDL) sensor using a multi-section laser technology to expand the tuning range capability, validation of the technology, and industrial testing with our three original partners, Charter Steel, Johns Manville, and Du Pont.

The actual program shown in Figure 2 with tasks completed underwent two major adjustments from the original plan. First, the unavailability of the multi-section laser changed the program direction to development of a TDL sensor based on standard off-the-shelf diode lasers. However, in the course of the transition significant time was lost. A detail on the background history of this event is discussed in the following section. The second major adjustment was a shift to industrial testing on an electric arc furnace (EAF) used for secondary steel melting. It was clearly recognized that adapting the technology original proposed for the EAF would require significant modifications because of the severe environment. In addition, to increase the likelihood for conducting a successful measurement campaign on the EAF, integration of several new technologies into the basic TDL sensor platform were identified as being necessary. These program changes and the complexity of the sensor installation greatly extended the overall program timing.

Finally, near the end of 2003 a multi-section laser was acquired from Agility Communication, Inc. and some characterization work, e.g., stability and tunability, was performed. The original objective was to integrate this laser into the TDL sensor platform, but this was abandoned because of the complexity in the EAF system upgrades and installation. However, the multi-section laser has been periodically used for different lab component tests and spectral survey work.

Figure 1. Original program planning.

Figure 2. Actual program tasks and timing achieved.

2. Introduction

This project focused on development and demonstration of a near-IR tunable diode laser (TDL) sensor for simultaneous monitoring of combustion species and gas temperature in industrial furnaces. The targeted combustion species selected for monitoring are CO, O₂ and H₂O. The chemical species selection is based on their potential for furnace control and optimization when operating with air, oxygen enriched air, or oxy-fuel. Measuring both CO and O₂ allows control of either a reducing or oxidizing furnace atmosphere. For temperature monitoring H₂O is used, since it's present at high concentrations in the furnace atmosphere independent of the process operating under fuel-rich or fuel-lean conditions.

For industrial monitoring applications, near-IR laser sources used in the telecommunication and data processing industries offer many advantages. The devices are available over a wavelength range of 600-2000 nm providing access to several key combustion species, e.g., O₂, CO, CO₂, H₂O, CH₄, and NO [1]. In contrast to other laser sources, near-IR diode lasers are compact, rugged, fiber optic compatible, operate near room temperatures and are relatively inexpensive. Of these features, fiber optic compatibility is particularly beneficial in allowing the location of the sensitive laser and associated electronics placed far from the process where the surrounding environment is often harsh for sensitive instrumentation.

The measurement principle of the sensor is based on a scan-and-integrate approach to determine the concentration and temperature. This is performed by measuring the transmission of a laser beam that is propagated through a medium containing the targeted gas species. As the laser is tuned over an absorption transition the laser intensity is attenuated. The measured attenuation of the laser radiation results from absorption along the measurement path described by the Beer-Lambert relation:

$$I_{\nu} = I_{\nu,o} e^{[-S(T)g(\nu-\nu_o)N\ell]} \quad (1)$$

where I_{ν} is the laser intensity at frequency ν measured after the beam has propagated across a path ℓ with N absorbing molecules per volume. The incident laser intensity, $I_{\nu,o}$, is referred to as the reference. The strength of attenuation is determined by the temperature dependent linestrength $S(T)$ and the lineshape function $g(\nu-\nu_o)$ whose product is the absorption coefficient. The linestrength is related to the internal energy distribution of the molecule and is governed by Boltzmann statistics whereas the lineshape is related to temperature and pressure broadening mechanisms. Inversion of Eq. (1) and integrating over a frequency range covering an absorption transition relates the number density N to the measured laser intensities for a known linestrength and pathlength given by

$$N = \frac{1}{S(T)\ell} \int \ln\left(\frac{I_w}{I_v}\right) d\nu \quad (2)$$

By tuning the laser across the absorption transition acquiring the full absorption lineshape allows direct application of Eq. (2) to obtain the absolute number density without instrument calibration. In addition to being immune to temperature and pressure broadening effects on the lineshape, sensitivity to broadband absorbers or scatters are reduced since the absorption being monitored is relative to the baseline. However, the temperature dependence on the linestrength does require knowledge of the gas temperature for accurate concentration monitoring.

3. Laser Selection Historical Background

The scope of the original program was to develop a near-IR sensor using a multi-section laser operating in the 1.5 μm region for CO and H₂O detection. Conventional single-frequency diode laser technology is based on a Distributed Feed Back (DFB) design where a Bragg reflectance grating is fabricated in the laser to force the device to oscillate in a narrow frequency range. These devices have typically laser bandwidths of about $3 \times 10^{-5} \text{ cm}^{-1}$ (1 MHz). The output wavelength can be tuned over about 5 nm by adjusting the temperature of the laser. However, this tuning is slow and typically requiring a few seconds to stabilize the device temperature at a new wavelength. Therefore, rapid tuning over a smaller range ($1\text{-}3 \text{ cm}^{-1}$, or about 0.5 nm) by modulating the injection current in the device is the general operating mode for gas sensing applications.

The disadvantage with current injection tuning on a DFB laser is the narrow wavelength range the laser can cover. This limitation often requires the need for a dedicate laser for each species or absorption transitions, thereby increasing the overall system complexity and cost. A significant simplification of the laser system and fiber-optic network can be achieved by replacing the multiple DFB lasers with a single multi-section laser. These lasers allow high-speed wavelength tuning over 40 - 100 nm range with only current control. The broadly tunable laser is fabricated with four discrete cavity sections, each with an electrically isolated contact point. Bragg gratings are fabricated in 3 of these sections and the injection current into these sections can be varied to select a feedback wavelength within the total gain envelope of the laser. Physical Sciences, Inc. (PSI) (20 New England Business Center, Andover, MA 01810) our key development partner for the sensor technology had previously demonstrated the operation for these lasers in a bench-top configuration for multiple species monitoring [2]. Therefore, the original program was developed to capitalize on PSI's previous experience in working with multi-section lasers.

At the start of this program Alitun, a small Swedish startup, was identified as our preferred multi-section laser supplier. To maintain the program schedule outlined in the proposal an order for a multi-section laser was placed in June of 2000, due to their

projected delivery date of November 2000. Shortly after our initial contacts with Alitun the company was purchased by ADC Communications. In December 2000, ADC/Alitun informed us that delivery would be delayed until March 2001 because of manufacturing problems on their side. A follow-up in January 2001 with ADC/Alitun we learned that our order was canceled. Furthermore, ADC/Alitun informed us that they will focus entirely on the telecommunication industry and consideration for customers outside their core business would not be addressed until 2002.

With the unforeseen position taken by ADC/Alitun, a search for an alternative supplier was launched. Two manufacturers Agere (a Lucent spin-off company) and Agility Communications, Inc. (start-up company out of the University of California at Santa Barbara) were identified as potential suppliers. Agere was testing a beta 2-section DBR (distributed Bragg reflector) laser at that time, but declined to offer any devices to non-telecommunication markets. Discussion with Agility Communications led to a similar outcome. At that time Agility was only interested in supplying a laser if a large capital investment (~\$1M) could be made. In summary, the number of manufacturers supplying multi-section lasers was limited and all were committed to only the telecommunication market. The consensus from the laser suppliers was universal, in that once the product matured in the telecommunication market and manufacturing was meeting the demand, opportunities for supplying other markets would be possible. The time horizon for this to occur was projected into 2002, a full two years after this project started.

The multi-section laser supply issues encountered resulted in refocusing the technical program to still meet the final objective of developing a multi-gas sensor targeting O₂, CO, and H₂O. However, considerable resources in preparation for sensor development around the ADC/Alitun multi-section laser were lost. Development for laser control strategies and initial spectral surveying for high temperature H₂O lines was already underway before learning of the supply problems. As a result, a delay of almost 1-year in developing the prototype sensor was encountered.

The alternative approach taken was to conduct a detailed high temperature spectroscopy study of H₂O vapor near 1.5 μm . This spectral region was selected to provide optimum temperature sensitivity of H₂O vapor and simultaneous access to strong CO absorption lines. Also, this spectral region was constrained by the requirement to fall within the tuning range of the ADC/Alitun multi-section laser. Despite the difficulty experienced in obtaining a multi-section laser, validation of the high temperature H₂O vapor in that spectral region was still of interest. The fundamental spectroscopy learned from the survey work is directly transferable once the multi-section lasers became available.

4. Laser Wavelength Selection Methodology

To identify a spectral region for high temperature CO and H₂O monitoring using a minimum set of standard DFB lasers a detailed theoretical and experimental spectral survey was performed. This procedure was necessary to identify the optimum set of CO and H₂O lines for the given set of constraints, viz., absorbance strength, temperature sensitivity, baseline quality, interference free, and minimum tuning bandwidth. In conducting this spectral survey, the ITU-GRID (International Telecommunication Union) c-band (conventional band) was used as a template for laser selection, thus insuring long-term supply of high quality devices. Furthermore, identification of the high temperature lines is directly transferable for use with other lasers, e.g., a multi-section laser or multiplexing with several DFB lasers. This avoids repeating the line selection process if future system modifications are required to meet a specific monitoring applications were different temperature or concentration sensitivity is needed.

Results from the survey identified the wavelength position of the H₂O and CO transitions selected and calibrated the H₂O line pair ratios over the temperature range of 1000-2100 K. An important conclusion from the survey showed that a single DFB laser can be used to access the multiple set of absorption lines with reasonable temperature sensitivity for combustion process monitoring. It was originally thought that multiple DFB lasers would be needed to meet the temperature range requirements. The important consequences of these findings are simpler system design using higher power lasers with an overall system cost reduction.

4.1 High Temperature Spectra Survey Experimental Set-up

The initial spectral survey work was conducted under well-controlled flame conditions using a small-scale laboratory Hencken-type flat flame burner, as illustrated in Figure 3. This flat-flame burner uses a dense array of diffusion flamelets which merge within 1 mm of the honeycomb surface to form a well-characterized gas flow that achieves near-equilibrium conditions over a range of fuel-oxidizer stoichiometries and temperatures. Flows of the various gases were delivered to the burner using commercial mass flow meters and precision needle valves. A multipass absorption path Herriot cell configuration was created over the flame by placing two f/2 spherical mirrors on either side of the burner as shown in Figure 4. Narrow slots in the mirrors permit a probe laser beam to enter the flame region, reflect off of the mirrors multiple times (29 passes), and exit the flame region onto a detector.

E-8532

Figure 3. A schematic of the experimental setup used to examine water vapor absorption in a flame at 1.56 μm.

Figure 4 shows three gas-flow regions that intersect at the burner surface. The innermost region is the honeycomb surface of fuel and oxidizer containing the flame and the high-temperature exhaust gases. Surrounding the flame are two regions of flowing dry-nitrogen gas, which serve to inhibit entrainment of atmospheric (water-containing) air. The flow immediately surrounding the flame, called the co-flow, is nearly matched in velocity to the burning gases. The outer region is a slower velocity flow of nitrogen and serves to transition the velocity gradient to the burner walls smoothly, and to prevent water vapor absorption from ambient humidity.

Figure 4. Optical multipass experimental geometry for flat flame burner experiments.

The laser source used for the survey was a broadly tunable ($1.4 \mu\text{m} < \lambda < 1.6 \mu\text{m}$) external cavity diode laser (ECDL). Light from the laser is fiber coupled into single mode communication fiber and connected to a 1×2 splitter. A portion of the energy is directed to the flat-flame burner. The beam directed to the burner passes through room air containing water vapor; however, the absorbance from room-temperature water vapor in the examined spectral region is over 2 orders of magnitude weaker than the expected transitions at high temperature. Empirically, no water-vapor absorption is observed with the flame off.

The other fiber-coupled portion is used for three different parts of an absorption measurement: center wavelength determination, spectral breadth measurement, and reference signal. The first part of the measurement is to determine the absolute center wavelength of the laser scan prior to beginning the scan. The laser cavity in an ECDL is made up of a highly reflected coating on one face of a diode laser while the other end is an adjustable mirror. In between the mirror and the laser is a diffraction grating. The grating provides the narrow spectral output and wavelength tuning is achieved by adjusting the mirror position with respect to the grating. Coarse wavelength tuning is brought about by a picomotor which mechanically adjusts the mirror position. Fine tuning is achieved by applying a controlled voltage to a piezoelectric tuner (PZT) fixed between the picomotor and the mirror. While the voltage applied to the PZT is zero, the laser's spectral output is measured by directing the light into a commercial wavemeter (Michelson interferometer) which measures the frequency to 0.01 cm^{-1} resolution. This provides the center frequency of the scan.

The second step of the measurement involves scanning the laser by applying a smoothly varying voltage to the PZT and measure the tuning range as a function of time. The tuning range was measured by coupling the fiber to a high-resolution confocal etalon. The time between two interference fringes represents a 2-GHz spectral shift in the laser.

A low-order polynomial fit between the fringe peaks permits one to transform the data from the time domain to light-frequency.

The third part of the experiment was to couple the fiber to the reference channel of the BRD (Balanced Ratiometric Detection) during a laser scan through the flat-flame burner to acquire an absorption measurement. The BRD sensing technique is based on a novel electronic noise canceling circuit. The basic circuit fragment is shown schematically in Figure 5. The technique was originally developed at IBM [3] and further refined at PSI [4]. As described above, the signal beam propagates through the absorbing gas sample (flame) while the reference beam does not. Cancellation of excess laser amplitude noise is achieved electronically with the BRD. Common mode laser noise in the two channels is reduced by more than 50 dB and output signal, $V_{\log}$, is directly proportional to the absorbance.

Figure 5. Schematic of the basic BRD circuit fragment

When establishing the laser scan rate, a compromise between scan rate and scan breadth must be made. While it is desirable to have a broad spectral range for the scan, the scan rate must be fast enough such that the temporal-frequency components of the absorption feature are appropriately offset from the AC time-constant of the BRD. However, the spectral breadth of a scan falls off rapidly with increasing scan frequency, due to mechanical damping and inertia in the ECDL. The AC time-constant of the BRD used in these experiments was measured to be approximately 16 Hz. Therefore, the scan rate was adjusted such that an individual absorption feature was scanned faster than 16 Hz. By driving the PZT over the maximum voltage range at 6.3 Hz, a spectral breadth of approximately 1 cm^{-1} was realized, and the temporal-frequency components of absorption features were approximately 50 Hz.

The measured absorbance with the BRD as a function of time is combined with the scan breadth measurement to compute the spectral absorbance. Finally results are combined with the measured center wavelength to form an absorbance measurement as a function of absolute spectral frequency.

An important aspect in using the BRD technology is the ability to scan-and-integrate true lineshapes from the absorbance spectrum recorded. This capability removes errors that can occur due to collisional and/or Doppler broadening of the absorbance line. The value of this capability is clearly seen in processes where conditions are dynamic with large changes in temperature and gas composition. To illustrate this point an example is presented in Figure 6 showing simulated H₂O absorbance spectra at 1000 K with different surrounding gas compositions. The resulting lines with the addition of H₂O as a collisional species shows the peak intensity decreasing and width increasing compared to the air only case, which appears narrower and stronger. Despite this overall change in appearance, the integrated area under the peak is the same for both cases. As illustrated by the shaded area under the selected lines.

Figure 6. Simulated spectra showing the effect of line broadening for 30% H₂O and 70% air at 1000 K.

4.2 Spectra Survey Results

Using the experimental set-up shown in Figure 3 absorbance spectra of H_2O were acquired at different flame temperatures by changing the stoichiometric conditions. Independent flame temperature measurements were conducted by radiation corrected thermocouples (Pt/Pt-13%) and compared to adiabatic temperature calculations with an equilibrium chemistry code. An example of the radiation correction to thermocouple measurements is shown in Figure 7.

Figure 7. Flat-flame burner temperature measurements and calculations.

The procedure for acquiring H_2O spectra at a measured temperature provides the necessary data for ranking the temperature sensitivity for the integrated absorbance ratios of multiple line pairs. The measurements were conducted in two steps. First, the H_2O lines were examined at known temperatures by in-flame thermocouple measurements over a range of temperatures as shown in Figure 8. Conducting a spectral survey for this range of conditions provides a selection process based on observed absorption strength, baseline quality, and proximity or isolation to CO spectral position. Verification of the CO spectral position and absorption strength is conducted in a second step by blending CO into the burner inlet gas.

A series of spectral scans were reconstructed to illustrate the 10 nm window of interest within the ITU-GRID are shown in Figure 9. Area ratio features were calculated resulting in 210 permutations as a function of temperature. For each pair of lines the sensitivity was determined for a low ($1100 \text{ K} < T < 1530 \text{ K}$) and high temperature ($1530 < T < 2060 \text{ K}$) range. The line pairs were then ranked according to their temperature sensitivity where the most sensitive line pair results in the smallest $\Delta T/\Delta R$ (R =ratio of the integrated absorbance).

Figure 8. Temperature profiles across the Hencken flat-flame burner using a .05 inch dia. type-R thermocouple. The line fit through the measured region was used to estimate the average temperature.

Once a potential set of H_2O lines were identified for thermometry CO was added to the flat-flame to verify any possible interference. In conducting, these test a discrepancy between the measured absolute frequency and the actual frequency using the HITRAN assignments as a frequency reference was discovered. This resulted in eliminating potential line pair candidates due to interference with H_2O . However, lines that were considered poor candidates based on CO interference from the assigned position by HITRAN [5] offered new opportunities for additional line pairs. In total, 25 lines were initially examined yielding 300 possible line pairs. From this set, upon closer examination the results were narrowed to 7 lines pairs that exhibited a sensitivity to better than $\pm 15 \text{ K}$ over 1100-1500 K and $\pm 35 \text{ K}$ over 1500-2100 K range, showed good SNR, and are located near an isolated CO line.

Figure 9. (Top) 3 survey scans at the specified overall equivalence ratio are shown. The colors along a survey alternate to aid scan identification. Additionally the CO linestrengths are superimposed on the survey scans to identify CO line positions. (Bottom) 2 calculated spectrum using HITRAN for water at 1100 K and 2100K. These calculations are included to demonstrate the necessity for line pair determination

4.3 Line Pair Selection for Temperature Calibration

The method used to phenomenologically calibrate the temperature dependence was to alter the flame temperature and quantify the resulting line area-ratio behavior. The motivation for measuring a linepair's area ratio as a function of temperature follows from Beer's law which describes the ratio of the transmitted laser intensity (I) to the incident intensity (I_o) through an absorbing species,

$$-\int \ln(I/I_o) dv = \sum SPL = PL \cdot \sum S, \quad (3)$$

where S is the absorbing species linestrength, P is the partial pressure and L is the light pathlength through the absorbing medium. The summation sign is to account for multiple absorption transitions which may be contributing to the overall absorption feature. Because the partial pressure and pathlength is common to all of the lines, the area ratio, R , is a ratio of the sum of the linestrengths. If an assumption is made that only a single line contributes to an absorption feature the ratio of two lines can be written as,

$$R(T) = \frac{S_{0,1}}{S_{0,2}} \exp \left[\frac{hc}{k} \frac{E_2'' - E_1''}{T - T_0} \right] \quad (4)$$

where $S_{0,i}$ is the linestrength at a reference temperature, T_0 of line i , E_i'' is its lower state energy. Thus the temperature can be solved for explicitly.

$$T = \frac{\frac{hc}{k}(E_2'' - E_1'')}{\ln \left(R(T) \cdot \frac{S_{0,2}}{S_{0,1}} \right)}. \quad (5)$$

The purpose of these measurements is to establish conclusively the absolute frequency scale of the measured absorption data. From the 7 identified lines 3 sets of line pairs (8-9, 21-24, and 23-24) were examined in detail to more precisely define their spectral position and to quantify their sensitivity to temperature from 1100 to 2100 K. Figure 10 shows calculated and measured spectral surveys from 6404 to 6411 cm^{-1} . The data plotted on top are results of HITEMP calculations for water vapor at 1500 and 2000 K. The data plotted below is a combination of H_2O and CO absorption measurements along with a set of markers for CO line positions which are tabulated in HITRAN.

Figure 10. Two spectral surveys from 6404 to 6411 cm^{-1} are shown. The upper curves are results from HITEMP calculations at 1500 and 2000 K. The Lower curves are measurements of H_2O and CO. Additionally, CO line-center positions are shown as downward pointing bars.

The CO measurements were performed in the flat-flame burner, but no flame was present. In this mode, the experimental set-up was used as a room-temperature flowing multi-pass cell. The H_2O measurements were in a hydrogen/air flame at an equivalence ratio of 0.5 ($T \approx 1600 \text{ K}$). The CO markers are used to calibrate the relative frequency scale (measured with a confocal etalon) of the CO absorption measurements. The markers were needed to correct for the hysteresis effect observed in the tuning mechanism of the ECDL. Using this approach the largest discrepancy[†] in assigning a spectral feature's line center was less than 0.02 cm^{-1} . The colors of the measured species in Figure 10 alternate to aid in differentiating one scan from the next. Additionally, the absorbance calculations at different temperatures are presented to demonstrate the differences between the HITEMP data base and measurements, and that the differences are consistent independent of temperature.

After confirming the spectral positions of H_2O in a flame using room-temperature CO as a reference, the position and lineshape of CO in a flame was measured. A fuel-rich hydrogen flame was seeded with CO to confirm the position and observe the linewidth at high temperature. The results of those measurements are shown in Figure 11. Room-temperature CO was measured along with water vapor in a flame at an equivalence ratio of 0.5 and 2.75. In another case using an equivalence ratio of 2.75, CO was added to observe the linewidth behavior at high-temperature. The width of the high-temperature CO line is less than that of the room-temperature feature. When considering Doppler

[†] This was obtained from overlapping scans which originated from adjacent CO absorption features.

broadening only, Δv_{Dop} , which is proportional to the square root of temperature, one would expect the line width to increase with temperature, however collisional broadening is important at one atmosphere. Collisional broadening, Δv_{Col} , is proportional to the inverse of temperature to a power, n

$$\Delta v_{\text{col}} \propto \left(\frac{1}{T}\right)^n. \quad (6)$$

Classically $n = 0.5$ and for CO in air it is equal to 0.7. Each of the broadening processes combine to form a Voigt width which is approximately equal to:

$$\Delta v_{\text{Voigt}} \approx \frac{\Delta v_{\text{col}}}{2} + \sqrt{\frac{\Delta v_{\text{col}}^2}{4} + \Delta v_{\text{Dop}}^2}. \quad (7)$$

Thus, at low to moderate flame temperatures, the Voigt width is dominated by the collisional width. Because for increasing temperature the collisional width decreases faster than the Doppler width increases, there is an overall reduction in line width.

Figure 11. Room- and elevated-temperature lineshapes H_2O and the $\text{CO } R_{(20)}$ line.

The survey spectra acquired at an equivalence ratio of 0.30, 0.50 and 0.85 in hydrogen-air flames to span a temperature range from 1100 to 2000 K was used to select potential line-pair thermometry candidates. Additional intermediate equivalence ratios were selected to obtain higher fidelity temperature correlations. A check on the flat-flame burner performance was made using a single-point (spatial) measurement in the flame. Three measurements at each equivalence ratio were made at one-minute intervals to indicate flame's steadiness. These results are shown in Figure 12, where a plot of non-radiatively-

corrected temperature as a function of equivalence ratio is shown. These results indicate that the temperature increases monotonically (as evidenced from equilibrium chemistry calculations), and that the temperature fluctuates by less than 10 K over the intervening time.

Figure 12. Single-point measurements of flame temperature indicate a monotonic increase in flame temperature as a function of equivalence ratio and that the temperature fluctuates by less than 10 K.

It follows from the monotonic behavior exhibited in Figure 12, that it is unnecessary to measure flame profiles for the intermediate equivalence ratios. Thus, interpolated temperatures were calculated as shown in Figure 13.

Figure 13. The interpolated flame-temperature values are shown at intermediate equivalence ratios.

Flat-flame H₂O absorption experiments in hydrogen-air flames were performed at each of the equivalence ratios indicated in Figure 13 over a spectral range to include the candidate lines for thermometry. The results of these measurements are shown in Figure 14, where they are compared to an ITU grid channel.

The areas were calculated under each of the identified lines indicated in Figure 14. The determination of the baseline used in each of the area calculations was motivated by the desire to simplify the data reduction procedure, and not to try and extract the detailed underlying spectroscopic phenomena. A simple line with consistent endpoints which were located in the trough between spectral features was fitted beneath each identified peak. The area between the peak and baseline was calculated using Simpson's 1/3 rule (a 4th order accurate numerical integration algorithm).

Figures 15a and 15b illustrate how the area changes as function of both water concentration and temperature. Because the temperature was adjusted by changing the fuel/air ratio, each line shows an increasing area with temperature. This reflects the fact that as the flame temperature changes from 1100 to 2000 K nearly 4 times more water vapor is generated in the overall fuel-lean combustion product gases.

Figure 14. Two spectral surveys from 6405 to 6410 cm⁻¹ are shown. The upper portion shows HITEMP linestrengths at 1500 and 2000 K, and an absorbance calculation is shown for 1500 K. Additionally, the top axis shows ITU-Grid channel 20 (black) along with an approximate acceptance band (grey). No axis is shown for the line strengths but their relative scale is accurate. The lower curves are measurements of H₂O absorption in the flat-flame burner over a range of temperatures.

Figure 15. Measured areas of the candidate lines 8,9 (left) and 21,23,24 (right).

Practical implementation of the temperature measurement into the sensor required examining simple expressions relating the measured area ratio (R) to the temperature (T). Three different analytical equations were considered. The first two are related to Eqs. (4) and (5) which are derived assuming a single radiative transition contributes to each peak. Because there are measurement errors in both T and R , a “least squares” fit was performed using Eq. (4) (minimizing the R error), and another fit was performed using Eq. (5) (minimizing the T error). A third fit was selected from attempts using analytical functions such as polynomials, power law, and an exponential function. Of these analytical functions, the exponential fit, provided the least difference between the measured data and the resulting fit.

$$T(R) = y_0 + A \exp(-B \cdot R), \quad (8)$$

Figure 16 shows the area ratio behavior against the flame temperature for the 21-24 line pair. The scatter and temperature insensitivity were not expected based on the preliminary measurements used to select candidate line pairs. Based on the measurement results this line pair was not considered for use. The results for the remaining line pairs showed greater promise and their results are shown in Figure 17 (8-9 line pair) and Figure 18 (23-24 line pair).

Figure 16. The flat-flame burner temperature is plotted against the measured area ratio for the 21-23 line pair.

Figure 17. The flat-flame burner temperature is plotted against the measured area ratio for the 8-9 line pair. The top portion of the figure shows the difference between the measurements and the respective line fits. See text for details.

Figure 18. The flat-flame burner temperature is plotted against the measured area ratio for the 23-24 line pair. The top portion of the figure shows the difference between the measurements and the respective line fits. Note, the scale in the top portion of the figure has twice the range as in Figure 16. See text for details.

Figures 17 and 18 contain the results of the area ratio analysis for the 8-9 and 23-24 lines respectively. The bottom portion of each figure shows the ratio of the measured areas with results from the three analytical functions, listed in Table 1, fitted through the data points, and extrapolated to a temperature beyond the measured range. The solid line is a least-squares fit using an exponential function and minimizing the least-squares temperature difference. The broken dashed line is a least-squares fit using Eq. (4) where the data was plotted as area ratio versus temperature and the area-ratio difference is minimized. Note, the fit has been transformed back to “temperature versus area ratio space” in Figures 17 and 18. The dashed line is a least-squares fit using Eq. (5) where the temperature is solved for explicitly, and the temperature difference is minimized (i.e., Δy between the line and the data point in the figure). On the top of each figure the difference between the experimental temperature and the fitted temperature difference is plotted. Text symbols are used where, “e” is with respect to the exponential fit, “R” is with respect to the fit using Eq. (4), and T is with respect to the fit using Eq. (5).

Table 1 shown below presents the exact mathematical form of the fitting functions, and the corresponding best fit coefficients. When fitting the analytical expressions from Eqs. (4) and (5), an offset (y_0) had to be included to achieve a converged solution.

Table 1. Summary of the Fitting Functions and Coefficient Values for the 8-9 and 23-24 Line Pairs

Equation	Line Pair	y_0	A	B
$T(R)=y_0 + A \exp(-B \cdot R)$	8-9	678.66	2604.4 0	0.34432
	23-24	624.84	3167.7 0	0.38074
		y_0	ΔE	R_0
$R(T) = R_0 \cdot \exp\left(\frac{hc}{k} \times \frac{\Delta E}{T - T_0}\right) + y_0$	8-9	-3.8915	415.01	4.270
	23-24	-2.4928	474.67	3.230
$T(R) = T_0 + \frac{\frac{hc}{k} \Delta E}{\ln\left(\frac{R - y_0}{R_0}\right)}$	8-9	-4.3913	484.79	4.2556
	23-24	-7.5747	297.49	7.6238
Note: $hc/k = 1.439$, $T_0 = 300$, y_0 is an offset used for fitting				

From the analysis, line pair 8-9 showed the best performance in terms of data scatter. Furthermore, using the empirical exponential fit, the temperature error is approximately 50 K throughout the measured range. The fact that the empirical exponential fit performs the best is acceptable given that in a rigorous sense, the analytical fits are applicable to a ratio of two single lines. However, as one can see, from the HITRAN-line information shown in Figure 14, the calculated spectral features consist of multiple lines. The H₂O features in the measured spectra are also composed of multiple lines. Furthermore, although a single line may be dominating the absorption feature; adjacent features will influence the baseline. Finally, given the non-ideal influences on the analytical fits, the exponential fit is also favored for extrapolations to 2500 K.

4.4 CO Concentration & Baseline correction

The selection of the lines for H₂O and CO based on the spectral survey presented above resulted in a compromise to achieve 2-line thermometry with H₂O and CO measurement from a single DFB laser. As a result the CO line monitored is not perfectly isolated from the surrounding water features, as seen from the calibration data shown in Figure 11. In the scan-and-integrate approach a negative area will result because of the baseline curvature from the H₂O contribution. To correct for the interference effect, a linestrength was empirically developed to account for the presence of H₂O. This was done by conducting a series of experiments over a range of equivalence ratios at known conditions and recording the integrated absorbance between fixed cursor positions to

establish an apparent CO linestrength, $S_{H_2O}^{CO}$ as a function of temperature. The apparent CO linestrength is used to determine the added area contribution from H₂O that is observed in the scan-and-integrate measurement. Once the temperature and H₂O number density (n_{H_2O}) is determined for a given pathlength (l) the area contribution of H₂O is obtained by

$$A' = n_{H_2O} (S_{H_2O}^{CO} l) \quad (8)$$

The measured area contribution for only CO is obtained using

$$A_{CO} = A_{Measured} - A' \quad (9)$$

where $A_{Measured}$ is the integrated area that includes both CO and H₂O contribution. The number density for CO is then given by

$$n_{CO} = \frac{A_{CO}}{S_{CO} l} \quad (10)$$

where S_{CO} is the CO linestrength for the measured temperature and l is the pathlength.

4.5 Upgraded Calibration Setup

The sensor was originally calibrated on the Hencken burner as described in section 4.2. However, upon testing the system on the Air Liquide pilot furnace (a description of the furnace is presented in section 6.0) the H₂O correction for CO measurements resulted in an error for CO concentrations less than ~2%. In this case, the CO concentration measurement returned by the sensor was negative. To address this issue a new calibration was performed in October of 2002 using the Air Liquide premixed flat-flame McKenna burner shown in Figure 19 with the Herriot cell optics in place instead of the Hencken burner. The calibration was performed as outlined in section 4.4 for different burner conditions.

At the time of recalibrating, a dedicated software package for processing the results was developed. The analysis package accepted the input from a complete set of measurements and processed the results for temperature, linestrength for H₂O, and H₂O correction linestrength ($S_{H_2O}^{CO}$) for CO. These results are summarized in Figure 20 showing the set of water absorbance features for the selected peaks along with the H₂O feature observed in the CO region. Figure 21 shows the processed temperature from the ratio value of the H₂O peak areas fitted to an exponential function. Results from the the processed linestrength for H₂O and the apparent $S_{H_2O}^{CO}$ linestrength used in Eq. 8 for correcting the CO measurement are shown in Figure 22. The new calibration results were implemented in January 2003 and have been used for the duration of the program.

An explanation for the difference observed between the two sets of measurements conducted on the Hencken and McKenna burner is not clear. However, the McKenna burner uses the 6 cm diameter combustion surface providing a larger pathlength that fully encompassed the multi-pass beam configuration. Whereas the Hencken burner having only a 2.5 cm square surface is likely to be more sensitive to edge effects between the laser beam and the combustion gases, as shown in Figure 4.

Figure 19. Premixed McKenna flat-flame burner used for new calibration parameters. Burner diameter is 6 cm.

Figure 20. Set of calibration spectra collected from the McKenna burner for a H_2 -air flame at different conditions

Figure 21. Temperature calibration obtained from the McKenna flat-flame burner for H_2 -air flame.

Figure 22. Linestrength calibration for line 8 and apparent $S_{H_2O}^{CO}$ linestrength (S_{corr}) for H_2O correction used in the R(20) CO measurement.

5. Multi-Gas Sensor System

The basic industrial prototype sensor design housing the lasers and data acquisition system was completed in February of 2002. The system design consisted of two main units packaged in hardened cases. The cases are made of heavy-duty thick-walled plastic that interlock into each other for stacking. A general schematic of the two units is shown in Figure 23. The Laser Control Case contains all the laser support hardware and manages most of the input and output signals. This case is positioned on the bottom with coasters affixed for easy mobility. The Computer Control Case rests atop the Laser Control Case and houses the computer, digital converters, and the AC power distribution. Additionally, four high-level signal outputs for temperature and concentration of oxygen, water vapor, and carbon monoxide, are located on the Computer Control case back panel. These output signals are the results from data reduction scaled over a 0 to 10 volt range.

Figure 23. Illustration of the major components of the multi-gas sensor that consists of two main units. The top case contains the computer while the lasers and support electronics are contained in the lower case.

The Laser Control Case contains a metal drawer which encapsulates all the electronics to shield from outside interference. A schematic of laser drawer minus the front cover is shown in Figure 24. The drawer contains the lasers and their controllers, DC power supplies, DC power distribution, and a signal breakout box (CA-1000). Additionally the BRD (balanced ratiometric detector) circuit is contained in a separate metal box to provide further shielding.

Figure 24. A schematic of the laser drawer which rests in the Laser Control Case illustrates the layout of the major electrical and photonics components.

The crated and assembled system is shown in Figures 25 and 26 highlighting the external features. The stack and interlock feature is advantageous in field-testing applications for transporting and set-up. Alternatively, all the electronic components housed in the cases are assembled on standard 19.5 inch rack mountable frames providing the option of permanent installation in a cabinet. The front view in Figure 26 shows the industrial PC with LCD screen attached to a sliding keyboard drawer. The bottom section of the unit houses the lasers and associated electronics. Both the fibers and signal input are connected on the front panel of the bottom unit. Output signals for each species concentration and temperature are accessible on the rear of the top unit. The output signals provide an analog signal used for coupling the measurement directly with a process control scheme or to an auxiliary data recording system.

- **Robust**
 - **Modular Design**
- Size: 37" x 23" x 15"**
Wt.: ~120 lb

Figure 25. Crated industrial prototype multi-gas diode laser monitoring system.

Figure 26. Industrial prototype multi-gas diode laser monitoring system.

5.1 Multi-gas Sensor Software Description

A graphical user interface (GUI) software was developed for controlling the two laser multi-gas laser sensor. The main structure of the software originated from a legacy single laser version, thus requiring only modifications for controlling two lasers and acquisition of two signals. The main modifications in the processing features were related to multiple peak selection and area integration for temperature and multiple species monitoring. Additional new features were added to the software overtime based on field-testing experience. These changes were mainly related to data collecting options for performance evaluation.

The main setup window for the Combustion Emissions Sensor depicted in Figure 27 is opened upon launching the program from Windows. The Control Parameter panel on the RHS of Figure 27 controls the power to the lasers, data acquisition rate, and gain for the BRD circuit. The main modifications to this panel included an on-off switch to operate the additional gas sensing and tracer (660 nm laser used for system alignment) lasers and the PGA setting control for the added BRD. Control of the acquisition rate allows the user to perform signal averaging for increased noise reduction. The number of averaged sweeps (n_s) is a function of the report rate (f_R) and laser survey rate (f_L , fixed at 200 Hz), given by $n_s = f_L / f_R$.

In the Runtime Parameter panel modifications were made to select the method of temperature input and separate pathlength settings for each laser was added if different positions or orientations were ever used. Three options are provided for temperature selection: the user can input a temperature directly, read an external temperature signal, e.g., thermocouple, or use the temperature resulting from the multiple H₂O line empirical calibration discussed in section 4.3. Whichever method used the temperature read by the software is used to determine the linestrength value to calculate the concentration. The linestrength values are reported on the screen for the temperature being used in the signal processing. Similarly, the pressure can either be input by the user or read in by an external sensor.

In the LASER PARAMETER panel modulation control of the lasers is set by the voltage values entered. The voltage inputs are used to form a voltage ramp used by a voltage to current converter to program a low-noise injection current to the laser. Multiple voltage settings are required to properly control the laser tuning characteristics, such as the start and end voltages that translate to the starting and ending wavelength sweep of the laser. One major modification to the software was the added capability to monitor multiple absorption features from a single laser scan. The CO/H₂O laser added to the system is current tuned to cover a spectral range that contains four absorption features. Three of the features are from H₂O and the other from CO. Since one of the three H₂O transitions is unused an option was incorporated into the software to jump over the unused H₂O transition to avoid wasting memory space. As a result, the CO/H₂O laser control panel in Figure 27 has a pair of start and end voltages that permit the laser to current-tune, and bypass the intervening water-vapor transition. However, in practice this option was not

used since the tuning behavior of the laser was found to work best by using a continuous ramped current profile.

Figure 27. The TDL Setup panel depicts controls for the O₂ laser (.76 μm), Visible tracer laser (.66 μm), and the CO/H₂O laser (1.5 μm).

The bottom portion of the Laser Parameters area displays laser monitoring values from the output of the laser controllers, such as current, temperature, and the photo current output from the photo diode in the laser package. The temperature set point is not controllable from the software and must be set on the laser control board to tune over the desired spectral feature.

At the bottom of the screen in Figure 27 the raw signal traces for each laser are displayed. These traces are designated Vsig (white curve) for the laser beam transmission signal received from the detector mounted near the process and Vref (red curve) which referred to as the reference laser signal. The reference signal is recorded from the laser radiation transported by fiber optic cable directly to a detector mounted on the BRD circuit board. The abscissa shows the channel number which can be related to wavelength. The ratio value displayed in the upper right corner above each plot is the average ratio of the Vref/Vsig. This ratio value provides feedback on the transmission level through the measurement zone. In addition, the ratio is used as a guideline for optimal measurement conditions, since the maximum temporal resolution of the BRD results when the ratio approaches 2. However, a ratio of 2 is not a strict requirement and we have made measurements with a ratio from ~1.2 to 10.

The acquisition GUI screen illustrating the features and operation of the sensor are shown in Figure 28. The screen is split into three main sections. The far left presents the most recent number density and concentration in ppm of O₂, CO, and H₂O along with temperature, pressure, and system runtime. The set of 6 plots displayed each has a corresponding label. The top four present the time averaged data in time-history form. A pull down menu at the top right of each species allows user to select the desired units, e.g., density, number density, ppm, or percent concentration. The bottom plots on Figure 28 displays the most recent averaged lineshape for each laser. The control button below each lineshape figure accesses the corrected view screen shown in Figure 29. In Figure 29 multiple H₂O lineshapes are shown taken from a laboratory flame measurement using the 1.56 μ m laser. The screen shows the raw uncorrected spectrum in the top plot with three plots displaying the baseline corrected absorption spectrum for each region defined by the cursor position. The additional feature that appears between channels 0-50 in the uncorrected spectrum is due to the laser recovery which occurs at the end of the preceding ramp.

For baseline correction of the spectrum either a linear or polynomial method can be used. The linear method simply fits a line between the cursor pair. Subtraction of the fitted line brings the absorbance to zero between the limits of the integration as defined by the cursor position. The resulting area from the integration is reported under each selected spectral region for both corrected and raw. The polynomial correction is applied by positioning additional cursors on the spectrum. This is performed by the user allowing selection of both the number of additional cursors and their location. Adding the polynomial baseline correction option was found useful when baseline curvature was present, which occurs from radiation loading on the signal detector. This option was mainly used for O₂ monitoring because the absorption transition is well isolated from interference by neighboring lines, as seen in the Figure 28 for the O₂ absorption lineshape plot.

Finally, after field-testing the system on the steel rehear and aluminum reverberatory furnaces software modifications were implemented. The industrial tests helped to identify what features are needed to improve the overall sensor performance and user experience. The following is a brief description of the software upgrades:

- User selection of output parameters to record in a log file. This is useful for tracking the overall performance of the sensor.
- Baseline polynomial fitting to the O₂ channel, as explained above.
- Data filtering to remove extraneous data that may occur because of plant disturbances.
- Software line-locking option for the O₂ channel. This helps in preventing the laser wavelength from drifting.

All of these software modifications were completed in June of 2003 and more explanation of the needs and benefits of these features will be discussed in the following sections covering the different industrial field-test.

Figure 28. Data acquisition screen showing simultaneous detection of O₂, CO, and H₂O concentration and gas temperature measured in a laboratory flat-flame burner.

Figure 29. TDLS software screen showing the detection of multiple H₂O absorption lines from a laboratory flame burner.

5.2 Launch and Receiver Modules for Semi-harsh Combustion Monitoring

Within the scope of this project two different module designs were developed. The designs can be classified for process monitoring on semi-harsh and extremely harsh conditions, where harsh refers to the environment the modules are exposed to. Some examples of semi-harsh process monitoring conditions would be steel reheat furnaces, secondary aluminum furnaces both rotary and reverberatory, and container glass melting tanks. In these applications, the environment near the process is acceptable for plant personnel to be in close proximity. Also, the potential for electrical noise sources are minimal and the distance between the modules and the laser electronics and acquisition system are within 100 ft of each other. For monitoring on extremely harsh environments such as electric arc steel melting furnaces (EAF) a different module and process interface design is used. Details of this design are discussed in section 10 covering the EAF work.

For semi-harsh monitoring applications, the beam launch and receiver design consisted of a module to house the optical components and mounting hardware to attach the module to the process. In mounting the modules, an interface joint, shown in Figure 30 as both assembled and disassembled, was developed. The key feature of the interface joint is the ability to externally adjust the launch and receiver module position with respect to the process. For example, the internal optical components in the launch module can be fixed with alignment made on the process by only adjusting the interface joint. The adjustment is made by four positioning screws that tilt the module up, down, left, and right. Mounting of the interface joint to the process is made by simply welding or bolting a threaded nipple to the process. The added flexibility in using the interface joint lowers the tolerances required for alignment, since the position of each module can be adjusted.

Figure 30. Module interface assembly used for coupling the launch and receiver modules to the process.

The launch and receiving module design developed and tested for semi-harsh process monitoring is shown in Figure 31. The launch module has a footprint of 12"x18"x 8" and weighs ~ 50 lbs while the receiving module is 18"x18"x8" and weighing ~ 65 lbs. Each module has a sleeve, as shown on the receiver, that slip fits into the interface joint and locked in place using a clamp. This provides an easy way to remove the modules if needed and still maintain a rough alignment once the module is reinstalled. A single input purge (N_2 or Ar) is used on each module to distribute the gas between the window that isolates the optical components and the internal module volume. The purge on the window is used for cooling and provides a positive pressure barrier to restrict the process atmosphere from coming in contact with the window. This helps in preventing any particulate matter or condensation from collecting on the window. The purge in the internal volume is also used for cooling in addition to removal of any residual air that can be detected with the O_2 laser. Typical purge rates vary from 50-150 scft/hr depending on the process conditions, e.g., temperature, pressure, and particle loading.

Figure 31. Launch and receiver modules for semi-harsh process monitoring. Also shown is the interface alignment system used for coupling the modules to the process.

The signals from the detectors in the receiver module are transmitted over two twinax cables plugged into connectors on the front of the unit. For the launch module a single input fitting for the multiple fiber optic cables is used. The fiber optic cables installed from the laser unit to the module are protected by either a solid conduit or flexible piping. Finally, for easy access during installation or general maintenance, shielding with a latched and removable shroud on each module protects the internal components.

Design of the internal optical component layout to launch and discriminate the multiple wavelengths ($1.5\ \mu m$ and $.76\ \mu m$) in the receiver module was modeled using Zemax® Optical Design Program. The design software was instructive in evaluating performance for different optical design layouts, identifying optical components, and overall

optimization of the optical system. The basic optical design was successfully demonstrated on the steel reheat, aluminum reverberatory, and EAF processes tested in this program. The design developed is protected under US 7,005,645.

The unique feature of the design is the ability to launch and receive vastly different wavelengths from one line-of-sight access location. Since the mode radii necessary for single-mode transmission for the .76 and 1.5 μm wavelengths are so different, it is not feasible to transport both wavelengths by a single fiber. To accommodate this constraint the launch module shown in Figure 32 accepts a dedicated fiber for each wavelength. A collimated beam is formed for each wavelength by allowing the exiting radiation from the fiber to diverge in free space to the desired working diameter, typically around 20 mm, to an achromatic lens where it is collimated. This configuration was later changed to a packaged collimator that avoided issues related to the sensitive position of the fiber with respect to the lens. In addition, with the fiber end exposed to the internal module atmosphere it was susceptible to collecting dirt on the small area (9 and 5 μm dia. fiber for the 1.5 and .76 μm lasers respectively) thereby potentially affecting the laser launch power.

Figure 32. Launch (LHS) and receiver (RHS) optic configuration for multiple laser beam monitoring.

The requirement for expanding the beam to a larger diameter was adopted from earlier measurement work performed on our pilot furnace. These earlier experiments showed sensitivity to both beam steering and particulate matter when using a small beam diameter. For industrial process monitoring, the likelihood of encountering temperature gradients and particulate matter along the measurement path is high. Both of these effects will degrade the measurement quality by introducing beam steering and temporal intensity variations. By expanding the beam diameter the sensitivity to these effects are

reduced through spatially averaging over the non-homogenous particle distribution and refractive-index variations.

Line-of-sight sensor installation on high temperature industrial processes requires minimizing the launch and receiver aperture diameters because of radiation loading and structural integrity of the refractory. These points are clear when considering that refractory walls can be .3-.6 m thick on industrial processes and have surface temperatures approaching 1870 K as in the case of an oxy-fuel fired glass-melting tank. Therefore, minimizing the apertures on the process becomes a tougher challenge when using multiple wavelength laser beams that are expanded. To meet this criteria, the beams are launched separated but are aligned so they overlap to minimize the required aperture diameter at the receiver module. For the side-by-side 20 mm diameter beams at the launch, a 50 mm diameter aperture in the refractory is sufficient. However, at the receiving side a larger diameter, e.g., 70-80 mm, is preferred to allow for spatial movement of the beam resulting from thermal gradients or process vibration to prevent beam clipping.

At the receiving module the multiple wavelength beams entering are spatially separated and focused through a combination dispersion prism, achromatic lens and convex mirror, as shown in Figure 32. The key feature of the receiving optics is the ability to discriminate the different laser wavelengths with minimum losses while maintaining the focal position on the detectors. This configuration reduces the sensitivity to spatial beam movement, since the beam focal position is independent of where the beams enter the receiver window. Once the laser beams are spatially separated they are directed using reflective optics to a Si and InGaAs detector for .76 and 1.5 μm monitoring respectively. In some instances, the radiation loading from the high temperature process can be problematic requiring additional filtering elements. In this case, gratings optimized for each wavelength are used.

6. Sensor Test Platform

In parallel to the sensor development work, the Air Liquide (AL) 500 kW oxy/air-fuel pilot furnace [6] was upgraded with additional instrumentation tools for sensor testing and characterization. The AL test platform is a critical tool that allows evaluating the sensor under simulated industrial conditions. This avoids relying solely on feedback from industrial measurements that often are restricted to a narrow range of conditions. Varying process parameters are generally prohibited by plant operators because of fear the process will be disrupted, thus impacting plant production. In addition, full knowledge of the process gas stream, e.g., particle concentration, gas temperature, gas composition, is often not known because of limited instrumentation available for making these measurements. Therefore, the added measurement capability to the AL pilot furnace provided a platform for evaluating the sensor under known and controlled conditions. These additional measurement tools were useful throughout the program and used at various stages for testing and optimizing the different system configurations developed.

The additional instrumentation tools installed on the AL pilot furnace for sensor characterization work are illustrated in Figure 33. All measurements are performed at the flue of the furnace exhaust having a .3 x .3 m internal dimension. Surrounding the TDL laser beam in the flue is suite of diagnostic tools that include an integration sampling probe, a suction pyrometer, real-time particle monitoring system, and real-time H₂O monitoring using a dilution probe. Beside the additional measurement tools, equipment

Figure 33. Illustration of the fully instrumented pilot furnace exhaust for TDL measurement characterization work under simulated industrial conditions.

was added to the furnace to simulate industrial conditions. For example, flue gases with particulate matter present are typical of industrial processes. To simulate these conditions on the pilot furnace a system with controlled injection of seed particles

through the burner is used. In addition, dynamic stoichiometric variations can be introduced to the combustion atmosphere through a retro-fit natural gas pulsating valve that can be mounted upstream of the burner. This equipment is used for testing the sensor time response under rapidly (.5-1 Hz) changing stoichiometric conditions. A brief description of these measurement tools are discussed in the following sections.

6.1 Integrating Sampling Probe

Previous studies using TDL measurements on the AL pilot furnace showed a high sensitivity to the purge gas flow rate used on the launch and receiver modules. The influence on purge gas flow rate was determined from comparative measurement results between the TDL and conventional extractive sampling. In this earlier work a single sampling probe was used positioned near the center of the TDL measurement path. In this configuration not only was the impact of purge gas flow observed, but the measurement agreement between the TDL and extractive sampling always deviated by 10-20%, with the TDL measurement being lower. The error observed was attributed to the TDL being a path averaged measurement and variations in the effective pathlength because of the purge conditions resulted in a corresponding change in the number density. To address this issue, an extractive integrating sampling probe (ISP) system was developed that would also provide a path averaged measurement. Gas analysis from the ISP was conducted by conventional NDIR for CO and CO₂, resonance paramagnetic for O₂, and gas chromatography for N₂. The ISP consists of four sampling probes positioned near the laser beam path as shown in Figure 34. Each probe has a valve allowing individual sample point recording to obtain concentration profiles across the flue width. Alternatively, all four probes can sample simultaneously resulting in an average concentration measurement.

Figure 34. Top view of the furnace exhaust section illustrating the integrating sampling probe assembly. At this location, the exhaust gases are flowing horizontally.

Figure 35. Modified furnace exhaust section showing the installation of the integrating sampling probe assembly.

The ISP was installed on the AL furnace in November of 2000 as shown in Figure 35 that shows both the position of the probes and location where the laser launch and receiver modules are mounted.

An example illustrating the added measurement capability of the ISP is shown in Figure 36 for O₂ monitoring. In this case, a profile of the O₂ concentration across the flue width by discrete probe sampling shows a concentration gradient under purge conditions, but no gradient is observed with the purge off. The purged volume represents the tube that interfaces the launch or receiver module to the furnace with a volume of approximately 1000 cm³. To protect the components inside the module from hot process gas a window separates the tube and module. Under purged conditions, the average O₂ concentration value from the resulting polynomial fit of the 4 data points yields an average concentration of 5.98% with a peak O₂ concentration value of approximately 6.5% at the centerline. The centerline concentration would correspond to a single sampling probe measurement positioned at the flue center, which indicates an error of approximately 10% compared with the average value. The discrepancy between the averaged and single point measurement under purge conditions supports previously observed differences between the pathaveraged laser measurements and single point probe sampling. The variation in pathlength is explained by the influence of the purge gas on the TDL measurement as illustrated in Figure 37. High or low purge flow rates will change the effective pathlength and thereby change the measurement result. The sensitivity to the gas purge is more pronounced in the test furnace because of the short .3 m pathlength. On many industrial processes, the pathlength would be much larger thus minimizing this effect. Nevertheless, these results illustrate how the detailed analysis incorporated into the test platform provided a better understanding of the subtle differences between the measurement techniques.

Figure 36. Effect of O₂ measurement using the integrating sampling probe under different purge and sampling conditions.

Figure 37. Schematic illustrating the pathlength variation observed resulting from the interaction between purge gas and flue gas.

6.2 Real-time Particulate Monitoring

Evaluation of the TDL measurement under dirty gas conditions, as encountered on industrial processes, is one of the key tests used in optimizing the sensor performance. Previous TDL studies showed the S/N degraded with particles present in the flue gas. Improvement in the S/N was demonstrated by expanding the beam diameter thereby averaging over a larger area to minimize the effect of the inhomogeneous distribution of particles. However, in that earlier work it was not possible to quantify the S/N observed at different levels of particle loading because the particle density was not known and was difficult to control.

To measure the real-time particle density in the TDL measurement zone a survey of vendors was conducted for a suitable off-the-shelf measurement system. Typical industrial stack particle monitoring is conducted using an iso-kinetic technique following the EPA protocol method 5. This technique is based on extractive sampling and particle collection on a filter. Particle density is obtained by weighing the material collected and accurately knowing the flue gas flow rate. If only averaged information is needed this method works fine. However, the scale of the AL pilot furnace and the seeding method prohibits routine continuous steady-state particle injection overlong periods. Therefore, an alternative approach based on laser extinction was implemented.

The laser extinction system installed on the pilot furnace consisted of a 500 mW Ar-ion laser and photodiode detector as illustrated in Figure 38. A large area (25 mm^2) Si photodiode was used to minimize the effect of beam steering, since the detector was placed several meters from the centerline of the furnace flue. The detector location was chosen to minimize the detection of hot gas and hot particle radiation using the inverse square

law relationship ($I \propto 1/d^2$, where I is the observed source intensity at distance, d). Further background discrimination was achieved using a narrowband filter (488 ± 10 nm) placed in front of the photodiode. The laser beam was launched in the flue just upstream of the TDL laser beam. Initial measurements were conducted to verify the level of background contribution using only seed particle injection with furnace flue temperatures near 1820 K. These measurements showed that the hot particle radiation had no significant contribution to the signal recorded by the photodiode.

The first tests performed with particle seeding used a reverse cyclone seeder [7]. In this case, NG fuel was partially diverted through the cyclone seeder to entrain the particles into the fuel stream, as shown in Figure 39. Particles were loaded into the canister at the start of the test. Because the system operates in a batch mode the particle entrainment level changed as the level of particles in the canister depleted. With this approach, it was nearly impossible to control a stable seed level or set the desired level because of the time variation of the particle volume. The instability of the method is clearly seen from the extinction measurement shown in Figure 39 for a short duration test. The irreproducibility and unstable nature of the cyclone seeder made it impossible to quantify the SNR from a TDL measurement.

Figure 39. Cyclone Aerosol Generator and a typical laser extinction measurement.

Figure 38. Schematic of the experimental configuration for monitoring the particle density high temperature furnace exhaust gas.

Improvement in controlling the particle level and stability was obtained by installing a screw feeder, manufactured by Metalfab, coupled to the fuel inlet, as shown in Figure 40. Adjustment of the screw RPM controls the particle feed rate supplying a stable and controllable level of particles (Al_2O_3 with dia. $< 10\ \mu\text{m}$) into the furnace. The level of seeding stability and control is shown in Figure 40 for three different screw RPM settings. The results illustrate the performance improvement over the cyclone aerosol generator. The system was found to be very reproducible and could operate at longer durations. The only limitation was on the furnace operation, since not all of the injected particles exited the exhaust. A portion of the particles that remained in the furnace did coat the heat transfer coil located on the furnace floor. This required operating at lower firing rates because of the heat transfer efficiency loss from the coated coil.

Figure 40. Metalfab DB1M particle feeder coupled to a 500 kW oxy-fuel burner.

The improved controllability and stability of the new particle feeder permitted calibration of the laser extinction measurement using the conventional iso-kinetic sampling following EPA method 5 protocol. The calibration was performed under enriched air conditions at acceptable temperatures and measurable flue gas volumes for our iso-kinetic sampling system. In conducting the calibration, the seeder operated at steady-state conditions while iso-kinetic sampling and laser extinction measurements were made. The seed particles used for all tests were Al_2O_3 with spec dia. $< 10\ \mu\text{m}$. Other size particles could be used but would require recalibrating the extinction measurement system. Therefore, all tests involving particle injection were made with particles having the same specifications and purchased from the same supplier.

6.3 Real-time Moisture Monitoring

To cross validate the H_2O concentration measurements from the TDL sensor a dilution probe manufactured by EPM Environmental, Inc. was installed on the AL pilot furnace. The probe is an *ex-situ* device designed to extract gas samples from process streams with a known dilution providing a sample in the measurement range and below a dew point

where condensation will occur for the gas analyzer. For example, the dilution probe system reduces the extracted H₂O sample from 66% (stoichiometric oxy-fuel conditions) down to .2% by using Ar or N₂ as the dilution gas. Reduction in the H₂O concentration permits the use of a standard H₂O NDIR analyzer. The measurement result can be related back to the undiluted concentration by knowing the calibrated dilution factor. The type of dilution probe implemented on the pilot furnace is referred to as an “Out of Stack System”. This probe design uses a special extractive probe and filtering upstream of the dilution system for use in high temperature or corrosive processes. The dilution system incorporates two gas driven aspirators in a heated sample block assembly. A control panel provides regulation and control of all dilution gases, along with PID control of the heated dilution chamber.

7. Real-time Pilot Furnace Test Results

Throughout this program evaluation of the sensor on the Air Liquide 500 kW pilot furnace was conducted. The pilot furnace provided a platform for testing the sensor under simulated conditions to identify and address any technical issues observed. However, because the test platform has its own limitations such as, well controlled ambient environment and no noise sources, e.g., electrical or vibration, not all technical issues could be identified. As a result, several improvements implemented on the sensor were from observations and experience gained during the industrial testing campaigns. In this section a summary of selected results are presented that demonstrate the test platform capability along with technical problems and solutions identified from both industrial and pilot furnace testing.

7.1 Fast-time Response Demonstration

To demonstrate the dynamic response time of the sensor tests were performed using Air Liquide's proprietary oscillating combustion technology [8]. In this test, a special valve is used on the fuel input of the burner to vary the flow rate at a set frequency and duty cycle. As the fuel flow rate varies with time the combustion atmosphere changes from a fuel-lean to fuel-rich condition. The time response of the TDL sensor is fast enough to capture the dynamic changes in CO concentration and temperature, as shown in Figure 41. In this case, the valve was operating at .5 Hz and 50 % duty cycle with an average burner power of 300 kW. In these measurements, CO and H₂O are being monitored simultaneously with the temperature being determined from the H₂O line pair ratio. Oscillating valve characterization studies conducted using N₂ gas showed the resulting flow from the valve to have a square waveform, similar to the shape observed from the TDL measurement. In addition, Figure 41 displays results from extractive CO and suction pyrometer temperature (TC) measurements. Clearly the conventional monitoring techniques cannot resolve the combustion dynamics and only provide an average result.

Figure 41. Dynamic response of the MGS system demonstrated by simultaneously monitoring CO and temperature (H₂O line pair) compared with extractive sampling of CO and suction pyrometer (TC) for temperature.

7.2 Problems Identified and Solutions

In the sensor characterization analysis of CO, O₂, H₂O and temperature on the test platform, step changes in the combustion conditions were typically used. This was performed by simply adjusting the burner input settings to achieve the desired fuel-lean or fuel-rich conditions in the exhaust stream. In the case of particle injection, either the burner stoichiometry was varied with constant particle injection or the particle seeding level was adjusted at fixed stoichiometry. The H₂O concentration monitoring was used to convert the dry extractive measurement results to wet values for direct comparison with the TDL measurement. However, H₂O concentration monitoring was not performed for the seeding tests because of potential probe plugging issues.

In the first phase of sensor evaluation on the pilot furnace conducted in 2001-2002 a number of technical issues were identified that impacted the measurement quality and accuracy. The main technical problems encountered were as follows:

- The level of noise observed in the O₂ signal was too large for conducting measurements. The combination of the short pathlength (.3 m) on the pilot furnace and the level of noise observed in the signal prevented any further tests with O₂ monitoring. Fortunately, this problem did not delay the first industrial trial on the CHARTER STEEL reheat furnace because of the long measurement pathlength used.
- Low-level CO monitoring (<1%) resulted in a negative concentration value. At high CO concentration levels (>1%) good agreement was observed between the TDL measurement and conventional extractive sampling.
- Monitoring in high particle flow conditions resulted in inaccurate temperature measurements that affected reported concentration values, since temperature and concentration are linked by the linestrength parameter.

7.2.1 Oxygen Signal Improvement

To determine the noise source on the O₂ channel a series of tests were conducted to systemically eliminate each optical and electrical component that could be responsible. In the test a simple launch and receive apparatus was set-up to measure ambient O₂ over a path of ~ 2.5 ft. The first test looked for electrical component sources that could contribute to the noise. This test used a collimating optic (3 mm beam dia.) for launching the beam to a collection lens combination that focused the light onto a detector. Results comparing the measured SNR using the existing and new detector sets (matched pair of detectors for Vsig and Vref) were 51 and 66 respectively. The observed differences in the SNR can be attributed to detector age, environmental exposure, and usage, and is not significant enough to account for the poor performance observed.

The second test replaced the collimating optic with the same optics used in the launch module. In this case, the beam is collimated by collecting the expanding beam exiting a flat end fiber with an achromate lens. This approach was used to allow flexibility in setting the beam diameter by using different focal length lenses. Results from the test showed a SNR of only 26, but using the same achromate lens and replacing the flat end fiber with an angle cut fiber increased the SNR to 161. Comparisons of these test results are shown in Figure 42. The poor performance observed for O₂ monitoring was linked to the flat end fiber that produces a back reflection generating an interference pattern on the monitored signal. Replacing the flat end fiber with an angle cut (FC/APC) completely removed the problem. This problem was also observed in the CO measurement, as shown in Figure 43, but to a much lesser extent. Pilot furnace tests with CO were not delayed, but this analysis did reveal the source of high frequency noise observed in the CO channel.

Figure 42. Transmittance measurements for O₂ comparing the effect of the fiber optic used to launch the beam. (ambient air measurement with a pathlength > 1 m)

Figure 43. Affect of launch fiber for CO monitoring on the pilot furnace with a .3 m pathlength (2% CO, 1530 K).

7.2.2 CO Monitoring

Comparing the TDL and extractive sample measurements several differences between the two measurements are seen. First, a time delay of ~80 sec for the extractive sampled measurement was observed. This is expected since the extractive system transports the gas from the process to the analyzer. In addition, there is an inherent delay in the electronics of the analyzer. The second noticeable difference between the two measurements is seen at zero CO concentration where the TDL measurement records a negative value. At CO concentrations > 1% the TDL measurements is within 5% of the extractive sample reading. However, at CO concentration < 1% the deviation between the two measurements is > 50%. The poor performance in the CO monitoring in this regime results from interference of a small H₂O background feature near the CO absorption transition, as discussed in sections 4.4 and 4.5. The pilot furnace test results provided the first indicated that a problem existed in the calibration measurement performed to correct for the H₂O interference. This led recalibrating the sensor to better account for the

H₂O interference. Reasons for the discrepancy are unclear, but are likely related to the differences in the burner designs used for each case, as discussed in section 4.5. Monitoring results using the new calibration parameters are shown in Figure 45 which shows a near zero baseline when the CO concentration drops to zero.

Figure 45. Comparative analysis of CO measured by the TDL system and conventional extractive sampling corrected for the H₂O concentration.

Figure 44. Real-time CO monitoring on the pilot furnace with updated H₂O correction parameters. Negative CO concentration readings are removed.

7.2.3 Dirty Gas Monitoring

With the program direction shifted to include tests on an EAF process, sensor performance evaluation under high temperature high particle density conditions was critical. Characterization studies of the TDL system under dirty flow (particles) conditions conducted in the 2nd quarter of 2002 showed a strong affect by the particle density on the reported temperature. In the presence of particles, the measured temperature increased several 100 K above the expected temperature. Since the temperature is also used in processing the concentration through the linestrength value the error observed in the temperature propagated to the concentration measurement. To sort out the anomaly observed additional tests were conducted to identify the source of error and provide a solution.

Analysis of H₂O spectra acquired in the pilot furnace under clean and dirty flow conditions was collected to identify the source of error. Results from the analysis indicated the root cause was from the combination of background radiation loading and laser beam attenuation. A signal enhancement solution using a grating optimized for 1.5 μ m was installed into the receiver module. To compare the effect of particles, measurements were conducted with and without signal enhancement. The results are reported in Table 2 comparing the different conditions along with temperature measurements using conventional suction pyrometer (SP). The reported temperature

represents the average over 2 minutes at a constant particle injection level. With no signal enhancement under dirty flow conditions, the temperature increase is several hundred degrees above the actual temperature. In addition, the scatter in the temperature is larger with a standard deviation (σ) of 200 K in the measurement. Adding the signal enhancement grating suppressed the background resulting in the measurement approaching the SP results and reducing the standard deviation.

Benefits of using the signal enhancement are also seen for clean flow conditions with improvement in both measurement accuracy and variability. This suggests that the gray body radiation from the hot gas is significant enough to affect the signal quality. Furthermore, the bandwidth of the zero order dispersion optic system used in the receiver module to separate the different laser wavelengths does not provide enough dispersion to reduce the background.

Table 2. Dirty gas monitoring results with and without signal enhancement.

	No Signal Enhancement		Signal Enhancement		Measured SP
	T(K)	σ	T(K)	σ	T(K)
Clean	1747	30	1648	8	1648
Dirty	2164	203	1694	42	1694

Similar improvements in measurement quality are observed for O₂ monitoring using a signal enhancement grating. Results from monitoring O₂ under dirty flow conditions are shown in Figure 46 for 15% excess O₂ at 1570 K. Using the calibrated laser extinction system a particle density of 1.2 g/dscf was measured. The O₂ spectrum (B) in Figure 46 was recorded with the first generation launch and receiving modules [9]. In this case, no signal enhancement was used in the receiver. As a result the combination of radiation loading on the detector and an unstable particle injection (tests were made with the reverse cyclone seeder) severely degraded the baseline.

Figure 46. Comparison of O₂ spectra acquired using different designed launch and receiver units. Spectrum A was acquired using launch and receiver units developed in this program. Spectrum B was acquired using modules developed under a previous SBIR (DE-FG02-96ER82254) program with the furnace operating at 1470 K and 10 % excess O₂. In case B, the particle concentration was not measured, but was less than case A based on operating experience.

7.3 Simultaneous CO/H₂O & O₂ Monitoring

After ungrading the launch fibers to remove the noise contribution discussed in Section 7.2.2, O₂ monitoring on the pilot furnace was revisited. Results for clean flow monitoring are shown in Figure 47 where a step change in the O₂ concentration was made by changing the combustion inlet conditions from lean to rich and then back to lean conditions. The results in Figure 47 show good agreement between conventional extractive sampling converted to a wet measurement and the TDL measurement. However, near the 1200 second point where the combustion goes back to lean conditions the CO stays higher than the measured value returned by the sampling probe.

Figure 47. Real-time O₂ and CO monitoring on the AL pilot furnace. Solid lines are extractive sampling measurements.

Figure 48. Real-time temperature monitoring comparing suction pyrometer (SP) and Two line H₂O thermometry from the TDL system.

This problem was traced back to the integrated H₂O line positions on the TDL sensor drifting because of the ambient temperature changes. At the time these measurements were acquired the TDL electronics were positioned near the furnace during the early part of September 2002 on an unusually hot day. As the furnace heated up a noticeable deviation between the two temperature measurements was observed, as shown in Figure 48. The stability problem of the laser system was easily resolved by moving the unit into the air-conditioned control room. However, this test illustrated the importance of locating the sensitive electronic components in a controlled environment and utilizing the advantages of fiber optic cabling to delivery the laser radiation at the point of use.

The O₂ did not show the same sensitivity to the temperature drift in these measurements for two reasons. First, O₂ monitoring is performed on a single interference free absorption feature. Therefore, there is tolerance for the O₂ line to drift without severely impacting the measurement. Second, the measurements were made over too short a time duration for drifting to affect the reported O₂ concentration. Overall the wavelength stability of the O₂ laser is a greater issue compared with the CO/H₂O laser. The main difference for thermal control between the two lasers is their packaging. The O₂ laser package has a much higher thermal mass compared to the CO/H₂O laser making

temperature stabilization of the laser more difficult. The problem is troublesome when the ambient temperature is varying. This was experienced during industrial tests conducted at IMCO Recycling, Inc., as discussed in Section 9.6, because location of the laser electronics could not be placed in a control room. Long-term solution to this problem was addressed through a software modification to line-lock the laser to the absorption feature. Preliminary tests of using soft line-lock were successfully demonstrated provided O₂ was present. If the O₂ is not present for a long period of time then an alternative approach such as incorporating a reference cell seeded with O₂ can be used. However, the drawback with this approach is the additional detection channel needed to monitor both the reference cell and process simultaneously, thus increasing the system complexity and cost.

8. 1st Industrial Test

In the original program, Charter Steel (steel), Johns Manville (glass), and DuPont (chemical) elected to be partners for the industrial demonstration phase of the sensor development. A representative from each of these companies participated in a kick-off meeting held in April of 2000. However, the Air Liquide market focus shifted by the time the sensor was ready for industrial testing. Interest in demonstrating the sensor on one of John Manville's glass melters or one of DuPont's SO₂ recovery furnaces was not a top priority. Instead sensor demonstration in the metal processing industries became the objective. As a result two new industrial host-site partners, IMCO Recycling, Inc. (now Aleris International, Inc.) for secondary aluminum processing and North Star Steel part of Cargill Inc. (now Gerdau Ameristeel, Inc.) for electric arc steel melting, were selected.

8.1 CHARTER STEEL PROCESS SELECTION

CHARTER STEEL (Saukville, WI) was selected as the first industrial host-site for testing the TDL sensor technology. From discussions with CHARTER STEEL personnel and conducting a site survey we identified the EAF (electric arc), reheat, and annealing furnaces as three main processes where *in-situ* gas temperature and composition monitoring is of interest. Each process has its own characteristics with different sensor installation and monitoring requirements.

For EAF off-gas monitoring, the CO concentration in the exhaust near the furnace is of interest for post-combustion control to recovery chemical energy from CO through the exothermic reaction with O₂ injected into the furnace. Knowing the level and time that CO appears by exhaust gas analysis using extractive sampling, controlled O₂ injection is used to react with the CO in the process. This method is well known and reported energy efficiency gains of 5-10% are not uncommon. However, the extractive sampling systems used for off-gas monitoring suffer from long delay times and high maintenance making routine usage of the technique difficult.

The problems faced with traditional extractive sampling for EAF off-gas monitoring can be addressed with the TDL sensor technology. The EAF process is dynamic requiring a fast-time response sensor such as the TDL for optimal control of the O₂ injection. Additionally, with the TDL being non-intrusive maintenance associated with extractive sampling is reduced. However, the environment surrounding the EAF is extremely demanding on sensor instrumentation. The sensor must endure high particle densities, mechanical vibration, strong electro-magnetic fields (EMF), high temperatures, and volatile operation. Addressing these aspects require special precautions in both the sensor module design and process interface.

For both the reheat and annealing furnaces issues related to high particle densities, mechanical vibration, EMF, etc., are not present allowing for a less stringent sensor

installation. The reheat furnace monitoring and control issues are related to the combustion stoichiometry for energy efficiency and product quality. The steel billets introduced into the reheat furnace are directly exposed to the combustion atmosphere gases. If the furnace atmosphere is not well controlled and is too high in O_2 , oxidation on the billet surface will occur forming a scale layer. The formation of scale on the billet is removed but represents lost product. Reheat furnace control systems are normally based on the air-to-fuel ratio by measuring and controlling the fuel and airflow rates. Therefore the atmosphere and energy efficiency control is directly linked to the accuracy and reproducibility of the flow rate monitoring and control. Some furnace also use zirconium oxide probes for O_2 monitoring control, but the measurement is generally made in the exhaust giving only a global O_2 measurement.

Gas sensing on the annealing process requires monitoring and control of O_2 , CO, CO_2 , H_2O and CH_4 for carburizing, and additionally NH_3 for nitriding. Current monitoring is performed by extractive sampling and analysis by conventional NDIR and paramagnetic analyzers. The single point measurement relies on homogenous gas mixing in the process for feedback control. Since the scope of this project focused only on O_2 , CO, and H_2O , inclusion of CO_2 and CH_4 monitoring is needed to match CHARTER STEEL's requirements for their annealing furnace control system.

Based on the site survey and monitoring requirements for each process a decision was made to conduct the first industrial field-test on the CHARTER STEEL reheat furnace. The limited species monitoring capability of the TDL sensor was not optimal for their annealing furnace. For the EAF, the potential benefits of the using the TDL sensor is clear, but the module and process interface design at that time did not meet the requirements for a sensor to survive and successfully measure the off-gas.

8.2 CHARTER STEEL Reheat Furnace Site Preparation

A site survey was conducted in December 2000 on CHARTER STEEL's reheat furnace to determine the location of the optical access ports, identify the required utilities, and locate where the sensor electronics and data acquisition system will be. To help in defining the optimal monitoring location the furnace manufacturer Danieli Centro Combustion was contacted. Defining the location of the TDL measurement is important since, either global or zone information on the process can be measured. For example, locating the sensor on the exhaust of the furnace will give an average concentration measurement of the process. Whereas locating the sensor near one of the furnace zones will provide information particular to that zone. Based on discussions with Danieli and Charter it was decided to utilize the non-intrusiveness and pathaveraging of the TDL technique and position the measurement directly above the billet in different processing zones. The objective was to evaluate the measurements of O_2 , CO, and H_2O concentration and temperature to better understand the impact of the atmosphere on scale formation, decarburization, and temperature homogeneity of the billet. All of these aspects are critical issues that the furnace operator would like to control.

A top and side view illustration of the CHARTER rehear furnace is shown in Figure 49. The furnace is a walking beam type of continuous rehear furnace in which the billet moves through distinct heating zones within the furnace. The billets move through the furnace by a walking mechanism that translates the billets forward through the furnace at a rate dictated by production and billet temperature. Operators control the speed through the zones to achieve the precise rolling temperature while minimizing fuel consumption. The furnace has a designed production rate of 100 ton/hr with a total thermal input of 30 MW that is distributed between the heat and soak zones. Figure 49 indicates the location of the different zones labeled preheat or recuperate, heat, and soak. The furnace width is ~ 51.6 ft and the billet lengths varied from 18 to 42 ft with a cross-section of 5.5 x 5.5 inches. The preheat zone uses only the combustion exhaust gases to preheat the billets as they first enter the furnace. This zone has no burners and typical operating temperatures are near 770 K. As the billets propagate to the heat zone, heating is supplied by radiative roof burners and conventional air burners located under the billets. For controlling this zone, the burners are subdivided into two groups, roof and bottom fired burners, with typical operating temperatures near 1150 K. When the billets reach the final soak zone the billet temperature homogeneity is achieved before exiting to the rolling mill. Here the soak zone consists of roof and bottom fired burners that are subdivided into four groups for controlling the temperature that is typically around 1450 K. Between the heat and soak zone a total of 56 air preheated burners are used. Temperature profiles in the furnace are controlled by the adjustment of the firing rate for each sub-zone based on a fixed air/fuel ratio.

The selected position of the sensors based on suggestion by Danieli Centro Combustion, is shown in Figure 49. The sensor monitoring locations were selected to be near the partitions extending from the roof and floor that separates the different zones. At this position the gas entering or exiting the zone can be monitored providing a zone measurement. The billets are moved down the furnace by a mechanical system that

Figure 49. Illustration of CHARTER STEEL's walking beam furnace indicating the different process zones and location of the TDL sensor installation.

translates them to the next forward position. During the translation phase, the billet moves upward 4 inches. Accounting for the vertical movement and the maximum billet size of 5.5 x 5.5 inches the beam height was set at 12 inches above the walking mechanism. Therefore, during the billet translation mode the laser beam was 2-3 inches above the billet.

Modifications to the furnace were made in January of 2002 during a 3-day maintenance shutdown. J.F. Harrison from Milwaukee, WI was contracted for installing the line-of-sight optical access and process interface for mounting the launch and receiver modules. Timing was critical for these modifications, since this was the only scheduled long maintenance shutdown for the year. These modifications were performed inside the furnace and consisted in removal of a section of existing refractory, adding a hole to the furnace skin, and installing new refractory, as shown in Figure 50. In addition, the line-of-sight alignment was set by using a HeNe laser mounted on the optical access port. The alignment was used to set the position of the opposing optical access port at the proper distance above the billet walking mechanism, as shown in Figure 51. Following this procedure guaranteed the opposing optical access ports were well aligned at least for a cold furnace. There was still some uncertainty in the tolerance between the optical ports once the furnace became fully operational.

Figure 50. Reheat furnace optical access modifications showing refractory removal and repacked.

Figure 51. Launch (LHS) and receiver (RHS) module installation on the soak zone of the reheat furnace.

The TDL sensor module installation and testing took place April 22 through May 1 2002 not including weekends. Since only one set of modules was available and the prototype was not configured for monitoring multiple locations, simultaneous monitoring of the different zones was not performed. Instead the measurement location was selected by moving the modules between the different zones. The soak zone was tested first since this section operates at the highest temperature and is the critical zone in the process for achieving the desired billet temperature homogeneity. Installation of the sensor modules on the 50 ft wide furnace was made during normal production and was transparent to their operation. The installation procedure consisted in first mounting the launch module on the process and using a visible 660 nm tracer laser for alignment. At the receiver side, the module was not mounted until the tracer laser exited through the center of the access hole. Alignment was conducted by adjusting the interface joint on the launch module based on feedback from an observer on the receiver side, using walkie-talkies. By using the interface joint for alignment, the internal components in the launch module did not require adjustment. Once the tracer beam was aligned, the receiver module was mounted on the furnace and optimized by adjusting a few key internal optical components. A picture of the module installation on the soak zone is shown in Figure 52 for both the launch and receiver side. In addition, an extractive sampling probe was installed near the position of the launch module. The extractive sampling probe length was limited to 10 ft so only the edge of the reheat furnace was being monitored. The sampling system consisted of analyzers for O₂, CO, CO₂ and NO_x monitoring.

Figure 52. LHS shows the alignment system used to establish line-of-sight optical access. RHS shows the interior of the furnace with alignment laser traversing across the furnace 12 inches above the walking beam mechanism.

8.3 Reheat Furnace Monitoring Results

The performance of the receiver module was exceptional in handling the beam distortion from thermal gradients over the 50 ft path of hot gas. An example of the magnitude of beam distortion is shown in Figure 53 for recorded images of the visible tracer laser beam. The image on the left shows the spatial variation in the launched beam shape. As expected the beam shape exiting the launch is uniform and close to being round. The flat edge on the right side of the image results from clipping on the internal mirror that directs the beam from the collimator to the exit window. After the beam propagates through the furnace atmosphere the resulting beam shape exiting the furnace is noticeably distorted. What is not shown is the spatial fluctuation of the beam shape in time, which was very evident. The temporal behavior of the beam on the receiver side resulted in a distorted spot falling randomly within the solid circle that represents the receiver entrance window. The receiver optic design accepted the distorted incoming beams, discriminated between the different wavelengths for O₂ and CO/H₂O monitoring, rejected background radiation from the process, and spatially controlled the beams to maintain optimum laser beam collection on the detectors.

Figure 53. Beam profile contours from the visible laser beam used for aligning the modules. The profiles shown are post-processed from a single shot images collected on a target.

Depending on the furnace operating conditions, e.g., billets moving or not moving through the furnace, dictated the stability of the alignment. The receiver aperture size was 2.75" diameter and overtime the launch beam would drift outside of this opening requiring an alignment adjustment. This is not surprising since over a 50 ft path it requires only .1° change in angle to move outside the diameter of the receiving aperture. To correct for the misalignment adjustments were made only to the interface joint on the launch module. The frequency for alignment adjustment varied anywhere from 30 minutes to over 8 hours. There were times when the alignment was lost and then recovered on its own from the natural expansion and contraction of the process. For routine day-to-day monitoring, a self-corrective alignment system incorporated into the modules would be required. However, stability improvements may be achievable through mounting hardware modification to the module interface as discussed in section

9.3 for the aluminum reverberatory furnace. With this being the first industrial test the duration of the data collection period was considered long enough for evaluation of the measurement results. Furthermore, tests were never conducted with the system unattended because of limited purge gas supply. If purge gas was lost, there was a risk in damaging the optical components. Therefore, the modules were removed from the furnace each day before leaving the plant. Remounting the modules and alignment on the following day took only 15-30 minutes. The biggest challenge in remounting the system was the feedback communication between the two people on opposite sides of the furnace.

Results from monitoring the soak zone gas temperature and O₂ concentration is shown in Figure 54. The top plot shows the measured temperature from the TDL and measured temperatures recorded from the process thermocouples designated by zones 3, 4, 5, and 6. Temperature control of each furnace zone is regulated by a furnace operator by varying the input power to that zone. During this operating period, the furnace temperature was gradually decreased through a series of set-point changes initiated by the furnace operator for zone 5 temperature. The set-point value is indicated on Figure 54. The resulting change in temperature for each zone thermocouple is shown along with the TDL measurement. Note the solid black line running through the TDL measurement points is a moving average to highlight the trend in the data. The TDL measurement shows a faster time response compared with the thermocouple readings. This is not surprising since the thermocouple time response will be dependent on the location of thermocouple with respect to the zone burners being adjusted.

Figure 54. TDL temperature and O₂ monitoring results from the soak zone compared with process data.

Simultaneously to recording the average gas temperature across the width of the furnace, the O₂ concentration was also monitored, as shown in the lower graph of Figure 54. In this case, the O₂ concentration is compared with the equivalence ratio for zone 5 only. Zone 5 was the only zone that exhibited the transient variation in O₂ concentration that was observed in the TDL measurement. For example, at ~22:38 the combustion went to leaner conditions for a short time as indicated by the decrease in the equivalence ratio, where equivalence ratio is defined as $(\text{fuel/oxidant})/(\text{fuel/oxidant})_{\text{theoretical}}$ with the theoretical ratio being stoichiometric. During this short transition the TDL sensor detected the change in O₂ as the combustion became leaner.

The TDL measurements for both temperature and O₂ concentration were sensitive to the billet movement through the process. The temperature and O₂ concentration measurements showed periodic decreases at the same frequency as the billet movement. These changes in temperature and concentration were directly linked to the billet movement. As the billet moves through the process the measurement distance relative to the billet surface decreased to a few inches during the translation period. The decrease in temperature can then be explained, since the billet acts as a heat sink and will be cooler than the surrounding atmosphere. For the corresponding O₂ concentration decrease observed, either a reaction is consuming the O₂, e.g., scale formation as one possibility, or it could be a gas dynamic affect from the billet movement. Further investigation would be needed to fully understand the phenomena observed and determine the potential impact, if any, that could be realized on improving the process through monitoring these small changes.

Another example of real-time monitoring results for temperature in the soak zone is shown in Figure 55. Comparing the TDL measurement with process thermocouple (TC) readings shows the overall trends between the two profiles are in good agreement, but the magnitude of the temperatures can differ by as much as 220 K. The difference observed between the TC and TDL measurements can be explained by the location of the TC, which is mounted in the refractory wall far from where the TDL measurement is made. In addition, the TC measurement shown in Figure 55 represents an average of four points in the soak zone, one for each sub zone, whereas the TDL is a path-averaged measurement spanning the width of the furnace. An expanded view of a short time interval from Figure 55 shows periodic downward temperature excursions of ~30 K that is not observed from the TC measurements. The minimum temperatures observed from the TDL measurement correspond to the billet position closest to the probe beam as the billet is transported through the furnace by the walking mechanism. As previously explained, the difference in temperature between the two measurement positions indicates the existence of a temperature gradient with the billet being cooler than the surrounding combustion gases. This is expected since the billet target exit temperature for forming was near 1350 K, which is less than the TC set-point value.

Results from TDL monitoring in the heat zone are shown in Figure 56 for temperature in the upper plot and O₂ monitoring in the lower plot. In this case, the change in temperature as the billet moves through the furnace is larger than the measurements observed for the soak zone. Again this is explained by the billet being cooler than the

surrounding atmosphere. As the billet temperature becomes closer to the atmosphere the temperature difference (ΔT) observed in the TDL measurement decreases, as seen in Figure 55. Therefore, a decrease in the ΔT measured by TDL can provide some indication that the billet is approaching the rolling temperature.

Figure 55. Comparison of real-time temperature monitoring from the TDL system with thermocouple measurements in the furnace soak zone.

In addition, the average recorded process temperature at two zone locations is shown in Figure 56. Overall, the trends between the two measurements are similar showing only a shift in time, but in this case, the TDL appears to respond slower than the thermocouple measurement. This is explained by the fact the TDL measurement is made near the much cooler billets whereas the thermocouple measurements are made in the refractory near the burners. The close location of the TC to the burner will then detect changes in temperature quicker. At times when billets are not moving, e.g., around 14:00, the modulations in temperature measured by the TDL disappear and the temperature begins to increase rapidly. This is observed for both the TC and TDL and results from billets beginning to equilibrate to the surrounding gas temperature. The cooler billets that would remove the heat are no longer moving through the furnace.

The lower plot in Figure 56 compares the O_2 measured between the TDL and extractive sampling system. The TDL results are lower than the sampled results because of the differences between wet and dry measurements. In addition, absolute agreement is not expected since we are comparing a single point measurement with a 50 ft. path averaged result. Despite the differences in the measurement techniques, the overall trend agrees

suggesting that the furnace gas mixture is fairly homogenous. Comparing these results with the equivalence ratios from zone 1 and 2, one can see that zone 1 has a greater impact on the observed O_2 concentration. In addition, the effect of the billet movement on the O_2 concentration measured by the TDL system is similar to what was observed in the soak zone. The measured water concentration, not shown here, also shows a dependence on the billet movement, but instead of an observed decrease in concentration, as seen with O_2 , the H_2O concentration increases suggesting the possibility of a reaction taking place.

Figure 56. TDL temperature and O_2 monitoring results from the heat zone compared with process data and extractive sampled O_2 measurements.

A closer examination of the variation in the real-time O_2 concentration observed in the heat zone for changes in the billet position is shown in Figure 57. In this case, up to 30 % change in the O_2 concentration was detected for the measurements close to the billet surface. This level of change observed is too high for surface oxidation alone. Therefore, other process dynamics such as the influence of the beam movement on the gas flow pattern through the furnace would need to be investigated. When compared to the similar changes in O_2 concentration observed in the soak zone, the reduction in O_2 was only 15%. This amount is still significant considering the overall level of O_2 observed was at 2-3% in the soak zone. The overall trend in the measured O_2

concentration correlated well with the burner operating conditions, as shown in Figure 57 for the total heat zone air/fuel ratio, divided by 10 for scaling purposes. As the air/fuel ratio was adjusted making the combustion more efficient the temperature increased and the O₂ concentration decreased. Several minutes of lag-time between the air/fuel ratio adjustment and temperature were observed. This is explained by the large volume of the process and the gases monitored in the heat zone are mixed with the exiting gas from the soak zone.

Figure 57. Real-time temperature and O₂ concentration monitoring from the heat zone of the furnace. Also shown is the total air/fuel ratio for the heat zone based on the burner flow rates.

8.4 Conclusions from the Reheat Furnace Measurements

The TDL measurement results for O₂, H₂O and gas temperature on the reheat furnace indicate that correlations between the measurements and the furnace operating conditions exist. This suggests that adjustment and optimization of the furnace operating conditions can be achieved using the sensor. This step was not pursued here since the sensor installation was not setup for 24/7 monitoring because of limited purge gas supply. In addition, integration of the sensor into the process control system would be necessary to fully evaluate the impact of the measurement for improving energy efficiency, product quality, waste minimization, and/or reduction in pollutants. As one example, waste minimization by scale control could be realized by maintaining an O₂ level near 1.5% as recommended by Abuluwefa et al. [10]. In this case, feedback from the TDL sensor to the process control system would continuously adjust the process to maintain the optimal O₂ level in the selected zones. Long-term testing over a several month period is required to evaluate the potential benefits or drawbacks.

9. Aluminum Recycling Furnace (2nd Industrial Test)

Aluminum recycling was selected as a 2nd industry to evaluate the TDL sensor for both rotary and reverberatory furnaces. The aluminum industry was identified by Air Liquide as having a potential need for process control and optimization using an advanced sensor technology. Since this also falls under the category “Industries of the Future” (IOF) with a need for sensor technology, it was viewed as good match for both Air Liquide and DOE. The objective for testing on the rotary and reverberatory furnace focuses on evaluating the measurement technique for potential energy efficiency improvements and material waste reduction.

9.1 *Aluminum Furnace Host-site Selection*

For the 2nd industrial sensor test IMCO Recycling, Inc. (IMCO has since changed to Aleris International, Inc. resulting from the merger of Commonwealth Industries, Inc. and IMCO Recycling, Inc. in 2004) was selected as a host-site partner with the objective of conducting the test on both a reverberatory and rotary furnace. The initial site selection was at IMCO’s Uhrichsville Ohio plant. However, a site survey conducted in July 2002 determined that their Uhrichsville reverberatory furnace would be a difficult installation because the charge well location on their furnace would interfere with the launch or receiver module installation. A clear line-of-sight optical path was not feasible with this furnace configuration; since the beam would have to propagate over the charging well. If only CO monitoring was of interest then the sensor could be adapted to launch the beam through the ambient air to a port above the charge well. Including O₂ in the monitoring would require shielding the beam from ambient air, which is possible however the shield must be removable for access by the puddler that stirs the aluminum chips. Because of the added complexities on this furnace, an alternative site at IMCO’s Loudon Tennessee plant having a clear line-of-sight access was identified.

A site-survey at the Loudon plant conducted during the first week of October 2002 determined that interfacing the TDL sensor to both their reverberatory and rotary furnaces was possible. The Loudon reverberatory furnace operates at a maximum production capacity of 5000 lbs/hr. The raw materials melted consist of machine turnings, wheels, and 357 aluminum alloy returned parts and ingots. Melt chemistry is held at tight specifications for their main customer who uses the melt for automobile brake caliper manufacturing. The IMCO rotary furnace uses a proprietary design so a description is not disclosed here. However, to address the rotary furnace monitoring requirements a special interface design was developed. Unfortunately, measurements on the rotary furnace were not made because of technical issues encountered on the reverberatory furnace that resulted in scheduling delays. Details of the problems faced and measurement results from the reverberatory furnace are discussed in the following sections.

9.2 Sensor Installation on Aluminum Reverberatory Furnace

In November of 2002 modification on the reverberatory furnace were started for installing the sensor launch and receiver modules. All process modifications made on the furnace took place during normal plant operation without introducing any process disturbances. The first step involved identifying the optical access port locations on the furnace using surveying tools. This approach was taken to insure line-of-sight optical access was achieved. Once the access port locations were identified, a 7.5 cm diameter hole was drilled through 40 cm of hot refractor. Extra time was required for the hole drilling operation because of special procedures adopted to avoid using water-cooled equipment. After drilling the holes, the alignment was checked before installing the interface hardware used in mounting the launch and receiver module.

The overall furnace dimensions and location of the laser measurement is illustrated in Figure 58. With this configuration, the measurement was conducted as close to the bath as allowed by IMCO. This set the beam position between .4-.56 m relative to the bath which varied depending on production demands. Ideally conducting the measurement closer to the bath would have been preferred to investigate the interaction between the gas and metal interface. The laser measurements were conducted along the centerline of the furnace between two North American HiRam™ burners. The burners operated with a nominal firing rate of 6 MMBtu/hr. The combustion control on the furnace operated either in high-fire (full power) or low-fire mode (2 MMBtu/hr) based on set-point temperatures of the furnace roof and metal bath. Material charging of machine turnings, casting rejects, and other scrap was loaded in the charge well area. Prime ingots were also loaded into the furnace through the skim door opposite the charge-well. The skim door was also opened every few days to remove the oxidized metal layer that builds-up on the bath.

A front view of the furnace indicating the sides where the launch and receiver modules are mounted is shown in Figure 59. The launch module is mounted on the same side where furnace tapping takes place. The electronics unit for the TDL sensor that houses the lasers and controllers was positioned on the furnace catwalk, as shown in Figure 60. This location was selected for ease of installing the fiber optic and signal cables and provided a safe location away from routine production traffic. However, the disadvantage is poor environmental temperature control and safety with respect to the access (ladder). Unfortunately, the furnace control room was not feasible because of limited space and alternative locations were prohibitive due to forklift traffic. For a permanent sensor installation the catwalk location would not be recommended, but was adequate for this short demonstration. In addition to installing the laser system, a conventional extractive sampling (O_2 , CO , CO_2) system was installed in the exhaust duct, as shown in Figure 58. For this system, a stainless steel probe was used to extract the gas sample in the lower temperature flue region. The use of water-cooled probes was forbidden by IMCO because of potential hazards if a leak occurred.

Figure 58. Schematic of the IMCO reverberatory furnace showing the location of the diode laser measurement relative to the bath.

Figure 59. Front view of the reverberatory furnace indicating the launch and receiver module sides.

Figure 60. Side view of IMCO reverberatory furnace indicating the position of the receiver module and location of the laser & acquisition system.

Module installation for the launch and receiver are shown in Figures 61 and 62. The installation was tight on both sides of the furnace because of the piping location and other process equipment. For the receiver side the module was rotated 90° to fit between the skim door hoist mechanism and an electrical distribution box. Additional support bracing was used for the module installation to decouple the unit from the furnace skin, as shown in Figure 61. The receiver module was mounted using a threaded nipple sandwiched between a top and bottom brace with insulation material placed between the skin and module interface. This support bracing was attached to the main I- beam structure of the furnace thereby decoupling the module from the thin metal furnace skin.

Figure 61. Launch module installation.

Figure 62. Receiver module installation with 90° rotation.

9.3 Measurement Stability Problem

The first reverberatory furnace measurements that began in November of 2002 revealed a problem with the stability of the laser beam alignment. Measurements could only be made for short duration (1- 30 minutes) before the signal degraded. Furthermore, stability of the measurement was found to be dependent on the furnace operating conditions, e.g., high-fire or low-fire. The instability observed in the measurement was unexpected, especially with the method used in decoupling the modules from the furnace skin.

To identify the problem a measure of both the launch and receiver module stability was conducted by attaching a HeNe laser to the module. The beam from the HeNe laser was then directed away from the furnace to a target mounted on the wall. By measuring the displacement of the beam, the angular movement of the module was measured. The quantitative measure of each module's angular displacement compared with the furnace pressure is shown in Figures 63 and 64. Depending on the operating mode of the furnace the pressure changes from negative at low-fire to positive at high-fire. For both cases the module displacement showed sensitivity to the furnace pressure. However, the launch module angular deflection was small and appeared somewhat random varying between 0 and -.12 degree. Measurements from the receiver module in Figure 64 show the degree of movement was an order of magnitude higher compared to the launch module. In addition, the receiver module displacement seemed to correlate well with the furnace pressure. Based on this analysis, the receiver module was identified as the main problem in maintaining measurement stability. For both modules, horizontal movement was insignificant compared to the vertical displacement.

Figure 63. Comparison between furnace pressure and vertical angular deflection of the launch module.

Figure 64. Angular deflection measurements taken from the receiver module that show the dependence on furnace operating pressure.

An explanation for the instability observed from the receiver module is illustrated in Figure 65. This location is susceptible to hot furnace gas penetrating the optical access hole because of the burner momentum and furnace pressure during high-fire mode. The receiver module location is on the opposite of the two North American burners. During high-fire mode the pressure and flow becomes high enough to overcome the opposing purge gas flow. This resulted in hot process gas penetrating into the optical access hole where many crevasses exist between the castable and furnace skin. The excessive heat load on the skin resulted in thermal expansion severe enough to deflect the module even though it was decoupled from the skin.

Figure 65. Illustration of the measurement stability problem encountered for the receiver module.

A solution to fix this problem using a modified interface piece original designed for pathlength control monitoring on the rotary furnace was adapted to fit the furnace access port. The modified interface, shown in Figure 66, used an extension tube inserted into the access hole up to the castable refractory. The extension tube provided a well-defined volume for the purge gas to flow preventing furnace gas from reaching the skin area. After installation of the modified interface, continuous monitoring was possible for several days with no evidence of the module instability problem. However, sorting out these technical issues delayed the overall test schedule and only 3.5 days of continuous monitoring was achieved. Therefore, a second test was scheduled for February 2003 to conduct a long-term evaluation of the TDL measurement stability and reliability. Another objective of the second test was to perform low-level furnace optimization based on the TDL measurements.

Figure 66. Illustration of the modified interface used to improve the stability of the receiver module.

9.4 Real-Time Monitoring on Reverberatory Furnace

After sorting out the technical issues related to stability of the modules on the furnace, a second test campaign took place in February 2003. A sample set of data acquired for simultaneous monitoring of O_2 , CO , H_2O and gas temperature with the TDL system is shown in Figure 67. In this example, the change in process operating conditions is indicated by low-fire (high O_2) and high-fire (high CO , H_2O and T) mode. Furnace operation switches between these two modes depending based on set-point temperatures of the roof refractory and metal bath. What's obvious in the measurements is that under low-fire conditions an excess level of O_2 is present whereas at high-fire conditions the combustion atmosphere switches to reducing. The reducing environment is preferred by the furnace operators to limit the metal losses due to oxidation. The observed O_2 concentration increase that occurs during low-fire results from the furnace pressure becoming negative. This allows air to enter the process mainly through the skim door seal that has an outer perimeter of 44 ft (see Figure 58).

The TDL sensor captured the dynamic changes in the process and showed good agreement with extractive sampling results, shown in Figure 68. However, some differences were observed between the two measurement techniques. First, the response-time of the TDL system was measured to be ~100 sec faster than the extractive sampling measurements. This is expected since the sampling line required for the extractive system was over 50 ft long. Other differences were observed in some of the concentration profiles recorded between the two techniques. For example, at around 1:00 the CO from

Figure 67. Measurement results from the TDL sensor showing simultaneous monitoring of temperature, CO, H₂O, and O₂ above the metal bath.

the TDL measurement showed a rapid increase whereas the extractive measurement displayed only a gradual increase. The occurrence of profile differences was not consistent suggesting the TDL sensor is capturing a real process change. Finally, the extractive dry CO measurement was consistently lower compared with the wet TDL measurements. This suggests that further CO oxidation or dilution most occur between the TDL measurement location near the melt bath and the extractive probe in the exhaust stack.

Figure 68. Extractive sampling measurement results collected simultaneously with the TDL measurements shown in Figure 67.

9.5 Reveberatory Furnace Optimization

After demonstrating the TDL sensors reliability for several days of around the clock monitoring, the next-step was to perform low-level optimization on the furnace. The measurements from the TDL suggested that the CO level above the bath was higher than the normal 2% target value the furnace operator tries to maintain. This furnace lacked gas monitoring instrumentation so the furnace operator had to rely completely on the burner air/fuel settings. The optimization was performed by varying the fuel flow rate and holding the combustion air fixed. Therefore, both the combustion atmosphere above the bath and total firing rate of the burners varied. This approach was taken to insure that the furnace operating conditions could easily be switched back to original settings. Alternatively the air could have been adjusted, but this required an off-site technician to go through a series of burner adjustments that would disrupt normal production.

A comparison of average CO levels collected during high-fire mode is shown in Figure 69 for both the TDL and extractive measurements at the different conditions tested. These results illustrate that for all conditions the level of CO near the bath is consistently higher than the stack measurement. The baseline operating conditions of the burner before adjustment was at 13.7 MMBTU/hr with a CO level > 4% detected by the TDL system. This suggests that improved combustion efficiency could be obtained by adjusting the stoichiometry to reduce the CO concentration to a more acceptable level near 2%. Whereas the extractive sampled measurements in the stack implied a higher firing rate is required to achieve the same 2% reducing atmosphere.

Results from the furnace optimization based on the combustion atmosphere are summarized in Table 3. The baseline case (initial conditions) and the final operating conditions set for long-term operation are indicated. Also shown in Table 3 is the fuel savings for 2003 natural gas cost when this test was conducted and updated 2006 fuel

cost. For the final burner setting, a conservative approach was taken to minimize any potential production disruptions or increases in dross formation. A power setting of 13 MMBTU/hr was used for long-term operation which resulted in an average CO concentration measured by the TDL near 3% suggesting that further reduction was still possible. Operating at 12.5 MMBTU/hr is acceptable and would have provided even further savings in fuel. The fuel savings reported in Table 3 is for operating the furnace 100% and 51% of the time in the high-fire mode. Because the furnace control system switches between high-fire and low-fire based on bath and roof temperature set-points, the furnace only operated 51% of the time in the high-fire mode. Therefore, the projected fuel savings should be based on the 51% high-fire mode. Finally, a follow-up several months later indicated that the optimization changes made had no impact on production or metal loss.

Figure 69. Furnace optimization results comparing average CO measurements between the TDL and extractive system.

Table 3. Combustion conditions tested and resulting fuel savings.

		2003						2006		
		NG Meter (scfh)	MMBTU/hr	MMBTU/yr	Energy Reduction (MMBTU/yr)	Percent Fuel Savings	Savings (HF 100%)	Savings (HF 51%)	Savings (HF 100%)	Savings (HF 51%)
Baseline Setting	→	14084	13.7	119782	0	0.0%	\$0	\$0	\$0	\$0
Current Setting	→	13745	13.3	116899	2883	2.5%	\$14,319	\$7,303	\$31,196	\$15,910
	→	13398	13.0	113948	5834	5.1%	\$28,976	\$14,778	\$63,127	\$32,195
	→	12840	12.5	109202	10580	9.7%	\$52,546	\$26,798	\$114,476	\$58,383
	→	11807	11.5	100417	19366	19.3%	\$96,179	\$49,051	\$209,535	\$106,863

2003 costs

Natural gas calculations based on 1030 scfh = 1MMBTU/hr

\$4.9665/ DecaTherm= \$4.9665/MMBTU

2006 costs

\$10.82/ DecaTherm

Further improvements in the process efficiency could be achieved by coupling the TDL sensor to a combustion control system. This would provide better control of the atmosphere above the bath and avoid the drastic swings between high-fire and low-fire mode. For example, the bath temperature would continue to rise after switching to low-fire, as shown in Figure 70. This indicates too much energy was being put into the furnace forcing the process to continuously switch between modes. Here the set-point temperature for the bath was at 1044 K and when the bath temperature exceeded this level the furnace automatically switched to low-fire mode.

Additional observations from the TDL sensor and process operating conditions are illustrated in Figure 70, which indicates the impact of charging the furnace with large ingot material (prime). In this case, 8994 lbs of ingot was added to the furnace by opening the skim door. Following the ingot charge, the bath temperature shows a large temperature drop followed by a gradual increase while high-fire mode is maintained. The TDL measurement for both temperature and CO shows a similar rate of increase during this period. This observation led to a detailed analysis of the data to determine if any correlations existed between the TDL measurements and furnace operating conditions. From the analysis the parameter that resulted in the best correlation was the temperature rate (dT/dt) during the addition of large ingots, as shown in Figure 71.

Despite the scatter in the results shown in Figure 71, the trend is clearly observed between the heavy ingot charges and rate of temperature increase. At first glance, it appears that the temperature rate may correlate at other times, e.g., around 18:30 and 19:42 in Figure 70, but the measured rate randomly varies and only correlates well with prime ingot. A large mass of ingot results in a large initial temperature drop of the metal that acts as a heat sink decreasing the gas temperature. The temperature measurement from the TDL appears to be more sensitive to this effect compared with the temperature rates calculated from the bath or flue temperatures shown in Figure 72. Therefore, monitoring the temperature rate of change could be used in projecting when the bath will reach the set-point value. A more extensive set of data would be required to assess the

Figure 70. Comparison of TDL measurements with furnace operating conditions.

reproducibility of these observations and determine how, if at all, this additional information could improve the process. Nevertheless, it does demonstrate the type of additional information obtained by the TDL sensor when conducting the measurement near the processed material. A similar phenomenon was observed from measurements performed on the steel reheat furnace, as discussed in section 8.3, showing the temperature variation as a function of the distance from the steel billet.

Figure 71. Rate of change in temperature measured by the TDL following an ingot charge.

Figure 72. Rate of change in temperature based on the process bath and flue temperature following an ingot charge.

9.6 TDL Performance Evaluation for Reverberatory Test

TDL measurements on the reverberatory furnace were made continuously for ~ 8 days. The main limitation for conducting a long-term test was the lack of a continuous and reliable purge gas supply at the plant. To maintain the purge on both modules during the test liquid N_2 dewars were used. However, this required periodic changing of dewars roughly every 20 hours. This procedure required that Air Liquide personnel be present to prevent any potential damage to the modules if the purge source was lost.

To assess the reliability and quality of the measurement an evaluation of the sensor data was performed. This evaluation determined the percent relevant data collected based on a post-processing filtering scheme to remove erroneous data points. The results of this analysis are summarized in Table 4. Here the percent relevant data is defined as usable data after filtering the extraneous data that was collected. At times a measurement was made for temperature or species concentration that was not physically realistic. Usually, the erroneous temperature or species data are coupled, e.g., if the temperature is high or low the corresponding concentration follows. The origin for the extraneous data comes from several possible sources such as vibration and beam extinction. Other sources observed during the IMCO test was channel crosstalk related to signal collection electronics, liquid N_2 droplets from the purge source scattering the laser light, and fiber optic cable disturbance.

The following conditions were used for the data filtering:

Table 4. TDL performance evaluation

$1000 < T < 2000$ $-.2 < \%H_2O < 30$ $-.2 < \%CO < 10$ $1.5 < CO/H_2O \text{ linear} < 10$ $1.5 < O_2 \text{ linear} < 10$	Date	Data collection Time (hours)	% Relevant Data	Comments
	25-Feb	0.6	71.9	Channel Crosstalk
	25-Feb	12.3	76.5	Channel Crosstalk
	26-Feb	1.8	81.5	Channel Crosstalk
	26-Feb	1.7	87.2	
	26-Feb	15.2	95.8	
	27-Feb	7.1	94.9	
	27-Feb	2.9	93.8	LN2 Scattering
	27-Feb	14.2	99.0	
	28-Feb	4.8	93.6	Fiber repair
	28-Feb	2.5	99.4	
	28-Feb	15.5	99.0	
	1-Mar	9.8	96.9	
	1-Mar	11.9	98.4	
	2-Mar	22.1	96.5	
	3-Mar	2.6	91.9	
	3-Mar	2.6	99.7	
	3-Mar	9.8	96.5	
	3-Mar	14.2	86.6	Channel Crosstalk
	4-Mar	9.8	96.5	
	4-Mar	13.8	93.6	
	5-Mar	3.1	98.8	
	5-Mar	4.9	93.5	
	182.9 hrs 7.6 days		Avg	92.8

If anyone of the monitored parameters fell outside the minimum or maximum value listed in Table 4 then all values at that time are flagged as being erroneous and removed. For example, if a temperature value of 3000 was recorded then the corresponding H₂O, CO, O₂, and linear data values were also removed for that period. The small negative values for % H₂O and CO are included in the filtering to obtain a baseline at low concentrations. An O₂ concentration minimum and maximum range was not included because of the high susceptibility of wavelength drifting caused by the unstable ambient temperature environment. This was not an issue most of the time, since the wavelength drift was periodically checked and corrected if needed.

Results from Table 4 indicate the TDL performance was poorest at the beginning of the test. Part of this reflects a certain level of optimization required during the initial set-up. Nevertheless, the results are tabulated to determine what actions are required to improve the measurement. In this case, the poor data quality was identified to result from the channel crosstalk problem related to the data acquisition electronics. Subsequent data collected after fixing this problem improved the relevant data from 71% to 95%.

Finally, the launch and receiver module was examined at the end of the 8-day continuous process monitoring test. Each module use a dielectric coated window that isolates the internal optic components from the process gas. The window interface design incorporates a purge gas flow over the surface to provide cooling and cleaning of the window. The window coating can be damaged at temperatures over 400 °C, but examination of the launch module window showed no degradation in the coating or dirt on the surface. However, the receiver module window was spotted with aluminum droplets, as shown in Figure 73. The source of the aluminum is likely due to either the skim operation for white dross removal or charging the furnace with large ingot. In the skimming procedure, an operator drags a large scraper across the bath surface to remove the dross build-up. Splashing of aluminum during the skim operation can occur as the operator churns up the bath surface. For charging ingots, the operator stacks ingots along the front shelf of the furnace in pairs. In this case, one ingot is partially submerged in the bath supporting a second ingot resting on the furnace shelf. As the ingots begin to melt the second ingot falls into the furnace, which can result in splashing. In addition, after ingots are loaded the furnace operates in high-fire mode, thus aluminum droplets can be transported by the flame momentum to the window. This may explain why deposits are only observed on the receiver module window, which is directly impacted by the flame gases. If the TDL sensor is used for day-to-day measurements a protective shutter that closes during the furnace skim operation or large ingot charging would be recommended along with a higher purge flow rate.

Figure 73. Receiver module window showing aluminum deposits after 8-days of operation

9.7 Sensor Improvements

Following the IMCO industrial trials several system improvements were implemented. Most of the improvements were software data acquisition related, as discussed in Section 5.1. The one major problem identified as signal crosstalk in the data acquisition electronics required further diagnostics and testing. This problem was observed during pilot furnace testing, but was not as obvious since these tests were performed under well controlled conditions. The origin of this problem was traced to result from residual charge on the A/D converter that was contributing to the signal crosstalk when a subsequent channel was monitored. Discussions with the A/D manufacturer led to a solution that was tested in the lab by simulating crosstalk, as shown in Figure 74. Here the O₂ signal generated on the LHS indicated by the dip also appears in the reference

channel of the CO/H₂O laser. After applying the fix, the ghost O₂ trace is removed, as shown in Figure 75 for an amplified O₂ signal. In this case, the isolation is better than 40 dB. However, some second order effects are still observed due to saturation of the digitizer in this example.

Figure 74. LHS shows an O₂ signal that also appears on the RHS in the reference channel of the CO/H₂O laser.

Figure 75. LHS O₂ signal > ±10 V is barely detectable in the RHS CO/H₂O reference channel.

10. Electric Arc Furnace Off-gas Monitoring

The industrial demonstration of the sensor technology on the steel reheat furnace and aluminum reverberatory furnaces set the groundwork for developing an off-gas monitoring system used on electric arc furnaces (EAF). The EAF can be considered one of the most demanding processes for a sensor application because of the harsh environment. Instrumentation in this environment must withstand exposure to high temperatures, immune to strong electromagnetic fields, resistant to mechanical vibration, and protected against flying debris. The challenge for the conducting measurements is the dynamic process conditions that are characterized as having large changes in temperature and composition with varying particulate levels in the gas stream. This combination of the environment and monitoring conditions requires special design considerations for successful operation of the sensor on the EAF.

To address the sensor requirements for EAF off-gas monitoring, the semi-harsh system developed in the first phase of this program was modified to incorporate several add-on options. In general, the diversity of industrial process that could benefit from using the TDL sensor technology developed under this program is broad. However, each process poses unique requirements related to interfacing or monitoring conditions or both. The development of the optional add-on modules used with the basic sensor platform addresses such needs as long-distance data acquisition, high and varying particle density gas streams, remote alignment, hardened modules, and an adaptable process interface design. Depending on the process demands different combinations of these add-on options can be used to adapt the basic sensor platform to the particular process. The details of the different add-on options are discussed in the following sections that cover the installation and testing of the sensor for EAF off-gas monitoring.

10.1 *EAF Host-site Selection*

At the end of 2002 a host-site selection process started in parallel to the work being conducted on the IMCO aluminum reverberatory furnace. CHARTER STEEL was considered as a prime candidate for this work, but their EAF used a moving exhaust duct. Adapting the sensor to their furnace exhaust would have added to the complexity of the module and interfacing design. Therefore, a more traditional EAF that employed a stationary exhaust duct configuration was sought. This approach was taken since the objective of the first EAF test was to successfully demonstrate the technology by identifying and solving the technical issues. Once demonstrated on the standard EAF configuration adapting to different process requirements will be easier.

The host-site survey consisted of contacting and visiting several plants. Results from the survey led to selecting North Star Steel (part of Cargill, Inc. that was purchased by Gerdau Ameristeel US, Inc. in 2004 and will be referred to as Gerdau in the remainder of this document) in Wilton Iowa. This site was selected based on the their level of interest in the project, the proximity of the plant relative to Air Liquide's research center, and the

moderate plant production levels. The Wilton facility has a single 80 ton 25 MW AC EAF with four sidewall burners. The burners consist of two natural gas oxygen burners and two others that also incorporate carbon injection. Maintenance is preformed on the furnace over an 8-hour shut down period that occurs weekly. It's during these shut down periods that access to the furnace for installation and testing are made. With the plant location being 190 miles from Air Liquide accessibility by car is easily handled for frequent visits.

After selecting the Wilton plant as the host-site, test agreement negotiations were launched. Delays encountered in the negotiations took until October 2003 to finalize the agreement. In the meantime preliminary testing and design work for process interfacing of the launch and receiver was on-going. This work also included plant survey work on temperature monitoring near the installation area planned for the modules and EMF (electric magnetic field) measurements at various locations. In addition, identification of utility requirements and contacting approved contractors for piping and electrical bids was started. For the TDL sensor, upgrades required for EAF off-gas monitoring was started by PSI upon completion of the IMCO aluminum reverberatory tests. The sensor upgrades included a fiber optic signal communication system, remote optical component alignment, and the on-demand laser power control system.

10.2 EAF Process Modifications

In the interim of finalizing the test agreement, several site visits were conducted for developing interface designs to the process, identifying the location of the electronics and data acquisition system, specification and location of utility requirements, and scheduling. In addition, preliminary measurements were conducted near the EAF to measure the ambient temperature and electro-magnetic field during several melt cycles. For the ambient temperature monitoring, thermocouple probes were placed near the planned module mounting location. The temperatures recorded showed an average temperature of 44°C and peak temperature of 90 °C. This information was critical for the module design, since electronic components, e.g., fiber-optic link and optic mount motors, are housed in the modules. These preliminary measurements were useful for determining cooling and shielding requirements.

A schematic of the EAF furnace shown in Figure 76 illustrates the furnace location relative to the drop-out chamber (DOC) downstream of the exhaust elbow. The DOC provides a first level of particulate removal by catching the larger debris that is not transported to the bag house by the exhaust flow field. Between the DOC and exhaust elbow a break flange is used to control the gap distance. At the gap, air is allowed to ingress and mix with the exhaust gases for cooling and combusting any residual CO. For off-gas monitoring, the measurement location of interest is indicated by the red circled region at the gap. In this region, the gas composition at the center of the duct is representative of the process gas composition. Measurements made farther down-stream of the gap are affected by the air ingress that dilutes the exhaust gas and reacts with CO.

Figure 76. Illustration of the EAF and drop-out chamber.

The monitoring location selected for the sensor installation was near the break-flange. Other options were considered such as direct monitoring in the furnace, monitoring in the gap, and monitoring in the exhaust elbow. However, each of these options is faced with technical hurdles. For example, direct furnace monitoring is prohibitive because of the steel loading and violent nature of the arcing process. Sensor location on the exhaust elbow is possible, but complications because of the roof moving during steel scrap charging and the modules experiencing a high-level of process vibration makes this location a riskier alternative. Measurement in the gap is the most attractive, since optical access exists. However, the high-level of particulate matter from the furnace requires a reduced pathlength measurement to ensure the laser radiation transmits across the exhaust flow.

To guarantee that laser light transmits across the duct a reduced pathlength approach was implemented using water-cooled pipes inserted into the exhaust duct. The laser beam is launched through one water-cooled pipe, allowed to cross the exhaust medium over a set distance, and is then received by the second water-cooled pipe. This approach shortens the measurement path and controls where the measurement is made. Adapting this idea to the gap is possible provided enough clearance between the exhaust elbow and break flange exists. Generally this is not a problem during the melting operation where the gap distance can vary from 3-6 inches. However, during the steel charging process the furnace roof and elbow assembly rotates. Depending on the furnace design the arc of the roof rotation can make the distance between the gap and elbow too small for probe insertion at this location. This was the case for the Gerdau furnace, so the pathlength controlled probes and module installation selected was just downstream of the gap. At this location, modification of the break flange was required to provide access for the

water-cooled path length control probes. One advantage of this location was the access to the main I-beam supports of the DOC structure for mounting the launch and receiver modules. Mounting directly on the I-beams provides a structurally sound installation that minimizes disturbances from mechanical vibration. Besides mounting the modules, provisions for an extractive sampling probe located directly above the laser measurement location was incorporated. The extractive sampling is used for comparative measurements by monitoring CO, O₂, and CO₂.

Selecting the break flange for the water-cooled shielding probes and extractive probe location required modifications to provide access holes. Adding access holes was complicated since the break flange structure is made up of water-cooled pipes. Inserting a hole required rerouting the pipe arrangement while still preserving the required flow rate for cooling. Ferrex Engineering, LTD. (253 Lake Driveway W., Ajax, Ontario Canada L1S 5B5) was contracted to develop design drawings for the break flange with access holes. Ferrex was the original designers of the DOC assembly and had the necessary expertise and experience in designing steel manufacturing equipment.

Fabrication of the break flange assembly based on the design developed by Ferrex was contracted out to Melter Manufacturing (Parque Industrial Almacentro C.P. 66600, Apdaca, N.L. Mexico). Melter was selected based on Gerdau's past experience, price, and estimated delivery time. Figure 77 shows the delivered assembly received in early March 2004 with the access holes pointed out. In addition, the water feeds and returns were modified to provide additional space needed for mounting the launch and receive module. The break flange installation was completed at the end of March 2004 and required an extended plant shutdown resulting in a production loss of ~\$36K.

Figure 77. Modified WCP designed by Ferrex Engineering and fabricated by Melter Manufacturing.

To illustrate the modifications made in the break flange, Figure 78 shows the original assembly with the water supply piping that would interfere with the module installation. In the RHS of Figure 78 the newly installed assembly is shown with an indication of the access hole and module locations. Rerouting of the waterlines was performed by our piping contractor Northwest Mechanical, Inc. (5885 Tremont Ave, Davenport, IA 52809). The changes in piping to the break flange assembly were the main reason for extending the installation by ~8 hours.

Figure 78. A comparison between the old and modified installed WCP.

All sensor utility requirements such as fiber optic cabling, electrical, water, and purge gas distribution were completed by the end April 2004. Based on Gerdau's recommendations the fiber optic cable installation shown in Figure 79 originates in the sensor room where the TDL electronics and data acquisition are located. Fiber patch cords are used from the sensor to the distribution panel. From the distribution panel the laser radiation and communication signals are transported to the modules. The fiber cables are protected in conduit pipe that runs along the buildings interior perimeter to a fiber splice panel located behind the DOC. From the splice panel fiber pigtails with the required termination ends were fusion spliced and distributed to the launch and receiver modules. Fusion splicing was necessary since the connectors on the fibers are angle cut (FC-APC style) to prevent back reflections. Each module has a junction box (j-box) located behind the I-beams for slack control of the fiber. From the J-Box the fiber is connected to the module by a flexible line. Before fiber installation a preliminary test was conducted to evaluate potential noise in the TDL signal resulting from the fusion splice process. This precautionary step was taken because we had no previous experience in using fusion spliced fiber components made in the field. Furthermore, the smaller 5-micron diameter fiber used by the O₂ laser is not a standard telecommunication size and the contractors had no experience splicing this size fiber. Results from the fusion splice test showed no evidence of signal degradation. All electrical and fiber optic cable installation that includes fusion splicing was contracted to Koehler Electric.

Figure 79. Layout for fiber-optic cable installation

Because of the limited work space available, Gerdau installed a platform work area behind the DOC, as shown in Figure 80. This area is used for locating the extractive sampling gas pump, chiller, and analyzers. The location provides both a safe work area during normal plant production and minimum distance between the analyzers and extractive probe. The area also houses the purge gas distribution manifold and fiber optic cable splice box.

Figure 80 Work platform for extractive sampling equipment, gas manifold for purge control, and fiber optic cable splice box.

Figure 81 Southside view of the process drop-out chamber showing the installation of the water feed manifold and piping along with the junction box for fiber optic cable delivery.

The water-cooling piping that supply each sensor module was installed by Northwest Mechanical. Two water feed lines are used for each module. One line is dedicated to the pathlength controlled water-cooled shielding pipe that is directly exposed to the high temperature furnace exhaust gas. The other line is dedicated to the module, which houses the optical and electro-optic components. To insure the internal temperature is maintained at the required level a thermocouple was installed in each module. In addition, each water supply line is accompanied by a dedicated return line with a thermocouple installed to monitor the heat removed by the cooling water. Figure 81 shows the water supply manifold installed on the south side of the DOC. Also shown are hard conduit runs for the fiber optic cable that end at the junction box where a flexible line is used for the connection to the module. A similar junction box and water supply lines with returns and purge gas supply lines are mounted on the opposite side of the furnace.

The purge gas supply to each module uses two lines. One purge line distributes the gas between the internal module components and to the window where the gas exits from the pathlength controlled shielding probe. This provides a continuous flow of gas to the shielding probe to help prevent dust build-up in the probe and on the window. The second line is dedicated only to the shielding probe and enters near the window. This line provides a high flow purge that is automatically activated every 30 minutes for probe cleaning.

10.3 *Module Design and Installation*

For monitoring the EAF off-gas, a pathlength-controlled shielding probe was used in the process interface design. This approach had two main objectives. First, it reduced the measurement pathlength to improve the laser beam transmission. The particle level in the EAF off-gas is too high for adequate laser beam transmission using standard telecommunication lasers. Furthermore, even with boosting the launch laser power by using an amplifier it was not clear if transmission across the exhaust duct could be achieved. The second advantage of using the pathlength-controlled probes is to provide a well-defined measurement region. This avoids measuring the region where air and process gas is mixed along the perimeter of the break flange and focuses the measurement to the center of the exhaust. The measurement pathlength was initially selected at 60 cm. This distance was compromise between the absorption strength and laser transmission. Experience from the pilot furnace tests suggested that 30 cm pathlength was on the short side and an increase in pathlength would improve the SNR.

The basic design concept for the pathlength-controlled probes was completed near the end of 2002 and only slight modifications were needed to finalize the design. The launch and receiver module did undergo numerous design iterations to meet several criteria identified from the plant surveys. The main issues addressed in the module design were structural integrity, cooling, accessibility, alignment and positioning, streamlined installation, Faraday cage design for EMI and EMF isolation, and sized for the space restrictions imposed by the mounting area. The finalized design for module assembly

interfaced with the pathlength controlled probes mounted on the support columns of the DOC is shown in Figure 82.

Figure 82 Assembly drawing for the launch and receiver module with the pathlength controlled water-cooled probes mounted on the exhaust of an EAF.

As shown in Figure 82 the modules are mounted on the main I-beam support structure of the DOC. The module assembly consists of two main pieces: an outer shell that serves as a protective layer and main mounting support and the internal water-cooled module housing the optic and electro-optic components. Positioning of the internal module is made by several adjustment screws that provide x, y, z, and tilt. Incorporating this level of positioning was necessary because of the unknown tolerances between the break flange assembly and DOC. The scale of the process equipment can easily tolerate $\pm .5$ inch errors whereas the sensor installation demands much stricter tolerances because of the line-of-sight requirement. Accessibility to the modules is obtained through the outer shell door followed by the inner module door. This is illustrated in Figure 83 showing the assembled launch module. The RHS shows the module in the sealed position used during normal furnace operation. The LHS shows the module with the different layer of doors in the open position to access the internal components.

Figure 83. Assembled launch module.

Streamlining the installation was considered in the design by incorporating a pivot point, as shown in Figure 84. The pivot point position was referenced to the break flange assembly using an alignment jig. Once the position was determined a support bracket at the pivot point was welded to the I-beam. The module can then be transported horizontally to the I-beam and attached to the support bracket. The module is then rotated vertically toward the I-beam and secured by mounting brackets. This approach was taken because direct installation of the modules in the vertical position was complicated by the surrounding piping that restricts the necessary mobility needed for mounting. The pivot design also provides a convenient way to access the water-cooled pathlength controlled pipes for maintenance and replacement.

Figure 84. Side view of the module illustrating the pivot motion incorporated in the design

In the design phase for the modules and probes, close attention was paid to alignment issues. The scale of the break flange assembly and the number of welds used in fabrication makes it difficult and costly to preserve high tolerances. Therefore, the pathlength controlled probe design incorporate a self-positioning system. Before installation on the DOC a test installation of the probes was performed to identify any potential problems. The test confirmed both the mounting support system and alignment of the probes were achievable. For alignment, the probes are mounted as a single unit using an alignment jig, as shown in Figure 85. The probes are allowed to float about the break flange assembly before fastening. Once the probes are securely fastened the alignment jig is removed, as shown in Figure 85.

Figure 85. LHS shows the WCP with the alignment jig probe assembly. The RHS shows the mounted pathlength controlled probes providing line-of-sight access with the assistance of the alignment jig.

The setup test showed the variation in concentricity of the break flange assembly access holes was off by 3/8 inches from side to side. However, this difference is easily compensated for by the self-positioning design incorporated in the probes. This same procedure was followed for probe alignment during installation on the process. The resulting location of the probes dictates the position for the module that houses the optic components. Therefore, once the probe position is set, adjustment of the internal modules x, y, z, and tilt position is made to mate the two together.

Module installation on the DOC support structure was performed during Gerdau's weekly maintenance shutdown days. Careful planning was required to minimize the access time at the mounting location and coordinate the installation around Gerdau's routine maintenance procedures. The installation was complicated by the need for a man-lift to access the location. This further complicated the installation because of the man-lift equipment size and availability resulting in shorter access times canceled maintenance days.

In April 2004 the smaller launch module installation was completed. From this first experience and observations made during the installation; a detail plan for all subsequent installation tasks was constructed. The intent of the detailed breakdown was to select tasks with stopping points to insure completion within the allotted time provided by Gerdau. Where a stopping point is defined as securing and protecting all hardware components from exposure to normal plant operation until the next scheduled maintenance shutdown is available to continue the installation.

During the module installation several setbacks were encountered requiring field modifications that delayed the installation. The following summarizes these field modifications and problems encountered:

- Launch module water-cooling feed line interfered with existing piping. This problem was discovered during the water hook-up and required cutting and welding a different fitting on to the module. The procedure was performed in the plant by pivoting the module away from the main support beam.
- In the modification of the water-cooled feed line, described above, a purge gas line was broken. The cause was from the orbited welded tube not properly aligned resulting in a weak weld that got hit during the repair. The purge tube was fixed during another maintenance shut down by pivoting out the module and silver soldering a new fitting.
- At the time the receiver module water-cooled pathlength control probe installation, the module was not fully pivoted back in position against the I-beam. This was discovered the following week and needed immediate attention. The receiver module is both large and heavy (~500 lbs) and was only held at one point during the initial installation step. With the module not being fully secured, posed a potential safety hazard and risk of damaging the module if it broke loose. This problem was addressed by resetting the module position as well as rewelding the main support bracket.
- Installation of the launch water-cooled pathlength control probe revealed a problem with the bolt hole pattern that required modifying the external shell. To obtain the desired bolt hole pattern the water connections to the probe interfered with external module shell. This required cutting a portion of the external shell to provide clearance for the water pipe connections.
- The external receiver module door accidentally got damaged when left open. In this case, contractors working on the fiber cable installation opened the receiver module and left it open without informing plant personnel. The furnace roof was moved and caught the door as it swung around. Fortunately, no damage to the internal module occurred, but it did force other work to stop for immediate repair before the furnace went back online.

Though the problems and fixes in this list sound trivial, each setback represents a major delay of 1 or 2 maintenance days that are scheduled only once a week. Full installation of the module hardware, not including the internal components, was completed by October 2004, as shown in Figure 86. The internal components were not included in the initial installation to minimize risk of damage. Because of the environment around the EAF being so harsh a conservative approach was taken

Figure 86. Installed modules identifying the measurement location

during the installation, especially since we had no prior experience with the module and process interface design. In hindsight a significant reduction in the installation time is possible if a more aggressive approach was taken. For example, the pathlength controlled probes and modules could have been mounted during the installation of the modified break flange assembly. If these steps were taken early on, a reduction of several months in the installation time could have been realized.

The first tests conducted after completing the module installation was to monitor the internal module temperature (IMT) to confirm safe operating temperatures for the electronic components were maintained. The internal components were not installed until the temperature was verified to be safe. The IMT was monitored using thermocouples installed on the module optic boards. Additional thermocouples were used to monitor the exit water temperature of both the launch and receiver module and the pathlength control probes. Historical recording of the temperature measurements during EAF operation are shown in Figure 87. The IMT for the receiver module showed a temperature variation between 19 and 21 °C, which was well within a safe operating range for the electronic components. The module exit water temperature for both the launch and receiver module are nearly identical with the overall temperature remaining < 25 °C and showing minimum fluctuations. However, variations in the pathlength control probe exit water temperature are obvious and correlated well to the EAF operating conditions. These probes experience direct contact with the furnace exhaust gas and will show a higher sensitivity to the process dynamics.

Figure 87. Historical temperature data collected from the sensor hardware components.

10.4 TDL Sensor Upgrades for EAF Testing

To adapt the TDL sensor for measurements on the EAF process, the TDL was upgraded to include new features such as a fiber optic communication system, remote alignment capability, and a laser power amplification system. These upgrades were packaged as add-on options to the basic TDL sensor platform. This approach increases the flexibility of the system for extension to other potential process monitoring applications, e.g., coal-fired boilers or waste incinerators.

10.4.1 Fiber Optic Communication System

The TDL sensor demonstrated on the steel reheat and aluminum reverberatory furnaces used fiber optic cables to transport the laser radiation to the process and a hardwire twinax cable for signal monitoring. Results from these tests showed no evidence of problems using the hardwire signal monitoring cable. However, in environments with strong electromagnetic fields, as found near the EAF, the hardwire cable can act as an antenna. As a result the small signal detection from the absorption measurement is overpowered by the strong electromagnetic fields picked up by the cable. This problem is even more amplified for long signal cables, which is the case for the Gerdau installation that requires several 100 ft of cable.

To address this problem the TDL was upgraded to use a fiber optic communication system. The system provided bi-directional signal transmission between the modules mounted on the furnace and the data acquisition unit located in the control room. By transmitting the signals over fiber optic cable the system was impervious to electrical noise pick-up. One drawback in using this configuration was the need to place the BRD circuit in the receiver module close to the detector. This was necessary since the photo-current balancing requires processing both the measurement and reference detector signals. In the previous system configuration, the BRD was located in the main laser cabinet, thus avoiding populating the modules with electronic components.

For this application, each detector has a dedicated BRD, one for CO/H₂O monitoring and one for O₂ monitoring. From each BRD three channels are monitored, signal, reference, and $V_{\log}$, that are transported as optical signal. At the data acquisition system the signals are reconverted to voltages and processed as before. Therefore, insertion of the fiber communication system is transparent to the system operation and can be viewed as a plug-and-play device. In addition, the bi-directional capability of the system also allowed remote communication to the modules. This is useful for remotely changing gain settings on the BRD and controlling the motors installed for optical alignment adjustment.

10.4.2 Remote Alignment

Adding remote alignment to the system was viewed as critical for the EAF test, since access to the modules is prohibitive during normal production. Therefore, optical alignment adjustments can only be performed when the furnace is shutdown. The question of alignment stability was uncertain because of the thermal cycling of the process and the severe mechanical vibration experienced when dropping 20-30 ton of steel scrap into the furnace shell. To address this issue, the optic mounts used in the receiver module were replaced with components using picomotors for well controlled adjustment. This also required installing controllers for each picomotor that increased the receiver footprint.

Alignment controlled is performed by a ± 10 V potentiometer controller, where the voltage level is proportional to the picomotor rate of travel and the voltage sign controls the travel direction. The ± 10 V control signal was transported through the fiber optic communication system. Selection of the optical component to adjust was made by an 8 position switch for remotely selecting the picomotor. In the initial design, multiple or simultaneous motor control was not considered. The approach taken was to first evaluate the alignment stability and if needed an automated optimization procedure could be added later.

10.4.3 Laser Power Amplification System

The ability to control the laser power is useful in cases where the power is attenuated from particulate matter. Near infrared diode lasers sold for telecommunication applications have limited power around 20 mW. After accounting for losses from optical components and splitters the delivered power to the process for measuring is typically < 15 mW. If the laser beam is launched through a process containing particulate matter then additional losses will result because of light absorption and scattering. For industrial monitoring applications, the level of particulate matter can vary from 100 mg/Nm^3 as in some glass furnaces to greater than 100 g/Nm^3 in EAF processes. In low particle processes such as the reheat and reverberatory furnaces discussed in sections 8 and 9 laser power boosting is not needed. However, the particulate level in the EAF is known to be very high and varying. Therefore, to maintain sufficient transmission through the process the addition of a fiber amplifier option was integrated into the sensor system for laser power control. Furthermore, on dynamic processes where the particle density is varying the control of the laser power has the added benefit of avoiding electronic saturation or component damage.

The system developed here for controlling the laser power is referred to as the On-Demand Power Control (ODPC). The ODPC uses two main components: an erbium doped fiber amplifier (EDFA) for boosting the laser power and a variable optical attenuator (VOA) for controlling the laser power. Figure 88 shows the ODPC arrangement where the laser light is transported first to the EDFA running in a saturated

gain mode to boost the power. In this mode of operation the laser output power from the EDFA is relatively constant independent of the input laser power. From the EDFA the laser beam is split in two parts with 99% of the power going through the VOA for launching across the process and the rest going directly to the BRD for use as a reference. The VOA provides linear control of the laser power delivered to the process. The maximum output power of the current amplifier is 25 dBm (316 mW), but higher powers up to 30 dBm (1 W) are available.

Control of the laser power delivered to the process is made with a PID control algorithm. The PID uses the reference-to-signal ratio based on the light transmission through the process as a set-point to adjust the VOA setting. In addition, a security system was installed in the receiver module for protection against transient high laser powers that could result under rapidly varying particle loading. The security system operates by continuously monitors a small fraction of the transmitted laser light. If the laser power reaches a set threshold limit, a trigger is sent to activate an electronic shutter. When activated the shutter closes in front of the measurement detector, thus preventing high laser power from reaching the detector. Once the VOA or the transmission through the process returns to a safe level the shutter will then open again allowing the measurement to continue.

Figure 88. Schematic layout of the ODPC add-on system.

Before industrial trials using the ODPC, laboratory and pilot furnace testing were conducted. The laboratory tests used the flat-flame burner to evaluate the empirical temperature and H₂O concentration calibration. Comparing these results against the

calibration from the standard sensor configuration with no amplifier showed no major deviations between the two techniques. For the 500 kW pilot furnaces tests, controlled particle injection was used to simulate industrial conditions. The level of particle density near TDL measurement was monitored independently using the calibrated laser extinction measurement described in section 6.2.

A comparison between the temperature from the TDL and conventional suction pyrometer (SP) probe taken on the pilot furnace is shown in Figure 89. Note the SP measurement was disabled mid-way during the particle seeding test to prevent probe damage. The particle density measurement shown on Figure 89 indicates when particles are present and the level achieved. For this test, a measured particle density $>100 \text{ g/Nm}^3$ was measured, which is in the range expected on the EAF process. The results show that before particle injection the TDL temperature tracked the SP measurement closely. The standard deviation in the TDL measurement was only $\pm 10 \text{ K}$ for the high temperature particle free measurements. With particle injection the TDL was still in agreement with the SP measurement. However, the presence of particles impacted the TDL measurement quality by introducing more scatter as indicated by the increased standard deviation of $\pm 87 \text{ K}$. These measurements were acquired for 1 second sampling representing 200 averaged spectra. Despite the larger standard deviation when particles are present, the value is still acceptable and further reduction in the scatter can be achieved by higher averaging. For example, a 2 second sampling time would represent 400 averaged spectra.

Figure 89. Real-time temperature measurements from the TDL (MGS) system compared with conventional suction pyrometer (SP) in the presence of particulate loading.

Monitoring a step change in the CO concentration with and without particle loading is shown in Figure 90. Data from both Figure 89 and 90 were obtained simultaneously. Figure 90 compares the CO concentration from conventional extractive sampling with the TDL measurement. The measurement delay time between the extractive and TDL measurements was around 1 minute. The width of the CO pulse for both measurements is similar, but the peak values differ because of the extractive sampling analyzers saturating. The variation in the laser power is also shown on Figure 90 resulting from the PID control of the VOA. In this example, a set-point value of 2.5 (Reference channel/Signal channel) was used as shown in the ODPC control screen that was developed in Figure 91. The resulting laser power delivered to the launch module shown in Figure 91 reaches a peak value of 80 mW. When the particle loading is quickly stopped, the PID control adjusts the VOA accordingly to reach the set-point Reference/Signal ratio value. In this case, the power adjustment exhibited a time lag during the rapid transmission recovery. This suggests that further optimization of the PID control parameters were needed.

Figure 90. Real-time CO measurements from the TDL (MGS) system compared with conventional extractive sampling in the presence of particulate loading. Also, shown is the variation of laser power with particle loading.

A captured screen taken during this test of the ODPC software control window is shown in Figure 91. The screen shows the PID parameters and displays the real-time ratio (Reference/Signal) recorded for this test when particle loading is initiated. During the initial onset of particles reaching the measurement zone, the ratio value reaches a value of 6 indicating the signal intensity (transmission) is decreasing because of the particles. As the laser power is adjusted by the VOA, the ratio approaches the set-point value. Other features displayed on the ODPC control window are an optional manual control of the VOA, display of the raw spectra, display of the raw reference and signal beam sweeps, and a soft shutter control switch.

Figure 91. ODPC control screen that was added to the TDL system for On-Demand Power Control.

In working with fiber optic communication and ODPC equipment in the laboratory evaluation several troubleshooting procedures were needed to optimize the system performance. During this phase of testing the original packaging of the equipment was found to be difficult to work on and needed redesigning. The motivation for the design change was based on the accessibility limitations to the equipment if maintenance or troubleshooting is required in the field. The original design integrated all of the fiber optic communication hardware in an existing empty space between the computer and keyboard drawer. Working with in this confined area was difficult and time consuming. Based on this experience the design shown in Figure 92 was developed. In this design the components are housed in standard 19 inch rack mount modules. The modules are mounted in a standard cabinet that can be nearby the main TDL sensor electronics. Another advantage in the new design is the added flexibility for using different sensor configurations. Not every application requires both ODPC and fiber optic communication.

Figure 92. Prototype packaging of the optical communication system and ODPC. This unit is located next to or on top of the exiting laser and data acquisition system.

10.5 Phase I EAF Off-gas Monitoring

PHASE I testing started in November 2004 and consisted of operating the standard TDL platform, i.e., no laser power amplification for the CO/H₂O laser. The only difference between previous industrial demonstrations and PHASE I EAF testing is the hardened modules with the fiber communication means and placement of the photocurrent balancing electronics (BRD) in the module. PHASE I testing focused on three main objectives. First, in using the standard TDL configuration assess the level of laser light that can be transmitted through the exhaust duct. This assessment is made for both the O₂ (.76 μm) and CO/H₂O (1.5 μm) lasers. The O₂ laser operates at a shorter wavelength which is more sensitive to scattering from particles and operates at less power (~ .3 mW) compared to the CO/H₂O laser (10-15 mW). Second, evaluate the quality of the spectrum that can be measured, if at all, from both lasers. In this test potential noise sources, e.g., background radiation, mechanical vibration, etc., are evaluated to determine the impact on the measurement quality. Finally, evaluate alignment stability, reproducibility, and overall maintenance issues.

The following are conclusions from PHASE I testing:

- In the current configuration, the success for O₂ monitoring during furnace operation is not likely. Two main technical hurdles exist that prevent successful O₂ monitoring. First, the laser output power is too low for transmission through the high particle density exhaust stream. The output power of the O₂ laser launched was an order of magnitude less than what was available from the CO/H₂O laser. Additional power loss from the O₂ laser was observed in the test and is attributed to the fusion splicing of the nonstandard 5 μm fiber used for O₂ laser light delivery. Second, the pathlength is too long for the available laser power and particle density present in the exhaust stream. A shorter pathlength test was not pursued because of the complications experienced with the installation. Furthermore, based on the O₂ signal evaluation and the known limitations of the laser power the likelihood of successfully performing an O₂ measurement in the exhaust gas is low. For these reasons the O₂ monitoring was aborted, but may be resumed in the future with a shorter pathlength and higher power O₂ laser.
- The CO/H₂O laser power was too low for routine monitoring during EAF operation. Some measurements were obtained during periods of low particle loading, but mostly the laser beam was completely extinguished. Figure 93 shows a recorded spectrum that indicates detection of water when transmission was good (Ratio = 7). The ratio value represents the laser power reference/signal and generally a ratio value of 2 is used for optimal temporal response of the BRD circuit. An increase in the ratio value is an indication the laser light reaching the detector has decreased. Therefore, a high ratio value indicates low laser power transmitted across the duct. Ratio values on the order of 20 were typical and as seen in Figure 93 no absorption features are resolved. Shortening of the

pathlength would improve the measurement, but the frequency of obtaining usable data would still be too low based on the PHASE I results.

Figure 93. Raw spectral data obtained with standard MGS configuration.

- Overall, the alignment stability was good and preserved over several weeks. This indicated the mechanical mounting and process interfacing was solid. Remote alignment was not needed and only operated to confirm it was working.
- Sensor maintenance was demonstrated to be minimal with only periodic cleaning (once per week) of the pathlength control probes. The cleaning performed used a high nitrogen flow and brush in the last 12 inches of the probes. Internal module window cleaning and internal optical component cleaning was not necessary.

Despite the poor results for O₂ and CO/H₂O monitoring using the basic TDL sensor, the modules alignment stability and low maintenance performance was exceptional. The poor results obtained from even the higher power CO/H₂O laser were not surprising. This was somewhat expected and was the motivation for developing the On-Demand Power Control system before the EAF testing started.

10.6 *Phase II EAF testing with the On-Demand Laser Power Control System*

PHASE II testing started in November 2004 and consisted of using the On-Demand Power Control (ODPC) system described in section 10.3. As seen in PHASE I, the CO/H₂O laser power was too low for routine monitoring under normal EAF operating conditions. The ODPC was developed specifically for measurement applications in dynamic high particle density process gas streams.

The objective of PHASE II testing focused on improving the signal quality and measurement frequency. The following summarizes the main observations from initial measurements using the ODPC:

- Compared to PHASE I testing the laser power transmitted through the exhaust duct was significantly improved. The detectable laser light transmitted across the duct was between 70 - 90% of the time. The transmission was dependent on the melt cycle, e.g., transmission was poorest just after the first scrap charge and improved with each consecutive charge before tapping. There were periods when the percentage of detectable laser light decreased to 20% or less, but compared to the entire melt cycle these periods were short.
- To detect the CO/H₂O spectral features signal averaging of 6000 to 12000 spectra was needed because of noise. A noticeable difference in the basic shape of the measurement signals was observed using the ODPC at the industrial site. Figure 94 shows a plot of the raw signal received on the detector for a period while the EAF was not operating. The signal shows a positive slope with the measured intensity increasing as the laser was scanned. This is opposite of laboratory tests that always showed a negative slope. However, the raw reference signal collected at the industrial site did show the correct shape.

Figure 94. Raw signal traces collected while the furnace was not running.

When the EAF is running the raw signal trace slowly oscillated between a positive and negative slope. However, the raw reference was stable independent of whether the furnace was operating or not. The oscillating behavior of the raw signal degraded the measurement quality as seen in the resulting set of $V_{\log}$ plots collected in Figure 95. The noise and random variation in the signal was obvious and no clear spectral features are seen from these results.

Figure 95. Vlog signal collected while the EAF was operating.

- Despite the noise present on the signal shown in Figure 95, spectral features representative of H_2O and CO are detectable (Figure 96) when 12000 spectra are averaged.

Figure 96. Comparison of the spectrum from a reference calibration (blue) and the one observed in Gerdau.

From the initial PHASE II tests, two main observations in the signal quality were made. First, the slope of the signal oscillated randomly from slightly positive to negative. The normal signal slope observed in the lab and in previous industrial tests always showed a negative slope behavior set by the laser scanning conditions. The second observation from the EAF test data was detection of packets of high frequency noise on the noise suppressed $V_{\log}$ measurement channel from the BRD circuit.

The problem related to the high frequency packets of noise on the $V_{\log}$ signal was traced back to the BRD circuit itself. This was discovered while working in the receiver module and observing the voltage setting for the gain control becoming unstable when the fiber communication to the module was disabled. The BRD was replaced with a new board with the gain adjustment set to manual operation. In this mode, the gain setting could no longer be adjusted from the computer that communicates to the receiver module through the fiber optic communication system. Nevertheless, this fixed the problem in the $V_{\log}$ signal and loss of remote gain selection is not critical.

Identifying the problem related to the variation in the signal baseline slope was more complicated and required some trial and error tests. The first test performed consisted of conducting the measurement without using the fusion spliced fiber optic cables. Concern over the quality of the splice was an issue since this was the only difference in the system configuration compared to laboratory tests. Furthermore, during the fiber optic cable installation several fibers needed resplicing because of the poor quality of the environment having a high dust level. All of these factors raised suspicion for a possible defect in the fiber optic cabling.

To bypass the spliced fibers the laser and acquisition system was moved from the control room to the platform near the extractive sampling analyzers. At this location, 50-foot fibers were used from the sensor electronics to both the launch and receiver modules. The real drawback for operating the system at this location was the environment, which had a high dust level and no ambient temperature control. As an indication of the poor environment, the computer keyboard failed because of dust and ice forming on the touch pad making it inoperable. Note these tests were conducted in February 2005 during a cold spell.

Results from the test showed some improvement in the signal behavior, but did not eliminate the baseline slope variation. A second test was conducted with the nonspliced fibers and with a modification of the optical configuration in the receiver module by removing the dispersive element used for background suppression. In this configuration the detector directly intercepted the laser beam. The laser beam still passed through the module window and the prism-lens-mirror system as described in section 5.2. Results from the test showed no indication of the baseline slope variation suggesting the problem was linked to the receiver optical components.

Further investigation showed the baseline slope variation in the signal was traced to the combination diffraction grating and the EDFA (erbium doped fiber amplifier) used in the ODPC. The oscillation in the signal result from using highly polarized amplified light

from the EDFA with a polarization sensitive diffraction grating. Laboratory testing using the same configuration did not show the same sensitivity because the fibers transporting the light in the lab were stationary. However, in the plant the fibers optic cables pick-up all the surrounding vibrations that cause stress and strain in the fiber altering the exit polarization. The shorter 50 ft fibers used in the test to eliminate using spliced fibers reduced the effect compared to the longer 400 ft runs, but did not remove it completely.

10.7 Signal Optimization

To understand the signal quality dependence on the polarization and evaluate different options for minimizing this problem it was decided in February 2005 to perform a set of laboratory tests under controlled conditions. The experimental set-up used is shown in Figure 97 that consisted of the On-Demand Power Control (ODPC) unit, a multi-section Agility Communications, Inc. c-band laser for a light source, and a digital LeCroy oscilloscope for data acquisition. The amplified light was transported by fiber optic cable to a collimating lens that launched the beam either through ambient air or a 10 cm sample cell filled with 40 % CO. Detection of the laser light used an InGaAs detector with the signal treated by the BRD circuit as done in the industrial plant measurements. The setup allowed testing different gratings, the impact of grating angle, combination of gratings, direct monitoring on the detector, i.e., no grating, and measurements with and without the ODPC.

Figure 97. Laboratory setup for evaluating measurement quality using different optical configurations and varying polarization due to stresses in the launch fiber.

For testing the impact of fiber movement, i.e., variation of the polarization output, a rotating device was implemented to stress the fiber. This device consisted of simply mounting the fiber to a cylindrical tube. Rotation of the tube applies a stress on the fiber that changes the output polarization characteristics in time. This setup allowed for a repeatable test for evaluation of different optic components such as, standard ruled diffraction grating, no grating, low polarization dependent loss grating, and polarization scrambler. A brief summary of some selected recorded $V_{\log}$ spectra for CO absorption collected while the launch fiber cable was stressed are shown in Figures 98-101. In this test the laser scanned at 200 Hz with 15 average spectra taken for a collection of 50-60 spectra acquired while the launch fiber was rotated. For all tests, stress of the launch fiber was applied by making a rotation of the device over 180 degrees.

The least sensitive configuration is when no diffraction grating is used, i.e., the laser beam directly intercepts the detector, as shown in Figure 98. However, using this configuration is not practical for EAF monitoring because of the large radiation background that is present. Results from the standard ruled grating, shown in Figure 99, showed similar behavior as observed in the EAF tests. The signal was observed to oscillate between positive and negative producing a bow tie appearance from the controlled test performed in the lab. In our previous industrial tests on aluminum reverberatory furnace a standard ruled diffraction grating in the optical train was used to suppress background radiation. In this case sensitivity to polarization was not severe, since no amplifier was being used and the launch fiber length was short (~30 ft) with minimal vibration present in the plant.

Figure 98. Series of spectra acquired while fiber was stressed with no grating.

Figure 99. Series of spectra acquired while fiber was stressed using a standard ruled diffraction grating.

Figure 100. Series of spectra acquired while fiber was stressed using a low polarization dependent loss grating

Figure 101. Series of spectra acquired while fiber was stressed with standard ruled diffraction grating and using a polarization scrambler.

The conclusion from these test indicate that low polarization dependent loss (LPDL) grating (Figure 100) performed consistently better than the standard ruled grating (Figure 99). The variation in the laser intensity from the LPDL showed only a shift in the vertical offset whereas the standard ruled grating had the characteristic oscillation in the slope. Furthermore, the strength of the oscillation from the ruled grating was dependent on the grating angle. Therefore, careful alignment of the angle of incidence is needed to minimize the oscillation. This complicates the installation on the EAF because of limited access making it difficult to precisely align the grating angle. Finally, testing of a polarization scrambler (Demo unit from Fiber Pro, Inc.) removed all intensity fluctuations when the launch fiber was stressed, as shown in Figure 101. This is a simple passive device that is placed between the ODPC and launch optic. It randomizes the polarization by stressing the fiber at high frequency. This high frequency noise was observed when signal averaging was low, but at higher signal averaging, e.g., 200 spectra per second, as typically used in the measurement the noise was removed.

10.8 2nd Round of EAF Testing

From the analysis discussed in section 10.7 the LPDL grating was installed in the receiver module in March 2005 for the 2nd round of EAF tests. During the start of these tests several small problems encountered with the fiber optic communication system and newly discovered bugs in the TDL sensor acquisition software resulted in delays. For the fiber optic communication system, a power supply component was identified as overheating producing excess noise on the recovered signals. The data acquisition software fix was related to memory usage causing the computer to lock when collecting data overlong periods. An additional software change was made at this time to allow continuous variation of the laser power based on transmission feedback independent of the averaging time selected. The earlier version only adjusted the laser power after

averaging was performed. For example, if 10 sec averaging is selected the laser power adjustment would occur from the average power over 10 sec. However, the transmission through the EAF is continuously changing requiring real-time adjustment of the laser power.

The initial results obtained with the LPDL grating were encouraging compared with the early work. Measurements could be made with reduced averaging from 60 sec (12000 spectra) to < 15 sec. Another improvement observed was in the frequency of the spectral features detected. Particularly for the W8 line of H₂O, since its present at high concentration and is a strong absorber.

An example of real-time process monitoring showing the variation in the laser power launched across the exhaust duct during a heat, is shown in Figure 102. A heat is defined as the tap-to-tap time of the furnace. Because the tap-to-tap time is not constant, Figure 102 represents the average laser power obtained from several heats of data. The arrows on the x-axis indicate when a charge (bucket of scrap metal) is being loaded into the furnace. After charging the furnace the laser power requirement increases because of the higher loading of particles. As the metal is melted the laser power requirement decreases. Power requirements are highest at the beginning of a new heat cycle and at the end of the cycle. In the last period of the cycle, oxygen and carbon injection is performed and different alloys are introduced to adjust the composition before tapping. During this last stage of the heat the laser power demands are high resulting in brief periods of complete light extinction even at maximum delivery power of 300 mW over the 60 cm pathlength.

Figure 102. Average laser launch power for one heat.

Long-term tests performed with simultaneous operation of the TDL sensor and the extractive probe were challenging because of the extractive probe frequently plugging. A sample set of data when both measurement systems were operating over a 24-hour period, is shown in Figure 103. Each point for the TDL data was collected for 10 sec average with the laser scanning at 200 Hz. Therefore 2000 spectra are averaged and then analyzed in the following order: gas temperature, H₂O concentration, and CO concentration. This order is required since the linestrength values are temperature dependent and a correction is applied for determining CO concentration because of H₂O interference. Since some of the data collected is erroneous a filtering procedure was performed to retain only data that meets certain criteria. For the processed data to be acceptable the light transmission level must fall within a usable range. For transmission monitoring the reference/signal ratio used to control the VOA also provides a measure of laser power reaching the detector. Data were retained for $1.2 \leq \text{ratio} \leq 9$ for these tests. Additionally the processed temperature (1090-2300 K) and H₂O (0-60%) concentration must fall within physically realistic ranges. The erroneous data collected results from several sources. For example, when the furnace power is off the exhaust gas temperature can fall below the sensor detection limit of 1090 K. Furnace power off condition occurs not only during tapping and charging, but also during normal operation. Other examples for resulting in erroneous data are related to laser beam attenuation and high background radiation.

The extractive probe data shown in Figure 103 is corrected for the H₂O concentration based on the laser H₂O measurements. Differences between the two techniques result from the extractive probe being a single point measurement whereas the laser sensor is path averaged measurement over 60 cm. Also the measurement locations of the two techniques are not identical, since the extractive probe must be located several inches above the laser beam path to avoid interference. Despite these differences the laser measurement clearly follows the trend of the extractive measurement. The figure also indicates the time when furnace tapping is performed.

Figure 103. Sample data comparing CO measurements from the laser sensor and extractive sampling over a long period.

A comparison between the laser and extractive measurement is shown in Figure 104 for the average of 7 heats of data. At the end of the heat high CO concentrations are generated and this trend is captured by the laser measurement

Figure 104. Averaged CO measurement for seven heats.

However, the CO concentration level is lower from the laser compared to the extractive measurement. This deviation may be a result of the differences in the measurement type (point vs. path averaged) and location. The other high excursions of CO that result are more clearly seen with the extractive measurement. This also may be attributed to the differences in the measurement, but these deviations will become clearer as the sample set becomes larger, e.g., 50-100 averaged heats.

For the same set of heats presented in Figure 104, H₂O and temperature measurements are shown in Figure 105. From the limited set of data a unique pattern is not clearly observed. The average H₂O concentration and temperature for seven heats displayed in Figure 106 shows the values of the H₂O and temperature falling in the same range throughout the entire cycle. There is no distinct pattern as seen in the average CO data in Figure 104.

Figure 105. Temperature and water measurements for a long run.

Figure 106. Averaged measurements of temperature and water for seven heats.

10.9 Background Suppression Improvements

Preliminary laser measurement results from the EAF showed that background radiation was affecting the measurement quality. The level of background radiation detected was dependent on the process operating conditions. At the beginning of a melt the background observed was not significant, however during the final phase of the melt before tapping the background was on the same order as the laser radiation. At this stage of the melt process oxygen lancing is performed. Variation in the background level because of the process dynamics and nonhomogenous particle distribution results in added baseline noise that impacts the measurement quality. Therefore, the first step to improve the measurement quality was addressed by removing or minimizing the background radiation.

To address the background problem a new optical layout was installed in the receiver module at the beginning of July 2005. Figure 107 shows background measurement results for the different receiver optics used. The measurement was made by turning off the launch laser thereby collecting only background while the EAF was operating. The data was collected for several heats and averaged with time being normalized, e.g., 0 at the start of the heat and 1 at the end (TAP). From Figure 107 the background level for the new configuration was noticeably lower at the end of the heat during the lancing operations where the radiation in the off-gas is the strongest. Unfortunately, the sample size (number of heats) for the old configuration was limited as indicated by the ability to resolve the effect of furnace charging. However, from our experience the new configuration performed better based on the reduced background level detected.

Figure 107. Comparison of averaged background radiation profiles detected while the EAF in the receiver module for different optical configurations

To address the issue of measurement quality and reliability, a higher power (HP) fiber-amplifier was tested in November 2005. A demo unit provided by Keopsys Inc. was used to produce 1 W of output power. However, this power level was too high for our optical components, so an attenuator was used to limit the output to 500 mW. Figure 108 compares CO monitoring results using the HP amplifier with the extractive sampling probe. The laser measurement captures the CO trend, but still shows large variation in the concentration as observed with the low power (300 mW) amplifier. The overall transmission did improve, thus benefiting from the higher laser power.

Figure 108. Comparison of CO concentration measurements from the laser and extractive sampling.

10.10 Signal Quality Analysis

To evaluate the data quality an analysis software package was developed to consolidate the data from the EAF process, TDL laser, and extractive sampling system for use with one central analysis program. The package aids in identifying the different process operating events such as, furnace charging, tapping, and furnace power on or off. The occurrence of these different events impacts the laser measurement because of the requirement that water must be present at temperatures $> 1000\text{K}$. In general these conditions are not met at times when the furnace is being charged or tapped. At low temperatures and low water concentrations the absorption features will not be detected and only baseline noise is processed that could give false results. To avoid these conditions a filtering process is used to accept only measurements that fall within physically realistic range, e.g., temperature between 1090 K and 2200 K. The filtering is performed on the temperature and concentrations calculated from the integrated

absorption features and evaluation of the light transmission level, as discussed in Section 10.8. Therefore, the results are dependent on the quality of the spectra recorded.

To assess the spectrum quality in more detail, the analysis software developed uses a correlation coefficient calculation between the recorded spectrum and a reference spectrum. Water is used as the target species for this analysis since it's present under both lean and rich conditions. In addition, two water features labeled W8 and W9 are monitored, since the ratio of these peaks is used for determining the temperature as discussed in section 4.3. The disparity in the absorption strength between these two features provides a test for the spectra quality of both a strong absorber like W8 and weaker absorbers such as W9 and CO. An example of the analysis is shown in Figure 109 for a set of spectra collected for both W8 and W9 water features. The correlation coefficient is computed against a reference spectrum that was obtained from the calibration burner discussed in Section 4.5. The reference spectrum is an average over the temperature and water concentration range used in sensor calibration. As seen in Figure 109, the quality of the measured spectra clearly differs from the reference spectrum.

Figure 109. Collection of normalized spectra for W8 and W9 water collected from the EAF. The spectra are compared with a reference spectra obtained on our calibration burner.

By tracking the correlation coefficient, as shown in Figure 110, helps identify what process operations impact the measurement quality. This result shows the impact of the data quality for the different process operating conditions, e.g., power on or off, furnace charging, and tapping. In general, the correlation degrades during furnace charging, tapping or when the furnace power is off. However, this is not always the case and poorly correlated data can be seen at other times. In addition, the weaker W9 water feature shows higher sensitivity to the process conditions as seen by the larger variation in the correlation coefficient. For W9, data showing correlation coefficients $< .9$ are suspect for introducing errors first in determining the temperature and then subsequently in the water concentration. This will affect the CO concentration both in the temperature error and in the correction applied for background water interference.

Figure 110 Historical trend of the correlation coefficient for W8 and W9 water peaks and EAF operating conditions.

10.11 Signal Quality Enhancement

Further improvements in the signal quality were investigated by the use of a particle impinger (PI) that is protected under US 6,943,886. This technology was developed and tested in October 2003 on the Air Liquide pilot furnace in anticipation that the high particle density flows present in the EAF off-gas would be problematic. As expected, the measurement quality issues with the spectrum collected on the EAF is believed to result from the particle density variation that adds noise to the baseline. In preparation for testing the PI on the EAF additional water feed and return lines were installed at Gerdau in November 2005. The actual installation and testing of the PI did not start until February of 2006. Figure 111 shows the installed PI on the Gerdau furnace which consists of a water-cooled bar just upstream of the laser beam. The principle of the PI is illustrated in

Figure 111. Installed water-cooled particle impinger on the Gerdau EAF. The RHS figure illustrates the basic principle of the impinger to reduce particles from interacting with the laser beam.

the RHS of Figure 111 and works by blocking the particles from crossing the laser beam path. Complete blockage of particles is not possible for the small particles with a low Stokes number. The low Stokes number particles follow the fluid flow field so they will be present in recirculation zones. However, large particles with Stokes number >1 will deviate from the fluid flow field because of their higher inertia. Therefore, reduction in particles interacting with the laser beam will occur, thus improving the measurement quality by reducing the baseline noise.

The initial test results on the EAF show a reduction in the scatter for the CO measurements. This confirms the reduction in particles interacting with the laser beam improved the baseline quality reducing the scatter in the measurement. Results comparing CO monitored between the TDL sensor and extractive sampling are shown in Figure 112. Comparing these results with the previous CO measurements shown in Figure 103 and 105 illustrates the signal improvement gained.

Figure 112. Comparison between the TDL sensor with particle impinger and extractive CO off-gas measurements on the EAF. Extractive measurements were corrected for H_2O and adjusted for delay time.

10.12 Maintenance

Maintenance of the launch and receiver modules located near the EAF exhaust duct has been surprisingly minimal. The system has been in operation for over 6 months (July – December 2005) with no user intervention for alignment or cleaning of any internal optical components. The only maintenance conducted has been cleaning the ends of the water-cooled pathlength controlled probes performed during maintenance shut downs. This maintenance procedure takes less than 5 minutes and consists of simply brushing off material build-up at the end of the probes. Figure 113 indicates the section of the probe that is cleaned. If the material buildup becomes significant it could potentially affect the laser beam transmission by partially or fully blocking the beam. It's not clear how long

the probes can be in operation without this cleaning step, but we have gone up to 4 weeks without cleaning and observed no degradation in the signal.

During the 7th month of operation a noticeable decrease in laser power was observed. In January 2006, an inspection of the internal receiver module components indicated the problem was not alignment, but related to a film deposited on the receiver entrance window that appeared to be from water. The window was cleaned and the laser power recovered.

Figure 113. Pathlength controlled laser beam shielding probe indicating the section that is periodically cleaned.

The system was not completely immune to problems and during long-term testing the data acquisition system would periodically lock-up. The problem occurred intermittently resulting in irregular data collection. This first started to show up during the summer months on particularly hot days. Eventually the problem was correlated to the ambient temperature conditions and traced back to the acquisition board on the computer failing. Unfortunately, the laser and acquisition electronics are located in a plant office with no temperature control, which contributed to this problem.

Demonstration of the *in-situ* TDL sensor as a zero maintenance technique for EAF off-gas monitoring was achieved. Whereas the ex-situ extractive sampling proved to be troublesome, consistent from experience using this technology for EAF off-gas monitoring. The main problem was keeping the probe and sample line free from plugging. Other problems were also encountered related to the gas conditioning system (pump and chiller) failure. The dust and high ambient temperature led to several components periodically failing on the gas condition system. As a result comparable data from the extractive system was sparse. Nevertheless, data was collected over long enough periods to demonstrate CO monitoring with the TDL sensor.

10.13 EAF Conclusions

EAF off-gas monitoring with the TDL sensor demonstrated the technology can hold-up to the harsh conditions surrounding the EAF process. The maintenance and alignment stability surpassed original expectations with essentially zero maintenance over 6-months of operations. The trends in CO are clearly seen from the TDL sensor, but the presence of baseline noise from the non-homogenous particle loading make coupling of the measurement to a process control system unattractive. To address this matter several

iterative steps were made that reduced the background radiation and improved the signal quality. Still further improvements in the signal were achieved using the particle impinger to reduce the particle interaction with the laser beam. The system is still in operation at Gerdau and the next-step under investigation is coupling the measurement to their process control system. The objective is to use the TDL sensor measurement for O₂ injection control to recovery the potential chemical energy from CO (and H₂) that would otherwise be exhausted [11].

11. Conclusion

The outcome of the project resulted in developing a multi-species high temperature gas monitoring sensor with several add-on optional modules, as summarized in Figure 114. These add-on options allow flexibility in configuring a system to meet the diverse range of monitoring requirements found in different industries. The central unit common to all process monitoring applications consists of the laser controller and data acquisition system for O₂, CO, H₂O, and gas temperature. This unit houses the sensitive lasers and acquisition electronics and can be located in a control room away from the measurement location.

Surrounding the central unit shown in Figure 114 are several add-on options that were developed and tested. Two module styles were developed for different process conditions. The semi-harsh launch and receiver module is used on processes where the ambient environment is safe for personnel to be near the process. For example, the steel reheat and reverberatory furnace industrial monitoring tests in this work used the semi-harsh modules. For harsh process monitoring where the modules can be exposed to high temperature, electro magnetic field interference, flying debris, and mechanical vibration the module design was hardened for these conditions. This hardened design has been in operation on the EAF for >1-year. In processes where laser transmission is an issue because of particle loading the On-Demand Laser Power Controller can be added to the

Figure 114. TDL sensor system with of add-on options used to configure a system for a diverse range of industrial process monitoring requirements.

central unit as a plug-and-play device. Added control of the measurement pathlength is achieved using the pathlength control probes to set the measurement distance and location. Finally, the fiber optic communication with remote alignment is used when the distance between the launch and receiver modules < 100 ft from the central unit or electrical noise pick-up is known to be problematic. Within this set of options different combinations can be used to meet the process monitoring requirements. The only drawback is the range of process conditions applicable for O₂ monitoring because of the laser power limitation.

The sensor technology was successfully demonstrated on a diverse range of industrial processes that included a steel reheat furnace, aluminum reverberatory furnace, and electric arc steel melting furnace. In each case, the process dynamics were captured and agreement with conventional extractive sampling was achieved. Measurements on the reheat and reverberatory furnaces explored the benefits of monitoring near the processed material and exploited the non-intrusive advantages of the technique. The long-term monitoring on the EAF demonstrated all the add-on optional features and achieved a near zero-maintenance system. These tests illustrate the cross-cutting potential of the TDL sensor technology and how it can be adapted to different process monitoring requirements. The sensor is still in operation on the Gerdau EAF and next-steps involve coupling the measurement to their process control system for evaluation of the potential energy reduction achievable from post-combustion of CO.

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13. Granted Patents and Published Applications

1. 7,005,645, Apparatus and methods for launching and receiving a broad wavelength range source
2. 6,943,886, Method for enhanced gas monitoring in high particle density flow streams
3. 6,859,766, Indirect gas species monitoring using tunable diode lasers

4. 20050225840, Dynamic laser power control for gas species monitoring
5. 20040027575, Wavelength tuning control for multi-section diode lasers
6. 20030132389, Method for monitoring and controlling the high temperature reducing combustion atmosphere
7. 20020031737, Method for continuously monitoring chemical species and temperature in hot process gases

14. Publications and Conference Presentations

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2. W. Von Drasek, O.Charon, K. Mulderink, D. Sonnenfroh, and M. Allen., *Multi-functional Industrial Combustion Process Monitoring with Tunable Diode Lasers*, SPIE The International Society for Optical Engineering, Environmental and Industrial Sensing, to be presented, Boston Massachusetts, November 2000.
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