# Robust EAF Laser Gas Analysis System-Zolo*SCAN*

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## INTRODUCTION

Considerable work has been done on the development of advanced process control for the Electric Arc Furnace (EAF) steelmaking process. Historically, many control systems have been employed which rely on static heat balance calculations coupled with power input profiles to generate recipe driven control models. Steelmakers have desired to have continuous information about the gases exiting the furnace. Due to the dynamic nature of the EAF, waste gas analysis on a real time basis provides valuable data which enables the operator to better control the input of chemical energy components as well as decarburizing and slag foaming additives. However, in the absence of real time off gas analysis, predictive process control models are used because no sensor has been available which can provide accurate, reliable data for real time process feedback.

Over the past decade, off gas monitoring systems which are based in conventional gas analyzers have been tried with limited success. These systems work by pulling a sample of the waste gas through water cooled probe extending into the duct using a mechanical pump, then sending it to analyzers located in a safe, remote location. The harsh EAF environment exposes serious shortcomings of these gas extraction sampling systems.

- The sample must be filtered, dried and sent to various gas analyzers. The reporting delay ranges from 20-30 seconds, which limits it usefulness for online control.
- As the gas sample is extracted, large masses of furnace dust are also extracted. The sample must then be cleaned of the dust prior to analysis which results in filter maintenance and clogging, that can shut down the system
- The gas sample must be dried prior to processing by the analyzers, which adds time and complexity to the system
- These systems cannot report water vapor content of the gas
- The extraction probes measure only a single point within the duct. Flickering of the flame and furnace tilt may result in inconsistent data.
- The analyzers require regular maintenance which includes calibration using a standard gas, along with regular filter and cell change outs.

This paper describes a non-contact laser system which is proven and robust. It overcomes all of the issues stated above while reporting data at intervals of less than two seconds. It takes a representative sample across the entire core of the furnace exhaust plume to assure accurate data. It is critical to point out that the laser will read water in the exhaust gas directly so changes are immediately identified with confidence.

## LASER TECHNOLOGY

Tunable diode laser absorption spectroscopy (TDLAS) utilizes diode lasers as a "high-tech" light source, but in most other ways, it is completely analogous to conventional spectroscopy using a lamp. In TDLAS, the wavelength of light is tuned over a very carefully selected wavelength increment which allows the measurement of a particular gas species of interest. Every molecule has a unique light absorption spectrum or fingerprint. Quantifying the amount of light that is absorbed as a function of wavelength allows one to calculate the concentration of the target gas species provided that the path length, pressure, and temperature are known. The relevant equation governing quantitative absorption is known as Beer's Law:

$$I/I_0 = \exp\text{-}[\chi PLS(T)\varphi(T,P)] \quad \text{where} \qquad (1)$$

$I$ = transmitted light intensity
$I_0$ = initial light intensity (intensity prior to transmission)
$\chi$ = partial pressure of the species of interest
$P$ = atmospheric pressure
$L$ = path length between the probes
$S(T)$ = line strength, which is a constant for a given temperature
$\varphi$= line shape function

Note that $I$, $I_0$ and $\varphi$ are all a function of wavelength which has been suppressed in the notation for simplicity. In order to calculate $\chi$, the desired quantity, the Zolo***SCAN – EAF*** measures $I$, $I_0$, and $\varphi$ as a function of wavelength (from a spectral scan similar to that shown in Figure 1, atmospheric pressure is measured by a sensor in the control rack, $L$ is known from the physical position of the probes, and $S(T)$ is known from quantum mechanical considerations and laboratory verification.

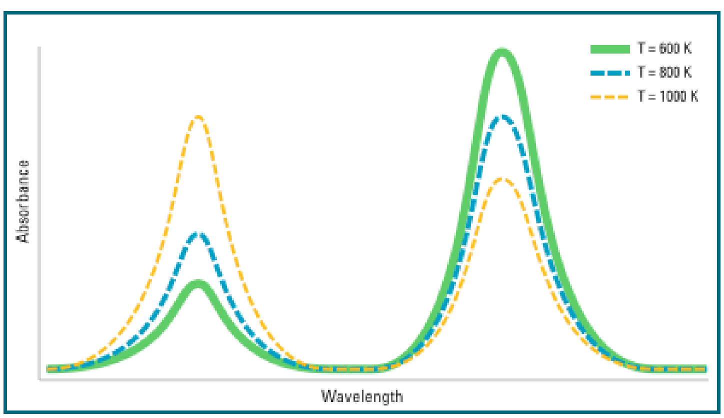


Figure 1: Schematic diagram of two absorption features that would be appropriate for temperature measurements.

Gas temperature can be quantified using TDLAS by measuring the ratio of the absorption amplitudes of two carefully chosen absorption features of the same molecule. For combustion applications, water is a convenient choice for a target molecule for temperature measurements as it is present in large concentration in combustion systems and is a strong absorber in the near-infrared portion of the spectrum where readily available diode lasers operate. The amplitude of the two chosen features must have different temperature dependencies as shown schematically in Figure 1. Note that increasing temperature makes one peak diminish in amplitude while the other increases in amplitude. Thus the ratio of the peak amplitudes is a monotonic function of temperature; that is, any measured ratio leads to a uniquely determined temperature. Two such features can be selected (with difficulty) using quantum mechanical considerations and laboratory verification procedures that are well beyond the scope of this paper. The features can be adjacent to each other as shown in Figure 1 or separated in wavelength – one of the advantages of the wavelength-multiplexed implementation of TDLAS utilized by the Zolo***SCAN-EAF*** described more fully below.

TDLAS has been practiced for over 30 years; however, the implementation of TDLAS that the Zolo***SCAN-EAF*** utilizes is unique and based on pioneering work performed in Stanford University's High Temperature Gas Dynamics Laboratory in the mid-1990s along with work that the Stanford group and Zolo Technologies performed circa 2005 to harden the technology for use in harsh environments. This type of TDLAS, wavelength-multiplexed TDLAS (WMTDLAS), allows multiple species to be measured simultaneously in time and in exactly the same measured volume of gas. The wavelength multiplexing scheme allows one to couple the wavelengths necessary for measurement of multiple species in to a single optical fiber. Multiplexing allows the Zolo***SCAN-EAF*** to quantify the concentrations of $H_2O$, CO, and $CO_2$, and measure temperature simultaneously. The measurement is *in-situ* and thus the update rate is fast (< 2 seconds) and unperturbed by the loss of species in the gas sampling process which can be significant when extracting gases from a reaction zone. Another advantage of WMTDLAS is that the wavelengths of light necessary for the measurements are transmitted to the measurement location on optical fiber. Fiber allows the light to be directed to a very harsh measurement location (or several locations via a switch or splitter); then the sensitive (and expensive) lasers and other electronics remain in a remote, safe location. In the Zolo***SCAN-EAF*** system, the only components near the fourth-hole measurement location are either passive (glass lenses, aluminum optics mounts, etc.), or robust electric stepper motors. The optical fiber carrying multiplexed light from the rack terminates in the SensALIGN transmit head. The fiber used for the transmission optical train is standard, single-mode, telecommunications-grade, SMF 28 fiber. An opposing SensALIGN receiver head is placed across the measurement region forming a measurement path about one meter in length on the Nucor EAF. The receive head is coupled back to the control rack via a standard Corning 50/125 multimode fiber. The stepper motors enable another huge advantage of the type of TDLAS utilized by the Zolo***SCAN-EAF*** – auto-alignment capability. Auto-alignment keeps the transmit and receive optics optimally aligned. In the high-opacity environments for which the Zolo WMTDLAS technology was designed, the auto-alignment function allows measurements to be made during exceedingly low periods of light transmission, e.g. during bore in. The Zolo***SCAN-EAF*** is capable of making measurements when only 1 part in $10^8$ of the light is transmitted over the measurement path of about 1 meter.[1]

In addition to the EAF application, the Zolo WMTDLAS technology has been utilized for almost ten years to optimize combustion in coal-fired power plants with over 50 installations on three continents. Similar to the EAF, the coal plant environment is a difficult one and can suffer from very high opacity depending on the type of coal burned and the path length involved. (Path lengths in coal plants can be very long - often up to 30 meters or more). Experience in the coal-fired power market has allowed the development and verification of the technology and algorithms needed to handle the EAF environment. In addition, optical amplifiers have been added to increase the available laser power and dynamic gain control of the operational amplifiers, which enables the signal level to be optimized for the analog to digital conversion.

## INSTALLATION

To be considered a successful installation, Zolo***SCAN-EAF*** must prove to be both reliable and accurate in reporting. The EAF exhaust gas environment is an onerous one for any equipment. The EAF is a violent, dynamic process which itself provides many challenges to keep a system running. Steelmakers demand robust equipment, so overcoming these challenges are necessary for an ongoing, low maintenance operation.

**Probe Design and Mounting**

The environment inside the exhaust duct of an Electric Arc Furnace consists of hot, corrosive and particulate laden gases. Probes inserted into the duct must be able to last for a long time so as not to be the cause of production delays for maintenance and replacement. The required location was determined to be as close to the gap as possible, mounting on the smoke ring.

The probe design is water cooled and fabricated from a non-ferrous alloy with a history of withstanding EAF duct applications. A further requirement was that it be of as small an overall diameter as possible, while holding to a two inch inner diameter specification and remaining rigid to minimize vibration. This requirement was achieved by a novel water cooling circuit which minimized the space required for water flow.

The probe performance has been outstanding. The first set of probes remained in service for over ten months. Eventually, during restart from a planned outage, water was inadvertently left off and the probes were rapidly damaged beyond repair. Intermittent inspections indicated that the probes should last well beyond a year if cooling water is maintained.

**Alignment**

Maintaining alignment throughout the heat is the first priority for establishing system integrity. The laser diameter is approximately 1 cm and the target area on the catch head is 3.8 cm. The laser must be aligned with some portion of the target area at all times. In some processes that Zolo***SCAN-EAF*** technology has been employed, this poses very little problem. However, in the EAF process, there is a tremendous amount of vibration from the electrodes and ensuing reactions, along with bombardment of the probe by a massive draft of air and particulate. Both horizontal and vertical probe configurations were considered. The primary concern with a horizontal arrangement is alignment due to vibration of the duct and probes. The primary concern with a vertical configuration is dust buildup on the lower probe lens blocking the light path. Zolo and Nucor analyzed the two configurations in depth and decided on the vertical configuration. The deciding factor was the concern over vibration of the probes if horizontal was chosen.

Both Zolo and Nucor believe the correct decision was made because there has been no issue with alignment and minimal maintenance associated with the vertical configuration. With regards to alignment, there clearly is vibration and subtle movement of the probes during operation. Zolo has overcome that with its SensAlign Heads, which as the name implies are equipped with auto alignment technology. Zolo's technology provides for the signal strength to act as the process variable in a proprietary alignment algorithm which commands head movement with x-y control in both heads in real time. This technology is continuously searching for the maximum power and can tolerate significant vibration while still maintaining enough alignment to receive a high enough signal to process data.

The success achieved (no alignment outages) is due to both the SensAlign Heads and the rigidity of water cooled probes. Future installations may require a horizontal configuration. This installation suggests that horizontal can be done with similar results. An additional support system has been designed to assure alignment in the horizontal configuration can be achieved.

**Establishing Critical Path Length**

Zolo had to prove the laser could penetrate the EAF gas and report data for the duration of a heat. It is critical to be able to report during periods of high opacity (usually immediately after charging and during times of high solids injection). In an earlier trial, the Zolo heads were mounted directly into the duct so that the path length was the full diameter of the duct. That test yielded about an 85% viewing for an average heat and was deemed unsuccessful.

From the earlier work, it was clear that Zolo had to establish a Critical Path Length (CPL) which is the maximum distance the laser can report throughout the heat on a regular basis. It was decided to design and install water cooled probes for the purpose of being able to find and set the CPL. A second reason for the addition of the water cooled probes was to locate the laser path so that it is reporting only furnace exhaust gas and not ingressed air from the gap.

The Zolo***SCAN-EAF*** SensAlign Heads needed to be mounted on the stationary side (D1 duct) of the gap after the elbow; but as close to the gap as possible, see Figure 2. Installing them here, along with locating the CPL in the center of the furnace gas plume provided a position that provides for analysis of only furnace gas and be long lasting with minimal maintenance.

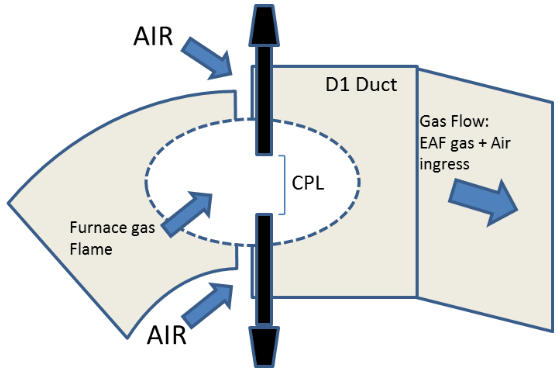


Figure 2. Location of Probes in D1 Duct

The first probes were manufactured extra-long, so that they could be adjusted once installed, allowing for movement to determine the CPL. A total of four (4) positions were tested. Complete visibility was achieved in more than one position which provided confidence for future installations that there is an acceptable range for CPL to meet different furnace configurations. In this case, a final CPL of approximately 1 meter was chosen. The CPL can be either too long or too short. If it is too long, ingressed gap air will be included in the analysis diluting the true furnace gas. If the CPL is too short, it may not be representative of the entire waste gas stream. In addition, in cases where the furnace is tilted, a short path may be only sampling edge gas and/or air. A proper CPL is shown in Figure 3.

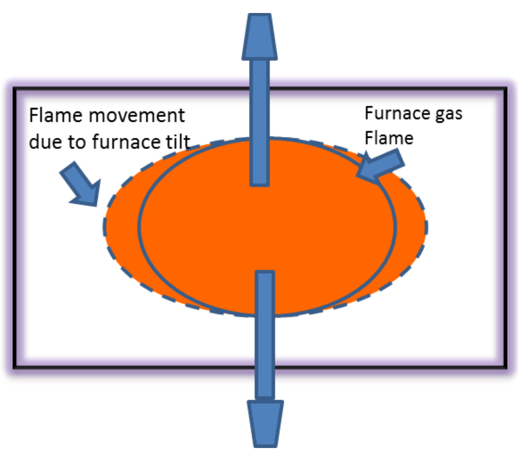


Figure 3. Furnace view of D1 Duct

**Operational Experience**

The Zolo***SCAN-EAF*** System was installed on Nucor's North EAF (NEAF) in February, 2013. The system was reporting data consistently on the first day. Zolo maintained 24/7 observation for the first week to insure the system was reliable and reporting data throughout the heats. The initial probe spacing was set to that the CPL center point was biased towards the top of the duct as shown in Figure 4.

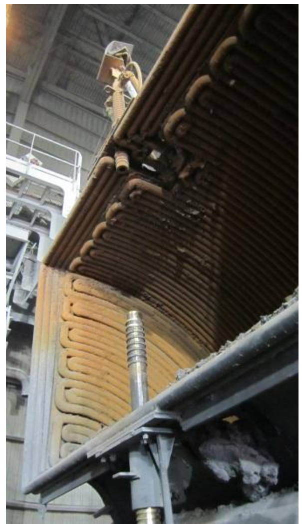

Figure 4. Original probe positions

This setting was based on the thought that the center of the furnace plume was approximately one third the vertical diameter down from the top of the duct. Observation, along with what appeared to be data showing higher than expected post combustion led to moving the CPL center point near the true center point of the duct. This setting (Figure 5) resulted in reliable continuous data, heat after heat.

Figure 5. Current laser path length (CPL)

If it is not properly sealed, the top probe is in a position that naturally can get overheated due to fugitive heat and flame escaping from the penetration made for the probe. This was a problem because the probes are mounted in a Smoke Ring (Figure 6), which is a fabricated slip joint for the gap. It is constructed like the duct, out of welded, water cooled pipes for the purpose of setting the proper gap opening. Because it is moveable, it was necessary to modify the duct itself to allow for that movement. In doing so, open spacing in the duct was created that proved to be difficult to properly seal. Despite early efforts, heat and flame found its way through leakage points and burned both the SensAlign head and fiber optic cable on a few occasions. The problem was cured by properly insulating both the cable and head, along with improving the seal in the duct opening. In summary, the Zolo***SCAN-EAF*** has operated with minimal attention required by operations or maintenance for its first ten months of operation. Loss of signal due to opacity has been less than 2% of the time with those losses primarily being of 5 seconds or less.

Figure 6. Probes being installed on Smoke Ring

The major concern of utilizing the vertical configuration was routine blockage of the bottom probe because of dust dropping down it during operation. If this became a regular problem it would significantly increase maintenance. It has however turned out to be a minor maintenance task. On occasion dust buildup does occur and requires maintenance personnel to clean out the probe. This is done by unsnapping a latch on the SensAlign Head which is mounted on a hinge, allowing the dust to drop out, then cleaning the lens with a clean cloth. This process is done as needed (deteriorating signal strength indicates dust buildup), which currently is about once every two weeks and takes 5 minutes. The design is such that dust has little incentive to drop down the probe. A small purge is maintained, which pushes air upwards. This works in conjunction with the substantial flow of air going across the tip, $90^{o}$ degrees to the centerline of the probe. The combination of purge air and velocity pressure created by the ID fan pulling the exhaust fumes creates negative pressure in the probe and resists particles falling into it. This is a dramatic difference from analyzer systems, which actually must suck a sample into a probe and take high levels of dust along for the ride. It was surprising at first as to how little dust falls into the probe. Another occasional problem is slag or molten steel falling into the probe. This may occur during charging of the second scrap bucket. Slag only causes a problem if the pieces cover the entire lens. Molten steel however will crack the lens. A lens change takes approximately 15-20 minutes. Over the first ten months of operation, three lens changes were required. Fortunately a steel splash is a random occurrence and a high purge flow during charging will further minimize it.

## RESULTS

The Zolo***SCAN-EAF*** was commissioned in February 2013 and has been running continuously ever since. The procedure Nucor chose for process improvement based on continuous gas monitoring is a methodical progression. Nucor has undertaken a program to use the Zolo***SCAN-EAF*** to help fully understand the EAF melting process-as opposed to merely adjusting carbon and oxygen flow rates to modify the post combustion ratio. The long term goal is to study the effects of all energy components (electrical, oxyfuel burners, other carbon+oxygen reactions), along with metallurgical and slag chemistry reactions before using the data in a real time model.

This approach has exceed expectations with respect to developing a deeper understanding of the EAF process while producing cost savings due to more efficient use of heat additives. The off gas data provided previously unknown insight into all aspects of the melting process. Heats were broken down on a minute by minute basis. Electrical power, carbon injection, oxyfuel burner heat energy, oxygen and slag foaming were all studied both individually and collectively. Table 1 shows results obtained on conversion cost savings when the input variables were controlled based on these studies using what became known as the New Profile. Comparison of the existing profile against the New Profile shows that the power on time for the North EAF dropped by **2%** and the injection carbon dropped by over **30%.** The total savings on conversion cost were ***$1.65 per ton***. It should be noted that further continuous improvement tests are being carried out with more complex algorithms to improve on the given results. Further improved conversion costs are being realized, with the intention of moving to on line control in the near future.

| Savings Generated over Existing Profiles (normalized) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Process Parameter® | Charge ton | Power On Time | Power | Oxygen | Nat. Gas | Carbon Injection | [C] | [O] | Temp | TOTAL SAVINGS |
| Existing Profile | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | |
| New Profile | 1 | 0.98 | 0.98 | 0.96 | 1.26 | 0.68 | 0.91 | 1.1 | 1 | |
| Cost Savings/ton | | ($0.04) | ($0.43) | ($0.05) | $0.12 | ($1.44) | | $0.19 | | **($1.65)** |

Table 1. EAF-Process Parameters and Conversion Cost Savings

**Zolo*SCAN-EAF* -ABILITY TO SENSE CHANGES IN THE WATER CONTENT OF THE EAF OFF GAS**

The ability to direct read water vapor is unique to TDLAS technology. The Zolo***SCAN-EAF*** tracks water throughout the heat. Small changes in water vapor can be detected. One of the project goals was to determine if the system can be used as an on line tool to detect system water leaks. A discussion follows outlining work done to validate the sensitivity and repeatability of the water response.

The following Electrode Spray Water Tests were carried out in order to determine the response time and accuracy of the Zolo***SCAN-EAF*** in detecting the change in $H_2O$-content in the furnace off-gas.

When the processing of a heat started as indicated by the Heat-Time count, the water flow to the electrode spray cooling (all three electrodes) was switched on for one minute (60 sec) and then off for the next minute. This on-off procedure was carried out repeatedly and continuously (with only one interruption) until the heat was ready for tapping. The alternating on and off for the spray water was interrupted during the approximately 2 minutes when the second scrap bucket was charged into the furnace. During this interruption, power to the electrodes was switched off and the EAF-roof was swung away from the furnace top. The electrode spray water was also switched off during this period. This test procedure was repeated for more than 10 heats and all showed a similar pattern of the $H_2O$-content of the Off-Gas for the duration of the melting process. Figure 7 shows the effects of the water validation test.

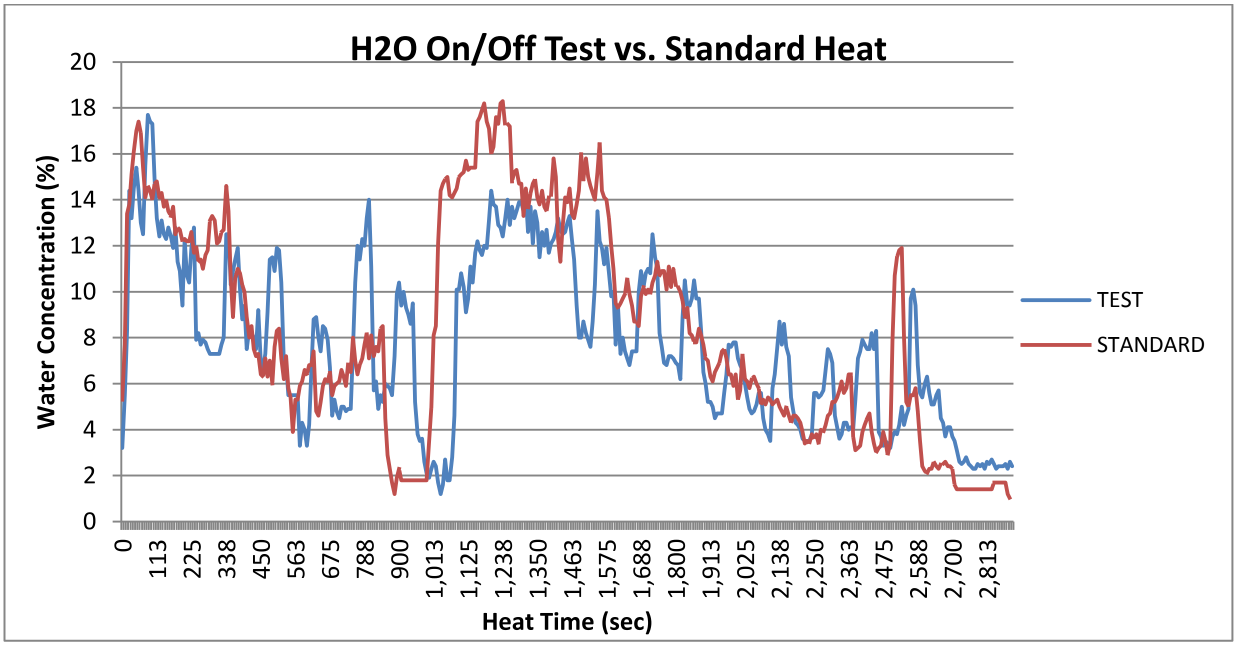


Figure 7. Test Heat with Electrode Spray Water Switched On/Off 1 Minute Intervals

Zolo***SCAN-EAF*** Off-Gas Composition (CO; $CO_2$; $H_2O$), Off-Gas Temperature and Laser Signal Strength as a function of process duration in seconds is shown in Figurer 8. Note that the units on both the primary and secondary axes are dimensionless. This is because the actual values of the parameters were multiplied by a constant in order not to reveal plant proprietary values. This means that the values of the parameters have the same ratio to each other as were the actual values but their magnitude has changed to give a relative number. Other input parameters that are of technical importance to the process have been omitted for proprietary reasons.

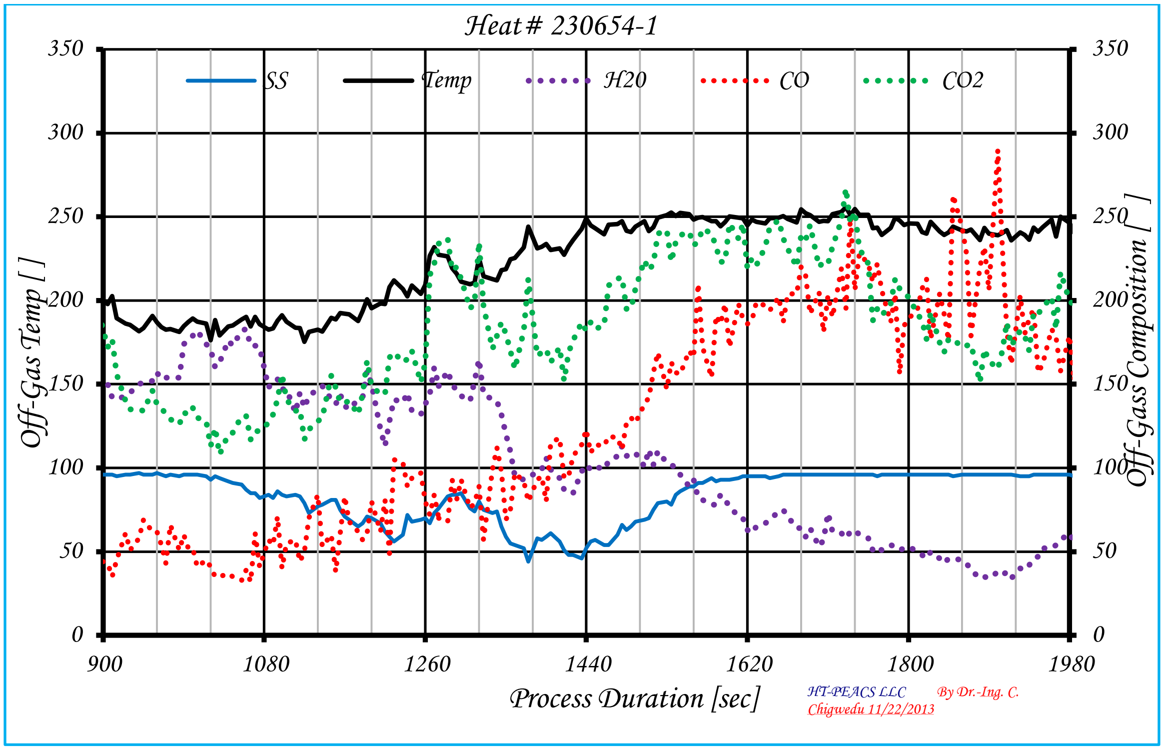


Figure 8. Typical Heat with Electrode Spray Water Switched On

**Discussion of Results**

When the $H_2O$-content of the off-gas is tracked in Figure 7 evidence of the spray water being switched on and off becomes clear just after Power On for the $1^{st}$ and $2^{nd}$ scrap bucket charges. The reasons for the delayed clarity of the $H_2O$-content reading are the high performance burners that become fully operational immediately after a scrap charge has been dropped. The products of combustion (mainly water) from these burners dilute the magnitude of the fluctuations caused by the electrode spray water variations. An uninterrupted study of the electrode spray water experiment in Figure 7 is possible for entire heat with the exception of charging the second bucket (900 to 1125 sec). The minute by minute rise and fall of the Off-Gas $H_2O$-content is clearly evident throughout the heat. As stated earlier on, all heats on which this test was carried out showed similar results. The results led to the conclusion that detection of $H_2O$ by the Zolo***SCAN-EAF*** was immediate and accurate. The accuracy was observed and tested when the flow rates of the electrode spray water and other important water input systems into the furnace were used in a water mass balance for the furnace. The techniques and equations used for the calculations are beyond the scope of this paper and will be fully divulged on another forum.

## CONCLUSIONS

The Zolo***SCAN-EAF*** was installed at Nucor Crawfordsville on the NEAF in February 2013 and has been running continuously with very little maintenance required. The Zolo***SCAN-EAF*** is a laser (TDLAS) based continuous off gas monitoring system which measures CO, $CO_2$, $H_2O$ and temperature on a real time basis (< 2 second response time). Opacity issues have been overcome with heat viewing capability over 98% on a regular basis. Concerns about robustness, accuracy and ability to monitor water to low levels have been answered. This data has allowed Nucor to study the EAF process start to finish and make intelligent process changes resulting in over $1.65 per ton savings to date. Additional work is continuing, including the optimization of DRI usage, which is expected to increase throughout 2014.


## ACKNOWLEDGEMENTS

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