EAF Water Detection at Nucor Steel Seattle, Inc. using Tenova's NextGen® Off-Gas Analysis Technology

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Nucor Steel Seattle, Inc., has equipped their Electric Arc Furnace with Tenova's Water Detection System (WDS) to alert operators of abnormal water conditions in the EAF. Effective water detection technology requires knowledge of BOTH forms of water in the EAF: H_2 & H_2O_{VAPOR}. Tenova's NextGen® off-gas analyzer, installed at Nucor Steel Seattle, effectively measures in real-time the complete EAF off-gas chemistry (H_2, H_2O_{VAPOR}, CO, CO_2, and O_2). This paper reviews the system implemented at Nucor Steel Seattle, Inc., including the NextGen® hardware, WDS software, and the results achieved which validates the system's capability to reliably detect abnormal EAF water levels of at least 15 gallons per minute with minimal false alarms.

INTRODUCTION

Off-gas analysis based water detection has a response time advantage over other water detection systems since abnormal water conditions in the EAF are seen rapidly by changes in H_2O vapor and H_2 concentrations. This is because when liquid water enters the EAF it immediately begins to boil to form steam i.e. H_2O vapor. However, depending on chemical conditions inside the EAF, oxidizing or reducing reactions taking place, a varying proportion of the H_2O vapor can further chemically react to produce H_2 (1,2). Therefore, to be effective in all operating conditions (i.e. in both oxidizing & reducing EAF freeboard chemistry) water detection technology requires knowledge of BOTH forms of water in the EAF: H_2 & H_2O_{VAPOR}, which can be measured using off-gas analyzers that are capable of providing a complete spectrum of gases in the EAF.

The NextGen® off-gas analysis system provides full process control functionality using "full spectrum" off-gas analysis for CO, CO_2, O_2, H_2, H_2O & N_2 (by difference). NextGen® is hybrid technology that combines the high reliability of off-gas extraction & filtration with the fast response time of lasers. By first extracting & filtering the gas prior to introducing the gas into the laser cells, NextGen® avoids any lost analytical signals caused by laser beam attenuation which can be the case with in-situ off-gas systems (3).

This paper describes the installation of the NextGen® off-gas system and Water Detection System (WDS) at Nucor Steel Seattle, Inc. (NSSEA) using the NextGen® off-gas analysis in real-time, the dynamics of the water in NSSEA's EAF was established. Any abnormal water conditions were identified by tuning the system based on electrode spray water injection trials, and real water leaks data. After successful water injection trials and tuning, the system proved to be capable of detecting and alarming for abnormal water conditions of at least 15 gallons per minute, with less than 3% false alarm rate.

DYNAMICS OF WATER IN THE EAF

When water enters the EAF during high temperature conditions, a portion of water may exist in the form of steam or water vapor (H_2O) and a portion can chemically dissociate or react to form H_2, O_2 and CO_2 with the following reactions.

Dissociation: $2\ H_2O \rightarrow 2\ H_2 + O_2$

CO Oxidation: $H_2O + CO \rightarrow H_2 + CO_2$

Fe Oxidation: $H_2O + Fe \rightarrow H_2 + FeO$

The off-gas exiting the EAF contains the key information that can help understand the dynamics of water in the EAF by considering these reaction scenarios. The levels of H_2, O_2, CO_2 and CO, which are variable depending on the combustion reactions and their presence in EAF off-gas, can then be used to indicate the level of water concentration within the EAF, more specifically any un-dissociated water vapor can be distinguished as H_2O and dissociated water vapor as H_2, CO or CO_2.

The ratio of H_2O vapor to H_2 in the off-gas will depend on many factors, such as where the abnormal water enters the EAF and the oxidization potential of the freeboard gases inside the EAF. If the EAF freeboard is overly oxidizing (for example when draft suction is high), then the reactions favor producing H_2O vapor. Alternatively, H_2 is favored if the freeboard is more reducing. While the most efficient and lowest cost operation usually occurs when the EAF off-gas is mildly reducing, in actual practice it is difficult to avoid swings between overly oxidizing and overly reducing freeboard chemistry due to process changes. For this reason, for water detection systems to be effective in both oxidizing & reducing conditions, the off-gas analyzer must measure all the critical gases including H_2O vapor, H_2, CO, CO_2 and O_2.

The measurements of H_2, CO_2 and CO provide useful information to classify the EAF state as either oxidizing or reducing, and explain dissociation of H_2O vapor. The oxidizing state of the EAF can be determined in two ways considering the CO Oxidation equation above. First, if the amounts of CO and H_2 seen in the off-gas measurements are low. Second, the ratio between H_2 and CO, where an increase in H_2 and decrease in CO would indicate more oxidation reactions are taking place, as well as the ratio of (H_2 x CO_2)/CO which is also in effect by the reaction taking place. The value and contribution of each of these measurements of dissociated water vapor are dependent on the specific operation conditions of the EAF.

Another approach to determine the water in the EAF is through evaluating the EAF operation through a dynamic model including the off-gas measurements (H2, CO, CO2, and O2), off-gas temperature, off-gas flow rates, EAF pressure, and process controlling information such as oxygen input, fuel input, carbon input. The dynamic model process inputs are as shown in Figure 1 below, which uses a combination of the information above to determine the water in-leakage rate into the furnace in real time.

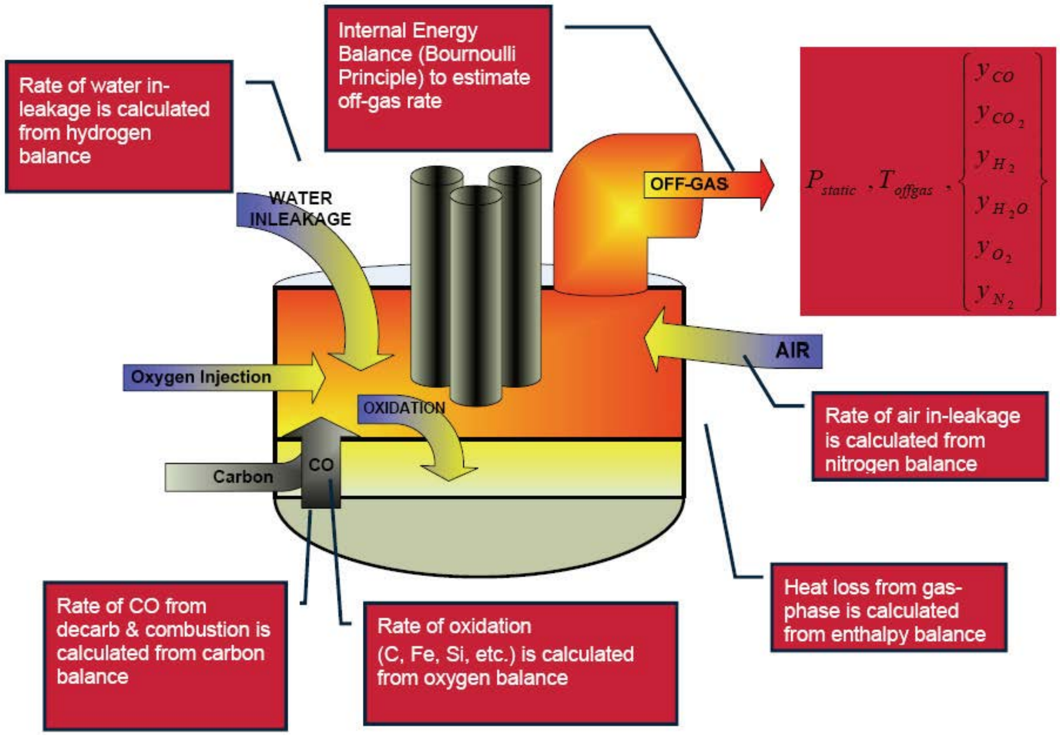

Figure 1. Dynamic Model of Water In-Leakage Calculation

The key variables and metrics for water detection in the EAF using off-gas measurements are:

1. H_2O vapor in the EAF
2. Gas concentrations measured in real-time: H_2, CO, CO_2, O_2
3. Off-Gas Temperature and EAF static pressure

To summarize, in order to achieve success in effective off-gas based water detection technology, it is necessary to have hardware and software that provide: (i) Off-gas measurements including both H_2O vapor and H_2 as well as CO & CO_2, (ii) fast response, (iii) reliable analysis without loss of data, and (iv) software that provides real-time alerts to operator when abnormal water conditions are seen. The NextGen® off-gas technology coupled with WDS has proven capable of effectively detecting abnormal water at NSSEA's EAF.

NEXTGEN® OFF-GAS TECHNOLOGY

Continuous EAF off-gas measurement technology was first commercialized in 1998 with the Tenova's EFSOP® extractive off-gas system. The system established the industry standard in EAF off-gas analysis and as a tool to conduct EAF process optimization [(4,5,6,7)]. Typically extractive systems provide complete off-gas analysis (CO, CO_2, O_2, H_2, H_2O and N_2), and continuous analysis under EAF power ON conditions, while in-situ systems provide incomplete off-gas analysis (typically only CO, CO_2,and H_2O) with faster response/measurements, but with possible lost signals during EAF power ON due to laser beam attenuation [(3)].

While both technologies have pros and cons, the newly developed Tenova NextGen® off-gas system is the evolution of Tenova's EFSOP® technology [(8,9)]. With 10 installations in North America alone since its commercial launch in 2015, it was designed to combine the excellent reliability of the traditional extractive off-gas technology and provide faster response by introducing laser technology, while minimizing hardware costs, installation costs, and required maintenance of the system [(10,11)].

The NextGen® off-gas analysis system utilizes off-gas extraction & filtration which ensures high system reliability and avoids lost analytical signals from laser beam attenuation. The system incorporates a multi-point optical analyzer which is designed to be located in the EAF meltshop control room, as shown in Figure 2(a). The off-gas is extracted by a probe located in the fume duct and directed at high flow rate to a sample station which is mounted directly on the shop floor without the need for a protective room. The sampling station filters and cleans the gas prior to introducing it into Tenova's proprietary laser & analytical cells. Each sampling station can be monitored directly for system working condition through the analyzer HMI, as shown in Figure 2(b). A single central optical analyzer can continuously analyze up to 6 separate off-gas sampling locations. The analyzer connects via fiber optic and coax cables to each remote sampling station as shown in Figure 3(a). The sample station is divided into a hot side and cold side as shown in Figure 3(b) which separates working components, providing the desirable working configuration and ease of maintenance. The sampling stations carry a high volume pump in the cold side which continuously extracts an off-gas sample from the EAF fume duct using a patented water cooled probe which is guaranteed for one year (Figure 4). The sampling stations are compact by design and require minimal maintenance from the meltshop personnel. The analyzer and sample stations are highly configurable depending on the melt shop layout and desired sampling locations as seen in many installations [10,12].

Figure 2 (a). Analyzer Cabinet

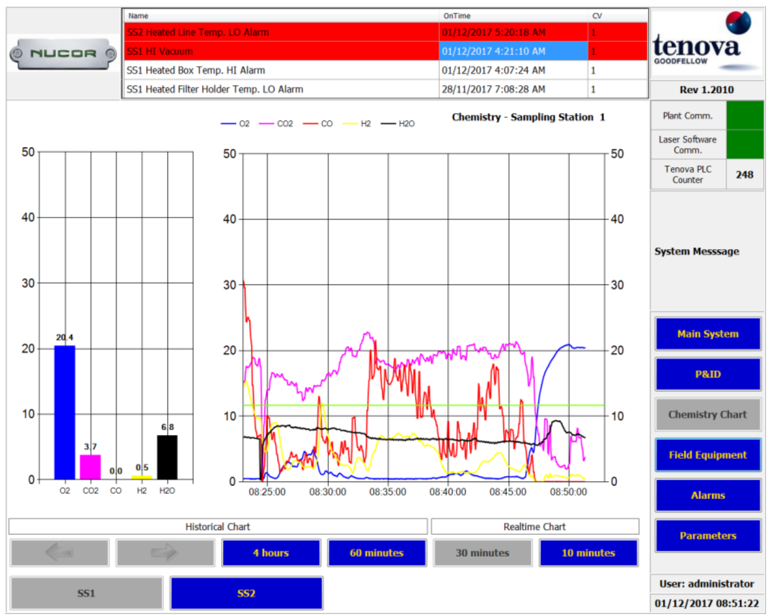

Figure 2 (b). Central Analyzer HMI Screenshot

Figure 3 (a). Sampling Station Installed at Nucor Seattle

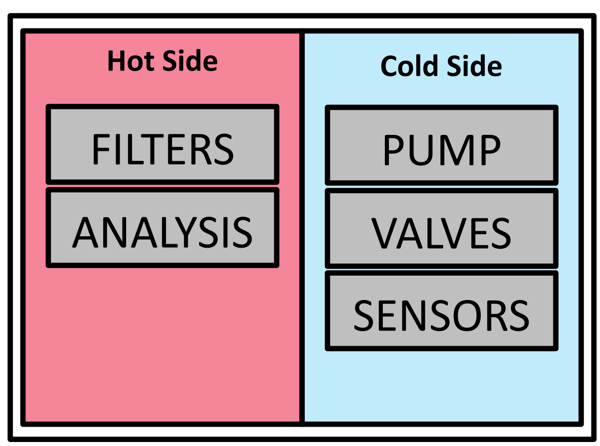

Figure 3 (b). Main Sampling Station Components

Figure 4. Patented Probe location at Nucor Steel Seattle, Inc. at the 4th Hole

The use of the NextGen® off-gas system can greatly benefit the EAF operation by providing chemical process control. In addition, the WDS module can provide real-time detection of abnormal water in the EAF. The Nucor Seattle installation includes one central multipoint optical analyzer in the EAF control room, two sampling stations (one at the 4th hole & one downstream), one optical off-gas temperature sensor, one optical off-gas velocity sensor as well as *i* EAF® process control software to dynamically control and optimize chemical & electrical energy inputs as well as predict C & T endpoint conditions. The true operation benefits of the *i* EAF® system are highlighted from results from plants around the world [13,14,15,16]. This paper describes the expansion of the original NextGen® / *i* EAF® project at Nucor Seattle to incorporate the WDS hardware & software modules which provide real-time alerts for abnormal water conditions in the EAF.

WATER DETECTION AT NUCOR SEATTLE

Nucor Steel Seattle, located in Seattle, USA, has been using an installation of Tenova's EFSOP® off-gas technology since 2001. The recent upgrade from the traditional Tenova off-gas analyzer to the up-to-date and established NextGen® analyzer was a campaign to modernize and improve their EAF process control, and improve upon safety practices.

At NSSEA, a single NextGen® multipoint analyzer was installed with two off-gas sample stations in the upstream and downstream locations, measuring a complete spectrum of the EAF's off-gas including CO, CO_2, O_2, H_2, H_2O vapor and N_2. The need for two off-gas sample stations is a part of Nucor Steel Seattle's use of Tenova's *i* EAF® technology which was proven to provide significant benefits to the EAF process [12]. The NextGen® off-gas analyzer and Water Detection System (WDS) are technologies that can be installed as stand-alone systems, without the *i* EAF® modules added on.

The WDS is composed of the NextGen® off-gas analyzer use as hardware to collect off-gas data that explains the EAF process and Water Detection System software which combines off-gas measurements, and process data to monitor and evaluate the water condition in the EAF.

WDS Software Description

The WDS software combines a series of models which monitor and alarm in case abnormal water is expected in the EAF. The software methodology can be broken down as:

i. Collection of real-time process data from the EAF including flows, temperatures, and pressures
ii. Collection of NextGen® off-gas system measurements: H_2O vapor ($H_2O_{Measured}$), H_2, CO, CO_2, and O_2
iii. Based on the process conditions including NextGen® analysis of H_2, CO, CO_2 & O_2 as well as real-time EAF operating conditions, Tenova's WDS software calculates the $H_2O_{Estimated}$. Subsequently an

$H_2O_{Threshold}$ is established based $H_2O_{Estimated}$ and tuning of the system using data from water injection trials used to simulate abnormal water conditions

iv. Whenever the $H_2O_{Measured}$ is greater than the $H_2O_{Threshold}$, the software monitors conditions closely and the level of abnormality is continuously evaluated

v. Alarms are sounded if the abnormality exceeds limits established from water injection trials and tuning of the system

Figure 5 shown below graphically illustrates the methodology for triggering an alarm for abnormal water in the EAF. The blue curve is the $H_2O_{Measured}$ from the NextGen® off-gas analyzer. The green dotted curve represents the $H_2O_{Estimated}$ based on the EAF process characteristics and the off-gas real-time chemistry status measured by the NextGen® system. The orange dotted curve represents the $H_2O_{Threshold}$ calculated to detect an abnormal H_2O condition in the EAF.

The $H_2O_{Threshold}$ calculation is based on the result of process modelling for the EAF, and controlled water injection into the EAF to simulate the effect of abnormal water conditions in the EAF. When the $H_2O_{Measured}$ is below the $H_2O_{Threshold}$, the WDS software shows a *'Green Alert'* indicating that the statistical probability of excessive amounts of water in the EAF is low, but not non-existent. When the $H_2O_{Measured}$ exceeds the calculated $H_2O_{Threshold}$, the system will enter in a warning state, or *'Amber Alert'*, meaning that the situation is being monitored closely. Based on the defined alarming parameters and alarming algorithm, when the real-time metrics exceed their limits, a *'Red Alert'* is issued indicating that the measured values are significantly out of the statistically normal range and that there is a high probability of abnormal water in the EAF. Situations where *'Red Alert'* trigger alarms are active, require immediate action by the operating personnel.

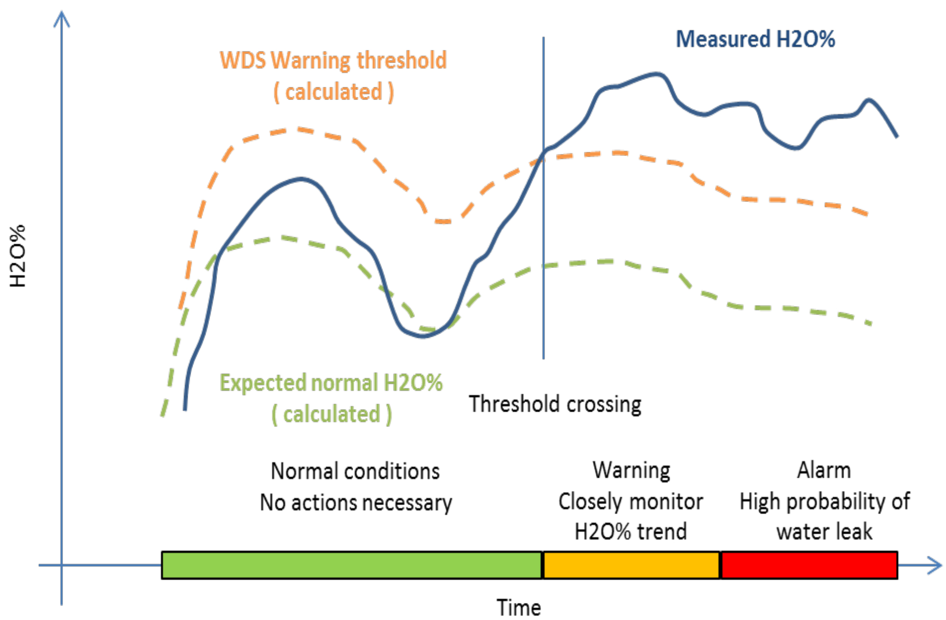

Figure 5. Methodology for the WDS software to trigger an abnormal water condition. The measured H_2O (blue) is compared to the expected H_2O (green) and the warning threshold (orange). If the measured H_2O crosses upward the warning threshold, a specific algorithm monitors the behaviour of H_2O and triggers an alarm

The WDS is not a failsafe safety system and is not guaranteed to detect all water leaks or explosive situations. However based on EAF installations to date, it does provide operators with valuable real-time alerts as well as rapid information that help operators to distinguish between normal and abnormal levels of H_2O vapor and H_2 in the EAF. The methods of evaluation and alarming for abnormal water is configured to maximize detection of abnormality while minimizing false alarming. A false alarm is defined as a condition when the system enters the 'Red Alert' stage, but no real water leak or abnormal water source is identified. Such situations are possible when excess H_2O is produced by the furnace, but the relevant additional source of water is not made available to the WDS software (i.e. rain, ice, or snow entering the furnace with scrap steel).

NextGen® WDS Results at Nucor Steel Seattle

At NSSEA, the WDS has demonstrated an up time of 95% during each heat when constraints in place of NextGen® hardware operation and EAF process are steady. The system has demonstrated the capability to quickly and correctly respond to controlled changes in abnormal water in the EAF. The system capabilities were tuned and demonstrated by first conducting on-site controlled water injection trials by adjusting the electrode spray water flows and secondly based on real confirmed water leaks.

Controlled Spray Water Trials

As the electrode spray water flows were pre-programmed, their input to the WDS calculated $H_2O_{Estimated}$ are minimal. Thus, using the electrode spray water proved to be a safe method of introducing abnormal water in the EAF. Water Injection trials were conducted by increasing the electrode sprays water flow rate and observing the increase in $H_2O_{Measured}$. The trial results were used to tune the WDS parameters for calculating the $H_2O_{Threshold}$ and effective parameters to determine whether a situation is showing normal or abnormal water in the EAF.

Figure 7 and Figure 8 show examples of two controlled electrode water spray trials at the NSSEA during the melting phase. The horizontal axis shows *i* EAF® Melt Percent to represent the measure of time during the heat, and the vertical axis shows the H_2O% for Measured and Threshold. The *START WATER* indicates that the electrode spray water was increased to its maximum flow rate and *STOP WATER* indicates that the electrode sprays were returned to their nominal flow rate per the electrode spray water program.

Figure 6 shows Heat #1 where the water injection was started and stopped within a 15 Melt Percent timing. The response in the $H_2O_{Measured}$ is clearly evident when the injection starts and stops with rapid increase and decrease respectively. When the water injection is stopped, the $H_2O_{Measured}$ returns to its normal condition as per the EAF process conditions.

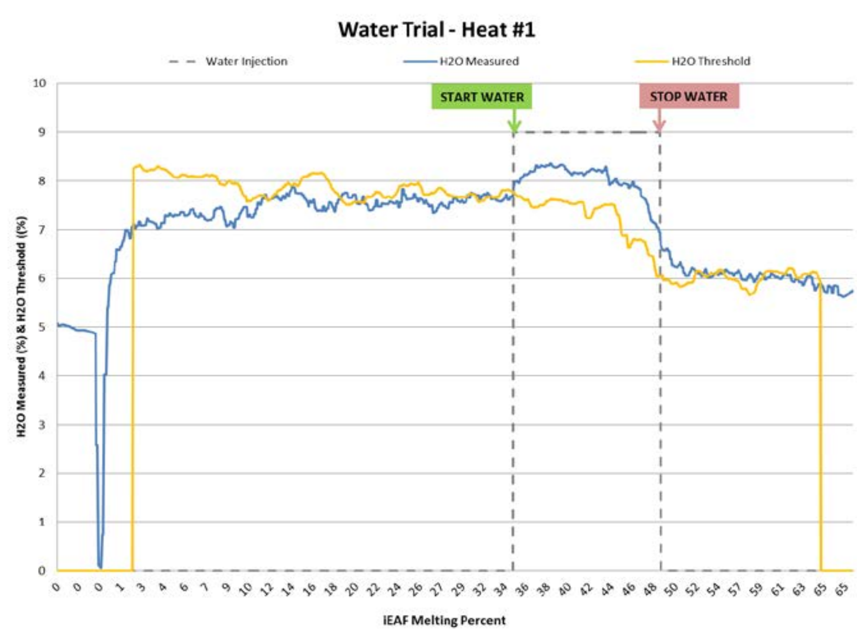

Figure 6. Electrode Spray Water Trial conducted on Heat #1

Figure 7 shows Heat #2 where the water injection was started and stopped twice with a 'reset period' for the $H_2O_{Measured}$ to return to its normal process state . The response in the $H_2O_{Measured}$ is apparent when the injection starts and stops in both cases with rapid increase and decrease. The purpose of this water injection trial is to determine if it is the electrode spray water alone affecting the $H_2O_{Measured}$ or if there are other factors. From observation, it is clear that the controlled electrode spray trials are the true factor for the increase and decrease observed in $H_2O_{Measured}$, the measurement is not affected by EAF process related changes, and that the $H_2O_{Measured}$ is a reliable metric.

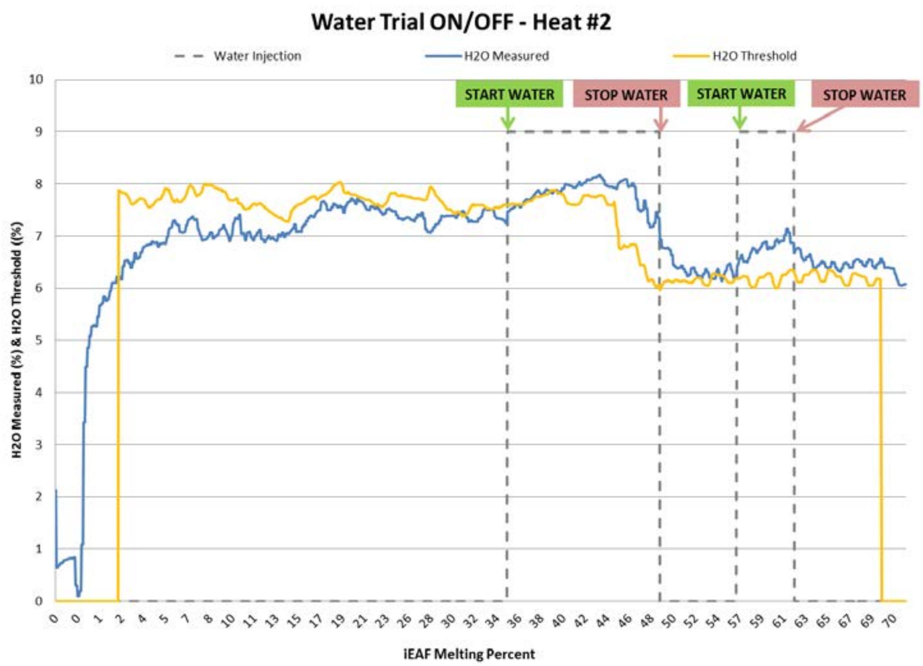

Figure 7. Consecutive ON/OFF Electrode Spray Water Trial conducted on Heat #2

Water Leaks & Results Summary

Since commissioning the WDS, the system has detected several actual water leaks of varying size. Below is a summary of the results from Nucor Steel Seattle over a four month period.

Table 1. Performance Summary of NextGen® WDS during four months of evaluation

	Number of Heats	Number of Alarms	False Alarm Rate	Estimated Leak Size
Non-Leak Heats	2125	69	~3%	-
Water Leak #1	13	12	-	~19 GPM
Water Leak #2	30	25	-	~15 GPM

The electrode spray water trials provided useful statistical data to evaluate the severity of real water leaks. By establishing the level of increase in $H_2O_{Measured}$ and comparing it to the amount of water injected using the electrode sprays, a ratio between visible increase in $H_2O_{Measured}$ and abnormal water was determined. This ratio was then applied to real water leaks to establish an estimated leak size.

Figure 8 shows the Refining phase of the heat when Water Leak #1 is expected to have started. Figure 9 shows the melting phase of the heat when Water Leak #2 is expected to have started. In both cases, the WD system provides the plant with an 'Amber Alert' when the $H_2O_{Measured}$ is greater than the $H_2O_{Threshold}$ and begins to evaluate the nature of the $H_2O_{Measured}$. When the duration, degree of increase and other alarming parameters surpass the defined threshold limits, a full alarm is triggered and the system is on 'Red Alert'.

For both Water Leak #1 and #2, the Alarming system provided alerts on the first heat when the water leaks were expected to have initiated. Both water leaks continued to alarm in subsequent heats

Because the system was in the tuning evaluation period, these real-time alerts were not made available to the EAF operator. The leaks were subsequently visually observed by operators and repaired accordingly. Both leaks were confirmed to have occurred in the EAF roof panels. Upon review of NextGen® WDS data and statistics, the heat when the leak initiated was identified.

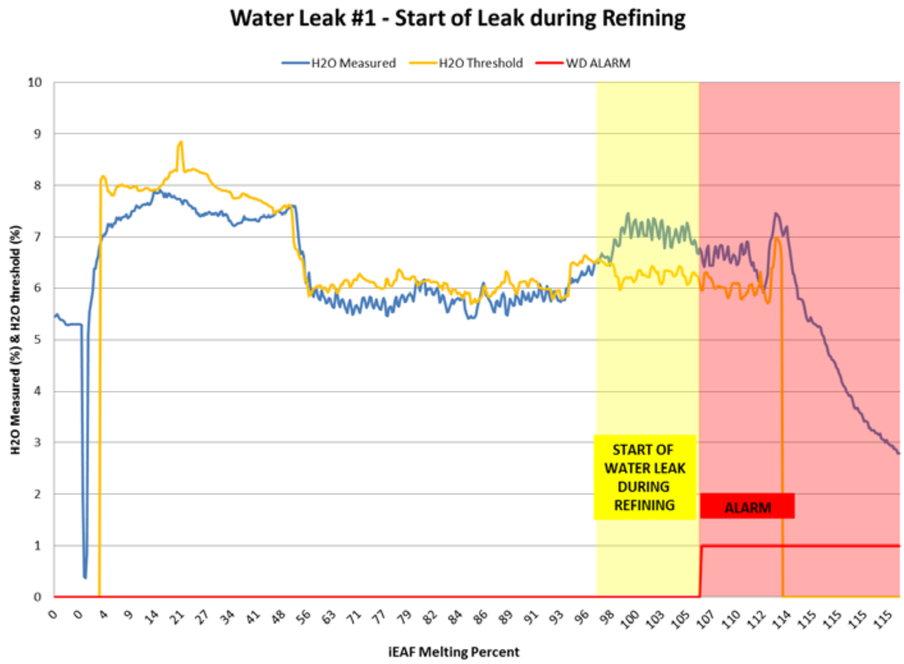

Figure 8. Start of Water Leak #1 during the Refining phase

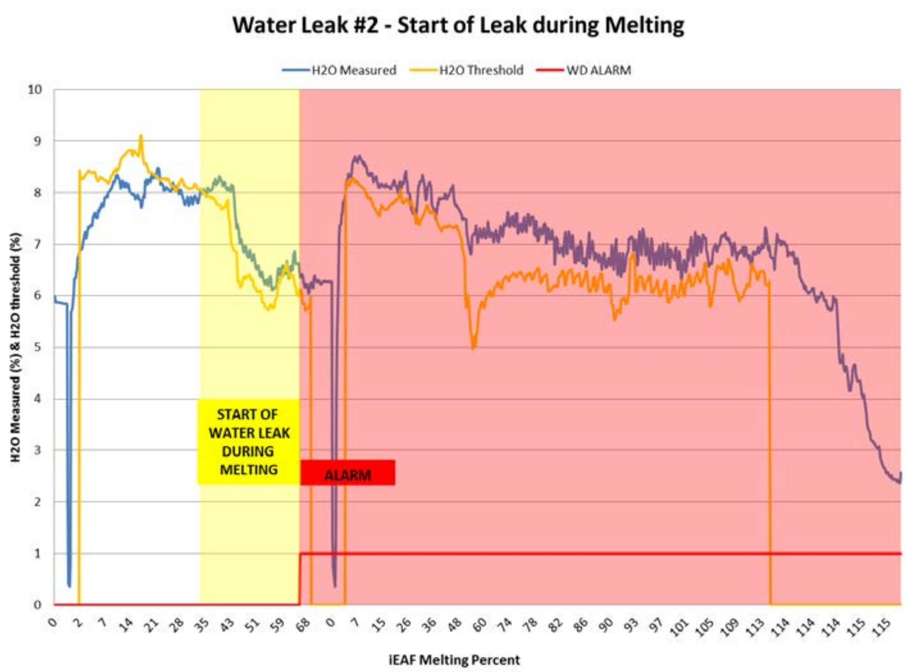

Figure 9. Start of Water Leak #1 during the Melting phase

The true cause of many of the false alarms encountered during normal operation are due to weather related scenarios that resulted in abnormal water entering the furnace through heavy rains in the humid Seattle area, resulting in wet and cold scrap. Adjustments to the WDS tuning parameters based on seasonal changes can certainly minimize the false alarms.

Water Leak Detection after System Commissioning

After the WDS commissioning, the system detected water leaks of varying size as early as the subsequent months. The WDS system was active for 90% of each heat during operations, and the system's metrics during real-time operation is summarized in Table 2.

Table 2. Performance Summary of NextGen® WDS for four months after commissioning.

Period After Commissioning	Data / Event Recorded	Number of Heats	Number of Alarms	False Alarm Rate	Estimated Leak Size
Month 1	All Heats	471	11	2.3%	-
	Water Leak #1	5	0	-	< 10GPM
Month 2	All Heats	412	7	1.7%	-
	Water Leak #2	3	3	-	~15GPM

Water Leak #1 occurred at the furnace roof and was described as a 'small drip' that was observed by a ladleman. While the leak occurred, an increase in off-gas humidity measurement was not visible and the leak was estimated to be less than 10GPM. The furnace operation continued until it was corrected during a scheduled maintenance.

Water Leak #2 occurred during operation with a visible increase in the measured water measurement and an estimated size of ~15GPM. The repeated alarming was observed by the furnace operator, and upon review it was concluded that the alarm was due to short electrodes which resulted in electrode water sprays to inject water directly in to the furnace and as a result introduce an abnormal water condition. The alarms were acknowledged by the operator and did not resurface after the electrodes were changed.

The objective of the NextGen® WDS tuning is to balance the detection of abnormal water and false alarms from the system. It is desirable for the WDS to perform with a high detection rate and low false alarm rate. It is imperative to maintain the hardware and software to keep the system up to date and effective.

In the case of NSSEA, the range of detecting abnormal water of at least 15GPM and 3% false alarm during normal operation is the case both during and after commissioning. Since commissioning the WDS has worked reliably and continues to detect water leaks greater than ~15 gpm. The actual False Alarm rate is expected to be in the range of 1.7% to 3.3%.

CONCLUSIONS

Tenova Goodfellow has developed an effective water detection technology capable of analyzing both H_2O vapor and H_2. The NextGen® off-gas system provides reliable and uninterrupted off-gas analysis from start-to-end of the heat. The WDS module has proven capable of rapidly and accurately distinguishes between "normal" and "abnormal" levels of H_2O vapor and H_2 in the EAF freeboard.

Controlled electrode water spray trials were conducted to simulate a water leak and tune the system. True water leaks were classified as abnormal water inside the EAF, visually identified and corrected. At Nucor Steel Seattle, the NextGen® WDS has proven to detect abnormal water conditions as low as 15 gallons per minute with less than 3% false alarms.

The NextGen® WDS can be provided as an add-on module to an existing Tenova off-gas analyzer or as a complete standalone system which in future can be upgraded to a full NextGen® off-gas analyzer system useful for EAF process control and optimization.

After the demonstration period of the NextGen® WDS results through four months of monitoring and tuning, Nucor Steel Seattle has continued to utilize the system and have identified several other water leaks in their early stages and thus improving the safety in their EAF operations.

REFERENCES

[1] Zuliani D., Alshawarghi H., Scipolo V., Khan M., Bilski, W., "Real-Time Water Detection at ArcelorMittal Coatesville", *AISTech Conference Proceedings 2014*

[2] Luccini M., Scipolo V., Zuliani D., Poli L., "Water Leak Detection in EAF based on Tenova's off-gas technology: recent developments and results in Lucchini RS, Lovere, Italy", *AISTech Conference Proceedings 2016*

[3] Schilt S., Tittel F.K., Petrov K.P., "Diode Laser Spectroscopic Monitoring of Trace Gases", *Encyclopedia of Analytical Chemistry, pages 1-29, 2011*

[4] Zuliani D., Scipolo V., Negru O., Khan M., "Breakthrough Technology for Real-Time Water Detection in EAF Steelmaking" *AIST 2013 Conference May 2013*

[5] Mistry S., Todorovic I., Vazquez A., Sabugal J., "Operating Results of Goodfellow EFSOP® at Tenaris Siderca, Argentina", *AISTech Conference Proceedings, 2014*

[6] Vensel D., Khan M., "EAF Performance Improvement at Nucor Steel Auburn using Goodfellow EFSOP®", AISTech Conference Proceedings, 2006.

[7] Missio M., Boin N., Khan M., "Optimization Results at Ferriere Nord using EFSOP Technology", *AISTech Conference Proceedings, 2010.*

[8] Zuliani D., Goodfellow H.D., Bianchi Ferri M., "EFSOP Holistic Optimization of Electric Arc Furnaces – Past, Present and Future", *9th European Electric Steelmaking Conference, May 19-21 2008, Krakow, Poland*

[9] Khan M., Mistry S., Scipolo V., Waterfall S., "Next Generation EAF Optimization at ArcelorMittal Dofasco Inc.", *AISTech Conference Proceedings, 2013.*

[10] Pal A., Zuliani D., Todorovic I., Scipolo V., Spencer A., "Installation of NextGen® Multipoint Off-Gas Analysis Technology at SDI Butler, IN", *AISTech Conference Proceedings 2016*

[11] Zuliani D., Scipolo V., Pal A., Negru O., "Next Generation EFSOP® Off-Gas Analysis Technology: A Hybrid Extractive – Optical Solution with Water Detection Capability", *AISTech Conference Proceedings, 2015*

[12] Iyer H., Babaei B., Scipolo V., "EAF Optimization using real-time Heat and Mass Balances at Nucor Steel Seattle", *AISTech Proceedings, 2017*

[13] Maolo, J., Scipolo, V, Clerici, P., "iEAF® Technology: Dynamic Process Control for the Electric Arc Furnace", *AISTech Conference Proceedings 2009*

[14] Gillgrass S., Galbiati P., Giugliano P., Scipolo V., Clerici, P., Pustorino M., "iEAF® Technology: Recent Developments and Results at Tenaris Dalmine, Italy", *AISTech Conference Proceedings 2010*

[15] Gillgrass S., Scipolo V., Zuliani D., Clerici P., Pustorino M., "iEAF® Technology: The Use of Off-Gas Analysis for Carbon & Temperature Prediction in Electric Arc Furnaces", *AISTech Conference Proceedings, 2012*

[16] Babaei B., Scipolo V., Leali M., Radoani A., "iEAF® Technology: Recent Developments and Results in IRO, Italy", *AISTech Conference Proceedings, 2016*