AVANÇOS NO CONTROLE DINÂMICO DE GASES DE EXAUSTÃO NO PROCESSO DO FEA UTILIZANDO A TECNOLOGIA NEXTGEN DA TENOVA *

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Resumo

A tecnologia Intelligent EAF da Tenova (i EAF®) fornece um roteiro de várias etapas para melhoria contínua, economia de custos e maior segurança. Um Sistema iEAF® completo é uma combinação de medições em tempo real, usando tecnologia de ponta e modelos de processo robustos, incluindo um balanço preciso de massa e energia em tempo real; com os objetivos de reduzir os custos operacionais e, ao mesmo tempo, aumentar o rendimento e a produtividade. O iEAF® também representa um mecanismo de controle de processo poderoso, estável e robusto para a automação EAF Nível 2 e pode ser aprimorado com a detecção de vazamento de água mais abrangente do setor usando a análise de vapor de H_2 e H_2O
Palavras-chave: EAF inteligente; Controle de processo iEAF, análise de gases, sensores EAF, Indústria 4.0, NextGen.

ADVANCEMENTS IN DYNAMIC EAF OFF-GAS PROCESS CONTROL USING TENOVA'S NEXTGEN® TECHNOLOGY

Abstract

Tenova's Intelligent EAF technology (**i EAF®**) provides a multistep roadmap for continuous improvement, cost saving and increased safety. A full **i EAF®**' System is a combination of real-time measurements, using state-of-the-art technology and robust process models, including a precise real-time mass & energy balance; with the objectives to reduces operating costs while increasing yield & productivity; The **i EAF®** also represents a powerful, stable and robust process control engine for EAF Level 2 automation and it could be enhanced with the industry's most comprehensive water leak detection using both H_2 & H_2O vapor analysis.
Keywords: Intelligent EAF; iEAF process control, off-gas analysis, EAF sensors, Industry 4.0, NextGen.

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1 INTRODUCTION

Tenova's original extractive EFSOP® analyzer installed in 1998 in England was the 1st off-gas analysis system on an EAF. This initial EAF off-gas solution developed the methodology for dynamic control of burners & lances with the aim of increasing "in-EAF" post combustion of CO & H_2 and improving energy utilization efficiency – today Tenova calls this 1st Step solution **i EAF®** MODULE 1.

Since that initial EAF installation over 20 years ago, the use of EAF off-gas analysis technology has expanded dramatically. Tenova has now developed broadly based off-gas process control systems for all electric furnace steelmaking processes including conventional EAF, Consteel, Twin-Shell & Shaft furnaces using combinations of scrap, DRI & hot metal as well as for BOF & AOD oxygen steelmaking furnaces.

This paper describes the evolution of Tenova's off-gas based solution for EAF steelmaking. As shown in Figure 1, this evolution has led to the development and commercialization of leading edge hardware, software and service & support programs incorporating Industry 4.0 cloud based computing which all together form a complete long-term sustainable solution that can be tailored to satisfy each EAF shop's particular needs [1, 2].

2 DEVELOPMENT

As shown in Figure 1, the complete i EAF® technology platform incorporates a combination of innovative & patented hardware, proprietary process control & water detection software and ongoing service & support programs utilizing cloud based computing technology:

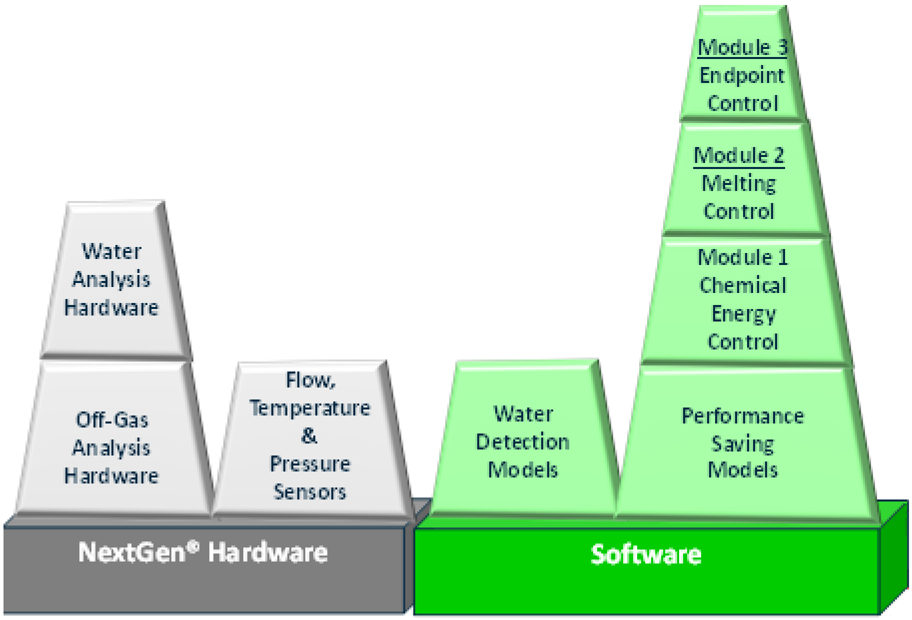

Figura 1. *Tenova's* i EAF® *Technology Platform*.

i. **NextGen® off-gas analysis hardware** provides actual measurements in critical process areas and thereby avoids control errors and inaccuracies that would result when using estimates & assumptions. Off-gas composition, flow, temperature & pressure sensors provide valuable real-time measurements necessary for effective Process Control and for comprehensive EAF Water Detection.

ii. **¿ EAF® Software** replaces statistical process models which are prone to excessive drift with a new generation of more fundamental thermodynamic & kinetic based process control models that incorporate real-time mass & energy balances. The **¿ EAF®** incorporates 3 distinct Performance Saving MODULES that dynamically control the quantity of chemical energy and furnace draft, dynamically control chemical energy & electrical set point timing and dynamically control oxygen injection during refining to finish the heat on C & T spec. In addition, the **¿ EAF®** package includes the industry's most comprehensive Water Detection software based on both H_2 & H_2O vapor off-gas analysis.

2.1 NextGen® Off-Gas Hardware

Virtually 100% of EAF off-gas consists of 6 species; CO, CO_2, O_2, H_2, H_2O vapor & N_2. Knowledge of this full spectrum off-gas analysis is important for controlling the EAF's oxygen potential, for dynamic control of fume system suction, to enable efficient O_2 lancing & carbon injection, to close a real-time EAF Mass & Energy Balance and for real-time Water Detection which all together dramatically improve EAF energy efficiency, reduce operating costs, improve yield & productivity and improve safety.

Figure 2 provides a synopsis of Tenova's NextGen® Off-Gas Hardware which can be divided into two main categories –

(a) the Off-Gas Analysis stream includes the corner stone full spectrum NextGen® hybrid extractive/laser, multipoint analyzer technology plus the optional add-on water vapor analysis technology.

(b) the NextGen® Sensor stream includes robust off-gas flow & temperature and EAF pressure sensors.

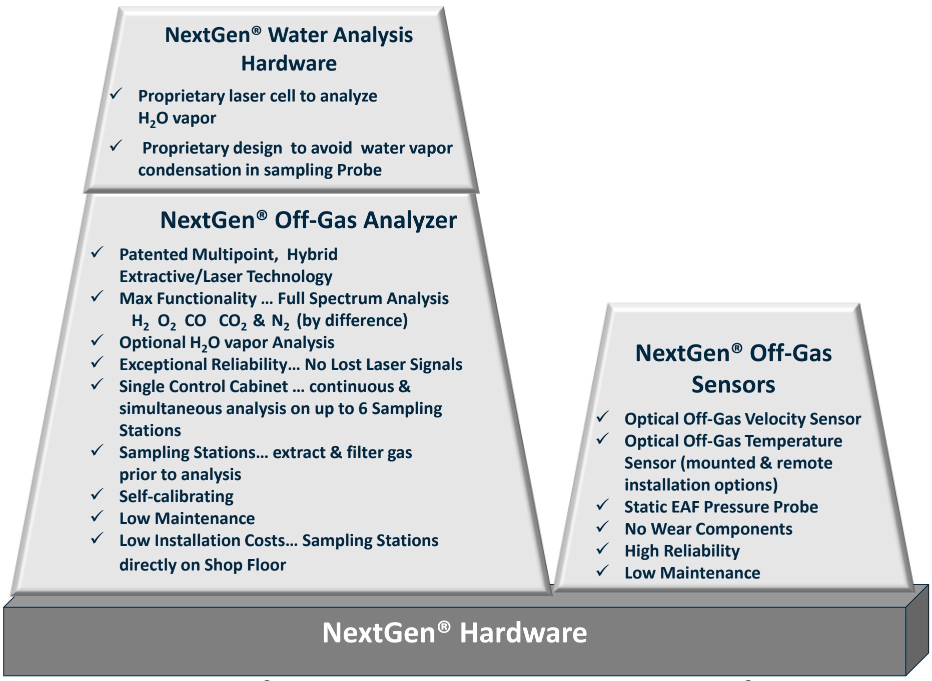

Figura 2. *Tenova's NextGen® Hardware Technology part of the* ¿ EAF® *Technology Platform*

(a) NextGen® Off-Gas Analysis

In 2015, Tenova Goodfellow developed and patented the 1st commercial next generation hybrid extractive/laser off-gas analysis system designed especially for harsh industrial processes such as exist in EAF & BOF steelmaking [3,4,6]. NextGen® technology replaces the original extractive ESFOP® system and is designed to combine the excellent reliability of this traditional extractive technology with the faster response time and the lower hardware installation costs of tunable diode lasers.

As shown in Figure 3, NextGen® hybrid technology utilizes off-gas extraction through a redesigned probe positioned directly in the cone of pure off-gas exiting the EAF at the 4th hole. Positive extraction remains the very best way to ensure high system reliability and avoid lost analytical signals. Compact Extractive Sampling Station(s) are mounted directly on the melt shop floor without the need for an environmentally protective room.

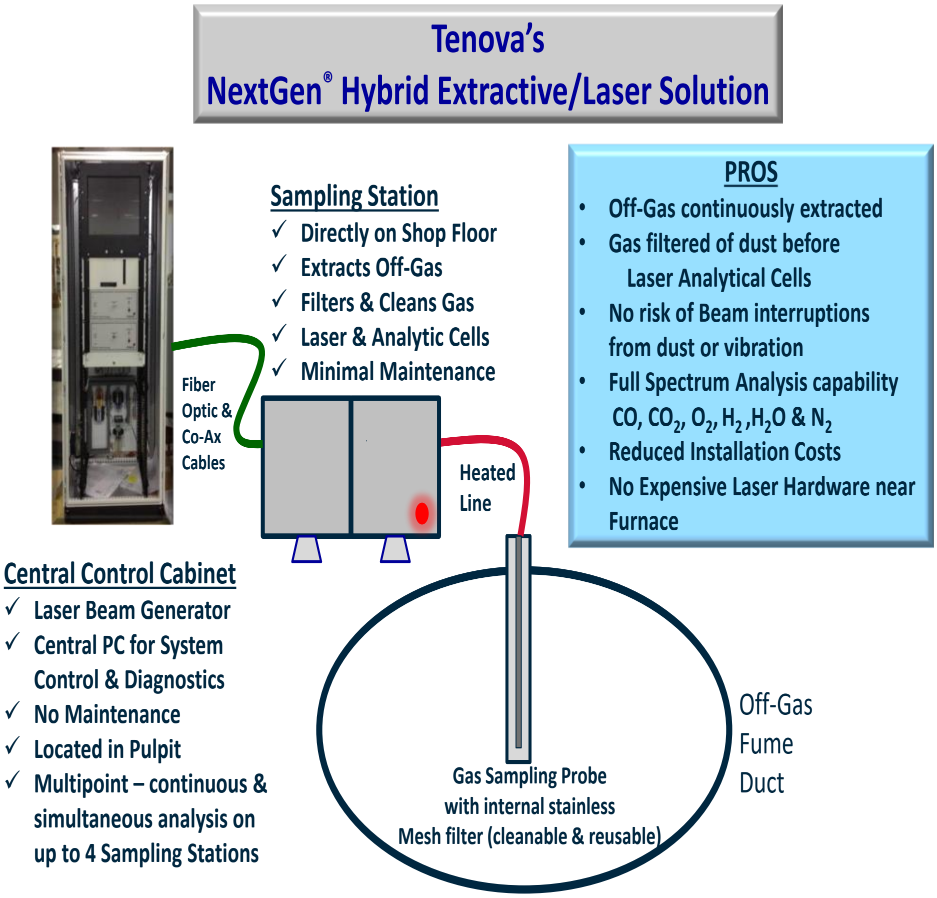

Figura 3. *Tenova's NextGen® Multipoint Hybrid Extractive/Laser Off-Gas Analysis Technology*

A heated line connects the Sampling Station to the gas sampling probe. Since the Station is compact in size, it can be located in close proximity to the probe thereby shortening the physical legth of the heated line and the time delay associated with transporting the off-gas sample to the analytical cells. The Extractive Sampling Station (Figure 4) first filters the gases of particulate matter then uses various types of laser & analytical cells to reliably analyze the off-gas for CO, CO_2, O_2, H_2, & H_2O vapor (N_2 analysis is provided by difference) Using clean filtered off-gas minimizes analytical cell maintenance and also ensures that there are absolutely no analytical signal interruptions due to dust interference or laser beam misalignment issues as is the case with Insitu lasers. The Sampling Unit is connected by fiber/coax cables to a compact multipoint Central Control cabinet (Figure 4) that is most often located in the EAF control room.

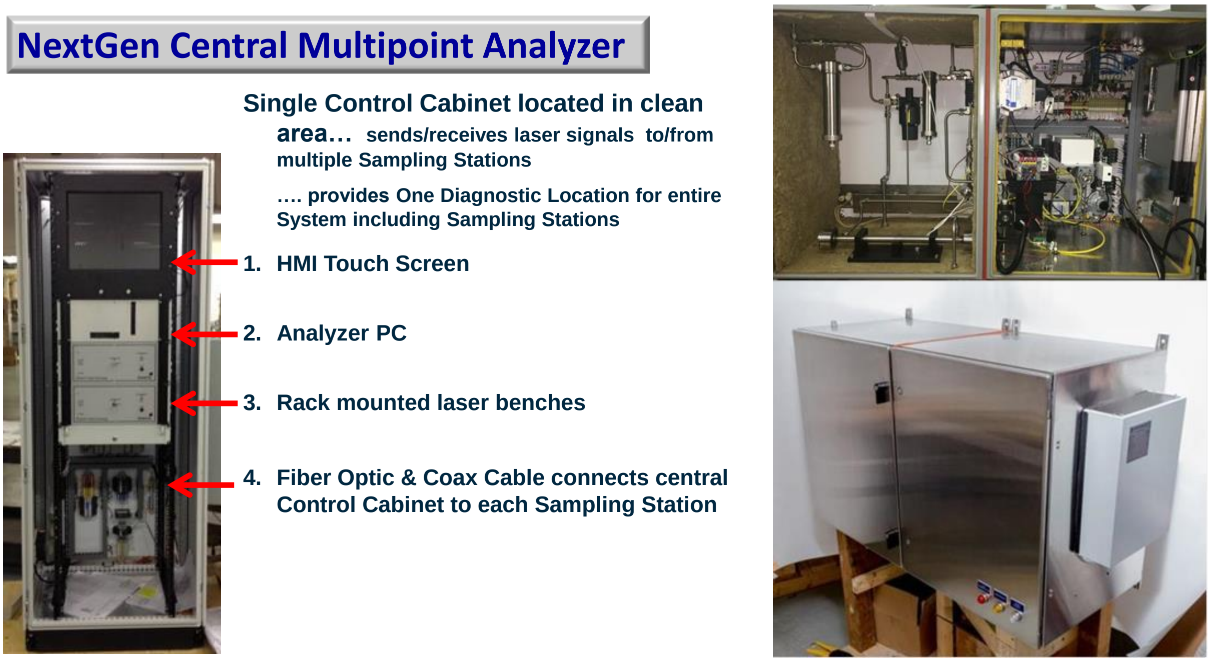

Figura 4*:* *Tenova's NextGen® Multipoint Hybrid Extractive/Laser Off-Gas Analysis Hardware-Central Cabinet & Sampling Stations*

The central unit physically houses the laser beam generators - it sends a continuous laser signal via fiber optic cable to each Extractive Sampling Stations analytical cells and receives the return signals by coax cable. Unlike Insitu lasers which mount expensive laser hardware on the fume duct near the EAF where it can be readily damaged, NextGen® hardware is protected within NEAMA cabinets located a safe distrance from the EAF.

NextGen® technology also has excellent multipoint capabilities and can seamlessly provide "continuous & simultaineous" off-gas analysis from up to 4 to 6 independent Sampling Stations with a single Central Control Cabinet. Unlike Insitu laser systems that need to use an optical switch to index the laser beam sequentially between analysis locations and produce a series of discrete analyses (8 seconds between individual readings for 2 sample locations, 12 seconds for 3 locations & so on), NextGen**®** uses a beam splitter to divide the central high powered laser signal into multiple continuous lower powered beams which are carried via fiber optic cables to each Sampling Station. This enables NextGen® to seamlessly provide "continuous & simultaineous" full spectrum off-gas analysis from multiple sampling locations.

As a result, NextGen® technology is ideally suited for multipoint applications such as upstream & downstream analysis on top charge EAF's as well as on Consteel, Shaft & Twin Shell instatllations.

(b) NextGen® Water Analysis Technology

As shown in Figure 2, the basic NextGen® system (CO, CO_2, O_2, H_2, & N_2 analysis) can be expanded to also include continuous H_2O vapor analysis by adding the following hardware:

- An additional laser to the Central Cabinet with a wavelength in the H_2O vapor range
- A proprietary H_2O laser analytical cell to the Extractive Sampling Station (Figure 5), and,
- Modifications to the water cooled off-gas Sampling Probe to prevent water vapor condensation

To date over eight NextGen® installations have been successfully equipped to continuously analyze H_2O vapor in addition to the standard CO, CO_2, O_2, H_2, & N_2 analysis.

(c) NextGen® Off-Gas Sensors

Real-time EAF mass & energy balance calculations require knowledge of not only off-gas % composition but also of off-gas flow and temperature. Tenova Goodfellow recently developed and commercialized a series of proprietary optical, noncontact sensors to measure both off-gas flow ("**OVM**") and temperature.("**OTM**").

As shown in Figure 5, the OVM consists of two compact optical sensors mounted to optical view ports in the fume duct. These inline sensors continuously measure off-gas velocity.

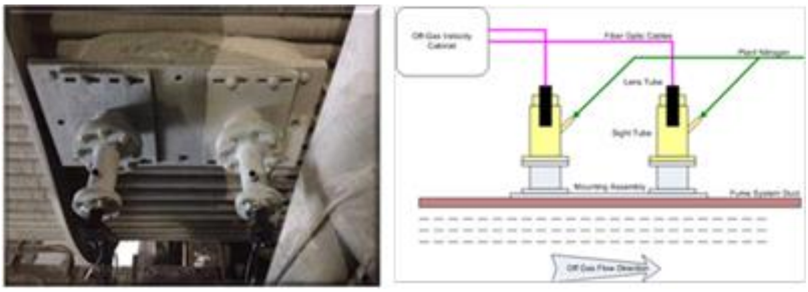

Figura 5: *Tenova's Proprietary OVM Optical Off-GasVelocity Sensors*

The OTM is an optical sensor that uses a wavelength ratio method to measure off-gas temperature. This design requires minimal maintence and avoids temperature inaccuracy problems often associated with excessive dust collecting on the optical lens. The OTM is available in two configurations, either as a remote sensor or as view port sensor (Figure 6).

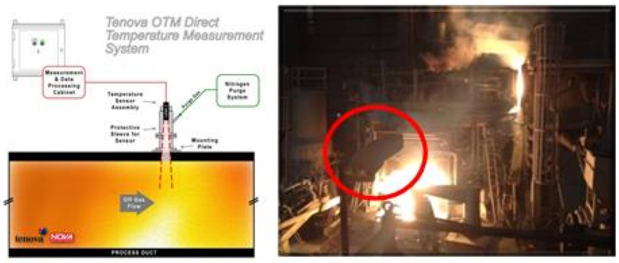

Figura 6: *Tenova's Proprietary OTM Optical Off-Gas Temperature Sensor*

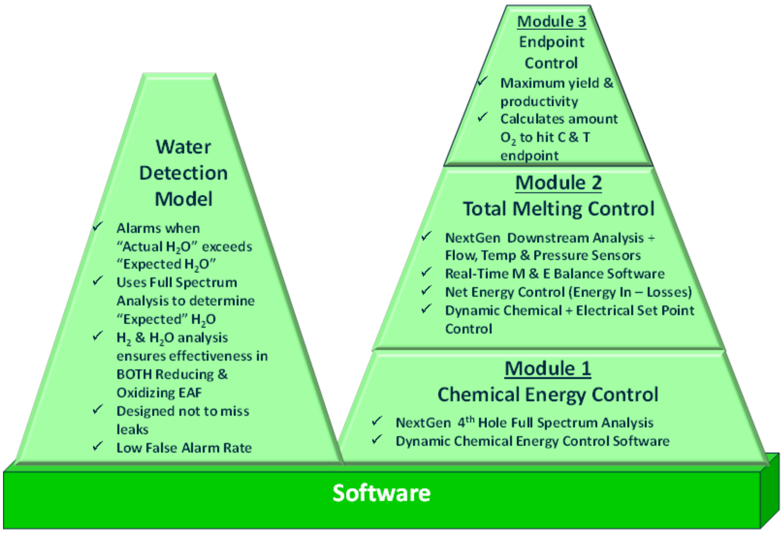

Figura 7: *Tenova's Software Technology part of the* ***¿*** **EAF®** *Technology Platform*

(ii) *¿* EAF® Software – Water Detection & Performance Savings

As shown in Figure 7, the ***¿*** **EAF® technology** platform offers two categories of Software:

(a) Water Detection Models

(b) Performance Saving Models

(a) *¿* EAF® Water Vapor Detection Models

Tenova's **2nd generation water detection software** tracks BOTH the H_2 & H_2O vapor concentrations in the off-gas chemistry. Importantly, NextGen® is the only laser analysis technology to analyze BOTH H_2 & H_2O vapor.

Even though H_2 is never added to EAF, Figure 8 indicates that during reducing freeboard conditions %H_2 can easily range between 15 to 35%. This confirms that H_2 must be forming inside the EAF primarily by the reduction of H_2O vapor by C, Fe & CO when the EAF is reducing. This means that if a water leak were to occur under reducing freeboard conditions, substantial amounts of H_2 can form. For this reason, effective detection of a water leak in an EAF with a reducing freeboard chemistry requires analysis of %H_2 in the off-gas.

Figure 8 also indicates that in an oxidizing EAF, the CO & H_2 concentrations are very low confirming that the chemical reactions thermodynamically reverse with H_2 reacting to form H_2O vapor. This means that if a water leak were to occur in an EAF with an oxidizing freeboard chemistry substantial amounts of H_2O vapor can form. Consequently, effective detection of a water leak in an oxidizing EAF requires analysis of %H_2O vapor in the off-gas.

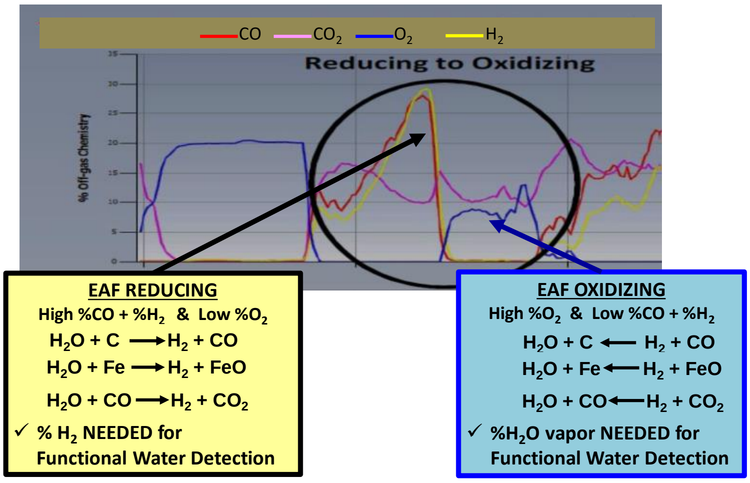

Figura 8: *Effective Water Detection requires BOTH H_2 & H_2O vapor Analysis to ensue Detection in BOTH Reducing & Oxidizing Freeboard Conditions*

To ensure maximimum functionality under oxidizing & reducing EAF operations, unlike Insitu laser systems Tenova's Water Detection Sytem uses BOTH H_2 & H_2O analysis. As shown in Figure 9, Tenova's 2nd generation water detection software uses NextGen's full spectrum analysis, a PLC interface to obtain Level 1 & 2 input data plus two models to provide accurate water detection with minimal false alarms.

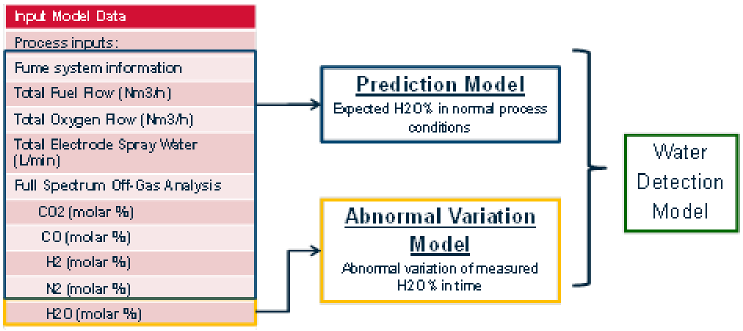

Figura 9: *Tenova's Water Detection Software*

Tenova's Water Detection system (hardware + software) has successfully detected water leaks with an acceptable level of false alarms [7,9,10]. Currently, over 10 2nd Generation Water Detection software systems are installed or underway worldwide.

	# Heats	# Alarms	False Alarms	Approx. Leak Size
Heats - No Leaks	2125	69	3.25%	NA
1st Water Leak	13	12	NA	19 gpm
2nd Water Leak	30	25	NA	15 gpm

Table 1: *Water Leak Detection Performance at Nucor Seattle [10]*

(b) ¿ EAF® Performance Savings Software

As indicated in Figure 9, **¿ EAF® technology** incorporates 3 Performance Savings Models:

- **MODULE 1**: Dynamic Control of Chemical Energy
- **MODULE 2**: Dynamic Melting Control
- **MODULE 3**: Dynamic Endpoint Control

MODULE 1 Software

MODULE 1 uses NextGen® full spectrum off-gas analysis of CO, CO_2, O_2 & H_2 to provide optimized control of Chemical Energy inputs to the EAF. MODULE 1 will dynamically increase the quantity of oxygen & decrease the quantity of methane (CH_4) injection in cases where the EAF off-gas contains excess combustible CO and H_2. Conversely, MODULE 1 will automatically increase methane & decrease oxygen injection if the furnace environment contains excess free O_2. By doing so, MODULE 1 dynamically controls & optimizes the amount of oxygen and methane injected into the furnace to maximize chemical energy efficiency.

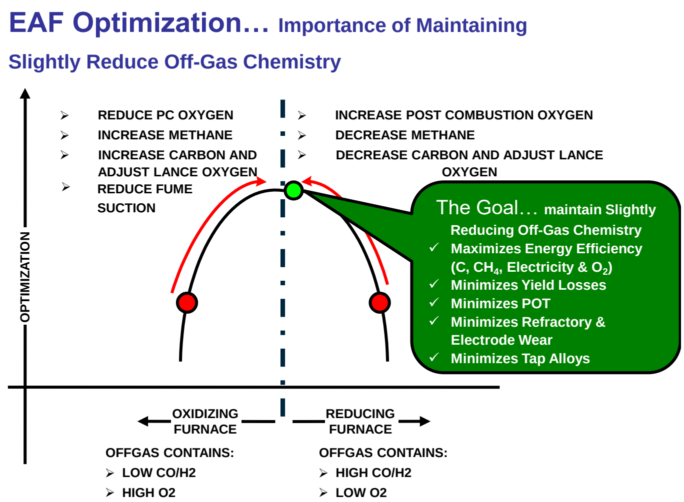

Figura 10: *MODULE 1 Optimization Strategies in Oxidizing & Reducing EAF Freeboard Chemistry*

Benefits MODULE 1 Off-Gas Optimization	Plant Signed Off Savings	
	Plant "A" initially Highly Oxidizing	Plant "B" initially Highly Reducing
Electrical	- 1.0%	- 3.8%
Oxygen	- 5.2%	- 12.8%
Fuel	- 15.2%	- 4.4%
Charge C	- 26.3%	- 9.1%
Injected C	- 30.2%	-
PON	- 3.4%	- 9.5%
Tons / hr	+ 3.3%	+ 10.8%

Table 2: *Typical MODULE 1 Cost Saving & Productivity Benefits*

MODULE 2 Software

¿ **EAF® MODULE 2** is an innovative breakthrough control logic that uses each Heat's actual real-time Mass & Energy Balance [5,8,11]. **MODULE 2** uses the real-time M&E Balance to tailor & optimize energy inputs & timing based on each individual Heat's actual chemical & electrical energy efficiency, actual heat & mass transfer efficiency & actual thermal losses.

¿ **EAF® MODULE 1 & 2** work together to control & optimize each Heat's energy inputs as follows:

- **MODULE 1** uses NextGen® full spectrum off-gas analysis to dynamically control the "quantity" of chemical energy added to the EAF (as in Figure 13), and,
- **MODULE 2** uses the "Actual Net Energy" received by the charge after actual energy losses as derived from the real-time M&E Balance to dynamically control the "timing" for indexing both chemical & electrical set points

¿ **EAF® MODULE 2** technology uses the real-time Mass & Energy Balance to calculate second-by-second the "Actual Net Energy" received by the charge/bath after allowing for Actual Energy Losses.

Actual Net Energy = [Actual Energy Inputs] – [Actual Energy Losses]
= [Electrical Energy In + Burner Energy In + Energy from Oxidation (Si, Mn, C, Fe, etc.)]
– [Energy lost in fume system] – [Energy lost in cooling panels & furnace bottom]

MODULE 2 can accurately determine the rate of heating & melting of the solid charge in the EAF and thereby MODULE 2 can provide a second-by-second measure of the "% **Melting Progress**" throughout the heat.

% Melting Progress = Net Energy Recieved by Charge / Total Energy Needed to Melt Charge Mix

The % Melting Progress is the ratio of the Actual Energy Receved after Losses over the Total Amount of Energy Needed to melt the Heat's specific charge mix – since % Melting Progress is calculated in real-time for every heat based on that heat's actual real-time M&E Balance, **% Melting Progress** precisely determines for each & every heat;

- The **quantity of unmelted scrap in the EAF** at any time during the heat. Melting Progress starts at 0% when the furnace is filled with solid charge material and subsequently increases with increasing Actual Net Energy until it reaches 100% when the charge is fully molten.;
- The **best time to charge scrap buckets**. Net Energy control indicates when sufficient net energy has been supplied to the solid charge to create enough space in the furnace to accept a new charge bucket;
- The time when there is **sufficient molten metal to initiate supersonic oxygen lancing**;
- The **onset of flat bath conditions** and operative refining has begun;

- The **degree of superheat** and as discussed below the **bath temperature**. This is valuable information to assist with when to take steel samples, take thermocouple readings and when to tap the heat.

The results in Table 3 confirm **MODULE 2 Net Energy Control** generates significant operating cost savings, increased productivity & increased yield.

	Average Benefits iEAF® Module 2
Electricity kWh per metric tls	**- 3.4 %**
Nat Gas Nm3 per metric tls	**- 6.7 %**
Oxygen Nm3 per metric tls	**- 2.2 %**
Total Carbon kg per metric tls	**- 10.5 %**
Productivity tons per hour	**+ 3.9 %**
Yield %	**+ 0.5**

Table 3: *Typical MODULE 2 Cost Saving, Productivity & Yield Benefits*

As of the time of publication, Tenova has over 13 *i* **EAF® MODULE 2** systems installed or underway worldwide.

MODULE 3 Software

Once %Melting Progress reaches 100%, **MODULE 3** takes over to predict %C & bath Temperature during refining with the objective of predicting endpoint conditions to:

- Maximize productivity by minimizing unnecessary delays that extend power on time,
- Maximize yield by avoiding over oxidation at the end of the heat
- Minimize the cost of excessive consumption of oxygen & temperature probes

3 CONCLUSION

This paper describes Tenova's industry leading "Intelligent EAF" (*i* **EAF®**) technology platform which incorporates 3 main streams:

i. Innovative & patented **NextGen® off-gas analysis hardware & sensors** that provide actual measurements in critical process areas and thereby avoid control errors and inaccuracies that can result when using estimates & assumptions. Full Spectrum off-gas composition and off-gas flow, temperature & pressure sensors provide valuable real-time information necessary for effective EAF Water Detection and for closing a real time EAF mass & energy balance;
ii. Proprietary *i* **EAF® Software** designed to provide both performance benefits from reduced energy & increased productivity plus provide low false alarm rate water detection effective in both oxidizing & reducing EAF operations;

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