A R C H I V E S O F M E T A L L U R G Y A N D M A T E R I A L S
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EFSOP® HOLISTIC OPTIMIZATION™ OF ELECTRIC ARC FURNACES – PAST, PRESENT AND FUTURE

HOLISTYCZNA OPTYMALIZACJA ELEKTRYCZNYCH PIECÓW ŁUKOWYCH EFSOP® – PRZESZŁOŚĆ, TERAŹNIEJSZOŚĆ I PRZYSZŁOŚĆ

EFSOP® (Expert Furnace System Optimization Process) is a unique process control technology that analyzes furnace off-gas chemistry including O_2, H_2, CO, and CO_2 providing a continuous real-time dynamic control of the furnace. The first generation EFSOP® technology was developed during 1996-1998 with financial support from the Canadian government. The objective was to commercialize a robust and reliable continuous off-gas analysis system capable of surviving in the steelmaking environment without excessive maintenance. As a result of this research effort, the first Goodfellow EFSOP® system was developed and subsequently demonstrated on the EAF at Lake Ontario Steel Company then part of the Co-Steel Group. The first commercial EFSOP® system was installed in the United Kingdom in 1998. Under the direction of Tenova (formerly Techint Technologies) the application of EFSOP® technology has expanded dramatically with more than 40 systems currently installed or underway in ten countries worldwide. To date, EFSOP® installations have cumulatively lowered green house gas emissions by more than 200,000 tonnes, reduced electricity consumption by over 300,000 megawatt hours and saved steelmakers over $90 million from reduced operating costs.

Keywords:holistic optimization, EFSOP, EAF

EFSOP® (Ekspercki Proces Optymalizacji Systemu Pieca) jest unikalną technologią kontroli procesu, która analizuje skład gazów wylotowych pieca, O_2, H_2, CO i CO_2 zapewniając ciągłą dynamiczną kontrolę pieca w czasie rzeczywistym. Pierwsza generacja technologii EFSOP® była rozwinięta w latach 1996-1998 z wsparciem finansowym rządu kanadyjskiego. Celem było utworzenie solidnego i niezawodnego systemu ciągłej analizy gazów wylotowych nadającego się do użycia przy produkcji stali bez nadmiernej konserwacji. W wyniku badań, pierwszy system Goodfellow EFSOP® został zbudowany i zademonstrowany na EAF w Lake Ontario Steel Company, wtedy części Co-Steel Group. Pierwszy rynkowy system EFSOP® został zainstalowany w Wielkiej Brytanii w 1998. Pod kierunkiem Tenova (dawniej Techint Technologie) zastosowanie technologii EFSOP® rozszerzyło się dramatycznie do więcej niż 40 systemów aktualnie instalowanych lub działających w dziesięciu krajach na całym świecie. Instalacje EFSOP® łącznie obniżyły emisje gazów cieplarnianych o około 200,000 ton, zmniejszyły zużycie energii o ponad 300,000 MWh i zredukowały koszty utrzymania hut o 90$ mln.

1. Development of EFSOP® Technology

Fig. 1. EFSOP® Installations as of January 2008

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The key components of the EFSOP® technology are:

- A patented water-cooled probe positioned upstream at the fourth-hole combustion gap.
- A proprietary continuous rapid response gas analyzer system.
- A supervisory control and data acquisition (SCADA) computer which interfaces between the EFSOP® analyzer and the plant Level 2 PLC network.

The EFSOP® patented probe is unique in the industry being the only design to survive the harsh environment and the intense conditions at the combustion gap. Even in this harsh environment probe maintenance is routinely only 15 min per week and life is typically more than one year.

The probe is mounted through an access port in the water-cooled elbow of the EAF (Figures 2). Tenova Goodfellow engineers have extensive experience with almost every possible furnace configuration to ensure successful probe positioning directly within the furnace off-gas cone to enable accurate furnace off-gas analysis without the effect of dilution air entering at the gap.

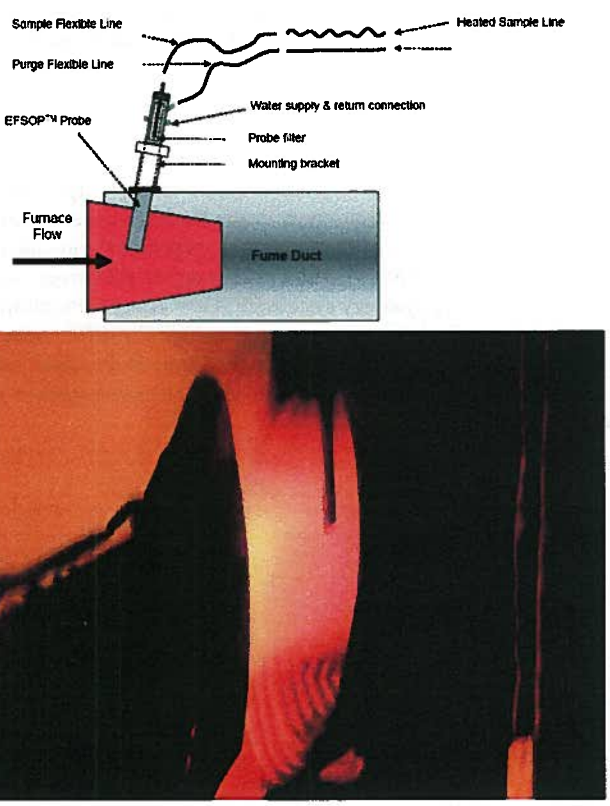

Fig. 2. The EFSOP® probe in action and schematic of probe positioning

The extended life and low maintenance features of the probe are due to its unique water-cooled construction which incorporates specialized welding and design features to withstand thermal expansion/contraction. The probe also uses a proprietary internal high temperature filter that removes dust from the gas stream and an automated high pressure purging system.

The off-gas sample is drawn to the rapid response EFSOP® analyzer through a heated sample line using a high volume pump. At the analyzer, a rugged conditioning system further cleans and dries the gas sample prior to analysis for CO, CO_2, H_2 and O_2. The analyzer is designed to ensure continuous off-gas analysis during power-on periods by employing an automatic nitrogen purge system sequenced to furnace operation. The analyzer is custom designed and proprietary to Tenova Goodfellow and has more than 40 unique features developed and implemented over years of constant improvement at various EAF installations. EFSOP® analyzer maintenance is typically 15 minutes per week. A 30 minute calibration is usually required every second week.

As shown in Figure 3, the EFSOP® SCADA computer is interfaced with the plant's Level 2 network. The EFSOP® computer reads and logs the off-gas analysis plus over 300 process data points from the plant PLC, it performs control calculations and sends process set-points back to the PLC. The system is equipped with an e-mailer that automatically forwards off-gas analysis and key heat summary data each day to Tenova Goodfellow's office for monitoring and analysis. To date over 300,000 heats have been monitored by the EFSOP® system.

The EFSOP® system has a proven high reliability with off gas measurements and the uptime of EFSOP® closed loop control being between 90 to 100%. The analyzer has an impressive life expectancy with the first unit installed in 1998 still in service today and continuing to generate ongoing savings for the plant.

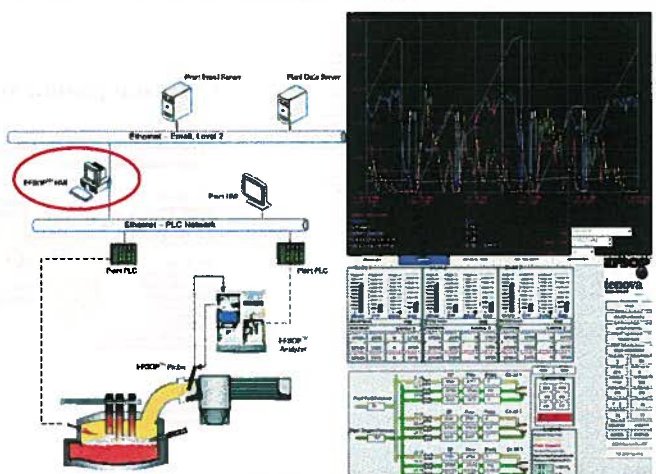

Fig. 3. Configuration of the EFSOP® SCADA computer and typical HMI displays

2. Evolution of the Original EFSOP® to Today's EFSOP® Holistic Optimization™ Technology

Originally developed in the 1990's as an off-gas analysis system, today's EFSOP® has evolved to become the EFSOP® Holistic Optimization™ system. EFSOP® Holistic Optimization™ factors in scrap and steel quality constraints, energy usage (electrical and chemical), furnace design, environmental requirements, injector design and function to develop a true holistic optimization strategy to ensure total process benefits.

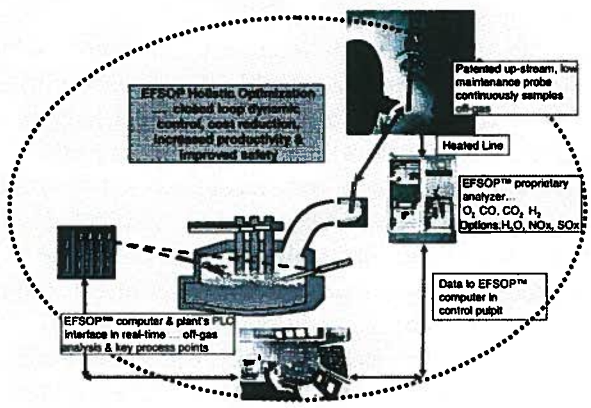

Fig. 4. EFSOP® Holistic Optimization™ System for EAF steelmaking

Figure 4 illustrates how EFSOP® Holistic Optimization™ works. The key to the EFSOP® Holistic Optimization™ system is the SCADA computer which is interfaced with the plant Level 2 network. It logs over 300 process points plus off-gas analysis thereby providing an unparalleled real-time and archived data bank to conduct process cause & effect analyses to develop optimization and dynamic closed loop control algorithms. Once Tenova Goodfellow engineers have established the optimum practice, the EFSOP® system is put in closed loop mode to dynamically control the burners and lances in real time thereby ensuring savings are maintained on an ongoing basis.

Figure 5 illustrates "process & practice points" which are analyzed as part of Tenova Goodfellow's holistic optimization approach. These include the fume system practice, bucket raw material distribution, burner practice, electrical system control, injector practice and foamy slag practice.

EFSOP® Holistic Optimization™ uses the EFSOP® off-gas chemistry for cause & effect analysis of these "process & practice points" to achieve a holistically optimized EAF practice that will reduce total energy consumption, increase yield and productivity plus lower operating cost.

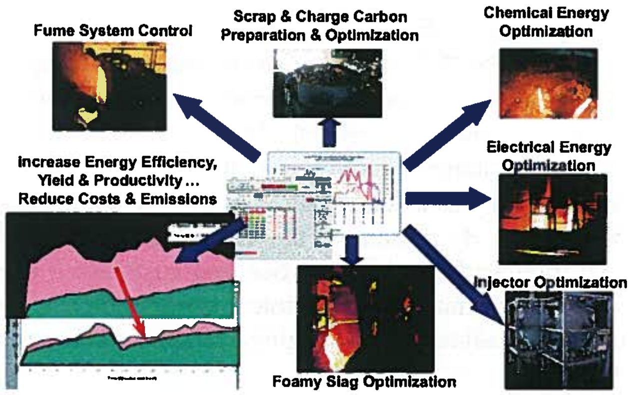

Fig. 5. EAF "Process & Practice Points" included in EFSOP® Holistic Optimization™

3. Recent Examples of EFSOP® Holistic Optimization™

To date EFSOP® Holistic Optimization™ has established an impressive performance record with 100% of installations achieving or exceeding the performance savings guarantee established at the outset as part of the purchase agreement.

Two recent EFSOP® installations, Riva Verona Italy (1) and Cape Gate Vanderbijlpark, South Africa (2) clearly demonstrate the dramatic power of EFSOP® Holistic Optimization™ for reducing operating costs, increasing yield and productivity, reducing fuels and electricity and lowering raw materials consumption even when there are widely differing furnace practices.

The EFSOP® off-gas analysis indicated the Cape Gate furnace was operating in a highly reducing condition due to an excess of uncombusted H_2 and CO. The highly reducing environment meant that excessive amounts of chemical energy was leaving the Cape Gate furnace thereby decreasing energy efficiency and increasing the heat load to the fume system.

Conversely, at Riva the EFSOP® off-gas analysis indicated the furnace operated much differently having an oxidized atmosphere from excessive air leakage due to high fume system suction.

EFSOP® Holistic Optimization™ proved highly successful for assessing and optimizing both the reducing furnace practice at Cape Gate and the oxidizing practice at Riva:

(i) Optimizing Chemical Energy Efficiency: At Cape Gate, EFSOP® off-gas analysis displayed an unusual composition during melting when on high burner power. High H_2 and CO spikes were measured once the burners reached the working point. Using the EFSOP® SCADA data base, Tenova Goodfellow engineers determined that these spikes of uncombusted gas were due to poor mixing of the oxygen and methane resulting in only partial combustion.

The EFSOP® off-gas analysis and closed loop control function was used to improve energy efficiency by dynamic control of methane flow to reduce excess fuel and by adjusting oxygen flow to ensure sufficient free oxygen was available for complete post combustion of CO and H_2 present in the Cape Gate furnace. The new improved standard practice and customized closed loop control maximized chemical energy efficiency, dynamically adjusted to changing furnace conditions, reduced consumables and increased productivity by reducing power on time (PON).

At Riva, Tenova Goodfellow used its proprietary DECSIM EAF simulator to conclude that chemical energy efficiency was excellent because the excessive air leakage with the high draft was fully combusting CO and H_2 inside the EAF. However, the analysis showed that the overall energy efficiency was low due to high off-gas heat losses from the large nitrogen ballast.

The first step at Riva was to use the EFSOP® system to establish a more efficient, slightly reducing environment by controlled reduction of furnace draft. It was then possible to optimize the existing burner and injector practices and subsequently implement customized closed loop control to dynamically adjust oxygen and methane injection. The new customized closed loop control reduced PON & consumables and increased productivity by maximizing chemical energy efficiency and dynamically compensating for variability in the furnace's chemical environment.

(ii) Electrical Practice: EFSOP® Holistic Optimization™ aims to synchronize the delivery of chemical and electrical energy in the EAF. At both Riva and Cape Gate, the electrical reactor tap and current set points were modified to synchronize electrical power with the EFSOP® controlled burner practice to increase the melting rate and achieve an additional reduction in PON.

(iii) Injection and Charge Carbon Practice: At Cape Gate, EFSOP® determined that there was no potential to reduce injected carbon consumption. However, EFSOP® Holistic Optimization™ still developed an optimized carbon injection practice by reducing flow rate while increasing injection time which improved slag foaming, reduced freeboard carbon particulate and lowered FeO levels.

At Riva, EFSOP® off-gas analysis proved invaluable for optimizing charge bucket practice including carbon layering and sizing plus optimizing raw material distribution patterns in the bucket. EFSOP® off-gas analysis was used to optimize bucket practice and improve overall chemical efficiency, dramatically reduce carbon consumption and increase melting efficiency.

(iv) Power Utilization Efficiency: With EFSOP® Holistic Optimization™ Riva and Cape Gate each saw a 3 to 4% reduction in PON which dramatically increased furnace productivity.

Riva had fume system limitations which caused the plant to have to switch power off whenever the heat load reached peak levels. Figure 6 shows that before EFSOP®, power was shut off an average of 14 – 18 min per day on each furnace. However, EFSOP® Holistic Optimization™ enabled the fume system temperature load to be linked to the EFSOP® dynamic burner control system. As soon as the EFSOP® system detected excessive fume system temperatures, it dynamically reduced chemical energy input ito enable the furnace power to be held at maximum. The net result was a reduction in Power-Off time for fume system overheats by 60 – 70%.

In summary, these two recent EFSOP® installations confirm the dramatic power of EFSOP® Holistic Optimization™ for analyzing and optimizing the entire EAF process even if there are widely different reducing or oxidizing operating conditions. In both cases dramatic improvements in burner and injector practice, fume system control, electrical and chemical energy utilization, foamy slag practice and charge bucket practice have been achieved.

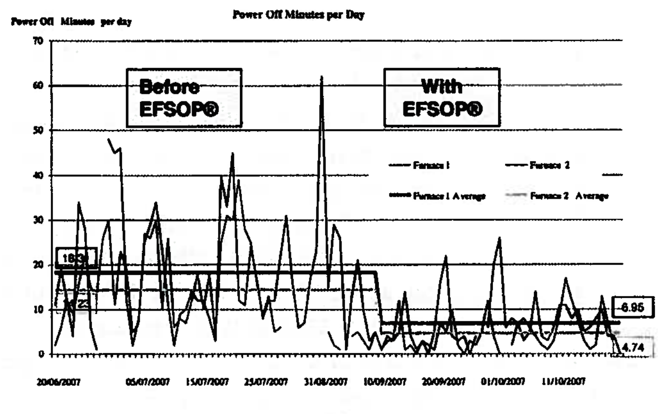

Fig. 6. Reduction in Power-Off Time for Fume System Overheating

Table 1 summarizes the dramatic improvements resulting from EFSOP® Holistic Optimization™ as verified by these two plants. While Riva would not permit public release of its actual operating cost savings, Cape Gate has reported a cost reduction of over US $2.00 per ton of liquid steel.

TABLE 1
Customer verified performance improvements with EFSOP® Holistic Optimization™

Parameter	Riva Verona – Initially Oxidizing	Cape Gate – Initially Reducing
Electrical Consumption	−1.0%	−3.8%
Oxygen Consumption	−5.2%	−12.8%
Fuel Consumption	−15.2%	−4.4%
Charge Carbon	−26.3%	−9.1%
Injected Carbon	−30.2%	–
Power on Time	−3.4%	−9.5%
Productivity, tons per hr	+3.3%	+ 10.8%

4. Tenova Goodfellow's Next Generation EFSOP® Technology

Tenova Goodfellow is now commercializing its "next generation EFSOP® technology" including:

(i) EFSOP® Enhanced Furnace Safety Alarm

EFSOP®Holistic Optimization™ is the only system to successfully commercialize an upstream probe directly in the cone of off-gas exiting the fourth hole which ensures the gas is sampled as soon as it exits the furnace prior to dilution with gap air. This extremely rapid response time is critical for both process optimization and to detect abnormal levels of H_2O, CO and H_2. Other EAF systems that measure off-gas composition further downstream suffer from both combustion gap air dilution (which contains ambient moisture) plus response delays.

While EFSOP® continuously samples furnace off-gas to provide dynamic process control and optimization, the system is now being adapted as an effective tool to detect abnormal levels of H_2O plus combustible gases CO and H_2 in real-time. When combined with other process sensors, EFSOP® off-gas analysis represents a dynamic tool that enhances EAF and bag house safety.

Beginning in 2008, Tenova Goodfellow is offering a three level enhanced furnace safety alarm that can be added onto existing EFSOP® systems or purchased as an option with new systems:

- **First Level of Protection:** Since EFSOP® optimizes EAF energy efficiency through more complete combustion of CO and H_2 inside the furnace, EFSOP® dynamic closed loop control means less likelihood that there will be excessive downstream concentrations of these combustibles in the bag house. EFSOP® has now further enhanced bag house safety with a **"High H_2 and CO Alarm"** that automatically alerts operators if these combustible gases exceed specified Threshold Limits.
- **Second Level of Protection:** The second level of detection is a newly developed **"Off-gas Tracking Alarm"**, see reference (3) for details. This alarm utilizes a statistical Finger Print of normal off-gas chemistry which accounts for the typical variations in H_2 and CO in the furnace from a variety of sources including oily/wet scrap, hydrocarbon injection and normal water such as electrode cooling. Once the normal practice Statistical Fingerprint is defined, Threshold Limits are set reflecting each plant's safety requirements. If these Limits are exceeded, EFSOP® will automatically trigger an alarm to warn operators that the amount of $H_2$from "reduced H_2O" has increased beyond the normal acceptable levels (see Figure 7). This "Off-gas Tracking Alarm" is a software module that can be added to the basic EFSOP® platform. It is currently in use at several EAF installations where to date it has successfully detected and alarmed over 80% of significant water leaks in real-time.

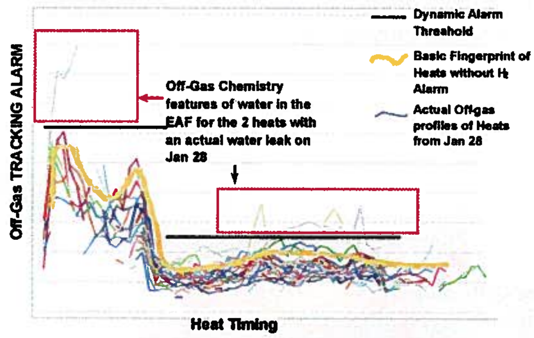

Fig. 7. Dynamic Off-Gas tracking alarm for real-time detection and alarming of abnormal hydrogen levels indicative of water leaks

- **Third Level of Protection:** EFSOP®'s third level of detection is a **"Water Vapor Detection Alarm"**, a newly developed hardware alarm that detects actual water vapor in the off-gas stream in real-time. This advanced alarm provides direct analysis of undissociated H_2O in the off-gas. When combined with the Off-gas Tracking Alarm, the Water Vapor Detection Alarm provides more comprehensive detection with fewer false alarms since both "reduced H_2O" (i.e. H_2) as well as "undissociated H_2O" are detected. The Water Vapor Detection Alarm is designed as an add-on module to the existing EFSOP® platform and will be available as an upgrade to all existing EFSOP® systems.

(ii) Intelligent Electric Arc Furnace (*i* EAF™) Technology

Tenova Goodfellow is now finalizing the development of its leading edge ***i* EAF**™ technology to provide real-time holistic optimization and control of the entire EAF process.

***i* EAF**™ technology includes:

1. **Additional instrumentation;** Off-gas pressure and temperature sensors; bath-slag level measurement;
2. **Process models:** Freeboard gas-phase model; Melting model; Bath/Slag model;
3. **Control optimization modules:** Electrical optimizer; Refining beginning detector; Foamy Slag optimizer; End-point (T&C) optimizer

i* EAF**™ technology is designed to be integrated with an existing EFSOP®system or integrated with a new EFSOP®–i* EAF**™. The combined **dynamic process analysis** using real-time input oxygen, methane and carbon rates together with EFSOP®off-gas chemistry measurements, off-gas temperature and static pressure at the fourth hole to determine the rate of off-gas leaving the EAF, of air in-leakage into the EAF, of carbon monoxide generated from decarburization and combustion, of water entering the gas-phase, and of gas-phase energy losses brings to significant benefits and to a complete process knowledge.

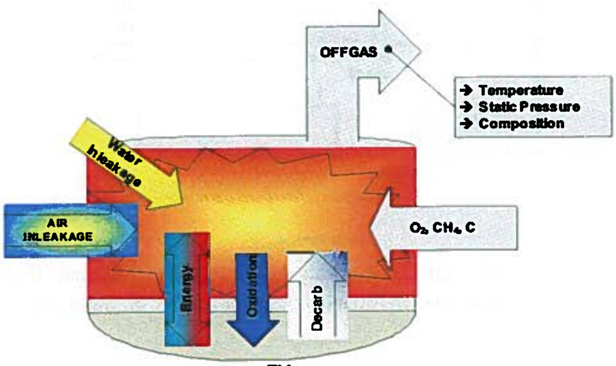

Fig. 8. Dynamics of the *i*EAF™ process model

Benefits of ***i* EAF**™ technology include:

- Real-time control of the EAF fume system heat-loads by dynamic control of the chemical energy use and efficiency in the EAF.
- Real-time determination of CO and H_2combustibles and H_2O in the furnace off-gas to calculate the water shift effect on chemical equilibrium and enhance furnace safety.
- A real-time cost-based post-combustion module to optimize benefits versus costs by using the mass/energy balance calculation plus actual plant costs and efficiencies of burners to the feed-back loop.
- A dynamic measure of off-gas composition and heat-load to optimize the draft and energy efficiency. Many EAF's attempt to minimize the threat of explosions by over-drafting practices however this results in a large nitrogen ballast entering the EAF and excessive energy inefficiency.
- A dynamic indicator of burner and injector efficiency during melting and refining for selecting and tuning EAF injectors - for example the injector decarburization efficiency (or alternatively the burner post-combustion efficiency) is dependent on parameters such as angle of injection, location, jet velocity, flame shrouding effects. In addition, injector efficiency will change during the heat depending on bath height and slag depth.
- Better pacing of the EAF according to the actual electrical and chemical energy that has been transferred to the scrap and steel bath. Most furnaces are paced according to either electrical kWh or kWh/ton. As more chemical energy is used, pacing of the furnace solely on electrical energy introduces inconsistencies in operation.

Tenova in cooperation with Tenaris-Dalmine and CSM (Centro Sperimentale Metallurgico) has carried out the full-scale development of its leading edge ***i* EAF**™ technology at Tenaris Dalmine steel plant and this next generation technology is now commercially available.

(ii) Intelligent Consteel®(*i* CONSTEEL™) Technology

Tenova's leading Consteel™ technology dramatically improves productivity and lowers energy consumption by continuous preheating and feeding of metallics to the EAF.

Tenova Goodfellow has now adapted its original EFSOP® system to form the basic platform for its next generation **i CONSTEEL™** process control and optimization technology. Phase 1 of the leading edge **i CONSTEEL™** technology is now commercially available and includes:

- **A dual probe EFSOP® system** has recently been commercialized by Tenova Goodfellow with sampling/purging alternating between probes to ensure a continuous off-gas analysis as required for dynamic Consteel® process control and optimization. In a conventional EAF, continuous off-gas analysis during power-on can be achieved with a single EFSOP® probe with back purging scheduled during process stops. However with a traditional single probe analyzer on a continuous Consteel®, approximately 1/3 of the process time would be without off-gas analysis due to the need for regular back-purging.
- **A thermal camera** installed upstream in the conveyor near the EFSOP® probes to improve control of thermal conditions in the conveyor and furnace.
- **Dynamic Post Combustion Control** between the furnace and the conveyor for real-time control of the

carbon feeding rate in the EAF, the O_2 injection rate in the EAF, the post combustion O_2 injection in the EAF/pre-heater conveyor and the fume system draft.

Figure 9 shows the dual EFSOP® probes are positioned upstream in the Consteel® conveyor to ensure a fast response time between burners/injectors for optimized furnace and pre-heater post combustion. This upstream location also minimizes any off-gas errors due to possible ingress air leakage which would influence downstream readings.

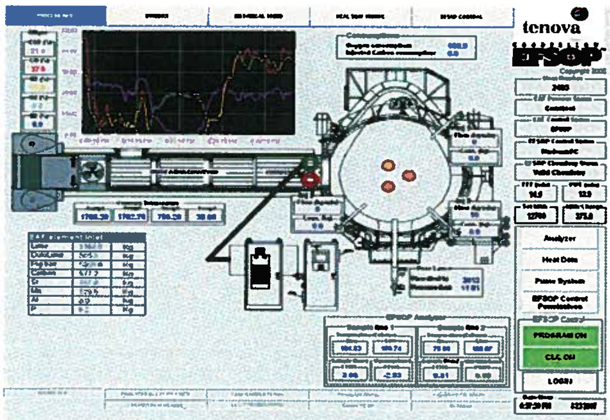

Fig. 9. Upstream Dual Probe EFSOP® System specially designed for Consteel®

Phase 2 of the **i CONSTEEL™** program is now under development for a 2008 launch will include dynamic real-time control of bath temperature, bath carbon, slag composition and conveyor feed rate. The intent is to ultimately develop a real-time energy and mass balance for the Consteel® process using real-time off-gas chemistry, temperature and flow. Tenova is currently undertaking the full-scale development of its next generation ***i* CONSTEEL™** technology as part of the European RFCS Project at ORI Martin in Italy.

5. Conclusions

Through ongoing R&D in cooperation with leading technology providers, universities and industry partners, Tenova Goodfellow's EFSOP® technology has continuously evolved from its inception in 1998 as a reliable off-gas analysis system to a real-time EFSOP®Holistic Optimization™ system.

Today, EFSOP®Holistic Optimization™ uses continuous EFSOP® off-gas analysis together with key process data from a Level 2 interface to develop process cause & effect relationships to optimize and dynamically control EAF steelmaking operations in real-time. With a 100% success rate to date, EFSOP® Holistic Optimization™ has proven to be the only reliable technology for analyzing and optimizing the EAF process whether the furnace is in a highly reducing or oxidizing condition. Dramatic improvements in burner and injector practice, fume system control, electrical and chemical energy utilization, foamy slag practice and charge bucket practice have been achieved resulting in significant customer verified benefits including reduced operating costs, higher yields, increased productivity and reduced electricity, fuel, oxygen and carbon usage.

Tenova Goodfellow's next generation technology includes the basic EFSOP® platform taken together with an array of advanced sensors:

- EFSOP®Safety Alarms to detect abnormal off-gas chemistry for enhanced safety.
- Intelligent Electric Arc Furnace (***i* EAF™**) Technology to provide an unparalleled level of EAF process control and optimization.
- Intelligent Consteel®(***i* CONSTEEL™**) Technology for dynamic control of post combustion, bath temperature & carbon, slag composition and conveyor feed rate.

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