UTILIZATION OF PROCESS FEEDBACK FOR OPTIMIZATION OF INJECTION TECHNOLOGIES IN THE ELECTRIC ARC FURNACE[1]

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Abstracts

Over the past 15 years, injection technologies have become much more important for EAF steelmaking. The chemical energy provided by injection provides significant process flexibility to EAF steelmaking as well as increasing the rate at which electrical energy can be added to the EAF. Chemical energy now contributes up to 50-55% of the total energy input to modern EAFs. However, the increased use of injection technologies in the EAF has not been without a price. Energy efficiency has suffered due to over-use of chemical energy during periods when energy transfer to the scrap or steel is low. Poor recovery of chemical energy leads to a waste of raw materials as well as unnecessary emissions of Greenhouse gases. Traditionally, energy efficiency has been determined only after the fact, through review of total energy, scrap yield and other bulk process parameters tabulated well after a heat is made. Most meltshops have simple instrumentation that could be used as feedback tools to increase understanding in injection energy efficiency. In recent years, advanced process analysis systems have also emerged. These systems monitor process parameters in real time so that adjustments can be made concurrent to steelmaking activities. This paper will provide specific examples of the application of advanced process analysis as applied to EAF operations and will show how some of these techniques can be used to improve the efficiency of injection technologies in the EAF process.

Key words: EAF; Optimization; Efficiency.

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Injection technologies have been utilized in the EAF since its birth. In the early days, oxygen was injected into the bath following melting, in order to refine the steel. During the period of 1975 – 1995, the use of oxygen injection grew considerably as steelmakers began to utilize greater amounts of chemical energy in the furnace in order to drive down tap-to-tap time and increase productivity. During the same period, oxy-fuel burners were installed in the EAF to provide heating to the "cold spots" in the furnace and also to reduce cycle times. As the desire to use more-and-more chemical energy in the EAF grew, injection of solids became much more important as well. Whereas carbon had conventionally been added only in the charge, the development of foamy slag practice required that carbon and in some cases, fluxes, be injected into the EAF. The focus in EAF technology during this period was:

- Increased use of chemical energy
- Reduced energy losses from the EAF – scrap pre-heating
- Flexibility in choice of energy inputs to the EAF
- Higher productivity – more energy, faster T-T-T
- Minor focus on raw materials – mainly focused on residuals
- Minor focus on environmental issues
- Many different EAF designs

The following table provides a snapshot of the Evolution of EAF technologies through the 90's. The data is obtained from the IISI EAF report published in 1990 and again in 1999.

Table 1: The evolution of eaf operations (from iisi, the eaf 1990, the eaf 1999)

Parameter	**EAF in 1990**		**EAF in 1999**	
	Best	**Median**	**Best**	**Median**
T-T-T (min)	60	80	45	70
Normalized Electrical Input (kWh/tonne)	360		315	392
Electrode Consumption (kg/tonne)	1.5		1.0	1.9
Total Oxygen Input (O_2 Nm^3/tonne)	30	24	40	30
Secondary Voltage (V)		600		900
Normalized Electrical Power (kVA/tonne)	800	590	1,400	800

Table 1 shows that the use of chemical energy has grown and that electrical energy consumption has been reduced. In the late 90's, the adoption of multi-point oxygen injection, greatly improved efficiency in the EAF and allowed greater quantities of oxygen to be utilized without suffering yield losses and equipment damage. However, as oxygen utilization was pushed further, oxygen efficiency suffered and overall EAF efficiency declined.

Several papers have been presented previously which discuss EAF energy efficiency and the factors that can affect efficiency.[1-3] In modern EAF operations, the typical amount of heat contained in the off-gas (both sensible and calorific heat) amounts to approximately 20% - 30% of the total energy input to the EAF. In operations using a higher proportion of chemical energy input energy losses to the off-gas can be higher at 30% - 50% of the total energy input. Energy losses to water-cooled EAF components can account for an average of 8% -10% of total energy inputs and in some cases can be as high as 20%.

Recent studies have shown[2,3] that energy efficiency has suffered as steelmakers attempt to use higher and higher levels of chemical energy in the EAF. In addition, steelmakers have begun to notice highly variable results which are typically related to:

- Inconsistency of feed materials
- Inconsistency of operating practices
- Inconsistent equipment availability
- Inconsistent slag foaming
- Inconsistent oxygen utilization

The main reason for all of this variability is that there exist very few tools that provide "real-time" feedback to the EAF operator. In many EAF operations, the only process feedback consists of electrical energy, oxygen and natural gas consumption along with indicators such as power-on time, tap-to-tap time, and yield. The operator usually only has feedback at the end of the heat, when he knows the amount of electrical and chemical energy that was used to make a known heat weight. Feedback of process information to the operator, metallurgists, and engineers is the key to continuous improvement of the steelmaking operation. **Most meltshops need simple tools that allow the EAF operator to obtain some immediate feedback on furnace performance**. In addition, such a tool must allow the operator to identify upset conditions and provide some insight as to the cause of these upset conditions. A lack of measurable process variables and feedback during steelmaking indicates that the EAF process is not "under control".[4,5]

Over the past five years, the focus of EAF technology has shifted from mechanical designs to process tools aimed at providing greater stability and reproducibility of EAF operations. It has been recognized that more attention needs to be applied to understanding the intricate reactions and interactions taking place within the EAF. This paper will show some examples of feedback for EAF operations and will provide a convincing argument for the adoption of greater feedback control for injection technologies in the EAF.

FEEDBACK CONTROL FOR INJECTION TECHNOLOGIES IN THE EAF

Background

Injection technologies in the EAF span several areas and include:

- Oxygen injection
- Oxy-Fuel burners
- Injection of carbon and carbon-flux blends for slag foaming
- Injection of inert gases to promote bath mixing
- Injection of fluxes
- Injection of Fe scrap materials

Some of these technologies are common in the EAF while others are only in use at a few EAF operations. The essential issue for all of these technologies is to "get the material where it is needed, when it is needed". Failure to achieve this goal will result in yield loss, energy inefficiency and damage to equipment. However, how can an operator know if he is getting the injected materials to the right place in the EAF in a timely manner? The answer is to provide the operator with process feedback.

Previous papers have outlined the potential gains obtained from greater process feedback for EAF operations.[4,5] An enormous amount of data is generated during steelmaking operations but very little of this is ever turned into useful information that the operator can use to adjust the EAF practices. Typically, it is necessary to filter this data in order to distill it down to just a few parameters that can be used to improve the furnace operation.

Simple Process Feedback

Pressure in EAF freeboard

Measuring the pressure in the EAF freeboard provides useful information about the environment inside of the furnace. If the pressure is positive relative to the ambient pressure, then the freeboard is likely rich in CO (reducing). If the pressure is negative relative to ambient pressure, then the freeboard is likely lower in CO and could be oxidizing (contain some O_2).

With a freeboard pressure measurement and the above information it is then possible to control the pressure and environment (reducing vs. oxidizing) using the furnace draft control damper. Achieving optimal draft control with closed loop control using the pressure transmitter and the draft control damper often results in lower electrode consumption and can also improve chemical energy recovery. Feedback from roof, sidewall, and off-gas energy loss monitoring systems greatly assist in finding the optimum furnace draft.

Energy Losses To Furnace Roof and Sidewalls

If the roof and sidewall energy losses can be reduced, some savings of energy and costs can also be realized. Energy losses to the water-cooled furnace components can be approximately 5-7 MWh per heat and in the author's experience, can be reduced by 50% with a change in slag practice. This reduction can result in savings of approximately $1.50 - $2.00 per ton based on energy costs alone. Even higher savings are generated if the increase in EAF productivity is taken into account.

Tracking the dynamic and cumulative energy losses to the furnace roof and sidewalls can provide useful information about the operation of the furnace. Trending the average energy loss to various cooling circuits alongside the "real-time" losses occurring in the current heat allows the operator to quickly identify when energy losses are higher or lower than normal. Once abnormal losses are identified, the cause can be identified and adjustments can be made to reduce the losses.

Figure 1 shows the instantaneous energy loss rate through each of four sidewall water-cooling circuits at one EAF operation. The figure shows that, at times, sidewall circuit 1 experiences a much higher energy loss rate than the other three circuits. It was determined that the sidewall panels corresponding to this circuit are located near a carbon injector and the peaks in energy loss occur during the operation of the carbon injector. Based on these observations, recommendations were made for reconfiguration of the carbon injectors to improve the carbon recovery.

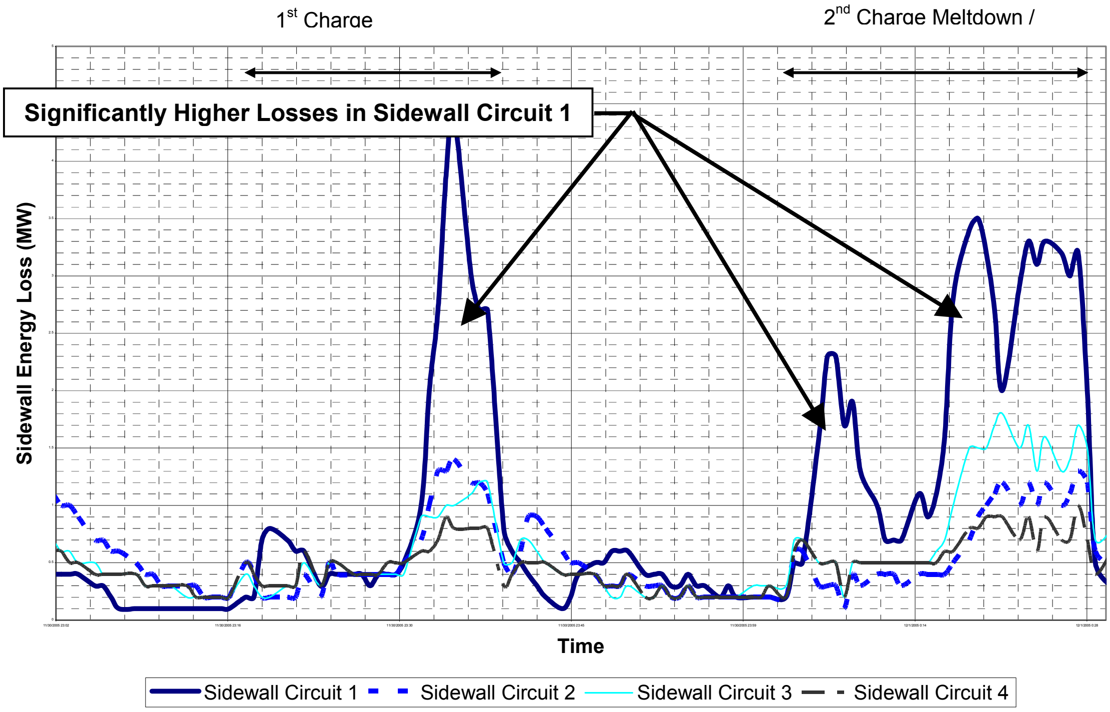

Figure 1. EAF sidewall water-cooling circuit energy losses

Table 2 shows data collected on two identical furnaces in the same meltshop.(6) It can be seen that the energy losses vary considerably not only between the two furnaces but also from one heat to another on the same furnace. The table shows roof losses for EAF #2 are, in fact, even higher than sidewall losses. This is contrary to EAF #1 where roof and sidewall losses are nearly equivalent. Analysis of the operations showed that EAF #1 had burner-injector profiles that were quite different from those being used on EAF #2. In addition, the heel size on EAF #2 was smaller than that in EAF #1 and slag chemistry was quite different. All of these factors contributed to poor efficiency of chemical energy input on EAF #2 leading to high off-gas temperatures in the furnace freeboard and loss of slag coating on the furnace roof. Up to the point at which this analysis had been carried out, the supervisors and managers had not been aware of any differences in the chemical energy input profiles between the two furnaces.

Table 2: Roof and sidewall energy losses for identical EAFs

Heat #	EAF #1		EAF #2	
	Roof losses (kWh/tonne)	Sidewall losses (kWh/tonne)	Roof losses (kWh/tonne)	Sidewall losses (kWh/tonne)
1	22	28	38	25
2	19	21	32	25
3	18	21	40	28
4	12	16	43	34
5	22	25	40	26

High sidewall energy losses can be due to little or no slag coating on the sidewalls or insufficient slag volume to cover the arc. The slag coating on the sidewall can be lost due to overly aggressive burner-injector energy inputs or ”blow-back” of injected oxygen or oxy-fuel flames due to dense scrap loaded too close to the furnace walls.

Regardless of the mechanism leading to loss of slag coating, it typically takes 2 – 4 heats to build the coating up on the sidewalls once it has been lost. During this period, energy losses to the cooling water system will be higher than normal.

Integrated Instruments and Models

Monitoring of the off-gas system and EAF water-cooled components allows EAF operators to identify periods of the operation where the energy transfer efficiency to the steel is low. During these periods the energy input to the EAF is ineffective. In addition, high energy losses to the shell and off-gas system during these periods account for a significant portion of maintenance issues related to the furnace. Through the monitoring of energy distribution to the furnace shell and to the off-gas, the efficiency of energy transfer to the steel can be inferred, based on the knowledge of the electrical and chemical energy inputs to the furnace.

Systems like Smart-Gas™ monitor the furnace energy inputs and losses in real-time. These systems provide real-time and average energy loss trends for each of the main circuits as well as for losses through individual water cooling circuits. These systems also provide tabulated cumulative total energy losses for the off-gas, off-gas system, furnace roof, and furnace sidewalls. The Smart-Gas™ energy reports are useful to engineers and managers to quickly identify peaks of high energy loss and correlate them to specific operations in the furnace.[7,8] Trends from heat-to-heat can also be used to recognize changes in flux, scrap, and injection carbon characteristics.

Overall Off-Gas Energy Losses

The energy losses to the off-gas system are the most under-estimated component of the furnace energy balance because few people measure it. The off-gas energy losses include the sensible and calorific energy contained in the gas exiting through the fourth hole. This information is the key to understanding where the 30% to 50% of the total energy goes during the melting process.

Figure 2 shows electrical energy input (solid line) and instantaneous off-gas energy losses (dotted line) versus operating time for an EAF operation. Energy losses to the off-gas system increase towards the end of each meltdown period once the furnace reaches flat bath. This is because there is no scrap to contain the arc radiation and without effective slag foaming, a portion of the arc energy is lost to the furnace shell and the off-gas. This period also represents the time when oxygen and carbon injection rates are the greatest. If the energy generated by the reaction of oxygen with carbon is not contained in the slag and transferred to the steel bath, energy losses to the furnace shell and off-gas will be realized.

Monitoring the off-gas energy content throughout the tap-to-tap cycle can be a very effective feedback tool. The off-gas energy content climbs when chemical energy efficiency drops and also can help to indicate that flat bath has been reached. It is also possible to use this information to decide when to drop the next charge.

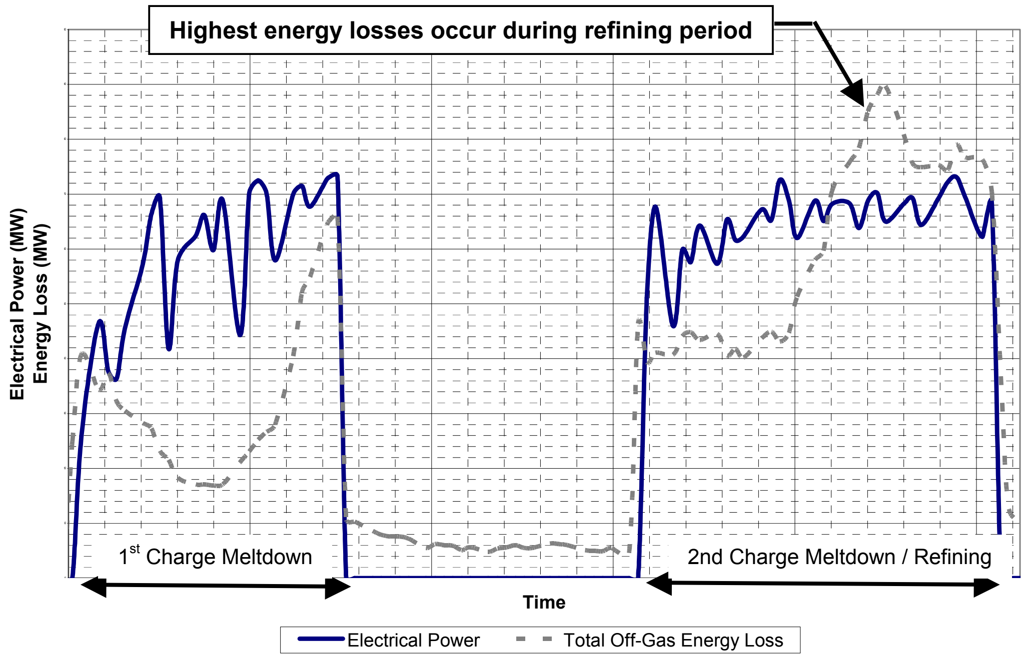

Figure 2: Electrical power input and off-gas energy loss profile through a heat

FEEDBACK TOOLS IN PRACTICE

Identify Burner Blow-Back and Arc Flare

In addition to providing an indication of the heel level, slag foaming and depth, and chemical energy recovery, the monitoring the sidewall energy losses can also indicate when blow-back is taking place. With proper programming, blow-back conditions can be recognized before the sidewalls sustain significant damage.

Improved Carbon Recovery

Carbon recovery is critical for any EAF operation to maintain the C/O/Fe balance and keep metallic yield at acceptable levels. The carry-over, or loss, of carbon from the furnace into the off-gas system results in extra heat load reporting to the gas handling system and greater Greenhouse gas emissions. The authors have worked with the plant personnel at several facilities to adjust charge carbon levels to improve yield and slag foaming in the EAF. At one installation, yield was improved approximately 0.8% with a small increase in charge carbon additions and modified practices aimed at better charge carbon recovery. In another instance, electrical energy and oxygen injection were decreased while carbon additions were increased to give an overall decrease in power-on and tap-to-tap time (reduction of approximately 3.3%).
Typically, it is very difficult for an operator to identify poor carbon utilization. Charge carbon recovery can only be determined after meltdown and injection carbon efficiency is difficult to monitor in real-time. Smart-Gas™ has developed a technique to identify injection carbon particles as they burn in the ductwork. There have been attempts to automatically control the effectiveness of carbon injection through the monitoring of arc stability. Initial improvements of 4% to 5% reduction in kWh consumption over a manual operation have been achieved.[(9)] However, arc stability does not directly tie to effective carbon injection operations. Good slag foaming may still be achieved even though carbon injection operations are inefficient.

In one case, energy losses to a sidewall panel (adjacent to the carbon feed location) coincided with high energy losses to the off-gas and an increase in off-gas temperature after it left the fourth hole, indicating that significant combustion was taking place in the off-gas duct. Carbon was added through the roof halfway through the meltdown period. The energy loss peaks during this period indicated that the carbon was reacting as soon as it was charged to the furnace and also indicated that very little of this carbon was being recovered to the bath and was not fulfilling its intended purpose – to help control bath chemistry. Analysis indicated that the charge carbon was likely breaking up and was burning in the off-gas as it was carried through the off-gas system. It was recommended that the carbon be charged onto the heel just prior to scrap charging so that the scrap would push the carbon down into the bath and result in better recovery.

Feedback for Oxygen Injection Operations

Simple feedback graphs can allow the operator to determine when the EAF is running well and periods when the EAF is losing more energy to the off-gas than normal. For example, if high energy loss to the off-gas coincides with high energy losses on specific cooling water circuits before flat bath, the cause might be burner flame blow-back onto the furnace sidewall. If this is coupled with high temperatures on some of the roof circuits, the cause might be channelling of the hot off-gas from the burner up the side of the furnace and across the roof to the fourth hole. This can result from dense scrap located in front of the burner. High roof circuit temperatures during oxygen blowing may correlate to insufficient slag cover and high radiant heat losses from the bath when the oxygen blows the slag back exposing the surface of the bath. This can quickly be evaluated by checking the arc stability to see if the arc is buried at flat bath. Sometimes the blowing rate on oxygen injectors is too high and this results in severe splashing and high radiative heat losses to the furnace shell even though, the arc is stable and is buried in the slag.

Optimum Charging

In many operations, the EAF is operated at flat bath for too long prior to adding the next scrap charge resulting in the loss of slag coating on the water-cooled panels and higher energy losses to the cooling water. When observing energy losses at one facility, it became apparent that high losses to the off-gas system were occurring at the end of the meltdown of the first scrap charge. Energy losses to the furnace sidewalls and roof also peaked during the same period. Based on this pattern, which occurred on every heat, the second charge was dropped sooner, thus reducing power-on time and at the same time improving energy efficiency.

Formation Of Stable Slag Earlier

A review of energy distribution in the EAF at one Smart-Gas™ installation indicated higher than normal energy losses to the sidewall panels and the furnace roof and that these losses increased as the scrap melted in. After extensive review of slag chemistry and EAF operating practices, it was concluded that the slag depth was insufficient to bury the arc and as a result, radiative heat losses were higher than expected. A review of flux addition practices indicated that the flux was injected through the roof approximately one-half to two-thirds of the way through meltdown. The lack of sufficient basic components in the slag early in the meltdown period was causing wear in the lower portion of the banks. The late addition of the fluxes to the furnace meant that the slag was still being formed during the period when slag foaming was required to bury the arc. A shallow furnace bottom provided minimal slag retention from the previous heat resulting in insufficient liquid slag volume to cover the arc and high energy losses to the furnace shell.

Trials were conducted where flux additions were made onto the heel prior to charging the scrap with additional flux added part way through meltdown. Earlier slag formation provided better arc stability and active power increased by 9%. Energy losses to the furnace shell were reduced, resulting in additional savings and an increase of almost 10% in productivity.

CONCLUSIONS – FUTURE WORK

The implementation of injection technologies in the EAF will only continue to grow. As process feedback is utilized to a greater degree to understand EAF operations, a much greater degree of automation of injection technologies will result.

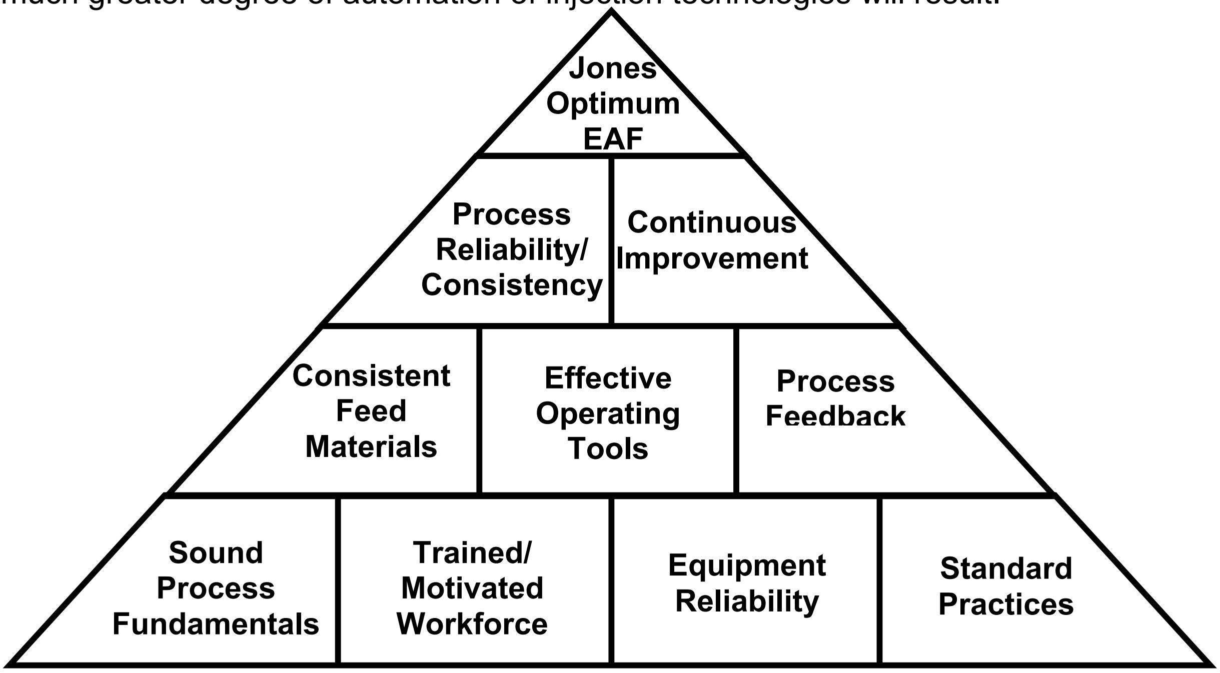

Figure 3: Components required for optimum eaf performance

Figure 3 depicts the key components required to achieve optimum EAF performance.[6-8] Just as a real pyramid requires a solid and complete foundation, the optimization pyramid requires each level to be complete before proceeding to the next. It should come as no surprise that process feedback is one of the key building blocks.

It is imperative that process measurements be made in order to evaluate the effect of process changes and to understand the overall behavior of the reactions in the EAF and auxiliary systems. If there is no feedback for a process, it is difficult if not impossible to control and optimization is out of the question. Several process tools exist that can be used to provide both real-time and historical process feedback for EAF operations. Through real-time analysis of the electrical and chemical energy distribution in the EAF, systems like Smart-Gas™ promote improved consistency and the ability to move towards real-time optimization of EAF operations. Every operation must be evaluated based on its own set of unique parameters.

Direct process feedback can greatly impact the efficiency of injection technologies in the EAF and allow us to control these technologies more effectively. It has been shown through specific examples that various forms of feedback can be used to help monitor and control injection operations in the EAF. Process feedback is an absolute necessity for any EAF steelmaking operation interested in reducing production costs and improving energy efficiency. Monitoring and assessing the distribution of energy in the EAF and auxiliary systems is the easiest way to gain a better understanding of EAF operations.

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