PYREJET – A MULTI-FUNCTION COMBUSTION/INJECTION SYSTEM FOR EAF STEELMAKING

ACI has developed a PyrJet a new proprietary multi-functional burner/injection system for the Electric Arc Furnace (EAF). The new PyreJet system combines the following operating capabilities:

- Efficient oxy/fuel combustion for EAF operating conditions
- Enhanced supersonic oxygen injection
- Carbon fines injection
- Useful post-combustion of CO

The PyreJet burner/injector utilizes a deep water-cooled combustion chamber for the active staged mixing and burning of natural gas streams positioned between a central and an outer streams of oxygen. The central oxygen stream is discharged through a Laval nozzle with supersonic velocity in excess of 2.0 Mach. This enables the PyreJet to inject a flame enhanced, tightly focused oxygen jet. The oxygen jet is capable of maintaining a supersonic velocity as far as 6 feet away from the burner discharging nozzle. This feature of the PyreJet burner provides the opportunity to introduce additional chemical energy to the cold spots, which are very difficult to reach with other devices (water-cooled lances, consumable pipes) during the early stages of scrap melting and refining.

Although many capabilities of the PyreJet technology were individually developed by ACI previously with Pyretron, Pyrelance and PyrOx burners, the first fully integrated PyreJet system was implemented only recently. This first implementation of PyreJet burner systems in two 50 ton AC EAF’s has resulted in significant operating improvements as well as elimination of all other oxygen and carbon injection devices. Multiple installations of this technology on high and ultra high power AC and DC furnaces are under way.

PYREJET BURNER SYSTEM DESIGN AND OPERATING PHYLOSOPHY

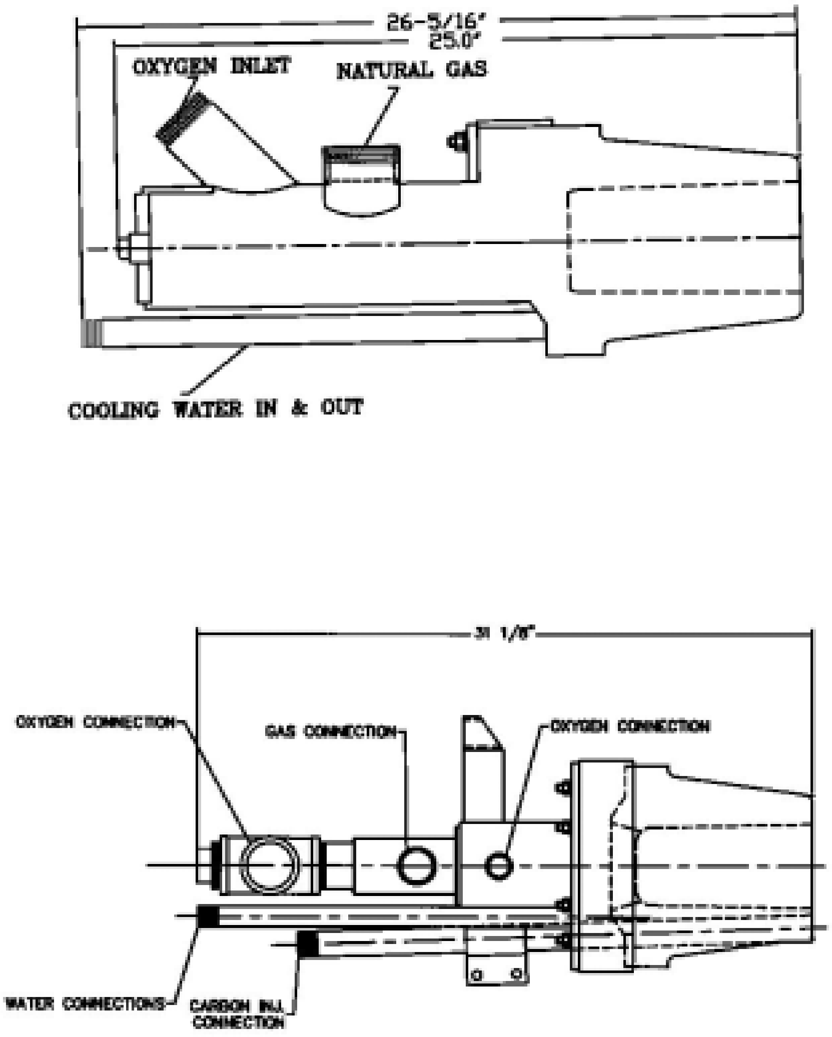
Burner Design

The PyreJet burner system comprises multiple burners, which are installed in several locations in the EAF to assist scrap melting and melt refining. The system includes two types (PyrOx and PyreJet, US Patent Nos 4,622,007; 5,599,375; 5,788,921; 5,858,302) of oxy-fuel burners.

Both of these burners are similarly designed and have the capability to melt and cut the scrap, but the PyreJet burner design comprises several additional features enabling this burner to be used for the efficient combined injection of carbon fines and supersonic oxygen to enhance slag foaming and melt refining.

Figure 1 shows a general arrangement of both types of burners illustrating the two major differences in their design.

Both burners utilize water-cooled copper burner tiles having a deep combustion chamber to control flame formation and flame shape. The combustion chamber also protects the gas and oxygen discharge holes from plugging with splashed slag and steel.



(a)

(b)

Figure1. PyrOx (a) & PyreJet (b) Burner Assembly

The inner part of the burner containing supersonic nozzle is affixed to the combustor and can be quickly and easily disconnected and removed from the combustor. This allows for ‘on-the-fly’ burner change out, when necessary. Natural gas and peripheral oxygen are introduced as a plurality of streams surrounding a primary oxygen jet stream directed along the central axis of the combustion chamber.

The PyreJet Burner combustor is also equipped with a replaceable carbon injection pipe located near the burner centerline. This allows carbon to be entrained and driven into the slag by a highly inspirating supersonic oxygen stream at 2.1 Mach exit velocity.

Use of two separate oxygen supply lines allows to further improve flame control and performance of the PyreJet as compared to PyrOx, which uses a single oxygen supply line to control the distribution between the central and peripheral oxygen flows within the burner.

It is preferable to control both supersonic and peripheral oxygen separately even though a combined control is possible in principle. During the high fire mode, for proper flame shape and chemistry, it’s important to have equal distribution of oxygen between the center and periphery streams. Later, when supersonic oxygen lancing is required, the oxygen distribution between the center and periphery changes considerably. The precise control of oxygen distribution is only possible when both flows are controlled individually. Individual oxygen control and distribution also allows for the ability to reduce gas and oxygen flows used for protection of the combustion chamber from slag and steel splashing.

It is preferable that both PyrOx and PyreJet burners be installed in water-cooled copper panels. ACI has engineered and designed a unique copper water cooled panel that allows for the easy change of the burner angle in both vertical and horizontal planes when adjustments are needed. A typical PyreJet burner installation is shown in **Figure 2.**

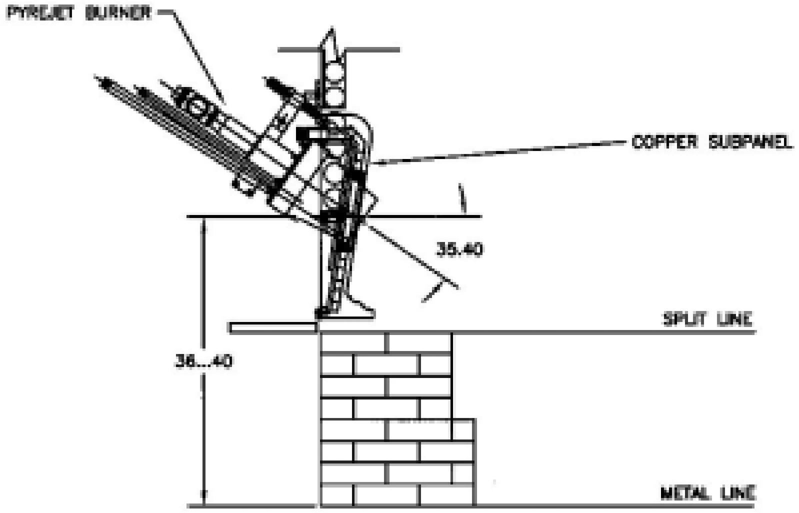


Figure 2 **Typical PyreJet Installation**

Each PyreJet burner is engineered and designed to enhance the following functions:

- Oxy/fuel combustion;
- Flame enhanced supersonic oxygen lancing;
- Injection of carbon fines;
- Post-combustion of CO.

In the beginning of each charge the PyrOx and PyreJet burners operate as regular oxy-fuel burners heating the scrap located in the cold spots. After the scrap is preheated and partially melted in, the fuel and oxygen flows are reduced and the central oxygen flow is increased to initiate soft lancing in order to cut scrap in the more remote areas and get access to the melt. It is very critical that the burner reliably and consistently cleans the adjacent area of scrap so that supersonic lancing is possible without any danger of rebound from the remaining scrap. The self-protecting design of the burners allows for a reliable, low maintenance operation.

When a passage to the bath is clear the PyrOx burners initiate holding fire while PyreJet burners begin to inject carbon for slag foaming and oxygen for melt refining. The central supersonic flow is increased to achieve 2.0-2.1 Mach exit velocity while a shrouding flame is maintained by the reduced flows of fuel and peripheral oxygen. A long, contained supersonic oxygen jet then impacts the melt to begin the refining process. In the impact area the melt temperature is raised from the exothermic oxidizing reaction and by the bath agitation and homogenization. Carbon injection by the PyreJet burners begins to deoxidize the slag and to maintain a thick foamy slag layer. The amount of oxygen and carbon introduced by the PyreJet burners are established based on scrap mix and aimed melt carbon. Carbon injection may be initiated simultaneously with oxygen lancing to balance the slag temperature and chemistry in the jet impact area, enhancing foamy slag formation. If the scrap mix contains a substantial amount of excess carbon, the carbon fines injection can be delayed to allow the oxygen jet to perform an initial rapid reduction of the melt carbon.

A thick layer of foamy slag generated by the use of PyreJet burners not only improves electrical efficiency and metallic yield but protects refractory from erosion. The thick slag layer helps to capture some amount of oxygen that rebounds from the metal interface as well as droplets of metal that are inevitably generated during lancing. The endothermic reaction of injected carbon with slag oxides reduces the temperature and slows the chemical attack of slag before its basicity increases due to the lime dissolution .

The carbon/oxygen co-injection continues until the required chemistry of the melt is achieved. The final melt carbon content as low as 0.03% can be accomplished by using PyreJet technology. The PyreJet system control program is fully automated to ensure the consistency of the EAF operation.

Flame Enhanced Oxygen Lancing

The length of a supersonic oxygen jet is greatly influenced by the condition of the gaseous atmosphere surrounding the jet. The main reason for a conventional supersonic lance’s jet normal disintegration is the interaction with surrounding atmospheric gases. The high velocity supersonic jet inspirates the surrounding atmosphere. This increases the mass of the jet stream and reduces its velocity.

Flame shrouding of the oxygen jet stream for the purpose of extending its length was first described and patented by ACI in 1986 (US Patent No 4,622,007). The use of an oxy-fuel flame provides for high temperature combustion gases accompanying the oxygen jet stream. High temperature combustion gases have very low density as shown in **Figure 3.** This reduces the mass of inspirated gases and keeps the oxygen jet stream focused much longer.

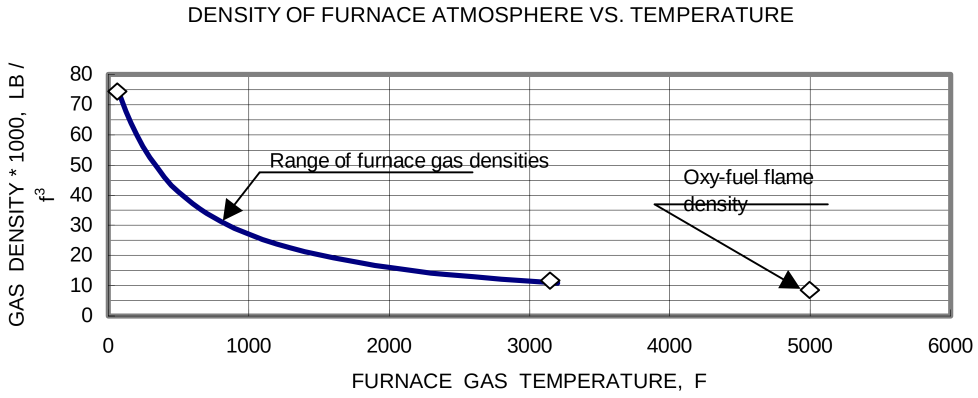


Figure 3

Figure 4 illustrates the effect of the reduction in the density of the surrounding gases on the penetrability of the supersonic oxygen stream exiting the Laval nozzle. Notable, the supersonic jet stream will maintain its velocity for a distance approximately five times longer than if the surrounding atmospheric density is reduced by a factor of 10. The absolute jet penetrability is proportionate to the nozzle diameter that is reflected on the ‘X’ axis of the graph in the figure below.

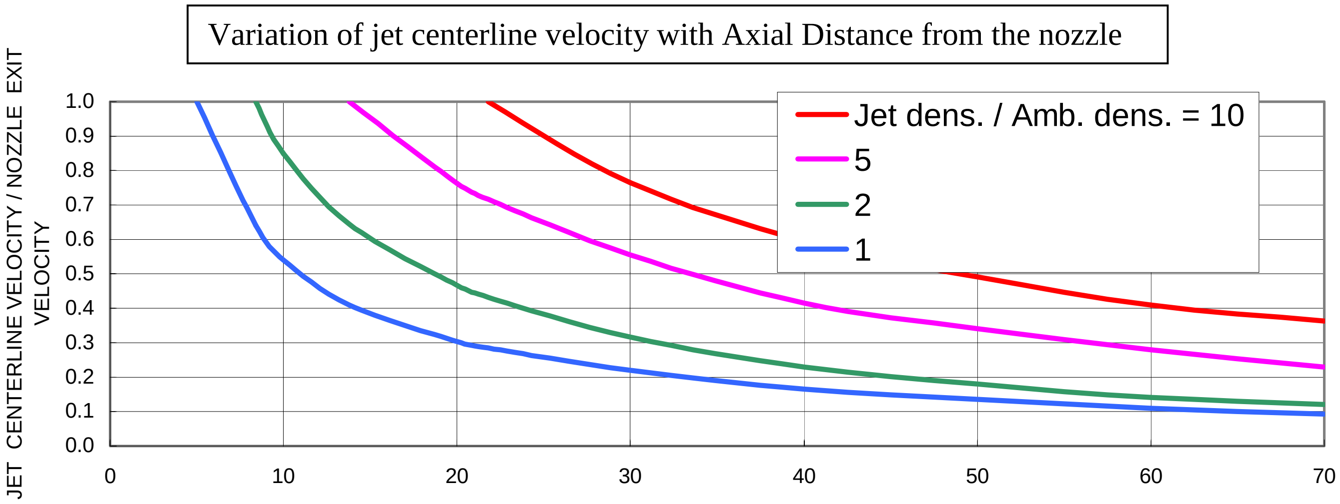


Figure 4

Another very important factor affecting supersonic jet disintegration is the presence of high velocity concurrent streams (shrouding of supersonic oxygen stream). Shrouding of the oxygen jet with a high velocity oxy-fuel flame, in the PyreJet provides for a significant increase in impingement length and kinetic energy retention. When high temperature oxy fuel combustion products, which have a different and lower velocity than the supersonic oxygen stream are inspirated into the supersonic oxygen stream, the increased mass of gases has an increased momentum. This further diminishes the jet disintegration due to inspiration of surrounding gases.

Figure 5 demonstrates supersonic lancing into ambient air and into the EAF by a PyreJet burner. The bars below are at one foot intervals.

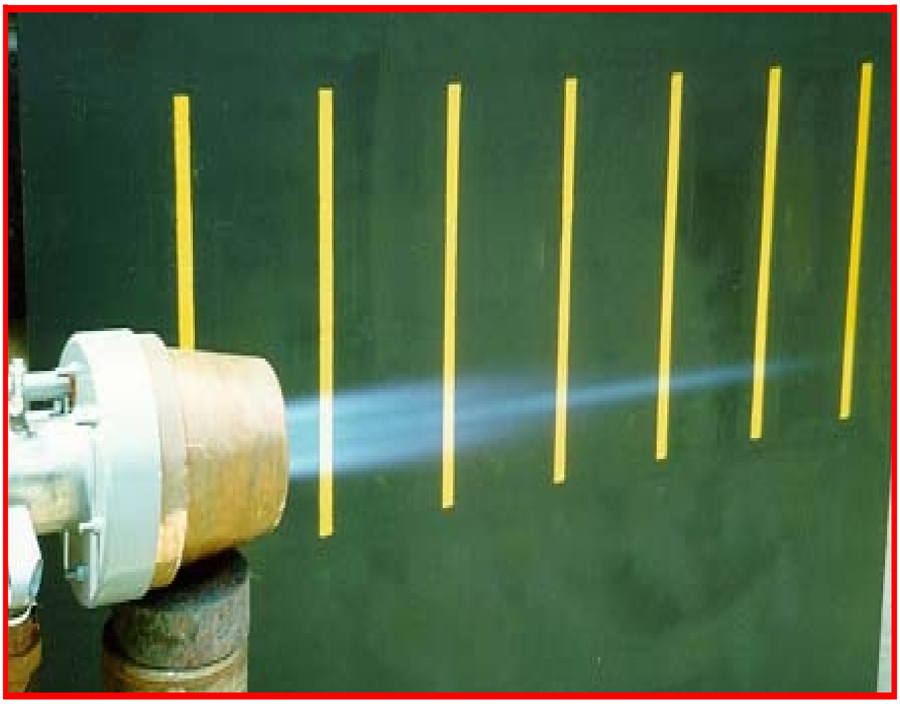


Figure 5. Supersonic Jet Produced by PyreJet Burner

Operating Philosophy

Recognizing that EAFs have different operating conditions, the PyreJet burner/injection system has been designed to optimize EAF performance by multi-point injection of auxiliary heat, oxygen and carbon fines, and post combustion. The main differences are due to a variation in furnace design, electrical power, scrap mix and established melt shop operating practices. Optimization of the Pyrejet system in each case is carried out during burner system design phase, installation and commissioning.

System Optimization includes the following:

- Selection of appropriate number of burners and their positions,
- Estimated firing schedule,
- Oxygen lancing schedule,
- Layout of carbon fines injection points and carbon injection schedule.

The operation of PyreJet burners influences temperature, oxygen and carbon delivery in areas adjacent to the burners. During supersonic lancing a major portion of oxygen reaching the melt surface is consumed by the oxidation of carbon and iron and by dissolution into the melt. Carbon oxidation is incomplete and is mainly oxidized to carbon monoxide.

Carbon content of the melt and melt temperature greatly influences thermodynamic equilibrium and the distribution of oxygen participating in oxidation of melt iron, carbon and other alloying elements and the completion of the carbon oxidation. Due to competition for oxygen only a small portion of CO can be oxidized to CO_2 at the melt surface. For example, only ~ 0.5% of oxygen flow is used to oxidize CO to CO_2 when oxygen jets react with the melt having a carbon content of ~ 0.2%. But the contribution of oxygen to this reaction of CO oxidation increases to ~ 10 % when the melt carbon content is reduced to 0.03%.

Quantitatively the oxygen content of metal can be approximated using the following C-O equilibrium equation:

$$[C][O]=0.0025; \qquad @2950^0F, \quad P_{CO}=1$$

Therefore, assuming that melt temperature stays constant during refining the variation in the theoretical amount of oxygen dissolved in metal during decarburization from the melt carbon content equal C_1 to C_2 can be approximated as follows:

$$d[O]=0.0025(1/C_2-1/C_1)$$

In practice oxygen content of metal is somewhat higher than the equilibrium concentration but the difference is usually insignificant, although it may vary throughout the refining period.

Similarly to the process of oxygen dissolution in the melt, the theoretical amount of oxygen reported in the slag during decarburization process can be approximated using the following equation:

$$d(FeO)=0.0163(1/C_2-1/C_1) \qquad (at \quad 2950^0F, \quad P_{CO}=1)$$

Figure 6 shows the distribution of oxygen between reactions of melt carbon oxidation, melt iron oxidation and oxygen dissolution in the melt during the refining period. Obviously, in the beginning of the refining period, when the melt carbon content is relatively high, nearly 90% of conveyed oxygen is consumed by the melt decarburization. During the final stage of refining the oxidation of iron becomes predominant.

If extremely low tap carbon (.02-.03%) is required, as much as 90% of supplied oxygen is going to form FeO.

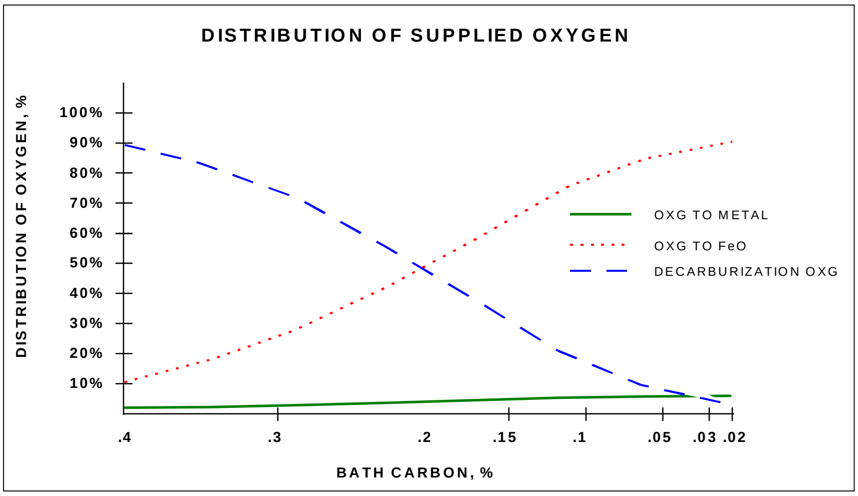


Figure 6

In case the intensive oxidation of iron at the end of the steel making cycle is not counterbalanced by an adequate foamy slag practice a significant yield loss and refractory erosion would be observed due to high FeO content of high temperature slag. **Figure 7** represents an estimated decarburization rate at various oxygen flows versus bath carbon content.

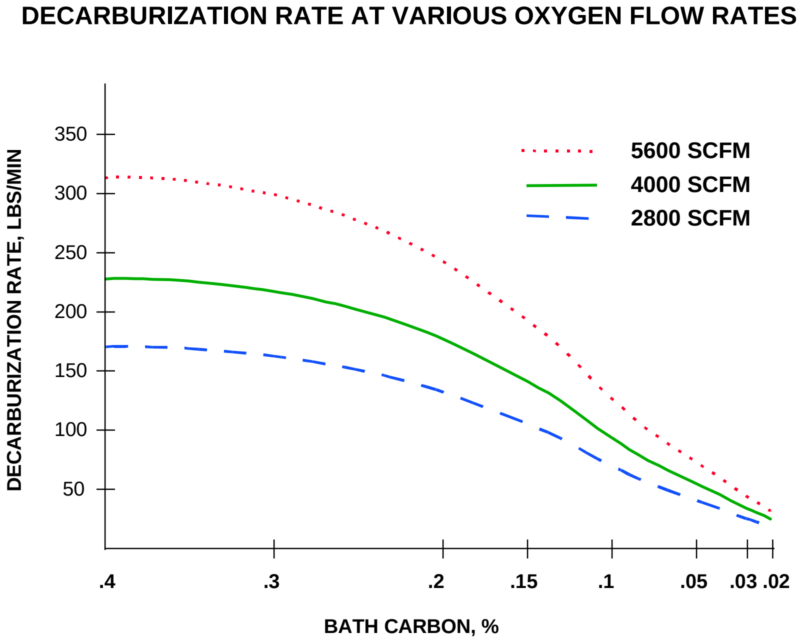


Figure 7

The removal of melt carbon is accomplished in two stages. During the first stage a film of iron oxide is formed when gaseous oxygen contacts melt surface and droplets of iron contained in the slag located in the lancing zone. Oxidation of Fe occurs via the reaction:

$$Fe + 1/2O_2 = FeO \qquad (+0.265\ kwh/scf\ O_2)$$

The film of iron oxide formed in the lancing zone is later partially reduced during the second stage by the dissolved melt carbon via the reaction:

$$FeO + C = Fe + CO \quad (-0.187\ kwh/scf\ O_2)$$

The first reaction is exothermic and takes place at almost any time during the steel making cycle when oxygen contacts melt iron. The second reaction is endothermic. At lower melt temperature (below 2850^0 F) this reaction is controlled by the diffusion rate of the carbon in the melt.

Based on the above the following practical rules are established for the PyreJet operation:

- To avoid local slag over-oxidation oxygen lancing is accompanied by simultaneous carbon co-injection, especially if the final melt carbon content is below 0.1%.
- Aggressive oxygen lancing begins when both stages of carbon removal are kinetically feasible to prevent slag over oxidation.
- Early oxygen injection in the melt will only be beneficial if it occurs in the hot furnace zone.

Oxygen utilization as well as consistency of foamy slag practice can be improved via utilization of multiple points of oxygen/carbon co-injection in the EAF. Multi-point co-injection also provides for better nitrogen control, lower refractory erosion and metallic yield increase. Bath boiling during oxidation of carbon results in homogenization of the metal and acceleration of all processes at the slag-metal interface. Carbon boil enhances the removal of hydrogen and nitrogen from the bath.

OPERATING RESULTS

Although PyrOx burners, featuring supersonic oxygen injection, were used for years in many EAFs in combination with different types of decarburizing oxygen lances, the use of the PyreJet version has been integrated recently allowing for a complete automation of chemical energy input including oxygen and carbon injection, solely via stationary side wall burners. The PyreJet technology was first implemented in two 50 ton AC EAFs. The furnaces are equipped with 25 MVA transformers. Each furnace has two PyreJet burners and one PyrOx burner. The tap carbon varies from 0.05 to 0.50%. No additional oxygen or carbon injection devices are used for the process.

It is worth mentioning that the logistics of the shop dictate strict control of power demand. Installation of the PyreJet system has allowed cutting power demand for the

EAFs by 20%. The table below summarizes main operating data before and after PyreJet system installation.

	BEFORE	AFTER	CHANGE, %
Electrical Consumption, Kwh/t	**480**	**400**	**17**
Natural Gas Consumption, scf/t	**0**	**280**	**N/A**
Oxygen Consumption, scf/t	**350**	**850**	**114**
Power on Time, min	**67**	**57**	**(15)**
Heats Between Relines	**400**	**1000**	**150**
Gunning Material Consumption, lbs/t	**7**	**4**	**(57)**