The Use of Oxygen to Decrease Electrical Energy Usage in the Electric Arc Furnace

by

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A thesis submitted in conformity with the requirements for the degree of Master of Applied Science

Graduate Department of the Faculty of Applied Science and Engineering

University of Toronto

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Abstract

The increased intensity of the Electric Arc Furnace (EAF) steelmaking process has resulted in corresponding increases in energy losses. The reduction of chemical energy losses, by the injection of targeted oxygen, has the potential to become an enormous advantage in today's highly competitive steel industry. A variety of methods have been used for the addition of this supplemental oxygen, including auxiliary lances, oxygen injectors and existing side wall burners.

In this study the ratio of natural gas to oxygen, flowing through the existing side wall burners, was modified in order to increase the amount of free oxygen flow to the EAF at Co-Steel Lasco. Decreases of 4.0% with respect to Specific Electrical Energy Consumption, 42.7% with respect to Specific Natural Gas Consumption, 5.0% with respect to Power on Time, and 4.5% with respect to Tap to Tap Time were observed.
Acknowledgments

This project would not have come to fruition without the assistance of certain key individuals and institutions.

Financial assistance for this project was provided by the Natural Science and Engineering Research Council of Canada and Goodfellow Technologies Inc. (GTI).

I would like to thank Co-Steel Lasco for providing me with an industrial size apparatus on which to conduct my experiments. The technical assistance, provided by too many to name, was invaluable.

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1. Introduction
The arena in which today's steelmakers compete includes companies from around the world, using a variety of technologies to produce a vast array of products. As a result, steelmaking has become a much more competitive business, which has forced many steelmakers to re-think their strategies and focus on their core competencies. Consequently, the spectrum of steelmakers is defined by two very different extremes. At one end is the steelmaker who produces small volumes of high priced alloys, with very precise chemical compositions, which are prized for their very specific properties. At the opposite end of the spectrum, is the steelmaker who produces a very large volume of low priced steel products, used in the construction of roadways and buildings.

For the former, the focus is on very precise chemical compositions and heat treating methods. For the latter, the focus is on high productivity and low costs, with relatively small variations in chemical compositions and heat treating practices.

In this environment, the Electric Arc Furnace (EAF) has been repositioned as a "melter" rather than a "melter and refiner", as it was used just a few years ago, in an effort to increase productivity and reduce costs. Where the EAF used to melt scrap and achieve target chemistries for a number of elements, it is now used to satisfy temperature specifications and a minimum of chemical specifications, often just dissolved carbon.

In the modern meltshop, alloys are generally added at tap or at the ladle station, where they used to be added at the EAF. The focus of the furnace operators is on high productivity of liquid metal so that it can be "alloyed" at the ladle station. Advances in technology, which coincided with this change in philosophy, allowed
significant decreases in energy input into the furnace, as well as tap to tap times to be realized.

The figure below shows some of the most notable EAF technologies which have been developed and how they have affected Tap to Tap times, electricity and electrode consumption.

![Figure 1.1. Impact of EAF Technology Developments on Operating Parameters.](image)

Two things which have had an enormous effect on the operation of the EAF are high powered transformers, and the availability of tonnage oxygen used in oxygen lances and burners. Both these advances have allowed steelmakers to add more energy, both electrical and chemical, to the furnace in a shorter period of time, leading to a more intense process.

The increasing intensity of the process has led to a corresponding increase in the amount of energy lost to the offgases, both in terms of sensible and chemical energy. Recent studies indicate that up to 220 kWh/te (200 kWh/t) is lost to the
offgas, and that 110 kWh/te (100 kWh/t) of this is in the form of chemical energy.

In an industry as competitive as steelmaking, any process improvement which increases already thin margins is considered to be a competitive advantage. This has driven steelmakers and suppliers to find techniques to return as much of this energy as possible to the process.

As a result, efforts such as the use of offgases to preheat scrap have been launched including the development of the shaft furnace, where hot offgases pass through cold scrap before entering the ventilation system. Efforts to retrofit this technology into existing meltshops have been stymied by the high cost of modifications to buildings, although many new meltshops have incorporated this design.

Another process development which does require a far smaller capital expenditure is the installation of post combustion technology. The capital requirements include the addition of oxygen injection equipment, and perhaps the addition of some oxygen capacity, a cost which is often borne by the oxygen supplier.

Although it is not required, it is highly recommended that an online offgas analysis system also be installed to monitor conditions in real time. As the conditions at the furnace exit are so extreme, with very high temperatures, high dust loadings and the cyclical nature of the process, the technology used to perform offgas analysis has only become available in the past few years.

Early efforts at offgas analysis clearly showed that significant amounts of chemical energy were available in the offgas. This was followed by the development of technologies to not only increase the injection of oxygen into the
furnace, but also to direct this oxygen flow to the areas in the furnace where the largest benefits could be realized. In doing so, the goal was to capitalize on this potential energy in the furnace, thus returning the energy to the charge and reducing the amount of electrical energy required to meet production specifications. As a result, reduction in tap to tap times would be observed leading to increased productivity without significant capital expenditures.

A reduction of chemical energy in the offgas could also result in a large decrease in the heat dissipative requirements for the ventilation system resulting in significant savings in capital and operating costs. These savings are independent of the savings which would be achieved if some of the energy is returned to the charge.

In short, the reduction of energy losses from the furnace can provide savings in terms of electrical energy consumption, tap to tap times, as well as operating and capital costs of the ventilation system.

This study evaluated the effect of increasing the amount of oxygen available for combustion in the furnace shell in order to decrease chemical energy losses from the furnace. Oxygen available for combustion in the furnace was increased by 19.0%, by decreasing the consumption of natural gas by 42.7%. Results of this study indicate that decreases in terms of Specific Electrical Energy Consumption (4.0%), Power On Time (5.0%) and Tap to Tap Time (4.5%) were realized.
2. Theory
Increases in energy losses from furnaces, both in the form of chemical and sensible energy, have been observed as the intensity of the EAF steelmaking process has increased. This increased level of intensity is a result of the efforts of steelmakers to increase productivity without substantial capital investments in new equipment.

It has been proven, in modest terms, that the increase in oxygen flow to the furnace in an effort to decrease chemical energy losses and the return of this energy to the charge can lead to substantial savings in energy consumption and increases in productivity.

2.1 Energy In The Offgas
Recent studies indicate that up to 220 kWh/te (200 kWh/t) is lost to the offgas, and that this energy is evenly split between sensible and chemical energy. Any technology which would be able to recover even a fraction of this energy could result in substantial savings for the steelmaker.

2.1.1 Sensible Energy In The Offgas
Although exact figures are not available, it is expected that the maximum offgas temperatures can reach the temperature of the bath itself, in the area of 1620 to 1649 °C (2950 to 3000 F), and represent a very significant amount of energy. Many efforts have been made to find ways of recovering some of this energy including the development of the shaft furnace where offgases first pass through cold scrap before entering the ventilation system. Another effort to recover some of this energy has been through the preheating of entire charged scrap buckets by the hot offgases.
2.1.2 Sources Of Chemical Energy In The Offgas

Substantial amounts of chemical energy are present in the EAF offgas, in the form of CO and H\textsubscript{2} gas. A typical offgas profile from the Co-Steel Lasco EAF is presented as Figure 2.1.

![Figure 2.1](image)

**Figure 2.1,** Typical EAF offgas profile, showing the meltdown and refining periods of the heat.

The chemical energy present in the offgas is the result of incomplete combustion of a number of components in the steelmaking process.

Chemical energy, in the form of Natural Gas and Carbon, is added to the furnace in order to increase productivity. Natural Gas is added through burners mounted on the furnace shell, or through a door burner positioned through the slag door. Oxygen, which is required for the combustion reaction to take place, is also added through the burners. Carbon is often charged along with the scrap, in addition to being lanced into the furnace during the refining phase of the heat.
Along with lanced oxygen, this carbon is used to develop a foam with the slag during the refining phase of the heat, a technique known as "foaming slag". Incomplete combustion of carbon and natural gas will result in the evolution CO and H₂ gases.

The carbon electrodes used in the AC EAF steelmaking process are consumed at rates of 2.5-3.0 kg/te (5-6 lbs/t) or higher. Incomplete combustion of the electrode carbon will result in additional chemical energy, in the form of CO gas, in the offgases.

Another source of chemical energy is "fluff" in the scrap charged to the furnace. Fluff is solid hydrocarbons which were once plastic parts of the vehicles shredded to make scrap. In addition to fluff, oils are present in many of the scrap types used in the steelmaking process. Although both are significant factors, they are difficult to quantify, and fluctuate widely.

Although water itself does not contain any chemical energy, at the conditions present in the EAF, significant amounts of water will react according to the water shift reaction, presented below:

$$H_2O(g) + CO(g) \rightarrow H_2(g) + CO_2(g) \quad \Delta H = -36,400 \text{ J/mol} \quad \text{Eq. 1}$$

As a result of this reaction, higher levels of H₂ and CO₂ will be observed in the offgases. Water is present in many of the scrap types used in the EAF steelmaking process. In addition, pinhole leaks in the furnace water cooled shell, and the cooling of electrodes with water will result in water entering the furnace.
2.1.3 Offgas Volume

Due to the extreme conditions present at the furnace exit exact figures for offgas flow are not available. It is estimated that this flow is approximately 510 Nm$^3$/min (18,000 scfm) to 623 Nm$^3$/min (22,000 scfm) during peak flow periods.

2.2 Chemical Energy Reactions

Although many reactions take place in a reactor as complex as the EAF, the following reactions are the most important from a chemical energy and heat transfer point of view:

\[ C(s) + \frac{1}{2} O_2(g) \rightarrow CO(g) \quad \Delta H = -111,700 \quad J/mol \]  
Eq. 2

\[ CO(g) + \frac{1}{2} O_2(g) \rightarrow CO_2(g) \quad \Delta H = -282,400 \quad J/mol \]  
Eq. 3

\[ C(s) + O_2(g) \rightarrow CO_2(g) \quad \Delta H = -394,100 \quad J/mol \]  
Eq. 4

\[ H_2(g) + \frac{1}{2} O_2(g) \rightarrow H_2O(g) \quad \Delta H = -246,000 \quad J/mol \]  
Eq. 5

\[ CH_4(g) + 2 O_2(g) \rightarrow CO_2(g) + 2 H_2O(g) \quad \Delta H = -816,980 \quad J/mol \]  
Eq. 6

The reactions and their heat of reactions, presented above, indicate that large amounts of chemical energy are present in these gases.

Examination of Equations 2 to 4 shows that the relationship between the reactions involving the oxidation of carbon. The fact that the reaction of CO to form CO$_2$ (Equation 3) will provide almost two times the amount of energy that is
produced when C reacts to form CO (Equation 2), makes the reduction of chemical energy losses from the EAF increasingly lucrative.

The heat of reaction of $\text{H}_2$ gas indicates that substantial amounts of chemical energy, according to Equation 5, are contained in the volume of hydrogen gas exiting the EAF furnace.

The reaction of methane, the principal constituent of natural gas, provides a substantial amount of energy to the charge through the burners, according to Equation 6.

Given the high offgas flow rates and concentrations of CO and $\text{H}_2$ gases, it is clear that very large amounts of chemical energy are contained in the EAF offgas. If these energies can be effectively transferred to the charge substantial savings will undoubtedly be realized.

2.3 Status Quo
In a conventional EAF, where a post combustion strategy has not been adopted, large volumes of CO and $\text{H}_2$ gas rise from the charge, mix with ambient air entering through the slag door and escape from the furnace into the ventilation system. Air entering through the combustion gap (the gap between the roof panels and the fixed water cooled panels of the ventilation system, shown in Appendix 1) is used to dilute and completely oxidize the offgases. The ventilation system contains a variety of technologies used to decrease the temperature of the offgases such that it can be filtered in the baghouse and released to the atmosphere.
2.3.1 Chemical Energy Post Combustion

Dilution air, entering at the combustion gap, is used to fully oxidized these gases according to Equations 2 and 4. This results in the release of chemical potential energy just beyond the combustion gap in the ventilation system. The energy contained in the offgases must be dissipated, using various technologies including water cooled panels and spray chambers, such that the offgas stream can be filtered in the baghouse. Typical normal operating temperatures of a baghouse is in the range of 93 °C (200 F), with maximum peaks in the range of 149 °C (300 F).7

It is clear that no process benefits are realized by the release of chemical potential energy in the ventilation system.

2.3.2 Natural Post Combustion

The term “natural post combustion” is used to denote the combustion of CO and H₂ with ambient air which enters through the slag door and other through-shell fittings. By its very nature, this combustion takes place high in the furnace, from where very little of the available energy is returned to the charge. Natural post combustion does, however, decrease the amount of chemical energy leaving the furnace.

Another problem associated with natural post combustion is the loss of energy to the “nitrogen ballast”. This term refers to the volume of nitrogen which also enters the furnace through the slag door. Nitrogen makes no contribution to the steelmaking process and may have a deleterious effect on the operation of the EAF by reacting to form NOₓ and by contaminating the bath with dissolved nitrogen. Effectively, this nitrogen serves no purpose in the steelmaking process other than to act as an energy sink as it enters the furnace to be heated to offgas temperatures and go to the ventilation system. As a result, the capacity
of ventilation systems must be increased, which has higher capital and operating costs associated with it.

2.4 Alternative: Post Combustion (PC)
The targeted injection of post combustion (PC) oxygen during the EAF steelmaking process will promote Equations 2 and 4 in the furnace shell such that the amount of energy returned to the charge is maximized. Two very distinct PC strategies have emerged, each of which reflect the different philosophies on which they were founded. The two strategies are: Post Combustion in the slag, and Post Combustion in the free space above the slag line.

2.4.1 PC In The Slag
In this type of PC, pioneered by Praxair, a water cooled piggy back lance is mounted on the existing lancing assembly\(^3\). During the periods of flat bath, while the conventional lances are injecting oxygen and carbon at the bath-slag interface, the post combustion lance is used to inject oxygen into the foamy slag. In this case, the objective is to promote the oxidation of CO gas, presented as Equation 2, in the foamy slag.

This technique is ideally suited for processes where flat bath conditions are prevailing for a significant proportion of the heat. Such processes include ones which include the continuous feeding of large amounts of DRI, or the Consteel furnace\(^8,9\) where a large bath is continually present and scrap is continually fed to the furnace using a conveyor.

2.4.1.1 Mechanisms Of Heat Transfer
Recent papers indicate that in the case of post combustion in the slag the dominant mechanism for heat transfer to the bath is the convective transfer of
heat to iron droplets in the slag. As the droplets return to the bath from the slag the energy is transferred to the bath by convective heat transfer once again³.

2.4.1.2 Problems
A number of problems exist with the foamy slag post combustion technique. One of the problems is that a large number of droplets must be present in the slag for heat transfer to take place. In order to get these droplets into the slag a very violent slag practice, or very vigorous mixing by porous plugs must be employed.

Additionally, the injection of oxygen into an iron rich slag could lead to the oxidation of these droplets to form FeO. Not only would this result in an increase in iron units lost to the slag, but the high concentration of FeO in the slag could have a deleterious effect on slag foaming ability¹⁰.

The amount of heat transferred to the charge is a function of two factors. The amount of heat available, and the heat transfer conditions. Although large amounts of CO are available during flat bath periods, at these elevated temperatures, CO₂ is less stable than CO, when in contact with C. As a result, even large amounts of oxygen injection may not have a significant impact on the amount of CO oxidized to CO₂.

It is also important to note that the heat transfer rate is a function of the temperature differential between the source and the target. In this technique, the temperature differential is at a minimum as the bath is at the maximum temperature, leading to relatively poor heat transfer conditions.
2.4.1.3 Published Results

The most notable paper on this subject was published by Mathur and Daughtrridge in 1994. Trials were conducted on the #1 furnace at Nucor's plant in Plymouth, Utah. These trials demonstrated that 81% heat transfer efficiency could be achieved, resulting in a 44 kWh/te (40 kWh/t) decrease in Specific Electrical Energy Consumption, to 366 kWh/te (332 kWh/t), and a 4 minute decrease in Tap to Tap Time. These results are summarized in Table 2.1 below.

Table 2.1, Summary of Post Combustion trial results from Nucor, Plymouth using Praxair foamy slag post combustion technology.

<table>
<thead>
<tr>
<th>Plant</th>
<th>Technology</th>
<th>Volume of PC Oxygen</th>
<th>Savings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nucor - Plymouth</td>
<td>Praxair (foamy slag)</td>
<td>Nm³ O₂/te (Nm³ O₂/t)</td>
<td>kWh/Nm³</td>
</tr>
</tbody>
</table>

|                |                       | 9.4 (8.5)           | 4.7      |

Other results have also been published which indicate that energy savings with foamy slag post combustion have ranged from 4-5 kWh/Nm³ O₂.

2.4.2 PC In The Free Space

The majority of the work that has been published involves PC in the free space. Generally, this has been done with the addition of oxygen through oxygen injectors mounted on the furnace shell.

The objective is to promote combustion and post combustion reactions above the slag line, in the free space of the furnace. As can be seen from Figure 2.1, during the meltdown periods, large amounts of carbon containing gases are evolved from the furnace. At this time there is also a large amount of cold, solid scrap in the furnace. These conditions are ideally suited for post combustion and the transfer of the resulting energy back into the charge.
2.4.2.1 Mechanisms Of Heat Transfer

In this technique, the heat transfer mechanisms are thought to be radiation and convection. Radiation from the actual combustion reaction will transfer energy to the nearby scrap. As the hot offgases travel through the scrap pile, heat is transferred to the charge by convection. Conditions for heat transfer are very favorable as the temperature difference between the hot offgases and the cold scrap in the furnace is at a maximum during the meltdown periods of the heat. In addition, the combustion and post combustion reactions take place in very close proximity to the scrap, contributing to increased heat transfer rates.

2.4.2.2 Strategies Employed

As the mechanisms of heat transfer depend on making large amounts of heat available, especially during periods when heat transfer conditions are favorable, periods of meltdown are emphasized. As can be seen in Figure 2.1, CO and H₂ concentrations are very high during these periods, and cold, solid scrap is also available leading to favorable heat transfer conditions. During these periods additional oxygen is injected into the furnace, generally through oxygen injectors mounted on the furnace shell.

2.4.2.3 Problems

A number of problems also exist with free space post combustion. The addition of oxygen may modify flow patterns in the furnace such that the combustion of CO or H₂ gases occurs in an area of the furnace from where heat transfer to the charge is inefficient. It is even possible that the oxygen may short circuit and not react in the furnace. Either of these situations could result in the inefficient use of oxygen leading to reduced decreases in Electrical Energy Consumption and Tap to Tap Time.
Additionally, the oxygen injectors could cause yield decreases if they are improperly configured. This would be the result of the oxidation of the charge by the injected oxygen. Increased electrode consumption could also result from poorly configured oxygen injection equipment. To ensure that unwanted decreases in yield and increases electrode consumption are not realized, low velocity oxygen injectors are usually used.

2.4.2.4 Published Results

Mathur and Daughtridge published results in 1994 which showed that 60% heat transfer efficiency could be achieved by injecting post combustion oxygen through the burners. During these trials, the burners were run in an oxygen rich mode after the normal cycle in order to promote the reaction of CO from the bath with the excess $O_2$. Once again, trials were conducted on the #1 furnace at Nucor’s plant in Plymouth, Utah. Average power savings of 3.6 kWh/Nm$^3$ $O_2$ were realized. The results are summarized in Table 2.2 below.

<table>
<thead>
<tr>
<th>Plant</th>
<th>Technology</th>
<th>Volume of PC Oxygen</th>
<th>Savings</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$Nm^3 O_2/te$</td>
<td>kWh/Nm$^3$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>($Nm^3 O_2/t$)</td>
<td></td>
</tr>
<tr>
<td>Nucor - Plymouth</td>
<td>Praxair (burners)</td>
<td>3.6 (3.3)</td>
<td>3.6</td>
</tr>
</tbody>
</table>

In 1995 Gregory published results that documented the process improvements realized at Cascade Steel Rolling Mills Inc. (CSRM) as a result of the implementation of post combustion technology, known as ALARC-PC™, including continuous offgas analysis to regulate low velocity, counter-current oxygen injection. The results included the reduction of Specific Electrical
Energy Consumption by 65 kWh/te (59 kWh/t) to 503 kWh/te (456 kWh/t), the reduction of Power On Time by 7 minutes to 47 minutes, and the reduction of Tap to Tap Time by 10 minutes to 76 minutes with the addition of 25 Nm³/te (23 Nm³/t) of post combustion O₂. This resulted in an average power savings of 2.6 kWh/Nm³ O₂. The results are summarized in Table 2.3 below.

Table 2.3, Summary of Post Combustion trial results from CSRM using ALARC-PC™ post combustion technology.

<table>
<thead>
<tr>
<th>Plant</th>
<th>Technology</th>
<th>Volume of PC Oxygen</th>
<th>Savings</th>
</tr>
</thead>
<tbody>
<tr>
<td>CSRM</td>
<td>ALARC-PC™</td>
<td>25 Nm³ O₂/te (23 Nm³ O₂/t)</td>
<td>2.6 kWh/Nm³</td>
</tr>
</tbody>
</table>

Gregory also found an increase in the power input rate of 1.3 MW, to 53.4 MW. Corresponding decreases in MVAR and increases in Power Factor were also measured. These improvements were attributed to the decrease in process times for each bucket, and to a reduction in cave-ins due to the installation the post combustion system.

The installation of an ALARC-PC™ system at Badische Stahlwerke (BSW) resulted in the reduction of Specific Electrical Energy Consumption by 39 kWh/te (35 kWh/t), to 382 kWh/te (347 kWh/t) with the addition of 11 Nm³/te (10 Nm³/t) of oxygen, to 51 Nm³/te (46 Nm³/t)⁴. Power On Time was reduced by 3.7 minutes, to 36.8 minutes, and the same reduction was realized with respect to Tap to Tap Time, which was decreased to 47.8 minutes. This resulted in an increase of 2.1 heats per day to a level of 30.1 heats per day. During this same study it was found that the use of a post combustion strategy had also reduced the load on the offgas system, while electrode consumption and yield had remained at acceptable values. The results are summarized in Table 2.4 below.
Table 2.4. Summary of Post Combustion trial results from BSW using ALARC-PC™ post combustion technology.

<table>
<thead>
<tr>
<th>Plant</th>
<th>Technology</th>
<th>Volume of PC Oxygen</th>
<th>Savings</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ALARC-PC™</td>
<td>11 (10)</td>
<td>3.5</td>
</tr>
</tbody>
</table>

Previous work done at Co-Steel Lasco, published by Evenson and Goodfellow, indicated that a 39 kWh/te (35 kWh/t) reduction, to 428 kWh/te (388 kWh/t), was realized by increasing the specific total oxygen consumption by 10 Nm³/te (325 scf/t), to 37 Nm³/te (1182 scf/t). These trials involved the modification of the burner ratio, as well as the use of a new lancing system. This increase in specific total oxygen consumption was realized by increasing the O₂ flow through the lances to 27 Nm³/te (854 scf/t), from 13 Nm³/te (425 scf/t), and decreasing the oxygen flow through the burners from 14 Nm³/te (432 scf/t) to 10 Nm³/te (328 scf/t). These same trials resulted in a 4 minute Power On Time decrease, to 52 minutes. The results are summarized in Table 2.4 below.

Table 2.5. Summary of Furnace Combustion trial results from Co-Steel Lasco using Goodfellow Technologies' technology.

<table>
<thead>
<tr>
<th>Plant</th>
<th>Technology</th>
<th>Volume of PC Oxygen</th>
<th>Savings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Co-Steel Lasco</td>
<td>Lasco and Goodfellow</td>
<td>10 (9.2)</td>
<td>3.9</td>
</tr>
</tbody>
</table>

2.5 This Study
Available offgas profiles from Co-Steel Lasco, such as the one presented in Figure 2.1, showed that high levels of chemical energy were being measured at the furnace exit, especially during the meltdown periods of the heats. If the levels of chemical energy, in the form of CO and H₂ gases, could be reduced,
and a portion of this energy could be returned to the charge, it was likely that substantial savings would be realized.

The reduction of chemical energy in the offgases could have been realized by increasing the flow of oxygen to the furnace during the meltdown phases. This would have likely promoted combustion in the furnace, leading to a reduction in chemical energy losses from the furnace while increasing the amount of energy available to the charge. The reductions in Power On Time and Specific Electrical Energy Consumption would have been a function of how much of this energy is transferred to the charge.

However, no excess oxygen was available from the on site air separation plant at Co-Steel Lasco. Another viable option was to decrease the amount of natural gas flowing to the furnace, while maintaining the same flow of oxygen. The ratio of natural gas to oxygen is known as the burner ratio, and its decrease would result in a greater number of oxygen molecules being available for reactions in the furnace.

By reducing the burner ratio, the amount of oxygen injected to the furnace beyond what is required for the complete combustion of the natural gas injected, known as free oxygen, would be increased.
3. Methodology

3.1 Outline Of Co-Steel Lasco Meltshop

The Co-Steel Lasco meltshop is comprised of a 1981 vintage EMPCO furnace, and was powered by a 93 MVA transformer during these burner ratio trials. The furnace is evacuated by a water cooled Direct Evacuation System (DES) and is tapped through Eccentric Bottom Taphole (EBT) into a ladle held in place by a ladle turret. Bulk alloying is done at tap, with trim alloys added at the ladle station.

3.2 Electric Arc Furnace

The furnace itself is refractory lined and has a water cooled shell above the slag line. The diameter of the furnace is approximately 6.3 m (20.6 feet), and is equipped with 71 cm (28 inch) diameter electrodes and current carrying arms. The average heat size is in the range of 123 to 125 t (136 to 138 t). A schematic of the furnace is included as Appendix 2 of this thesis. The furnace also has a water cooled roof and the entire assembly is on a hydraulically tilted platform. A porous plug, which injects nitrogen to increase bath mixing, is also located in the furnace bottom. Generally the flow through the plug is set at 0.06 Nm³/min (2 scfm), but is capable of a maximum of 0.14 Nm³/min (5 scfm).

3.3 Gas Injection Equipment

During the burner ratio trials, the Co-Steel Lasco EAF was equipped with a Badische Stahl Technologies (BST) lance manipulator, as well as three oxyfuel burners mounted on the furnace shell. A Beak burner was also mounted on the furnace shell, just above the EBT.
3.3.1 Lancing System

The furnace is outfitted with a two head lance manipulator supplied by BST. Oxygen is injected by two lances, one on each manipulator head and carbon is injected through another lance on the assembly. The maximum flow rate was approximately 40 Nm³/min (1400 scfm) of oxygen, per lance.

3.3.2 Burners

There are also three burners on the furnace shell. During the burner ratio trials experiments the burners were approximately 1.1 m (3.5 feet) above the slag line and were set at an angle of approximately 22° from the horizontal. A "protect mode", with settings of 3.7 Nm³/min (130 scfm) oxygen and 1.7 Nm³/min (60 scfm) natural gas for each burner, is used in order to keep the burners free of slag and steel when they are not required during the process. Maximum oxygen flow from each burner during these trials was approximately 13.6 Nm³/min (480 scfm).

3.3.2.1 Burner Operation

The burners are operated such that they will remain in a protect mode until approximately 2,000 kWh of electrical power has been supplied to the charge. At that point they go to a high flow rate, where they remain until the second charge is put into the furnace at approximately 19,000 kWh. At this point they are set to the protect mode. Following the second charge they are set to a high flow rate at approximately 21,000 kWh.

The endpoint of the burner program is determined by the control system based on the mass of the charge, but is generally in the range of 37,000 to 45,000 kWh. Once this endpoint is achieved, the burners are once again set to the protect mode, which ensures that sufficient flow is present to ensure that the burners do not become plugged by slag or bath particles.
3.3.2.2 Beak Burner

A burner is located just above the tap hole of the furnace, on the shelf made by the EBT. It is also variable and is operated at an oxygen to natural gas ratio of 2.1:1, with flows of approximately 1.4 Nm³/min (50 scfm) natural gas.

It is important to note that the operation of this burner was not modified during these trials.

3.4 Carbon Addition

Carbon is added to the furnace in a variety of ways at Co-Steel Lasco. A 907 kg (2000 lb.) bag of carbon was added to the first charge of each heat during the burner ratio trials. In addition, carbon is lanced into the furnace with the BST lancing mechanism using air as the carrier gas. The use of carbon during the refining phase of the heat was left to the discretion of the operator. Typically 225 to 270 kg (500 to 600 lbs.) were injected per heat.

3.5 Location Of Offgas Extraction Probe

The water-cooled offgas extraction probe on the Co-Steel Lasco furnace is located just downstream of the combustion gap, and is positioned such that it can draw a sample before dilution and post combustion effects take place. A schematic which shows the location of the probe is presented in Appendix 1.

3.6 Offgas Analysis System

The Co-Steel Lasco EAF is equipped with a permanent offgas analysis system, supplied by Goodfellow Technologies Inc.. This system, known as EFSOP™, was installed in June, 1995.
The offgas analysis system cabinet is located roughly 6 m (20 feet) from the probe on a platform next to the DES. Particulate is removed from the offgas sample using a number of filters, including primary filtration at the probe. Secondary filtration is done in the analyzer cabinet after water vapor is removed by condensation. The remaining sample volume then passes through an Infrared analysis cell which determines the concentration of carbon containing gases. The offgas sample then passes through another Infrared analysis cell which determines the concentration of CO in the sample. Following this step the concentration of H₂ is determined as the sample passes through an IR compensated thermal conductivity cell. The sample then passes through a cell where the concentration of O₂ is determined using paramagnetic principles.

3.7 Discreet Sampling

Discreet samples were taken using a remote controlled BST sampler. This equipment was used to take bath temperature measurements, as well as to capture bath samples for chemical analysis. Multiple samples of both temperature and chemistry are usually taken during each heat.

In addition, slag samples were taken from the Co-Steel Lasco Furnace upon which X-Ray Fluorescence Spectrometry Analysis (XRFS) and Powder X-Ray Diffraction Analysis (PXRD) was performed. XRFS analysis was performed to provide information on the elemental composition of the slag samples, while PXRD analysis provided information on what compounds were present in the slag samples.
3.8 Oxygen Supply

The oxygen was supplied to the plant by an on site BOC Gas air separation plant. During the burner ratio trials the plant was capable of supplying up to 127 t (140 t) per day at a purity of 92.0%.

3.9 This Study

As Co-Steel Lasco is oxygen limited, it is critical that the available oxygen is used to maximize efficiency and productivity, while minimizing production costs. This would be achieved by undertaking process modifications which would not only decrease the amount of chemical energy leaving the furnace, but also transfer as much of this energy as possible back into the charge.

Based on offgas profiles which were available, it was clear that large amounts of chemical energy, in the form of CO and H₂ gas, were exiting the furnace during the meltdown phases of the heat, just after cold scrap was charged to the furnace. As a result, during these periods, the charge was at a minimum temperature. During these periods electrical and chemical energy was being supplied to the furnace to increase the temperature of the scrap and eventually to melt the charge.

As both conditions, energy availability and heat transfer, were at their optimum at this point, it was decided that it was this period which would be targeted for process modifications. Ideally, additional oxygen would be supplied to the furnace using another source, such as oxygen injectors.

Realistically, no additional oxygen was available, and another oxygen source inside the furnace would require significant modifications to the furnace shell and the control system.
The reduction of the burner ratio did not involve the use of any additional oxygen, but rather a reduction in the amount of natural gas entering the furnace through the burners, and would result in an increase in the amount of free oxygen entering the furnace.

It was expected that this would lead to the increased combustion of the CO and \( \text{H}_2 \) gases, in better contact with cold scrap, resulting in a decrease in chemical energy exiting the furnace, and a high degree of heat transferred to the charge. These factors would combine to transfer significant amounts of energy to the charge which would yield an increase in productivity and a decrease in production costs.

Before the burner ratio trials, operators at Co-Steel Lasco had noted that chemical specifications are usually met before temperature specifications are satisfied. As a result, additional energy must often be added in order to increase the temperature of the bath once the aim chemistry of the heat has been achieved. It was expected that by promoting combustion and post combustion reactions in better contact with the scrap, sufficient energy would be transferred to more than compensate for the decrease in energy input as a result of the reduction in natural gas injection.

In the past, the burners had operated at a ratio of 3:1 oxygen to natural gas when the burners were at a high flow rate setting (flow of 13.6 Nm\(^3\)/min (480 scfm) \( \text{O}_2 \) and 4.5 Nm\(^3\)/min (160 scfm) natural gas, through each burner). In order to make as much free oxygen available as was possible, the burner ratio was changed to 8:1 which was the maximum oxygen flow coupled with the minimum natural gas flow (flow of 13.6 Nm\(^3\)/min (480 scfm) \( \text{O}_2 \) and 1.7 Nm\(^3\)/min (60 scfm) natural gas through each burner).
This study included the study of the furnace and its operation during two trials. The first was executed when the burners were at a 3:1 ratio and the second when the burners were set at an 8:1 ratio.
4. Results

4.1 Collected Data
Data was collected at Co-Steel Lasco from June 6, 1997 to June 25, 1997. In total 331 heats were tapped during this period.

The EFSOP™ system collected data from the meltshop computer system for over 80 parameters relating to the operation of the furnace and the ventilation system. A complete list of parameters, which were recorded every 20 seconds, is available in Appendix 3.

In addition, complete records of charge compositions, bath chemistry and temperature measurements were received from Co-Steel Lasco.

Periodic slag samples were taken from 38 heats by having the furnace operator tilt the furnace at 33,000 kWh such that a stream of slag would be poured from the furnace to the slag pit. About 50 grams of slag were collected during each of these heats.

4.1.1 Number Of Heats And Elimination Of Heats
Heats which were atypical with respect to the power program or scrap charge were purged from the test group. In addition, heats where certain pieces of equipment, such as the oxygen lances, burners or offgas analysis system were malfunctioning, were also purged. The first heats just after startup were deemed to be atypical and were purged from the data set as well.

Elimination of heats was done by manually inspecting the charge and process records from each individual heat and eliminating heats which were clearly atypical.
After this purging process 99 heats were left from the 3:1 burner ratio trial and 122 heats were left from the 8:1 burner ratio trial. As there had been 331 heats tapped during this period, the 221 heats used represent approximately 66.8% of the total heats tapped.

4.1.2 Averaging And Normalization Process

The EAF steelmaking process is mostly controlled on the basis of electrical energy input into the furnace. As such, much of the operating data collected, such as offgas analysis, Total Harmonic Distortion and gas flows was normalized on a “kWh into heat” basis.

The normalization process contains a number of steps. The first consists of calculating the kWh settings for landmarks during the process. In this case, two landmarks were selected: the power off during the second charge to the furnace, and the end of the heat. The average values for each landmark in both the 3:1 and the 8:1 burner ratio trials were calculated. The second step involves the assignment of kWh settings at each data point in a fictional “average heat”. In this case 200 data points were used for the entire heat. Values at each interval are then matched to each of the 200 points such that each data point is at the same point relative to the landmarks. An average, and standard error, is then calculated at each “kWh into heat” value.

The graphs presented in the following sections are the normalized average values for each component measured, on a dry volume basis.
4.1.3 Statistical Analysis

Statistical analysis was conducted on the collected data. Two types of analysis were performed: Multiple Linear Regression and Two Tailed t-test.

4.1.3.1 Linear Regression

Temperature and Dissolved carbon concentration data was analyzed using regression analysis, including 95% confidence interval calculation\textsuperscript{15,16}. A number of different regression models were employed to determine which would provide the best fit, represented by the maximum $R^2$ value. In all cases, the $R^2$ values were equally unspectacular. As a result, the linear model was presented in the results of this thesis. The $R^2$ figure indicates how closely the line of best fit approximates the data set (a perfect approximation would result in an $R^2$ value of 1.0).

In the case of linear regression, the line of best fit is of the form:

\[ y = mx + b \quad \text{Eq.7} \]

where, $y$ is a dependent variable

$m$ is the slope of the line

$x$ is the independent variable

and, $b$ is a constant

Approximations for $m$ and $b$, as well as their 95% confidence interval values were calculated and are presented in each case.

4.1.3.2 Two tailed t-test

This statistical test is designed to determine how much of the variation in the measurements arose from differences between data sets and how much came
from variation within data sets\textsuperscript{15,16}. Using the mean, the standard deviation and
the sample size, this test determines if the differences between two data sets are
statistically significant. The formula for the extended t-test, used for two groups
of unequal sample size, is presented as Equation 8 below.

\[
t = \frac{(\bar{X}_1 - \bar{X}_2)}{\sqrt{\frac{(n_1-1)s_1^2 + (n_2-1)s_2^2}{n_1 + n_2 - 2} \left( \frac{1}{n_1} + \frac{1}{n_2} \right)}}
\]

\text{Eq. 8}

where,
- \(t\) is the \textit{t value}
- \(\bar{X}_1\) is the mean of data set 1
- \(\bar{X}_2\) is the mean of data set 2
- \(n_1\) is the sample size of data set 1
- \(n_2\) is the sample size of data set 2
- \(s_1\) is the standard deviation of data set 1
- \(s_2\) is the standard deviation of data set 2

Following the calculation of \(t\), it is checked against values published as a function
of confidence interval and degrees of freedom. If the value of \(t\) is greater, in
absolute terms, than the published value, the difference between the data sets is
statistically significant. In this thesis, all tests were compared against values for
two tailed t-tests, at 95\% confidence intervals.

4.2 Gas Injection

Gas is injected into the Co-Steel Lasco EAF through burners mounted on the
furnace shell and lances which enter the furnace through the slag door. The
effect of modifying the burner ratio can most clearly be seen in Figures 4.1 to
4.5.

4.2.1 Burner Operation

The effect of changing the burner ratio from 3:1 to 8:1 was done by decreasing
the amount of natural gas flow to the burners. The burner profiles are presented
in the following sections.
4.2.1.1 Burners

Comparison of Figure 4.1 to Figure 4.2 shows how the oxygen flow through the burners remained unchanged while the natural gas flow was decreased from approximately 15.0 Nm³/min (530 scfm), during high flow periods of the 3:1 burner ratio trials, to approximately 6.5 Nm³/min (230 scfm) during the corresponding periods of the 8:1 burner ratio trials.

The normalized burner profile from the 3:1 Burner Ratio trial is presented in Figure 4.1 below.

![Burner Profile Graph](image)

Figure 4.1, Normalized burner profile at a 3:1 Burner Ratio.
The normalized burner profile from the 8:1 Burner Ratio trial is presented in Figure 4.2 below.

![Normalized burner profile at a 8:1 Burner Ratio](image)

**Figure 4.2**, Normalized burner profile at a 8:1 Burner Ratio.

4.2.1.2 Burner Ratio

Figure 4.3 shows the burner ratio profiles during the two trials. It is important to note that the ratios do not appear as exactly 8:1 or 3:1 because the Beak burner is also included in this calculation. The Beak burner was unaffected by the change in burner ratios, and operated at a ratio of 2.1:1 throughout both trials.
The normalized burner ratio profile is presented in Figure 4.3 below.

![Normalized burner ratio profile](image)

**Figure 4.3**, Normalized burner ratio profiles for both burner ratio trials.

### 4.2.2 Lancing

Figure 4.4 illustrates the lance operating profiles and how they remained virtually unchanged throughout both trials. During the meltdown periods of the heat the lances are at a maximum flow of approximately 39.7 Nm³/min (1400 scfm) each. During the refining phase the lance is used to de-carburize the bath and to maintain a foamy slag. During this period, the use of the lance is generally left to the discretion of the operator.
The normalized oxygen lance profile is presented in Figure 4.4 below.

![Normalized oxygen lance profile](image)

**Figure 4.4**, Normalized oxygen lance profile for both burner ratio trials.

### 4.2.3 Free Oxygen Flow

Figure 4.5 shows the free oxygen profiles for both burner ratio trials. The effect of changing the burner ratio resulted in an increase of approximately 17.0 Nm³/min (600 scfm) during peak free oxygen flow periods. This figure also clearly shows that these periods occurred during the meltdown periods of the heats.
The normalized free oxygen profile for both trials is presented in Figure 4.5 below.

![Normalized free oxygen profile](image)

**Figure 4.5**, Normalized free oxygen flow for both burner ratio trials.
4.3 Offgas Analysis
The normalized offgas profile for the 3:1 burner ratio trial is presented in Figure 4.6 below.

![Graph showing offgas profile](image)

**Figure 4.6**, Normalized offgas profile for the 3:1 burner ratio trial.
The normalized offgas profile for the 8:1 burner ratio trial is presented in Figure 4.7 below.

![Graph showing normalized offgas profile](image)

**Figure 4.7**, Normalized offgas profile for the 8:1 burner ratio trial.

### 4.3.1 CO Gas Profile

Figure 4.8 indicates that a significant difference in CO levels were recorded during the meltdown periods. These differences are most pronounced during the meltdown phases (between 0 and 30,000 kWh) with a difference of up to 3.0% recorded a number of times. During the refining phase of the heat the CO levels are virtually identical for both trials.
The normalized CO offgas concentration profile for both burner ratio trials is presented in Figure 4.8 below.

![Normalized CO offgas concentration profile for both burner ratio trials](image)

**Figure 4.8**, Normalized CO offgas concentration profile for both burner ratio trials.

### 4.3.2 CO₂ Gas Profile

Figure 4.9 indicates that approximately 2% more CO₂ gas was measured during the first meltdown phase of the heat of the 8:1 burner ratio trial, while the CO₂ levels recorded during the second meltdown phases were very similar. Figure 4.9 also indicates that during the 8:1 burner ratio trials, the CO₂ levels during the refining phase of the heat (from 35,000 kWh to the end of the heat) were slightly higher, with differences of up to 2% recorded.
The normalized CO₂ offgas concentration profile for both burner ratio trials is presented in Figure 4.9 below.

Figure 4.9, Normalized CO₂ offgas concentration profile for both burner ratio trials.
4.3.3 O$_2$ Gas Profile

The normalized O$_2$ offgas concentration profile for both burner ratio trials is presented in Figure 4.10 below.

![Graph showing normalized O$_2$ offgas concentration profile for both burner ratio trials](image)

**Figure 4.10**, Normalized O$_2$ offgas concentration profile for both burner ratio trials.

4.3.4 H$_2$ Gas Profile

Figure 4.11 indicates that the offgas profiles of H$_2$ gas are very similar to those of CO. H$_2$ and CO often follow very similar profiles, as both are reducing gases and are indicative of an oxygen starved furnace. Significant differences were observed during both meltdown phases (up to approximately 30,000 kWh) with difference up to 3.0%. During the refining phases of the heat, the H$_2$ levels recorded during the 8:1 burner trials were slightly lower than those recorded during the 3:1 burner trials.
The normalized \( \text{H}_2 \) offgas concentration profile both burner ratio trials is presented in Figure 4.11 below.

![Normalized \( \text{H}_2 \) offgas concentration profile for both burner ratio trials.](image)

**Figure 4.11**, Normalized \( \text{H}_2 \) offgas concentration profile for both burner ratio trials.

### 4.3.5 Total Carbon Containing Gases Profile

Although Figure 4.12 indicates that the total carbon containing gas profiles of the two trials were very similar, it is clear that higher levels were consistently measured during the 8:1 burner ratio trials. These differences were most pronounced during the meltdown phases, although some difference also exist during the refining phase.
The normalized total carbon containing offgas concentration profile for both burner ratio trials is presented in Figure 4.12 below.

![Normalized total carbon containing offgas concentration profile](image)

**Figure 4.12**, Normalized total carbon containing offgas concentration profile for both burner ratio trials.

### 4.3.6 Post Combustion Ratio (PCR)

The Post Combustion Ratio (PCR) is indicative of how oxidized the offgases are. It is defined by the following equation:

\[
PCR = \frac{\%CO_2 \text{ Conc.}}{\%CO_2 \text{ Conc.} + \%CO \text{ Conc.}}
\]

Eq. 9

The PCR profiles presented in Figure 4.13 indicate that during the 8:1 burner trial lower PCR values were recorded. These decreases were particularly pronounced during the meltdown phases with decreases up to 12% observed.
During the refining phases, the PCR was slightly higher in the case of the 8:1 burner trial. These differences exist despite the fact that the amount of free oxygen was increased, which should have increased the PCR values.

The normalized Post Combustion Ratio (PCR) profile for both burner ratio trials is presented in Figure 4.13 below.

![Normalized Post Combustion Ratio (PCR) profile for both burner ratio trials.](image)

**Figure 4.13**, Normalized Post Combustion Ratio (PCR) profile for both burner ratio trials.

4.3.7 \( \text{N}_2 \) Gas Profile

It is generally accepted that what is not \( \text{CO}, \ \text{CO}_2, \ \text{O}_2 \) or \( \text{H}_2 \) in the offgas is \( \text{N}_2 \) gas, on a dry basis. By summing the values for the components shown above and subtracting this value from 100%, the concentration of \( \text{N}_2 \) can be calculated.
The normalized N₂ offgas concentration profile for both burner ratio trials is presented in Figure 4.14 below.

![Normalized N₂ offgas concentration profile](image)

**Figure 4.14**, Normalized N₂ offgas concentration profile for both burner ratio trials.

4.4 Periodic Samples
Data was obtained from Co-Steel Lasco regarding periodic measurements of Bath Temperature and Bath Chemistry. In addition, slag samples were analyzed by X-Ray Fluorescence Spectrometry (XRFS) and Powder X-Ray Diffraction (PXRD).
4.4.1 Bath Temperature Measurements

Multiple bath temperature measurements were taken during each heat by the furnace operators, using the remote controlled BST sampler. These measurements were taken during the refining phase of the heat, between 42,000 and 60,000 kWh.

Comparison of Figure 4.15 to Figure 4.16 indicates that bath temperature measurements were higher during the 8:1 burner ratio trial. Data indicating that the difference between the two data sets is statistically significant is presented in Table 4.1.
4.4.1.1 3:1 Burner Ratio

The results of periodic temperature measurements taken during the 3:1 burner ratio trials, are presented in Figure 4.15 below.

![Figure 4.15](attachment:image.png)

Figure 4.15, Temperature vs. kWh into heat measurements for 3:1 burner ratio trials, including line of best fit.
4.4.1.2 8:1 Burner Ratio

The results of periodic temperature measurements taken during the 8:1 burner ratio trials, are presented in Figure 4.16 below.

![Graph showing temperature vs. kWh into heat measurements for 8:1 burner ratio trials, including line of best fit.]

Figure 4.16, Temperature vs. kWh into heat measurements for 8:1 burner ratio trials, including line of best fit.

4.4.1.3 Statistical Analysis

The statistical analysis of the temperature vs. kWh into heat measurements for the burner ratio trials is presented in Table 4.1 below.
Table 4.1, Statistical Analysis results for Temperature vs. kWh into heat data.

<table>
<thead>
<tr>
<th>Burner Ratio</th>
<th>( m )</th>
<th>95% Confidence Interval for ( m )</th>
<th>( b )</th>
<th>95% Confidence Interval for ( b )</th>
<th>( R^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>3:1</td>
<td>0.005974</td>
<td>0.003382 0.008565</td>
<td>2597.61</td>
<td>2461.24 2733.99</td>
<td>0.18388</td>
</tr>
<tr>
<td>8:1</td>
<td>0.012308</td>
<td>0.009836 0.014780</td>
<td>2310.35</td>
<td>2185.55 2435.15</td>
<td>0.45387</td>
</tr>
</tbody>
</table>

As neither \( m \) nor \( b \) from either case is included in the confidence interval of the other, the difference between the lines is statistically significant. It is important to note that the \( R^2 \) values for each approximation are considerably lower than what is normally acceptable. This indicates that at least one other factor, other than the kWh into heat, influenced temperature measurements. As such, this data suggests that a difference exists, but does not definitively prove it.

4.4.2 Bath Chemistry Measurements

Bath chemistry measurements were taken during each heat, using the remote controlled BST sampler.

Figures 4.17 and 4.18, and the supporting statistical data presented in Table 4.2 indicate that the difference in bath dissolved carbon concentrations is not statistically significant.
4.4.2.1 3:1 Burner Ratio

The results of periodic dissolved carbon concentration measurements, taken during the 3:1 burner ratio trial, are presented in Figure 4.17 below.

![Dissolved carbon concentration vs. kWh into heat measurements for 3:1 burner ratio trial, including line of best fit.](image)

**Figure 4.17,** Dissolved carbon concentration vs. kWh into heat measurements for 3:1 burner ratio trial, including line of best fit.
4.4.2.2 8:1 Burner Ratio

The results of periodic dissolved carbon concentration measurements, taken during the 8:1 burner ratio trial, are presented in Figure 4.18 below.

![Graph showing dissolved carbon concentration vs. kWh into heat measurements for 8:1 burner ratio trial, including line of best fit.]

**Figure 4.18**, Dissolved carbon concentration vs. kWh into heat measurements for 8:1 burner ratio trial, including line of best fit.

4.4.2.3 Statistical Analysis

The statistical analysis of the dissolved carbon concentration vs. kWh into heat measurements for the burner ratio trials is presented in Table 4.2 below.
Table 4.2, Statistical Analysis results for dissolved carbon concentration vs. kWh into heat data.

<table>
<thead>
<tr>
<th>Burner Ratio</th>
<th>95% Confidence Interval for m</th>
<th>b</th>
<th>95% Confidence Interval for b</th>
<th>R²</th>
</tr>
</thead>
<tbody>
<tr>
<td>3:1</td>
<td>-2.982E-6 1.36615E-6</td>
<td>0.289924</td>
<td>0.070656 0.509191</td>
<td>0.02461</td>
</tr>
<tr>
<td>8:1</td>
<td>-2.03208E-7 2.65688E-6</td>
<td>0.133640</td>
<td>-0.004717 0.271997</td>
<td>0.00020</td>
</tr>
</tbody>
</table>

As both m and b from either case are included in the confidence interval of the other, the difference between the lines is not statistically significant. However, due to the low R² values, no significant conclusion can be drawn based on this analysis.

4.4.3 Slag Analysis

The results of the slag analysis, presented in Table 4.3, indicate that no significant differences existed between slag samples taken from each burner ratio trial. In terms of the elemental analysis by XRFS, statistical analysis, also presented in Table 4.3, indicates that the levels of Al and Ca differed between the two trials. PXRD analysis indicated that the slag samples contained very complex oxide formations. Although not totally oxidized, all samples indicated high levels of oxidation and no free Fe whatsoever.

XRFS analysis was conducted on slag samples from 38 heats. In addition, 6 samples were analyzed by PXRD.
4.4.3.1 X-Ray Fluorescence Spectrometry Analysis (XRFS)

Fluorescence Spectrometry Analysis (XRFS) was performed to determine what, if any, differences existed in the elemental composition of the slag samples from each burner ratio trial. Information about XRFS sample preparation is provided in Appendix 4.

Results from the XRFS analysis are presented in Table 4.3 below.

Table 4.3, Results of slag elemental analysis using XRFS, including statistical analysis.

<table>
<thead>
<tr>
<th></th>
<th>Al</th>
<th>Ca</th>
<th>Cr</th>
<th>Fe</th>
<th>K</th>
</tr>
</thead>
<tbody>
<tr>
<td>3:1</td>
<td>3.01</td>
<td>25.15</td>
<td>1.38</td>
<td>24.28</td>
<td>0.07</td>
</tr>
<tr>
<td>8:1</td>
<td>3.61</td>
<td>21.55</td>
<td>1.40</td>
<td>25.54</td>
<td>0.06</td>
</tr>
<tr>
<td>Delta</td>
<td>0.60</td>
<td>-3.60</td>
<td>0.02</td>
<td>1.27</td>
<td>-0.01</td>
</tr>
</tbody>
</table>

*two tailed test at .05 level*  
t(38)=2.03  
t(38)=2.03  
t(38)= 2.03  
t(38)= 2.03  
t(29)= 2.05  
t  
<table>
<thead>
<tr>
<th></th>
<th>Al</th>
<th>Ca</th>
<th>Cr</th>
<th>Fe</th>
<th>K</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mg</td>
<td>2.05</td>
<td>3.50</td>
<td>0.32</td>
<td>4.61</td>
<td>0.23</td>
</tr>
<tr>
<td>Mn</td>
<td>2.23</td>
<td>3.84</td>
<td>0.25</td>
<td>5.31</td>
<td>0.26</td>
</tr>
<tr>
<td>Delta</td>
<td>0.18</td>
<td>0.34</td>
<td>-0.07</td>
<td>0.70</td>
<td>0.03</td>
</tr>
</tbody>
</table>

*two tailed test at .05 level*  
t(38)=2.03  
t(38)=2.03  
t(29)= 2.05  
t(38)= 2.03  
t(38)= 2.03  
t  
<table>
<thead>
<tr>
<th></th>
<th>Mg</th>
<th>Mn</th>
<th>Na</th>
<th>Si</th>
<th>Ti</th>
</tr>
</thead>
<tbody>
<tr>
<td>3:1</td>
<td>2.05</td>
<td>3.50</td>
<td>0.32</td>
<td>4.61</td>
<td>0.23</td>
</tr>
<tr>
<td>8:1</td>
<td>2.23</td>
<td>3.84</td>
<td>0.25</td>
<td>5.31</td>
<td>0.26</td>
</tr>
<tr>
<td>Delta</td>
<td>0.18</td>
<td>0.34</td>
<td>-0.07</td>
<td>0.70</td>
<td>0.03</td>
</tr>
</tbody>
</table>

Table 4.3 (continued), Result of slag elemental analysis using XRFS, including statistical analysis.

The last two rows refer to statistical *t-test analysis* which was conducted on these data sets. If the value of *t* is higher, in absolute terms, than the value
listed above it for "two tailed test at .05 level", the difference is statistically significant. This analysis indicates that a statistically significant difference was observed in the concentrations of Al and Ca between the two burner ratio trials.

4.4.3.2 Powder X-Ray Diffraction Analysis (PXRD)

Several samples were analyzed by Powder X-Ray Diffraction (PXRD). The analysis report is submitted as Appendix 5 of this report.

Samples 21611, 21613, 21848 and 21857 are slag samples which were crushed and analyzed using PXRD.

Samples 21613-A and 21848-A and were also analyzed using PXRD but were crushed and then put into an oxidizing furnace for 2 hours at 1000 °C (1832 F), similar to the samples prepared for XRFS analysis.

Generally, the results indicate that the slag samples contain very complex oxide formations containing Fe, Ca, Si and Mg. In addition, no unoxidized Fe was found in the samples.

4.5 Operating Data

4.5.1 Gas Consumption

Comparison of the gas consumption figures, presented in Tables 4.4 and 4.5, indicates that the modification of the burner ratio to 8:1 led to a statistically significant decrease in natural gas consumption from 761 Nm³ or 6.1 Nm³/te (26,846 scf or 194.5 scf/te) to 432 Nm³ or 3.5 Nm³/te (15,248 scf or 111.5 scf/te). This represents a 42.7% reduction in natural gas consumption, on a per ton basis. Although not exactly the same, the volume of Burner Oxygen, Lanced Oxygen and Total Oxygen consumed during each trial remained effectively
unchanged. As a result of the decrease in natural gas consumption, an increase in free oxygen consumption from 3,507 Nm³ or 28 Nm³/te (123,787 scf or 897.0 scft) to 4,139 Nm³ or 33.7 Nm³/te (146,120 scf or 1068.5 scft), was observed. This increase of 633 Nm³ or 5.4 Nm³/te (22,333 scf or 170.46 scft) represents an 19.1% increase in free oxygen consumption, on a per ton basis.

The average gas consumption figures on a heat wise, and on a per ton basis, are presented below in Tables 4-4 and 4-5, respectively.

Table 4.4, Average gas consumption, on a per heat basis, for both Burner Trials.

<table>
<thead>
<tr>
<th>Burner Ratio</th>
<th>Natural Gas (Nm³)</th>
<th>Burner Oxygen (Nm³)</th>
<th>Lanced Oxygen (Nm³)</th>
<th>Total Oxygen (Nm³)</th>
<th>Total Free Oxygen (Nm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3:1</td>
<td>761 (26,846)</td>
<td>2,075 (73,243)</td>
<td>2,953 (104,236)</td>
<td>5,028 (177,479)</td>
<td>3,507 (123,787)</td>
</tr>
<tr>
<td>8:1</td>
<td>432 (15,248)</td>
<td>2,019 (71,280)</td>
<td>2,984 (105,336)</td>
<td>5,003 (176,616)</td>
<td>4,139 (146,120)</td>
</tr>
<tr>
<td>Delta</td>
<td>-329 (-11,598)</td>
<td>-56 (-1,963)</td>
<td>31 (1,100)</td>
<td>25 (863)</td>
<td>633 (22,333)</td>
</tr>
<tr>
<td>two tailed test at .05 level</td>
<td>(t(213)=1.98)</td>
<td>(t(213)=1.98)</td>
<td>(t(213)=1.98)</td>
<td>(t(213)=1.98)</td>
<td>(t(213)=1.98)</td>
</tr>
<tr>
<td>(t)</td>
<td>52.83</td>
<td>2.44</td>
<td>-0.87</td>
<td>0.68</td>
<td>-16.14</td>
</tr>
</tbody>
</table>

The statistical analysis indicates that the differences in Natural Gas, Burner Oxygen and Total Free Oxygen between the two burner trials are statistically significant.
Table 4.5, Average gas consumption, on a per ton basis, for both Burner Trials.

<table>
<thead>
<tr>
<th>Burner Ratio</th>
<th>Natural Gas Nm³/te (scf/t)</th>
<th>Burner Oxygen Nm³/te (scf/t)</th>
<th>Lanced Oxygen Nm³/te (scf/t)</th>
<th>Total Oxygen Nm³/te (scf/t)</th>
<th>Total Free Oxygen Nm³/te (scf/t)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3:1</td>
<td>6.1 (194.54)</td>
<td>16.7 (530.75)</td>
<td>23.8 (755.33)</td>
<td>40.5 (1,286.08)</td>
<td>28.3 (897.00)</td>
</tr>
<tr>
<td>8:1</td>
<td>3.5 (111.51)</td>
<td>16.4 (521.24)</td>
<td>24.3 (770.28)</td>
<td>40.7 (1,291.52)</td>
<td>33.7 (1,068.52)</td>
</tr>
<tr>
<td>Delta</td>
<td>-2.6 (-83.03)</td>
<td>-0.3 (-9.51)</td>
<td>0.5 (14.95)</td>
<td>0.2 (5.44)</td>
<td>5.4 (171.52)</td>
</tr>
</tbody>
</table>

The statistical analysis indicates that the difference in Natural Gas and Total Free Oxygen between the two burner trials is statistically significant.

4.5.2 Total Harmonic Distortion (THD)

Comparison of THD profiles from each trial, presented in Figure 4.19, indicates that a minimum value was reached at a lower "kWh into the heat" value during the 8:1 burner ratio trial. This indicates that flat bath conditions were achieved at a lower electrical energy consumption value.
The normalized profile for Total Harmonic Distortion (THD) for both burner ratios is presented in Figure 4.19 below.

![Normalized THD profile](image)

**Figure 4.19**, Normalized THD profile for both burner ratios.

Statistical analysis of the interval from 32,000 kWh to 37,750 kWh indicates that the THD profile from the 8:1 burner ratio trial is lower, and that the difference is statistically significant.

### 4.5.3 Electrode Consumption

Figure 4.20 indicates that Electrode Consumption remained at acceptable levels throughout the burner ratio trials. This figure suggests that this parameter was unaffected by the burner ratio trials.
Monthly electrode consumption figures are presented in Figure 4.20 below.

Figure 4.20, Monthly Electrode Consumption figures, including month of June, 1997 when burner ratio trials were conducted.

The monthly electrode consumption figures are based on shipments of electrodes arriving at Co-Steel Lasco during each month. As such, the degree of variation shown in Figure 4.20 is well within acceptable levels.

4.5.4 Yield

Figure 4.21 indicates that Yield remained at acceptable levels throughout the burner ratio trials. This figure suggests that this parameter was unaffected by the burner ratio trials.
Yield figures, as "Percent of Target Yield", are presented in Figure 4.20 below.

![Figure 4.20: Percent of Target Yield](image)

**Figure 4.21, Monthly yield figures, including month of June, 1997 when burner ratio trials were conducted.**

Percent of Target Yield is presented in Figure 4.21 as the exact figures are of a confidential nature, and are not released by Co-Steel Lasco.

**4.5.5 Electrical Energy Consumption**

Comparison of the electrical energy consumption figures, presented in Table 4.6, indicate that a statistically significant decrease in Total Electrical Energy Consumption, from 56,095 kWh or 448.06 kWh/te (406.48 kWh/t) to 53,389 kWh or 430.35 kWh/te (390.41 kWh/t), was observed during the 8:1 burner ratio trial. This decrease of 2,706 kWh or 17.72 kWh/te (16.07 kWh/t) represents a decrease of 4.0%, on a per ton basis.
The average Electrical Energy Consumption on a heat wise, as well as on a per ton basis, was calculated for each burner ratio trial. This data is presented in Table 4.6 below.

Table 4.6. Energy consumption results for both Burner Trials.

<table>
<thead>
<tr>
<th>Burner Ratio</th>
<th>Electrical Energy Consumption</th>
<th>Specific Electrical Energy Consumption</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>kWh</td>
<td>kWh/te</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(kWh/te)</td>
</tr>
<tr>
<td>3:1</td>
<td>56,095</td>
<td>448.06</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(406.48)</td>
</tr>
<tr>
<td>8:1</td>
<td>53,389</td>
<td>430.35</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(390.41)</td>
</tr>
<tr>
<td>Delta</td>
<td>2,706</td>
<td>17.72</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(16.07)</td>
</tr>
<tr>
<td>two tailed test at .05 level</td>
<td>t(219)=1.98</td>
<td>t(219)=1.98</td>
</tr>
<tr>
<td>t</td>
<td>7.54</td>
<td>6.16</td>
</tr>
</tbody>
</table>

The statistical analysis, presented on the last two lines of Table 4.6, indicates that the difference in electrical energy consumption, on a heat wise basis, as well as on a per ton basis, between the two burner trials is statistically significant.

4.5.6 Power On Time And Tap To Tap Time

Comparison of the Power On Time and Tap to Tap Time figures, presented in Table 4.7, indicate that statistically significant decreases were observed for both. During the 3:1 burner ratio trial, the Power On Time was 00:56:17 and the Tap to Tap Time was 01:12:20. During the 8:1 burner ratio trials the Power On Time was 00:53:17 and the Tap to Tap Time was 01:09:04. The statistically significant decrease of 00:02:47 for Power On Time represents a decrease of 5.0%, while
the statistically significant decrease of 00:03:15 in Tap to Tap Time represents a reduction of 4.5%.

The average Power on Time and Tap to Tap Time was calculated for each burner ratio trial and is presented in Table 4.7 below.

### Table 4.7, Power on and Tap to Tap time results for both burner ratio trials.

<table>
<thead>
<tr>
<th>Burner Ratio</th>
<th>Power on Time</th>
<th>Tap To Tap Time</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>hh:mm:ss</td>
<td>hh:mm:ss</td>
</tr>
<tr>
<td>3:1</td>
<td>0:56:17</td>
<td>1:12:20</td>
</tr>
<tr>
<td>8:1</td>
<td>0:53:30</td>
<td>1:09:04</td>
</tr>
<tr>
<td>Delta</td>
<td>0:02:47</td>
<td>0:03:15</td>
</tr>
<tr>
<td><strong>two tailed test at .05 level</strong></td>
<td>t(219)=1.98</td>
<td>t(219)=1.98</td>
</tr>
<tr>
<td>t</td>
<td>7.00</td>
<td>3.91</td>
</tr>
</tbody>
</table>

The statistical analysis, presented on the last two lines of Table 4.7, indicates that the difference in Power On Time and Tap to Tap Time between the two burner trials is statistically significant.

### 4.6 Observations

Furnace operators remarked that less scrap was “hanging up” on the furnace shell, leading to a decrease in “cave ins” during the 8:1 burner ratio trials. This led to a slightly smoother operation of the furnace during this trial.
5. Discussion

5.1 General

The primary objective of this study was to modify the oxygen injection practice in order to decrease Specific Electrical Energy Consumption and Power On Time. This was accomplished by modifying the burner ratio such that additional free oxygen was available for the combustion of CO and H₂ gases in the furnace shell.

The results presented in the previous section show that statistically significant decreases were observed in the Specific Electrical Energy Consumption and Power On Time between the two trials. These results are summarized in Table 5.1 below:

<table>
<thead>
<tr>
<th>Burner Ratio</th>
<th>Specific Electrical Energy Consumption kWh/te (kWh/t)</th>
<th>Power on Time mm:ss</th>
</tr>
</thead>
<tbody>
<tr>
<td>3:1</td>
<td>448.06 (406.48)</td>
<td>56:17</td>
</tr>
<tr>
<td>8:1</td>
<td>430.35 (390.41)</td>
<td>53:30</td>
</tr>
<tr>
<td>Delta</td>
<td>17.71 (16.07)</td>
<td>2:47</td>
</tr>
</tbody>
</table>

Table 5.1, Specific Electrical Energy Consumption and Power on Time for both burner ratio trials, including statistical analysis results.

<table>
<thead>
<tr>
<th>two tailed test at .05 level</th>
<th>t(219)=1.98</th>
<th>t(219)=1.98</th>
</tr>
</thead>
<tbody>
<tr>
<td>t</td>
<td>6.16</td>
<td>7.00</td>
</tr>
</tbody>
</table>
The results of statistical analysis, shown in the last 2 rows of Table 5.1 indicate that the differences between the two burner ratio trials is statistically significant with respect to Specific Electrical Energy Consumption and Power On Time.

The reasons that these savings had been realized are very complex and are the result of a number of factors. Although two separate figures appear, it is important to note these figures are not unrelated.

The reason that the Specific Electrical Energy Consumption is lower in the 8:1 burner ratio trial is because electrical power was being supplied for a shorter period of time, i.e. Specific Electrical Energy Consumption for the 8:1 burner ratio trial is lower because the Power on Time was shorter. No modifications were made in the way that the electrical energy was supplied to the furnace (Active Power and Power Factor profiles are presented in Appendix 6). A clear understanding of this concept is critical to understanding the results of this study.

The reason the heats were ended after consuming less electrical energy, in the case of the 8:1 burner ratio trials, is because the appropriate temperature and chemical characteristics had been achieved after less electrical energy was consumed. In other words, during the 8:1 burner trials, the same endpoints were reached, in terms of bath temperature and chemistry, while less electrical energy was used.

A comparison of the measurements taken during the two burner ratio trials is presented in the following sections.

5.1.1 Gas Injection

Data relating to gas injection into the furnace was recorded in order to determine the effect of the burner ratio modification on the free oxygen flow to the furnace.
This would provide qualitative data relating to how much oxygen was made available for combustion reactions inside the furnace shell.

Figures 4.1 to 4.5 show the flow of various oxygen and natural gas sources into the furnace. As a result of the burner ratio modification, natural gas consumption was decreased from 761 Nm$^3$ or 6.1 Nm$^3$/te (26,846 scf or 194.54 scf/t) to 432 Nm$^3$ or 3.5 Nm$^3$/te (15,248 scf or 111.51 scf/t), while free oxygen consumption was increased from 3,507 Nm$^3$ or 28.3 Nm$^3$/te (123,787 scf or 897.00 scf/t) to 4,139 Nm$^3$ or 33.7 Nm$^3$/te (146,120 scf or 1068.52 scf/t). These figures represent a 42.7% reduction in natural gas consumption, and a 19.1% increase in free oxygen consumption, on a per ton basis.

The gas injection data clearly shows that as a result of the burner ratio modification, more oxygen was made available to react with CO and H$_2$ gases generated during the EAF steelmaking process.

5.1.2 Offgas Analysis

Offgas analysis was conducted during the burner ratio trials to monitor the expected decrease in chemical energy exiting the furnace as a result of the increase in free oxygen flow. In addition, offgas analysis would provide data relating to air inleakage patterns, which are indicative of furnace pressure.

The results of offgas analysis indicate that CO, H$_2$ and CO$_2$ concentrations were higher during certain periods of the 8:1 burner ratio trials. The fact that these differences are most pronounced during the meltdown phases of the heats suggests that a higher level of hydrocarbons, in the form of fluff, was present in the scrap fed to the furnace. This is corroborated by the fact that lower PCR values were observed, whereas an increase was expected as a result of the increase in free oxygen feed to the furnace. An increase in scrap hydrocarbons
levels could have a significant impact on many of the furnace operating parameters as these hydrocarbons will act as a fuel source, and their proximity to cold scrap will lead to higher heat transfer rates.

The fact that N₂ concentrations were generally lower, especially during the meltdown phases of the heat, suggest that a change in furnace pressure was observed. This was likely the result of the increase in scrap hydrocarbons levels. A change in furnace pressure could also have a significant impact on many of the furnace operating parameters as it has a large effect on the amount of air inleakage into the furnace.

5.1.3 Periodic Sampling

Sampling of the bath and slag was conducted to monitor the effect of the burner ratio modification on the bath and slag chemistry and temperature. It was expected that the modification of the burner ratio would result in an increase in bath temperatures, and a decrease in bath dissolved carbon concentrations. It was important to ensure that any process improvements did not come at the expense of iron units.

In terms of temperature, it was expected that an increase in bath temperatures would be observed as a result of the burner ratio modification. It was expected that the resulting increase in free oxygen flow to the furnace would lead to combustion and post combustion reactions in closer proximity to the cold scrap, leading to better heat transfer conditions and a resulting increase in heat transferred to the charge. Linear Regression Analysis of bath temperature measurements suggests that an increase in bath temperatures was observed.

It was also expected that as a result of the increase in combustion of charged carbon hung up in the scrap pile, a lower concentration of dissolved carbon
would be observed during the 8:1 burner ratio trials. Statistical analysis of the dissolved carbon measurements during these trials was inconclusive. It is therefore assumed that no difference is dissolved carbon concentrations was observed.

These facts, combined with the offgas analysis results lends credence to the theory that an increased level of scrap hydrocarbons was present in the scrap used during the 8:1 burner ratio trials. The combustion of these hydrocarbons in close proximity of the cold scrap during the meltdown phases would result in an increased amount of energy being available to the charge, as well as very favorable heat transfer conditions.

Slag analysis by XRFS and PXRD was conducted to monitor the effect of the increased burner ratio on the chemistry and oxidation level of the slag. The results of the XRFS analysis indicates that statistically significant differences were observed only with respect to Al and Ca concentrations in the slag. Although very interesting, these results are beyond the scope of this study. The primary objective of the PXRD analysis was to ensure that no free Fe was contained in the samples. Results of PXRD analysis indicated that no free Fe was contained in any of the samples, and that the slag samples are composed of a number of very complex, oxidized compounds.

5.1.4 Operating Data
Operating data was recorded in order to quantify the differences between the two burner ratio trials, and to monitor the effect of the burner ratio modification on electrode consumption and yield. THD was also tracked to determine if flat bath conditions were reached at a lower “kWh into heat” value during the 8:1 burner ratio trials.
These results indicate that the modification of the burner ratio resulted in a statistically significant decrease in Natural Gas Consumption and a statistically significant increase in Free Oxygen Consumption, as expected.

As no significant differences were observed with respect to electrode consumption and yield, it is clear that the savings realized did not come at the expense of either of these two parameters. These figures confirm that the results came from combustion improvements, and not from the oxidation of the bath or electrodes.

Analysis of THD results indicate that a statistically significant difference exists between the THD profiles in the interval from 32,000 kWh to 37,750 kWh. In this interval, THD values for the 8:1 burner ratio trial were slightly lower, indicating that flat bath conditions had been achieved at a slightly lower "kWh into heat" value, when the free oxygen flow was increased. This is a significant result as it indicates that combustion and post combustion improvements had taken place during the meltdown periods, leading to the earlier achievement of flat bath conditions. During flat bath conditions, when a foamy slag has been established, increased electrical input rates can be achieved\textsuperscript{13}, and the energy from the arcs is transferred to the bath more efficiently during this period of the heat\textsuperscript{17}.

Analysis of the operating data also shows that statistically significant reductions in Specific Electrical Energy Consumption, Power on Time and Tap to Tap Time were observed. The significance of these results is that they indicate that the objectives of this study had been achieved. The modification of the burner ratio had resulted in changes in furnace combustion conditions in such a manner that a significant amount of this energy had been transferred to the charge.
5.2 Comparison Of Results

The results obtained in the course of this study compare favorably with other published results. The volume of free oxygen fed to the furnace was increased by 4.8 Nm$^3$, and resulted in a decrease of 3.3 kWh/Nm$^3$ of O$_2$. This information is presented in Table 5.2 and can be compared with Tables 2.1 to 2.5.

<table>
<thead>
<tr>
<th>Plant</th>
<th>Technology</th>
<th>Increase in Free Oxygen</th>
<th>Savings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Co-Steel Lasco</td>
<td>University of Toronto and Goodfellow Technologies</td>
<td>5.3 (4.8)</td>
<td>3.3</td>
</tr>
</tbody>
</table>

However, this study involved the increase of free oxygen consumption, without the increase in net oxygen consumption which took place in all of the studies whose results were presented in Chapter 2 of this thesis. In addition, the results of this study suggest that an increase in scrap hydrocarbons was observed. This additional fuel source was not observed in any of the other studies.

Consequently, the results of this study can not be objectively compared to the other published results.

5.3 Factors Contributing To Achieved Savings

The 8:1 burner ratio trial achieved the appropriate temperature and chemical characteristics with lower Specific Electrical Energy Consumption and lower Power On Time because of the following factors:

- Increase In Scrap Hydrocarbons
- More Uniform Distribution Of Fuel And Oxygen Throughout Charge
- Reduced Air Inleakage
- Earlier Achievement Of Foamy Slag Conditions

Although each one of these factors played a role in the savings that were realized, sufficient data is not available to accurately quantify the contribution of each. A more rigorous analysis of each of these mechanisms and their contribution to the savings realized would have been possible had offgas temperature and flow rate been measured as part of this study. Without this information it is not possible to execute an accurate mass and energy balance.

The results of this study indicate that these four factors contributed to the 4.0% reduction in Specific Electrical Energy Consumption and 5.0% reduction in Power On Time. Each factor is discussed in detail in the following sections.

5.3.1 Increase In Scrap Hydrocarbons

The results of offgas analysis indicate that most differences existed during the meltdown phases, suggesting that something was different in the scrap. The higher levels of carbon containing gases and H₂ gases suggest that a higher level of hydrocarbons entering the furnace was recorded. The effect of modifying the burner ratio would have decreased the amount of hydrocarbons entering the furnace, but the offgas profiles presented suggest that this intended deficit was overcome.

The amount of energy transferred to the charge from combustion and post combustion reactions is a function of two factors: the amount of energy available for transfer, and the rate of heat transfer. As a result of the increase in scrap hydrocarbons, combustion of these hydrocarbons resulted in a larger amount of energy released in the furnace which was available for transfer to the charge during the meltdown periods. An increase in energy transferred to the charge
would have resulted in a decrease in Specific Electrical Energy Consumption and Power On Time, as was observed.

The source of these hydrocarbons was likely the scrap fed to the furnace. The amount of fluff fluctuates and is an extremely difficult parameter to quantify and control. Further investigation of Co-Steel Lasco records indicated that there had been some differences between the source of the scrap used in each trial. Because of the fluctuation in fluff concentrations, it is possible that dynamic control systems (such as closed loop oxygen control, based on on-line offgas chemistry analysis) may be able to yield better results and characterize scrap, in order to minimize chemical energy losses from the EAF. The results of this study suggest that it is likely that these hydrocarbons were combusted during the meltdown phases and that this additional fuel source transferred energy to the charge, contributing to the savings observed.

This is supported by the bath temperature measurements which indicated that higher temperatures were recorded during the 8:1 burner trials.

5.3.2 More Uniform Distribution Of Fuel And Oxygen Throughout Charge

Higher scrap hydrocarbon levels can not by themselves accelerate the meltdown periods of the heat; oxygen and favorable heat transfer conditions are also required.

The modification of the burner ratio resulted in a significant increase in free oxygen entering the furnace, especially during the meltdown phases of the heat. This is best illustrated by Figure 4.5 which shows that an increase of approximately 14.2 Nm³/min (500 scfm) was recorded during the 8:1 burner ratio trials.
Other than just the increase in free oxygen, the modification of the burner ratio had an effect on the distribution of free oxygen throughout the furnace. Figure 4.10 indicates that very low concentrations of $O_2$ were measured in the offgas during both burner ratio trials, especially during the meltdown periods. This indicates that the injected oxygen reacted inside the furnace, but does not indicate where, and with what, this oxygen reacted.

During the 3:1 burner ratio trial, most of the oxygen injected through the burners likely reacted with natural gas at the burner outlet. The temperature of the stream at the burner outlet was likely close to that of the flame temperature of natural gas combustion ($2260 \degree C$, or $4100 \degree F$)\textsuperscript{18} giving the stream of gases a large amount of buoyancy.

During the 8:1 burner ratio trials, it is likely that the temperature of the gas stream at the burner outlet was substantially lower, reducing the amount of buoyancy. This would have had two effects on furnace combustion. The first effect would have been an increase in residence time in the furnace. The second effect would have been better distribution of oxygen in the lower areas of the furnace. These two factors could cause changes in gas flow patterns throughout the furnace leading to combustion of scrap hydrocarbons in intimate contact with the scrap charge in the furnace, resulting in more favorable heat transfer conditions.

In addition to the hydrocarbons, carbon which is charged along with the first charge remains "hung up" in the scrap. This creates another fuel source which is relatively well distributed throughout the scrap.

The more even distribution of fuel and oxygen throughout the scrap charge during the meltdown phases, promoted combustion and post combustion reactions in much more intimate contact with the scrap, resulting in conditions
which are more conducive to heat transfer. Further gains were also made because the hot byproducts of these reactions "percolated" through the scrap charge before exiting the furnace. The results of this study suggest that these factors made a contribution to the gains which were realized.

Based on this information, it is clear that virtually all of the oxygen which entered the furnace, through the burners, the lances and from air inleakage, participated in combustion or post combustion reactions, but the location of these reactions and the heat transfer conditions at that point are not clear.

5.3.3 Reduced Air Inleakage

Figure 4.14 indicates that the $N_2$ profile measured during the 8:1 burner ratio trial was lower than the profile measured during the 3:1 burner trials. This decrease is most significant during the meltdown phases, and reaches a maximum of approximately 11%. During the refining phase of the heat no significant change in $N_2$ levels is evident.

A decrease in $N_2$ levels is indicative of an increase in furnace pressure, which will result in a significant decrease in air inleakage into the furnace from through-shell fittings. It is likely that this change in furnace pressure was caused by the higher levels of hydrocarbons in the scrap. When combusted, these hydrocarbons release gases which could have a significant effect on the furnace pressure.

This increase in furnace pressure will influence the furnace operation in two significant ways. First, losses attributed to increasing the temperature of the "nitrogen ballast" to offgas temperatures were decreased. It is estimated that the Co-Steel Lasco EAF has a peak offgas flow of approximately 510 Nm$^3$/min (18,000 scfm) to 623 Nm$^3$/min (22,000 scfm). Based on the nitrogen
concentrations presented in Figure 4.14, a significant amount of energy is required for this volume to reach offgas temperatures. As a result, a decrease in the amount of nitrogen entering the furnace will result in significant energy savings.

Additionally, due to the increase in furnace pressure, a corresponding amount of oxygen did not enter the furnace which would decrease the amount of "natural post combustion". *Natural post combustion* refers to the post combustion of CO and H₂ with oxygen from inleaked air which occurs high in the furnace, from where heat transfer to the charge is extremely inefficient.

It is believed that, in the trials with the lower burner ratio, a significant amount of natural post combustion occurred high in the furnace, which provided very little, if any, process benefits. In the 8:1 burner ratio trials, it is likely that the degree of natural post combustion was decreased, while the amount of combustion and post combustion in closer proximity to the charge was increased. It is likely that this decrease in natural post combustion contributed to the decreased PCR which was observed.

Based on the results of this study, it is clear that the decrease in air inleakage made a contribution to the savings which were observed.

5.3.4 Earlier Achievement Of Flat Bath Conditions

Figure 4.19 indicates that the Total Harmonic Distortion (THD) reached a minimum value at a lower “kWh into heat” value during the 8:1 burner ratio trials, indicating that flat bath conditions were achieved at lower electrical energy consumption values.
It important to note that the electrical supply characteristics remained virtually identical for both trials, as did the power factor (Active Power and Power Factor profiles are presented in Appendix 6). The variation in THD indicates that flat bath conditions were realized earlier. The significance of this finding is that increased electrical input rates can be achieved earlier\textsuperscript{13}, and that energy from the arcs is transferred more efficiently during this period of the heat\textsuperscript{17}. 
6. Conclusion

The findings of this study lead to a number of very interesting conclusions:

6.1 Cost And Energy Savings Were Achieved
As a result of this study, cost and energy savings were realized. A 4.0% reduction in the Specific Electrical Energy Consumption was realized, as well as a 42.7% reduction in the specific consumption of natural gas. It is important to note that many of the figures provided in this report are on a per ton basis, and must be extrapolated to represent the annual savings realized by Co-Steel Lasco, as they produce approximately 1.0 million tons per year.

Increases in productivity were also achieved. These increases are manifested in the Power On Time, which was decreased by 5.0%, as well as the Tap to Tap Time which was decreased by 4.5%.

These increases in productivity and reduction in production costs, were made by redistributing, and in some cases reducing, the gases which were being used. As a result, improvements were made without significant capital investment.

The cost and energy savings achieved are summarized in Table 6.1 below.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Decrease</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific Electrical Energy Cons.</td>
<td>4.0%</td>
</tr>
<tr>
<td>Specific Natural Gas Cons.</td>
<td>42.7%</td>
</tr>
<tr>
<td>Power On Time</td>
<td>5.0%</td>
</tr>
<tr>
<td>Tap to Tap Time</td>
<td>4.5%</td>
</tr>
</tbody>
</table>
6.2 Post Combustion Ratio Calculations Can Be Misleading

Based on this thesis, it is clear that the Post Combustion Ratio Calculations can be misleading. The PCR, by its very nature, uses the concentration of the offgases to calculate the degree of post combustion. As such it does not refer to the location of the combustion or post combustion reactions. This study suggests that the location of these reactions is of greater significance than the degree of oxidation, with respect to the amount of heat transferred to the charge.

It is believed that, in the 8:1 burner ratio trials, it is likely that the degree of natural post combustion was decreased, while the amount of combustion and post combustion in closer proximity to the charge was increased. It is likely that this decrease in natural post combustion contributed to the decreased PCR which was observed.

6.3 Importance Of Targeted Oxygen Addition

The findings of this study also indicate that chemical energy losses are still at a very high level. Despite the increase in free oxygen flowing to the furnace, significant increases in free oxygen would likely decrease chemical energy losses, resulting in additional savings. Additional oxygen could be added both through the burners and through the lances, in order to minimize chemical energy losses.

At a more generic level, this study confirms that oxygen should be injected at targeted periods during the heat when chemical energy is present and furnace conditions are conducive to heat transfer. During this study it became clear that these conditions are both present during the meltdown phases of the heat. As such, maximum benefits will be realized if these periods are targeted for increased oxygen flow.
6.4 The Addition Of Oxygen Should Be Considered In Conjunction With The Addition Of Fuel

This study reinforces the point that the injection, or addition, of fuel in the form of carbon and/or hydrocarbons, should be considered in tandem with the addition of oxygen. In this study, more fuel was clearly available than oxygen for full combustion to take place. Enormous amounts of chemical energy were lost to the furnace ventilation system as a result.

Maximum benefits will be realized when oxygen and fuel are balanced and are both delivered early in the charge meltdowns. This would result in lower chemical energy losses from the EAF, resulting in a decrease in the heat load that ventilation systems must accommodate. Significant capital and operating cost could be realized in this eventuality.

6.5 Scrap Chemistry Variations Have Significant Ramifications

Results of this study show that scrap chemistry variations can have a significant effect on a number of key process parameters including offgas concentrations, evolution patterns and furnace pressure. These results suggest that dynamic control systems would yield better results than static systems in certain key areas. Two such technologies are closed loop control of adjustable speed drive fans for ventilation systems based on furnace pressure, and closed loop oxygen control based on on-line offgas analysis.

6.6 Offgas Analysis May Be Used To Characterize Scrap

The findings of this study suggest that the hydrocarbon level of the scrap feed to the furnace will have a significant effect on the offgas concentration. This information could be used to characterize scrap such that furnace parameters are adjusted to accommodate any particular type of scrap.
This study makes it clear that offgas analysis, along with other process parameters, such as offgas temperature and flow, can be used as a tool to characterize the hydrocarbon content of scrap. With this information, furnace operations can be modified to accommodate process variations due to changes in hydrocarbon content of scrap in order to maintain high levels of efficiency.
7. Future Work

This findings of this study have brought a number of areas to light where additional work is required to completely understand what benefits can be realized by improved furnace combustion and post combustion.

7.1 Increased Oxygen

Based on the offgas profiles included in this report, it is clear that optimum oxygen injection rates have not yet been achieved. The EAF operation at Co-Steel Lasco would likely realize additional savings if additional oxygen were injected. It is believed that there is a level of oxygen injection beyond which increases of injected oxygen would be deleterious. This level, as it relates to the operation of the Co-Steel Lasco EAF, is as yet unknown.

Additional oxygen could be injected through a number of different sources. Ideally oxygen injection would be done through injectors mounted on the furnace shell, such that the burners could offer process benefits in their use as burners. In this way the addition of free oxygen would be done through the oxygen injectors and the lances. Additional savings would undoubtedly be realized under these circumstances.

7.2 Hydrocarbon Combustion At The Burners Versus In The Scrap

This study has highlighted the difference in combustion of hydrocarbons in the scrap versus the combustion of hydrocarbons at the burners. Although it is clear that process benefits can be realize by either method of hydrocarbon combustion, mechanisms of heat transfer between the two are very different. Presently, these difference are poorly understood and should be investigated further.
Better understanding of the heat transfer mechanisms would have a significant effect on the use of chemical energy in the EAF steelmaking process.

7.3 Flow And Temperature Measurements

This study has also highlighted the need for data relating to the flow and temperature of the offgases from the EAF furnace. Despite the extreme conditions that exist at this point of the ventilation system, these measurements are critical to constructing accurate mass and energy balances.

Ideally continuous flow and temperature data would be available. Using this information, it would be possible to calculate the concentration of water vapor in the offgas, as well as develop mass flow rates of the gases exiting the furnace. This type of information would allow a much more rigorous analysis of process modifications such as the one undertaken in this study.

7.4 Further Slag Analysis

Slag sampling and the analysis of those samples has also highlighted areas where additional investigation is required.

Further work is required in slag sampling techniques, especially with respect to slag samples taken in the course of the heat.

Powder X-Ray Diffraction results indicated that a number of interesting oxide compounds were present in the slag. The production of these compounds and their effect on the steelmaking process is not completely understood and should also be studied further.
7.5 Scrap Characterization

The characterization of scrap with respect to hydrocarbon concentrations, in a quantitative manner could have very significant operational ramifications.

With the aid of sophisticated analysis system (which are presently available), offgas patterns could be related to scrap feed sources. Ultimately, this could lead to the adjustment of furnace practices to account for the changes in offgas concentration and compositions that are associated with scrap of varying hydrocarbon content. This could have a significant effect on the amount of carbon charged or lanced to the furnace, as well as the amount of natural gas and oxygen injected to the furnace.

The development of technologies which can effectively return the energy which is already in the scrap would undoubtedly be a large competitive advantage for any steelmaker.
References


Appendix 1
Figure A.1, Schematic of Offgas Probe location, including Water Cooled Elbow and Fixed Duct.
Appendix 2
Figure A.2, Schematic of Co-Steel Lasco EAF, including gas injection equipment and fourth hole location.
Appendix 3
The following parameters were recorded every 20 seconds by EFSOP™ during the burner ratio trials.

<table>
<thead>
<tr>
<th>Date</th>
<th>DES2FANAMP</th>
<th>MW_PH3</th>
<th>MW_TOT</th>
</tr>
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<tbody>
<tr>
<td>Time</td>
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<td>O2_CALC</td>
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<td>EL_DELPH</td>
<td>O2_LANCE1</td>
<td>O2_LANCE2</td>
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<td>EL_TEMP</td>
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<td>OXY1</td>
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<td>ELECT_KWH</td>
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<td>OXY3</td>
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<td>PHASE2_VLT</td>
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<td>PHASE3_VLT</td>
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<td>BH2-DAMP2</td>
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<td>PUR_PROGRESS</td>
<td>ROOF_UP</td>
</tr>
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<td>ENERGY_H2</td>
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<td>BH2-DELP</td>
<td>FCE_POWER</td>
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X-Ray Fluorescence Spectrometry (XRFS) Sample Preparation

Slag samples are grinded and passed through a 100 mesh screen. The 1.00 g samples are then heated to 1000 °C in an oxidizing furnace, where they remain for 2 hours. Once they are removed from the furnace and allowed to cool, they are mixed with 7 g of Lithium Tetraborate ($\text{Li}_2\text{B}_4\text{O}_7$). The mixture is then fused in a platinum crucible at approximately 1000 °C. Following this step the fused samples is analyzed by XRFS.
Appendix 5
Attention to: Mr. Kournetas, N., Dept of Met. & Mat. Sci./U of T.


Re: X-ray Powder Diffraction Analysis of 6 samples No's: 21611, 21613, 21848, 21857 and additionally submitted samples 21848-A and 21613-A.

The main components identified in all 6 samples are Fe-oxides, Ca-Ferrite and high temperature β-Ca$_2$SiO$_4$, Belite/Lamite. Additional identified phases as a minors are olivines and complex mixture of Ca,Fe-oxides. The samples were very hard and it was impossible to grind them to appropriate for PXRD analysis particles size. This, along with the high X-ray fluorescence which is common for Fe-rich samples could explain the poor quality of the obtained diffraction data despite the high resolution, slow step scan run that was applied on all 6 samples. Note that it is not possible some accurate quantitative data to be evaluated or calculated from these powder pattern. The information provided below is related mostly to the phase(s) composition and notification of the major, medium and minor components in terms of their abundance (quantities) in the analyzed samples.

Results (see attached plots):

I. Phase composition of sample 21611 (Fig. 1):

1. FeO, Wuestite - the major phase in the sample. This Fe-oxide here shows an enlarged unit cell (a = 4.341 Å, compare with a = 4.308 Å for the common FeO phase).
2. Calcium Ferrite (could be with some Al in it).
3. β-Ca$_2$SiO$_4$, Lamite/Belite.
4. Magnetite, Fe$_3$O$_4$ - a minor.
   Note: There are no Hematite, Fe$_2$O$_3$ in this sample.

II. Phase composition of sample 21613 (Fig. 2):

1. Hematite, Fe$_2$O$_3$ - the major phase,
2. Magnetite, Fe$_3$O$_4$ - the medium phase,
3. β-Ca$_2$SiO$_4$, Lamite/Belite,
4. Mg,Fe - olivine, a solid solution of Fajalite - Forsterite isomorphous series.
   Note: There are no Wuestite, FeO and Ca-Ferrite in this sample.

III. Phase composition of sample 21613-A (Fig. 3):

1. FeO, Wuestite - the major phase in the sample. (Normal lattice, a = 4.308 Å).
2. β-Ca$_2$SiO$_4$, Lamite/Belite - a medium abundant phase,
3. Magnetite, Fe$_3$O$_4$ - a medium abundant phase (a = 8.31 Å, a significant contraction of the lattice of Magnetite for this sample,
4. Mg,Fe - olivine, a solid solution of Fajalite - Forsterite isomorphic series - minor phase.
   Note: There are no Hematite, Fe₂O₃ and Ca-Ferrite in this sample.

IV. Phase composition of sample 21848 (Fig. 4):

1. FeO, Wuestite - the major phase in the sample. (Normal lattice, a = 4.308 Å).
2. Calcium Ferrite (could be with some Al in it),
3. β-Ca₂SiO₄, Larnite/Belite - a medium abundant phase
4. Magnetite, Fe₃O₄ - a minor phase.
   Note: There are no Hematite, Fe₂O₃ in this sample.

V. Phase composition of sample 21848-A (Fig. 5):

1. Hematite, Fe₂O₃ - the major phase in the sample,
2. Magnetite, Fe₃O₄ - the second major phase in this sample
3. Calcium Ferrite (could be with some Al in it),
4. β-Ca₂SiO₄, Larnite/Belite - a medium abundant phase,
5. Mixed Ca-Fe-Oxides. There are a large group of different Ca-Fe-oxides. Some of them are well defined crystallographically. Two of them are identified as a mixture in this sample: Ca₃Fe₁₅O₂₆ and CaFe₂O₇, but some other could also be there.
6. Others, non-identified minors (marked with d-spaces peaks).
   Note: There are no Wuestite, FeO in this sample.

VI. Phase composition of sample 21857(Fig. 5):

1. FeO, Wuestite - the major phase in the sample. (Normal lattice, a = 4.308 Å),
2. β-Ca₂SiO₄, Larnite/Belite - second phase, medium abundance,
3. Fe₂O₄/Fe₂O₃-C - a modified, slightly different from the common Magnetite, phase. This could be one of the few known defect structural varieties such as: maghemite, gamma-Fe₂O₃ and/or Fe₂O₃-C. The unit cell parameter of this sample shows a large deviation from a typical magnetite lattice (a = 8.332(5) Å, compared with 8.396 Å).

VII. For better understanding of the complex and variable composition of those samples, these results must be combined with the results from some elemental analysis which could provide a valuable information for the composition of the identified components.
**Fig. 2:** X-ray Powder Diffraction Pattern of sample "21613":

**Composition:**

1. Fe$_2$O$_3$, Hematite, the major.
3. B-C2S, B-Ca$_2$SiO$_4$, Belite
4. (Mg,Fe)$_2$SiO$_4$ - Olivine (minor)
Sample from: Nicolas Kournetas, Dept of Met. & Mat. Sci./U of T.

Fig. 3: X-ray Powder Diffraction Pattern of sample "21613-A":

Composition:
1. FeO, Wuestite - the major,
2. Fe3O4, Magnetite (a = 8.32A).
3. B-Ca2SiO4, Belite,
4. (Fe,Mg) - Olivine, traces.
**Fig. 4:** X-ray Powder Diffraction Pattern of sample “21848”:

**Sample # 21848**

**Composition:**

1. FeO, Wuestite-the major phase
2. CAF: Ca-Al-Ferrite, Ca₄Al₂Fe₂O₁₀
3. Betta-CaSiO₄, Larnta/Beilte
4. Magnetite, Fe₃O₄
Sample from: Nicolas Kournetas, Dept of Met. & Mat. Sci./U of T.

Fig. 6: X-ray Powder Diffraction Pattern of sample “21857”:

Sample # 21857

Composition:
1. FeO, Wuestite-the major phase
2. beta-CaSiO4, Larnite/Beelite
3. FeO4/Fe2O3-C, Magnetite.

C:\D5000\DATA\SRWMTN21857.RAW MTN21857 (CT: 2.0s, SS:0.020dg, WL: 1.5406Ao)
Appendix 6