CONTROL OF SLOPPING IN BASIC OXYGEN STEELMAKING

by

© GEORGE K. CUTHILL, B.Sc.

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AUTHOR: George K. Cuthill, B.Sc.

SUPERVISORS: Dr. W-K. Lu

Dr. T. R. Meadowcroft (Stelco)

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ABSTRACT

Methods for controlling slopping (slag overflow) were studied in the Steel Company of Canada's Hilton Works basic oxygen furnace installation. A link was established between slopping and various operating conditions by drawing on the experience of the furnace operators and by examining ingot yield data. An on-line control system was developed which used changes in the temperature of the furnace waste gases to signal when corrective action should be taken to prevent slopping. During trials, this system reduced slopping and increased ingot yield by approximately one percent.

The chemical composition of slag from normal and slopping heats was studied in an attempt to determine why slopping occurs. The results of this study support a mechanism proposed by F. Bardenheuer (Ref. 21) which relates increases in slag foaming in the B.O.F. to the precipitation of dicalcium silicate and overoxidation.

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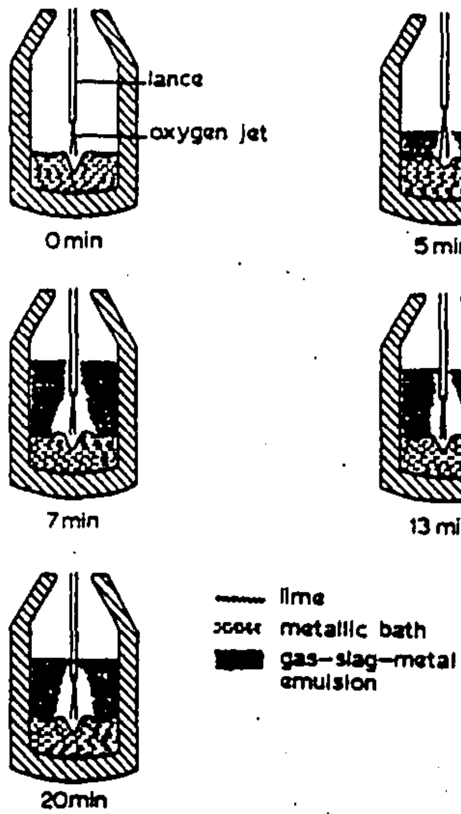
CHAPTER 1

INTRODUCTION

"All went quietly at first, but after about 10 minutes a rapid change took place, a voluminous white flame and an ever-increasing stream of sparks being ejected from the mouth of the vessel, followed by explosions and evolutions of molten slag and metal, the apparatus becoming a veritable volcano in a state of active eruption.", [27]. This graphic account describes one of Sir Henry Bessemer's first experiments in pneumatic steelmaking, however, it could equally well apply to the slopping of a modern basic oxygen furnace. Despite the advances in steelmaking technology which have taken place since Bessemer's day, slopping remains a problem which has never completely been solved.

Slopping is related to the process of slag formation in basic oxygen steelmaking. As oxygen is injected into a basic oxygen furnace, carbon, silicon, manganese and iron are oxidized (a more complete description of B.O.F. operation is given in Appendix II). The resulting silica, iron oxide and manganese oxide react with fluxes charged into the vessel and the refractory lining of the furnace forming a slag. The oxidation of carbon generates carbon monoxide, some of which rises through the slag making it foam (figure 1). Normally there is enough space inside the furnace to contain this foaming, however, occasionally the capacity of the furnace

Figure 1: Sections through a BOF Showing the Development of a Foaming Slag



(After Chatterjee [22])

is exceeded and the slag overflows. This overflow of slag is referred to as slopping.

Slopping creates several problems for steel producers. Since iron is lost along with the slag, slopping reduces the amount of hot metal and scrap which can be recovered as usable product. This decrease in yield increases the cost per ton of steel produced in B.O.F. shops. Also, the number of tons of steel which can be produced by a furnace per hour is reduced, because the operation of the furnace must be delayed to take corrective action to stop slopping and to remove ejected slag. By reducing the number of heats which slop, furnace productivity could be increased and operating costs lowered.

Many difficulties face an investigator trying to develop a workable method for preventing slopping. One major problem is the large number of factors, many of which are interrelated, which affect the operation of a basic oxygen furnace. Isolating those factors which are related to slopping requires large amounts of data and demands careful analysis. Time, money and the physical constraints of basic oxygen furnace operation limit the depth to which the problem of slopping can be studied. Ultimately, the degree of success which is achieved depends upon the investigator's ability to make the best use of the resources at hand. This thesis describes a study into methods of controlling slopping which was carried out in the Steel Company of Canada Ltd.'s Hilton Works, basic oxygen furnace shop.

CHAPTER 2

RELATION BETWEEN OPERATION CONDITIONS AND SLOPPING

2.1 Background: Off-line Control

All methods of controlling B.O.F. slopping can be categorized as either on-line or off-line systems. In on-line control systems, corrections are made during the blow in response to some 'real time' signal which indicates whether the heat is about to slop. In off-line control systems, on the other hand, the corrective action is taken before the blow starts and is based on past experience of how various operating conditions affect slopping.

Off-line systems for controlling slopping seek to reduce the number of heats which slop by either eliminating or minimizing the effect of factors which have been found to cause slopping. The following factors have been reported in the literature as causes of slopping:

(i) Hot metal silicon above 1.2 percent [1,2];

(ii) Hot metal manganese outside the range 0.5-0.9 percent [1,3,4];

(iii) Charging more than the furnace's designed capacity [1];

(iv) Use of fluorspar to speed lime dissolution [1,5];

(v) Use of iron oxide as a coolant [1];

(vi) Use of a newly relined furnace [6];

(vii) Choice of oxygen lance design [7,8];

(viii) Blowing with the lance higher above the steel bath than normal [5,7].

Because operating conditions vary from company to company, some of these factors will be more of a problem in one B.O.F. shop than another (e.g., the amount of overcharging varies from company to company).

A variety of actions can constitute off-line control of slopping. For example, restricting the aim manganese content of the hot metal for the B.O.F. [3] and regularly checking the lance to bath separation [7] are both off-line methods of control. Because problems differ, off-line control practices vary from company to company. Off-line control practices can often only be implemented to a limited extent because they conflict with other aspects of a company's operation. For example, although it is desirable to eliminate overcharging to reduce slopping, the need to produce as much steel as possible from existing steelmaking facilities may force a company to exceed the design capacity of their B.O.F.s.

2.2 Characteristics of Slopping Heats at Stelco

Before attempting to improve methods of off-line control, the factors which are linked to slopping in Stelco's B.O.F. operation had to be identified. Rather than examining all the factors reported in the literature, Stelco's B.O.F. operators were asked which of the factors they felt were most important. These men reported, based on their operating experience, that the following factors caused slopping:

(i) Vessel lining life less than approximately 400 heats.

(ii) Use of an oxygen lance with damaged nozzles.

(iii) Hot metal manganese concentration greater than approximately 1.2 percent.

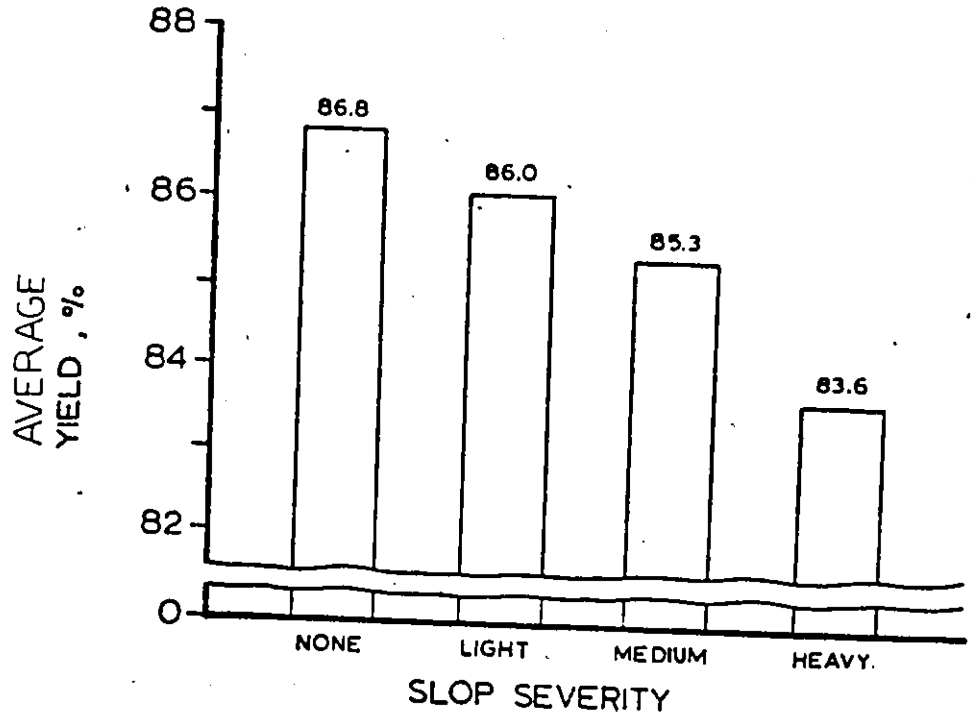
(iv) Hot metal silicon concentration greater than approximately 1.0 percent.

An attempt was then made to quantify the effect of each of these four factors on shop operation. Since records are not kept of which heats slop, ingot yield was used as a measure of the severity of slopping. As figure 2 shows, the average ingot yield drops as slopping becomes more severe. Ingot yield was also used because it is an indicator of productivity familiar to the B.O.F. supervisors (This was an important consideration since these were the men most concerned with the problem).

Only heats teemed into 24 x 28 inch big end up ingot molds were selected for this study. Attention was restricted to these heats because of the small ingot size (the 5.9 ton B.E.U. ingot is the smallest size produced at Stelco.) Iron losses are most likely to reduce the number of ingots produced on these heats so that their yield is very sensitive to the effect of slopping. Data was collected on over 3000 heats produced between October, 1975 and October, 1976.

In analyzing this data, heats with similar lining

Figure 2: Influence of Slop Severity on Average Ingot Yield (BEU Ingots)



Description

No slopping

Light slopping; approximately 0 to 40% of the conical section of the vessel shell covered by molten slag.

Medium slopping; approximately 40 to 80% coverage.

Heavy slopping; approximately 80 to 100% coverage.

lives, lance lives, hot metal manganese contents and hot metal silicon contents were grouped together. By comparing the average ingot yields among these groups, an attempt was made to evaluate the effects of each factor on slopping.

This analysis of yield data supported the observations of the vessel operators. The average ingot yield was found to increase steadily as the vessel lining life increases (figure 3). This trend is consistent with the observation of the vessel operators that slopping is more frequent when there are less than 400 heats on the furnace lining. A drop in yield was also noted when heats were blown using a lance which had been in service for more than 100 heats (figure 4). This drop in yield reflects the increase in slopping which occurs as the nozzles in the oxygen lance gradually deteriorate (figure 5). The average ingot yield also dropped when the hot metal silicon content was over 1.0 percent and the manganese content over 1.2 percent (figure 4). Both of these findings support the operators' observation that slopping is more frequent when the concentration of manganese and silicon in the hot metal is higher than normal. (See Appendix III)

As a result of this study, further research on off-line control has been undertaken. Methods of reducing oxygen lance nozzle deterioration are currently being investigated. The effects of reducing the hot metal silicon and manganese concentrations on the steelmaking and iron making operations are also being evaluated.

Figure 3: Effect of Vessel Life on BEU Yield

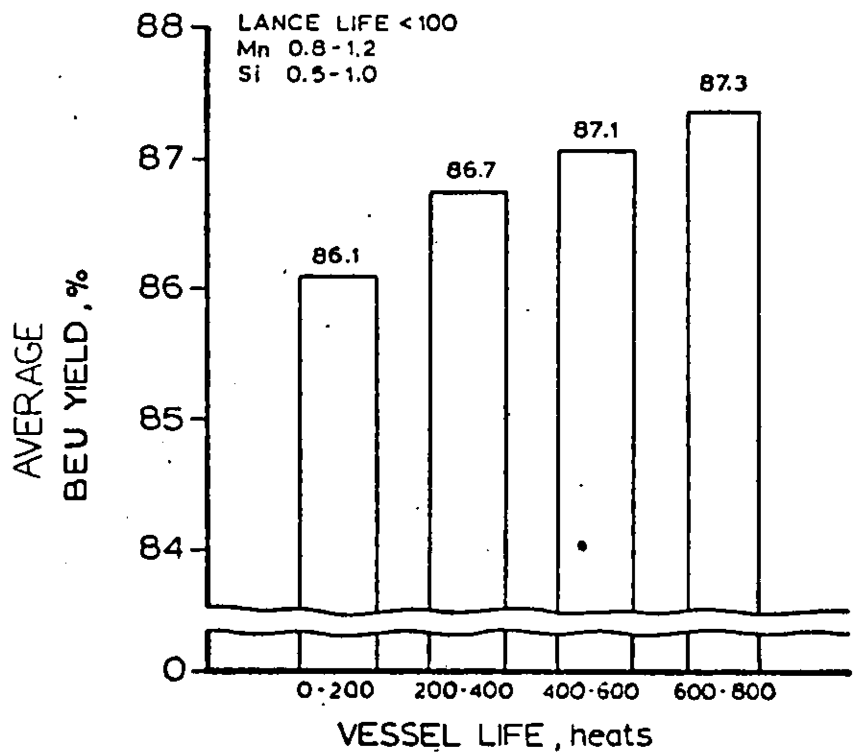


Figure 4: Influence of Hot Metal Silicon, Hot Metal Manganese, and Lance Life on BEU Yield (Vessel Life 0-800 heats).

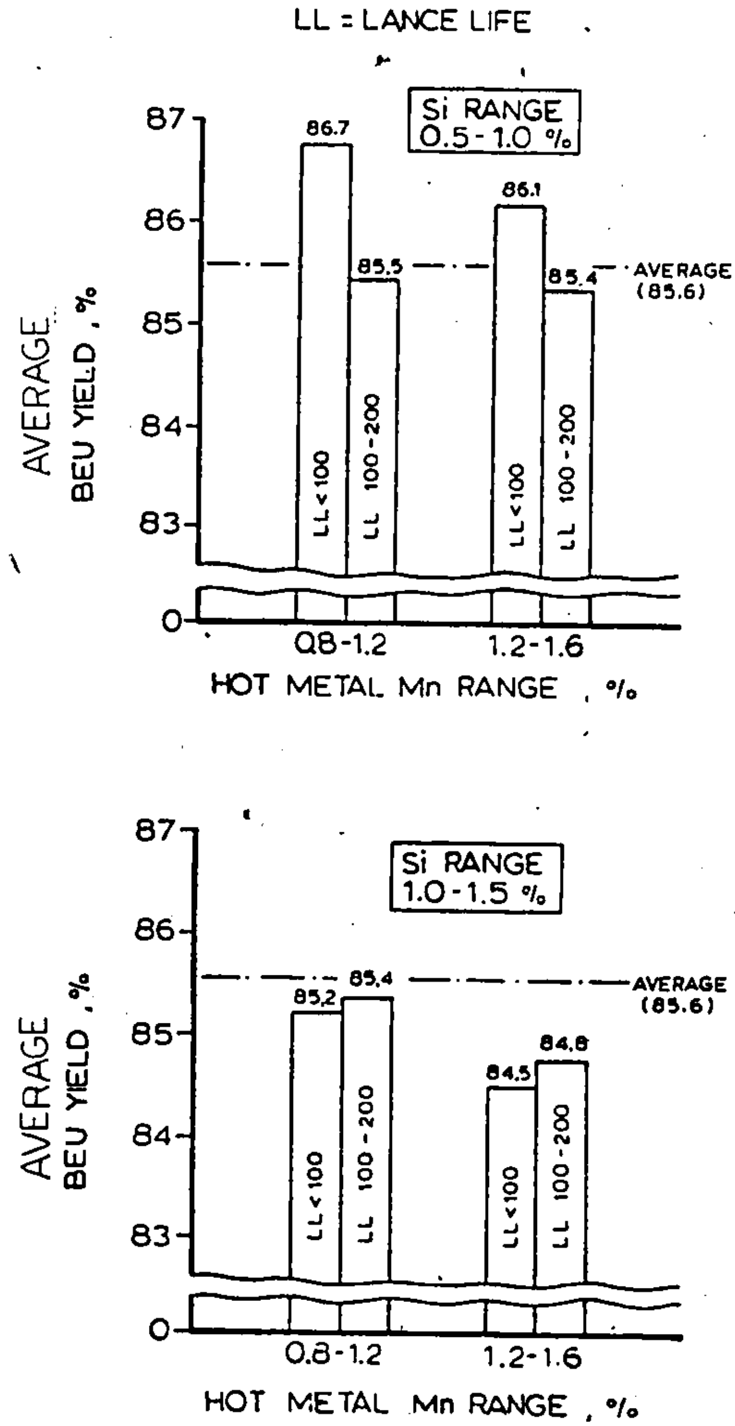
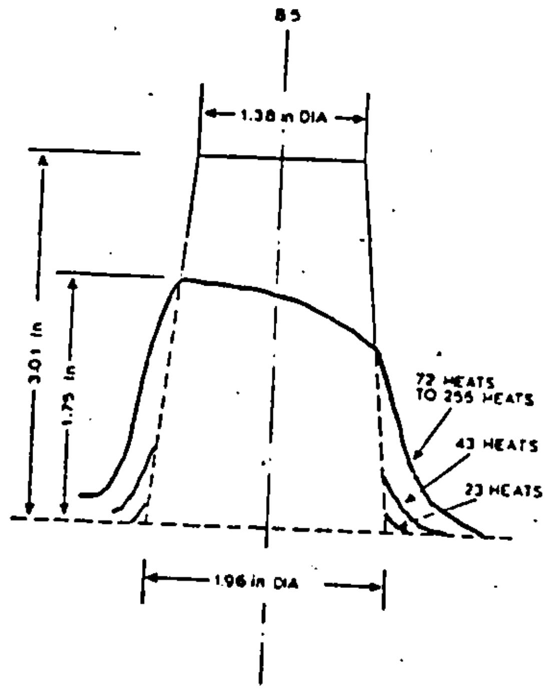


Figure 5: Typical Lance Nozzle Wear (Mach 2.2 Lance).



CHAPTER 3

ON-LINE CONTROL TRIALS AT STELCO

3.1 Background: On-line Control

On-line control is the other method of preventing slopping. In an on-line control system, each heat is monitored during the blow for some sign that slopping is imminent. During these periods, the operation of the furnace is adjusted so that slopping can be prevented. The vessel operator is responsible for on-line control in most B.O.F. shops; by watching for the first sign of slag ejection, it is usually possible for an experienced vessel operator to make corrections in time to prevent further slopping. Unfortunately, because there is little visible indication that a furnace is about to slop before the first ejection of slag, it is almost impossible, even for an experienced operator, to completely eliminate slopping. To improve on this performance, some means of determining what is occurring inside the furnace is required. A variety of methods have been developed (Table 1). Each of these techniques is described briefly below.

(i) Chemical Analysis of the Waste Gas

In a B.O.F., oxygen from the lance oxidizes both slag forming elements (principally iron, silicon and manganese) and carbon. It has been found that whether or not a heat slops

Table 1:

Monitoring Systems for Controlling Slopping

Monitoring Technique	References
Chemical Analysis of the Waste Gas	9, 10
Waste Gas Temperature	11, 12
Lance Expansion	13
Lance Water Temperature	14
Flame Emissivity	15
% CO_2 in the Waste Gas	6
Noise Level in the Furnace	10, 16
Furnace Weighing	17

depends on how oxygen is distributed between the slag and carbon [10]. Slopping frequently is preceded by accumulation of abnormally large amounts of iron oxide in the slag. By continuously analyzing the chemical composition and flow rate of the waste gas coming out of the furnace, it is possible to measure how much of the lance oxygen is being used to oxidize carbon. The amount of oxygen which is being used for slag formation can then be computed by difference. By monitoring many heats, a distribution of oxygen between the slag and carbon can be established which will prevent slopping. Slopping can then be controlled by regulating the operation of the furnace so that every heat maintains this correct distribution of oxygen.

Control systems, based on waste gas analysis have both advantages and drawbacks. The major advantage of such a system is that the waste gas analysis can also be utilized to estimate the carbon content of the steel while the heat is being blown. With this information the amount of oxygen which must be blown to reach the desired end-point carbon concentration can be estimated much more accurately. This procedure, known as dynamic control, can reduce the number of reblows which are required, thus cutting heat time and increasing shop productivity (for a fuller description of dynamic control see reference [9]). The principal disadvantage of using waste gas analysis as an indicator is the problem of maintaining the gas analysis equipment. In the dirt and heat typical of a B.O.F. shop, gas analysis equipment requires frequent maintenance and calibration by trained personnel to ensure that it gives reliable readings.

(ii) Waste Gas Temperature

In most basic oxygen furnace shops, the carbon monoxide generated by the decarburization reaction is allowed to mix with air at the vessel mouth before passing up the exhaust system. This carbon monoxide burns completely to carbon dioxide raising the temperature of the gas mixture (known as waste gas). If air is drawn in at a relatively constant rate, the temperature of the waste gas will vary with the rate of carbon monoxide generation. Changes in the waste gas temperature then give a qualitative indication of the distribution of oxygen between the slag and carbon. By monitoring many heats a characteristic temperature evolution profile can be established for heats which did not slop. Slopping can then be avoided by adjusting the operation of the furnace so that this same pattern of temperature evolution is maintained on every heat.

The only equipment required to measure the waste gas temperature is a thermocouple mounted in the gas stream and some form of read-out device, such as a chart recorder. Because it uses such simple equipment, a control system based on waste gas temperature can be installed easily and inexpensively in most B.O.F. shops and will operate reliably with minimal servicing. The major disadvantage of using the waste gas temperature as an indicator is its susceptibility to changes in the rate of air intake or carbon monoxide generation. For example, if the rate of decarburization were increased by raising the oxygen blowing rate, the waste gas temperature would increase and its evolution would change.

Control systems using lance expansion, lance water temperature, waste gas carbon dioxide concentration and flame emissivity as indicators all work on similar principles to those using waste gas temperature. All these indicators give a qualitative indication of the decarburization rate. As with waste gas temperature, slopping is prevented by adjusting the furnace operation so that the indicator follows the same pattern on every heat. The operating advantages and disadvantages of these control methods are similar to those of systems based on waste gas temperature.

(iii) Noise Level

When the jets of oxygen from the lance strike the surface of the metal bath, they generate noise. This noise is loudest early in the blow when there is little slag to muffle it. As the blow proceeds, more slag is formed. As this slag builds up, it covers the lance head attenuating the noise of the jets. By measuring the loudness of this jet noise, an indication of the volume of slag in the furnace can be obtained. The noise level which can be tolerated without slopping is determined by monitoring many heats. Slopping then can be prevented by adjusting the operating conditions whenever the noise level indicates that the slag volume is approaching the capacity of the furnace.

A significant drawback of control systems based on noise level is the large amount of development work which is required. The equipment used to measure the sound intensity must be tuned to the characteristic frequency of the jet noise so that the signal will be unaffected by background sound. Since furnaces have different characteristic frequencies, the results in one BOF shop cannot be used in another; extensive tuning tests must be conducted before any attempt can be made to develop a workable control system. Maintenance of the sensitive microphones, necessary for these systems, can also be a problem in a BOF shop.

(iv) Vessel Weighing

The changes in the weight of a basic oxygen furnace and its contents can be measured continuously by mounting load cells in the pedestals used to support the furnace's trunnions. By measuring the changes in weight throughout the blow, it is possible to determine whether oxygen is being used for slag formation (weight increase) or decarburization (weight decrease). An oxygen distribution between carbon and slag which will prevent slopping can be established by experience. Slopping can then be prevented by altering the furnace operation to maintain this correct distribution.

The information from a vessel weighing system can be used for other functions besides controlling slopping. It is reported that the vessel weighing systems can be used for dynamic control of end-point carbon and temperature, to monitor the weights of hot metal and scrap charged and to measure refractory wear. The chief disadvantages of vessel weighing are cost of the equipment required and the difficulties associated with jacking up the furnace so that the load cells can be installed in the pedestals.

The signals from any of these sensors can be used in several ways. In some on-line control systems, the signal from the monitoring system is displayed in the pulpit to help the furnace operator decide when a correction should be made. This approach has the advantages of requiring little extra equipment (i.e. a chart recorder or C.R.T. display) and allows the furnace operator to choose the corrective action which he has found to be the most effective. The major disadvantage of this method is that the furnace operator must pay constant attention to the display and this requirement may often conflict with his other duties. The signal from the sesnsor can also be linked to a controller which will automatically adjust the operation of the furnace. This method allows the signal to be continuously monitored without burdening the furnace operator. Its major drawback is its lack of flexibility; the ability of the system to decide on the proper correction depends upon the sophistication of the controller.

During the blow, there are only three ways of altering the operation of the furnace to prevent slopping: the oxygen flow rate can be changed, the lance height can be altered or material can be added to the furnace. Reducing the rate of oxygen injection will cause a drop in the decarburization rate and an increase in the iron oxide concentration in the slag. Increasing the lance height (i.e. lance to bath separation) also will bring about a reduction in the rate of carbon removal and an increase in the iron oxide content of the slag. On the other hand, if the blowing rate is increased or the lance height reduced the rate of decarburization will rise and the iron oxide content of the slag will drop (this is known as hard blowing). In most BOF shops any or all of the following materials can be added during the blow to change the slag composition:

(i) Burnt lime (CaO)

(ii) Dolomitic lime (CaO and MgO)

(iii) Limestone ($Ca\ CO_3$)

(iv) Fluorspar (CaF_2)

(v) Iron ore (Fe_2O_3)

3.2 Development of Equipment for Measuring the Waste Gas Temperature

Since the resources available for this study were limited, only one of the on-line control techniques could be tested. Waste gas temperature was chosen as the indicator because it had been used successfully in a B.O.F. shop similar to Stelco's [11]. Also, the equipment needed to measure the waste gas temperature was inexpensive, readily available and easy to install.

By trying various designs, a reliable thermocouple assembly was finally developed (figure 6). Chromel-alumel thermocouples were used because they were inexpensive yet responded well over the temperature range encountered in the waste gas stream (approximately 500 to 2500°F). A stainless steel sheath was fitted over the thermocouple to prevent the dust carried in the waste gas from abrading the tip. To prevent the uneven heating in the gas stream from causing the sheath to warp, a water cooled jacket was installed to house all but the last 6 inches of the thermocouple probe. The thermocouple assembly was mounted in the waste gas duct approximately 40 feet above the mouth of the vessel (figure 7).

The signal from the thermocouple was recorded on a multi-channel chart recorder located in the vessel control room. The rate at which the waste gas temperature changed was also recorded during the blow by passing output from the thermocouple through an electronic signal analyzer. The remaining channels on the chart recorder were used to monitor the signals from the following devices:

(a) Oxygen flow rate indicator

(b) Lance height indicator

(c) Waste gas pressure sensor

(d) Waste gas oxygen analyzer

(e) Waste gas carbon monoxide analyzer

(f) Waste gas carbon dioxide analyzer

Figure 6: Thermocouple Assembly for Measuring the Waste Gas Temperature

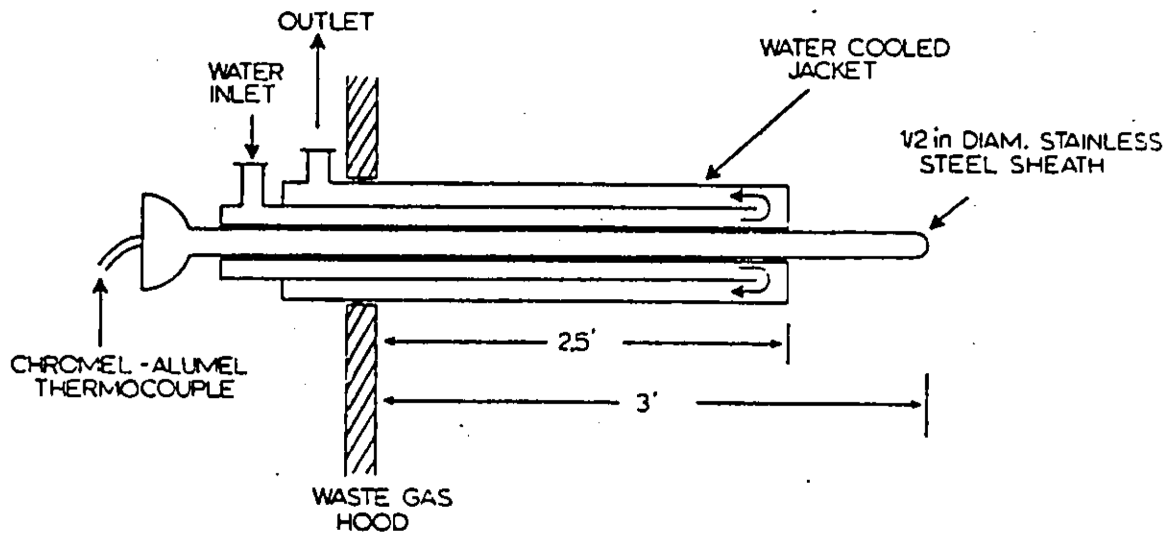
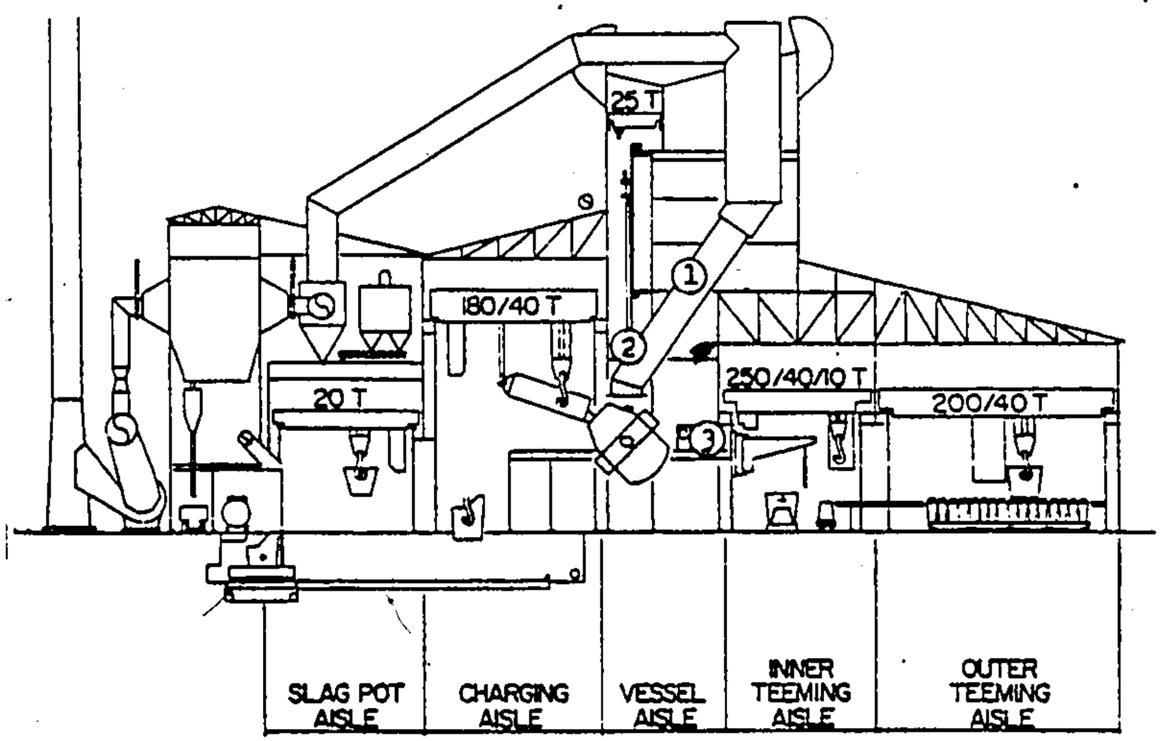


Figure 7: Cross Section through Stelco's Hilton Works B.O.F. Shop



1. Thermocouple and waste gas analyzers
2. Lance entry port
3. Furnace control room

3.3 Development and Testing of Procedures for Controlling Slopping

Before an on-line control system could be developed, slopping had to be related to changes in the waste gas temperature. To establish this link, more than 70 heats were monitored over a two month period. The waste gas temperature and the time at which any slopping occurred were recorded and the amount of slag ejected was estimated on all of these trial heats. It was found that on heats which did not slop, the waste gas temperature rose more or less steadily over the first third of the blow and leveled off at approximately 2000°F (figure 8). The waste gas temperature drifted less than ± 100°F from this plateau level up until the end blow on high carbon heats (i.e. turndown carbon analysis greater than approximately .20%). On low carbon heats, the temperature remained at the plateau level until the final few minutes of the blow when it started to drop slowly. Slopping almost always occurred during this plateau period; only 10 percent of the heats which slopped ejected any slag during the first third of the blow (figure 9). On all heats which slopped, a rapid increase in the waste gas temperature always immediately preceded the ejection of slag (figure 10).

It appeared from these trials that slopping could be prevented if the furnace operation were adjusted to maintain the correct waste gas temperature trace. As a test, a series of trial heats were produced in Stelco's "number six" basic oxygen furnace using the waste gas temperature to indicate

Figure 8: Waste Gas Temperature Trace - Normal Heat

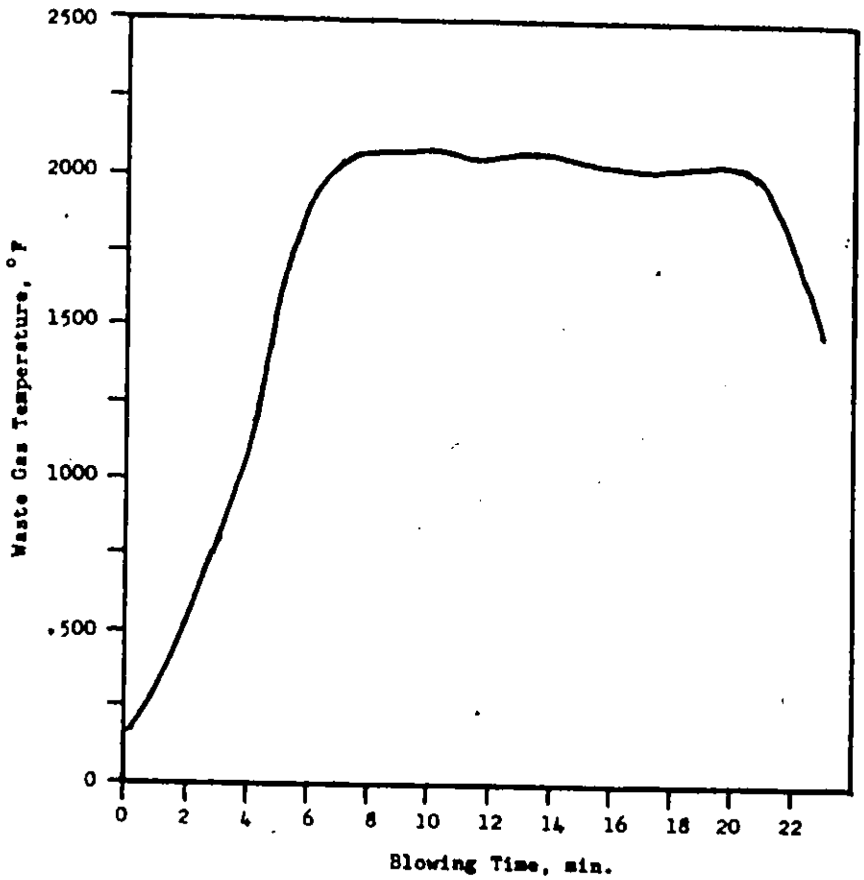


Figure 9: Period During the Blow at which Slopping Starts

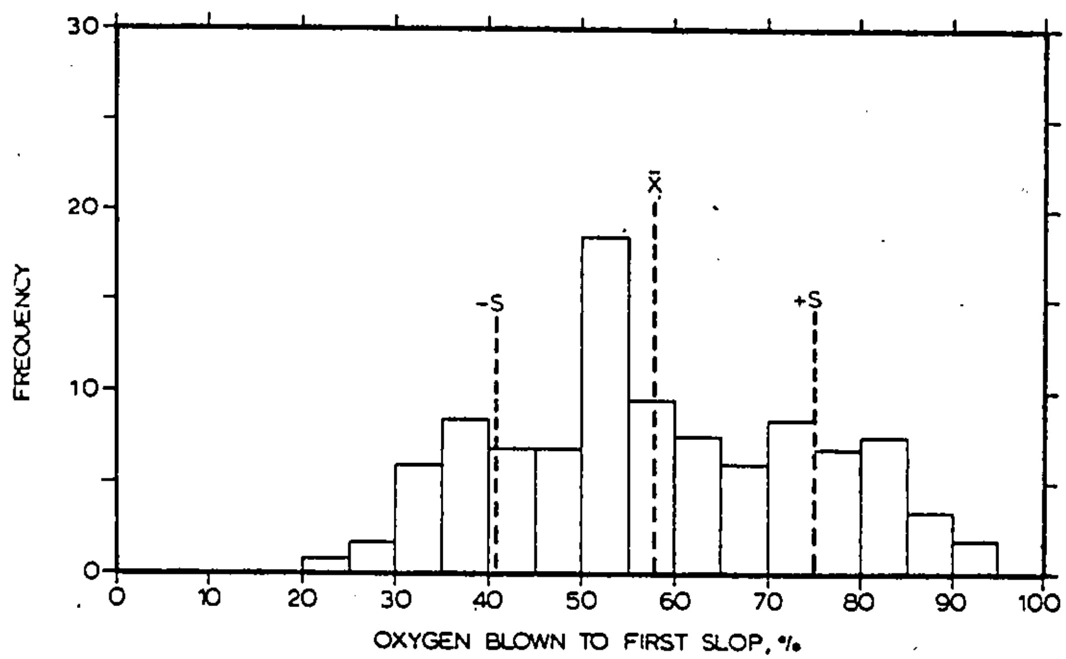
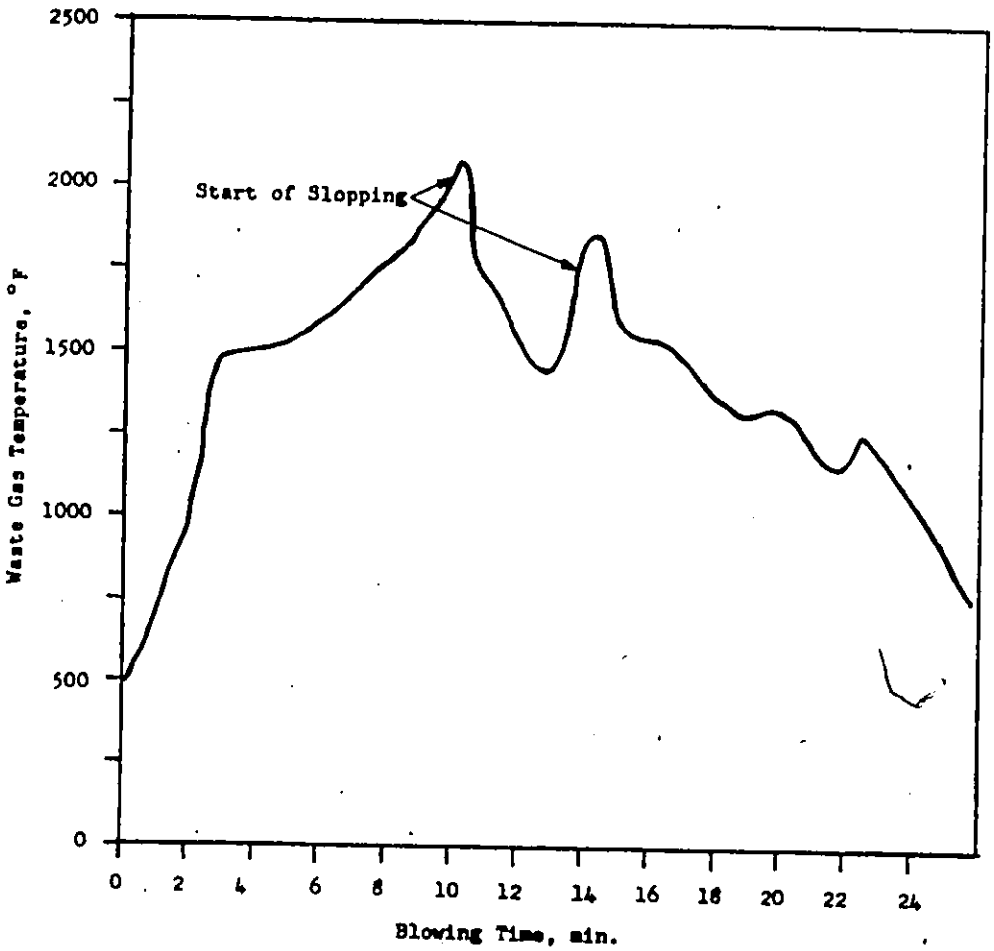


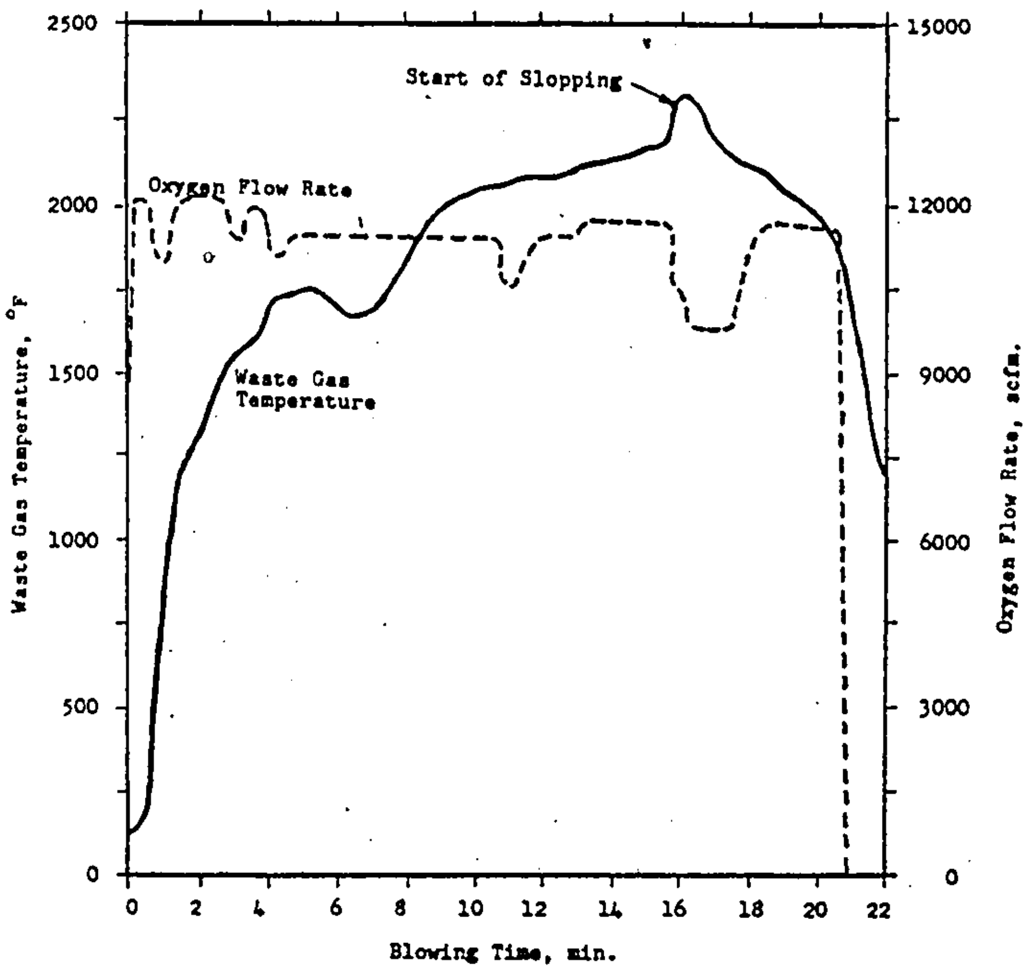
Figure 10: Waste Gas Temperature Trace - Slopping Heat



when corrections should be made to prevent slopping. The furnace operation was altered by reducing the oxygen flow rate. This method was selected because Stelco's furnace operators have found that it is the most rapid way of stopping slopping.

The procedure, basically, was to force the waste gas temperature trace to conform to the pattern which had been observed earlier on heats which did not slop (figure 8). If the waste gas temperature rose at a rate greater than approximately 300^{o}F per minute during the first third of the blow, the oxygen flow rate was reduced to slow the rate of increase. Throughout the remainder of the blow, the oxygen flow rate was reduced if the waste gas temperature increased at greater than approximately 50^{o}F per minute. Figure 11 shows the progress of a heat controlled in this manner. As can be seen from the graph, at about one minute into the blow the oxygen flow rate was reduced to 10500 scfm, for about 30 seconds to counter a rapid rise in temperature and then returned to 11500 scfm. The flow rate was subsequently reduced at 4, 5 and 11 minutes into the blow because of rapid temperature increases. No slopping occurred during this period. At 16 minutes into the blow, the oxygen flow rate was reduced to 10,500 scfm in response to a rapid rise in temperature. Some slag was ejected shortly after and the oxygen flow was reduced further to approximately 10,000 scfm to halt this slopping. The flow rate remained reduced until 18 minutes into the blow

Figure 11: Changes to the Oxygen Flow Rate in Response to the Waste Gas Temperature - Manual Control Procedure



at which time it was returned to its normal setting. The remainder of the blow passed without incident.

To determine if the control system had significantly reduced slopping, the average ingot yield achieved on the trial heats was compared to the average yield of heats made using the standard practice. The standard heats selected for the comparison were produced in the same furnace, on the same days as the trial heats. This method of selection ensured that operating factors, such as lance life and hot metal composition, would be similar for the two groups, and so would not affect the comparison.

It was found that, by adjusting the oxygen flow rate based on the waste gas temperature, the yield could be improved significantly. The trial heats which were made during the period when slopping normally occurred most frequently (i.e. less than 500 heats on the furnace lining) had an average yield 0.9% higher than that of the standard heats (table 2). When the number of heats on the furnace lining increased to beyond 500, few of the heats made using the normal blowing practice slopped. As a result, the average yield of the trial heats made during this period was not significantly better than that of the standard heats. From these results, it was concluded that the number of heats which slop could be reduced by varying the oxygen flow rate in response to changes in the waste gas temperature.

Although these trials had proven the feasibility of using the waste gas temperature as the basis for a control

Table 2 Comparison of the Average Ingot Yield Achieved on Control and Normal Heats (0-500 heats on lining)

	Average Yield (%)	Standard Deviation (%)	Duration of Main Blow (min)	Sample Size (Heats)
Normal	84.2	3.3	21.1	222
Control	85.1	2.4	21.8	56
Change	+0.9*		+0.7	

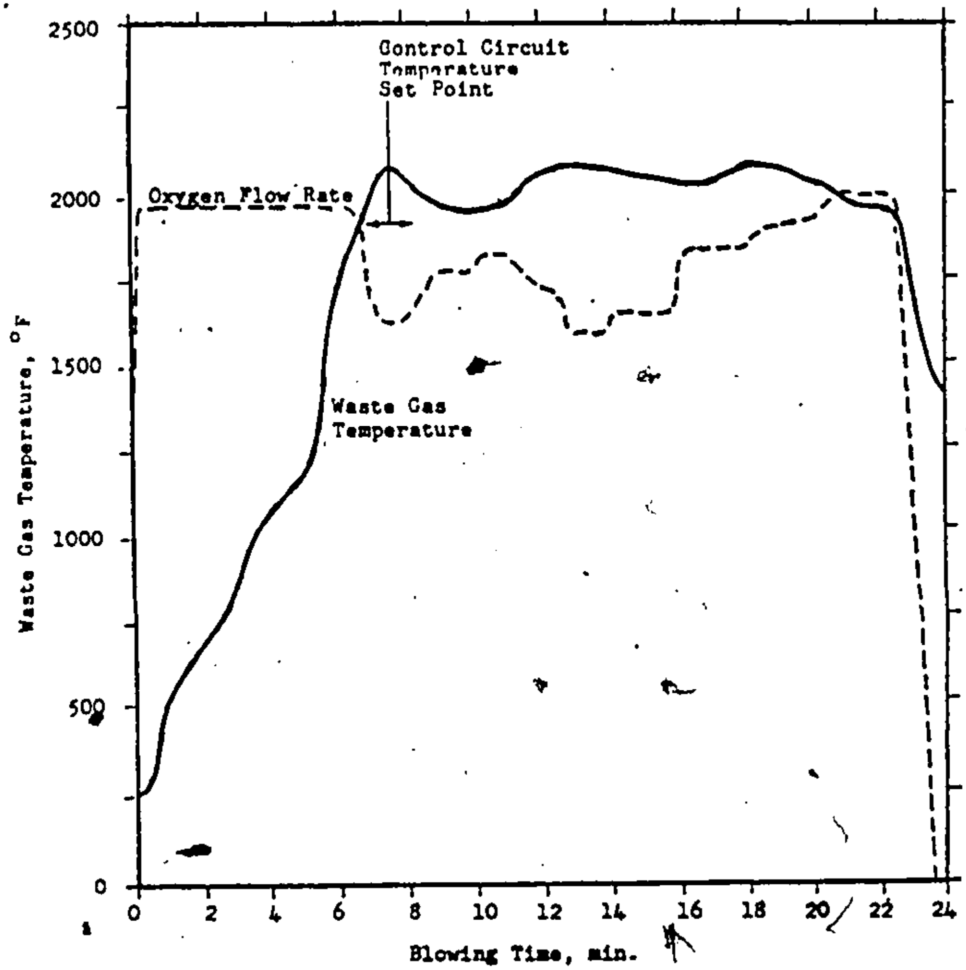
* Greater than 99% significant based on a 1 sided t test.

system, a practical method for preventing slopping had yet to be developed. The practice of manually adjusting the oxygen flow based on the waste gas temperature, which was employed for the trial heats, was impractical for day to day use. Because of their other duties, the B.O.F. operators did not have enough time to continually monitor the changes in the waste gas temperature during the blow. Therefore, a control system was built which would automatically adjust the oxygen flow rate using the waste gas temperature as a signal.

The control system was designed to prevent the waste gas temperature from exceeding a specific threshold level. During the trials, the threshold temperature was set at between 1800 and 2000^{o}F so that the controller would come into operation only when the temperature of the waste gas exceeded the normal plateau level. Sudden increases in the waste gas temperature, such as those which occur prior to slopping, would trigger the control circuit and the oxygen flow rate would be reduced until the temperature dropped back below the limit. A gain control was also built into the control circuit which adjusted the amount by which the oxygen flow rate was cut for a given change in waste gas temperature above the threshold. No specific gain setting was used during the trials; the gain level was selected by the observer on a day to day basis depending on his assessment of the behaviour of the furnace.

The waste gas temperature and oxygen flow rate traces from a heat produced using this control system are presented in figure 12 to better illustrate its operation. As may be seen from this figure, the control circuit came into operation approximately 7 minutes into the blow when the waste gas temperature exceeded the set-point temperature of 2000^{o}F. The oxygen flow rate was reduced to 10,000 scfm as a result. No slopping occurred during this period. As the temperature dropped, the control circuit gradually increased the oxygen flow rate until 11,000 scfm was reached 10 minutes into the blow. At about 12 minutes the circuit again detected an increase in waste gas temperature and reduced the flow rate to 10,000 scfm. Sparks were being ejected from the furnace at this time and at 13 minutes some light slopping occurred. About 16 minutes into the blow, the waste gas temperature again dropped and the circuit responded by increasing the oxygen

Figure 12: Changes to the Oxygen Flow Rate in Response to the Waste Gas Temperature - Control Circuit



flow rate. From this point, no further increases in waste gas temperature occurred and the blow proceeded smoothly.

The equipment for the control circuit was constructed by personnel from Stelco's B.O.F. instrument repair department and installed in "number six" vessel pulpit. The performance of the circuit was tested by using it to control the oxygen flow rate on a series of heats over a full campaign. As with the previous trials, the performance of the control was assessed by comparing the yield of normal and test heats (table 3). Use of the control circuit brought about a 1.2% improvement in average yield through reduced charge loss from slopping.

Table 3 Comparison of the Average Ingot Yield Achieved on Control and Normal Heats (0-500 Heats on Lining)

	Average Yield (%)	Standard Deviation (%)	Duration of Main Blow (Min)	Sample Size (Heats)
Normal	84.6	3.5	21.4	253
Control	85.8	2.6	20.9	77
Change	+1.2*		-0.5	

* Greater than 95% significant based on a 1 sided t test.

During these trials, several difficulties were encountered with this control system. One major problem was how to select the correct set-point temperature. To ensure rapid reaction to potential slopping conditions while avoiding unnecessary reductions in oxygen flow rate, the set-point temperature on a given heat should be as close as possible to the normal (i.e. non-slopping) waste gas temperature. The temperature of the waste gases, when they reach the thermocouple, depends on the rate at which air is being drawn into the entrance to the waste gas duct to burn carbon monoxide coming from the vessel. This flow of air into the stack is controlled by dampers in the waste gas cleaning system. Usually, the damper settings do not change from heat to heat so the waste gas temperature reaches approximately the same level. Occasionally, however, the dampers open wider than normal because the pressure sensors which control them become clogged with dust. As a results, more air is drawn into the stack and the temperature of the waste gases is depressed. Under these conditions the normal set-point temperature is too high and the ability of the control circuit to react to potential slopping conditions is impaired.

Throughout these trials, operating conditions were found to have a significant bearing on the effectiveness of the control system. Slopping was generally both severe and persistent under the following conditions:

i) High manganese content in the hot metal (greater than approximately 1.3%).

ii) Converging-diverging nozzles on the oxygen lance damaged.

iii) Lance to bath separation greater than normal.

To control slopping under any of these conditions, it was often necessary to run at reduced oxygen flow rate through much of the heat. Brief reductions in the oxygen flow rate (i.e. one to two minutes in duration), such as those instituted by the control circuit, brought only a temporary halt to the ejection of slag; on restoring the flow rate to its normal level slopping would return.

Since there were no simple solutions to these problems, the control circuit was withdrawn from service. Work on on-line control was suspended at this point so that more attention could be directed to developing methods of off-line control.

CHAPTER 4

OBSERVATIONS ON THE MECHANISM OF SLOPPING

Testing methods of on-line and off-line control in a BOF shop is laborious and time consuming because care must be taken to ensure that operating factors (e.g. lining life, hot metal composition) do not bias the results. If the effect of a change in operating conditions could be predicted from theory, changes in practice which are unlikely to reduce slopping would not need to be tested in production. Therefore, a literature search was conducted to find a mechanism which would explain why slopping occurs.

4.1 Mechanism of Slag Foaming Proposed by F. Bardenheuer

Slopping occurs when the slag foams to such an extent that it exceeds the capacity of the furnace. To determine why slopping occurs it is thus necessary to understand the mechanism of slag foaming. Bardenheuer [21], drawing upon his own extensive experience and the work of other investigators such as Kozakevitch, has proposed a mechanism to explain the causes of slag foaming. The following is a description of this mechanism.

If the rate at which gas enters the slag exceeds the rate at which it leaves the volume of foam will increase. Thus foaming will increase if gas is generated more rapidly or if the gas bubbles remain in the slag longer. Bubble residence time increases as the gas bubble's size, rate of coalescence and rate of rise decrease. Bubble size may be influenced by many factors including the size of the site for its growth. The rates of bubble coalescence and rise decrease with increasing slag viscosity and decreasing interfacial tension. These two properties, in turn, are affected by the chemical composition of the slag, the presence of precipitates and the temperature.

The rate of gas generation in the BOF depends on the decarburization rate. Early in the blow, carbon must compete with manganese and silicon dissolved in the charge metal for the gaseous oxygen supplied through the lance and so the rate of decarburization, initially, is slow. As the silicon and manganese content drops, progressively more of the oxygen is consumed by the oxidation of carbon until, after approximately 40 percent of the oxygen has been blown, the decarburization rate reaches a maximum which it maintains almost to the end of the blow. The rate of decarburization during this period is controlled mainly by the rate at which oxygen is supplied through the lance.

The oxidation of carbon occurs at several sites. Part of the decarburization occurs via reaction between the slag and iron droplets ejected from the metal bath by the force of the oxygen jet. It is believed that the carbon monoxide generated by this reaction between carbon dissolved in these tiny iron droplets and the slag oxygen causes foaming.

Slag foaming will thus increase as the number of droplets in the slag increases and as the rate of the slag-metal reaction increases. The amount of iron emulsified in the slag depends on the rate of droplet generation and the residence time. The rate of droplet generation in the BOF is relatively uniform throughout the blow because a fixed blowing practice (constant oxygen flow rate and lance to bath distance) is used. The droplet residence time increases when the slag viscosity rises and interfacial tension drops, as was the case for the gas bubbles. It is thought that the rate of reaction is controlled by the rate of oxygen transport in the slag and is dependent on the activity of FeO in the slag.

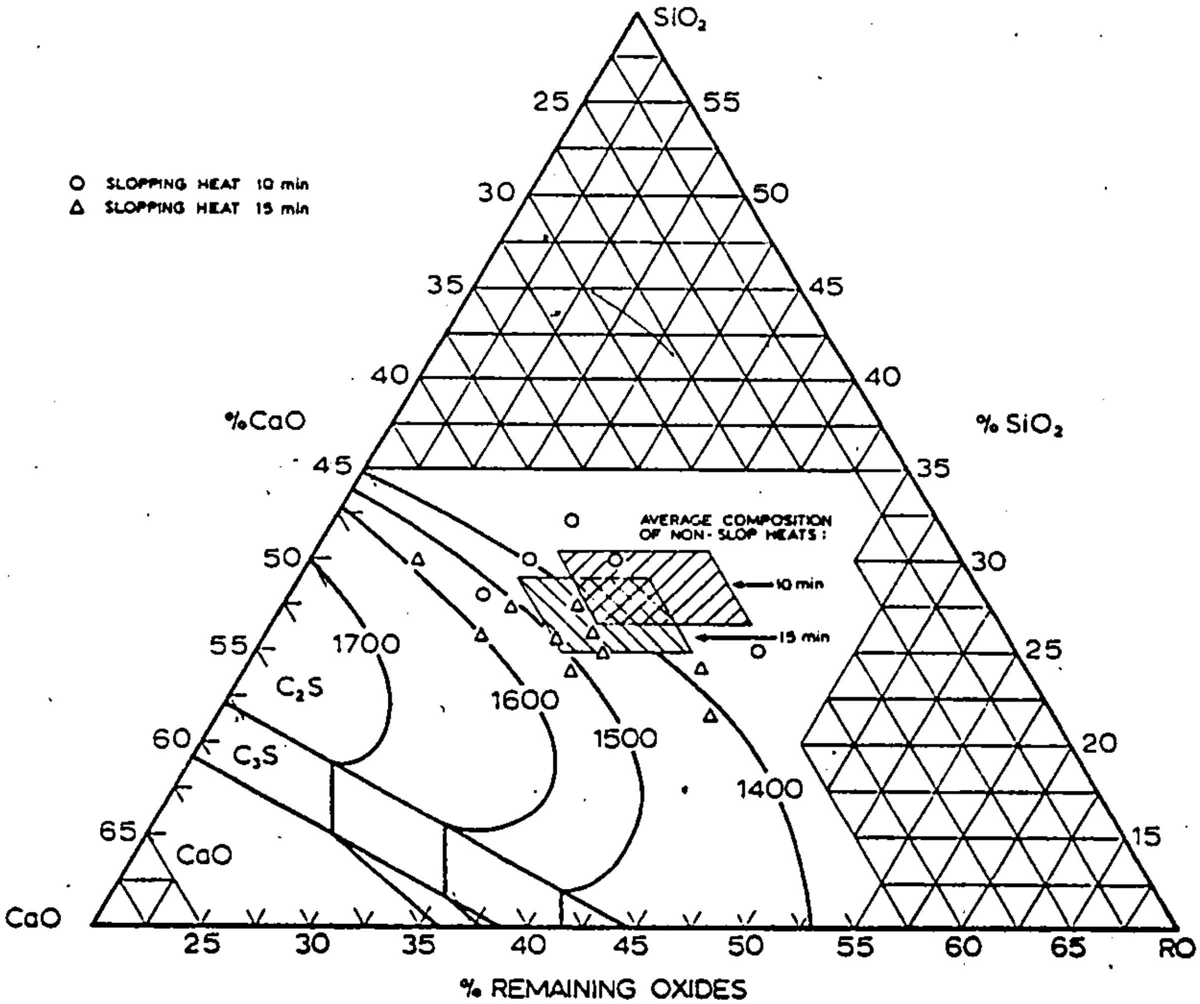
Briefly then, the foaming of the slag will increase with increasing gas bubble residence time, iron droplet residence time and reaction rate, all of which are strongly dependent on the composition of the non-metallic portion of the slag. The concentrations of iron oxide and manganese oxide strongly affect the foaming of the slag. As the concentration of manganese oxide or iron oxide increases, the activity of FeO will rise, resulting in an increase in the rate of reaction between the slag and carbon dissolved in the entrained iron droplets. As a result, foaming will tend to increase as the level of iron oxide or manganese oxide increases. Set against this increase in the reaction rate, the residence time of droplets and gas bubbles tends to fall as the concentration of iron oxide or manganese oxide rises because these oxides reduce the orthosilicate liquidus temperature. If the concentrations of these two oxides are too low, the liquidus temperature may exceed the slag temperature. The fine precipitates which result hinder the coalescence of both the rising gas bubbles and iron droplets by adhering at the interface with the slag and by increasing the bulk viscosity. By increasing the residence time of the bubbles and droplets, these conditions tend to promote foaming.

Extending this theory to slopping, slopping will occur more frequently when conditions promote foaming. High concentrations of iron or manganese oxide in the slag and precipitation of dicalcium silicate are both likely to be associated with slopping.

4.2 Investigation of the Mechanism of Slopping at Stelco

A study was undertaken to find evidence which might either support or contradict this mechanism. On 37 heats, slag samples were taken during the period when heats most frequently slop to determine if slopping is related to the chemical composition of the slag (details of the sampling and analysis procedures are given in Appendix I). The chemical analyses of these samples were plotted on a $CaO-SiO_2-RO$ (where $RO = FeO + MnO + MgO + Al_2O_3$) phase diagram so that the composition of the slags could be easily compared (figure 13). For simplicity, the analyses from heats which did not slop were summarized by plotting the means and standard deviations

Figure 13: Composition of the Slag at 10 and 15 Minutes into the Blow



only. The analyses of the samples taken during or just prior to the ejection of slag were plotted for the 15 heats which slopped (figure 13).

The slag samples from slopping heats varied greatly in composition. At one extreme, the composition of some of the slag samples approached the 1600°C dicalcium silicate isotherm. Some of the slag samples from slopping heats had much higher RO contents; the composition of some samples lay outside the 1400°C dicalcium silicate isotherm.

These results together with other observations made during this study support the mechanism proposed by Bardenheuer. The sudden increases in the temperature of the waste gas which were always observed at the onset of slopping indicate that slopping is linked to an increase in the rate of decarburization. In the BOF, during the portion of the blow in which slopping occurs, the rate of decarburization is limited by the rate at which oxygen is supplied [18]. Since the rate of oxygen injection through the lance is constant, this increase in the decarburization rate must be caused by some change taking place inside the furnace. It is logical to suspect that the properties of the slag must be different during periods of slopping since the slag is the only other source of oxygen. Many of the slag samples from heats which slopped had compositions which lay further within the dicalcium silicate zone on the phase diagram than normal. Other slag samples from heats which slopped had abnormally high 'RO' contents. These results support the contention that slopping is linked both to dicalcium silicate precipitation and the concentration of FeO and MnO in the slag. Since the proposed mechanism agrees with these observations made in Stelco's BOF shop, it appears to be a valid explanation of the causes of slopping.

4.3 Use of the Mechanism to Explain How Operating Conditions Cause Slopping

Using this mechanism, an attempt can be made to explain why slopping is related to certain operating conditions.

a) Vessel Lining Life

The thickness of the refractory lining decreases slightly with every heat as a result of attack by the slag. Over a campaign (approximately 1000 heats), this gradual erosion of the lining increases the volume, available within the furnace, from 3,880 ft^3 to approximately 5,300 ft^3. More space is available to contain the foaming of the slag because of this gradual increase in furnace volume and, as a result, slopping occurs less frequently.

b) Hot Metal Silicon Content

In most BOF's, the amount of lime charged is varied to maintain a lime to silica ratio (V-ratio) which will ensure adequate sulfur removal. As the silicon content of the hot metal increases, more silica is generated and the weight of lime charged must be increased. As a result the slag volume tends to increase as the silicon content of the hot metal increases. This increase in slag volume hinders the escape of carbon monoxide bubbles and so promotes foaming.

Slopping often results from this increase in foaming.

c) Hot Metal Manganese Content

An increase in the manganese content of the hot metal tends to cause the MnO concentration in the slag to increase. Such an increase, in turn, increases the activity of FeO [18, 23]. As the activity of FeO increases, the rate of decarburization (slag-droplet reaction) increases and foaming is encouraged. Thus, increasing the manganese content of the hot metal gives rise to conditions which are likely to cause slopping.

d) Oxygen Lance Height and Nozzle Damage

It has been found that the FeO content of the slag increases if the oxygen lance is operated farther above the bath than normal or if the nozzles, through which the oxygen passes, are damaged [7, 24]. This increase in the FeO content increases the rate of decarburization (slag-droplet reaction) and, as a result, tends to promote foaming. Consequently, using a lance with damaged nozzles or blowing with the lance too high produces conditions which can cause slopping.

e) Oxygen Flow Rate

When the oxygen flow rate is reduced, the total rate of carbon monoxide generation decreases leading to a decrease in foaming. It is this ability of the oxygen flow rate to produce rapid changes in the rate of gas generation which makes it so effective in stopping slopping.

Although reducing the oxygen flow rate is an effective method of stopping slag ejection, it will not necessarily correct the conditions which give rise to slopping. Reducing the oxygen flow rate changes the distribution of oxygen so that the iron oxide content of the slag increases [7]. Where slopping is initially caused by a high content of MnO and FeO in the slag, this additional iron oxide will only aggravate conditions. On such heats, slopping will return when any attempt is made to restore the oxygen flow rate to normal levels. On the other hand, in cases where slopping is related to the formation of precipitates, the increase in FeO resulting from the reduction in oxygen flow rate can be beneficial. On these heats, the fluxing action of the iron oxide and the heat generated by the oxidation of the iron bath promote the dissolution of the dicalcium silicate precipitates. Because of this limitation, an on-line control system which is only capable of varying the oxygen flow rate will likely be only partially successful in preventing slopping.

CHAPTER 5

CONCLUSIONS

It would be a mistake to think that all of the findings of this study can be applied to the operation of all basic oxygen furnaces. The relation between slopping and operating conditions and the results of the on-line control trials are relevant specifically to Stelco's B.O.F. operation. In another steel company, where the B.O.F.'s are operated differently, slopping could be related to different operating conditions and another approach to on-line control might be required. A generalization can be made, however, with respect to the relation between slag formation and slopping. Any steel company which is trying to reduce slopping must develop operating practices for its B.O.F.'s which minimize the chances that the slag will become over-oxidized or precipitate dicalcium silicate.

APPENDIX I

DESCRIPTION OF PROCEDURES FOR SAMPLING AND ANALYZING SLAG

The slag was sampled, while the furnace was operating, by dropping a chain through the lance entry port in the waste gas duct (figure 7). Slag, frozen on the links, could be chipped off the chain when it was withdrawn from the furnace. Two slag samples were taken in this manner during each heat; samples were taken at 10 and 15 minutes into the blow. Because of the thorough mixing inside the furnace, this technique should provide a representative sample of the liquid non-metallic portion of the slag for chemical analysis. Other advantages of this method of sampling are its safety, simplicity and low cost.

Before chemical analysis, the slag samples were ground to -80 mesh and any metallic iron was magnetically separated.

Analysts, employed by Stelco's Research and Development Department, determined the composition of these samples. An optical emission spectrograph was used to measure the concentrations, in weight percent, of CaO, SiO_2, MgO, MnO and Al_2O_3 in the slag. A solution, prepared by dissolving a small amount of the powdered slag (less than 1 gram), was passed through the spectrograph where an electric discharge was used to excite the ions (Ca^{2+}, Mg^{2+}, etc.) into emitting light of a characteristic wavelength. The concentration was determined by comparing the intensity of the emitted light to the reading when a standard solution was used. The FeO content was determined by dissolving several grams of the slag in acid, then titrating with a standard solution of potassium dichromate. Since the spectrograph does not distinguish between CaO dissolved in the slag and CaO present as undissolved lime, a further analysis was run to measure the "free lime" content of the samples. For this analysis, several grams of the sample were leached with a solution of sucrose and water (20 g. of sucrose per 100 ml. of water). The resulting liquid was then titrated with a standard acid solution. The percentage of CaO present as "free lime" was subtracted from the value from the spectrograph to give the percentage CaO dissolved in the slag. The slag analyses (i.e. CaO dissolved in the slag, MgO, MnO, FeO, SiO_2 and Al_2O_3) were then normalized so that their sum came to 100 percent (Table IAI). (Note: A more detailed description of these analysis procedures can be obtained by contacting Stelco's Research and Development Department.)

The pseudo-ternary diagram, used to present the analyses, was developed by researchers from the Institut de Recherches de la Siderugies Francaise [25]. This phase diagram was selected because it was developed using slags with compositions similar to those found in this study (Table IAII). The axes of this diagram show the weight percentages of CaO, SiO_2 and RO in the slag; where RO = FeO + MnO + MgO + Al_2O_3.

Table IAI: Composition, in Weight Percent, of Slag Samples Taken From Stelco's BOFs

Slag Composition @ 10 min.						Slag Composition @ 15 min.						Slop
CaO	SiO_2	MgO	MnO	FeO	Al_2O_3	CaO	SiO_2	MgO	MnO	FeO	Al_2O_3	Rating
33.8	27.1	6.3	17.4	12.4	2.6	40.2	26.8	7.3	12.8	9.8	2.8	0
39.5	34.6	7.3	10.8	5.7	1.2	41.3	32.1	7.7	9.5	7.4	1.1	0
41.8	31.0	7.1	12.2	6.0	1.6	44.4	28.0	8.1	11.0	6.7	1.5	0
36.8	31.0	6.3	15.8	7.8	1.6	38.7	30.2	7.3	13.9	7.5	1.8	0
34.9	28.1	9.3	15.2	10.7	1.5	38.3	25.8	9.7	14.7	9.8	1.5	0
36.9	27.4	7.6	14.1	11.2	1.9	38.7	28.2	7.4	11.9	11.0	2.2	0
35.3	27.0	7.0	16.3	12.3	1.9	40.1	26.2	7.6	14.1	9.7	1.7	0
38.1	28.5	7.2	16.4	8.8	0.8	37.6	29.9	7.8	14.4	8.2	1.1	0
39.9	28.7	6.9	13.6	9.0	1.9	40.3	23.9	10.6	11.4	11.7	1.9	0
31.2	26.0	7.6	15.7	17.3	1.8	36.0	25.6	7.7	13.6	14.1	2.6	0
35.8	31.2	5.6	18.1	7.6	1.2	40.4	29.2	6.4	15.7	6.6	1.1	0
32.4	31.1	8.2	15.0	8.9	3.7	34.4	28.0	9.2	13.1	11.2	3.5	0
35.3	27.7	6.6	16.3	11.8	2.3	34.8	25.3	6.6	14.4	15.9	2.4	0
27.4	28.4	9.7	16.8	15.6	1.7	31.7	25.7	9.9	14.4	15.8	1.7	0
35.0	28.9	8.7	15.3	9.0	2.4	38.0	26.3	9.2	13.5	10.0	2.4	0
32.8	27.8	6.4	15.9	13.6	2.6	33.3	25.6	6.6	13.7	17.5	2.7	0
35.4	27.1	5.8	16.8	13.9	0.8	38.3	26.2	6.8	14.6	12.5	1.0	0
34.9	28.4	7.9	16.0	10.8	1.7	38.0	27.8	8.6	14.2	9.4	2.1	0
37.9	28.0	6.2	14.5	7.5	5.0	40.0	24.5	6.0	12.0	12.2	4.6	0
33.3	27.6	7.1	16.4	13.6	1.8	38.8	27.1	7.4	14.5	10.1	2.0	0
27.1	24.7	8.2	19.5	18.2	2.0	35.7	21.8	10.3	16.8	13.1	1.9	0
33.7	27.1	6.5	19.2	10.6	2.5	42.1	24.4	7.1	15.6	7.5	2.6	0

Slag Composition @ 10 min.						Slag Composition @ 15 min.						Slop Rating
CaO	SiO_2	MgO	MnO	FeO	Al_2O_3	CaO	S_iO_2	MgO	MnO	FeO	Al_2O_3	
31.7	24.8	6.8	15.5	18.6	2.1*	29.3	27.3	6.2	17.2	17.2	1.9	1
34.0	25.6	7.5	17.6	13.6	1.3	39.3	25.8	7.2	14.4	11.4	1.7*	1
39.9	29.8	8.3	13.0	7.5	0.8*	No Sample						2
35.8	30.0	7.5	16.0	7.3	3.2*	38.3	29.4	7.6	13.1	7.4	3.5	2
33.7	25.3	7.0	19.8	11.2	2.2	38.7	24.7	7.0	15.9	18.6	3.3*	2
30.8	26.4	6.4	20.7	12.9	2.4	35.2	24.4	6.3	17.8	13.0	2.5*	2
36.0	30.0	7.8	18.2	5.3	2.6	38.6	27.3	8.5	16.0	6.8	2.3*	2
38.3	29.4	6.2	12.4	11.8	1.2	43.9	25.8	5.6	10.6	12.0	1.2*	3
41.3	31.4	6.0	11.3	8.0	1.8	45.2	29.7	6.6	10.0	6.0	2.3*	3
34.6	27.4	10.5	10.5	13.1	3.1	36.2	21.5	7.2	8.2	23.5	2.6*	3
38.4	30.1	6.0	16.0	7.9	0.8	40.8	25.5	5.7	14.9	11.4	0.8*	3
40.3	28.7	9.3	13.1	6.1	2.2	41.8	27.3	9.1	10.6	8.9	2.2*	3
37.7	27.7	7.8	17.3	6.0	2.6	40.6	24.2	7.3	13.8	10.6	2.6*	3
36.6	31.7	7.6	15.4	6.2	2.0*	37.8	29.2	8.7	14.2	7.4	2.1	3
42.7	28.0	6.7	13.8	6.4	1.9*	44.4	23.6	6.0	12.9	10.5	1.8	3

Asterisk (*) indicates the composition of the sample which was taken closest to the time slopping occurred.

Table IA II: Slag Composition Ranges Used by IRSID [Ref. 25]

Range	Analysis in Wt. %						
	CaO	SiO_2	RO				Total RO
			FeO	MnO	MgO	Al_2O_3	
Minimum	32.2	7.5	10.0	5.0	6.5	2.0	23.5
Maximum	56.4	26.7	30.0	12.0	6.5	2.0	50.5

APPENDIX II

II.1 Description of B.O.F. Operation at Stelco

The operating practices, employed in Stelco's B.O.F. shop differ little from those used in similar plants around the world.

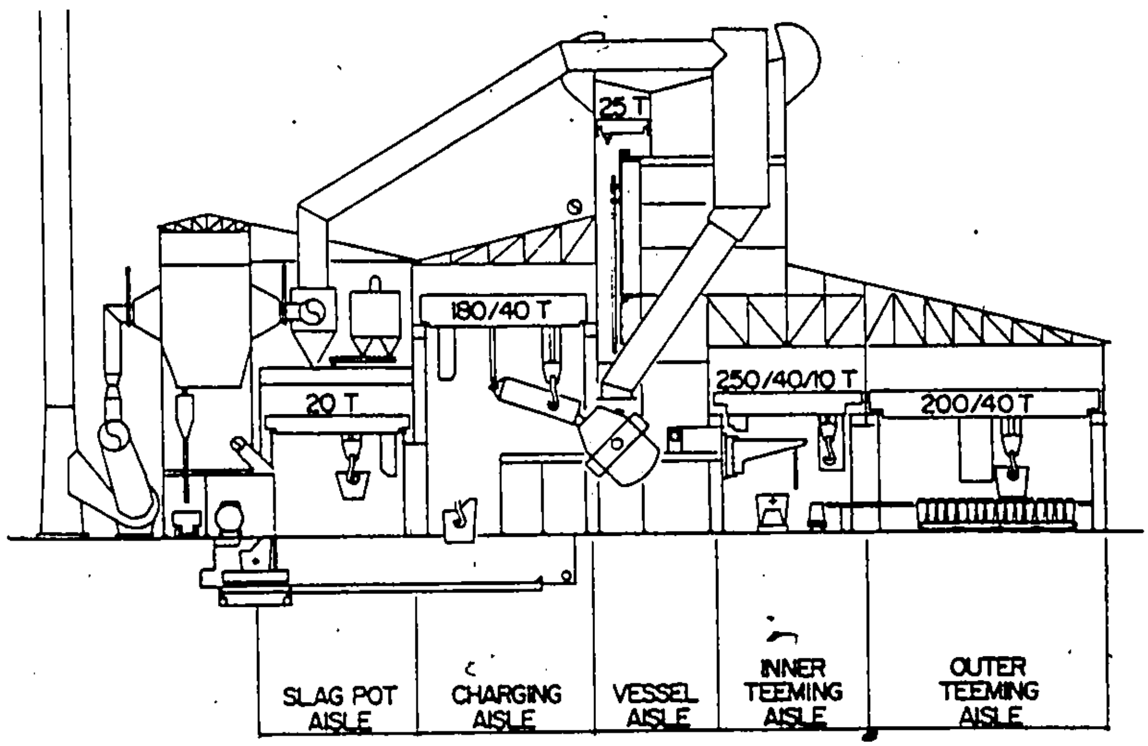
The hot metal, scrap and flux weights and the volume of oxygen required for each heat are calculated by computer based on heat and mass balances [26]. Hot metal, arriving in torpedo cars from the blast furnace, is weighed out into a ladle where its temperature is measured and a sample is taken for chemical analysis (silicon, sulfur and manganese). Scrap is loaded into a scrap box using a crane equipped with an electromagnet. Cranes are used to charge both scrap and hot metal into the furnace (figure IIA.1).

After the scrap and hot metal have been added, the furnace is rotated to the vertical position, the lance is lowered to a spot a fixed distance above the bath and oxygen is injected at 12,000 scfm. Lime, dolomitic lime and fluorspar are charged through a vibratory feeder system over the first 4 minutes of the blow; they are added to prevent dissolution of the furnace refractories and to promote sulfur removal. During the blow, silicon, manganese and carbon are oxidized to provide heat to melt the scrap and to bring the carbon concentration in the steel down to the required level. Carbon monoxide, generated during the blow, is allowed to mix with air at the mouth of the vessel and burns to form carbon dioxide. This waste gas passes up through a duct to the gas cleaning system where fine particles of iron oxide (fume) are removed before it is exhausted into the atmosphere.

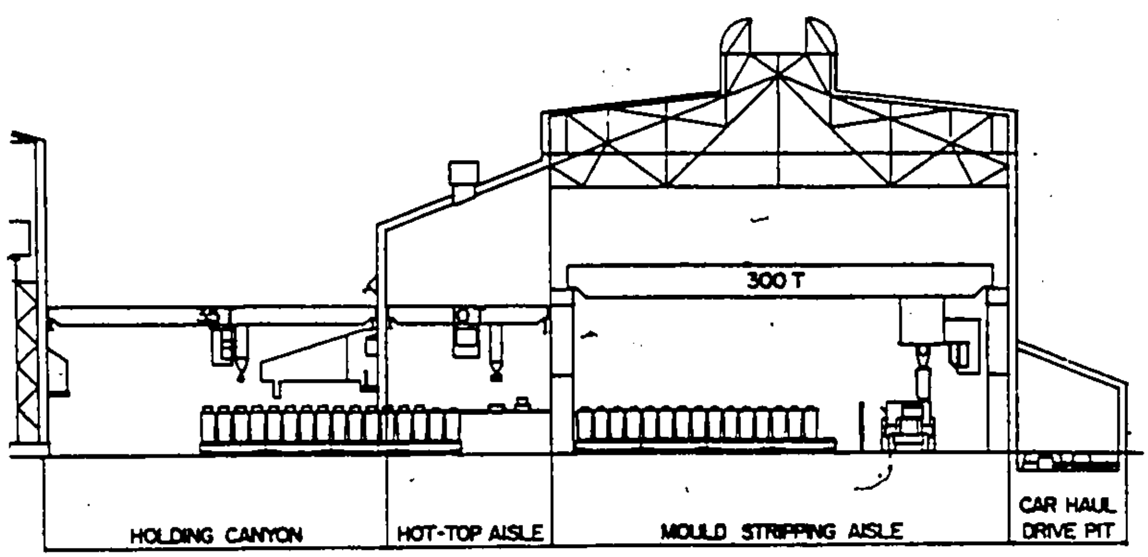
After the specified volume of oxygen has been blown, the lance is retracted and the vessel is turned down into a horizontal position. The steel temperature is then measured and a sample is taken for chemical analysis (carbon, manganese and sulfur). If the temperature, carbon concentration or sulfur concentration do not meet specification, a second short blow (reblow) takes place after which the temperature is remeasured and a new sample is taken. When the steel meets specifications, the furnace is rotated into a horizontal position so that the steel drains out into a teeming ladle through a tap hole in the furnace wall. Ferroalloys are added to the steel while it is being tapped into the teeming ladle to bring it to the required composition.

After tap, the furnace is rotated to the charging side and the spent slag is poured out into a steel pot in which it is carried to the slag dump.

Figure IIA.1: Cross Section through Stelco's Hilton Works B.O.F. Shop



Cross section through the main building of the BOF shop.



Cross section through the holding canyon and the mould/stripper building.

II.2 Glossary

II.2.1 Definition of Terms

B.E.U.: Short for Big End Up. A type of ingot mold, which widens toward the top, used for casting steel.

Blow: The injection of oxygen into a B.O.F.

B.O.F.: Short for Basic Oxygen Furnace (also BOF)

Charge: The raw materials added to a furnace: scrap, hot metal and fluxes.

Charge to Tap Time: The time interval from the start of charging to the finish of tapping.

Fluxes: A general term for the slag forming materials added to the furnace: lime, dolomitic lime, fluorspar and limestone.

Fume: Fine particles of dust (consisting mostly of Fe_2O_3) which are generated during blowing and are entrained in the waste gas.

Heat: B.O.F. steelmaking is a batch operation; each batch of steel is called a heat.

Hot Metal: Molten pig iron received from the blast furnace.

Lance: A water cooled steel pipe fitted with a copper head used to inject oxygen into a B.O.F.

Lance Height: The distance between the end of the lance and the surface of the quiescent steel bath.

Lance Life: The number of heats made using a given lance.

<u>Lime</u>: Calcined limestone (Also known as Burnt Lime)

<u>Lining</u>: The refractory brickwork inside the steel shell of a furnace.

<u>Lining Life</u>: The number of heats made in a furnace since the last lining was installed (also referred to as Vessel Life).

<u>Pulpit</u>: A furnace control room.

<u>Reblow</u>: A brief period of oxygen injection used to adjust the temperature and/or carbon content of the steel.

<u>s.c.f.m.</u>: Short for <u>s</u>tandard <u>c</u>ubic <u>f</u>oot <u>p</u>er <u>m</u>inute. It is the unit usually used to measure the oxygen injection rate.

<u>Slop</u>: The overflow of slag and metal from a B.O.F. during the blow.

<u>Tap</u>: The period during which finished steel is emptied from the furnace into a ladle.

<u>Teem</u>: The period during which steel is drained from a ladle into a series of cast iron molds.

<u>Waste Gas</u>: A mixture of gases generated during the steel refining operation.

<u>Yield</u>: The percentage of the hot metal, scrap and ferroalloys which is recovered as usable ingots. (Also known as Ingot Yield).

II,2.2 Operating Conditions in Stelco's BOF Shop During 1975

1.	Heat Size	design (tons)	120
		average (tons)	138
2.	Vessel Volume:	new (ft^3)	3,880
		worn (ft^3)	5,300
3.	Average Hot Metal Composition:	Silicon (%)	1.04
		Manganese (%)	1.32
4.	Average Flux Usage:	Burnt Lime (lb/T)	114
		Dolomitic Lime (lb/T)	53
		Fluorspar (lb/T)	4.5
5.	Average Oxygen Consumption:	(ft^3/T)	1,750
6.	Oxygen Lance Design:	Configuration -	3 Holes
		Blowing Rate (scfm)	12,000
		Velocity	Mach 2.2

II.2.3 Conversion from British to Metric Units

Quantity	British Unit	Metric Unit	Conversion Factor
Length	in. ft.	cm m	2.54 3.048×10^{-1}
Heat Size	T (2000 lb)	t (1000 Kg)	9.072×10^{-1}
Flux Usage	lb/T	Kg/t	5.000×10^{-1}
Volume	ft^3	m^3	2.832×10^{-2}
Oxygen Flow Rate	scfm (ft^3/min. @ S.T.P.)	sm^3/min. (m^3/min. @ S.T.P.)	2.832×10^{-2}
Oxygen Consumption	ft^3/T	m^3/t	3.121×10^{-2}
Waste Gas Temperature	°F	°C	5/9 (°F-32)

°F	°C
0	-17.8
250	121.1
500	260.0
750	398.9
1000	537.8
1250	676.7
1500	815.6
1750	954.4
2000	1093.3
2250	1232.2
2500	1371.1

APPENDIX III

FACTORS AFFECTING INGOT YIELD

Variation in B.O.F. ingot yield is not caused solely by slopping. The following factors also affect ingot yield:

(i) Hot metal silicon and manganese content;

(ii) Contamination of the hot metal and scrap;

(iii) Steel grade;

(iv) Variation in ingot weight;

(v) Teeming practice.

Most of the manganese and practically all of the silicon in the hot metal charged to the B.O.F. oxidizes and enters the slag. As a result, as the silicon and manganese content of the hot metal increases, less of the charge can be recovered and the ingot yield drops. Increasing the hot metal silicon content from 0.75% to 1.25% will cause a drop in ingot yield of approximately 0.4%. Similarly, if the manganese content of the hot metal rises from 1.0% to 1.4%, the ingot yield will fall by about 0.2%. The yield differences, shown in figure 2, represent the effect of hot metal silicon and manganese on both oxidation losses and slopping.

Contamination of the hot metal and scrap reduces ingot yield by lowering the iron content of the charge. Hot metal is contaminated when blast furnace slag is carried over with the iron while the charging ladle is being filled from torpedo cars. In the Hilton Works B.O.F. shop, an average of 3000 pounds of blast furnace slag is charged per heat. Non-ferrous materials, left behind during recycling, contaminate the scrap. It is estimated that the scrap charge for a B.O.F. heat contains 2500 pounds of waste material. The total amount of charge contamination varies randomly from heat to heat.

Low carbon grades of steel tend to have lower ingot yields. Typically, a grade which taps below 0.2% carbon will have an average ingot yield 0.5% lower than a grade tapping at 0.5% carbon. This difference is caused partly by the extra carbon lost through oxidation. In addition, a rapid increase in the concentration of iron oxide in the slag occurs when the carbon level drops below 0.2% reducing the amount of recoverable iron.

The total ingot weight used in yield calculations is computed by multiplying the number of ingots of a given size by the nominal weight per ingot. All ingot molds of a given size are assumed to produce ingots of exactly the same weight. In reality, however, manufacturing tolerances and service wear cause molds of the same nominal size to produce ingots of slightly different weight. Because of this problem, it is estimated that the ingot yield for any single heat is only accurate to 0.5%.

Teeming practice can greatly affect the number of usable ingots which can be produced from a heat of steel. Any residual steel left in the teeming ladle is cast into a scrap ingot known as a butt which is not included when the yield is calculated. Grades teemed into small molds generally have lower butt losses and so have higher average ingot yields. Steel can also be lost during teeming through spills and solidification on the refractory lining of the teeming ladle (i.e. skulling).

In this study, care was taken to ensure that any differences in ingot yield could be related directly to slopping. Large samples were used to calculate the average ingot yield to minimize bias caused by random changes in charge contamination, grade mix, ingot weight and teeming practice. Also, during the control trials, test heats were compared to standard heats made over the time period to be sure that shifts in hot metal silicon and manganese concentrations would not affect the results. Statistical tests were used to validate the yield differences between the standard and test samples.

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