

Report on

B.O.F. OXYGEN LANCE ELECTRICAL CURRENT MEASUREMENTS*

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ABSTRACT

This report systematises thoughts concerning the B.O.F. lance electrical currents. The thinking has evolved in the search for a theory to understand and more fully exploit these lance currents signals for improved furnace control.

The report proceeds by discussion of the following subtopics.

- The pros for exploiting the signals.
- The cons, or rather the limitations of the signals.
- The possibilities to assist operator furnace control,
- The possibility for fully automated control.
- Steps to exploit the current state of the art.
- Recent experiments on the effect of control actions on the process and lance currents.
- Observations, lance current theories must explain
- Questions, conjecture and evidence on the lance currents.
- Recommendations for research.

B.O.F. OXYGEN LANCE ELECTRICAL CURRENT MEASUREMENTSThe Pros.

1. Present Lance Current Measurements can indicate if the blow is soft or hard. Hardness depends on height of the lance above the melt, the oxygen flow rate, the slag properties and the patterns of circulation established in the furnace. The Lance Current Measurements consistute a Blow Hardness Indicator. The signals can be processed by computer to give a single variable hardness indication. There is more in the signal than this single entity, however.

2. A softening of the blow can signal the onset of slop, particularly near the eight minute mark. A hardening of the blow at this time usually avoids slopping. Thus the Blow Hardness Indicator can be used as a Slop Predictor.

3. To achieve a stable blow without slop, a harder one or one of increasing hardness seems best on average. A softening of the blow in the last few minutes can ensure that low phosphorous levels are achieved. Slopping will not occur when the decarburization rate is low as in the last few minutes of the blow and the blow is softened. Processing of the Blow Hardness can achieve a Phosphorous Predictor.

4. The Lance Current Measurements can be processed to indicate blow stability. This can be more accurately assessed by introducing fluctuations in the oxygen flow rate or lance height. The harder the blow the more stable the regime in rough terms, but some hard blowing patterns are more stable than others. The more stable the blow, the more radical the control actions required to effect change as when softening the blow at the end of the heat. Thus it is useful and possible to process the signals to achieve a Stability of Blow Indicator.

5. The magnitudes of the Lance Currents, when positive, increase substantially as the lining on the vessel develops a hole in the region of the melt surface. Thus the signals could possibly be processed to form a Lining Wear Alert. The probabilities of a false alarm and of a miss detection of an actual hole would take a year or so to accumulate.

6. The above uses for the processed Lance Current Measurements are for one-line control of the furnace. The signals can also be used, and have been used, to assist in the off-line evaluation of certain control strategies for slop and phosphorous control. For example, the effect of late lime or ore drops can and has been studied.

7. There is a need for more precise end point control without the expense of a sublance. There is a potential for detecting certain critical points in the heat concerning Si and C removal, but such potential is not adequately assessed at this stage.

8. The signals clearly have a role to play in any future fully automated B.O.F. control to optimize performance. Bottom Bubbling and Audiometric information can only assist in the optimization of performance.

The Cons

1. Present Lance Current Measurements give no information in the first four to six minutes of the heat. Switching of lance load resistances in the near future could help here.
2. Lance currents cannot indicate directly if the blow is dangerously hard, although experience suggests that metalization of the lance may take place only in negative regimes. (This latter point should be further assessed). There appears to be no direct indication when to increase lance height to avoid metalization or to decrease oxygen flow rate to avoid exceeding stack thermal capacity. However, a blowing strategy can be evolved whereby response to fluctuations in lance height, or more conveniently oxygen flow rate, can be used to ensure that the lance is not unnecessarily low.
3. Lance current patterns in themselves cannot indicate or predict temperature, carbon and silicon levels in the steel or prill levels, basicity, or ore content of the slag. There is some measure of phosphorous content and thereby manganese and slag fluidity.
4. With the present measuring techniques for lance currents, the signal is absent during lance height changes so that feedback control of the lance height change is out of the question. This situation is avoidable at some cost.
5. When the lance swings to its extremity, the lance currents are shorted so monitoring may be intermittant. Again this situation is avoidable and low cost changes are now being assessed.

The Possibilities

1. Assisting the Operator. A crucial step in employing the lance current measurements to improve B.O.F. performance is to extract useful information from the signals so that appropriate control actions can be taken. Human operators appear to be able to learn quite quickly to interpret the signals and achieve improved control. They are able to cope with the moments when the signals are ambiguous, or are influenced by special circumstances. They are able to make useful correlations with other instruments so improving functional redundancy and consequently reliability. They are also able to use the heat to heat information and day to day information. The signals from a chart recorder, although variable in their patterns, are simple to interpret at a glance. They do not constitute an overload to the operator.

There is the possibility for the signals to be augmented or enriched so as to resolve ambiguities or to provide additional information. To achieve this it is suggested that a clock or operator controlled lance load resistance variation be permitted. For example, with a higher load resistor than the current $2.5 \text{ m}\Omega$ (say $10 \text{ m}\Omega$), information in the first six minutes of the heat may become available.

Computer processing of the signals to give Hardness, Stability or Phosphorous indications may assist the operator to interpret the chart recorder signals. Likewise, computer processing may give recommended control actions. The recorded and processed data should be the means whereby improved control strategies are developed.

2. Automatic Control. For the B.O.F. at Newcastle, lance height adjustments are not conveniently made on a continuous basis, and when made, the signal is lost. On the other hand, oxygen flow rate can be adjusted continuously within limits, although there is a penalty if the average flow rate decreases. Moreover, it has been

assessed that as far as the lance current measurements are concerned, there is an equivalence in effect on the lance current patterns of lance height changes and current flow changes as follows. On the 250 tonne vessel, 15 cm lance height increase is equivalent to 100 cu.m/min. oxygen flow rate decrease.

Using the above information, a feedback arrangement can be readily devised which controls blow hardness and stability and thereby slopping and phosphorous levels. The oxygen flow rate would be continuously adjusted to control hardness and stability and occasional lance height adjustments made to ensure that the oxygen flow rate kept within its limits and to its desired average value.

There is also the possibility of incorporating parameters from the Lance Current Measurements to include in a dynamical model of B.O.S. operation. The model would seek to estimate and predict the key melt and slag parameters of interest. The model would include all the a priori information on the heat and what is learnt from previous heats. Such a model may be useful in end point control without the use of a sublance. The key ingredient not available previously would be the Lance Current Measurement. It is not claimed that such a model would overcome all the weaknesses of existing models, but the possibility of achieving an improved model is perhaps worth exploring.

Steps to Exploit the Current State of the Art

1. There is an immediate productivity improvement that is to be gained by upgrading current B.O.F. control practice to incorporate the information which can be readily gleaned from Lance Current Measurements. Small monitors can be installed at minimal expense into the control cabins, and operators and melters formally briefed on their pros, cons, and future possibilities.

2. Algorithms for calculation of Blow Hardness and Stability from the Lance Current Measurements can be further developed. To date two algorithms have been studied. One based on a simple feature extraction approach tries to do what a human observer of the trace does. The other approach is via more abstract statistical methods. With new microprocessors becoming available which are five to ten times faster than the MINC computer, there should be no difficulty blending more feature extraction into the statistical framework for increased reliability.

3. The signal processing algorithms can be expanded to make control recommendations. Alternative control strategies can then be assessed. One attractive strategy is to blow with gradually increasing hardness* for the first ten minutes following the appearance of the signal. Then prior to the use of a subblow or two and a half minutes before the end, raise the lance one metre to blow softly for 30 seconds, and then return it to its previous value until the end of the blow. The operator has the choice of blowing harder initially so as to maintain predominately negative lance currents, or to be content

* but constrained to avoid excessive hardness.

with a less stable blow and work with positive lance currents which are perhaps better understood. These alternatives need to be further assessed, along with other variations.

4. The Lance Current Measurements can be enriched by facilitating load resistance changes controlled by the clock or operator or computer. Switching between three or four load resistances potentially provides more information. For example, with higher than the present $2.5 \text{ m}\Omega$ resistor, signals could be monitored in the first four or so minutes when existing lance currents are negligible. It appears that normal contactors and solenoids are inadequate for the job having contact resistances of tens of milliohms. Mercury switches may be required. A further enrichment of the signal is suggested by measuring the differential voltage between the lance tip and clamp. This can be done by monitoring the voltage at the oxygen intake to the lance across to the lance outer shell. This voltage in relation to the lance tip voltage can indicate current flow to and from the lance between the tip and clamp and possibly where this flow is taking place. Such information may give slag height or other useful information. Injection of currents into the lance is another source of signal enrichment.

Recent Experiments on Lance Electrical Current Measurements

1. Late Ore/Lime Drop Experiments

Hypothesis tested. It is known that Phosphorous content of the high temperature steel at turn down is roughly proportional to FeO and basicity which is approximately CaO/SiO_2 . Additions of ore and lime in the last few minutes may then reduce the turn down P levels lower than otherwise would be the case. Should this be so, then perhaps the need to soften the blow in the last few minutes may be obviated.

Experiments. Six late drops were organized with variations to the timing of the drop, whether lime or ore or both were dropped, and if both, whether together or apart. The quantity of ore dropped was also varied. Predictions of the P levels were made by G. Kemlo based on the trace and final temperature. Also the effect of the late drops on the trace, and the stack temperatures was noted.

Results of Experiments

1. Phosphorous predictions based on the Lance Current Measurements and the final temperature and made by G. Kemlo without compensation due to the late drops, were not significantly different than that given by the analysis. This suggests that any influence of the drops is reasonably reflected in the trace, but further assessment would be necessary to be sure of this.

2. If there is an immediate or subsequent influence of the late drops on the trace, this is assessed at not more than a 10 cm lance height decrease. It is suggested that there should be a corresponding lance height increase to suitably soften the blow for good phosphorous control.

3. Stack temperatures did not increase excessively even with a two ton ore drop in the last two minutes, although a two ton drop did appear to be a limit of reasonableness.

4. Yield figures for the six or so late drop experiments averaged in excess of 91%. The FeO content of the slag was 20% higher than for virtually all other high yield low carbon heats studied. Slag Fe content was also high. Further experiments could assess if these are representative figures.

2. Response of Trace to Radical Control Changes

(i) Rocking of the vessel. This experiment was performed three times with very little effect on the trace as far as visually could be assessed. If anything, a mild softening of the blow occurred. It is conjectured that tilting when scrap is unmelted could more effectively stir the vessel and achieve the improvements normally associated with Bottom Bubbling or Lance Stirring. Extensive testing would be required to support this conjecture.

(ii) Lance height/oxygen flow rate equivalence. It has been conjectured that 15 cm lance height increase is equivalent to a 100 cu.m/min. oxygen flow rate as far as the trace is concerned. From a number of trials when such changes were made simultaneously no apparent effect was discernible. This suggests that in forcing a different trace pattern, oxygen flow rate could be used within limits to achieve the desired pattern followed by cancelling flow rate/lance height adjustment to achieve the desired flow rate.

(iii) Radical oxygen supply reductions. The influence of cutting oxygen flow rate from its upper limit of 525 cu.m/min. to 250 cu.m/min. was assessed. The patterns on the trace simply indicated a softening of the blow as expected with signal level

reduction. Accidental situations have indicated on other occasions a total loss of signal when a complete oxygen cut occurred with the lance and clamp in position. Reductions of 100 cu.m/min. and increases of 50 cu.m/min. had relatively small effects on negative traces.

(iv) Radical lance height changes. A one metre lance raising trial for 20-30 secs. was carried out two minutes prior to the end of the heat in order to reduce Phosphorous levels by softening the blow significantly to generate FeO. The experiments did achieve target Phosphorous levels in each case, and significantly these were predicted accurately from the nature of the trace and final temperature. A surprise occurred when a one metre lance height increase had no apparent influence on the stable negative trace regime except when made in the last two minutes of the blow. At one time, the metre lance raising caused a lance hissing sound to be heard suggesting a low slag foam level. This low level is in the conventional wisdom thought to be undesirable for dephosphorization, but the phosphorous levels were reasonably low in this heat suggesting that there are compensating effects. The yields on the six or so heats in which this high blow technique was employed is in excess of 91%, also the FeO slag analysis levels were consistently 20% higher than for other heats in the trial.

Observations Lance Current Theories must Explain

In generating hypothesis concerning the Lance Current Measurements, it is believed important that any hypothesis explain the following observations associated with trace patterns. The observations are classified to be associated with negative traces or positive ones.

Negative Traces - Observations to be accounted for

1. The trace fluctuates either negative to zero or negative to positive or fluctuates over a negative range.
2. The lance/earth terminals behave as a virtual fluctuating voltage source with an internal resistance usually much less than $1\text{ m}\Omega$.
3. The voltage level has not been recorded in excess of 40 mV .
4. The melt has virtually the same voltage as the lance. This was assessed on one heat using a bottom electrode.
5. A wall electrode installed at the point where the vessel becomes cone shaped recorded an approximately equal but opposite in sign signal except when the lance clamp is off in which case it decreased in magnitude by a large factor.
6. Signal collapses to zero when oxygen is cut.
7. Seiching of the bath appears as oscillations in the signal and is detected more often than in the positive regimes.
8. Fluctuations are typically of lower frequency with negative traces.
9. On ignition there is a positive pulse followed by a smaller negative one and then negative pulses. These are detected with a high resistance load ($220\text{ m}\Omega$).

10. On a reblow, the signals may be negative for 30 secs. before becoming positive. For this a low lance is necessary.

11. The negative signals occur when blowing hard in an older (larger) vessel, and arise with "softer" blows on a newer vessel.

12. Hard blowing negative signals are less sensitive to lance height/oxygen flow rate changes - even one metre increase in lance height may not disturb the pattern.

13. Signal level is initially zero for the first third of the flow and goes positive in the last minute or so (typically) unless the blow is deliberately softened earlier.

14. The following observations are not necessarily confirmed. Colder vessels more easily give rise to negative signals. There is virtual elimination of slop with negative traces, if the lance is not too low. Flames associated with negative regimes are leaner and stack temperatures lower. Slag contact of some sort appears necessary. These notions should be subjected to further study.

Positive Traces - observations to be accounted for

1. The signal has the appearance of the filtered sum of three Poissonly distributed intermittent processes as explored in the report by Siromath, equivalently it has the appearance of conductivity changes in a foam bath bubbled with an air lance explored by J. Mathieson.
2. The average magnitude varies from heat to heat and changes during the heat.
3. Frequently the magnitude within the heat corresponds to the decarburization rate and perhaps temperature increase, but sometimes there is an increase towards the end of the heat that appears out of correspondence (perhaps it corresponds to CO₂ generation).
4. Slopping occurs following a softening of the blow except in the last few minutes of the heat. A time constant of 1-2 minutes is usually involved. The signal does not seem to be influenced by a spillover event.
5. The signal collapses to zero with an oxygen cut (with or without a lance withdrawal).
6. The average signal magnitude is largest for a furnace with a lining hole which penetrates to within a few inches of the shell. Gunning the hole with MgO reduces the signal level in subsequent heats.
7. The frequency of fluctuation increases as the slag emulsion is less viscous.
8. Lance height decreases of 15 cm. and oxygen flow rate decreases of 10 cu.m/min. have a cancelling effect. Independently they increase the hardness patterns and decrease the hardness patterns respectively.

9. Slag contact appears necessary for positive traces. When the slag slumps the signal suddenly drops in magnitude and is not the same pattern. Lance hiss can indicate loss of contact.

Questions, Conjectures and Evidence on the Lance Currents

Q.1: Where is the lance electrical current flow?

C.1: On ignition, the current flows between lance and melt and via the coated surface of the lining of the vessel wall to the rim and vessel shell - a 25 mΩ pathway. For the last three quarters of the heat, the path is the flame (as shaped by the slag within the vessel) together with the vessel lining surface above the slag to the rim.

E.1: * Trunion voltage drops are in antiphase from the lance voltages suggesting a vessel shell pathway to earth. This is to be tested further.

* The wall electrode experiment suggests a wall lining surface pathway to the vessel rim and shell.

* A hole in the lining near melt/slag interface decreases path resistance to earth.

* The signal strength fluctuates as the decarburization rate fluctuates which suggests a flame pathway.

* The bottom electrode showed antiphase behaviour for the ignition pulse, and sympathetic behaviour during high decarburization indicating a "shorted" lance and melt for this period.

* Negative traces are observed on "hard" reblows possibly before slag foam has time to develop. This should be further assessed.

* Pathway conductivity appears to depend on blow hardness and decarburization rate. It may fluctuate by a factor of up to ten over a few seconds period with the higher conductivity evidence of higher decarburization. A cut in oxygen flow shorts the signals and suggests that the slag of itself could only have a relatively low conductivity given a reasonable lance contact.

Q.2: What generates the lance negative electric currents?

C.2: These are generated by electron flow thermionically emitted from the surface of the vessel wall lining via flame ionization to lance. The flame is assumed to be neutral. There is assumed to be positively charged CO^+ and Fe ions for particles in the flame, and of course impurity Na or K ions.

E.2: * The pathways are exceedingly low resistivity, suggesting the more mobile electron charge carriers rather than ions or particles. The electrons can be emitted by hot slag and refractory (CaO, MgO) on the vessel lining surface and arrive via the metalization on the vessel lining near the rim.

* The electron flow can be due to charge gradients of a neutral plasma between lance and vessel well. For negative lance currents the gas velocity is greatest near the lance and so pressure and concentration is least there, allowing an electron flow to the lance.

* For negative traces, it may be that the flame is smooth and lean, with the Fe/FeO ratio high. The CO may not get into turbulent contact with the air so the stack temperature is cooler. Also, the CO/CO₂ ratio may be higher than otherwise in the vessel, explaining again lower stack temperature since oxidation of CO is exothermic. This evidence needs further assessment.

Q.3: What generates the positive lance currents?

C.3: These are generated by (predominantly) CO_2^- losing charge on the vessel wall lining. The surface area of the vessel is larger than that of the lance, and because of turbulence

patterns, the pressure is less adjacent to the walls giving a gradient to the wall. The lower pressure is because the CO_2^- streams up the side walls out of the slag. The electronic charge is generated by thermionic emission at the lance tip and travels via the O_2 as O_2^- to the melt. Also impurities enrich ionization and perhaps some electrons flow along the charge gradients.

E.3: * The pathways are less conducting for positive traces suggesting lower mobility carriers such as CO_2^- and O_2^- . Note CO_2 is roughly 10% of the CO.

* The lance penetration is such that the generated gas moves to the side wall and up around and through the slag giving turbulence around the lance, and more contact of charged Fe to form oxide.

* The currents appear in proportion to CO_2 generation and temperature. We assume CO_2 is roughly in proportion to CO.

Concerns: The above theory has difficulty with the apparent necessity for "slag contact" to achieve positive traces, and also the fact that slopping itself is not detected explicitly in any signal window. Maybe slag is necessary to achieve the relevant circulation pattern and consequent charge gradients? Maybe the electron transfer across vessel lining surface takes place below the slag level? Maybe the wall of the vessel has to be lined with active metalized slag to achieve a signal? Also there is some conflicting evidence that slag contact is required for negative traces.

Another concern is that on a late 2 tonne ore drop with a consequent brilliant flame, the trace was not any more different than a 10 cm lance change would give.

At this stage it is therefore not possible to isolate for certain the dominant signal source and pathway or even rank the various possibilities. This is an objective of current research.

Recommendations for Research

With more knowledge of the Lance Current Pathways and Sources, perhaps parameters can be identified from the signals with more direct physical interpretation than at present. The path conductivity which can be extracted using switched loads could indicate the state of slag, flame, or melt surface for example. The source voltage magnitude and sign could tell us the temperature, rate of chemical reactions, or some such. At present, definitive experiments to pin point the pathways and sources do not appear simple. Earlier bottom electrode, wall electrode, and trunion electrode experiments give significant leads, as does the theory devised to interpret the lance signals. Small laboratory scale experiments also have value, but again definitive ones are elusive at this stage. Forthcoming trunion electrode experiments, switched load facilities, and differential trace studies could give a significantly clearer picture, as could statistical analysis of the heats now fully monitored.

Specific experiments or studies which could lead to useful information are now listed.

Off-Line Studies

1. Investigate the time to initiation of significant lance currents from ignition. In particular correlate this with the Si level in the hot metal, furnace life, time to previous heat, lance height, etc.
2. Investigate the heats with predominantly negative traces but with last minute (or two) soft blowing to establish if these give higher yield, better specs. etc.
3. Examine furnace linings (electrically) on next furnace reline.

4. Measure resistance to earth of melt on turndown.

(This has now been done giving a minimum of 25 m Ω).

On-Line Studies

1. Establish whether negative trace stable regimes can be established at any time during the first three quarters of a heat with the view to achieving this automatically.
2. Seek lance/earth conductivity information on-line via switched load resistors and possibly external 2 volt lead/acid batteries (\approx \$44 with high current ratings). In particular, if the O₂ supply is suddenly cut to zero without raising the lance, test that the conductivity of the slag pathway is low. Determine its magnitude.
3. Trunion voltage drop can be monitored on the next furnace reline.
4. A photo cell mounted near the lance heat shield hole could correlate with the lance currents.
5. Do a "hard" reblow after removing the slag.
6. Try blowing more O₂ in negative regimes watching stack temperatures. Also do the same in the last two minutes or so.
7. Does negative signal level change as a lining hole develops?
8. Insulate lance with earthenware pipe lowered down lance during a blow - hoping it doesn't break and that it acts as an insulator.
9. Explore the merits of a differential trace between oxygen connection to the lance and outer lance shell. This in conjunction with the oxygen connection voltage may give information on slag height since it could tell current losses or gaining between the lance tip and

clamp.

Theoretical Work

1. Carry out calculations on possible Fe ion and particle densities and CO_2^- densities and gradients to confirm the explanations of lance currents.
2. Develop a dynamic model using blow hardness profiles which on-line will estimate C, P, Si, T etc. levels so that reliable prediction and control can be achieved.