

Dynamic models contain all the features of static models; and in addition have terms for reaction kinetics and process dynamics. The possible approaches include the following.

- (i) Instantaneous equilibria amongst the reacting phases may be assumed, i.e. the process is treated as being thermodynamically reversible. However, this is not very commonly followed, since the BOF reactions are far away from equilibrium, except at the end of the blow.
- (ii) Reactions are assumed to be mass transfer controlled. Having made this assumption, it is possible to adopt different levels of sophistication. This has been attempted in the past, but it has been found that in view of the complexity of the BOF process, it is not worthwhile to go in for a very high degree of sophistication. Instead, it is preferable to treat the reactions as first order, and adjust the coefficients obtained by statistical fitting of plant data.
- (iii) After silicon is oxidised, the major oxidation reactions are those of carbon and iron. In the case of fully dynamic control, the rate of decarburisation as well as the amount of oxygen consumed by carbon is continuously determined from the exit gas data. This allows computation of the rate of iron oxidation as well.

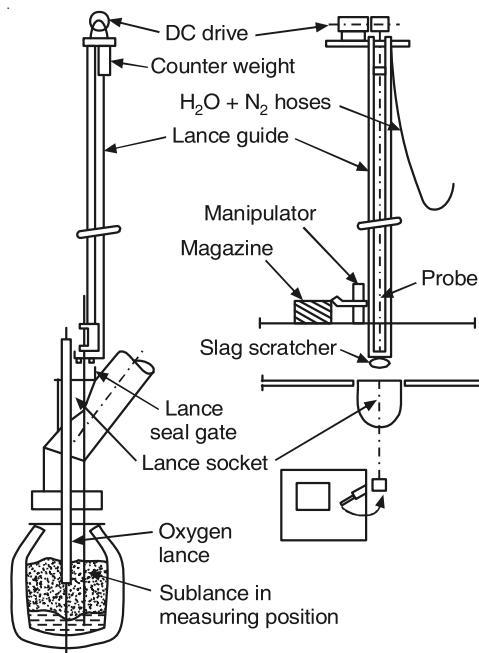
### 18.3 SEMI-DYNAMIC CONTROL

As stated in Section 18.1, in semi-dynamic control, some measuring probes—thermocouple, carbon sensor, and oxygen sensor—are immersed into the bath with the help of the sub-lance, generally 2 to 3 minutes before the estimated blow end, in order to obtain the actual temperature, dissolved carbon and oxygen contents of the bath. Using the sub-lance it is also possible to withdraw metal/slag samples from the bath for chemical analysis without tilting the converter. Oxygen blowing is normally stopped or the flow rate decreased during the immersion of the sub-lance, the total operation taking less than 30 seconds.

The data thus obtained are fed into the control computer, which compares the actual temperature and carbon in the bath with those predicted by the static model. The computer then provides advice for corrective additions and modifications in the blow, as required. For doing this, the computer uses another programme based on either a static model or a dynamic model.

#### 18.3.1 The Sub-lance

Different designs of the sub-lance are available depending on the manufacturer, but in all cases the sub-lance has to be sturdy enough to withstand repeated usage in the converter atmosphere. Figure 18.1 shows the sub-lance employed by Voest-Alpine AG, Linz, Austria. (Kostersitz et al. 1986). Like the main oxygen lance, the sub-lance is also water-cooled. It is driven by a winch, which uses a computer-controlled variable DC drive along with a counterweight. The probe manipulator is hydraulically-controlled. Before immersion, the probe magazines (cartridges) are electrically-heated. They are then immersed in the bath for 3–5 seconds and the entire measurement operation completed in around 90 seconds.

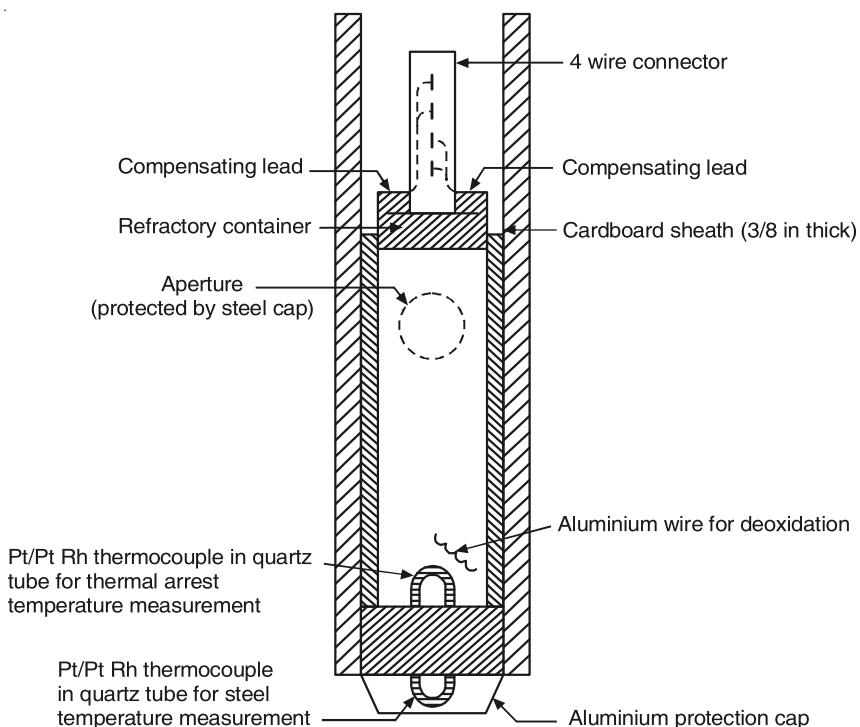


**Figure 18.1** Typical sub-lance used for process control.

### 18.3.2 Immersion Carbon Sensor

The carbon sensor is used for virtually instant *in situ* determination of bath carbon. The probe measures the *Liquidus Temperature* of the steel sample collected from the bath by the standard *Thermal Arrest* technique. The liquidus temperature of iron is lowered by the presence of impurities—for example, 1 wt. % carbon, lowers the temperature by 90°C. In the case of manganese, the lowering is to the tune of 1.7°C, silicon: 6.2°C, sulphur: 40°C, phosphorus: 28°C. Therefore, it is evident that carbon has the most predominating effect and some minor corrections are good enough to determine the carbon content on the basis of liquidus temperature measurements.

Different designs of the sensors are available; one design is shown in Figure 18.2 (Bosworth 1971). It combines the measurement of both temperature and carbon. The carbon sensor is of the disposable type, i.e. one sensor can be used only once since the aluminium cap in the sensor melts when it is immersed. The bottom thermocouple in the sensor measures the bath temperature as soon as liquid metal rushes into the evacuated chamber containing another thermocouple. Once the sub-lance is withdrawn, the metal freezes in less than 30 seconds. The inner thermocouple records the liquidus temperature, from which the carbon content is immediately known with an accuracy of around  $\pm 0.01\%$  carbon.



**Figure 18.2** Sectional view of an immersion-type carbon and temperature sensor.

### 18.3.3 Immersion Oxygen Sensor

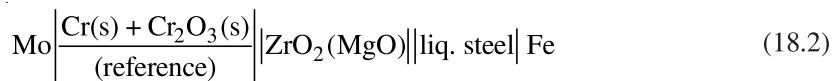
This is also a combined sensor used to measure both the temperature as well as the dissolved oxygen content of the bath, within 5 seconds of immersion. The most popular version is the CELOX probe, marketed by Electro-Nite of Belgium. The objective of *in situ* measurement of bath oxygen is primarily to help in quick estimation of the bath carbon. It has already been pointed out in Chapter 17, Section 17.7 that carbon and oxygen in the bath before tapping are inter-related, and some statistically averaged empirical relationships are in use. Therefore, the oxygen sensor is an effective tool used in many modern BOF shops before tapping molten steel from the converter.

The oxygen sensor is a tiny EMF cell of the disposable type, which can be used only once. The electrolyte is a solid ceramic material, which is  $\text{ZrO}_2$  doped with either  $\text{CaO}$ , or  $\text{MgO}$  or  $\text{Y}_2\text{O}_3$ . It has vacancies in the  $\text{O}^{2-}$  lattice sites through which oxygen ions can move freely, thereby allowing it to be used as an *oxygen concentration cell*, whose EMF ( $E$ ) is related only to the difference of chemical potentials of oxygen at the two electrodes.

$$\mu_{\text{O}_2} \text{ (liquid steel)} - \mu_{\text{O}_2} \text{ (reference)} = -ZFE \quad (18.1)$$

where  $Z$  is valency of  $\text{O}_2 = 4$ , and  $F$  is the Faraday constant.

In standard CELOX probes, the cell is:



Mo and Fe constitute the leads. Since these are dissimilar, the total voltage includes *thermo-emfs*, which have to be deducted to arrive at the correct EMF. The solid electrolyte is in the form of a tube, with one end closed and a mixture of Cr + Cr<sub>2</sub>O<sub>3</sub> packed inside it.

On the basis of Eq. (4.24), Chapter 4,

$$\begin{aligned} \mu_{\text{O}_2}(\text{reference}) &= RT \ln p_{\text{O}_2}(\text{reference}) \\ &= \Delta G_f^0 \text{ for formation of Cr}_2\text{O}_3(\text{s}) \text{ per mole O}_2 \end{aligned} \quad (18.3)$$

In liquid steel, the reaction in question is

$$\frac{1}{2} \text{O}_2(\text{g}) = [\text{O}]_{\text{wt}\%}; K_{\text{O}} = \left\{ \frac{h_{\text{O}}}{(p_{\text{O}_2})^{1/2}} \right\}_{\text{eq.}} \quad (18.4)$$

So,  $\mu_{\text{O}_2}(\text{steel}) = RT \ln p_{\text{O}_2}(\text{steel}) = 2RT \ln \left[ \frac{h_{\text{O}}}{K_{\text{O}}} \right] \quad (18.5)$

Here,  $h_{\text{O}}$  is the activity of dissolved oxygen in one wt. per cent standard state, and  $K_{\text{O}}$  is the equilibrium constant. Since  $\mu_{\text{O}_2}$  (reference), and  $K_{\text{O}}$  are known as a function of temperature, from measurements of  $T$  and EMF,  $\mu_{\text{O}_2}$  (steel) and  $h_{\text{O}}$  are determined. From  $h_{\text{O}}$ , the wt. % O is determined.

Cook et al. (1993), have presented a comprehensive coverage of the semi-dynamic control of the BOF adopted at Armco Steel Corporation, USA.

### EXAMPLE 18.2

- Upon immersion of a CELOX oxygen sensor into a bath of molten steel at 1600°C, the EMF (after correction of thermo-EMF) was -0.10 volt. Calculate wt. % dissolved oxygen in the melt.
- Assuming [Al]-[O]-Al<sub>2</sub>O<sub>3</sub> equilibrium, calculate wt. % dissolved aluminium in the bath.

Ignore all interactions.

**Solution:** From Eq. (18.1),  $\mu_{\text{O}_2}(\text{liquid steel}) - \mu_{\text{O}_2}(\text{reference}) = -\text{ZFE} = -4\text{FE}$

In Chapter 4, Table 4.1 gives the value of  $\Delta G_f^0$  for formation of Cr<sub>2</sub>O<sub>3</sub>(s). Noting that  $\Delta G_f^0$  per mole of O<sub>2</sub> is 2/3 of that, and at 1873 K, from Eq. (18.3),

$$\mu_{\text{O}_2}(\text{ref}) = -434.13 \times 10^3 \text{ joules per mole of O}_2$$

For reaction 18.4, Table 4.2 gives the value of  $\Delta G^0 = -117150 - 2.89T$  J/mol.

At 1873 K, this gives the value of  $K_O$  of Eq. (18.5) as 2619.

$$-ZFE = -4 \times 96500 \times (-0.1) = 38.6 \times 10^3 \text{ joules}$$

Ignoring interactions,  $[h_O] = [W_O]$ . Therefore, from Eq. (18.5),

$$\mu_{O_2}(\text{Steel}) = 2 \times 8.314 \times 1873 \ln(W_O/2619).$$

(a) Inserting the above values in Eq. (18.1), and solving, it is possible to get  $[W_O] = 0.008 \text{ wt. \%}$ ,  $[W_{\text{Al}}] = 2.2 \times 10^{-4} \text{ wt \%}$ .

(b) From Chapter 20, Table 20.2, different values at 1873 K can be obtained.

For the reaction,  $2[\text{Al}]_{\text{wt. \%}} + 3[\text{O}]_{\text{wt. \%}} = \text{Al}_2\text{O}_3(\text{s})$ ,  $K_{\text{Al}} = \{[W_{\text{Al}}]^2 \cdot [W_O]^3\}_{\text{eq.}} = 2.51 \times 10^{-14}$ . This gives the wt. % dissolved Al in liquid steel as  $8.94 \times 10^{-4} \text{ wt. \%}$  (i.e. 8.94 ppm).

## 18.4 DYNAMIC CONTROL

As stated earlier, dynamic control based on a dynamic model is the most sophisticated type of control. It has all the features of semi-dynamic control and in addition, it also has features like the following:

- (i) Chemical analysis, flow rate and temperature measurements in the exit gas
- (ii) Continuous in-blow data, e.g. acoustic noise intensity measurement by using a sonic meter.

The data gathered during the course of blowing are fed back to a control computer, which automatically adjusts the lance height, oxygen flow rate, etc.

### 18.4.1 Measurements on Exit Gas

The exit gas from a BOF consists primarily of CO and CO<sub>2</sub>, the volume fractions of which can be determined by a sophisticated gas analyser (mostly mass spectrometer). Gas flow rate measurements are more difficult. In one technique that is commonly used, argon is used as a tracer and is introduced as a pulse-input into the exit gas stream. Its concentration at the exit end allows the calculation of the volumetric flow rate.

The wt. % carbon in the bath at any time during the blow ( $W_C$ ) is given as:

$$W_C = \text{Initial wt. \% carbon in bath } (W_{C,i}) - \frac{\text{total carbon loss through exit gas } (\Delta m_C)}{\text{mass of metal } (m_{\text{steel}})} \times 100 \quad (18.6)$$

Gas flow rate ( $Q$ ), temperature of exit gas ( $T$ ) and mole fractions ( $X$ ) of CO and CO<sub>2</sub> are related to the carbon loss rate ( $r_C$ ) in the following manner:

$$r_C = Q \frac{273}{T} (X_{\text{CO}} + X_{\text{CO}_2}) \frac{12}{22.4} \quad (18.7)$$

where  $r_C$  is in  $\text{kg} \cdot \text{s}^{-1}$ ,  $Q$  is in  $\text{m}^3 \cdot \text{s}^{-1}$  and  $T$  is in kelvin.

$$\Delta m_C = \int_0^t r_C dt; \quad \Delta W_C = \frac{\Delta m_C}{m_{\text{steel}}} \times 100 \quad (18.8)$$

where  $t$  is the time from the start of the blow. In a similar way, the oxygen going out with carbon can be computed.

It needs to be recognised that precise determination of  $\Delta m_C$  and  $\Delta m_O$  pose several difficulties owing to the following reasons:

- Dust laden and hot gas
- Non-uniformity in gas composition and temperature across the duct
- Leakages to and from the surrounding atmosphere.

Suppose,  $W_{C,i} = 3.2\%$ ,  $\Delta W_C = 3.0\%$ . Then,  $W_C = 0.2\%$  from Eq. (18.6). If the measurement has 5% error in  $\Delta W_C$ , which is 0.15%, then actual  $W_C = 0.2 \pm 0.15\%$ , which is a significant error band. That is the reason why sub-lance based measurements towards the blow-end are a must. Tani et al. (1993) have discussed the dynamic control of BOF at the Kashima Steel Works, Japan.

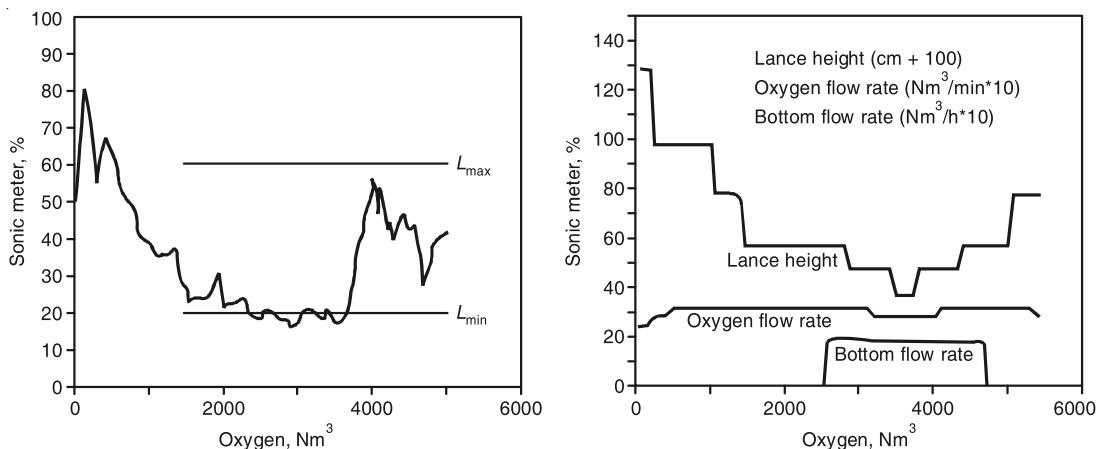
#### 18.4.2 Application of Sonic Meter

The intensity of acoustic noise emanating from the converter during the blow depends on the slag volume and the nature of the slag (i.e. the emulsion volume during the peak decarburisation period). The greater the slag volume (i.e. slag height), the higher is the noise level. A sonic meter measures the sound intensity continuously during the blow, and this information is fed back into a control computer, which on the basis of this data, adjusts the lance height, oxygen flow rate and bottom gas flow rate automatically to control the emulsion height. By doing this, excessive foaming and slopping can be prevented along with better refining.

Dynamic slag control in the BOF is practised in many plants, for example, ILVA/PIOMBINO Steel Works (Beneini et al. 1993). Figure 18.3 presents a typical situation where slopping was prevented by automatic control of the lance height, etc. by employing a dynamic slag control model. A reduction of 50% in slopping events, improvement in refining control and consequent improvement in converter life have been claimed.

### 18.5 CONCLUDING REMARKS

The fundamental objective of computer control of basic oxygen steelmaking in the early stages was to achieve endpoint carbon and temperature control, without the need of taking recourse to re-blowing. Even in modern BOF shops, the basic aim remains the same; however, several other objectives have also been incorporated such as the following:



**Figure 18.3** Model action based on sonic meter to prevent slopping.

- Longer lining life
- Better overall yield of Fe
- Better control of P, Mn and nitrogen
- Lower bath oxidation levels at tap leading to lower consumption of deoxidisers
- Ease in process control by the operating personnel
- Less slopping
- Standardisation of the operating practice
- Data acquisition for further evaluation.

A large volume of literature on this subject is available (some important references have already been cited). Most of the efforts have been directed towards end-point carbon and temperature control. Both semi-dynamic and dynamic controls have brought about significant improvements in endpoint control, particularly after the advent of sub-lance-based measurements. Additional use of continuous in-blow data, for example through sonic meters has led to better control techniques.

The parameters that are employed to evaluate the efficacy of endpoint carbon and temperature control are as follows:

- (i) **Hit rate:** reported as the percentage of heats where the endpoint carbon and temperature are within the specified tolerance bands (100% is the maximum value).
- (ii) **Standard deviations** from the aimed values of carbon and temperature (lower the value, the better is the control).
- (iii) **Percentage of re-blows** required to arrive at the aimed endpoint (no re-blow is ideal).

With modern semi-dynamic and dynamic control systems, it is possible to achieve hit rates of 90–95% for temperature tolerance of  $\pm 10^\circ\text{C}$  and carbon tolerance of 0.015–0.02%; standard deviations of 6–10°C and 0.01% carbon; percent re-blows of 5–10%.

It is important to mention here that automation and control systems require capital investment that is best made at an opportune time. The facilities provided require regular maintenance and their operation also calls for meticulous attention to the adoption of proper procedures in order to limit the operating expenditure (carbon/temperature/oxygen probe cassettes are fairly expensive). The extent of utilisation of these tools in a BOF shop also depends on factors like the consistency of input materials, state of standardisation of operating practices, etc.

## REFERENCES

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