

The furnace unit itself includes the following parts:

- (i) Furnace body consisting of the shell, the hearth, the walls, the spout, doors, etc.
- (ii) Gears for furnace body movement
- (iii) Arrangements for moving the roof
- (iv) Electrodes with their holders and supports
- (v) Electrode lifting and lowering mechanism
- (vi) Electrical equipment—i.e. transformer, cables, electrode control arrangements, etc.

The furnace shell is made by welding or rivetting steel plates. Its side wall is cylindrical in shape and the bottom is shallow and bowl-shaped. To give an idea, the shell diameter is about 6 to 6.5 m for a 100 t capacity furnace and 5 to 5.5 m for a 50 t furnace.

Large transformers are required for supplying power to any EAF. The primary voltage may be 33 KV or more, and the secondary voltage anywhere from 200 V to 1000 V depending on the furnace size and power supply. The electrical characteristics of the circuit are schematically shown in Figure 19.6. Since the voltage as well as the power factor decrease as the current is increased, the maximum power is obtained at an optimum current.

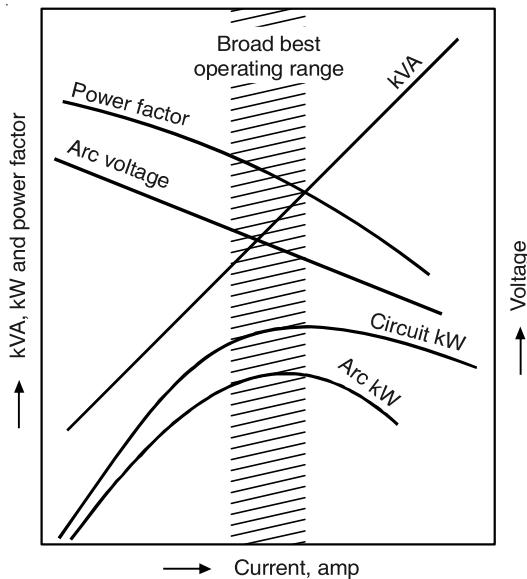


Figure 19.6 Electrical characteristics of an arc furnace during operation (schematic).

It should be mentioned here that whatever has been described above pertains to a conventional furnace set up. Modern EAFs have retained most of the basic design with some additional features that will be taken up later.

19.2.3 Conventional EAF Steelmaking Practice

As mentioned already the process of electric arc furnace steelmaking is about 100 years old.

Through decades of efforts till about 1970, electric furnace steelmaking practices got significantly standardised. This is what is denoted by the term *conventional*—it is practised even now in smaller and relatively older units.

Section 19.1.2 has described the stages in heat making in basic open hearth furnaces. EAF steelmaking involves most of those stages, with the exception of the following:

- Hot metal is not used in conventional practice
- The refining and finishing practices differ widely.

The basic purpose of refining in EAFs is two-fold:

- Removal of undesirable impurities (C, Si, P, S, N, H, etc.)
- Finishing the bath so as to ensure maximum alloy recovery.

Chapter 15 has discussed the reactions in primary steelmaking and their physicochemical aspects. Chapter 5 focused on the reactions of silicon and sulphur, and hence need not be repeated. EAFs produce a wide variety of steels. Therefore, depending on the type of the solid metallic charge and the grade of steel to be produced, the refining practice differs considerably. The type of refining employed may be broadly classified into the following.

Oxidising single slag practice: It is employed to produce tonnage grades of carbon and low alloy steels, as well as non-deoxidised, semi-deoxidised and deoxidised steel. The physical and chemical specifications are not very stringent, i.e. the quality of steel is similar to what is attainable in open hearths using a basic oxidising slag as the medium of refining.

Double slag practice: In this case, after refining using an oxidising slag, further refining is carried out under a reducing slag. The reducing slag allows attainment of lower sulphur levels and also assists in higher alloy recovery after tapping. In this practice, the original oxidising slag can be modified by the addition of reducing agents; however, it gives rise to danger of reversion of phosphorus from the slag back into the metal (see Chapter 15). To preclude this possibility, generally the oxidising slag is completely removed and fresh reducing slag is made by charging lime, fluorspar and silica. The reducing agent may be graphite or coke breeze. This type of slag is commonly referred to as *carbide* slag, since the carbon added reacts with CaO to form some amount of CaC₂. Carbide slags do not allow very low carbon contents to be attained in the bath; in such cases, ferrosilicon is used as the reducing agent instead of carbon. The typical compositions of slag are shown in Table 19.1.

Table 19.1 Slag compositions used in two slag EAF steelmaking

Type of slag	Wt. % of constituents						
	CaO	SiO₂	FeO	MnO	MgO	CaC₂	V-ratio
Oxidising	38–45	10–15	13–20	10–15	5–10	—	1.7–3
Reducing—carbide	65–70	20–25	0.5	—	5–10	1–2	3–3.5
Reducing—non-carbide	55–60	25–30	1.0	—	5–10	—	2–2.5

At this stage, it is worth noting some salient differences in the metallurgical features of basic open hearth and EAF steelmaking. These are noted below.

1. Since EAF steelmaking is primarily scrap/DRI based and both these materials have relatively low levels of residual impurities, the extent of refining is much less than in BOH steelmaking.
2. As a process, EAF is far more versatile than BOH and can make a wide range of steel grades.
3. Sorting out of scrap and choosing the proper scrap grade are important for EAF steelmaking, since the extent of refining has to be managed accordingly. For this purpose, scrap may be classified into the following categories:
 - (a) scrap containing elements that cannot be removed by oxidation during refining, such as Cu, Ni, Sn, Mo, W, etc.
 - (b) scrap containing partially oxidisable elements, such as P, Mn, Cr, etc.
 - (c) scrap containing completely oxidisable elements, such as Al, Si, Ti, V, Zr, etc.
 - (d) scrap containing volatile elements, such as Zn, Cd, Pb, etc.

Scrap of type (b) and (c) can be tackled easily during refining. Type (d) scrap would require some special attention. However, type (a) scrap gives rise to problems like *undesirable residuals* in the final steel. This is where DRI scores over scrap—it is totally free from all the above undesirable elements.
4. In BOH steelmaking, refining begins with the bath containing about 1% excess carbon (often referred to as the opening carbon) in order that evolution of CO following the oxidation of carbon provides the necessary agitation for homogenisation of the bath as well as for enhancing the reaction rates. In EAF steelmaking also, the initial bath carbon is maintained at about 0.3% above the final carbon specification during oxidising refining. However, stirring is absent during refining under a reducing slag, and some other stirring technique (use of mechanical stirrers called rabbles) is required.

19.2.4 Modern Developments in EAF Steelmaking

Introductory comments

Recent developments in EAF steelmaking have taken place primarily in the context of large-scale production of plain carbon and low alloy steels. Of course, some of these developments have also been implemented in smaller scale of operation as well as for the production of high alloy steels, such as stainless steels. Besides a distinct trend towards increase in furnace size, the important developments may be summarised as follows.

- Ultra high power supply (UHP)
- DC arc furnace
- Oxygen lancing (in some cases along with carbon/coke breeze)
- Use of water-cooled elements in the furnace shell, water-cooled electrodes, etc.
- Foamy slag practice
- Bath stirring by argon
- Auxilliary secondary steelmaking facility
- Use of sponge iron (DRI/HBI) to substitute scrap

- Hot metal or cold pig iron as scrap substitute
- Pre-heating of scrap and DRI
- Eccentric bottom tapping
- Emission and noise control
- Process automation and control.

What has already been discussed in Chapters 15, 17 and 20 and is of relevance here is not being repeated. Towards the end of this chapter, a short discussion has been included on the quality of plain carbon and low alloy steels made through the electric furnace route. Hence, the accent here will be on the impact of modern developments on improvements in process efficiency through enhancement in productivity, superior energy utilisation efficiency, cost savings and environmental pollution control. In summary, it can be stated that modern strategy is directed towards employing the EAF primarily for *melting followed by some refining using an oxidising slag. The metal is then tapped from the furnace into a ladle and the rest of the refining, adjustment of composition as well as temperature are carried out during secondary steelmaking.*

Specific developments

For the sake of concise presentation, the modern developments in specific areas are being divided into the following groups.

- (a) GROUP 1—First six items of Section 19.2.4, i.e. UHP to foamy slag and argon stirring
- (b) GROUP 2—The next three items covering alternative charge materials.
- (c) GROUP 3—Other items like charge pre-heating, eccentric bottom tapping, emission control and automation.

(a) GROUP 1

1. Transformers supplying power to electric arc furnaces have been classified as given below.

	Capacity in kVA per tonne steel
(i) Regular power, i.e. for old furnaces	100–400
(ii) High power	400–700
(iii) Ultra high power (UHP)	above 700

Use of UHP enables faster melting of the solid charge, thereby decreasing the tap-to-tap time with consequent increase in the production of steel. An EAF of 100 tonne capacity will require a transformer capacity of above 70 MVA for UHP operations. It has been possible to achieve such figures owing to major advances in electrical engineering in the last few decades.

Another important development is the *use of DC (direct current)* in the furnaces. This requires conversion of three-phase AC into single-phase AC supply, and after the step-down transformer conversion of AC into DC. A DC arc has one electrode and the circuit is completed through the conducting electrodes embedded in the furnace bottom. It offers certain distinct advantages over three-phase AC arc, such as smoother arc operation, less noise, etc.

2. Oxygen lancing through a top lance gives certain advantages that include: oxidation of carbon and some iron from the bath releasing chemical energy with consequent saving of electrical energy as shown in Figure 19.7 (Kohle 2000); faster removal of carbon and other impurities following faster slag formation and the generation of a foamy slag.

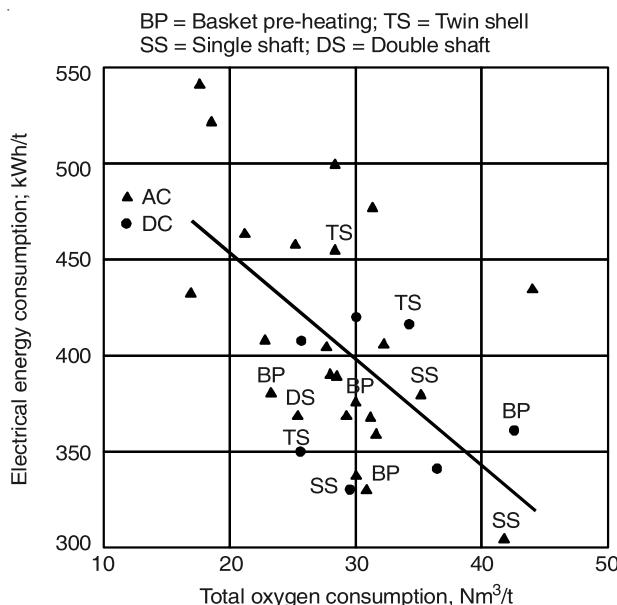


Figure 19.7 Electrical energy consumption versus total oxygen consumption.

In large EAFs the top lance is supersonic, as in BOFs. For greater saving of electrical energy, coke or carbon breeze is also injected along with oxygen in some plants. *Coherent jet* lance design makes these injections more efficient and has been adopted in some EAF shops.

3. Ultra high power input and oxygen/oxy fuel injection, with consequent higher temperature in the arc zone, causes more heat losses. This tends to heat up the furnace shell, the graphite electrodes as well as the connecting electrical cables, etc. thereby causing damage to these parts. The concurrent use of a *foamy slag* helps in insulating some areas thereby lowering the heat loss and providing protection to the electrodes and other parts of the furnace.

Use of *water-cooled* shell panels and water cooling of electrodes, cables, etc. decrease the consumption of refractories/electrodes.

Chapter 17, Section 17.4 introduced the concept of foams and emulsions in the context of BOF steelmaking. These are applicable to the foaming of slags in EAFs as well. To summarise, a slag foam is *transient* and is basically sustained by vigorous evolution of CO following the reaction of bath carbon with oxygen. A foamy slag is actually an emulsion of metal droplets and gas bubbles in slag. Higher slag viscosity and the presence of undissolved solid particles assist foaming, which speeds-up slag–metal reactions, such as dephosphorisation. All modern EAF shops have adopted foamy slag practice.

The subject of mixing and homogenisation of the bath in BOFs has been elaborately discussed in Chapter 17. To help bath mixing, concurrent top and bottom blowing has been adopted by all modern BOF shops. In large EAFs also the problem of mixing exists, to some extent. Oxygen lancing and flow of current through the metal bath in DC arc furnaces induce some amount of bath motion, which is sometimes insufficient. Better mixing in the bath is desirable for all the advantages described in Chapter 17. Therefore, many modern EAFs are equipped with bottom tuyeres for injection of argon, etc. (McIntyre and Landry, 1993).

(b) GROUP 2

For the production of plain carbon steels in electric arc furnaces, steel scrap constitutes the principal metallic iron feed. With the growth of EAF steelmaking, the following problems were faced with all scrap charge in EAFs.

- (i) Technologically advanced countries, such as the USA originally had plenty of obsolete scrap, the stock of which has gradually been coming down. Developing countries like India and Brazil do not either have much obsolete scrap nor do they generate large amounts of scrap. For charging into EAFs import of scrap at high cost to supplement home scrap is necessary. Therefore, DRI usage as a substitute for scrap became popular.
- (ii) As mentioned earlier, some alloying elements are more difficult to oxidise than Fe, such as Cu, Ni, Sn, Mo, W, etc. Hence, they cannot be satisfactorily removed during steelmaking and are also known as *tramp elements*. One way of getting around this problem is not to use scrap containing these tramp elements, but this is not always economically viable. Substitution of scrap, partly or fully, by alternative iron sources (AIS) is a solution, since these inputs do not contain tramp elements.

Many publications deal with the use of AIS, for example, Jones (2000) and Millman (1999). Besides DRI, the other alternative iron sources are:

- *Hot briquetted iron* (HBI), which is a dense, compacted form of DRI
- Solid pig iron
- Hot metal (i.e. molten pig iron).

Use of AIS is gaining popularity in EAF steelmaking. DRI/HBI is now the principal feed stock next to scrap. In 2005, the worldwide DRI/HBI production was just over 56 million tonnes, which was slightly more than 15% of the scrap consumption.

Solid pig iron and hot metal are also important AIS, constituting about 5–8% of the total feed. In the case of EAF shops located inside an integrated steel plant, blast furnace hot metal is available. Otherwise, hot metal can be produced either in a mini blast furnace or in a smelting reduction unit. Both these have been used in EAF steelmaking, since hot metal charging

- is advantageous from a thermal point of view being already molten and the oxidation of its impurities provides chemical energy; 1 kg hot metal charge per tonne of steel saves electricity by about 0.5 kWh/t
- promotes foaming by the evolution of CO and gives all the advantages of a foamy slag.

However, excess hot metal usage can prolong the refining time and give rise to uncontrolled foaming. Therefore, it is recommended that hot metal charge is restricted to a maximum of 40–45% of the total charge and the best method of usage is to charge it continuously through a side launder.

DRI/HBI has very low impurity content (i.e. P, Si, S, and, of course, the tramp elements) [see Chapter 13, Sections 13.3 and 13.4] and hence does not require any additional refining time. However, it is a porous material that tends to get severely oxidised in contact with moist air at high temperature. Up to about 30% DRI (of the total charge) can be charged along with scrap in buckets, if bucket charging is practised. First a layer of scrap, then DRI and then another layer of scrap are used in each bucket. If continuous charging facilities for charging DRI throughout the heat in small amounts are available, the proportion can be increased to 50–60% and sometimes, even more. In all cases, HBI is preferred since it is dense and does not get oxidised very readily.

With the use of DRI/HBI, melting and refining can proceed simultaneously. In some EAF shop even up to 100% DRI is used by adopting what is known as the *hot heel* practice. Here, molten steel from a previous heat is not tapped out completely and is allowed to remain in the EAF to provide a liquid metal bath for DRI charging right from the beginning of the next heat. Figure 19.8 shows the typical change of weight of metal in the furnace as a function of time during an EAF heat for hot heel practice.

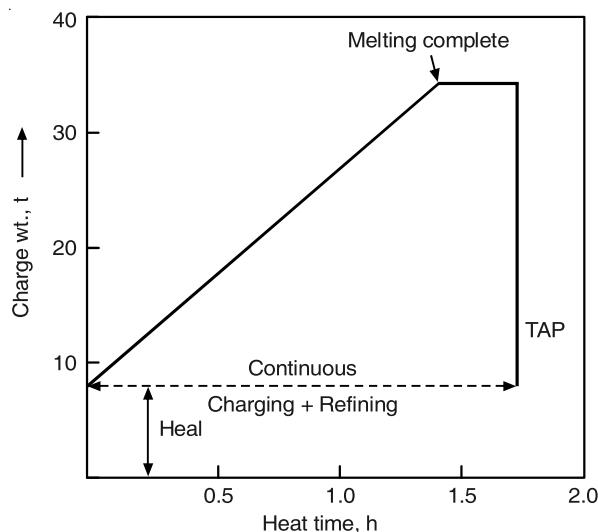


Figure 19.8 Arc furnace operation with high percentage of DRI in the charge using hot heel practice.

The quality of DRI is judged by its following characteristics:

- Gangue content
- Percentage metallisation
- Carbon content
- Levels of other impurities.

The gangue in DRI consists principally of silica and alumina associated with the iron oxide feedstock. For optimum usage in steelmaking, the gangue content should be as low as possible; otherwise, large slag volumes and hence more lime addition are required. This has an adverse effect on the consumption of energy. The *percentage metallisation* (i.e. the percentage of metallic iron in the DRI as a percentage of total iron—the remaining iron is present as wustite) should also be high to keep the energy consumption low. Typically, steelmakers prefer metallisations between 92% and 96% (too high metallisation lowers the turbulence that is induced in the bath when FeO in DRI reacts with the bath carbon).

During the production of DRI (particularly gas-based DRI) carbon in the form of iron carbide gets absorbed in the final product. The carbon percentage in DRI depends on the process of sponge ironmaking—in coal-based processes it is about 0.10–0.15%, while in gaseous reduction processes it can be varied anywhere from 1.5 to 4% depending on the customer demand. Carbon in DRI lowers its melting point and when it reacts readily with any un-reduced iron oxide, CO is evolved, which contributes towards the formation of a foamy slag. This is required for efficient steelmaking and hence, steelmakers prefer higher carbon containing DRI, say above 1%. In case this amount of carbon is not available in DRI, additional carbon input by injection of coke breeze along with oxygen becomes necessary. The addition of hot metal can also provide a source of carbon.

(c) GROUP 3

Charge pre-heating: If the solid charge can be pre-heated, it can obviously reduce electricity consumption. The economics would depend on the cost of pre-heating. Under normal circumstances, scrap is charged into the furnace in cold condition and during the progress of the EAF heat, vigorous evolution of CO and some amount of hydrogen takes place. This gas can be an additional heat source by *post-combustion* of CO and H₂, either in the furnace atmosphere or above the furnace in a separate pre-heating chamber. The oxygen required can be supplied by injecting pure oxygen at the appropriate location. Several systems of pre-heating within the furnace chamber or in a separate vessel have been used in EAF steelmaking.

Separate pre-heating of DRI/HBI is difficult since it would oxidise. At the same time, since it is at high temperature when it comes out of the reduction reactor, it is a matter of retaining this temperature during the transport of DRI/HBI to the electric furnace. Several systems have been reported in literature. One of the latest that has been developed by Midrex Corporation, USA consists of conveying hot DRI through an insulated pipeline directly into the EAF shop and then charging it with the aid of gravity. Essar Steel, India, has developed refractory lined containers for transport. Using such techniques, it is possible to charge hot DRI at a temperature of 600–700°C, resulting in 10–15% power saving. As a result, use of pre-heated DRI/HBI has become a standard practice in many EAF plants.

Eccentric bottom tapping: The primary steelmaking slag has iron oxide as well as P₂O₅. This slag is undesirable for subsequent secondary steelmaking. In the case of basic oxygen furnaces, most of the slag is retained in the vessel and not allowed to flow into the ladle during tapping by the use of slag arresting devices (see Chapter 20). In modern EAFs, the bottom has been made eccentric to achieve the same result. The eccentric part of the bottom is suitably covered and insulated. During tapping, when the furnace is tilted, liquid steel primarily flows out it with

very little slag and this metal can be tapped through a nozzle at the bottom of the eccentric portion. Some liquid steel is retained in the furnace (hot heel practice). Therefore; the top slag gets very little chance to escape into the ladle during tapping.

Noise control and emission: Day-by-day stricter norms are being formulated for noise control. EAF steelmaking is prone to noise—the arc struck between the electrode and the solid charge right at the beginning of each heat is the principal source of noise. Through improved circuit design, arc control and use of DC arc, noise levels have been brought down significantly.

As far as emissions are concerned, the objectionable emissions from EAFs are:

- Poisonous CO gas
- Toxic NO_x gas
- Dust.

Post combustion of CO into CO₂ is the solution as far as carbon monoxide is concerned. NO_x denotes a group of air pollutants that include: nitric oxide (NO), nitrogen dioxide (NO₂) and nitrous oxide (N₂O). The principal component is NO, typically comprising 90% of the total NO_x emission. NO_x gases are formed primarily by the reaction of atmospheric nitrogen with oxygen at the high temperatures prevailing in the arc zone of EAFs. The most effective means of control is to reduce the formation of NO_x gases by preventing the ingress of air near the arc zone. This can be achieved by using the foamy slag as a shield. The other options are to seal the furnace as much as possible by keeping the doors etc. closed, and maintaining a slightly positive pressure inside the furnace.

Huber et al. (2000) have elaborately discussed dust formation in EAFs. EAFs generate 15 to 25 kg of dust per tonne of steel. The dust comprises mostly spinel-type metal oxide (Fe, Zn, Mn) O.Fe₂O₃, some vitreous phases (Fe_xO + SiO₂ + CaO glass) and ZnO. It is, therefore, composed of elements/compounds coming from the steel bath as well as from the slag layer and from volatiles. Zinc, for example, comes from scrap containing galvanised steel. Moreover, the dust also contains small quantities of elements like lead, chromium and cadmium, which are volatile as well as toxic. Although earlier steelmaking dust used to be considered as a process waste, in recent times the higher cost of waste disposal and stricter environmental regulations are leading steelmakers to switch to a co-product recycling strategy.

The mechanism of dust formation in EAFs is shown in Figure 19.9 (Huber et al. 2000). It consists of:

- Localised volatilisation in the arc zone (1) and oxygen zone (1')
- Ejection of large droplets by CO bubbles and oxygen jet in the arc zone (2) and jet zone (2')
- Ejection of fine droplets by bursting of CO bubbles (3)
- Fast decarburisation of fine particles in zone (4)
- Direct fly-off of solid particles from the charge (5).

Literature has dealt comprehensively with the subject of emission control in EAF shops. The emissions during the progress of any heat are known as *primary emissions*, which are the most important. These emissions are taken out through a duct attached to an opening in the furnace roof as shown in Figure 19.9. The dust-laden gases are cooled by mixing with cold air before

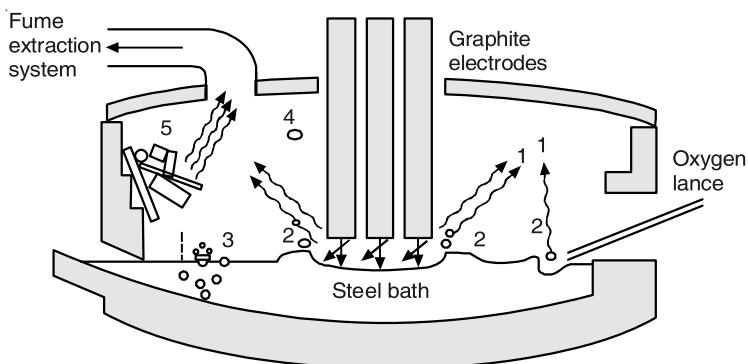


Figure 19.9 Mechanism of dust formation in EAFs.

being passed through dust catchers, scrubbers, and electrostatic precipitators for the removal of dust before the gas is let off into the atmosphere. The dust is collected in a pond as sludge, then separated and used as a by-product for various purposes in a similar way as is done in blast furnaces and BOF shops.

Secondary emissions are defined as those that are emitted during activities other than melting or refining—i.e. during the periods of charging, tapping and slagging, and a result of leakages through the furnace doors, etc. In order to handle these emissions, two systems are available:

- installation of large *canopy hoods* above the furnace where these emissions can be collected by suction
- sealing the entire building and sucking the emissions out through the roof.

Process automation and control: In Chapter 18, various features of process control in basic oxygen furnaces were presented. Elaborate control measures are used including systems such as sub-lance, exit gas monitoring, sonic meter, dynamic and semi-dynamic control with feedback, sensors like carbon sensor, oxygen, sensor, etc. The principal objective of process control in BOFs is to attain the correct end-point, in terms of both carbon and temperature. The additional objectives are to reduce phosphorus, oxygen and nitrogen in molten steel and iron oxide in the slag to as low levels as possible. These objectives have to be achieved in the minimum possible time and without the need for additional steps like reblowing, which has an adverse effect on the final yield and converter lining life.

The same objectives are applicable to electric arc furnaces as well. However, the situation is different, to some extent, as noted below.

- (i) The EAF bath is accessible through the doors; hence, gadgets like sub-lance, etc. are not required.
- (ii) The extent of refining in EAF is relatively less in comparison to BOF because the former is primarily a melting unit.
- (iii) EAF steelmaking is not as fast as BOF.

Therefore, the metallurgical process control features in EAFs are far less elaborate. Automation and control in EAFs are primarily restricted to: