32

Modern Steelmaking Processes

2. The LD Process

Ref: Rashid / Ch. 4.3.1 - 4.3.2

Lecture Outcome

At the end of this lecture, students should be able to

- understand and **explain** the characteristic features of Basic Oxygen Steelmaking (BOS) Process.
- **describe** the sequence of operation in top-blown BOS process, and
- **explain** the process reactions and energy balance that take place during top-blown BOS steelmaking process.

1. Introduction

- Basic Oxygen Process is the dominant method of producing steel from blast furnace hot metal.
- The process involves the treatment of blast furnace molten iron in a basic lined BOF vessel.
  - Blast furnace hot metal contains

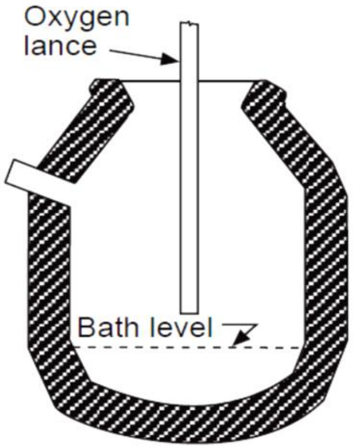
    C = 3-4%, Si = 0.8-1.0%,
    Mn = 0.6 - 0.8%, P = 0.15-0.20%
- Steel scrap are also used in some degree
- High purity oxygen is injected onto the surface of the bath by a water-cooled, vertical pipe or lance inserted through the mouth of the vessel.
- In most of the steelmaking practices, hot metal is pretreated to remove Si, P and S from hot metal to the extent it is possible.

- In the basic oxygen steelmaking process, refining of hot liquid iron is performed by top-, bottom-, or combined blowing of oxygen in a converter

- The top-blowing process has different names:
  - in European steel plants, **LD** (Linz-Donawitz) process;
    in the UK, **BOS** (basic oxygen steelmaking);
    in the Far East and America, **BOF** (basic oxygen furnace) process;
    in the U.S. Steel, **BOP** (basic oxygen process)

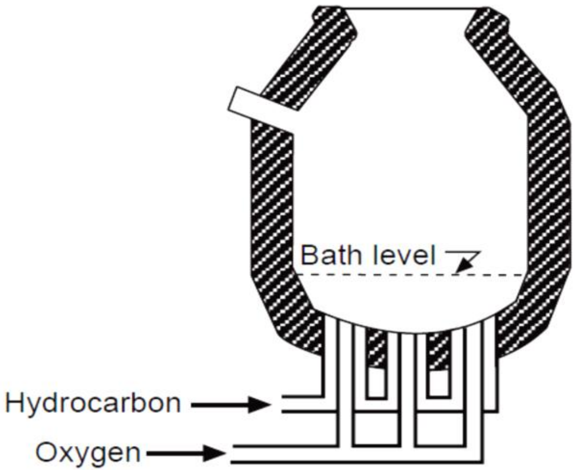
- The bottom-blowing processes:
  - in Europe, **OBM** (Oxygen Bottom-blown Machine) Process;
    elsewhere, **Q-BOP** (Quiet/Quick Basic Oxygen Process)

- The combined blowing processes are used mainly to increase the rate of production



Top-blown (BOF) process

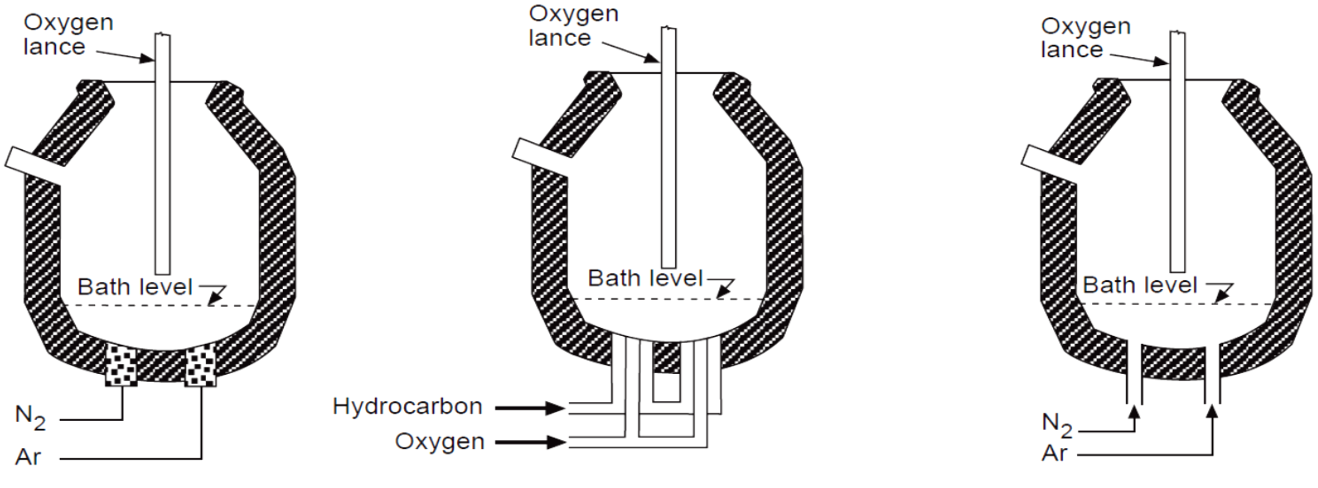
Oxygen of commercial purity, at high pressure and velocity, is blown downward vertically into the bath through a single water-cooled pipe or lance, indicated by arrow.



Bottom-blown (OBM or Q-BOP) process

Oxygen of commercial purity, at high pressure and velocity, is blown upward vertically into the bath through tuyeres surrounded by pipes carrying a hydrocarbon such as natural gas.

General BOF vessel classifications



Top lance plus permeable elements in bottom

Top lance plus cooled bottom tuyeres

Top lance plus uncooled bottom tuyeres

Combination-blown processes

Oxygen is blown downward into the bath, and oxygen and/or other gases are blown upward through permeable elements or tuyeres.

General BOF vessel classifications

2. The Basic Oxygen Process Description

- The oxygen steelmaking process rapidly refines a charge of molten pig iron and ambient scrap into steel of a desired carbon and temperature using high purity oxygen.

- Steel is made in discrete batches called heats.

- The furnace or converter is a barrel shaped, open topped, refractory lined vessel that can rotate on a horizontal trunnion axis.

- The overall purpose of this process is
  - to reduce C from ~ 4% to <1% (usually <0.1%),
  - to reduce or control S and P, and
  - to raise the temperature of liquid steel made from scrap and liquid hot metal to approximately 1635°C.

- A typical configuration is to produce a 250-ton heat in about every 45 minutes, (the range is approx. 30 to 65 minutes).

- Required quantities of hot metal, scrap, oxygen, and fluxes vary according to their chemical compositions and temperatures, and to the desired chemistry and temperature of the steel to be tapped.
- Fluxes are added early in the oxygen blow, to control S and P and to control erosion of the furnace refractory lining.
- Energy required to raise charges to steelmaking temperatures is provided by oxidation reactions.
- Principal elements to control: Si, C, Mn, P.
- The liquid pig iron or hot metal provides almost all Si , C, Mn and P,
  with lesser amounts coming from the scrap.
- The high temperature and intense stirring (resulted during oxygen blow)
  - contribute to the fast oxidation of these elements, and
  - cause a rapid, large energy release.

- Carbon, when oxidized, leaves the process as CO.
- Si, Mn, Fe and P form oxides, which in combination with the fluxes, create a liquid slag.
    - The vigorous stirring fosters a speedy reaction and enables the transfer of energy to the slag and steel bath.
- During the blow, the slag, reaction gases and steel (as tiny droplets) make up a foamy emulsion.
    - The large surface area thus created allow quick reactions and rapid mass transfer of elements from metal and gas phases to the slag.
- When the blow is finished, the slag floats on top of the steel bath.

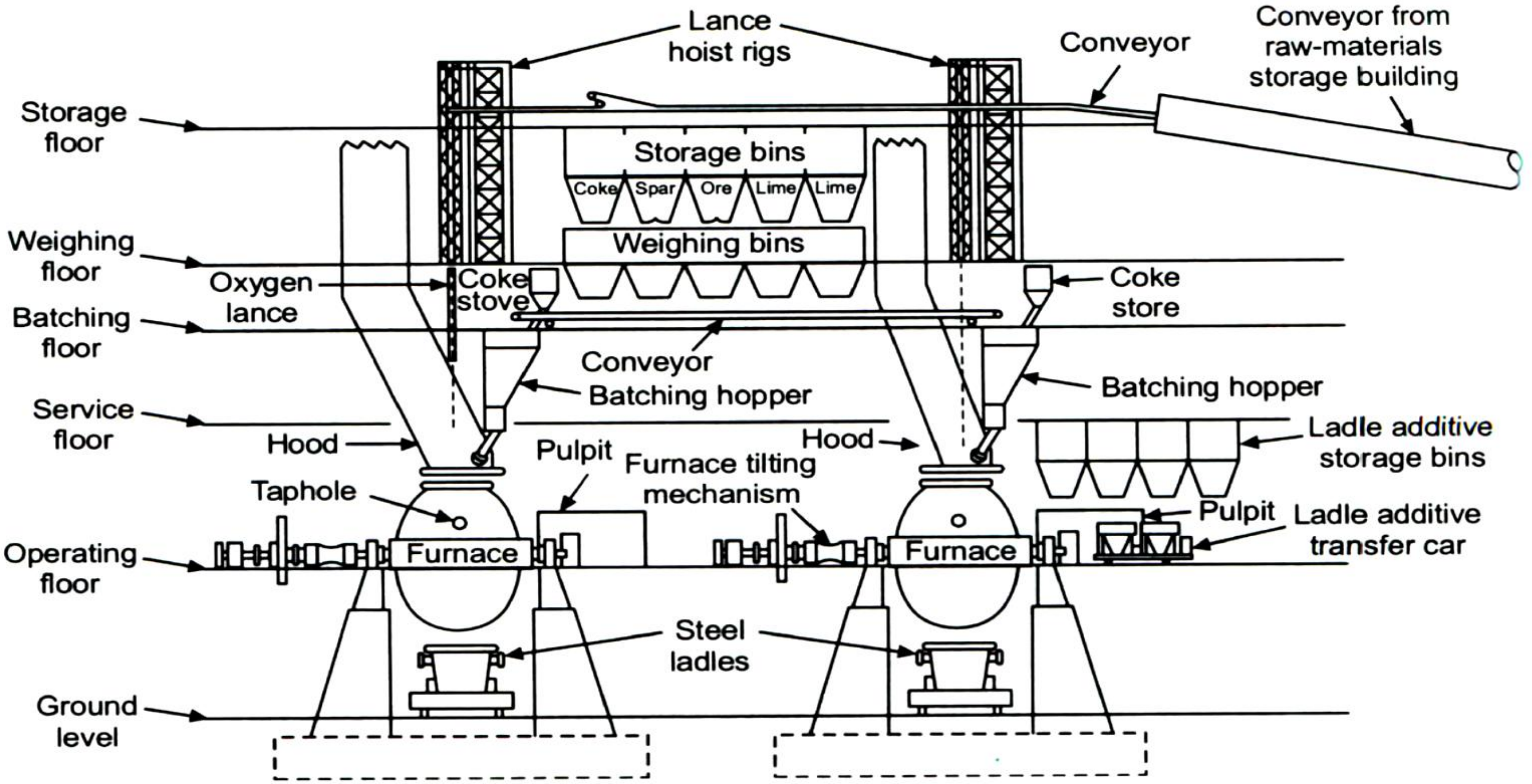
- Controlling sulfur is an important goal of the steelmaking process.
- This is accomplished by
    - first removing most of it from the liquid hot metal before charging, and
    - later, inside the furnace, by controlling the chemical composition of slag with flux additions.

3. The BOP Shop Layout

- A BOF installation consists of the basic oxygen furnace with
  - furnace support foundation,
  - furnace tilt drive and controls,
  - furnace water cooling system,
  - exhaust and cleaning system,
  - oxygen injection system,
  - auxiliary furnace bottom stirring system,
  - process additives system,
  - scrap and hot metal charging system,
  - molten steel delivery and slag disposal system,
  - furnace de-skulling system, and
  - other auxiliary steelmaking requirements such as sampling, refractory inspection and relining systems, process computers, etc.

Shop Layout

- requires rational arrangement of equipment to ensure smooth handling of solid raw materials, movement of oxygen lance and hot metal.
- it should ensure smooth flow of ladles containing hot metal and steel.
- refining process is very fast and hence an efficient system of material transport and weighing is required.



Layout of a typical two-converter BOF shop

4. Design of Converter

- From the metallurgical point of view, an ideal converter keeps the liquid steel in space and allows all necessary metallurgical reactions to take place within the temperature range of 1400−1600 °C.

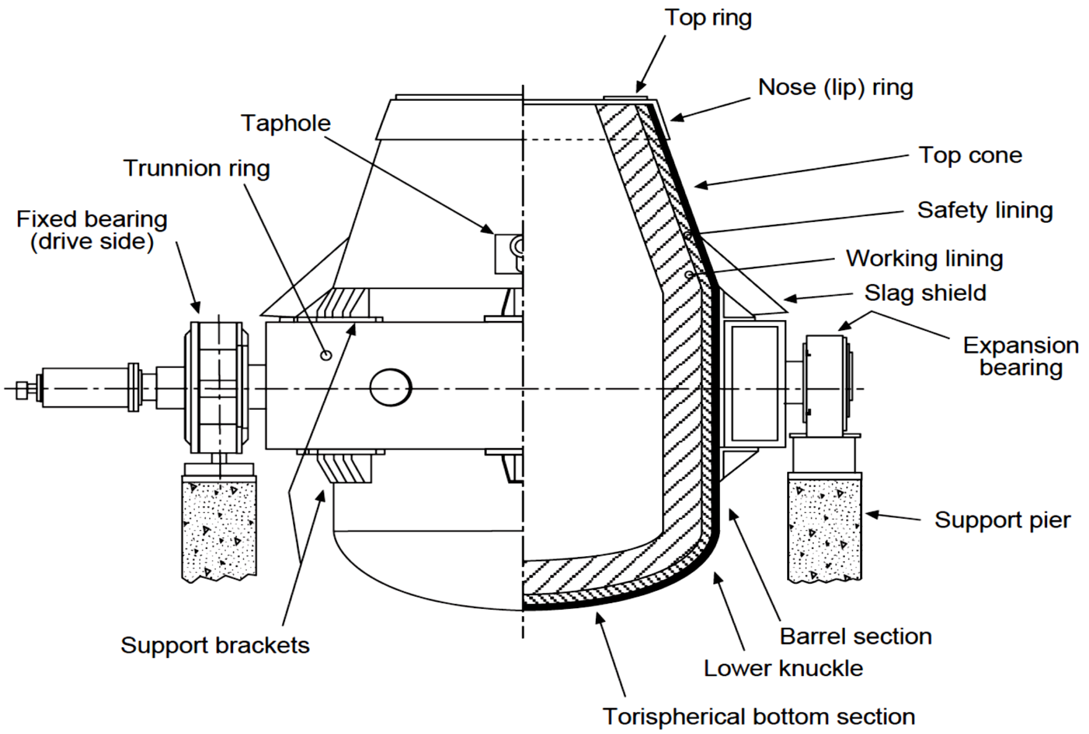
- The mechanical part, which keeps the liquid steel in space, is a steel shell lined with refractory material.

- The inner volume is maximized to achieve an optimum metallurgical process without sloping of slag.
  - a ratio of 3 m^3 internal volume/ ton of liquid is typical in converter design.

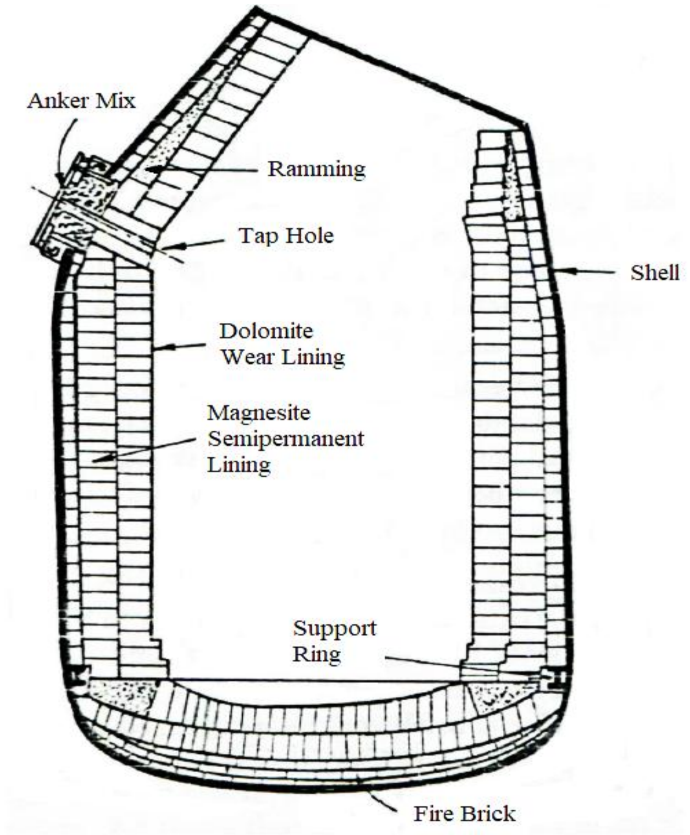
- The vessel is supported by a suspension system which transmits the load to the trunnion ring.

- An operating BOF consists of
  - the vessel and its refractory lining,
  - vessel protective slag shields,
  - the trunnion ring,
  - a vessel suspension system supporting the vessel within the trunnion ring,
  - trunnion pins and support bearings, and
  - the oxygen lance.

- The size of BOF vessel varies between 30 – 400 ton



Typical components of a BOF vessel



Lining details of BOF vessel

- compared to conventional processes of steelmaking, the refractories used in lining BOF vessels are expected to stand more severe chemical and mechanical abuse.
- the attack of molten metal and slag is severe if the liquid iron contains more silicon and manganese content and/or if steels with low carbon steels in BOF vessel are to be produced.

Safety lining

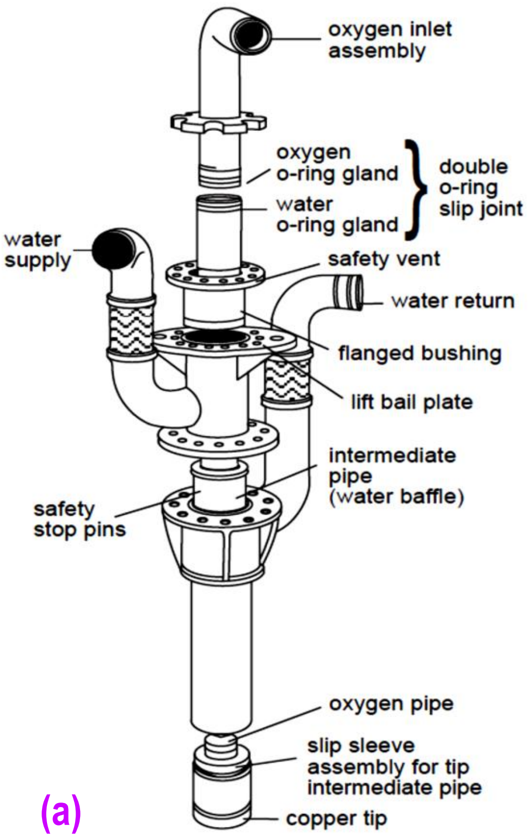
- burned pitch impregnated magnesite refractories
- typical thickness is 20 cm (45 cm on the bottom)

Working lining

- thickness varied on type of operation and wear rate
- normally lasts 300-1000 heats
- higher wear areas require greater thickness or higher quality materials

Normally 3-5 kg refractory consumed per ton steel made

5. The Oxygen Lance



(a)

- 8-10 m long and 20−25 cm diameter
- designed to produce non-coalescing free oxygen jet at an operating oxygen pressure of 10-12 kg/cm^3
- water requirements are around 50−70 m^3/hr at a pressure of 5−7 kg/cm^3

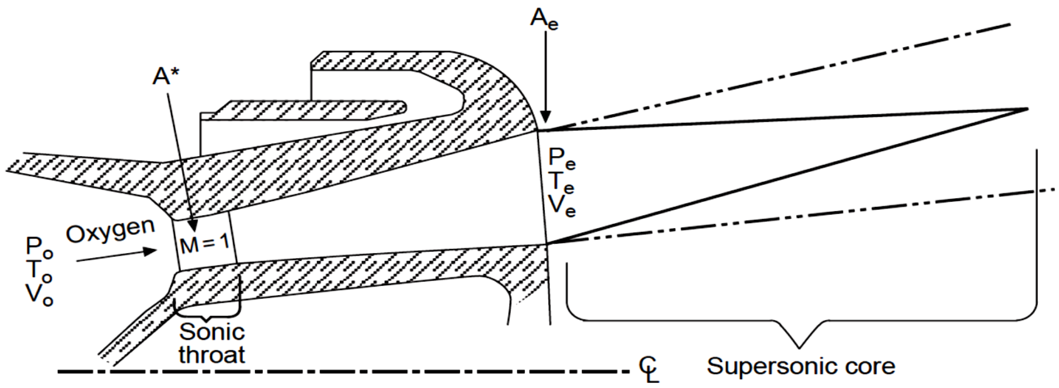
(b)

High purity oxygen (at least 99.9 % purity) is supplied at supersonic speed (about 1.5 -2.5 Mach) on bath surface through a water-cooled vertical lance, inserted through the mouth of the vessel.

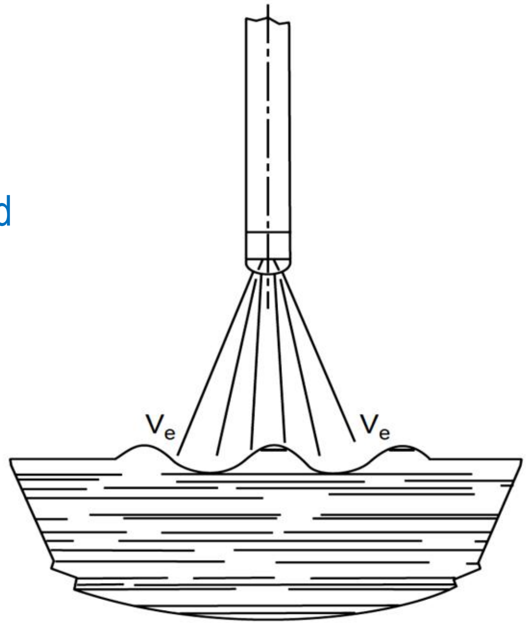
(a) Adapter assembly of the BOF oxygen lance
(b) Various types of BOF lance tips

- Nozzles are designed for a certain oxygen flow rate, resulting in a certain exit velocity (Mach number), with the required jet profile and force to penetrate the slag layer and react with the steel bath in the dimple area.

- Supersonic jets are produced with convergent/divergent nozzles. The oxygen accelerates in the converging section up to sonic velocity, Mach = 1, in the cylindrical throat zone. The oxygen then expands in the diverging section. The expansion decreases the temperature, density, and pressure of the oxygen and the velocity increases to supersonic levels, Mach > 1.



Mechanics of supersonic jet formation



Effect of nozzle design on impact angle and jet thrust

Multi-hole lances

- large volume of oxygen (typically 60 m^3/ton at 10^9 m^3/hr) can be blown with the restricted total blowing time of 15-20 minutes.
- causes the total jet energy gets dispersed along the diameter of the vessel rather than in the vertical direction
- this results more liquid metal to be exposed to oxygen, faster slag-metal reaction and higher productivity

Lance life

- determined by the life of the nozzles.
- failures of lance is caused due to faulty cooling, manufacturing defects, and differential expansion between copper tip and steel tube.
- the usual life of a lance does not exceed a few hundred heats.

6. Feed Materials

- The major inputs for BOF steelmaking:
  - Hot metal (75-95% of the charge, 1250 – 1300 °C; low S, high Mn)
  - Cold pig iron
  - Steel scrap (source of Fe) and ore (as coolant)
  - DRI (source of Fe or coolant)
  - Alloy additions (common alloying elements are Cu, Cr, Mo and Ni)
  - Fluxes (reduce softening point and viscosity; burnt lime, dolomite, limestone, fluorspar)
  - Gaseous oxygen (very high purity, 99.7 – 99.8%)
  - Deoxidiser (aluminium, ferrosilicon and ferromanganese) and recarburiser (graphite)

7. Sequence of Operation
in Top Blown (LD) Process

1) Scrap handling
2) Hot metal pouring
3) Hot metal treatment
4) **Charging the furnace**
5) Computer calculation
6) **Oxygen blow**
7) **Flux additions**
8) Final oxygen adjustment and dynamic sensors
9) **Turndown and testing**
10) Corrective actions
11) **Tapping**
12) **Slagging off** and furnace maintenance

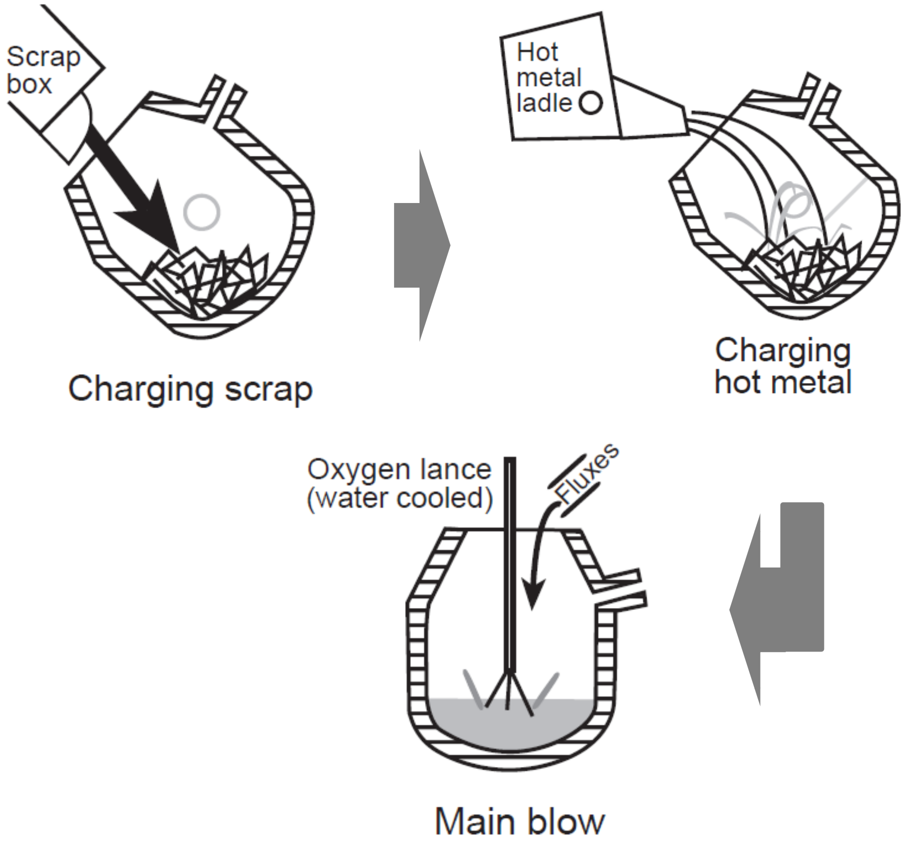
Basic Operational Steps of Top-Blowing (LD) Process

1. Scrap charging (in inclined position) **[3-5 min]**

2. Vessel rocking to drop scrap at the bottom and hot metal charging (in horizontal position) **[1-5 min]**

3. Rotating to vertical position, lowering the lance and first blowing of oxygen starts **[1-1.5 min]**

4. As soon as ignition starts, flux is charged to form early slag; blowing continues **[15-25 min]**



Batch	Lance Height, inch	Oxygen Volume, Nm^3	Purpose
1	150	850	safely establish the oxidizing, heat generating reactions
2	120	1700	increase the reaction rate and control the early slag formation
3 (main)	90	Balance (approx. 14200)	most of the action occurs

Lance is too high → slag over stirred and over-oxidized with higher FeO; higher yield losses; reduced C removal; increased slag volume; increased slopping and spilling

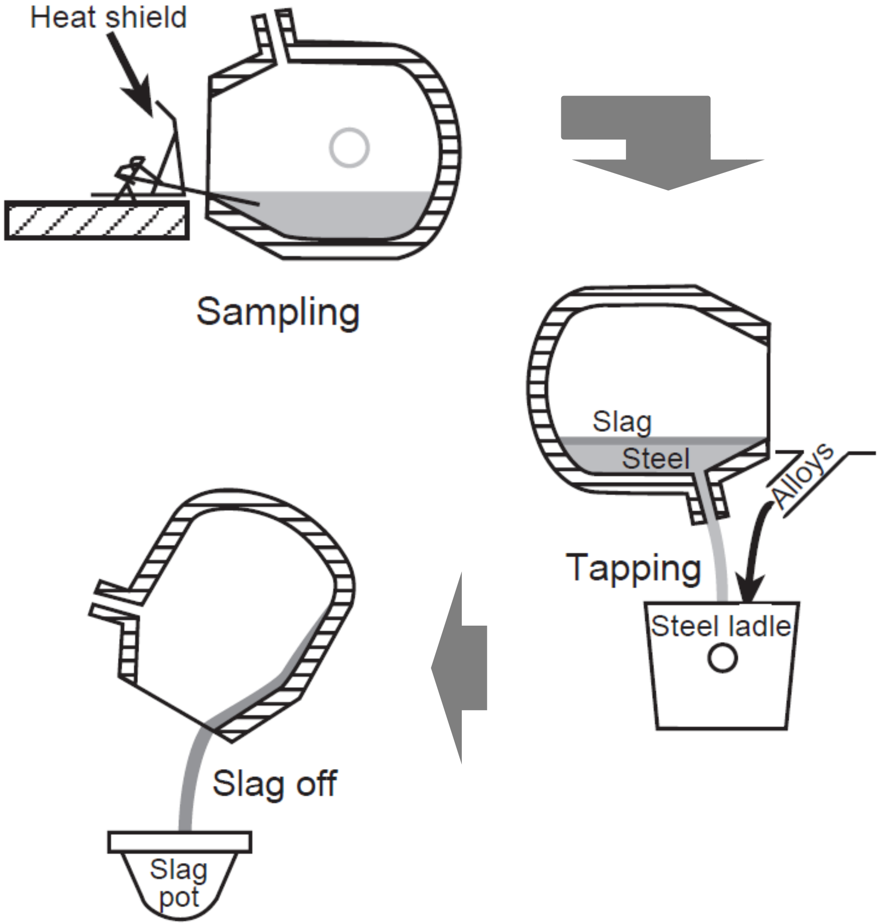
Lance is too low → increased carbon removal; reduced slag formation and slag reactivity; reduced FeO; causes S and P removal problems

Lance is very low → splitting of metal droplets; severe and dangerous metallic deposits, called skulls, on the lance; lower waste gas hood

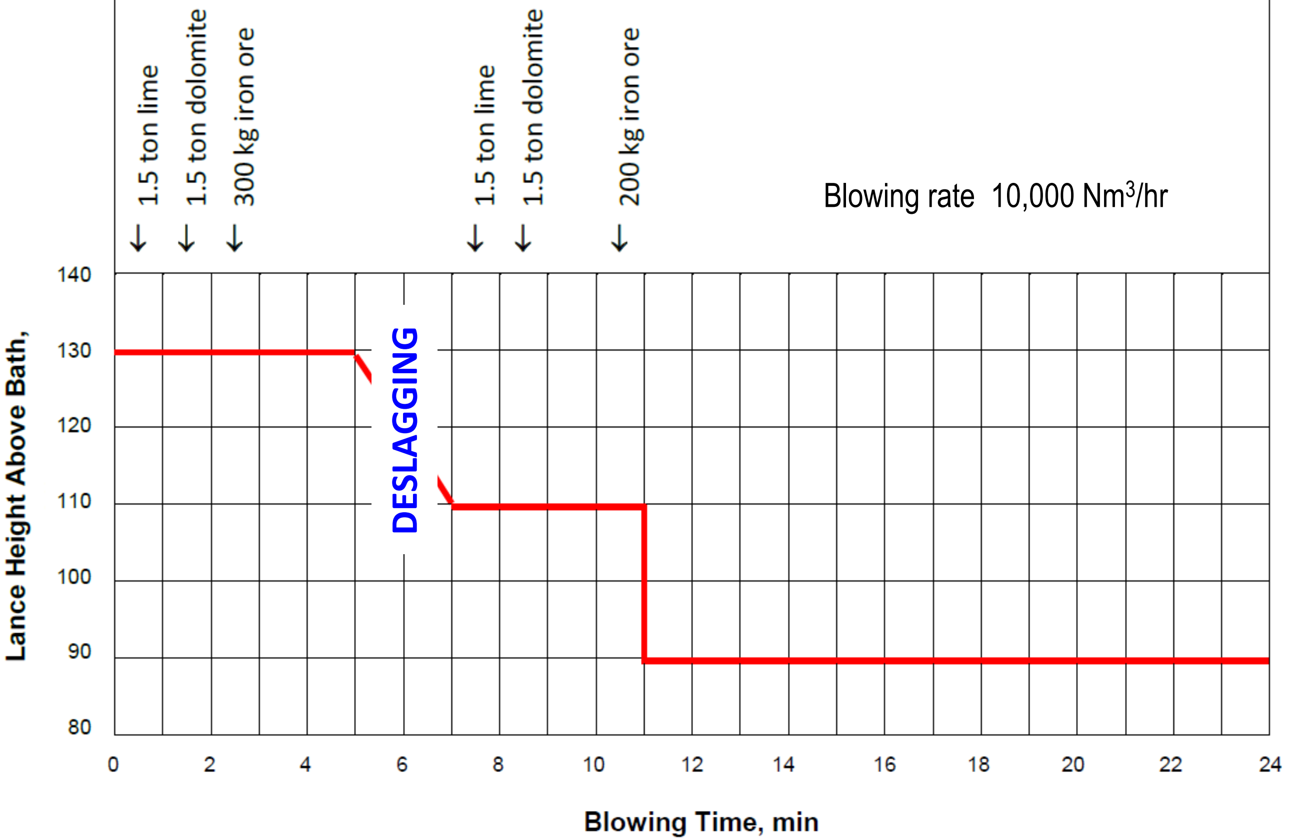
5. Blowing is stopped, lance is raised, vessel inclined position for <u>bath analysis and temperature measurement</u>; <u>alloy additions made</u>; 2-3 min waits for homogenisatiton **[5-8 min]**

6. If analysis and temperature is correct, vessel is rocked in tapping position and <u>tapping in ladle</u>; <u>deoxidation and alloy addition in ladle</u> **[4-7 min]**

7. As slag appears, vessel is inclined further to tip out the slag **[variable]**



- Efficient tap-to-tap time : 30 – 33 minutes
- Good tap-to-tap time : 40 – 45 minutes



typical blowing practice in LD process

1st stage:

blow time – 5-6 min
oxygen pressure – 11 atm
lance height – 130 cm

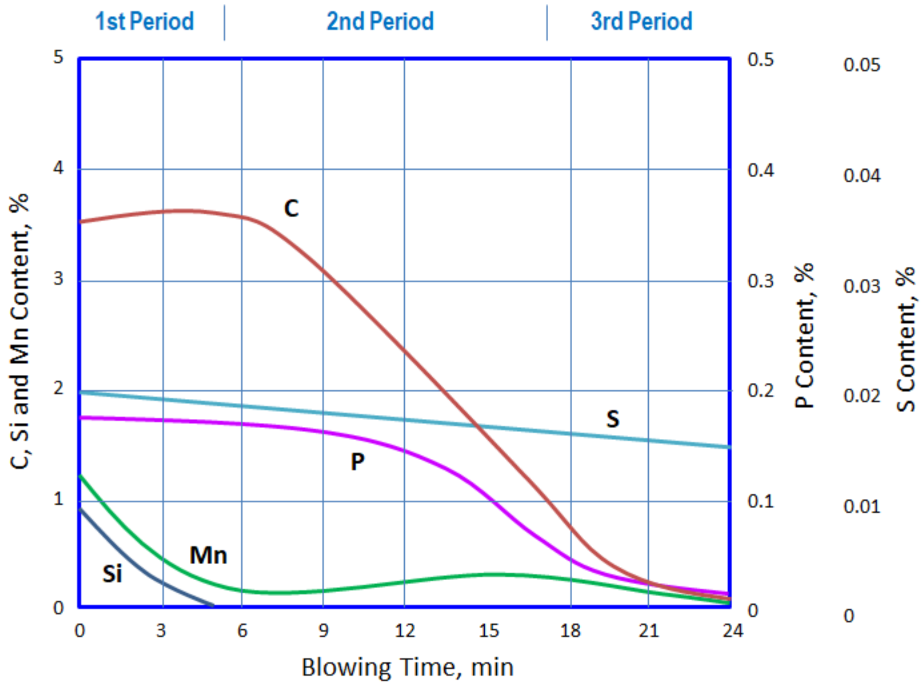
2nd stage:

blow time – 5-6 min
oxygen pressure – 8-9 atm
lance height – 110 cm

3rd stage:

after all lime addition,
blow time – 10-12 min
oxygen pressure – 11 atm
lance height – 90 cm

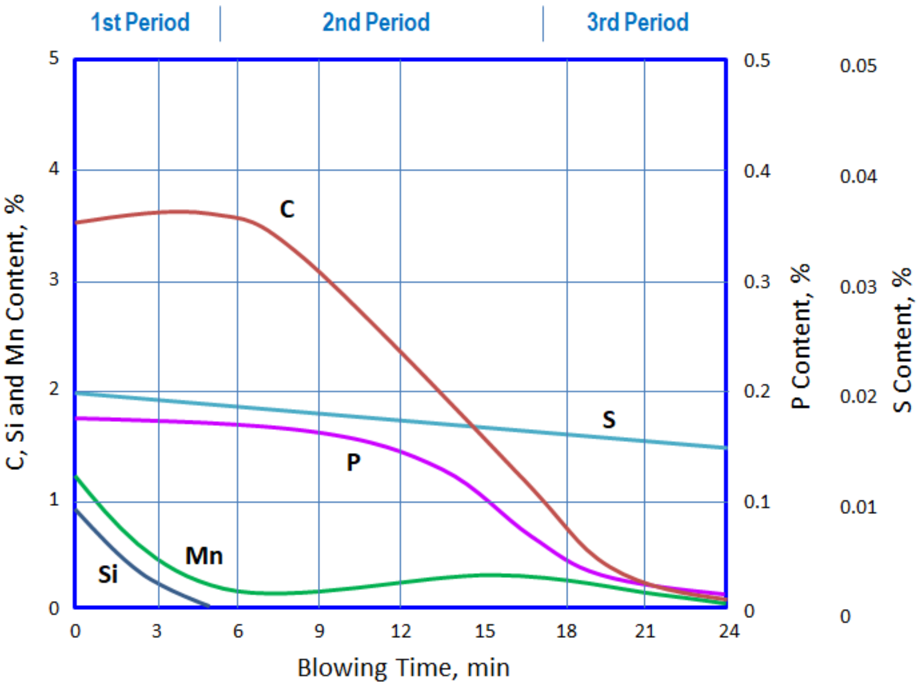
8. Process Reactions and Energy Balance



Variation of composition of metal during the blow

Silicon Reaction

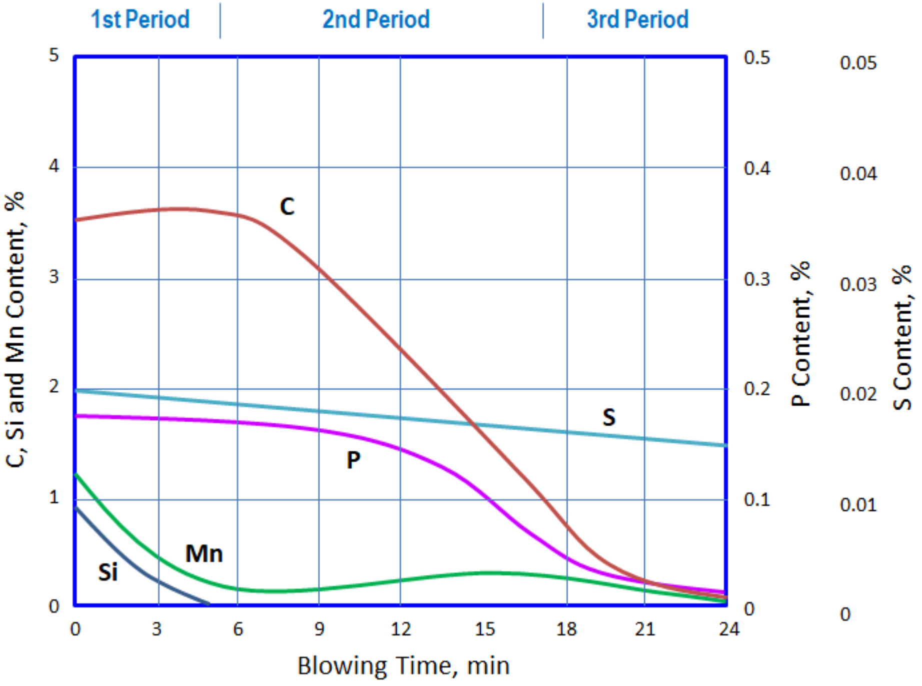
- Strong affinity of oxygen for Si results removal of almost all Si early in the blow.
- Si dissolved in hot metal (0.25–1.3 wt.%) is oxidized to very low levels (<0.005 wt.%) in the first 3 -5 minutes of the blow.
- The silicate slag reacts with the added lime (CaO) and dolomitic lime (MgO) to form a basic steelmaking slag.
- Exothermic reaction produce significant heat, raises bath temperature and strongly affects the amount of scrap that can be melted.
- It also determines slag volume and consequently affects iron yield and dephosphorization of the metal. In general, more slag causes less yield but lower P.



Variation of composition of metal during the blow

Manganese Reaction

- Like Si, Mn is oxidized to MnO early in the blow up to a certain level and it remains there for almost the rest of the blow.
- However, after most of the silicon has been oxidized, some Mn reverts into the metal at the end of the second period.
- Towards the end of the blow, the Mn in metal decreases again as more oxygen is available for its oxidation.



Variation of composition of metal during the blow

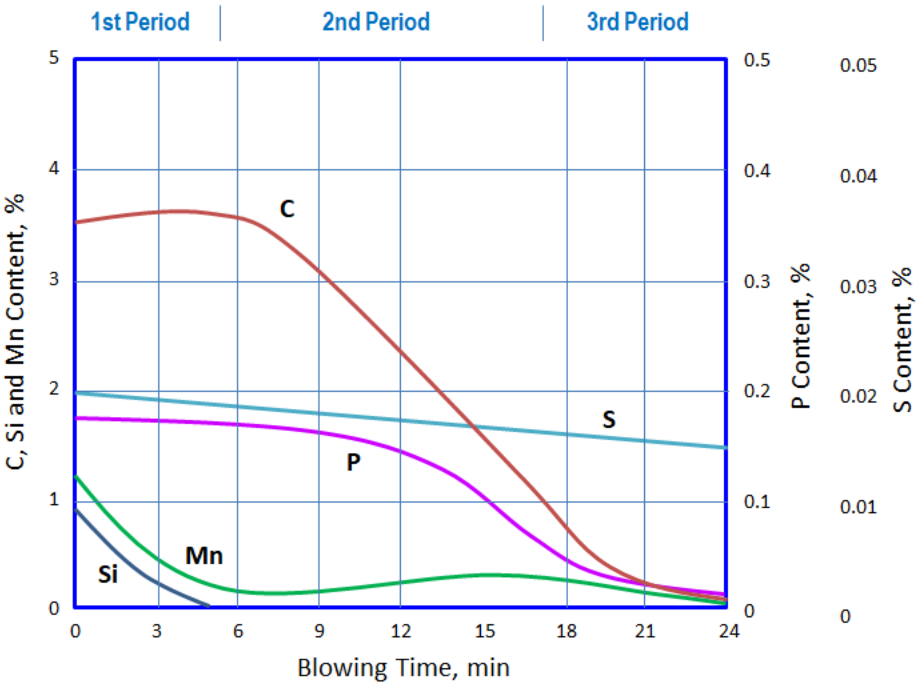
Carbon Reaction

- C in hot metal is oxidized to CO and CO_2 during the oxygen blow, and steel with less than 0.1 wt% carbon is produced.

- Change in carbon content shows three distinct periods.

  ① The first period, occurs during the first few minutes of the blow, shows a slow decarburization rate as nearly all the oxygen supplied reacts with the silicon in the metal. In fact, the curve shows a slight increase as percentage of Si and Mn decreases in the bath.

  ② The second period, occurring at high C contents in the metal, shows a constant higher rate of decarburization and it is controlled by the rate of supplied oxygen.

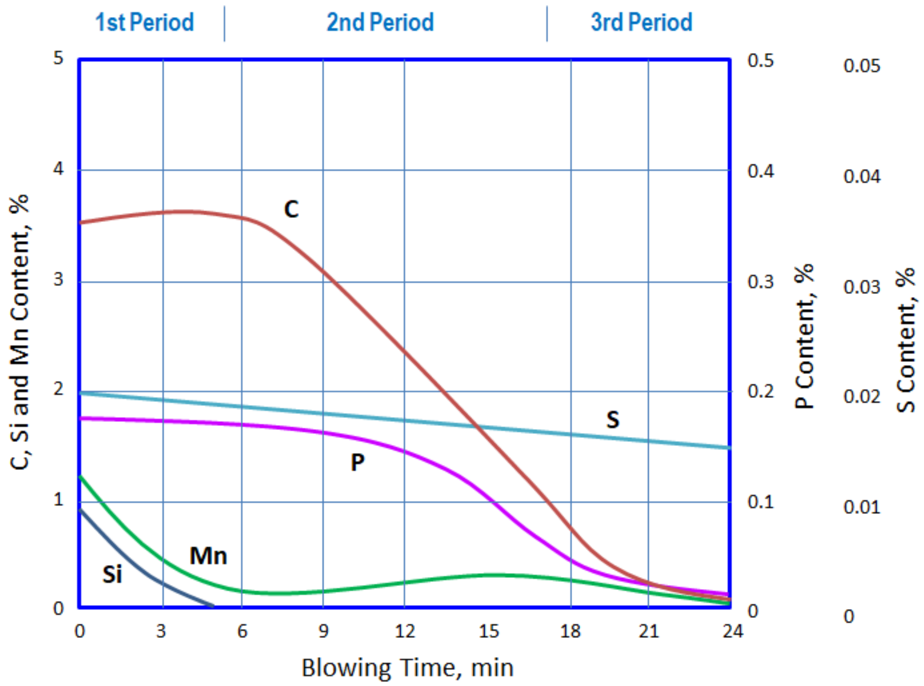


Variation of composition of metal during the blow

③ Finally, at the third period, decarburization rate drops as C becomes less available to react with the oxygen supplied.

At this stage, the rate is controlled by mass transfer of C, and the oxygen will mostly react with Fe to form FeO.

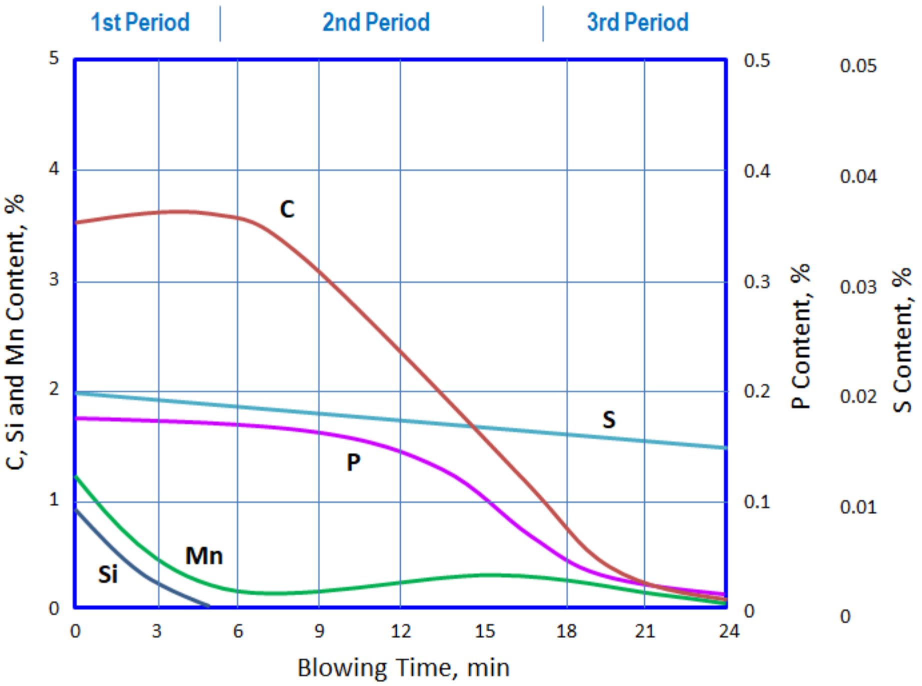
Also in this stage, the generation of CO drops and the flame over the mouth of the furnace becomes less luminous, and practically disappears below about 0.1 wt.% carbon.



Variation of composition of metal during the blow

Phosphorous Reaction

- Dephosphorization is favored by the oxidizing conditions in the furnace.
- As P removal is favored by high slag basicity (high CaO/SiO_2 ratio), high slag FeO, and high slag fluidity, P content **decreases very slightly up to the end of the second period of the blow**.
- During this period, FeO increases, stirring due to CO formation improves slag-metal mixing, CaO addition and its dissolution raises slag basicity, and fluorspar added to raise fluidity of the bath.
- Thus, P removal rate accelerates till the end of the blow when temperature is high and the bath is deoxidised.



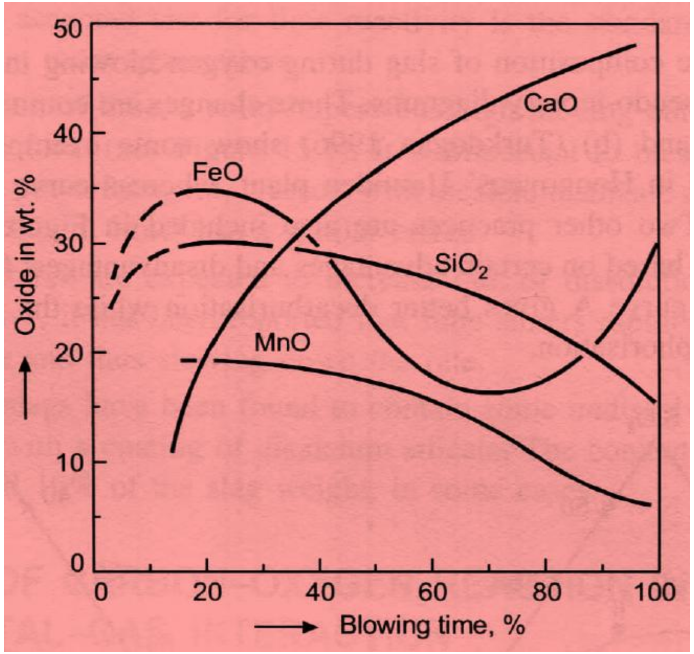
Variation of composition of metal during the blow

Sulphur Reaction

- The BOF is **not very effective for sulfur removal** due to its highly oxidizing conditions.
- Sulfur distribution ratios (S)/[S] in the BOF is about 4–8, which are much lower than the ratios in the steel (~300–500) during secondary ladle practices.
- In the BOF, about 10 to 20% of sulfur in the metal reacts directly with oxygen to form gaseous SO_2.

Slag Formation

- Fluxes are charged into the furnace early in the blow and they dissolve with the developing oxides to form a liquid slag.
- The rate of dissolution of these fluxes strongly affects the slag-metal reactions occurring during the blow.
- At the beginning of the blow, the tip of the oxygen lance is kept high above the bath surface, which results in the formation of an initial slag rich in SiO_2 and FeO.
- During this period large amounts of burnt lime and dolomitic lime are charged into the furnace.

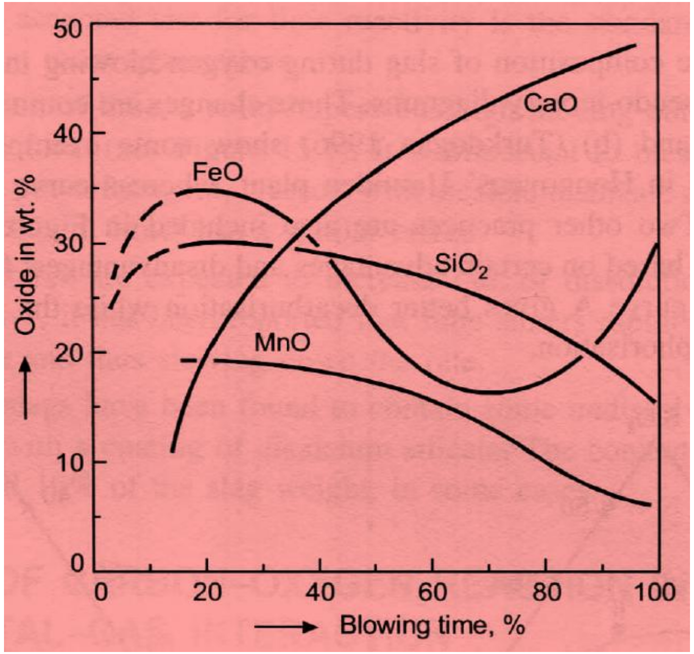


change in slag composition with blowing time

- The lance is then lowered, and the slag starts to foam at around one third of the blow due to the reduction of the FeO in the slag in conjunction with CO formation.

- Also, as the blow progresses, the CaO dissolves in the slag, and the active slag weight increases.

- Finally, after three quarters into the blow, the FeO content in the slag increases because of a decrease in the rate of decarburization.



change in slag composition with blowing time

- During the blow, the temperature of the metal gradually increases from about 1350°C to 1650°C at turndown, and the slag temperature is about 50°C higher than that of the metal.

- The slag at turndown may contain regions of undissolved lime mixed with the liquid slag, since the dissolution of lime is limited by the presence of dicalcium silicate ($2CaO \cdot SiO_2$) coating on lime, which is solid at steelmaking temperatures and prevents rapid dissolution.

- The presence of MgO in the lime weakens the coating. Thus, charging MgO early speeds up slag forming due to quicker solution of lime.

- The resulting slag at turndown in top-blown converters (BOF or BOP) have typical ranges:

42–55 % CaO	**3–8 %** MnO
2–8 % MgO	**10–25 %** SiO_2
10–30 % FeO_T	**1–5 %** P_2O_5
1–2 % Al_2O_3	**0.1–0.3 %** S

- In the OBM (Q-BOP) or bottom-blown converter, the total FeO in the turndown slag is lower, ranging between 4–22 %.

- The quantity of slag, which is zero at the beginning, keeps increasing during the blow as lime dissolution continues.
- Total lime used depends primarily on the SiO_2 content so that $CaO/SiO_2 = 3$ is maintained in the final slag to ensure adequate refining.
- Extent of lime added varies between 60-70 kg/ton liquid steel for 0.5-0.7 % Si to up to 120 kg/ton for 1.2 % Si.

Heat Balance of Basic Bessemer Process

Heat Input Item	Per Cent	Heat Output Item	Per Cent
Heat of molten pig iron	**42 – 44**	Heat of steel	**52 – 54**
Carbon oxidation	**18 – 20**	Heat of slag	**18 – 20**
Oxidation of Si and Mn	**7 – 9**	Heat of waste gas	**22 – 24**
Iron oxidation	**2 – 3**	Blast moisture dissociation	**1 – 1.4**
Slag formation	**7 – 9**	Heat losses	**3 – 4**
	100		**100**

- Total heat input (and output) is roughly equal to **2500 MJ** in BOP.