Steel Making (MT410601)

Program: B.Tech.	Branch: Metallurgical Engineering
Subject: Steel Making	Semester: VI
Subject Code:	MT410601

UNIT 2

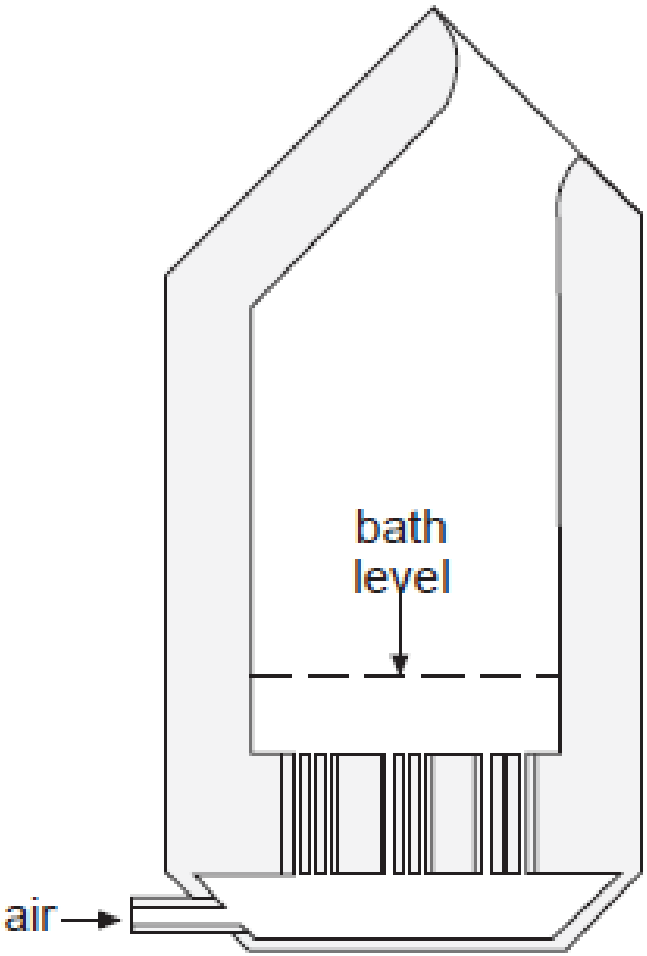
Overview of Steelmaking Processes and Their Development

- Bessemer
- Open hearth
- Oxygen steelmaking
- EAF
- Induction furnace

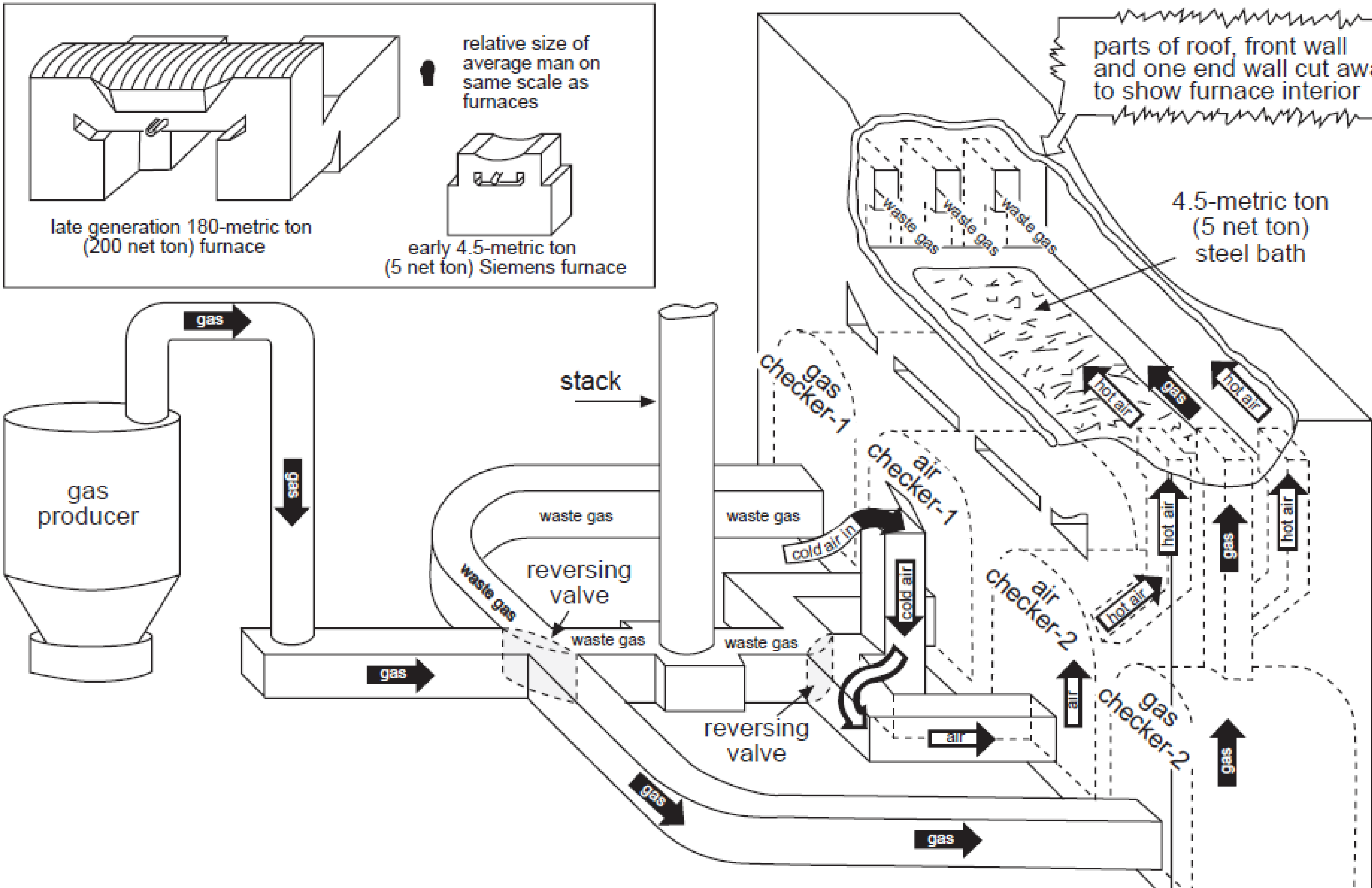
Bessemer

- Acidic lining
  - P removal difficult
  - S removal difficult

- Basic lining
  - Basic lining
  - Addition of flux



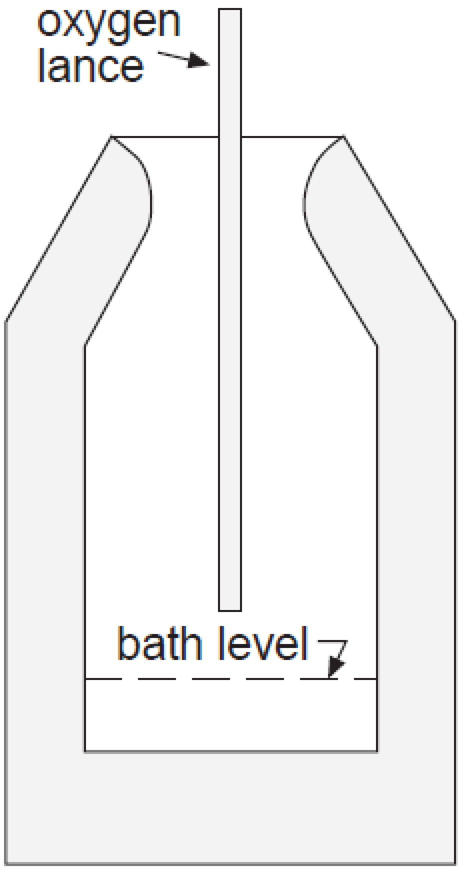
Open Hearth Process

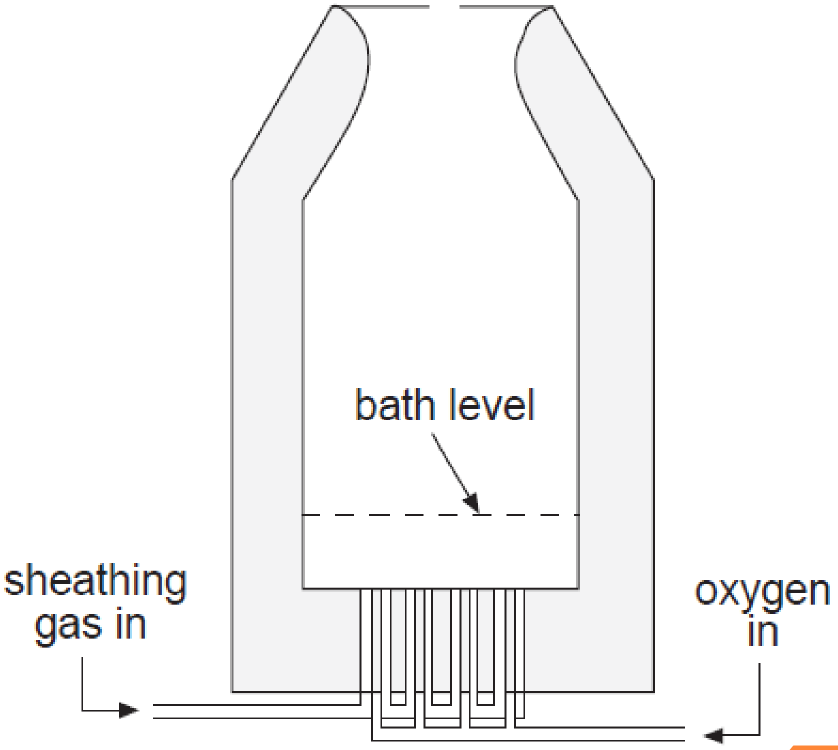


Open Hearth Process

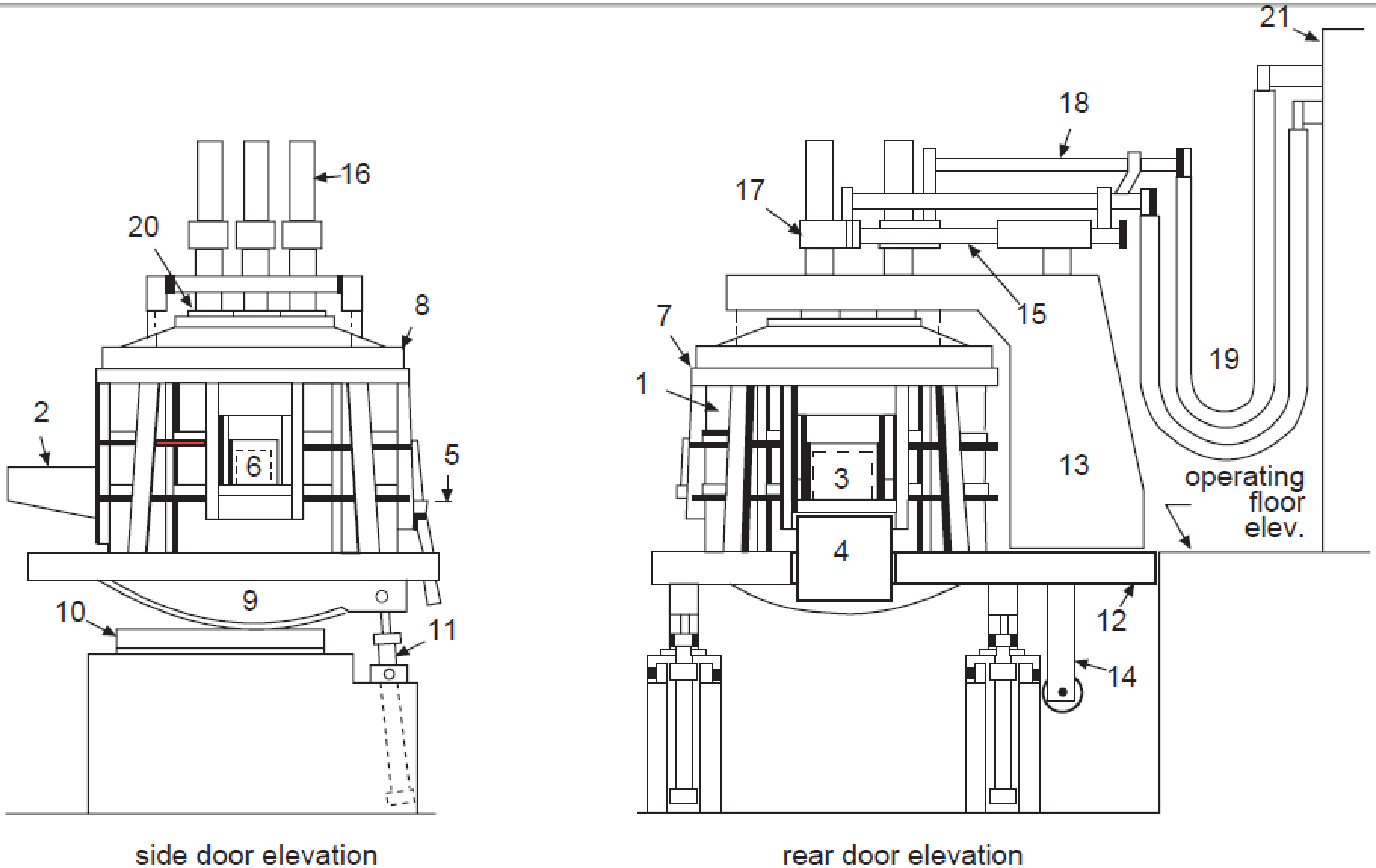
- Hot air
- Hot gas
- Use of Iron ore

Oxygen steelmaking

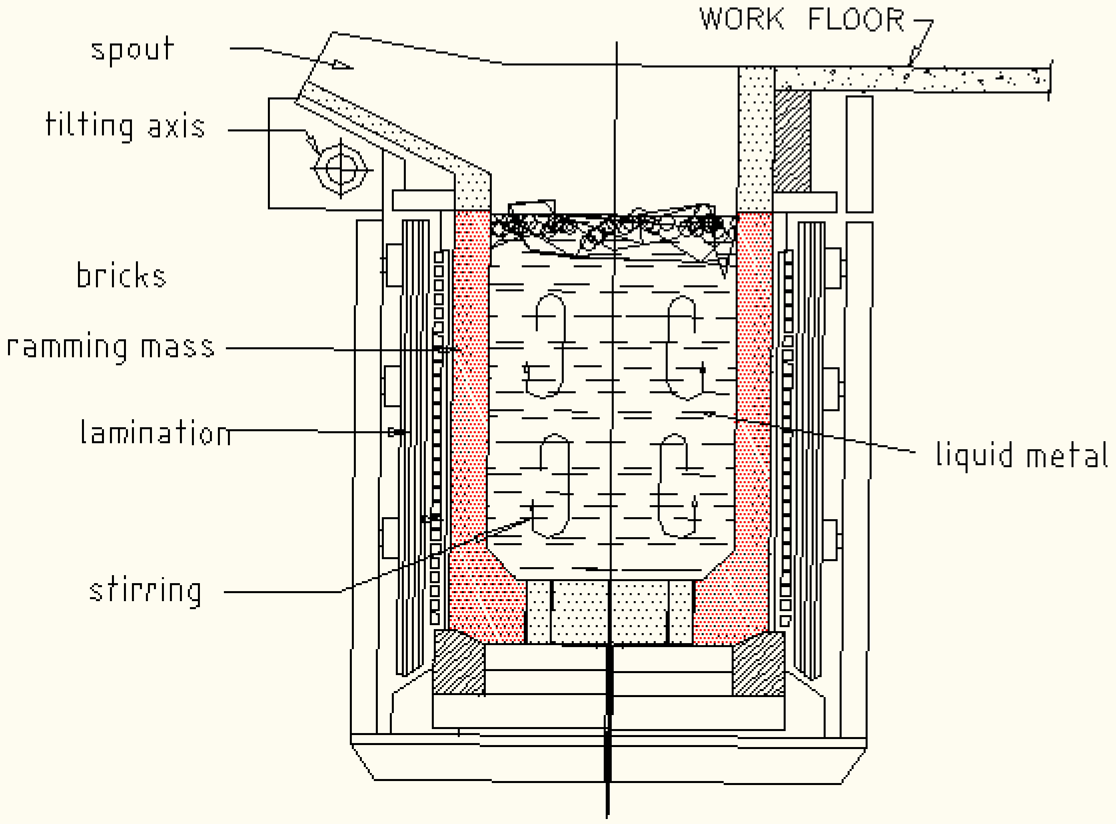




ELECTRIC ARC FURNACE



INDUCTION FURNACE



Induction furnace

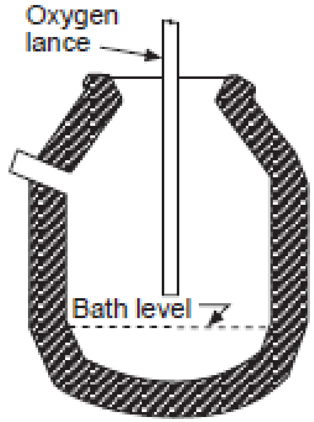
Integrated steel plants in India

1. Tata Iron and Steel Company (TISCO)
2. Indian Iron and Steel Company (IISCO)
3. The Visweswaraya Iron and Steel Ltd
4. Bhilai
5. Rourkela
6. Durgapur
7. Bokaro
8. The Salem Steel Plant
9. Vijayanagar Steel Plant
10. Vishakhapatnam Steel Plant (VSP)
11. Daitari Steel Plant
13. Dolvi Steel Plant

Basic Oxygen Furnace (BOF)

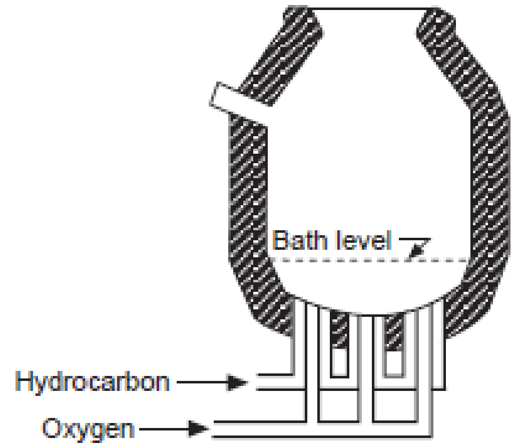
Types of Oxygen Steelmaking Processes

- There are basically three variations of introducing oxygen gas into the liquid bath. These are shown schematically in the next slide.
- The most common configuration is the **top-blown converter (BOF), where all of the oxygen is introduced via a** water-cooled lance.



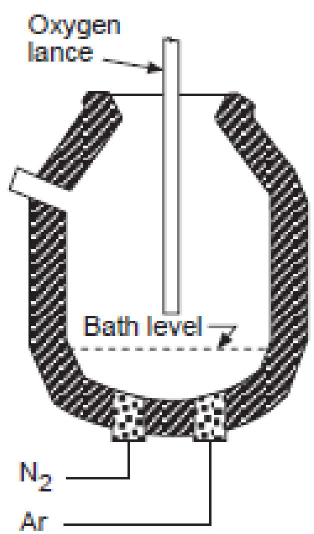
Top-blown (BOF) process

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.

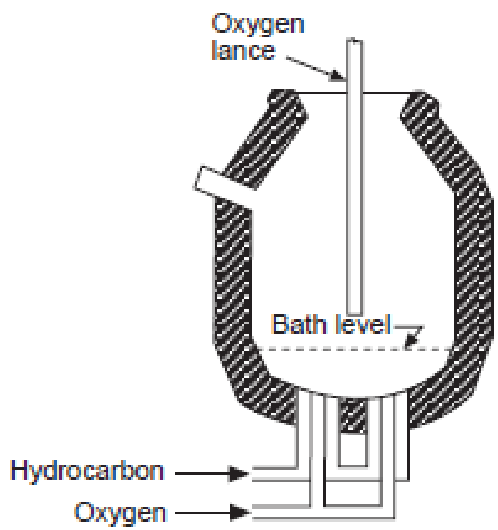


Bottom-blown (OBM or Q-BOP) process

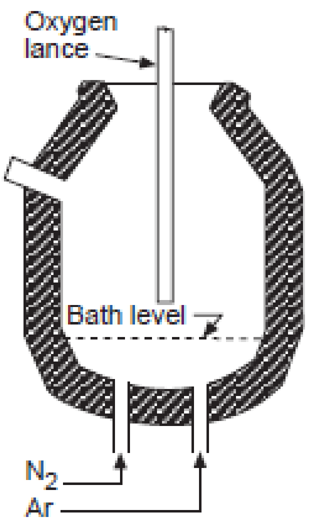
Oxygen of commercial purity, at high pressure and velocity, is blown upward vertically into the bath through tuyeres surrounded by pipes carrying a hydrocarbon such as natural gas.



Top lance plus permeable elements in bottom



Top lance plus cooled bottom tuyeres



Top lance plus uncooled bottom tuyeres

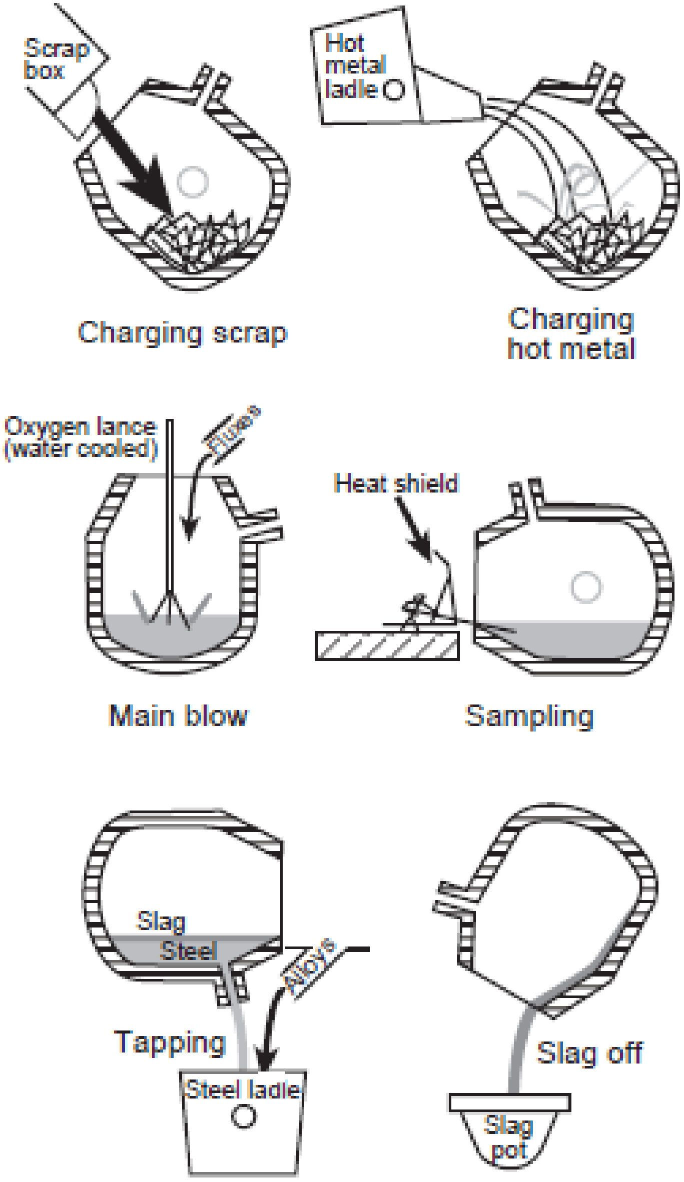
- The blowing end of this lance features three to five special nozzles that deliver the gas jets at supersonic velocities.
- In top blowing, the stirring created by these focused, supersonic jets cause the necessary slag emulsion to form and keeps vigorous bath flows to sustain the rapid reactions.
- The lance is suspended above the furnace and lowered into it.
- Oxygen is turned on as the lance moves into the furnace. Slag forming fluxes are added from above the furnace via a chute in the waste gas hood.

- In the **bottom-blown converters (OBM or Q-BOP), oxygen is introduced via several tuyeres** installed in the bottom of the vessel. Each tuyere consists of two concentric pipes with the oxygen passing through the center pipe and a coolant hydrocarbon passing through the annulus between the pipes.
- The coolant is usually methane (natural gas) or propane although some shops have used fuel oil.

- The coolant chemically decomposes when introduced at high temperatures and absorbs heat in the vicinity, thus protecting the tuyere from overheating.
- In bottom blowing, all of the oxygen is introduced through the bottom, and passes through the bath and slag thus creating vigorous bath stirring and formation of a slag emulsion. Powdered fluxes are introduced into the bath through the tuyeres located in the bottom of the furnace

- The **combination blowing or top and bottom blowing, or mixed blowing** process is characterized by both a top blowing lance and a method of achieving stirring from the bottom.
- The configurational differences in mixed blowing lie principally in the bottom tuyeres or elements.
- These range from fully cooled tuyeres, to uncooled tuyeres, to permeable elements.

Process description



Event	Min.	Comments
Charging scrap and hot metal	5–10	Scrap at ambient temperature, hot metal at 1340°C (2450°F)
Refining–*blowing* oxygen	14–23	Oxygen reacts with elements, Si, C, Fe, Mn, P in scrap and hot metal and flux additions to form a slag
Sampling–chemical testing	4–15	Steel at 1650°C (3000°F), chemistry and temperature
Tapping	4–8	Steel is poured from furnace into a ladle, typical size = 250 tons
Pouring *slag off* at furnace	3–9	Most slag is removed from furnace, in some shops slag is used to coat furnace walls

Oxygen Blow

- After scrap and hot metal are charged, the furnace is set upright and the oxygen is supplied through a water-cooled lance.
- There are two lance lift carriages above each furnace but only one lance is used at a time; the other is a spare.
- The oxygen blow times typically range from 13 to 25 minutes from one shop to another with an average of about 20 minutes.
- The oxygen is added in several batches. Each batch is characterized by a different lance height above the static steel bath and sometimes by an oxygen rate change

- The first batch lance height is very high to avoid the possibility of lance tip contact with the scrap and to safely establish the oxidizing, heat generating reactions. If the lance would contact the pile of scrap in the furnace, a serious water leak could result causing a dangerous steam explosion

- The second batch lance height is usually approximately 20 to 30 inches lower than the first batch and approximately 20 to 30 inches higher than the main batch. The purpose here is to increase the reaction rate and control the early slag formation.
- This second or middle batch generates some early iron oxide to increase proper slag formation

- The main batch is where most of the action occurs—it is by far the longest batch. The lance height is an empirical compromise between achieving faster carbon removal rates and proper slag making.

- The position of the lance is very important for proper functioning of the process. If the lance is too high, the slag will be over stirred and over-oxidized with higher FeO percentages.
- This will cause higher than normal yield losses and lower tap alloy efficiencies due to oxidation losses.
- Further, the rate of carbon removal is reduced and becomes erratic. Slag volume increases and there is an increased chance of slopping, *which is an uncontrolled slag drooling or spilling over the top of the* furnace.

- When the lance is too low, carbon removal increases somewhat, slag formation, slag reactivity, and FeO are reduced and sulfur and phosphorus removal problems often occur. If the lance is very low, then spitting of metal droplets or sparking occurs which cause severe and dangerous metallic deposits, called skulls, on the lance and the lower waste gas hood.

Flux Additions

- Soon after the oxygen is turned on, flux additions are started and are usually completed at the end of the second batch of oxygen.
- The fluxes control the chemistry and sulfur and phosphorus capacity of the slag. The principle active ingredients from the fluxes are CaO (from burnt lime) and MgO (from dolomitic lime). The CaO component is used principally to control sulfur and phosphorous.

- The dolomitic lime is used to saturate the slag with MgO. The principle ingredient of the furnace refractories is MgO. Steelmaking slags without it are very corrosive to the lining.
- The corrosion rate is reduced dramatically when MgO is added to saturate the slag. It is much cheaper to satisfy the slag's appetite for MgO from dolomitic lime than by dissolving it from the lining.

TAPPING

- For tapping, the furnace is rotated to the tap side and the steel flows through a taphole into a ladle sitting on a car below. The slag floats on top of the steel bath inside the furnace. Near the end of tapping (four to ten minutes) a vortex may develop near the draining taphole and entrain some of the slag into the ladle.
- There are various devices used to minimize or detect the onset of slag. Heavy uncontrolled slag entrainment into the ladle has a significant adverse effect on production costs and steel quality

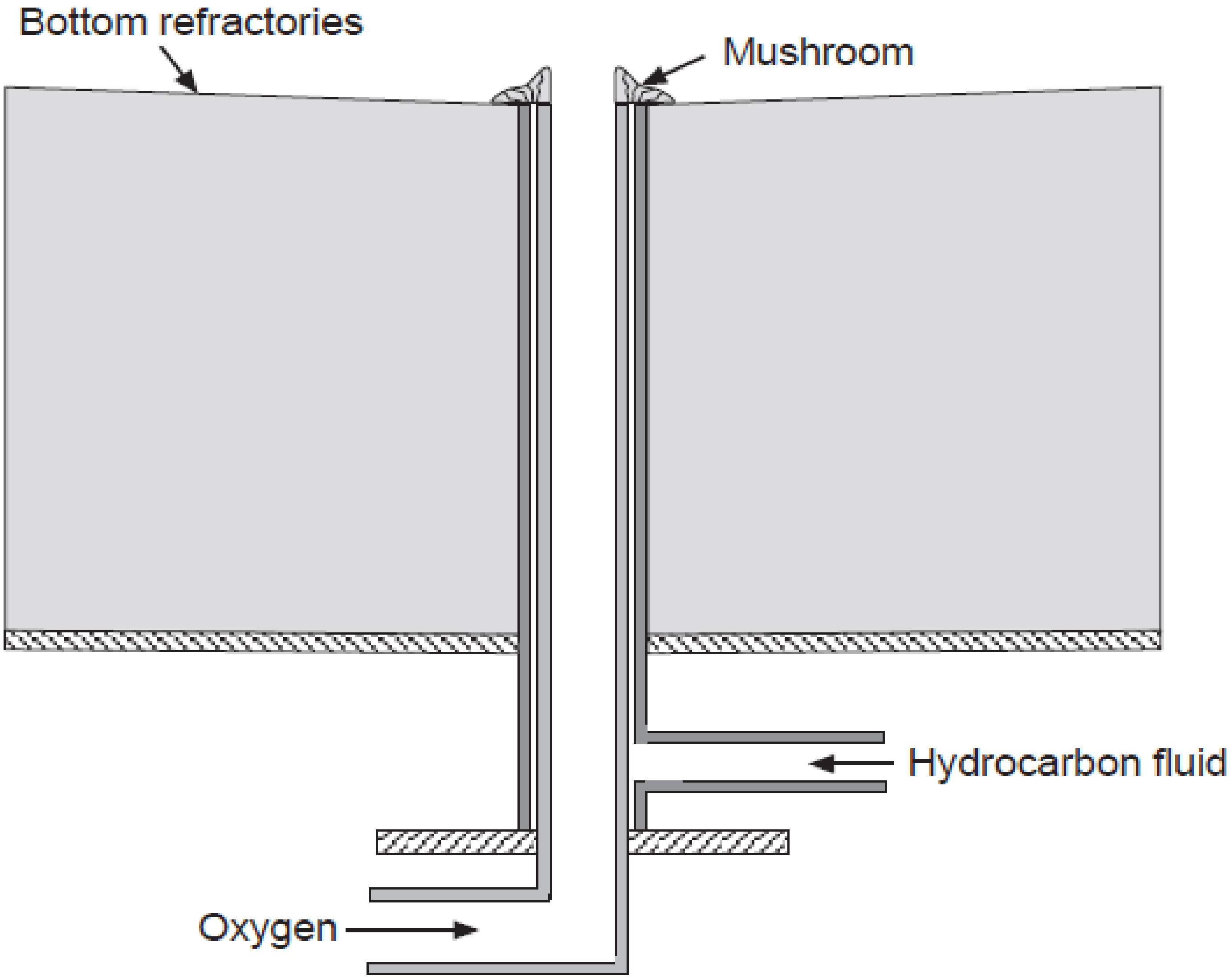
- The condition and maintenance of the taphole and the furnace wall around it can influence alloy recovery consistency and metallic yield.
- Poor taphole maintenance and practice can lead to a burnthrough in either the furnace shell or the taphole support frame. A very small taphole can significantly increase the tap time, reducing productivity, steel temperature, and nitrogen pickup in the ladle.
- A very large taphole will not allow enough time to add and mix the alloy additions in the ladle. Further, aged tapholes have ragged streams with higher surface areas that will entrain air, which in turn dissolves more oxygen and makes control of oxygen levels in the steel difficult

- A newly installed taphole yields a tap time of seven or eight minutes. Tapholes are generally replaced when the tap time falls below four minutes. A very important aspect of the melter/operator’s job is to carefully monitor the condition and performance of the tap hole.
- Steel is often lost to the slag pot, a yield loss, when a pocket or depression develops near or around the tap opening. Such a depression can prevent several tons of steel from being drained into the ladle. Again, the operator must carefully monitor yields and furnace condition and make repairs to prevent this problem.

The Bottom-Blown Oxygen Steelmaking or OBM (Q-BOP) Process

- The successful development and application of the shrouded oxygen tuyere in the late 1960s led to the development of the OBM (Q-BOP) process in the early 1970s.
- Oxygen in this process is injected into the bath through tuyeres inserted in the bottom of the furnace. Each tuyere is made from two concentric tubes forming an inner nozzle and an outer annulus

- Oxygen and powdered lime are injected through the central portion of the tuyeres, while a hydrocarbon gas, typically natural gas or propane, is injected through the annular section between the two concentric pipes, as shown in Fig.
- The endothermic decomposition of the hydrocarbon gas and the sensible heat required to bring the products of the decomposition up to steelmaking temperatures result in localized cooling at the tip of the tuyere.



: Schematic drawing of an OBM (Q-BOP) tuyere.

- The localized cooling is enough to chill the liquid metal and form a porous mushroom on the tip of the tuyere and part of the surrounding refractory.
- This mushroom reduces the burn back rate of the tuyere, and the wear of the surrounding refractory.
- The injected lime provides additional cooling to the tuyere, and results in better slag refining characteristics

- Top lances in OBM (Q-BOP) furnaces have also been adopted, mainly for the purposes of increasing the post-combustion of the offgases within the furnace, and to control the buildup of slag and metal in the furnace cone area.
- Top lances used in OBM (Q-BOP) furnaces are normally stationary, since they are not used for refining purposes. Tuyeres, located in the upper cone area of furnaces with a heat size larger than approximately 150 tonnes have also been used, but typicallyresult in higher refractory wear.

- For this reason, their application has been limited to shops which require increased scrap melting capabilities (resulting in shorter lining lives), and with a heat size smaller than 150 tonnes.

Sequence of Operations

- After the steel is tapped, the furnace is rotated to the vertical position, and nitrogen is blown to splash the slag onto the furnace walls.
- This results in a coating that extends the life of the furnace barrel. The furnace is also rocked to coat the bottom with slag.
- This operation can be done with the slag as is, or with conditioned slag.

- The furnace is then ready to receive the scrap and hot metal.
- Nitrogen is injected at sonic flow to protect the tuyeres during the hot metal charge. The furnace is rotated to its vertical position, and the bottom and top oxygen blow are started.
- Burnt lime is injected with the oxygen through the bottom, and the dolomitic lime is added through the top at the beginning of the blow.

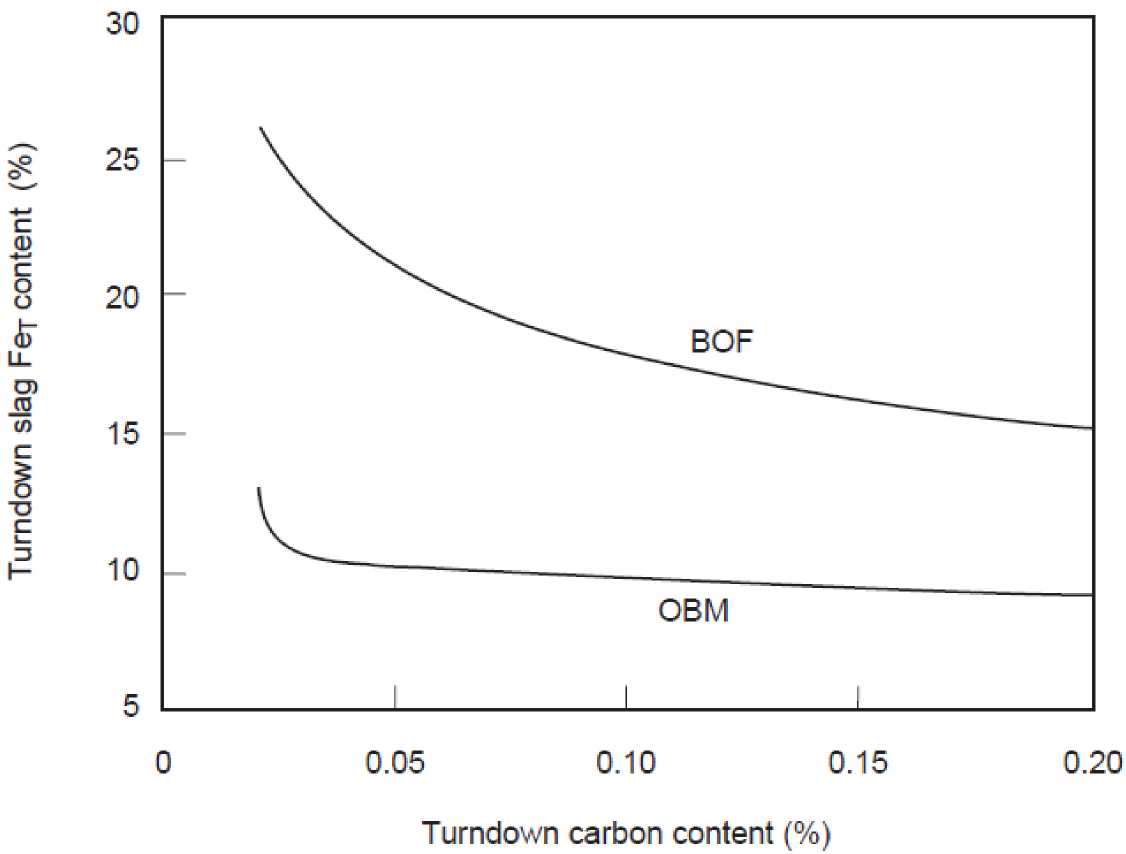
- Typically the lime is injected within the first half of the oxygen blow.
- When the calculated oxygen amount has been injected, the gas is switched to nitrogen or argon and the furnace is rotated for sampling.
- A sample for chemical analysis is taken, and the temperature and oxygen activity are measured. If the desired temperature and chemistry have been obtained, the heat can then be tapped.

- If necessary, small adjustments in temperature and chemistry can be made by injecting additional oxygen through the bottom, by injecting more lime, or by cooling the heat with ore or raw dolomite.
- Since the process is very reproducible, the heat is normally tapped after these adjustments, without making another temperature measurement or taking another sample for chemical analysis.

Process Characteristics

- The injection of the oxygen and hydrocarbons through bottom tuyeres results in distinct process characteristics.
- The oxygen reacts directly with the carbon and silicon in the liquid iron melt, resulting in lower oxidation levels in the metal and slag at the end of the blow.
- The bottom injection also results in very strong bath mixing. Steel decarburization is enhanced by the strong bath agitation, particularly during the last portion of the blow, when mass transfer of the carbon in the melt controls the rate of decarburization at carbon contents below 0.3%.

- This results in less iron being oxidized and lost to the slag, as shown in Fig.,



- The manganese content at turndown is also higher than in the top-blown vessels, due to the lower bath and slag oxidation.
- The variability in blow behavior introduced by the top lance in top-blown vessels is eliminated.
- By injecting the oxygen and lime through the bottom tuyeres in a controlled manner, a highly reproducible process control is obtained

Process Name	Origin	Description
Obsolete bottom-blown processes that preceded modern furnace configurations:		
Bessemer Converter		An early bottom-blown converter developed by Henry Bessemer in 19th Century England, blowing air through simple tuyeres using acid refractories.
Thomas Converter		Similar to bessemer but using basic refractories in US.
All Top Blowing:		
LD	Voest, Austria	Linz-Donawitz. First top-blown process with water-cooled lance, lump lime.
BOF	Worldwide	Basic Oxygen Furnace. Common term for LD top lance-blown, lump lime.
BOP	USX and others	Basic Oxygen Process. Same as LD and BOF
[illegible]	[illegible]	[illegible]

Mixed Blowing, Inert Stirring Gases:

LBE	ARBED, Luxembourg IRSID, France	Lance Bubbling Equilibrium. LD with permeable plugs on bottom for inert gas. Lump lime.
LD-KG	Kawasaki, Japan	LD with small bottom tuyeres Ar and/or N_2.
LD-KGC	Kawasaki, Japan	LD with number of small nozzles using Ar, N_2 CO for inert gas bottom stirring. Unique in that it uses recycled CO as a stirring gas. Lump lime.
LD-OTB	Kobe, Japan	Similar to LD-KG
LD-AB	Nippon Steel, Japan	LD with simple tuyeres to inject inert gas. Lump lime
NK-CB	NKK, Japan	Top-blown LD with simple bottom tuyere or porous plugs to introduce Ar/CO_2/N_2, lump lime

Mixed Blowing with Oxygen and/or Inert Bottom Gases:

OBM-S	Maxhutte, Germany Klockner, Germany	Mostly bottom OBM type with top oxygen through natural gas shrouded side tuyere, powdered lime through bottom.
K-BOP	Kawasaki Japan	Top and bottom blowing. Natural gas shrouded bottom tuyeres, powdered lime through tuyeres.
TBM	Thyssen, Germany	Top and bottom stirring with bottom nozzles and N_2/Ar.
LET	Solmer, France	Lance Equilibrium Tuyeres. Top blowing with 15 to 35% bottom-blown with fuel oil shrouded tuyeres.
LD-OB	Nippon Steel, Japan	OBM tuyeres (natural gas shrouded) on bottom with top lance, lump lime.
STB	Sumitomo, Japan	Mostly top-blown with lance, with special tuyere on bottom. Inner pipe O_2/CO_2, Outer pipe CO_2/N_2/Ar. Lump lime.
STB-P	Sumitomo, Japan	Similar to STB except powdered lime through top lance for phosphorus control.

All Bottom Blowing:

OBM	Maxhutte, Germany	Original 100% bottom-blown. Natural gas shrouded tuyeres, powdered lime through tuyeres
Q-BOP	USX, USA	OBM type 100% bottom-blown. Natural gas shrouded tuyeres, powdered lime through tuyeres.
KMS	Klockner, Germany	Similar to OBM. Early trials of oil shrouded tuyeres, now use natural gas. Can inject powdered coal from bottom for more scrap melting.
KS	Klockner, Germany	Similar to KMS only modified for 100% scrap melting.

(Note: **Bold** lettered processes are still in regular use today.)

Bottom Stirring Practices

- Inhomogenieties in chemical composition and temperature are created in the melt during the oxygen blow in the top-blown BOF process due to lack of proper mixing in the metal bath.
- There is a relatively dead zone directly underneath the jet cavity in the BOF.

- Bottom stirring practices using inert gases such as nitrogen and argon are being used extensively to improve the mixing conditions in the BOF.
- The inert gases are introduced at the bottom of the furnace by means of permeable elements (LBE process) or tuyeres. In a typical practice, nitrogen gas is introduced through tuyeres or permeable elements in the first 60 to 80% of the oxygen blow, and argon gas is switched on in the last 40 to 20% of the blow.
- The rapid evolution of CO in the first part of the oxygen blow prevents nitrogen pickup in the steel.

Some of the effects of bottom stirring and the resulting improved mixing include

- *(a)*
- *Decreased FeO content in slag. Better mixing conditions in the vessel causes the* FeO in the slag to be closer to equilibrium conditions, which results in lower concentrations of FeO in the slag.
- Plant studies have shown that for low carbon heats, bottom stirring can cause a reduction in the FeO level in slag by approximately 5%.

- This results in better metallic yield, lower FeO level in the ladle slag and reduced slag attack on the refractories. Improvements in iron yield by as much as 1.5% or more have been reported.
- Lower levels of FeO in the steelmaking slag reduces the amount of heat generated during the oxygen blow, and hence reduces the maximum amount of scrap that can be charged in a heat.

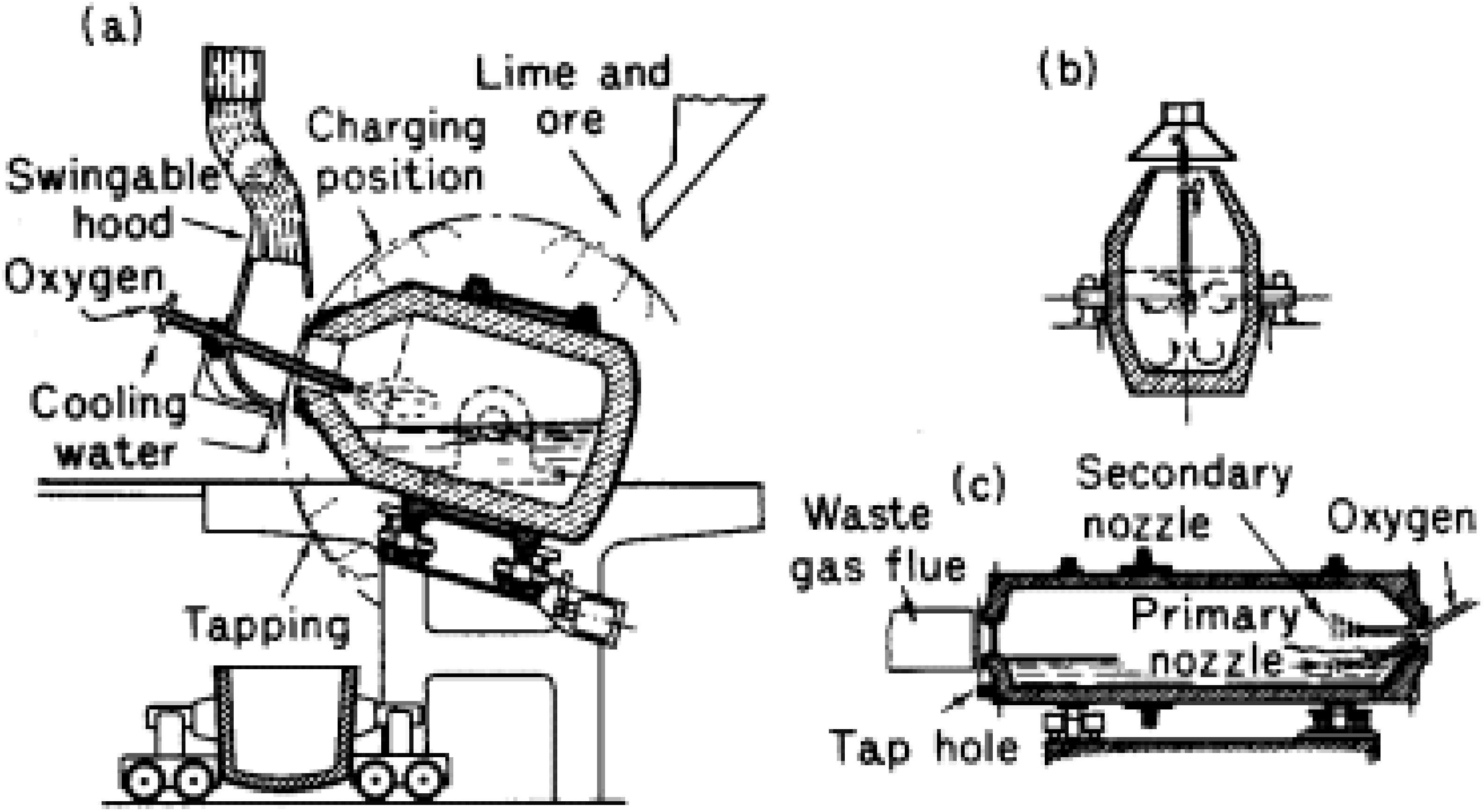
- (b)
- *Reduced dissolved oxygen in metal. A study shows that bottom stirring can reduce the* dissolved oxygen level in a low carbon heat by approximately 225 ppm.
- This lowering of dissolved oxygen leads to lower aluminum consumption in the ladle. Studies have shown aluminum savings of about 0.3 lb./ton due to bottom stirring.

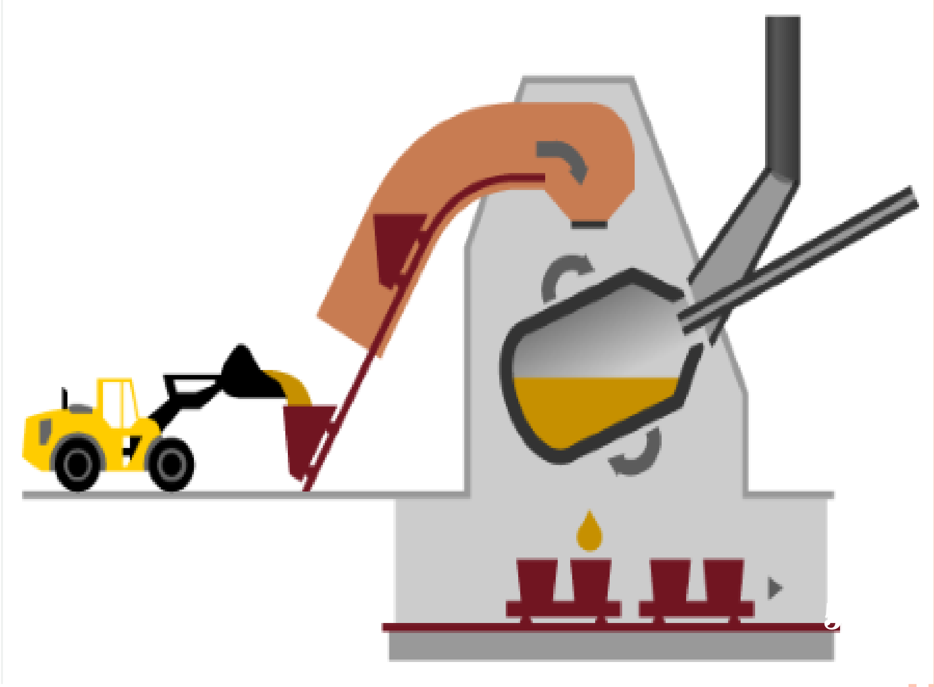
- (c)
- *Higher manganese content in the metal at turndown. An increase of approximately* 0.03% in the turndown manganese content of the metal has been shown.
- This leads to a reduction in the consumption of ferro-manganese.

- *Sulfur and Phosphorus removal. Bottom stirring has been found to enhance desulfurization* due to improved stirring.
- However, phosphorus removal has not been found to improve substantially in some studies.
- Although bottom stirring drives the dephosphorization reaction towards equilibrium, the reduced levels of FeO in steelmaking slags tend to decrease the equilibrium phosphorus partition ratio ((%P in slag)/[%P in metal])

Kaldo Furnace

- In the Kaldo process refining is carried out in vessel which is similar in shape and about the same size as that of LD converter with a solid bottom.
- It is lined much in the same way as the LD vessel.
- The Vessel is places in a cradle and is rotated therein, around its long axis, at any desired speed upto maximum of 30 rpm during refining.
- The cradle is mounted on trunions so that the vessel can be tilted in various positions to permit charging, tapping, slagging etc.


(a)
Lime and ore
Charging position
Swingable hood
Oxygen
Cooling water
Tapping
(b)
(c)
Waste gas flue
Secondary nozzle
Oxygen
Primary nozzle
Tap hole



- In the blowing position the vessel is held at an angle of 16-20^o horizontal.
- The waste gases are carried through a water cooled hood which swings into fit over the mouth of the vessel during blowing.
- The oxygen lance is inserted through the hood into the vessel at an angle to the surface of the bath.
- A water cooled feeder is also provided besides the charging chute at the top, to make solid additions without interrupting the blow.

- The facilities required for scrap and flux charging, hot metal pouring, tapping, slagging etc. are in a way similar to the LD process.

HEAT SEQUENCE

- The hot vessel, containing some slag from the previous heat, is rotated into vertical position and it receives lime, ore and other fluxing materials.
- Scrap is charged after making the vessel nearly horizontal.
- Scrap is literally poured in the vessel. Hot metal is charges immediately after the scrap. The vessel is tilted to blowing angle of 16-20^o
- the lance is inserted through the hood at a proper angle. The rate of oxygen supply and speed of rotation of the vessel are varied during blowing.

- Blowing commences at oxygen flow rate nearly 50-60 % of the maximum allowable value. The vessel is also rotated slowly.
- Both of them are increased progressively and they attain their respective maximum values in about 5-7 min.
- Initial conditions are such that all the silicon most of the manganese and some iorn are oxidised.
- The formation of SiO2, MnO and FeO take lime in solution and form a thin, basic and oxidizing slag. The slag retained in previous heat is helpful

- Scrap : chilling effect and refractory wear due to rotation in bath.
- At the end of 18-20 minutes of blowing all the solids are completely molten. The oxygen flow rate is then decreased by nearly 50% and the speed of the rotation is reduced to about 10-12 rpm.
- the lance angle is also decreased. This is de-phosporisation period. The blow is stopped after nearly 25 minutes of blowing and the phosporic slag is removed as completely as possible.

- The slag at this stage should be thin and slightly foamy so that the metal shots do not remain entrapped and get lost along with the slag removal.
- In two slag removal almost 80% of the oxygen is blown before the removal of the first slag.
- In two slag practice the second blow continues for a pre determined time and the heat is tapped. If a very low phosporous level is to be achieved one more intermediate slag is removed and the blow is continued.

- The third blow is very short. Fresh charges of lime and ore are made before blowing. The heat is finished by withdrawing the lance and the hood.

Problems associated

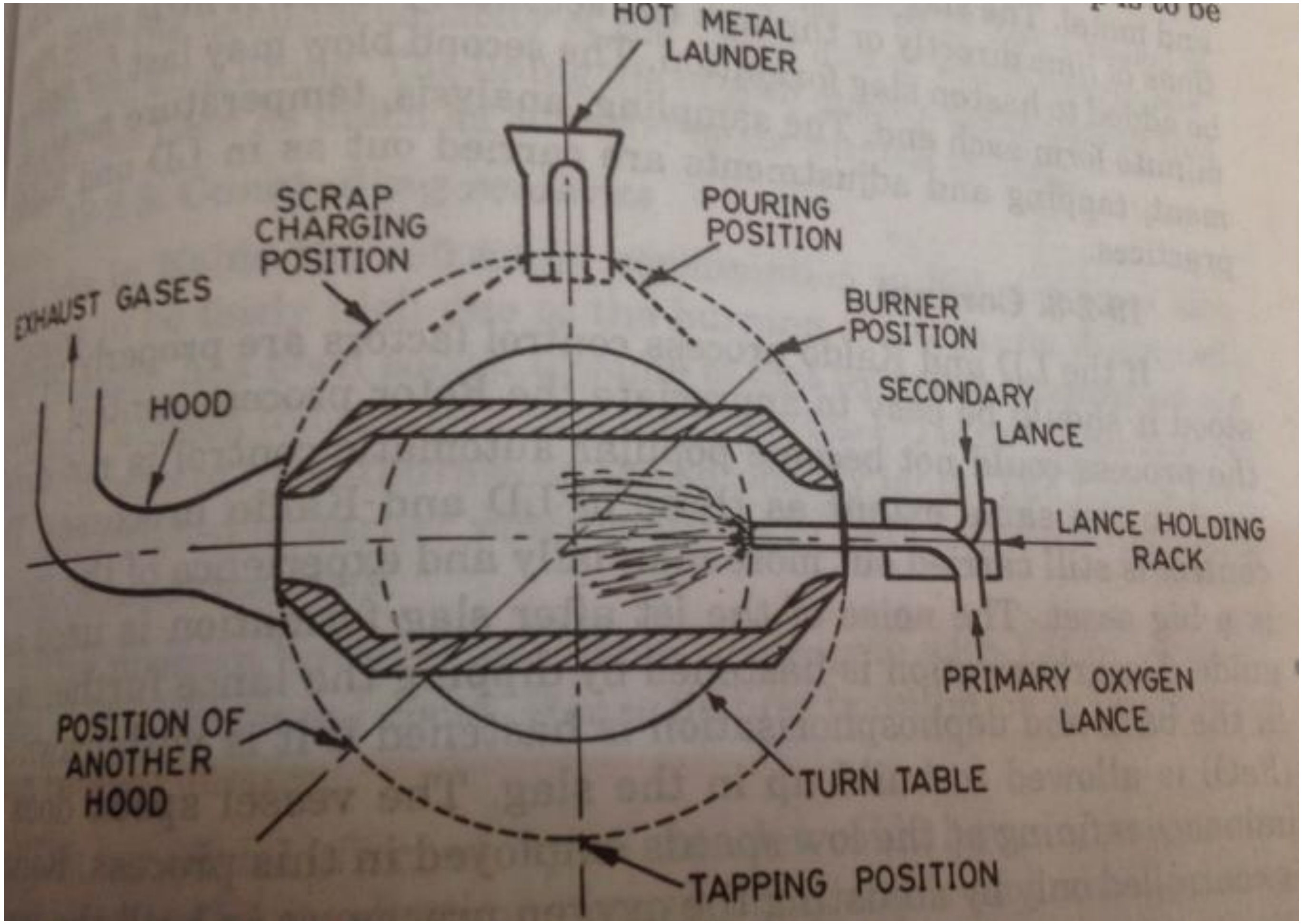
- In spite of being a very scientifically designed and developed process and hence a promising process at the beginning, it could not be widely adopted for the simple reason that the refractory consumption per tonne of steel produced is still very large in kaldo vessels.
- The lining life is nearly 60-100 heats as against 200-300 heats then for similar material in LD vessel.

Rotor furnace

- A long cylindrical vessel (L=4D) is used to provide enough space for burning most of the CO evolved during refining to CO_2, and thereby utilising the heat for steel making.
- The primary oxygen lance or refining lance is dipped in the slag-metal system whereas a secondary lance is inserted well above the slag surface to burn the evolved CO to CO_2.
- The turbulence caused by the primary submerged lance and the sweeping of gases over almost the entire slag surface in the vessel causes a good proportion of heat to be released.

- The rotation of the vessel is essential to safe guard the lining from over heating and assist in heat transfer.

Plant Design



- For 100-120t: 15m Long and 4.5m Dia with nearly 1-1.2m openings at both ends.
- The vessel is rotated around its own axis in horizontal plane at a fixed speed of 0.2-4 rpm.
- The vessel is mounted on a turntable of about 8m diameter and which can be rotated on a horizontal plane.
- The arrangements around the table are such that the lance and gas-offtakes are located at diametrically opposite points .

- The table has tapping and de slagging positions, the vessel can be raised in a vertical plane upto 90^0.
- For tapping as inclination of few degrees is given.
- The lining is much similar to LD and Kaldo vessels.

OPERATION

- Some or all the final slag from the previous heat is retained for thenext heat. The heat commences with hot repairs, followed by charging some lime. The vessel is rotated to spread it all over the lining.
- The remainder of lime, scrap, ore and hot metal are then charged. If scrap proportion is more it is charged from both ends.

- The vessel is moved to blowing position. The lances are inserted and blowing started.
- Simultaneously the vessel is also rotated.
- The primary oxygen flow is nearly constant throughout the blow at about 70-85 m3/min.
- The secondary lance is put-on a little after the primary is put-on and it blows air as per the design.
- It is also equipped to feed lime powder if required. The vessesl is blown for half the time from each end to even out the lining wear over the entire length of the vessel

ELECTRIC ARC FURNACE

ELECTRIC ARC FURNACE:

An **Electric Arc Furnace** (**EAF**) is a furnace that heats charged material by means of an electric arc.

Arc furnaces range in size from small units of approximately one ton capacity (used in foundries for producing cast iron products) up to about 400 ton units used for secondary steelmaking

TEMPERATURE RANGE

- Industrial electric arc furnace temperatures can be up to 1,800 °C, (3272 °F) while laboratory units can exceed 3,000 °C. (5432 °F)
- Arc furnaces differ from induction furnaces in that the charge material is directly exposed to an electric arc, and the current in the furnace terminals passes through the charged material.

HISTORY

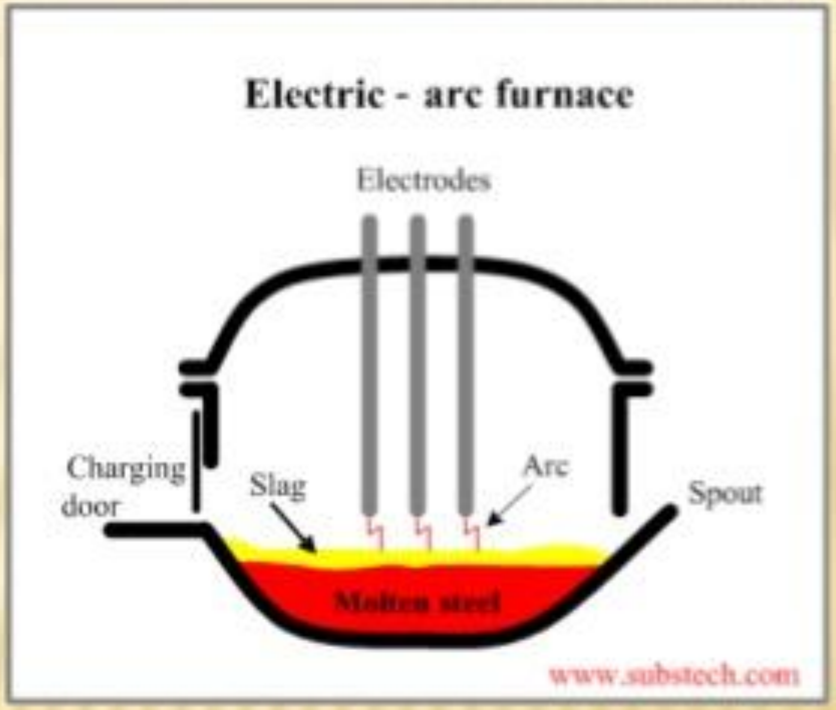
- The first electric arc furnaces were developed by Paul Héroult, of France, with a commercial plant established in the United States in 1907.
- The Sanderson brothers formed The Sanderson Brothers steel Co. in Syracuse, New York, installing the first electric arc furnace in the U.S.
- This furnace is now on display at Station Square, Pittsburgh, Pennsylvania.

TYPES OF EAF

- Two kinds of electric current may be used in Electric Arc Furnaces:
- direct (DC) EAF
- alternating (AC) EAF
- Three-phase AC Electric Arc Furnaces with graphite electrodes are commonly used in steel making.

CONSTRUCTION

- The furnace consists of a spherical hearth (bottom), cylindrical shell and a swinging water-cooled dome-shaped roof.
- The roof has three holes for consumable graphite electrodes held by a clamping mechanism.
- The mechanism provides independent lifting and lowering of each electrode.


Electric - arc furnace
Electrodes
Charging
door
Slag
Arc
Spout
Molten steel
www.substech.com

- The charge door, through which the slag components and alloying additives are charged, is located on the front side of the furnace shell.
- The charge door is also used for removing the slag (de-slagging).

REFRACTORY LINING OF AN EAF

- Refractory linings of Electric Arc Furnaces are made generally of resin-bonded magnesia-carbon bricks.
- When the bricks are heated the bonding material is coked and turns into a carbon network binding the refractory grains,preventing wetting by the slag and protecting the lining the from erosion and chemical attack of the molten metal and slag.

OPERATION/WORKING

- The scrap is charged commonly from the furnace top.
- The roof with the electrodes is swung aside before the scrap charging.
- The scrap arranged in the charge basket is transferred to the furnace by a crane and then dropped into the shell.

- Lower voltages are selected for this first part of the operation to protect the roof and walls from excessive heat and damage from the arcs.
- Once the electrodes have reached the heavy melt at the base of the furnace and the arcs are shielded by the scrap,
- the voltage can be increased and the electrodes raised slightly, lengthening the arcs and increasing power to the melt.

CHEMICAL AND PHYSICAL PROCESSES IN AN EAF

- *Melting*
- Melting process starts at low voltage (short arc) between the electrodes and the scrap.
- The arc during this period is unstable.
- In order to improve the arc stability small pieces of the scrap are placed in the upper layer of the charge.
- The electrodes descend melting the charge and penetrating into the scrap forming bores.

- The molten metal flows down to the furnace bottom.
- When the electrodes reach the liquid bath the arc becomes stable and the voltage may be increased (long arc).
- The electrodes are lifting together with the melt level. Most of scrap (85%) melt during this period.

Temperature of the arc reaches 6300ºF (3500ºC).

OXIDIZING STAGE

- At this stage excessive carbon, phosphorous, silicon and manganese oxidize.
  The process is similar to that in Basic Oxygen Furnace.
- Basic oxidizing slag composed of lime (CaO) and ion ore (FeO) is used during the oxidizing period.
  Gaseous oxygen may be blown into the melt for additional oxidizing.

REDUCING STAGE

- New slag composed mainly of lime (CaO), CaF2 (as slag fluidizer) is added at this stage for formation of basic reducing conditions.
- The function of this slag is refining of the steel from sulfur and absorption of oxides, formed as a result of deoxidation ("killing").
- The excessive oxygen dissolved in the melt during oxidizing period is removed by metallic deoxidizersMn, Si, Al:

[Mn] + [O] = (MnO)

[Si] + 2[O] = (SiO_2)

2[Al] + 3[O] = (Al_2O_3)

Basic reducing slag is favorable for desulfurization in accordance to the reaction:

[S] + (CaO) = (CaS) + [O]

Oxide and sulfide non-metallic inclusions are absorbed by the slag

- Iron oxide causes increase of Oxygen content in the molten steel according to the reaction:
  (square brackets [ ] - signify solution in steel, round brackets ( ) - in slag, curly brackets {} - in gas)

  (FeO) = [Fe] + [O]

  Oxygen dissolved in the melt oxidizes carbon, phosphorous, silicon and manganese:

  [C] + [O] = {CO}

  $[Si] + \{O_2\} = (SiO_2)$

  $[Mn] + 1/2\{O_2\} = (MnO)$

  $2[P] + 5/2\{O_2\} = (P_2O_5)$

  Carbon monoxide partially burns in the atmosphere:

  $\{CO\} + \{O_2\} = \{CO_2\}$

ADVANTAGES OF ELECTRIC ARC FURNACE

- The use of EAFs allows steel to be made from a 100% scrap metal feedstock.
- This greatly reduces the energy required to make steel when compared with primary steelmaking from ores
- . Another benefit is flexibility: while blast furnaces cannot vary their production by much and can remain in operation for years at a time,

- EAFs can be rapidly started and stopped, allowing the steel mill to vary production according to demand.
- During the peak of global financial meltdown in 2009, an estimated quantity of only 1 million tonne was produced in USA employing EAF technique.
- Although steelmaking arc furnaces generally use scrap steel as their primary feedstock,

- if hot metal from a blast furnace or direct-reduced iron is available economically, these can also be used as furnace feed.

- A typical steelmaking arc furnace is the source of steel for a mini-mill, which may make bars or strip product. Mini-mills can be sited relatively near to the markets for steel products, and the transport requirements are less than for an integrated mill, which would commonly be sited near a harbour for access to shipping.

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- Steelmaking in electric arc furnace has emerged as an important steelmaking process in recent years.
- The flexibility and easy adoptability of EAF steelmaking to accommodate the fluctuating market demand have evolved into the concept of mini steel plants to produce different grades of finished products (long or flat or mixed) of plain carbon or alloy steels from scrap and other metallic charge materials.

- Although scrap is the preferred raw material but sponge iron and iron carbide are being used regularly in most plants because of shortage of steel scrap and to dilute the concentration of tramp elements.
- Several developments in the design and operation have made EAF steelmaking to contribute significantly to the overall total production of steel in the world.
- According to an estimate, the proportion of electric steel is around 40 to 45% in the total world steel production.
- It must be noted that EAF consumes lot of electric energy and hence the cost and availability of electrical power are important issues in electric steel development.

Type of Electric furnaces

- In principle an electric arc is formed between the electrode and the metallic charge and charge is heated from the arc radiation.
- Electric arc furnaces are of two type (a) alternating current and (b) direct current.
- In alternating current, furnace operates by means of electric current flowing from one electrode of three to another through the metallic charge.
- In direct current, the current flows from carbon electrode, which acts as cathode, to an anode embedded in the bottom of the furnace.

Construction of AC Electric Arc Furnace

- The furnace consists of a steel shell, lined with suitable refractory materials and is mounted on the tilting mechanism.
- The shell thickness is around 0.005 times the shell diameter.
- Three electrodes enter through the roof. The hood may be swung away for charging.
- Heat is generated by the hot area formed between the electrodes and the charge.

Hearth

- The hearth contains metal and slag.
- The hearth lining consists of backing lining and working lining. The backing lining is few layers of high fired magnesite bricks on which working lining is rammed with either dolomite or magnesite mass.
- Permeable blocks or porous refractory elements are introduced through the bottom to inject inert gas for stirring.
- The EAF steel bath is shallow.

ROOF

- The roof is exposed to more heat than other furnace elements.
- Its lining is also subjected to radiant heat reflected from the walls and slag.
- High alumina bricks and magnesite – chromite bricks are used for roof lining.
- The roof lining is water cooled which increases the life of refractory lining to at least 10-20 times more than without water cooling.
- The roof has three holes to allow insertion of the electrodes.

ELECTRODE

- A typical alternating current operated EAF has three electrodes.
- Electrodes are round in section, and typically in segments with threaded coupling, so that as the electrodes wear, new segments can be added.
- Graphite electrodes are preferred over carbon electrodes because of better electrical conductivity.
- The electrodes are automatically raised and lowered by a positioning system.

- Electrode consumption depends on
  - Oxidation of the surface of the electrode
  - Mechanical losses due to fracture
  - Dissolution in slag during carbon boil
- The diameter of the electrode should correspond to the current supplied; if current density is excessively high, electrodes will be heated and oxidized vigorously.
- The electrode current could vary from 12 to 16Acm2/ for 400 to 600 m electrode diameter. Larger electrode diameter increases electric energy consumption.

- The electrodes are positioned at apexes of an equilateral triangle.
- The diameter of the circle passing through the centers of electrodes is called the diameter of the electrode spacing.
- If the electrodes are placed close to each other and far from furnace walls, the charge at the furnace banks will be heated belatedly.
- With large spacing diameter, electric arcs will burn near the walls, which will result in rapid wear of the lining.

- The electrode spacing diameter for the bath diameter could be 0.45 for small furnaces, 0.35 for medium- sized and large furnaces, and still lower for super- powerful furnaces.
- For a bath diameter of 5560 mm of a 100 ton furnace the electrode spacing diameter would be $0.35 \times 5560 = 1900$mm.

Side walls

- The side walls refractory materials should be able to withstand thermal shock and corrosive action of slag.
- Hot spot is formed on the side walls due to the radiation from arc flames, reflected from bath surface during power input.
- The side wall is lined with magnesite, dolomite or chrome magnesite bricks up to the slag line.
- The side wall thickness is usually 450 to 500mm for 10 to 50 ton furnaces and 550 to 650mm for 100 to 200 ton furnaces.

Transformer power

- Electric furnaces are powerful consumers of electric energy.
- The operating voltage of a furnace is 100-800V and the current may reach several thousand amperes.
- The furnace transformer transforms high voltage energy into low voltage.
- The melting process consists of two periods: melt-down and refining period.
- In melt down period higher electric energy is required as compared with the refining period.

- In small furnaces, the power consumption for melting is about 600kWh/ton and it falls to 450kWh/ton in big furnaces.
- Additional 150 to 400 k Wh/ton power is required during refining depending on the practice.

- Large transformers are required to run electric arc furnaces.
- During melting more power is required than during refining.
- The transformer capacity is designed to suit melting requirements.
- The capacity of the transformer is usually 470-650 KVA per tonne of furnace capacity.
- In terms of hearth area, the transformer capacity is in the range of 750-900 KVA per square meter

Charging materials

- Steel scrap is the principle raw material. It may constitute 60 to 80% of the charge.
- In some practices sponge iron and or pig iron is also used for chemical balance.
- In basic furnaces slag formers like limestone, fluorspar, sand, and quartzite are used to form a slag to refine the metal.

- For decarburization oxygen lancing is used. Iron ore is also added.
- Ferro-manganese, ferrosilicon or aluminium are used for deoxidation.
- To produce alloy steels, alloying elements are added.

Plant layout

- Layout of an electric arc furnace steelmaking shop varies from plant to plant due to difference in the quality of the product and the scale of production.
- Some plants have just one EAF while others have two.
- The variation is also due to whether the shop is provided with oxygen lancing and carbon injection facilities, gas cleaning equipments and finished castings or ingots.

Broadly electric furnace steelmaking shop comprises of the following:

a) Electric furnace
b) Transport facilities for ladle
c) Scrap charging
d) Auxiliary injection facilities
e) Electrode movement mechanism
f) Charging of raw materials and weighing system
g) Slag disposal.

In an ideal layout, all the above facilities should be arranged so as to ensure smooth input and output of materials.

Arc Furnaces Operation

- It consists of charging, melt down period and refining. The large baskets containing heavy and light scrap are preheated through the exit gas.
- Burnt lime and spar are added to help early slag formation. Iron one or mill scale may also be added if refining is required during melt- down period.
- The roof is swung off the furnace, and the furnace is charged. Some furnaces are equipped with continuous charging. Hot metal is also charged as per the requirement.

- In the meltdown period, electrodes are lowered and bored into the scrap.
- Lower voltages are selected in order to protect the roof and walls from excessive heat and damage from the arcs.
- Once the arc is shielded by scrap, voltage is increased to form molten metal pool to reduce the meltdown period.
- During meltdown period, silicon, manganese and carbon oxidizes.
- Also oxidizing and limy slag is produces which promotes dephosphorization as well.

MELT- DOWN TIME DEPENDS ON

- Arc conditions: larger arc requires lower current and lower heat losses
- Deep or shallow bath: deep bath shortens the meltdown period.

- Refining continues even during melting. Removal of phosphorus must be complete before the rise in temperature and carbon boil.

- The single oxidizing slag practice is employed when removal of sulphur is not required.
- When both P and S are required to be removed double slag practice is used.
- In double slag practice, oxidizing slag is removed and reducing slag is formed after deoxidation with ferrosilicon or ferromanganese or aluminum.

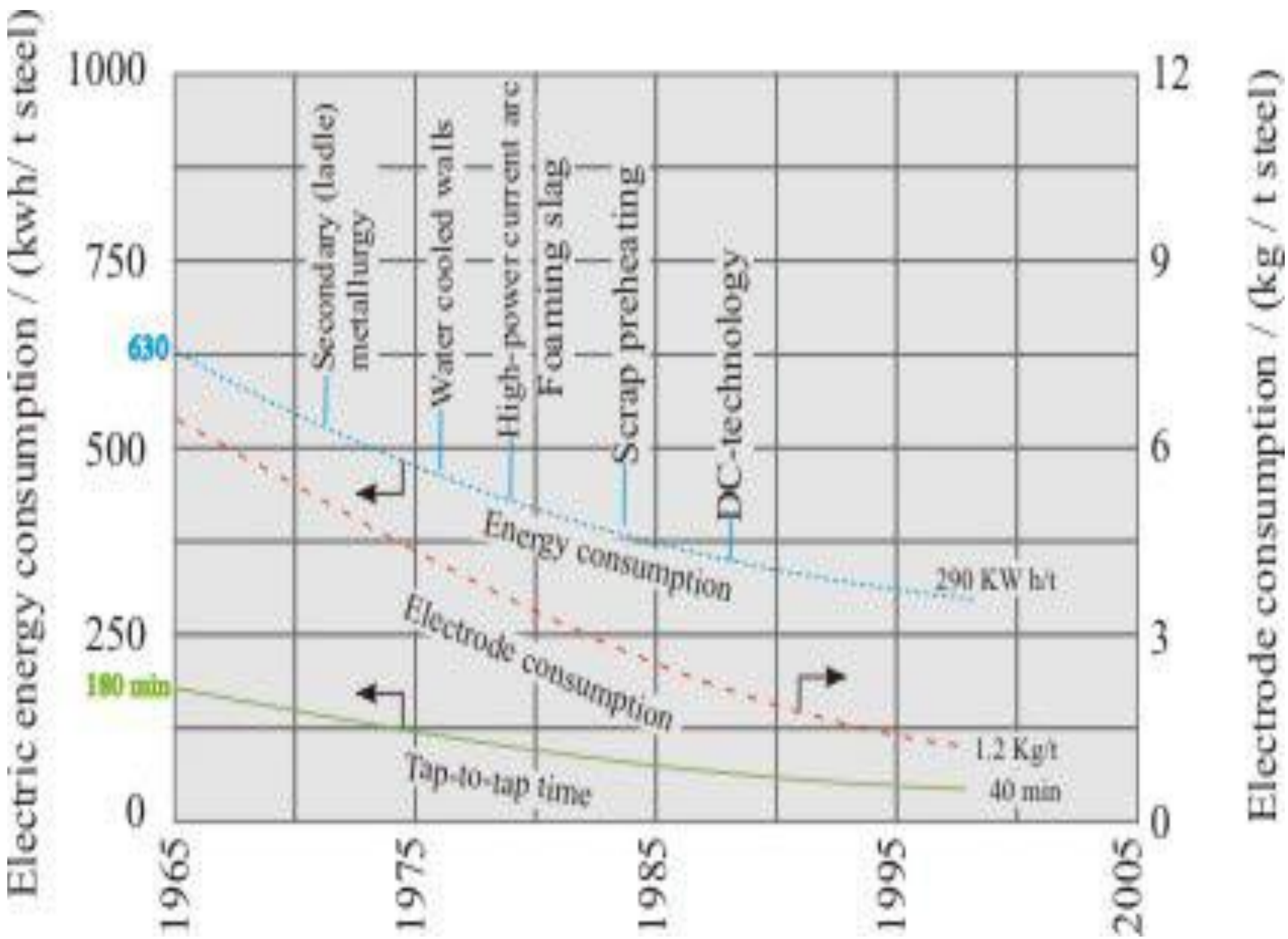
- Reducing slag helps to avoid loss of alloying elements
- Once the bath chemistry and its temperature are attained, heat is deoxidized and finished for tapping

Comparison with oxygen steelmaking

	EAF	Oxygen steelmaking
Source of energy	Electric + chemical energy	Chemical energy; Autogeneous process
Iron containing raw material	Hot metal + directly reduced iron + scrap in the suitable proportion as per practice	Hot metal + 20 – 30% scrap
Operating procedure	Oxygen lancing is to promote decarburization, scrap melting and post combustion.	Oxygen supply is continuously done to refine hot metal to steel. A three phase dispersion of slag/metal/gas forms to accelerate the refining rates.
	Slag foaming is induced to shield refractory lining from the heat of arc.	
	Carbon injection is done to induce foamy slag practice	

Modern Developments in Arc furnace

- The growth of electric steel production around the world has been driven by lower investment, higher operational flexibility and easy adoptability to market demand on long or flat products of either plain carbon or alloy steels.
- Growth has been supported by updating installations and technologies to reduce the electric energy, electrode consumption and tap to tap time.


Electric energy consumption / (kwh/ t steel)
Electrode consumption / (kg / t steel)
1000
750
630
500
250
180 min
0
12
9
6
3
0
1965
1975
1985
1995
2005
Secondary (ladle) metallurgy
Water cooled walls
High-power current arc
Foaming slag
Scrap preheating
DC-technology
Energy consumption
290 KW h/t
Electrode consumption
1.2 Kg/t
Tap-to-tap time
40 min

- Figure shows the developments in electric steelmaking technologies.
- Developments in EAF technologies are strongly supported by secondary steelmaking. One can note in the figure that the power consumption has decreased from 630
- Kwh/ton of steel to 290kWh/ton. Similarly tap tp tap time has decreased from 180 minutes to 40 minutes and electrode consumption has decreased from arounf 6.2 kg/ton to as low as 1.2 kg/ton within the periods of representation in the figure.
- This became possible with the several simultaneous developments in the secondary steel-making method. Table shows the various developments

Development in EAF

Furnace design	Process operating technologies	Chemical energy	Charge materials
Split shell design Transformer power DC arc furnace	Bottom stirring Foamy slag practice Scrap preheating	Oxidation reaction Post combustion oxy fuel burner Carbon injection	Directly reduced iron, hot metal

FURNACE DESIGN (1)

- Construction of hearth and lower side section of the shell of larger diameter than the top opening. This leads to increase in shell volume which results in larger tonnage charge, lower heat losses and improved thermal efficiency.

(2)

- In the split shell design, shell structure is constructed in two sections: lower section which contains hearth and free board allowance for slag, and upper section containing side wall and roof. The two sections are coupled such that the upper section can be repaired easily. This reduces the downtime and increases furnace availability.

(3)

- High powered transformers are the current trends. Most modern furnaces operate at 500k VA/ton and the trend is towards ultra high power ranging in between 700k VA/ton to1000k VA/ton.
- Developments are in progress to install transformer with 1500k VA/ton capacity.
- It is claimed that a 120 tons operating at 180 MVA transformer capacity and by using refining combined burner technology through oxygen gas and carbon injection, it is possible to increase capacity by up to 50%.
- The largest transformer in AC EAF corresponds to a rated power 0f 240 MVA for 300 ton furnace.

(4)

- Eccentric bottom taping reduces tap times, temperature losses and slag carry over into ladle. The strip producing plants are equipped with eccentric bottom tapping in electric arc furnaces.

(5)

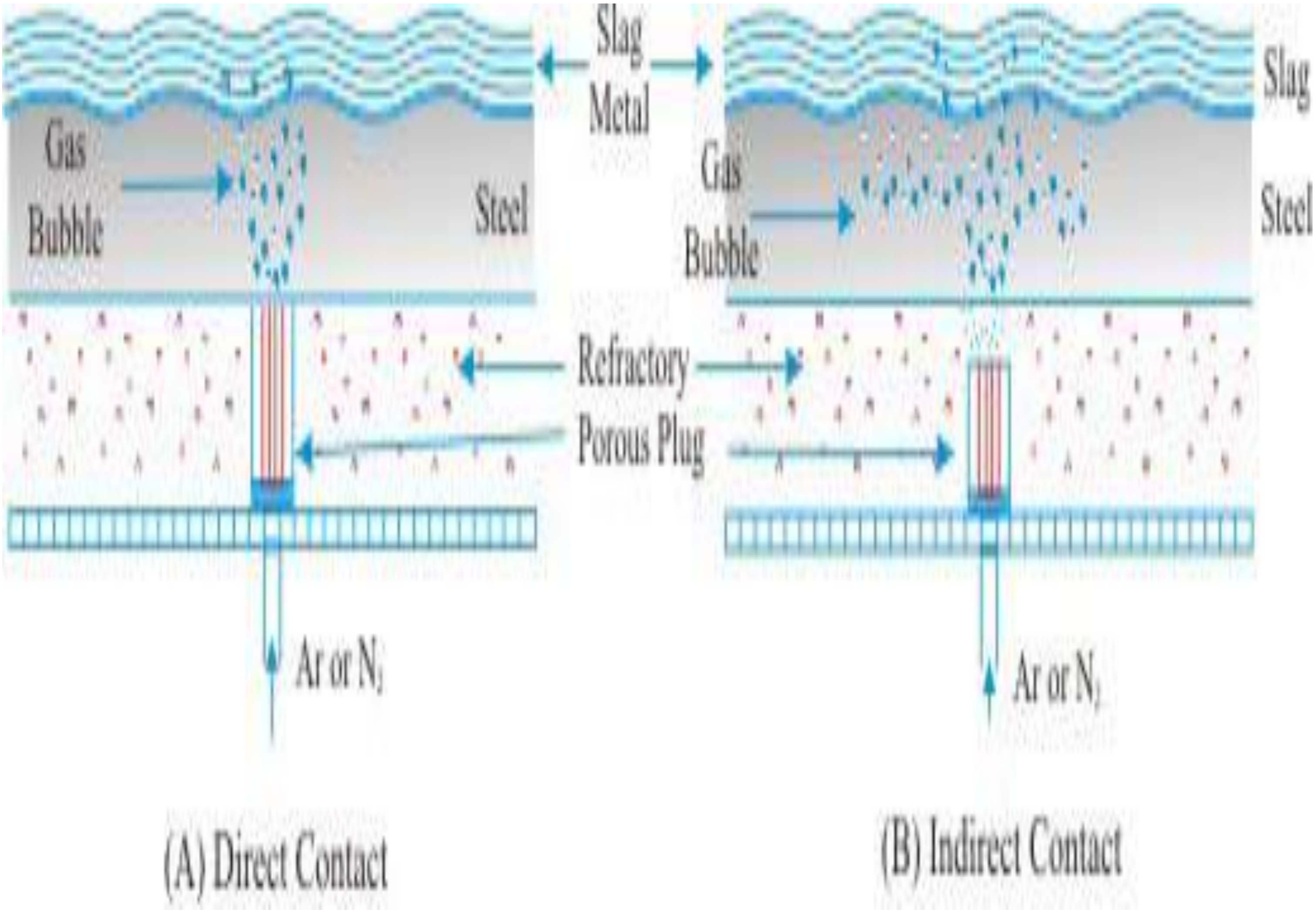
- DC (direct current) arc furnaces represent a different concept in arc furnace design.
- Most DC furnaces are with single electrode where current flows down from the carbon electrode to an anode mounted in the bottom of the furnace.
- Reduced electrode consumption of the order of 50 to 60 % is the major benefit of a dc furnace compared to a convectional three- phase arc furnace.

- Noise levels for the dc furnaces are lower.
- Lower maintenance costs are claimed and refractory costs are less for sidewall but more for the furnace bottom.
- A dc arc furnace requires an addition of the bottom electrode (anode), a dc reactor, and a thyristor all of which add cost to a dc furnace.
- The electrode technology limits diameter to a maximum of 700 mm allowing a dc current of 100kA and 70 MVA power for single electrode furnace. Furnace size is limited to 200 tons.
- Further developments are in progress.

Process operating technologies

- Most of the developments in process operating technologies are in AC- electric arc furnaces as these furnaces are popular.

- i) Bottom stirring
- In convectional arc furnaces there is little natural electrical turbulence within the bath. Due to absence of stirring large piece of scrap can take a long time to melt and may require oxygen lancing. Argon or nitrogen stirring
  - Eliminates temperature and concentration gradients
  - Shortens tap-to-tap times
  - Reduces refractory, electrode and power consumption and
  - Improves yield of iron and alloys


Slag
Metal
Slag
Gas
Bubble
Steel
Gas
Bubble
Steel
Refractory
Porous Plug
Ar or N2
Ar or N2
(A) Direct Contact
(B) Indirect Contact

- Industrial systems for bottom stirring are either with direct contact plug or with indirect contact plug. In direct contact plug, the plug is in contact with molten metal, whereas in indirect one the plug is embedded in a porous bottom refractory.
- In the indirect contact, the plug is not directly in contact the molten metal. The gas enters the bath via the porous refractory hearth which results in stirring over a large area when compared with direct plug as shown in the figure.
- Figure shows the direct contact and indirect contact plug for bottom stirring. Note that in indirect contact large area of the bath is stirred as compared with direct contact plug.

II) Foamy slag practice

- In EAF steelmaking, progressive melting of scrap increases the irradiative heat transfer from arc to the side walls of the furnace. By covering the arc in a layer of slag, the arc is shielded and more energy is transferred to the bath. The foaming slag during this period is beneficial.
- The effectiveness of slag foaming depends on slag basicity, FeO content of slag, slag temperature and availability of carbon to react with either oxygen or FeO of slag.

- Slag foams in steelmaking due to entrapment of gas bubbles. Gas producing reactions in steelmaking are:

a) Reaction between FeO of slag with carbon

- (FeO) +C=[Fe]+{CO} -----------------------(1)

b) Between carbon and oxygen dissolved in metal

- [C]+[CO]={CO} -------------------------------(2)

c) Between chromium oxide and carbon:

- $Cr_2\ O_3+3C=2Cr+3CO$ ----------------------(3)

- Reactions 1 and 2 are important in carbon steelmaking whereas reaction 3 is important in stainless steel making.
- Injection of carbon and oxygen at several places in the bath assures slag foaming practice, when carbon content of the bath is insufficient.
- Typically carbon injection rates for slag foaming are 2.5 to 5 kg/ ton of steel. In high powered furnaces carbon injection is 5-10 kg/ton of steel.

Scrap preheating

- Preheating of scrap brings thermal energy into the furnace. Preheating of scrap to 540°C brings 81kwh/ton of additional energy. Scrap preheating gives the following advantages:
  - Reduction in energy consumption by 40-60 kwh/ton depending on the scrap preheat temperature
  - Electrode consumption reduces by 0.3 to 0.36 kg/ton
  - Refractory consumption decreases by 0.9 to 1.4 kg/ton
  - Tap to tap time reduces by 5 to 8 minutes.

- It is important to note that scrap preheating technology needs to be developed. Thermal energy is required to preheat the scrap and is economical only when the waste heat from the furnace is utilized.

Future of EAF steelmaking

- The EAF needs a metallurgical reactor that has the largest growth potential both in terms of production capacity and technology evolution.
- Future EAF will be equipped with all modern technologies- like Ultra high power input (up to1500 kVA/t), latest oxygen and carbon injection technology and design features- like ultra high shell design, heavy mill type components

- This combination leads to an Electric Arc Furnace where the tap to tap times can be extremely short and the corresponding productivity reaches the level of larger furnace sizes or converter plants.
- The two main reasons for this are:
  - The possibility of a higher electrical power input and
  - A far higher efficiency of chemical energy, decarburization and scrap preheating compared to the same size (tap weight) standard furnace.

It is interesting to compare a conventional 120ton EAF with the ultimate 120 ton EAF.

Conventional 120 ton EAF	Ultimate 120 ton EAF
2- bucket charge Scrap bucket 130 m^3 Furnace volume 145 m^3	1-bucket charge Scrap bucket 185 m^3 Furnace volume 210 m^3
Transformer design upto 1,000kVA/t, 120MVA for 120 ton tapping weight, Secondary voltage up to 1,200V	Transformer design upto 1,500kVA/t, 180MVA for 120 ton tapping weight, Secondary voltage up to 1,500V
Utilization of chemical energy 3 oxygen gas burners 3 refined combined burners (RCB) 2 carbon injectors	Utilization of chemical energy 3 oxygen gas burners 5 refined combined burners (RCB) 4 carbon injectors 4 post combustion injectors

- Refined Combined Burner (RCB) technology combines a conventional oxy/gas burner with a supersonic oxygen injection lance and is designed to optimize the injection of carbon and oxygen into EAF. It supplies chemical energy through chemical reactions of fuel and gas, oxygen, and carbon injected into the furnace.