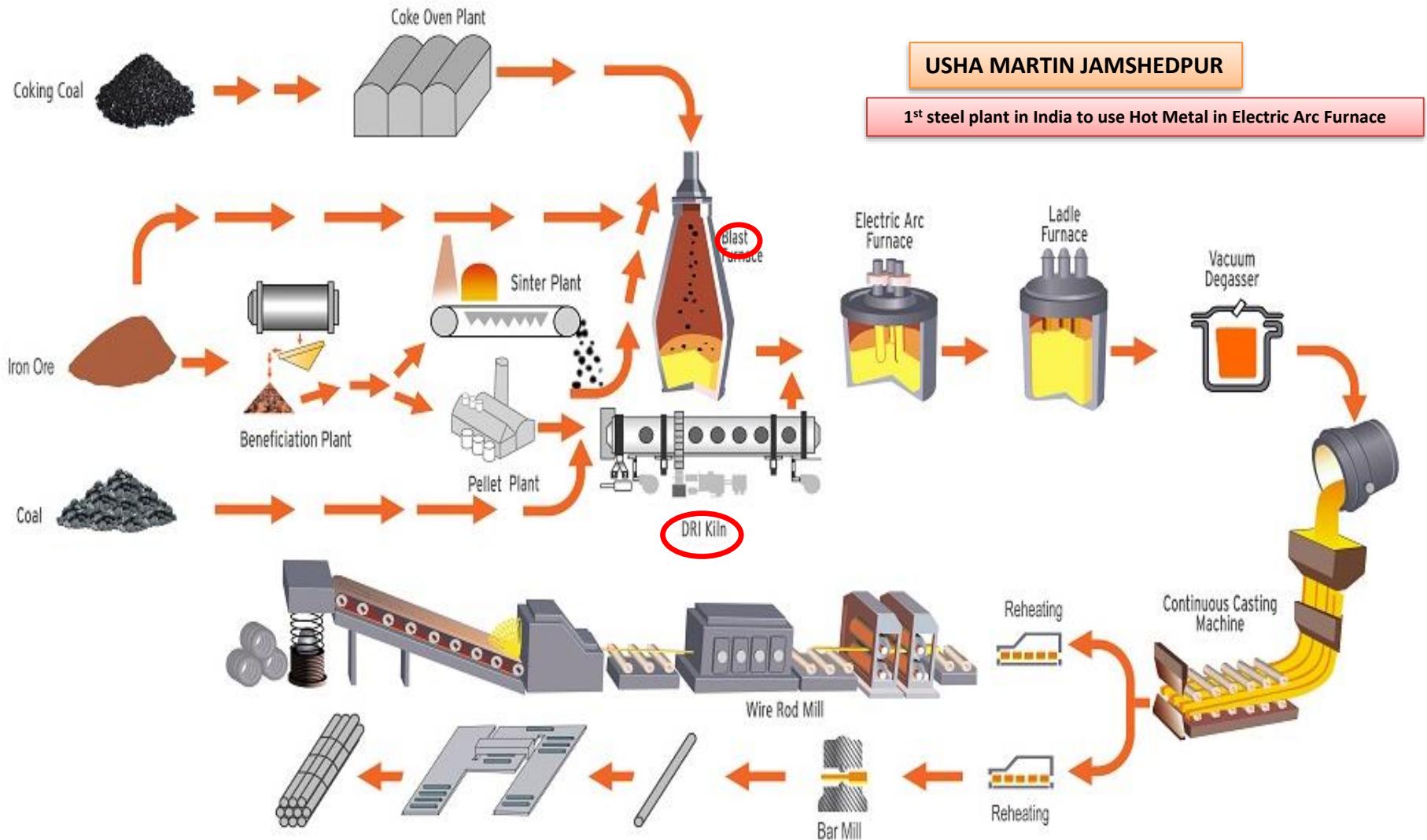


RAW MATERIALS USED IN BLAST FURNACES, DIRECT REDUCTION / SMELTING REDUCTION

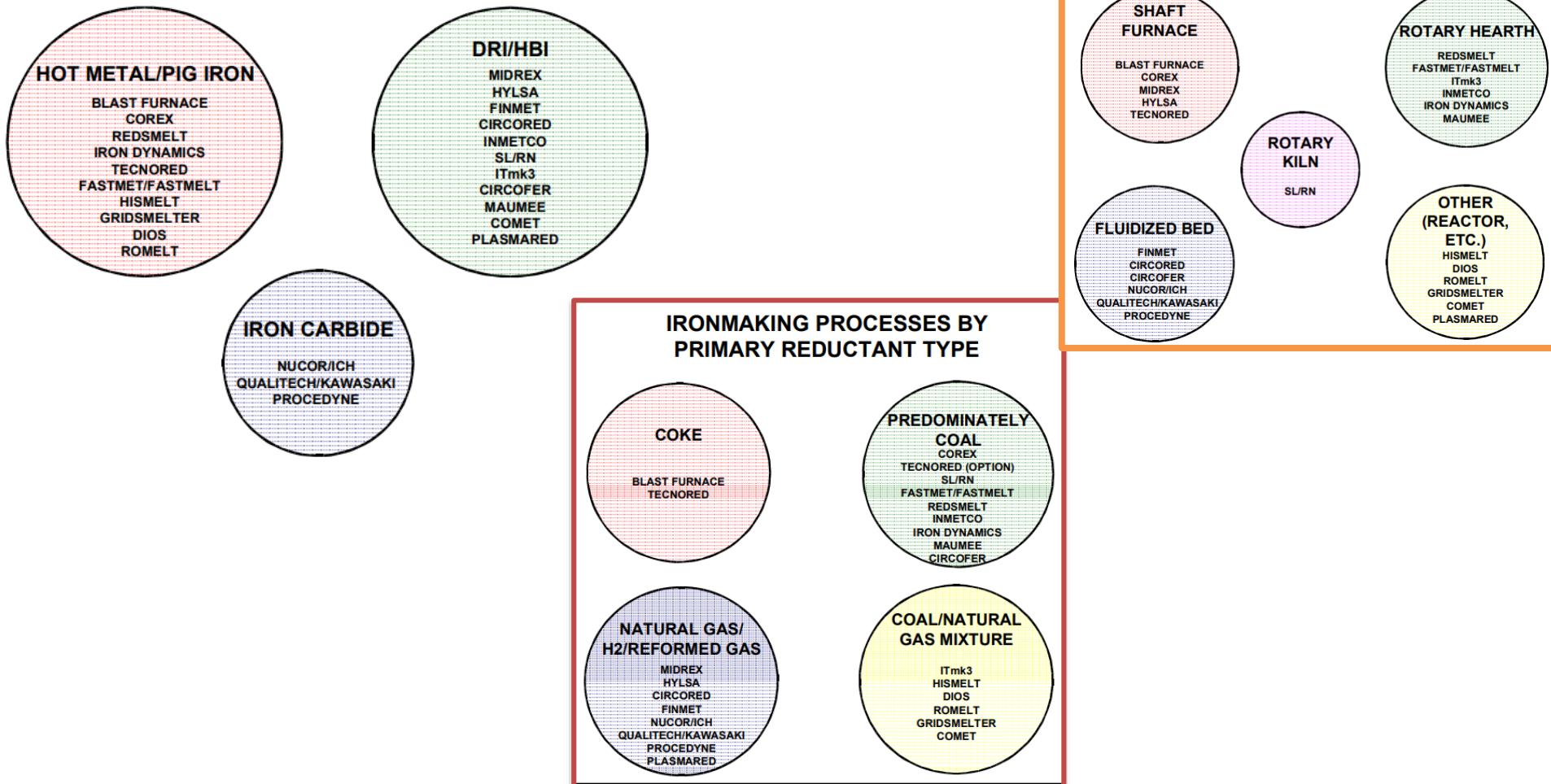
Process	Oxide Feed	Reductant	Product
Blast furnace including mini blast furnace	Lump ore, Sinter, Pellets	Coke, Coal, Oil, Tar, Natural Gas	Hot metal essentially for BOF steelmaking
Direct reduction	Lump ore, Pellets	Coal, lignite, natural gas (LNG, CNG)	DRI (sponge iron) for EAF steelmaking in particular
Smelting reduction	Ore fines, Lump ore, Waste iron oxides	Coal, Oxygen, Electricity	Hot metal (synthetic hot metal) for EAF / EOF steelmaking

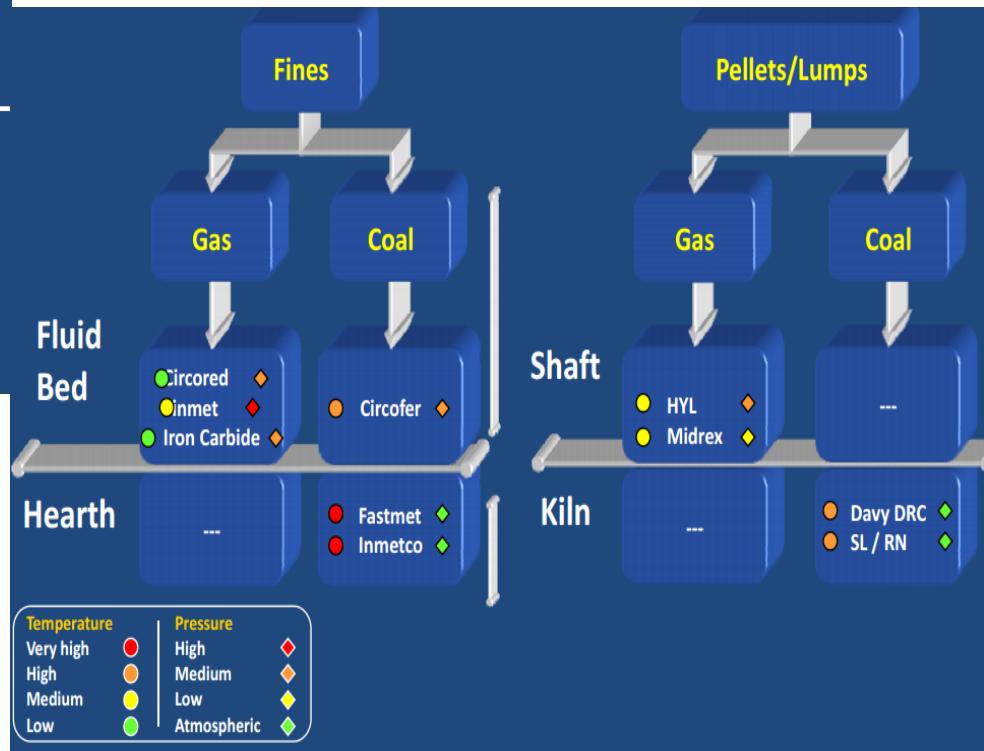
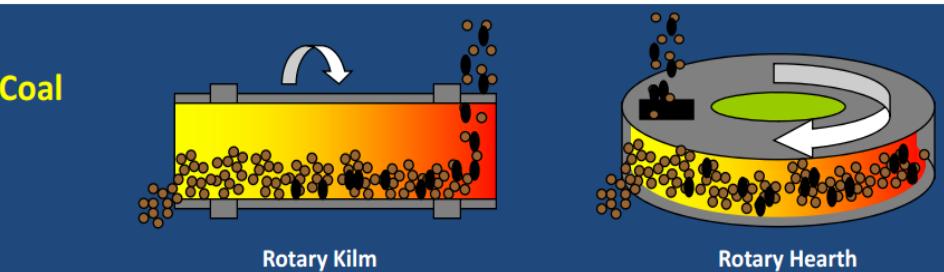
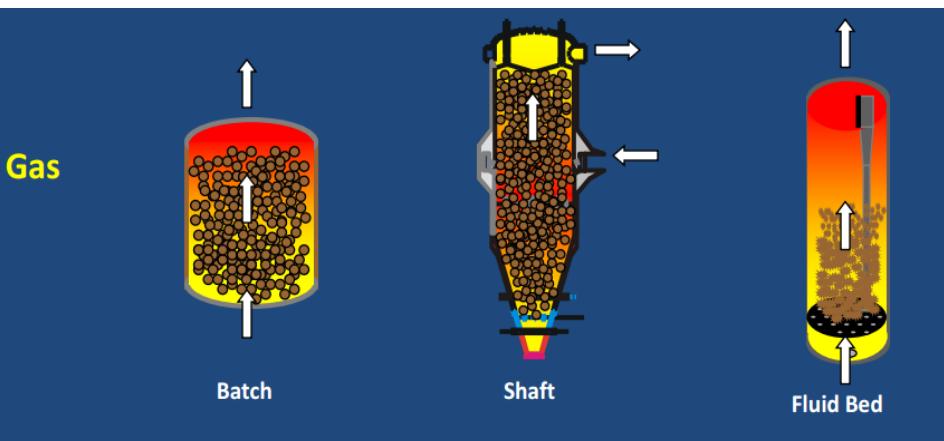
Important to note that coke is not used in DR and SR. New ironmaking processes avoid usage of coke.

- In India, DRI is mainly used as a substitute of steel melting scrap in steel making through DRI-EAF/IF route
- DRI doesn't require coking coal-imported in huge quantities. DRI-EAF/IF route accounts for 40% of the steel produced in India
- Gas-based DRI/HBI is cleanest and an environment friendly steel making route (CO₂ emission in DRI-EAF route is less than half of Blast Furnace - BOF route).
- Preferred raw material for making alloy and special steels for vital sectors like automobile, defence, aviation, space etc.
- Gap between supply & demand of steel, low investment & low pay back period, high profitability, subsidies & tax holidays in different states, proximity to main raw materials, etc.



IRONMAKING PROCESSES BY PRODUCT TYPE





Blast furnace

A BF is a huge shaft furnace that is top fed with iron ore, coke, and limestone. These materials form alternating layers in the furnace and are supported on a bed of incandescent coke. Hot air is blown through an opening into the bottom of the furnace and passes through the porous bed. The coke combusts, producing heat and carbon monoxide (CO) gas. The heat melts the charge, and the CO removes the oxygen from the iron ore, producing hot metal.¹ Hot metal is a solution of molten iron at approximately 1480 °C, which contains 4 percent carbon and some Silicon. This hot metal flows to the bottom of the furnace, through the coke bed and is periodically “tapped” from the furnace into transfer cars and transported to the BOF where it is refined into steel. The BF is the most energy-intensive step in the BF/BOF steelmaking process, generating large quantities of CO₂. Energetics, Inc. gives a range of energy use of 13.0–14.1 GJ/t pig iron

Direct reduction

Direct reduction is the removal (reduction) of oxygen from iron ore in its solid state. This technology encompasses a broad group of processes based on different feedstocks, furnaces, reducing agents, etc. Natural gas (and in some cases coal) is used as a reducing agent to enable this process. In 2000, 92.6 percent of direct reduction worldwide was based on natural gas and took place in shaft furnaces, retorts, and fluidized bed reactors. **The metallization rate of the end product, called Direct Reduced Iron (DRI) or ‘sponge iron’, ranges from 85-95%.** In 2008, 68.5 Mt of DRI was produced worldwide, using primarily MIDREX technology (58.2 %). The MIDREX process typically consists of four stages: (1) reduction, (2) reforming, (3) heat recovery, and (4) briquette making. A mixture of pellets or lump ore, possibly including up to 10 percent fine ore, enters the furnace shaft. As the ore descends, oxygen is removed by counter-flowing reduction gas, which is enriched with hydrogen and CO. The iron is then formed into briquettes, and heat from the process is recovered.

No slag, impurities entrained

Smelting reduction

Smelting reduction iron (SRI) is an alternative to the BF, as it also produces liquid iron. Smelting reduction was developed to overcome the need for the energy-intensive products-coke and sinter (if sinter is used in BF). Instead smelting reduction is aimed to use coal and iron fines. Several processes are under development; some have been commercially proven (COREX, FINEX, ITmk3), others under demonstration (e.g. Hismelt). Iron ore first undergoes a solid-state reduction in a pre-reduction unit. The resulting product at this stage – similar to DRI – is then smelted and further reduced in the smelting reduction vessel where coal is gasified, producing heat and CO-rich hot gas that can be further oxidized to generate additional heat to smelt the iron. Coal gasification is the result of a reaction with oxygen and iron ore in a liquid state. The heat is used to smelt iron and the hot gas is transported to the pre-reduction unit to reduce the iron oxides that enter the process. This process is called post-combustion and leads to a tradeoff in the utilization of the gas between increased pre-reduction potential or increased heat delivery for smelting. Commercial smelting reduction is still dominated by first-generation processes, notably the COREX process developed in Germany and Austria.



Iron Ore



Coal



Dolomite



Rotary Kiln



Rotary Cooler



Vibrating Screen



Magnetic Separator

Dolomite is mainly used as a desulphurising agent.

For 1 tonne of DRI:

Iron ore: 1.6 tonnes

Coal: 1.3 tonnes

Dolomite: 0.05 tonnes



Direct Reduced Iron: DRI is typically produced in pellet form and can be loaded directly into an EAF, Blast Furnace, or Basic Oxygen Furnace. It contains a very high iron content (typically >90%). DRI exits the DRI module at a high temperature, and can be fed directly into furnaces as a means to reduce energy costs.



Hot Briquetted Iron: HBI is a compressed form of DRI that facilitates easier transportation and handling. HBI is formed as DRI exits the module, and it compressed while still hot. DRI reacts more easily with water and requires tighter standards for shipment; HBI is less reactive and ships easier.

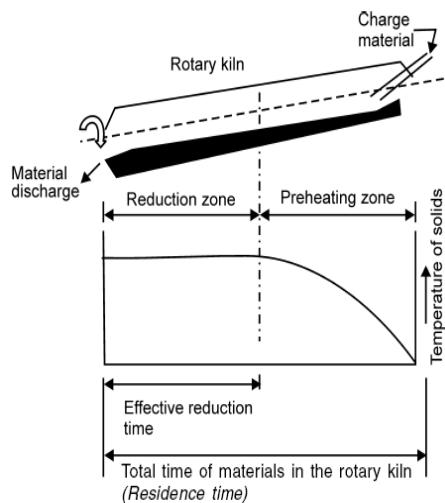


Merchant Pig Iron: MPI is produced in a blast furnace and cast into small "pigs" suitable for transportation. MPI has a higher iron content (around 96%) and less slag elements than DRI or HBI, and will typically sell at a premium. That said, MPI, HBI, and DRI are all substitutes for one another.



- Rotary Kiln, a cylindrical vessel, inclined slightly to the horizontal, which is rotated slowly about its axis.
- The material to be processed is fed into the upper end of the cylinder. As the kiln rotates, material gradually moves down towards the lower end, and may undergo a certain amount of stirring and mixing.
- Hot gases pass along the kiln, sometimes in the same direction as the process material (co-current), but usually in the opposite direction (counter-current).
- The hot gases may be generated in an external furnace, or may be generated by a flame inside the kiln.

✓ Sponge iron or Direct-reduced iron (DRI), is formed, when naturally available Iron Ore is reduced to its metallic form.
 ✓ This reduction process occurs below the melting temperature of both metallic iron and its oxidised form. Though this process is carried out at lower temperature than melting point so there is less volume reduction but a large amount material get eliminated during reduction reaction.
 ✓ Oxygen removal from iron ore creates lots of microscopic pores. This microscopic pores gives the iron an sponge texture as shown in fig.



In the metallization zone the final reduction of ferrous oxide to metallic iron takes place. Most of the carbon dioxide gets converted to carbon monoxide by reacting with the excess fuel. High reactivity coal is preferred in order to make this conversion faster.

In the pre-heat zone (900-1000C) moisture is removed and thermal decomposition of coal takes place releasing hydrocarbons and hydrogen. Iron oxide gets oxidised to ferrous oxide.

Iron ore lumps (typically 5-18mm size) are tumbled with a 'select' grade of non-coking coal and little dolomite inside an inclined rotary kiln and combusted in the presence of air for about 12 hours before the products are air cooled, magnetically separated, screened and stored sizewise.

The process entails a direct reduction of the iron ore in solid state to metalize the ore at a 'critical' temperature to make this possible and yet at that temperature, the coal ash should not fuse.

In the event the coal ash fuses at the temperature required for the iron ore reduction process to take place, then it inevitably results in **accretion formation** which continues to build in a ring formation along the inner circumference of the kiln which eventually closes the passage and does not allow the materials to travel to the other end.

This requires the kiln to be shutdown (periodically) for the accretions to be removed, adversely affecting the efficacy and efficiency of the process and productivity of the kiln. This means that it is essential for the 'select' coal to have a high ash fusion temperature (in excess of 1200C) to prevent it from fusing inside the kiln at normal operating conditions.

Direct reduced iron (DRI) is technically defined as iron ore which has been reduced to metal without melting it. Hot briquetted iron (HBI) is a densified form of DRI to facilitate its handling and transport.

- Solid metallic iron is obtained directly from solid iron ore without subjecting the ore/metal to fusion.
 - Since the reduction reaction takes place in solid state, the lump or pellet retain their original shape, considerably lighter due to the removal of the oxygen from the ore
 - Since DRI is produced by removing oxygen from iron ore, its structure is just like sponge with a network of connecting pores. These pores results in a large internal surface area which is about 10,000 times greater than the internal surface area of solid iron. HBI is produced by compacting DRI under very high pressure at temperatures in excess of 650C. This closes many of the pores and limits the contact area which is available for reaction with air.
 - Major DRI production processes are either gas based or coal based. Feed material in a DRI process is either iron ore sized to 10-30mm or iron ore pellets.
 - Gas based, reduction reaction takes place is a shaft furnace which works on counter current principle where the iron ore feed material moves downward in the furnace by gravity and gets reduced by the up flowing reducing gases.
 - Coal based, reduction reaction is a inclined horizontal rotary kiln. In this kiln both coal and the iron ore feed material is charged from the same end of the kiln. During the movement of feed material forward the oxidation reaction of carbon in coal and reduction reaction of CO gas is carefully balanced. A temperature profile ranging from 800-1050 deg C is maintained along the length of the kiln at different zones and as the material flows down due to gravity the ore is reduced.
-
- Reduction above the melting point results in pig iron. Above melting point, most of the gangue materials segregate from the liquid iron, and float upon it.
 - Because of the high temperature and the liquid state of the iron, carbon readily dissolves in the pig iron, resulting in typical carbon contents 4-6%.
 - Reduction and dissolution of some of the gangue material may result in silicon and manganese contents of about 1%, depending on the ore composition and process conditions. In addition, pig iron contains some S, P
-
- Reduction below the melting point results in directly reduced iron (DRI), which retains the original shape of the ore, and includes the gangue material present in the ore.
 - At the temperature of reduction, the carbon of the reducing agent hardly dissolves in the iron, therefore DRI contains virtually no carbon. For conversion of DRI to steel, removal of the gangue material is necessary. **1200C upper limit for the DR process, above which the metallic iron formed absorbs carbon resulting in fusing and melting of the solid.**
 - The product was initially popularised as a substitute for melting scrap in electric process of steel making due to volatility in scrap prices and its uncertain availability.

- Silica, which is absorbed in the blast furnace slag, is removed. In DRI, however, the quality of reduced iron is not as desirable as blast furnace pig iron, seeing that the remaining oxygen and silica contained in the reduced product, need to be removed in the steel furnace, at some added cost.
- Unlike blast furnace pig iron, which is almost pure metal, DRI contains some siliceous gangue, which needs to be removed in the EAF, increasing the power consumption
- Unreduced ore compounds remain as undesirable oxides (Gangue: Rock minerals in the iron ore such as silica (SiO_2), alumina (Al_2O_3), calcia (CaO), magnesia (MgO).

As there is no melting and no slag phase in DRI production, all gangue elements of the iron ores remain in the DRI and need to be separated via a slag in the EAF. This increases the electrical energy consumption of the EAF compared to steel scrap melting. If hot DRI is immediately transferred to the EAF melt shop, the heat from the direct reduction process lowers the cost of melting the DRI in the EAF, significantly cutting these energy costs and electrode consumption.

- Iron content in the DRI is in two forms. One is in metallic form Fe (M), and the second form is residual iron oxides, Fe (O). Metallic iron is the aggregate quantity of iron, either free or combined with carbon (as cementite) present in DRI.**
- Metallization of DRI is a measure of the conversion of iron oxides into metallic iron (either free or in combination with carbon as cementite) by removal of oxygen due to the action of the reductant used.**

DRI has a porous, sponge like form which has a large surface area relative to its mass, which enhances its reactivity. If it becomes wet, it oxidizes and liberates hydrogen gas from the water. This particularly is true if the water contains dissolved salts such as sodium chloride (e.g. sea water).

As part of the reaction, it heats up significantly, which further stimulates the oxidation of the still dry lumps or pellets, resulting in chain reaction that spreads rapidly throughout the DRI pile. When sufficient oxygen is available, temperature can reach as high as 1500 deg C.

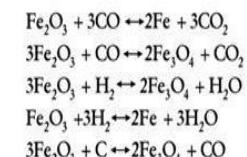
Gas based processes today account for about 92% of the DRI production in the world. In gas based processes the reduction of iron oxide is carried out by a mixture of carbon monoxide and hydrogen at a temperature of about 750-950 C.

New iron-making processes that use coal directly will generate a large volume of carbon monoxide, hydrogen, and hydrocarbons, which must be utilized to avoid condensation of complex and hazardous hydrocarbon compounds and improve the energy efficiency of the processes. **Post combustion to supply a large amount of the energy required for the endothermic reduction of iron oxide. The post-combustion degree (PC) can be measured as the proportion of the combustion products and reactants in the off gas of the reactor.**

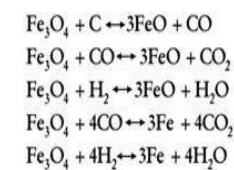
$$\text{PC} = \frac{\text{CO}_2 + \text{H}_2\text{O}}{\text{CO}_2 + \text{H}_2\text{O} + \text{CO} + \text{H}_2}$$

Chemical reactions during DRI production

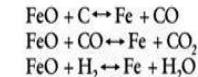
Hematite
Fe_2O_3
Fe=69.9%
O=30.1%



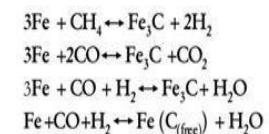
Magnetite
Fe_3O_4
Fe=72.4%
O=27.6%



Wustite
FeO
Fe=77.7%
O=22.3%



Metallic Iron
Fe
Fe=100%
O=0%

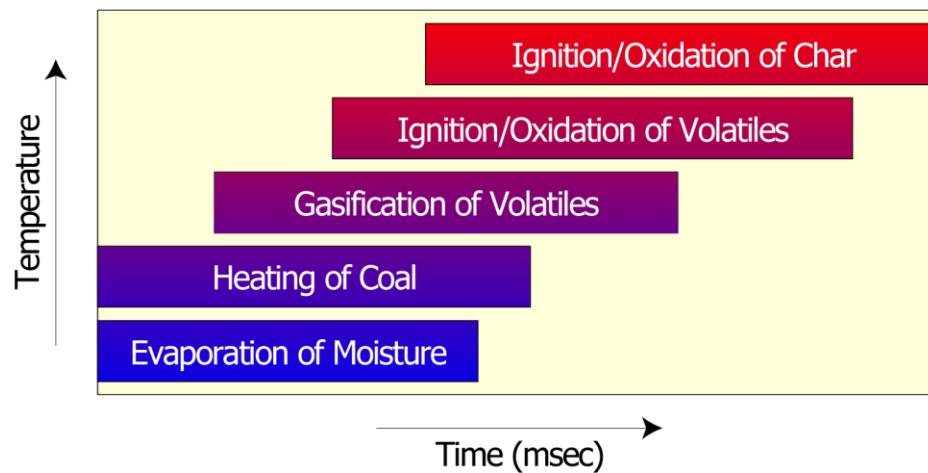


Average composition of DRI pellet (wt pct)

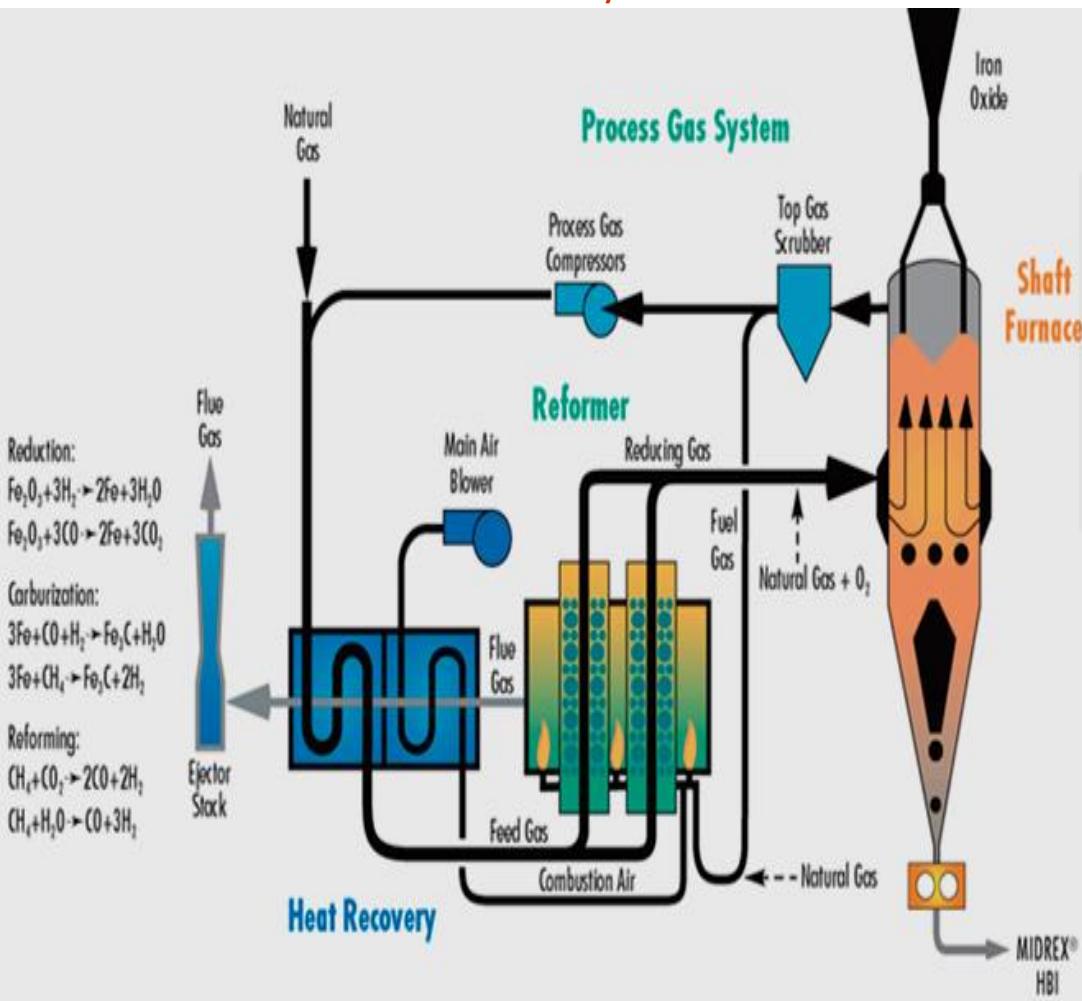
Total Fe	C	S
92	SiO_2	Al_2O_3
	CaO	MgO
	2.2	0.006
	2.15	0.5
	0.6	0.5

Regarding coal

- Further, the 'select' coal has to have a metallurgical property known as 'reactivity' for it to be suitable for sponge iron manufacture. Coals with high reactivity will facilitate the carbon in reacting with the oxygen (in the iron ore) to form carbon monoxide (CO) whereas coals with a low reactivity will not react sufficiently with the iron ores to facilitate direct reduction and will tend to remain largely inert in the process and exit the kiln as high carbon char/waste product.
- The resulting sponge iron would be of low metalization unsuitable as an electric furnace charge material. Therefore, for a rotary kiln coal based sponge iron manufacturing process to be successful it is absolutely essential to use non-coking coals having high reactivity characteristics and high ash fusion temperatures. Unfortunately, most Indian non-coking coals do not satisfy the above criteria and are, therefore, not suitable for sponge iron manufacturing.
- Such non-coking coals having low ash fusion temperature and/or low reactivity can be used as fuels for heating in any cement kiln and/or for firing the boilers of power plants where there is no need for 'metallurgical reduction.' In the sponge iron manufacturing process, the coal acts more than as a reductant and, therefore, as a feedstock than as a fuel for providing heat to the process
- Lower rank coal coals have high reactivity. All high volatile bituminous coals are suitable for sponge iron making. **A fuel ratio (FC/VM) value should be lower than 1.5 and up to 1.8. An increase in ash content by 1% reduces kiln productivity by 2%**



Midrex Process Flow Sheet – DRI/HBI Production



- The main components of the process are the DRI shaft furnace, gas reformer, and cooling gas system. The furnace has a refractory lining in the reducing zone.
- The charge material is fed into the furnace from the top through seal legs, and the discharge is also done through them from the bottom.
- Reducing gas enters the furnace from the bottom of the reducing zone. Oxide is reduced to metal by the counter-current flow of the reducing gas.
- DRI is then cooled and screened for removing fines.

Smelting Reduction Processes

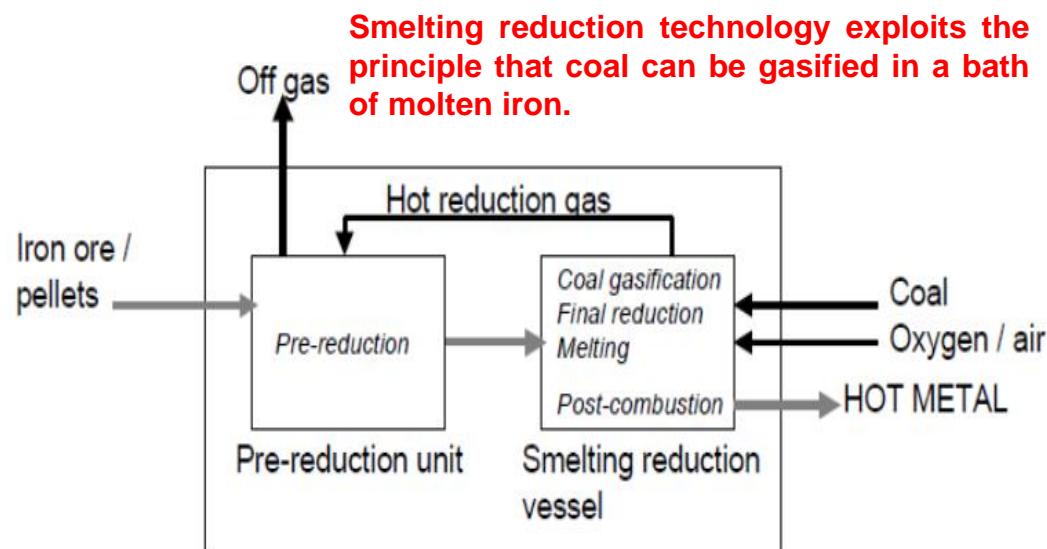
- ✗ Primary objective is to produce liquid iron directly from iron ore (fines & concentrates) and noncoking coal, by-passing agglomeration and coke-making requirements (reduced investment cost: 10-15%).
- Plant emissions contain only insignificant amounts of NOx, SO2, dust, phenols, sulfides and, ammonium besides far lower waste-water emissions.
- The promising alternative technologies that have been commercialized/ are in the process of commercialization and appear to be relevant are COREX, FINEX, HISMELT, etc.
- Single stage: Reduction & melting in the same vessel and **Two-stage : Reduction in one vessel; melting in the 2nd vessel**
- Ideally, an SR process should have a near 100 % reduction of iron oxides in the liquid state in one step in a single reactor

• The coal is fed into the smelting reduction vessel, where it is gasified, which delivers heat and hot gas containing carbon monoxide. Heat is used to melt the iron in the smelting reduction vessel. The hot gas is transported to the pre-reduction unit (pre-reducing the iron oxides (in a solid state), which is fed directly into the pre-reduction unit. The pre-reduced iron is subsequently transported to the smelting reduction vessel, where the final reduction takes place.

The hot gas produced in the smelting reduction vessel has a high chemical energy content due to carbon monoxide, which can be used to reduce iron oxides in the pre-reduction unit.

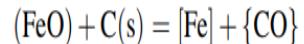
Secondly, the carbon monoxide can be oxidized in the smelting reduction vessel, which then delivers more heat for smelting the iron. This is called post-combustion. The initial reduction of iron oxide begins in the temperature ranges of 850-1050°C.

• After post-combustion, the hot gas is transported to the pre-reduction unit, and the remaining carbon monoxide is used to reduce iron oxides. **The richness of carbon monoxide in the hot gas determines the degree of pre-reduction.**



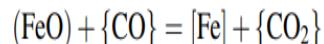
The basic principle of a SR process is to melt the pre-reduced iron ore/pellets with non-coking coal and oxygen in a reactor. SR technology consists of a pre-reduction unit and a smelting unit. In the pre-reduction unit, ore/pellets/fines are partially reduced and pre-heated using the gas generated in the smelting unit. The partially reduced ore is injected or fed into smelting vessel containing iron-carbon melt and slag.

The overall reaction is:

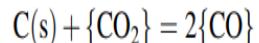


There is a general agreement that the above reaction takes place in two stages.

First stage → slag-gas reaction:

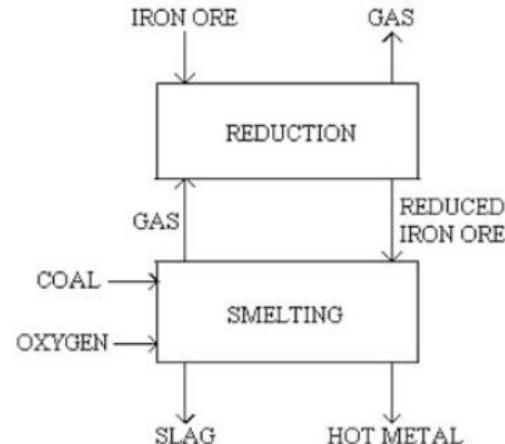


Second stage → carbon gasification reaction:

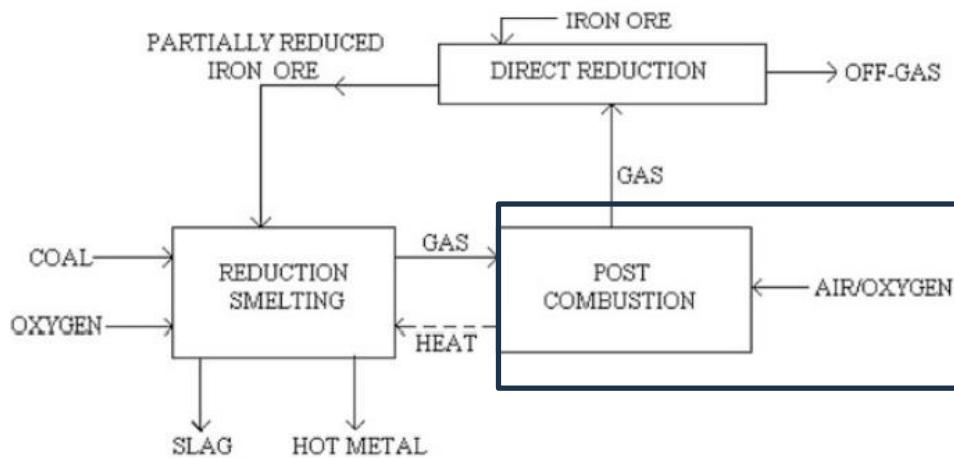


Limitations of the smelting reduction processes

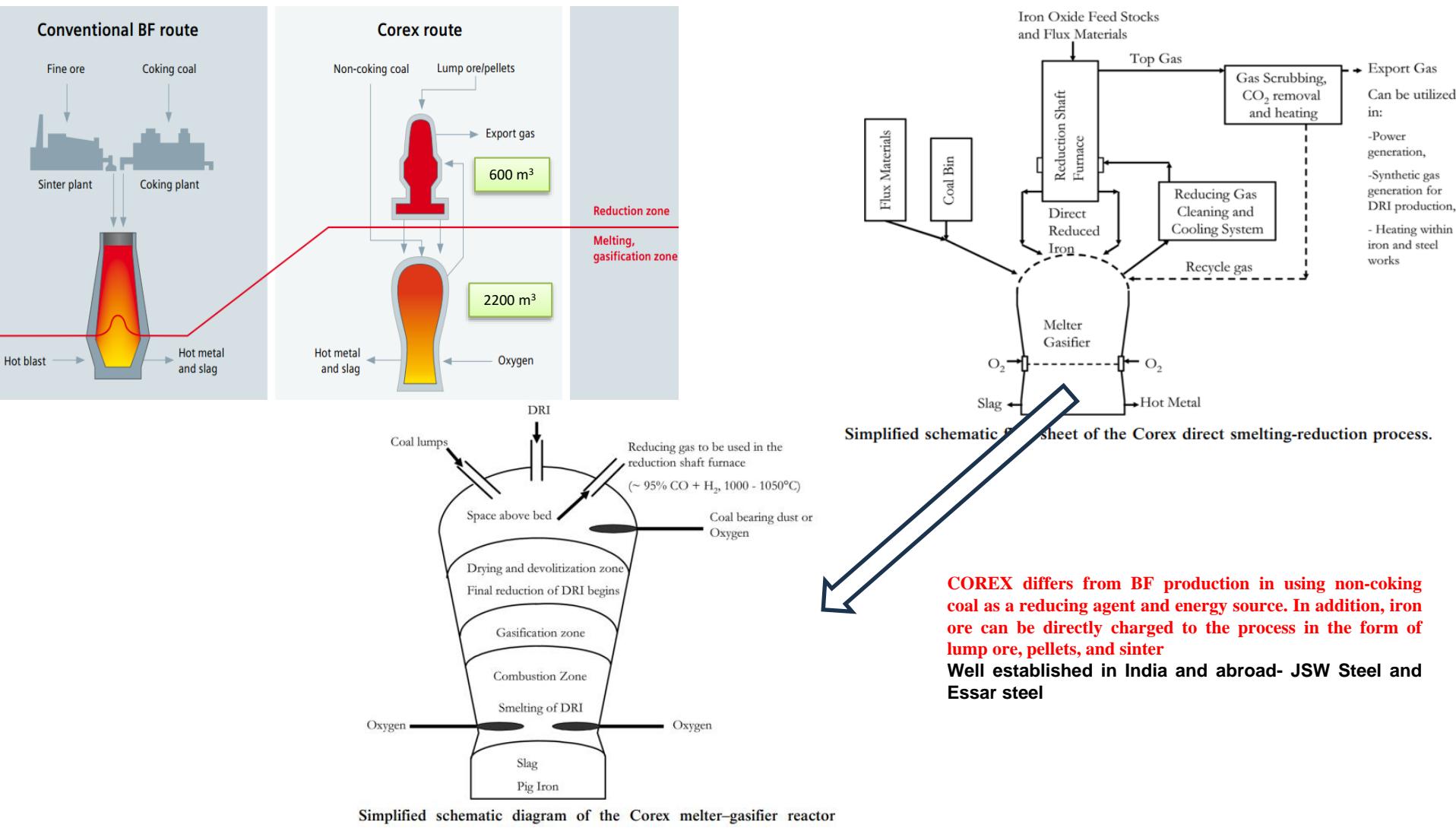
- (i) Consumption of a large amount of oxygen,
- (ii) The process generates a large amount of high calorific value export gas
- (iii) The maximum module size of a SR unit may be limited to 1 Mt/annum
- (iv) Pre-reduction of ore fines is mandatory and
- (v) Needs highly efficient post-combustion necessary to meet the energy requirement of the smelting processes.



(a) Two stages



(b) Two stages with post combustion

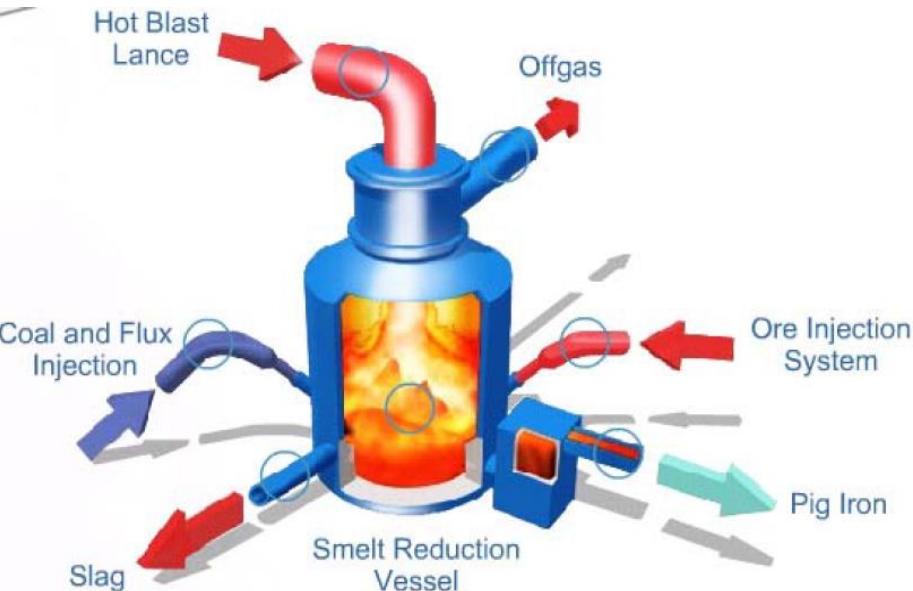


- Is a shaft furnace-based process. It requires pellets and lump ore (can accept high alkali containing ores), but only lump ore operation is difficult if not impossible.
 - Specific melting capacity is higher than in blast furnaces- productivity of the order of 3-3.5 t/m³/d can be achieved.
 - The process is capable of operating at 50-115% of its nominal capacity.
 - It takes only half an hour to stop the plant and four hours to restart it, whenever required.
 - Hot metal quality is comparable with blast furnaces (C=4.0-4.5%, Si=0.30-0.80%, S=0.02-0.09%, P depends on inputs).
 - It has outstanding environmental superiority in comparison with the blast furnace process in terms of generation of dust, SO_x, NO_x, phenol, cyanides, etc.
- Emits at least 15% less CO₂ as compared to BF route for hot metal production.
 - Air emissions lower than the conventional BF units.

Process Characteristics	Merits/Demerits
<p>Corex is a two-stage process: in the first stage (Reduction Shaft), iron ore is reduced to DRI using the reduction gas (65-70% CO + 20-25% H₂) from the Melter Gasifier and in the second stage (Melter Gasifier), DRI produced in reduction shaft is melted to produce hot metal.</p>	<ul style="list-style-type: none"> • Can't use ore fines directly • Restriction on non-coking coal (VM of carbonaceous material to be maintained at ~25% (blending of coal and coke. <p>Total fuel rate requirement = 950 kg/thm. Out of which ~200 kg coke is required.</p> <p>All the non-coking coal is imported.</p> <p>~ 100% pellets are charged.</p> <p>Oxygen requirement = 550 Nm³/thm (very high!)</p> <p>Corex HM ~ BF HM:</p> <p>Limited modular size (largest corex plant is of 1.5 million tonne capacity), necessity of gainful utilization of Corex gas and generated coal fines.</p>

Comparison of some of the properties of blast furnace and mini-blast furnace process and direct-reduction and smelting processes

Processes/properties	Blast furnace and mini-blast furnace processes	Smelting-reduction processes
Product	Hot metal essentially for basic oxygen furnace steel making. In granulated form, it can be used in electric arc furnace steelmaking, as a coolant and diluent for electric arc furnace and basic oxygen furnace operations, and as unit charge for ferrous foundry operations.	Hot metal essentially for electric arc furnace steel making. In granulated form, it can be used as coolant and diluents for electric arc furnace and basic oxygen furnace operations and as a unit charge for ferrous foundry operations.
Iron Oxide Feed Stocks	Pellets, lump ore, sinters, briquettes	Self-reducing green balls, pellets, lump ore, fine ore, oxide wastes
Reducing/Carburizing Agents	Blast furnace processes—metallurgical grade coke Mini-blast furnace processes—charcoal	Non-coking coal for most processes For some processes, non-coking coal and coke or coke breeze (i.e., Tecnored process)
Operational Temperatures (°C) and Pressures (atm)	>1535 °C 1.5–2.5 atm	>1300 °C For some processes, up to 5 atm (i.e., Corex process)
Typical Operational Problems for the Processes	<ul style="list-style-type: none"> – Environmental emissions caused by coke ovens and sinter plants – Dependence on high-quality raw materials such as sinter, pellets, and coke – Need for auxiliary plants such as coke ovens, sinter plants, and pellet heat-hardening kilns and, consequently, increased capital and operational costs – Reliance on large-scale operations – Beneficiation of only a limited range of iron oxides – Lack of operational flexibility – Inflexible product characteristics – Frequent furnace-relining requirements 	<ul style="list-style-type: none"> – High refractory costs – Iron losses due to reactive FeO-rich slag – Hot metal desulphurization is needed since the smelter metal can contain up to two or three times as much sulfur – Need to control char in the slag for optimum reduction and slag-foaming rates – Low re reduction efficiencies – Consumption of large amounts of coal and oxygen – Fluctuations in raw material chemistry – Problems with tapping the liquid metal and slag



SOME KEY FEATURES OF HISMELT

- Incorporates many BF features – hot blast stoves, air blast, etc.
 - Can be single stage process; better, with separate pre-reduction.
 - Pre-reduction of iron oxide and oxygen enrichment of hot air (1200°C) blast provide substantial productivity enhancement.
 - Hot metal contains $4.3 \pm 0.15\%$ carbon, phosphorus and silicon levels are extremely low viz. $< 0.05\%$ P and $< 0.05\%$ Si%.
 - Process can use high phosphorus iron ore – can be of significance in India since many Indian ores have high phos.
 - 50-70% FC, 10-38% VM and 5-12% ash coals have been used in Pilot/Demo plant. Typical coal rate reported – 640-690 kg/thm.
 - Utilisation of export gas not as critical as in the case of processes like Corex on account of in-bath smelting.
- Economics under Indian conditions still not proven. Demo plant not proven on sustained basis at full capacity though process has promise (capacity 0.6-1.2 Mtpa).**

Process Characteristics

Direct use of iron ore and coal fines in a single step reactor. A distinguishing feature of the process is oxidation level of the slag bath (5% FeO in slag), which helps in post partitioning of a large portion of phosphorous to slag.

Involves moderate to high degree (>70%) of post combustion. The gas generated during the reactions is further combusted to around 50% just above the bath and metal an ideal feed for BOF.

the heat energy of the post combustion is transferred back to the main process through the liquid fountain of handling high alumina ore is resolved to a large extent.

molten iron bath, instead of recovering it as export gas. However, Process is not yet fully proven This reduces the coal and oxygen requirement of the process.

Merits/Demerits

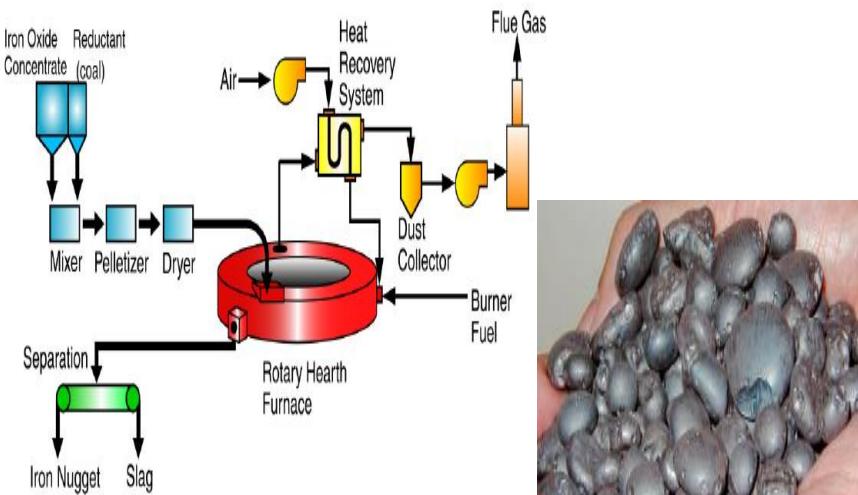
Being a bed less process, problem faced in BF in back to the main process through the liquid fountain of handling high alumina ore is resolved to a large extent.

ITmk3 Process: Production of Iron nuggets

- Disadvantage in DRI: gangue remains within it

Kobe Steel, Japan: ITmk3

- Ore + coal composite pellets: Reduction & melting at 1500C in RHF
- It produces almost low sulphur pure iron nuggets (& slag globules)
- 0.25 mtpy plant at Minnesota, USA



Slag is separated by partial melting.

Nugget Formation: The series of reactions are completed in around 10 minutes. To begin with, pellets are converted into DRI with un-reacted core which later convert into a dense metallic iron shell containing molten slag and large void space. Immediately thereafter, in the last zone the temperature is raised to 1350–1450 °C, where the metallic iron melts and starts separating out from slag.

In the last two minutes of the process of the RHF, the molten iron and slag are cooled which further cooling in the cooler follows. The solidified iron nuggets are separated from the slag with the help of a magnetic separator.

Product: The quality of Iron nuggets depends on the quality of iron ore and coal used in the process. However, typically, iron nuggets are highly metallised product containing over 97% metallic iron with very low phosphorous. A typical composition of nuggets is Metallic Iron(Fe) +97%, Carbon(C) 2–2.5%, Sulphur(S) 0.07–0.10% & Phosphorus(P) 0.01–0.02%.

The sensible heat of the off-gas from the RHF is substantially recovered by a recuperator thereby heating the air for combustion of natural gas used in the process. The hot air is also utilised for drying the green pellets.

In ITmk3 process, phosphorous removal is substantial leading to a very low content of phosphorous in iron nuggets as against in blast furnace where phosphorous removal is minimal. This is mainly because of shorter reaction time, essentially around 6 minutes, and iron and slag are separated after 2 minutes cooling time. In other words, the operation does not reach equilibrium to allow phosphorous to transfer to the metal. When iron and slag were allowed to stay together longer during plant demonstration trial it was observed that phosphorous content of the metal was increased.

SOME KEY FEATURES OF ITmk3

- First step produces iron nuggets in a very short reduction time (10-12 min) along with some slag removal in a RHF.
- High-purity iron nuggets contain 96-97% iron and 2.5-3.0% C, 0.05 S. i.e. nearly same composition as blast furnace pig iron. Coal consumption reported to be 500 kg/t nuggets.
- The process is flexible as far as the type of iron ore that can be used. Magnetite, haematite as well as pellets made of taconite (low-grade iron ore found in USA) have been processed.
- Emits at least 20% less carbon dioxide than blast furnaces.
- Overall less NOx, SOx and particulate matter emissions.
- Easy start-up, shut down and change in production rate.

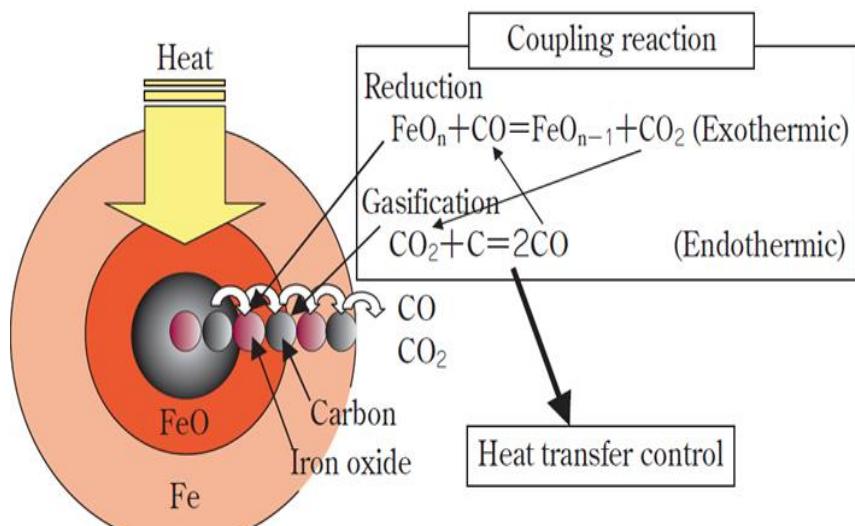
Over last 10-12 years has gone through laboratory, small pilot plant and demonstration plant testing. Nuggets melted in EAFs. Commercial plant (0.5 Mtpa) just commissioned (USA). Could be of immense interest to India in future.

The process is referred to as third-generation ironmaking, generation one being the blast furnace process and generation two being natural gas-based direct-reduction processes. The process has been developed to overcome the refractory wear problems associated with the smelting of iron oxide bearing (especially wustite) and gangue-containing DRI in the electric ironmaking furnaces.

Metal quality comparison of blast furnace and smelting-reduction process pig iron

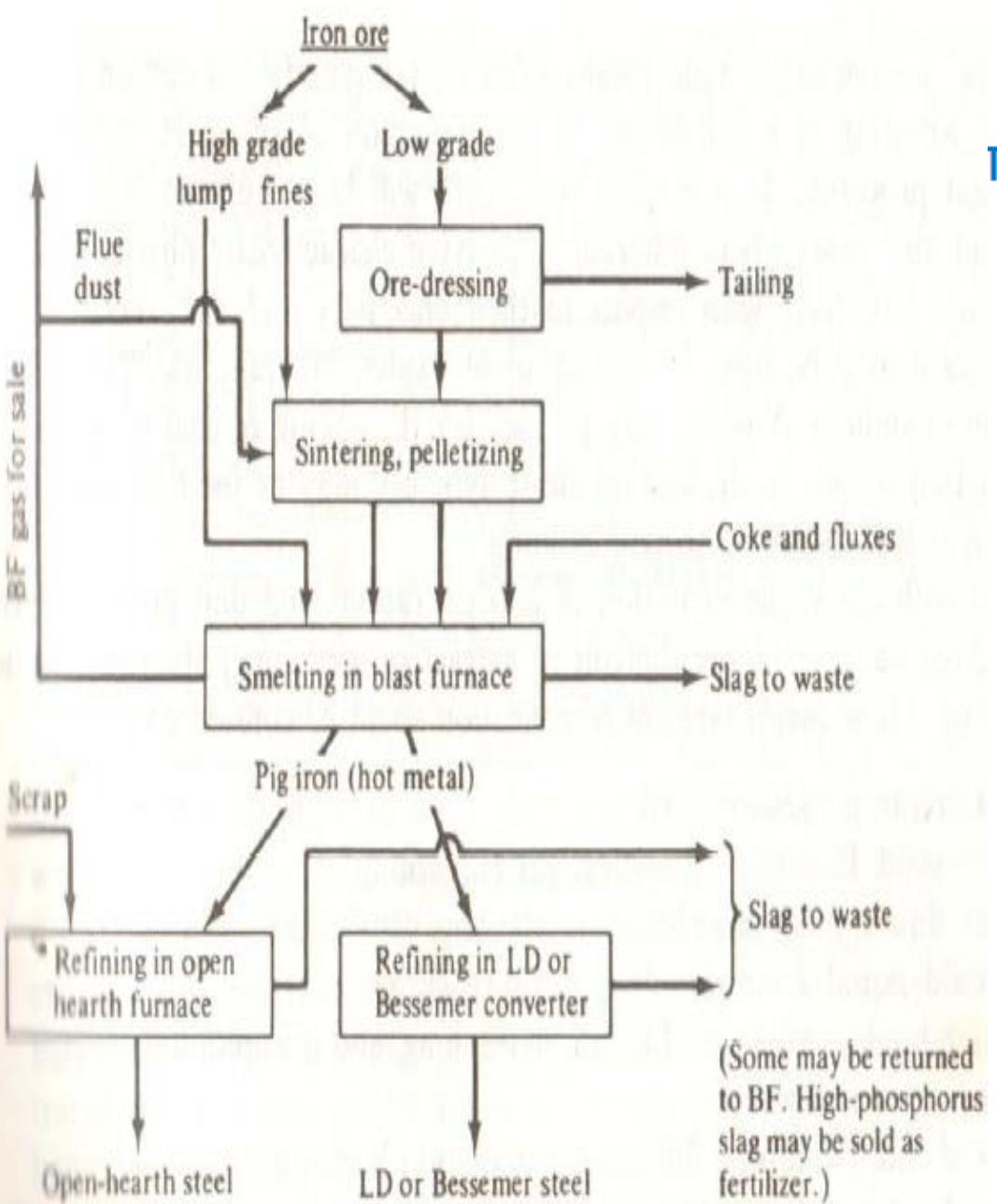
Metal composition/ processes	Wt% C	Wt% Si	Wt% S	Wt% P	Wt% Mn	Wt% FeO
Blast Furnace Pig Iron	4.0–5.0	0.2–1.5	0.03–0.8	0.04–0.2	0.2–0.22	—
HIs melt	3.5–4.5	0.001	0.1–0.15	0.01–0.05	0.02–0.06	3.0–6.0
Corex	4.4–4.8	0.6–0.8	0.01–0.03	0.10–0.15	0.2–0.5	<0.5
Finex	4.0–5.0	0.2–0.8	0.01–0.05	0.10–0.15	No data	<0.5
ITmk3	2.5–4.3	0.2	0.05–0.06	0.05–0.06	0.1	<0.2

The reduction reaction kinematic for conventional pellets and sintered ore is controlled by reduction gas diffusion from outside. On the other hand, **the reaction of carbon composite agglomerates occurs inside the agglomerates themselves**, which consist of iron ore fines and pulverized coal. Once the agglomerates are heated, carbon monoxide is generated inside them, promoting the reduction of iron oxide. Thus, the reduction reaction proceeds faster in the carbon composite agglomerates than in conventional pellets and sintered ore, whose reaction is controlled by diffusion from outside

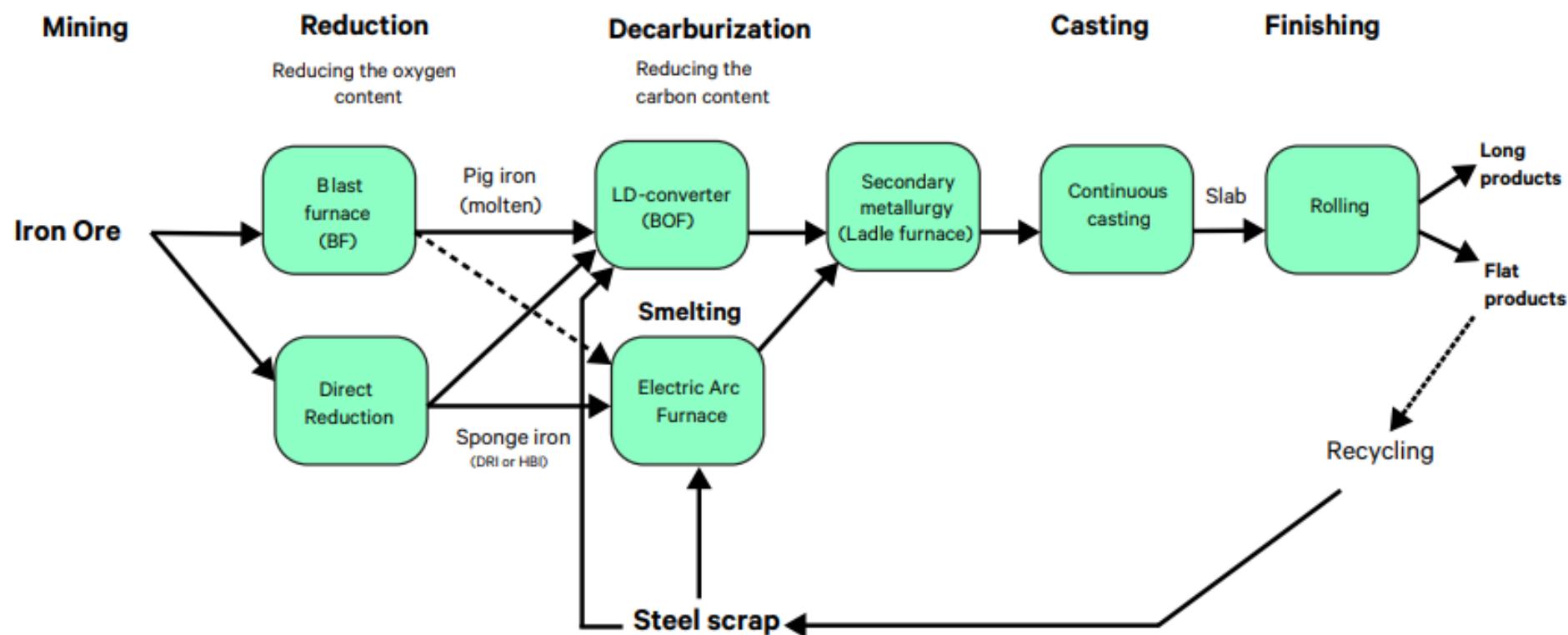


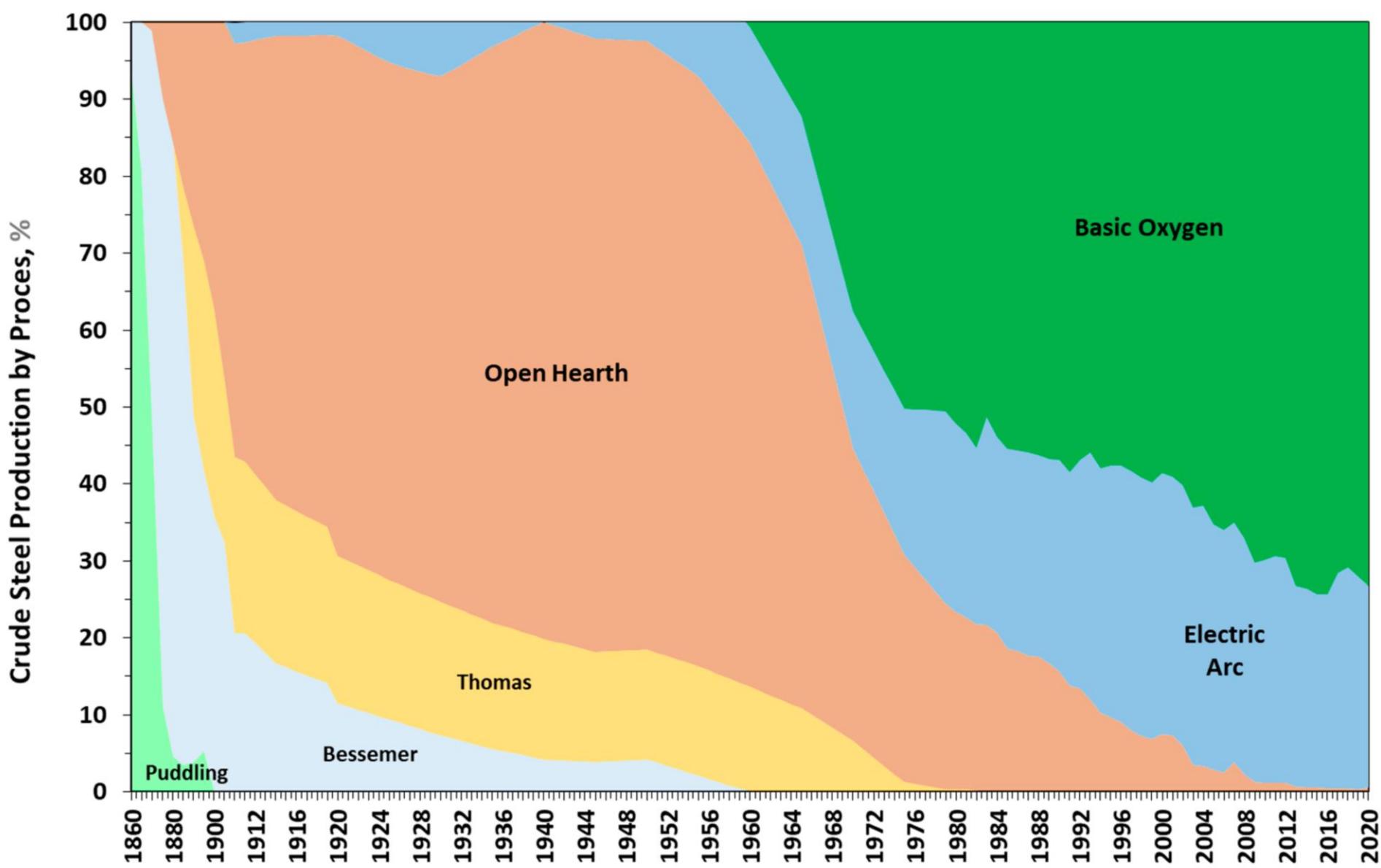
Reduction mechanism of carbon composite pellet

TECHNOLOGY MIX OF IRON & STEEL MAKING



Process Route	World	India
Oxygen Route (%)	70	BF/COREX/BOF/THF/EOF: 40
Electric Route (%)	30	EAF/DRI-EAF : 25 EIF/DRI-EAF : 35





Steelmaking is a process of selective oxidation of impurities, which is the reverse of ironmaking. In principle, it is similar to the fire refining of nonferrous metals but the end product is an alloy, not a pure metal. However, the conversion of pig iron/sponge iron into steel is a complex process.

OTHER AIMS OF STEELMAKING

- **Removing of P, S, Si**
- **Removing of metals Zn, Cu, Pb, Cd, Al, ...**
- **Removing of diluted gases N, CO, H, O**
- **Removing of solid non-metal particles**
- **Addition of alloying metals (e.g. Ni, Cr, Co, Mo, Mn, Si, V, ...)**

Modern steelmaking is often viewed as the brainchild of Sir Henry Bessemer, the *Leonardo da Vinci* of metallurgy, who first produced steel by blowing air through a bath of molten pig iron using a submerged fireclay blow-pipe.^[6] The process was described in Bessemer's patent application of 1855^[7] as "... a current of air ... is then to be forced into the fluid metal and allowed to bubble up through it". Scientific understanding of the associated metallurgical reactions has evolved over the subsequent years. The oxygen supplied to the molten metal bath causes oxidation of carbon, silicon, manganese, phosphorus and other oxidisable impurities, along with some amount of iron.^[8]^[9]^[10] This has remained the fundamental principle of steelmaking and the various industrial processes, developed over the years, differ mainly in the way oxygen is supplied to the metal bath. Oxygen can be made available in the form of air (e.g. Bessemer and Thomas process), solid iron ore (e.g. open hearth furnace) or as pure oxygen gas (basic oxygen furnace). In all cases, the products of oxidation can either join the slag (e.g. SiO_2) or escape as gas (e.g. CO).

Steelmaking involves several physicochemical processes like melting, dissolution, chemical reactions, solidification etc. It involves dynamic interaction among ions/atoms/molecules along with interfacial interactions of slag-metal-gas phases existing simultaneously at high temperatures. Steel is produced either by using Molten iron (as an output of blast furnace) or direct reduced iron, DRI (produced by solid reduction of Iron-oxides) along with recycled steel scrap : The Steelmaking process is categorized into three stages: →

- (a) Primary Steelmaking Process (BOF, EAF)
- (b) Secondary Steelmaking Process (Ladle furnace
Vacuum Treatment
in Ladle)
- (c) Casting Process (Top Pouring, Continuous Casting Process).

Overall :

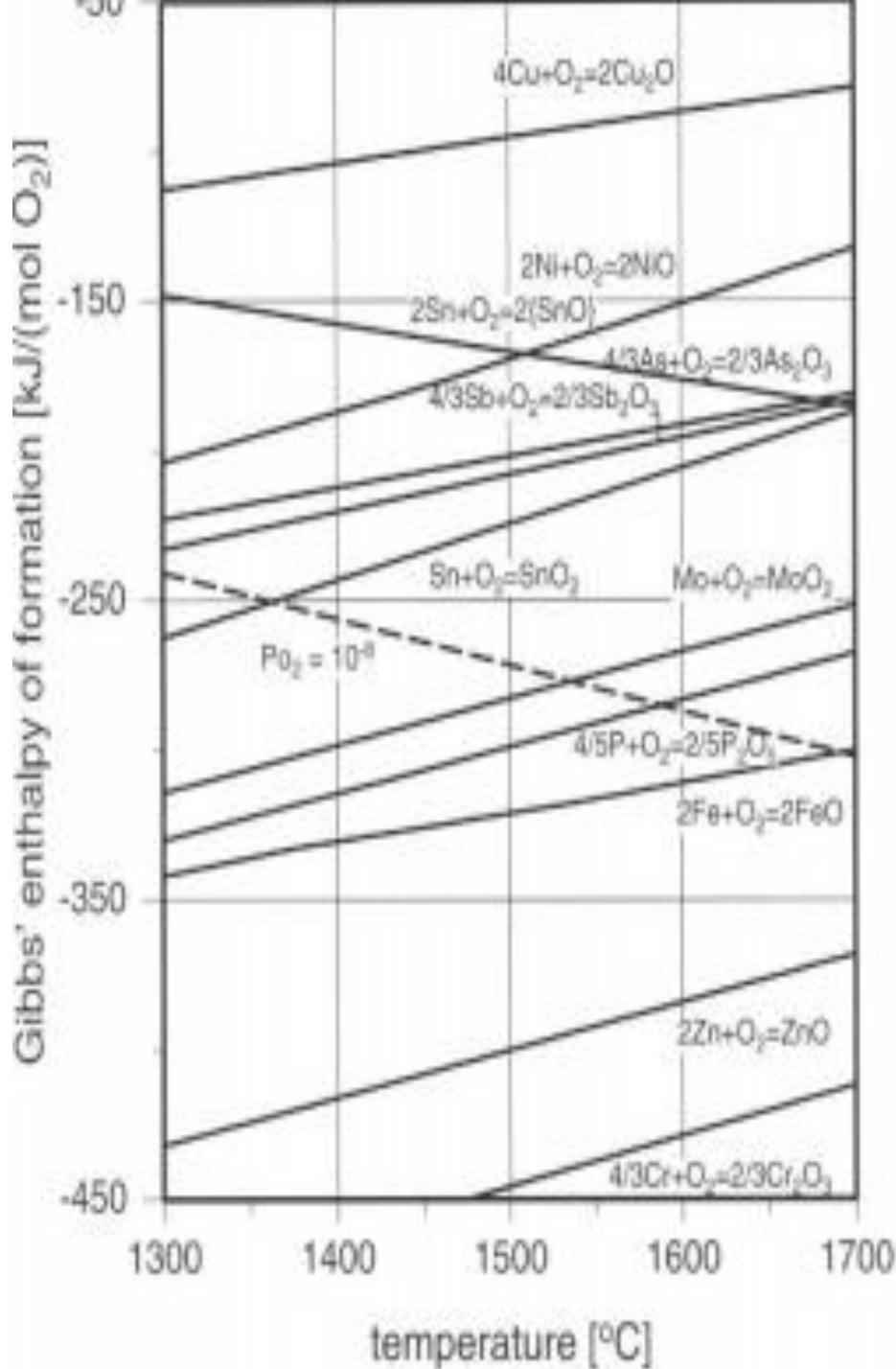


Richardson-Jeffes diagram

A tramp element signifies an element which is not deliberately added into the steel or is present in the heat as a result of the process.
Si, P, S,Cr,Mo,Ni,Cu,Al,N,Nb,V,Ti,B,As,Sn

- Diagram shows the free formation enthalpy of the elements with oxygen for formation of the respective oxides, as a function of temperature
- Initial information on the affinity of the various elements for oxygen.
- Provides only initial information on the slagging behavior to be anticipated from the individual tramp elements.

Oxygen affinities for the elements at a steelmaking temperature of 1600°C:
Copper has the lowest affinity for oxygen;
 $\text{Ni} < \text{As} < \text{Sb} < \text{Sn} < \text{Mo} < \text{P} < \text{Fe} < \text{Zn} < \text{Cr}$ (Cr highest)
The curve for an oxygen partial pressure of 10^{-8} bar is also plotted which normally prevails in the steel heat during the steelmaking processes. Only oxidation of iron, zinc or chromium would thus be possible at 1600°C.



The diagram is relevant to the actual steelmaking process only to a limited extent, since it applies only to pure elements and their pure oxides, and the tramp elements under examination here are present in the steelmaking process in dissolved and diluted form, while the oxides produced are also present in the slags in dilute form and may form complex compounds with other oxides.

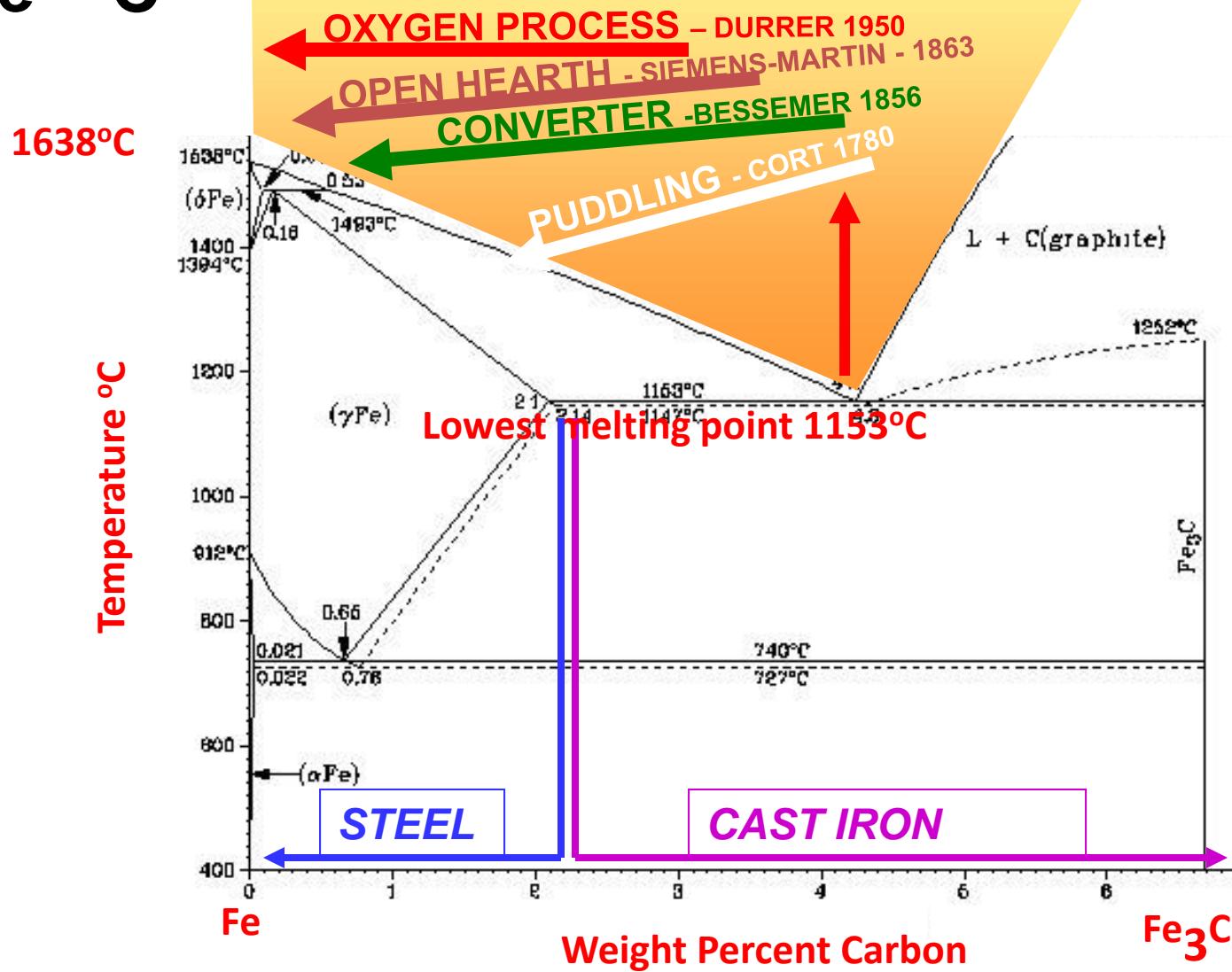
If the removal of tramp elements by means of oxidation and the formation of the corresponding oxides is not possible, there remains the possibility of their removal under vacuum.

Importation of tramp elements in steel and their removal

input	element	W	Cu	Mo	Bi	Ni	Co	As	Sn	Sb	Cr	P	N	H	S	O	Pb	Zn	B	Nb	V	Ti	Si	Al	Ca	
atmosphere													•	•		•										
stirring gas													•													
refractory														•	•									•	•	
premelted heat		•		•	•	•		•		•						•						•				
ore								•		•							•									
scrap		•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	
hot metal			•		(•)			•		•	•	•	•			•									•	
slag																		•								•
additions													•		•	•	•							•		•
desoxidiser																										•
alloying elements												•	•			•			•		•	•	•	•	•	
		non - removable					removable to a limited extent					easily removable														

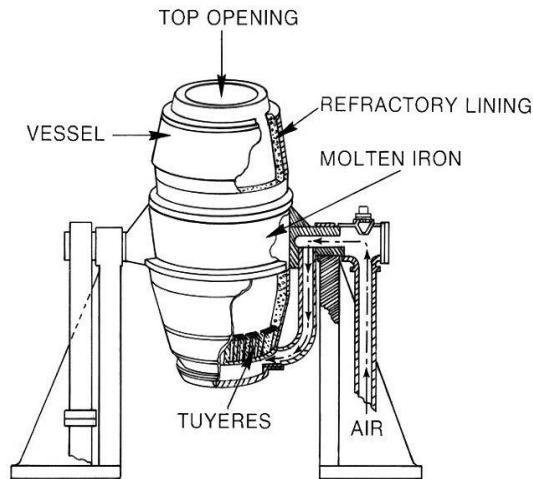
Fe – C

LIQUID STEEL



• The Bessemer converter:

- Used for REFINEMENT:
 - Takes pig iron with high C content and removes C.
 - Removes impurities such as Si and Mn (via oxides)
- Much smaller furnace (vs. Blast furnace)
- Lowered cost of steel making
- Poured into molds to form ingots



Replaced by basic oxygen process and electric arc furnace.



This process worked particularly well with pig iron that was low in phosphorus, high in manganese and with adequate silicon.

- The Bessemer process was the first inexpensive industrial process for the mass-production of steel from molten pig iron. The process is named after its inventor, Henry Bessemer
- Removal of impurities from the iron by oxidation with air being blown through the molten iron. The oxidation also raises the temperature of the iron mass and keeps it molten. The process is carried on in a large ovoid steel container lined with clay/ dolomite.
- Capacity of a converter: 8-30 tons of molten iron. At the top of the converter is an opening, usually tilted to the side relative to the body of the vessel, through which the iron is introduced and the finished product removed. The bottom is perforated with a number of channels called tuyères through which air is forced into the converter.
- The converter is pivoted on trunnions so that it can be rotated to receive the charge, turned upright during conversion, and then rotated again for pouring out the molten steel at the end.

The conversion process called the "blow" was completed in around twenty minutes. During this period the progress of the oxidation of the impurities was judged by the appearance of the flame issuing from the mouth of the converter. After the blow, the liquid metal was recarburized to the desired point and other alloying materials are added, depending on the desired product.

- The Bessemer process was so fast (10–20 minutes for a heat) that it allowed little time for chemical analysis or adjustment of the alloying elements in the steel.
- Bessemer converters did not remove phosphorus efficiently from the molten steel; as low-phosphorus ores became more expensive, conversion costs increased.
- The process permitted only limited amount of scrap steel to be charged, further increasing costs, especially when scrap was inexpensive.

Open-hearth processes

In the Siemens process, both acid and basic, the necessary heat for melting and working the charge is supplied by oil or gas. But the gas and air are preheated by regenerators, two on each side of the furnace, alternatively heated by the waste gases. The regenerators are chambers filled with checker brickwork, brick and space alternating. The furnaces have a saucer-like hearth, with a capacity which varies from 600 tonnes for fixed, to 200 tonnes for tilting furnaces. The raw materials consist essentially of pig iron (cold or molten) and scrap, together with lime in the basic process. To promote the oxidation of the impurities iron ore is charged into the melt although increasing use is being made of oxygen lancing. The time for working a charge varies from about 6-14 hours, and control is therefore easier than Bessemer process.

Electric arc process :The heat required in this process is generated by electric arcs struck between carbon electrodes and the metal bath. Usually, a charge of graded steel scrap is melted under an oxidising basic slag to remove the phosphorus. The impure slag is removed by tilting the furnace. A second limey slag is used to remove sulphur and to deoxidise the metal in the furnace. This results in a high degree of purification and high quality steel can be made, so long as gas absorption due to excessively high temperatures is avoided. This process is used extensively for making highly alloyed steel such as stainless, heat-resisting and high-speed steels. Oxygen lancing is often used for removing carbon in the presence of chromium and enables scrap stainless steel to be used.

Oxygen processes

The high nitrogen content of Bessemer steel is a disadvantage for certain cold forming applications and continental works have, in recent years, developed modified processes in which oxygen replaces air. In Austria the LID process (Linz-Donawitz) converts low phosphorus pig iron into steel by top blowing with an oxygen lance using a basic lined vessel. To avoid excessive heat scrap or ore is added. High quality steel is produced with low hydrogen and nitrogen (0.002%). A further modification of the process is to add lime powder to the oxygen jet (OLP process) when higher phosphorus pig is used.

In the bessemer process air is forced through the metal. In the open-hearth furnace the metal is protected from the flaming gases by a slag covering. Therefore it is reasonable to suppose that the final product will not contain so much gas.

OPEN HEARTH FURNACE - 1863

Sir Charles William Siemens
Émile et Pierre Martin

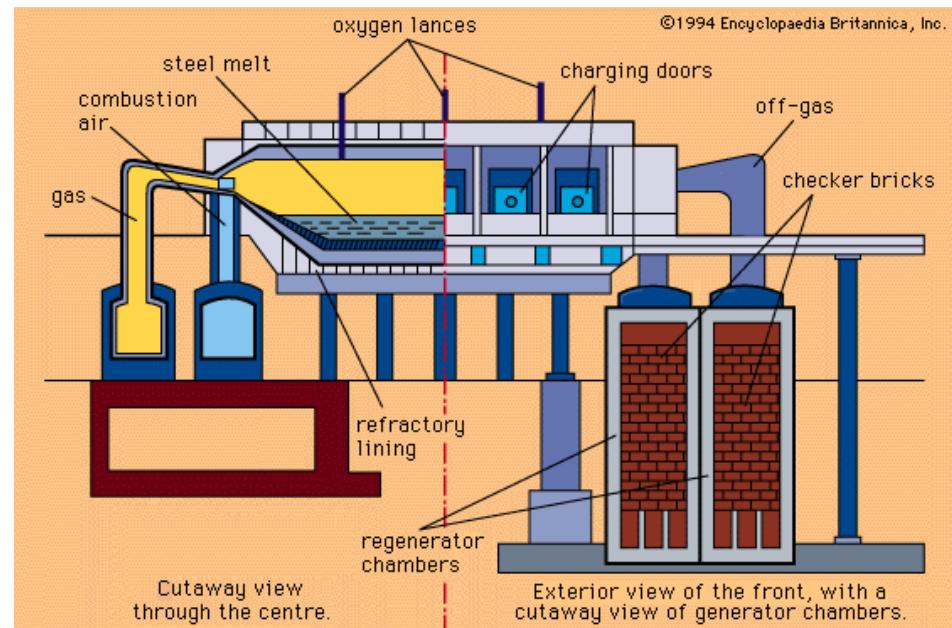
- Melted iron (pig iron + scrap)

- + hot air

- + flue gas

- + magnesite lining

- + CaO powder



Slower process compared to converters

However higher quality of the product

Open-Hearth Furnace - A reverberatory melting furnace with a shallow hearth and a low roof. Heat is supplied from a large, luminous flame over the surface, and the refining takes 7-9 hrs.

Steelmaking Process

Open Hearth furnace (OHF) is a shallow, refractory-lined basin in which scrap and molten iron are melted and refined into steel. Scrap is charged to the furnace through doors in the furnace front. Hot metal from the blast furnace is added by pouring from a ladle through a trough positioned in the door.

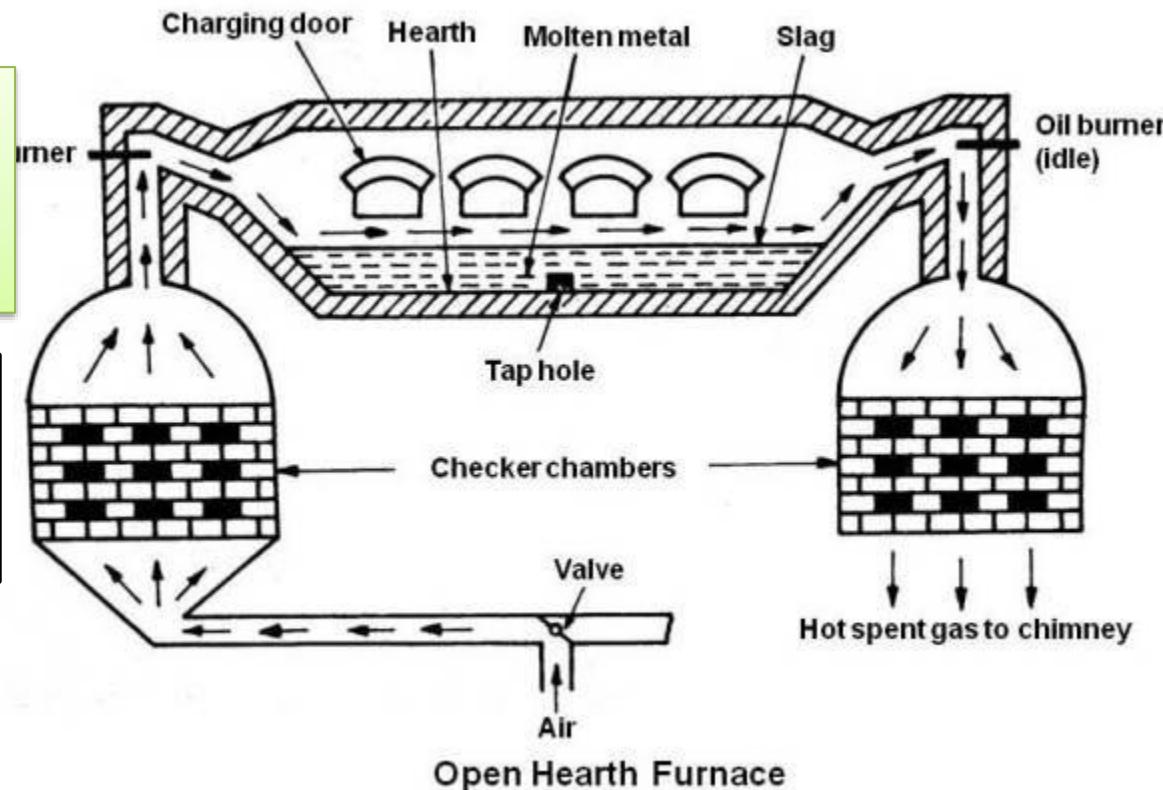
The mixture of scrap and hot metal can vary from all scrap to all hot metal, but a half-and-half mixture is most common. Melting heat is provided by gas burners above and at the side of the furnace. Refining is accomplished by the oxidation of carbon in the metal and the formation of a limestone slag to remove impurities.

Most furnaces are equipped with oxygen lances to speed up melting and refining. The steel product is tapped by opening a hole in the base of the furnace with an explosive charge. The open hearth steelmaking process with oxygen lancing normally requires from 4-10 hours for each heat.

Difference between two open hearth methods basic/acidic is due to construction material of the hearth lining.

Basic process can remove P from pig iron while acid process (also bessemer) can't remove.

Regenerators are brick checker-works at both ends of the hearth, provide alternating sources of hot air that plays over the charge to melt it.

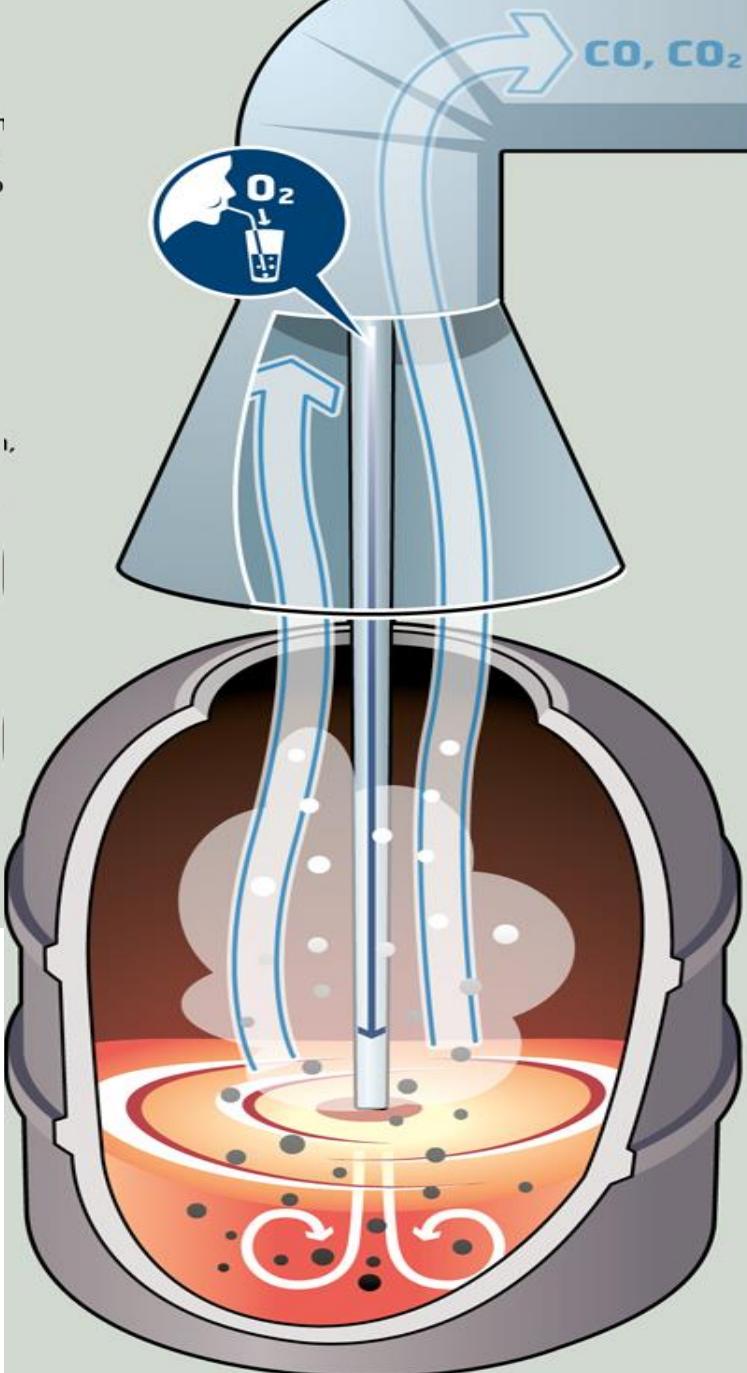


Advantages

- Compared with the Bessemer process, which it displaced, its main advantages were that it did not expose the steel to excessive nitrogen (which would cause the steel to become brittle), was easier to control, and permitted the melting and refining of large amounts of scrap iron and steel.
- This furnace operates at a high temperature by using regenerative preheating of fuel and air for combustion. In regenerative preheating, the exhaust gases from the furnace are pumped into a chamber containing bricks, where heat is transferred from the gases to the bricks. The flow of the furnace is then reversed so that fuel and air pass through the chamber and are heated by the bricks.
- In 1990's most of the open hearth furnaces are replaced by basic oxygen furnaces.

The LD-process

The LD process is an oxygen method used for refining the iron i.e., lowering the carbon content so that the iron is converted into forgeable steel.



The LD converter has a thick lining of special refractory brick. The refractory brick and tap holes are worn and must be changed at regular intervals.

The oxygen lance is lowered toward the melt, and oxygen is blown at high pressure onto the steel bath.

The oxygen reacts with the carbon and forms a gas consisting of carbon monoxide and carbon dioxide. Oxygen blowing continues until the ordered carbon content has been achieved. 1.7 percent is the limit between brittle hot metal and forgeable steel.

The tapping temperature is above 1,600°C.

'Basic Oxygen Steelmaking (BOS)' and even 'vessel' are other terms commonly employed, the 'basic' referring to the type of lining in the vessel which has to be alkaline (basic) in nature when treating iron made from ores containing phosphorus.

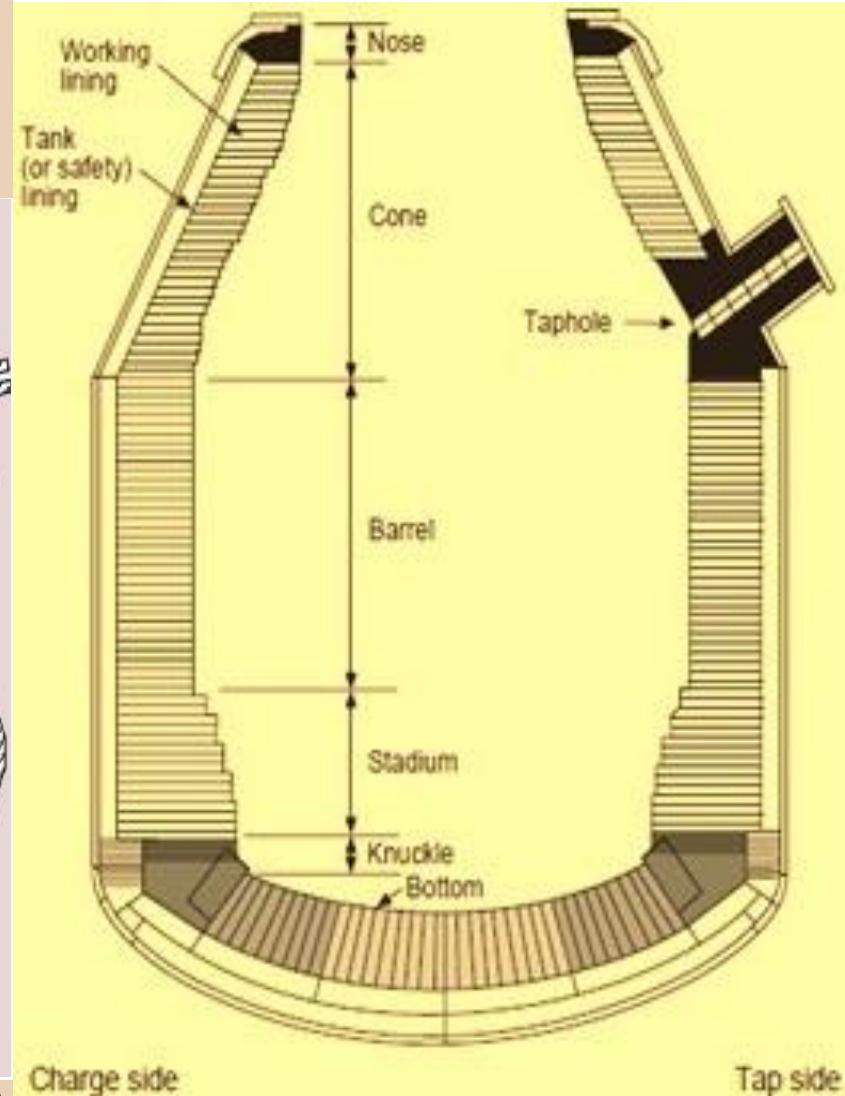
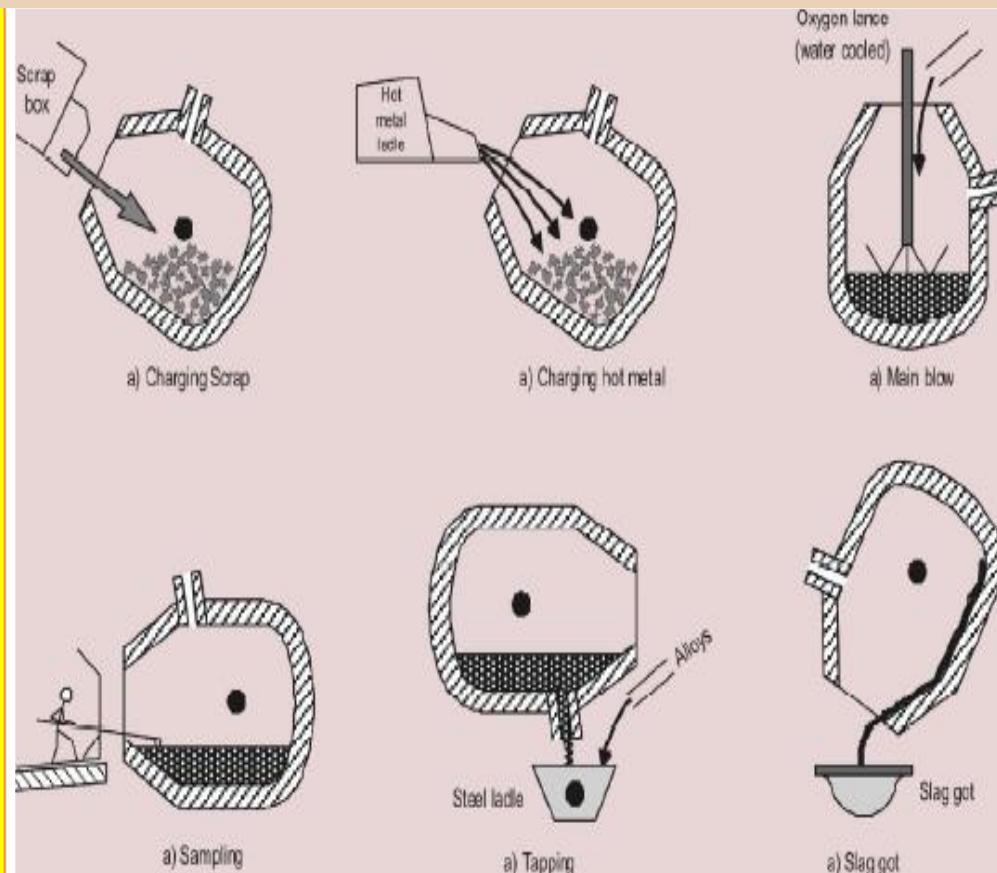
With the original process concept, only the impinging oxygen jet will provide mixing of the metal bath, a drawback compared with the bottom-blown Bessemer and Thomas processes.

- In 1950, at Linz and Donawitz, a process was tried in a pear shaped vessel; refractory line, hot metal, pure oxygen was blown from the top and he was able to convert hot metal to steel. This particular technology has revolutionized the steel industry because it was highly flexible; there was no problem with the plugging up the bottom as it was there in basic Bessemer
- The only problem is, that in the beginning they have used the mild steel as a material of Linz which was melting, but later on, the development took place and this process has become the modern steel making. Now, parallel to these developments, the ladle was also explored to use as a reactor and as a result, several secondary steelmaking processes also came into existence; so, a large number of secondary steelmaking were developed around the 60s; in 60s, also this top blown oxygen steelmaking was converted to top and bottom blowing steel making; that is how, the modern steel making through top and bottom blowing has come into existence.
- **Integrated steel plant**, the capacity may vary from 1 to 5 million ton per annum; then we have mini steel plants and their capacity may go from 0.5 to 1 million ton per annum. The essential different between integrated steel plant and mini steel plant - integrated steel plant, it starts from ore and produces the steel; whereas, mini steel plant mostly, they have scrap and then to steel.

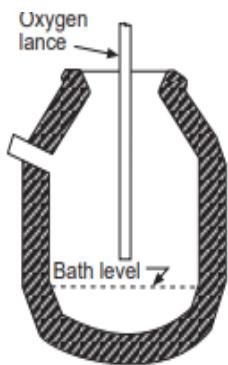
Present steel production methods fall into two categories:

- (i) The blast furnace (BF) and basic oxygen furnace (BOF/LD) route of steel making followed in Integrated Steel Plants (ISP). These plants are large in capacity ranging from 1 to 5 million tonnes per year and covering a fairly large area of 4 to 8 sq.km.
- (ii) Scrap/DRI or sponge iron and electric arc furnace (EAF) and induction furnace (IF) route of steel making as adopted in Mini Steel Plants (MSP). These are small in capacity ranging from 0.5 to 1 million tonne and in some cases up to 2 million tonnes per year, covering an area up to 2 sq. km.

Process steps involved in BOF steelmaking

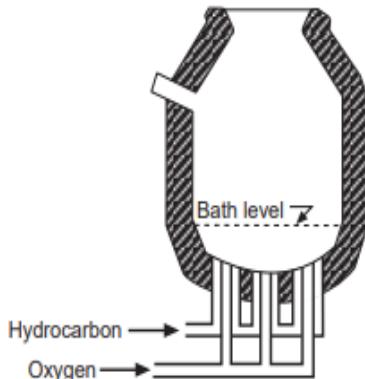


The growth of the top-blown basic oxygen converter steel making process, originally known as the LD process, has revolutionised steel making technology in the world. LD stands for Linz and Donawitz, towns in Austria where the process was developed. The process is also known as BOF (Basic Oxygen Furnace). The BOF process was introduced in India in the Rourkela Steel Plant in late 50s. Later, almost all the major integrated steel plants in India adopted this steel making technology.



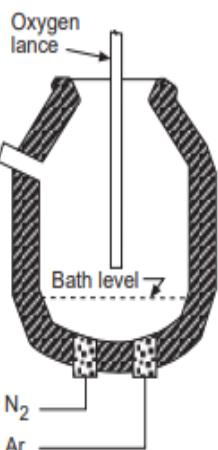
Top-blown (BOF) process

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.

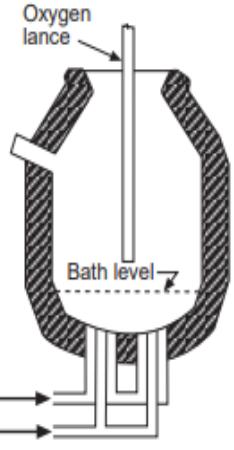


Bottom-blown (OBM or Q-BOP) process

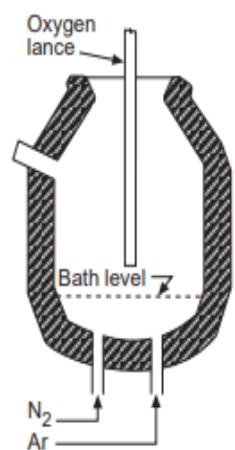
Oxygen of commercial purity, at high pressure and velocity, is blown upward vertically into the bath through tuyeres surrounded by pipes carrying a hydrocarbon such as natural gas.



Top lance plus permeable elements in bottom



Top lance plus cooled bottom tuyeres



Top lance plus uncooled bottom tuyeres

Combination-blown processes

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

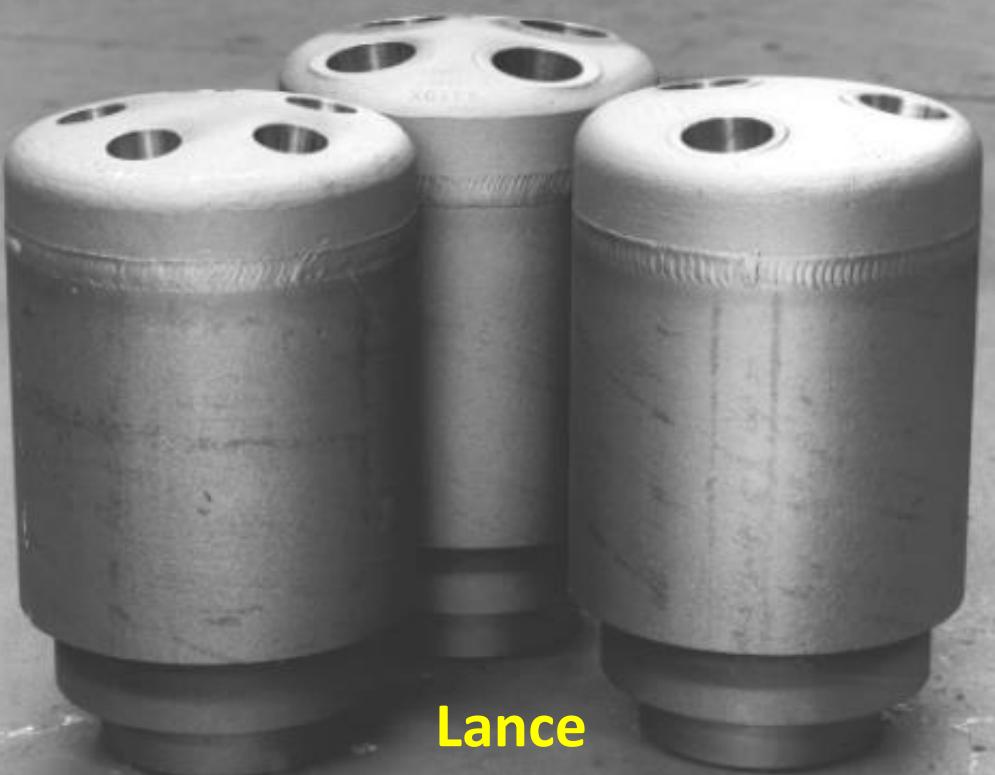
As the iron-bearing charge materials (i.e. hot metal, scrap and coolants) used in the BOS process all contain high levels of elements (e.g. silicon), which will form acid liquid oxidation products (e.g. silica), basic slag formers need to be added to create a slag phase with appropriate basicity. Burnt lime, alone or in combination with burnt dolomitic lime, is used.

Type	Abbreviation	Name	Process principals
Top-blown	LD	Linz & Donawitz	Oxygen blown against metal surface via top-lance lowered into the steelmaking vessel
	LD-BAP	LD – Bottom Agitation Process	LD, with bottom injection of inert gas via tuyeres
	(LD-)TBM	Thyssen Blowing Metallurgy	
	LD-KG	LD – Kawasaki Gate	LD, with bottom injection of inert gas via permeable elements
	LDS	LD – Spüler	
	LD-LBE	LD – Lance Brassage Équilibre LD – Lance Bubbling Equilibrium	
Bottom-blown	OBM or Q-BOP (Am.)	Oxygen Boden Maxhütte Quick Basic Oxygen Process	Oxygen via concentric bottom tuyeres, with cooling hydro carbon (gas/liquid) in outer slit
	LWS	Creusot Loire, Wendel Sidelor, Etablissements Sprunck	
Combined	K-BOP	Kawasaki Basic Oxygen Process	Oxygen via top-lance and bottom tuyeres

Example for the Mounting of Furnace Linings



Slopping is the general term used when, due to excessive foam growth, the foam cannot be contained within the steelmaking vessel. The foam will flow down the outer side of the vessel



Lance

Torpedo ladle for hot metal transfer



Hot Metal Addition to a Basic Oxygen Furnace (BOF)



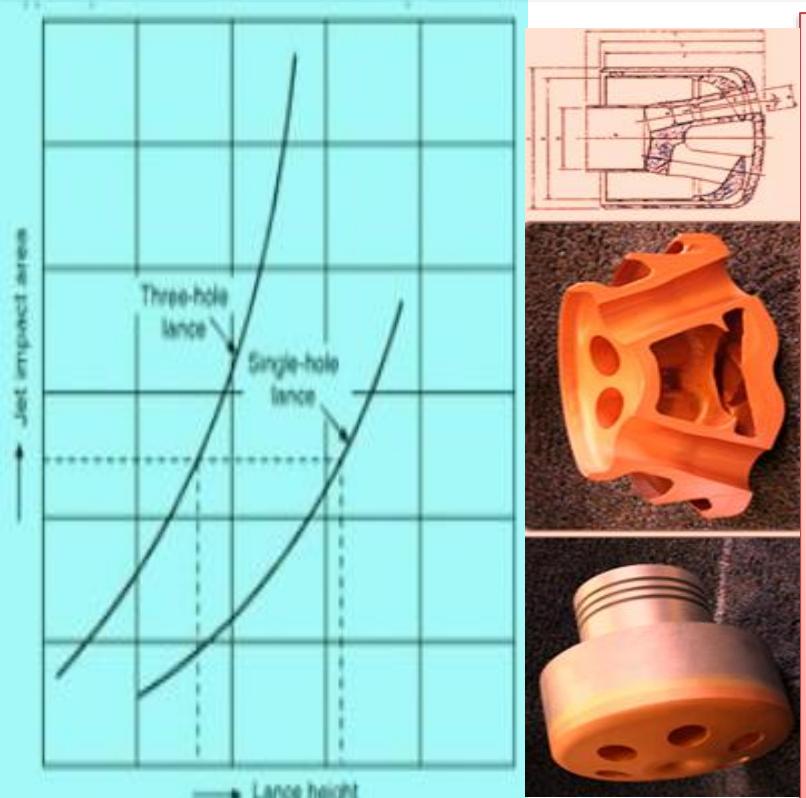
Basic Oxygen Steelmaking Event Times

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 blowing lance and lance tips in converter steel making

In the 1950s when the top blown converter size was limited to **50t maximum** then a **single hole lance** was being used for the oxygen blowing. With the passage of time the converter size went on increasing. This has necessitated increase **of number of holes in the lance for better distribution of oxygen over a larger surface of the bath in the converter**. Today 5-6 holes lances are very common. Even 8 holes lances are under use. The axes of each of the nozzles in a multi hole lance are typically inclined at around 10 deg with respect to the lance axes. Fig shows schematically the increase in jet impact area on the bath for a three holes lance when compared with a single hole lance.

Oxygen lance is subjected to the heating load in the converter from radiation, convection and conduction. It is subjected to continuous corrosion by high temperature slag and splashing. Further during the converter blowing molten slag particles gets solidified on the lance surface and sticks to the lance. These slag particles impact the transfer of heat to the lance.



Oxygen is blown in the converter through a water cooled lance with a convergent-divergent (CD) nozzle at high pressure (Around 11-14 bar) and at supersonic velocity (Mach >1). Supersonic jet of oxygen from the nozzle helps higher oxygen entrainment in the melt. During the blow, a three phase dispersion consisting of slag/metal droplets/gas bubbles is formed. The most important part of the lance is the nozzle. **The functions of the nozzle are:** i) Supply and distribution of oxygen, ii) To produce a gaseous jet, iii) To induce bath agitation, iv) To produce metal droplets

Oxygen lance is made up of two cylindrical pipes. The outer layer of lance carries the circulating cooling water while the inner layer carries the oxygen. The material for the lance pipe is seamless pipe of low carbon steel and thickness to withstand the pressure requirements in the lance.

Splashing from the injection of oxygen plays an important role in the kinetics of the process

In oxygen steelmaking, the metal droplets are generated due to impact of supersonic jets.

The supersonic jet strikes the metal surface and is deflected upwards. Then, with the **shearing action of the gas, metal droplets are torn from the cavity surface**. This phenomenon is generally referred to as “spitting” or “splashing”.

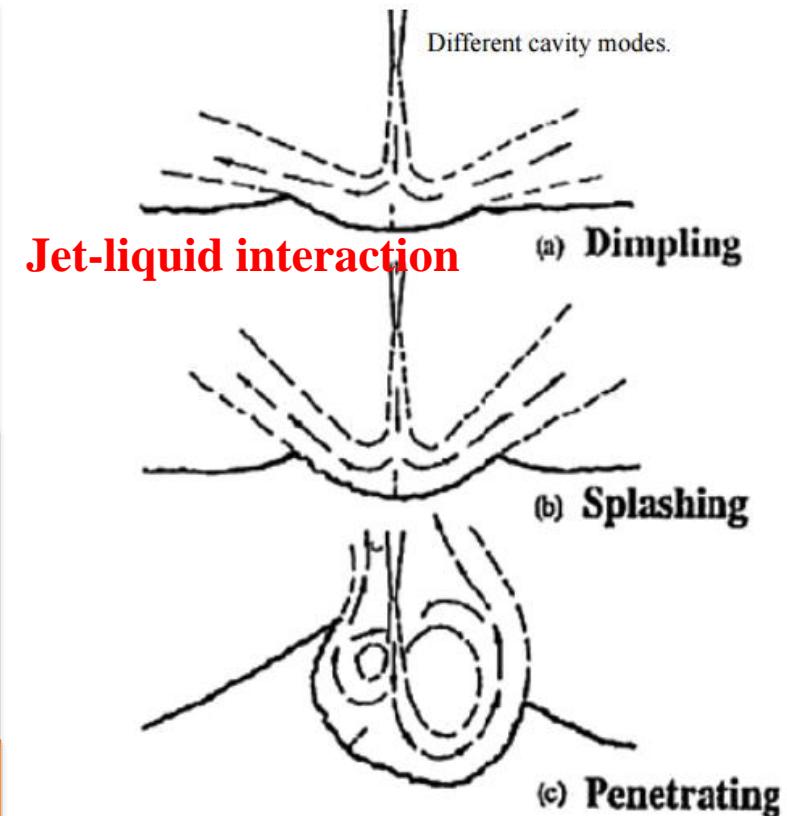
Many of the key reactions occur in the emulsion, which in turn is directly related to the **quantity of splash generated from the injection** and subsequent behaviour of the droplets in the emulsion.

Dimpling is termed as the cavity condition when there is a slight depression but no droplet formation.

Splashing, there is a shallow depression as well as large outwardly directed splash.

Penetrating mode, there is decrease in outward splash with much deeper cavity.

Three modes depending on the general appearance of cavity, change in sound of the bath and reduction of splash.



The metal droplets are generated as a result of the jet impact and the shearing action of the gas flow from the impact region when the jet strikes the metal surface, and the gases are deflected upwards.

The number of iron droplets splashed into the gas and the slag influences metallic yield, refractory wear, and the progress of decarburization.

A basic oxygen converter is a pear-like vessel with a concentrically positioned oxygen lance. The steel shell is suitably lined with basic refractories. Hot metal, scrap, fluxes and ferroalloys are charged into the converter through the throat. Oxygen (99.9% pure) is blown through a water-cooled lance fitted with a copper nozzle. The position of the lance with respect to the bath and the flow-rate of oxygen are automatically controlled. The impingement of the oxygen jets at supersonic speed on the molten iron bath, results in metal droplets being ejected from the bath by impact, thereby increasing the metal surface area and the rate of oxidation of the impurities like silicon, phosphorus, manganese and carbon which are all exothermic reactions. Right at the beginning of each heat, scrap is charged into the converter along with hot metal to act as coolant for the heat generated by the oxidation reactions. The process is very quick and the steel of required carbon content could be made in less than 60 minutes. The capacity of modern BOF may range from 100 tonnes to 400 tonnes.

The charge for an oxygen converter melt is composed of hot metal, steel scrap, lime, fluorspar, etc. The proportion of blast furnace hot metal may range from 70–100%. The silicon content in the hot metal should be low, otherwise more lime will be necessary to neutralise the silicon and slag volume will become large. In some plants, blast furnace hot metal is first de-siliconised by oxygen lancing and then the low silicon hot metal is charged into the converter. Major part of the lime is added before starting the blow. Fluorspar is used to accelerate the dissolution of lime and ensure the required fluidity of the slag. Steel scrap is used to chill the bath. The pieces of steel scrap to be charged into the vessel should be suitably sized to ensure quick melting and also to avoid deflecting the oxygen jet. The proportion of steel scrap in the charge may be up to 30%. Optionally, iron ore and mill scale is also used in limited quantities to chill overheated bath. However, the gangue content of the iron ore should be low.

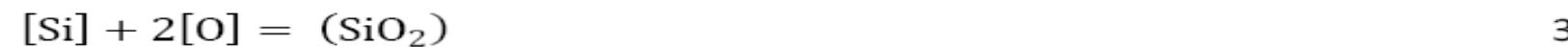
The blown metal needs to be deoxidised. Ferromanganese, ferrosilicon and aluminum are added in the order indicated into the ladle during tapping the steel.

- The BOF process is autogenous, or self sufficient in energy, converts liquid iron (hot metal) into steel using gaseous oxygen (O_2) to oxidize the unwanted impurities in hot metal (HM). The O_2 used must be of high purity, usually 99.5% minimum, otherwise the steel may absorb harmful nitrogen (N_2).
- The primary raw materials for the BOF are generally HM (around 80 % or more) from the blast furnace and the remaining steel scrap. These are charged into the BOF vessel. O_2 is blown into the BOF at supersonic velocities. It oxidizes the carbon (C) and silicon (Si) contained in the HM liberating great quantities of heat which melts the scrap. There are lesser energy contributions from the oxidation of iron(Fe), manganese (Mn), and phosphorus (P).
- The flux used in this process is primarily calcined lime (with CaO content of more than 92 %). This lime is produced by the calcining of limestone with low silica (SiO_2) content. The post combustion of carbon monoxide (CO) as it exits the converter also transmits heat back to the bath. The product of the BOF is liquid steel with a specified chemical analysis at a temperature of around 1650 deg C.
- The term ‘basic’ refers to the refractory linings of the furnace which are made of alkaline materials (dolomite and magnesite). Refractory linings must have specific properties to withstand high temperatures, the corrosive action of the highly oxidized and basic slags, and abrasion during charging and blowing. Basic slags are required to remove P and sulphur (S) from the liquid charge.

- The BOF vessel also known as converter, is simply a barrel/pear shaped steel shell with a refractory lining and supported on a tilting mechanism. **The ratio between the height (H) and diameter (D) of the converter is in the range of 1.0 to 1.3.** The converter shell consists of three parts namely (i) spherical bottom, (ii) cylindrical shell, and (iii) upper cone. The converter shell is attached to a supporting ring equipped with trunnions. The supporting ring provides stable position of the converter during O₂ blowing.
- The converter is capable to rotate in a vertical plane about its horizontal axis of 360 degrees on trunnions driven by electric motors and can be held in any position. This rotation (tilting) is necessary for various converter operations during a heat. Only 8 % to 12 % of the converter volume is filled with the liquid steel after a heat is made. The bath depth is about 1.2-1.9 m.
- Capacity (heat size) of a BOF converter ranges from 30 tons to 400 tons, but most of the converters are in the range of 100 -250 tons range. A BOF steel melting shop normally have one to three converters. The tap to tap time for a BOF heat is around 40 – 50 minutes, of which 50 % is the O₂ blowing time. This rate of production made the process compatible with the continuous casting of liquid steels.
- The top blown converter is equipped with the O₂ lance for blowing O₂ into the bath. The lance is water cooled with a multi hole (ranging from 3 to 6) copper (Cu) tip. O₂ flow is normally in the range of around 6 to 8 cum/min.t. The O₂ pressure is usually in the range of around 12 to 16 atmosphere.

Principle chemical reactions

Hot metal contains C ~ 3.5 to 4%, Si ~ 0.6 to 1%, Mn ~ 0.6 to 0.8% and P ~ 0.1 to 0.2%. Oxygen is blown from top and the following reactions occur:



• No heat is supplied from outside. The heat produced due to chemical reactions is sufficient enough to raise the temperature of hot metal from around 1250°C to 1300°C to molten steel tapping temperature of 1600°C to 1650°C.

• Except carbon which is removed as a gaseous phase rest all other elements form slag. Slag formation of desired chemistry and physico-chemical properties is vital for the successful operation of converter steelmaking technology.

• Typically converter steelmaking technology allows to tap liquid steel in approximately every 50 to 60 minutes with specified steel chemistry and 500-1000ppm dissolved oxygen.

• Typically oxygen blowing time is independent of converter capacity i.e. O₂ is blown for 15 to 20 minutes irrespective of the converter capacity.

- The energy required to raise the fluxes, scrap and hot metal to steelmaking temperatures is provided by oxidation of various elements in the charge materials.
- Both the high temperatures of the liquid pig iron and the intense stirring provided when the oxygen jet is introduced, contribute to the fast oxidation (burning or combustion) of these elements and a resultant rapid, large energy release.
- Silicon, manganese, iron and phosphorous 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. Carbon, when oxidized, leaves the process in gaseous form, principally as carbon monoxide.
- During the blow, the slag, reaction gases and steel (as tiny droplets) make up a foamy emulsion. The large surface area of the steel droplets, in contact with the slag, at high temperatures and vigorous stirring, 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 the slag with flux additions.

- Lance is used in the converter for blowing the oxygen at a **high pressure (42 kgf/cm²)** so as to form an emulsion on the surface of the metal which increases the surface area to an extent; the separation of impurities takes place very fast, thus giving the process unique distinction i.e. a very fast process for the steel making.

- As blowing begins, an ear-piercing shriek is heard. This is soon muffled as silicon from the hot metal is oxidized forming silica, SiO₂, which reacts with the basic fluxes to form a gassy molten slag that envelops the lance.

- The gas is primarily carbon monoxide (CO) from the carbon in the hot metal. The rate of gas evolution is many times the volume of the vessel and it is common to see slag slopping over the lip of the vessel, especially if the slag is too viscous.

- Blowing continues for a predetermined time based on the metallic charge chemistry and the melt specification. This is typically 15 to 20 minutes, and the lance is generally preprogrammed to move to different heights during the blowing period.

- The lance is then raised so that the vessel can be turned down towards the charging aisle for sampling and temperature tests.

- Furthermore, below 0.2% C, the highly exothermic oxidation of iron takes place to a variable degree along with decarburization. The "drop" in the flame at the mouth of the vessel signals low carbon, but temperature at turndown can be off by +/- 100°F.

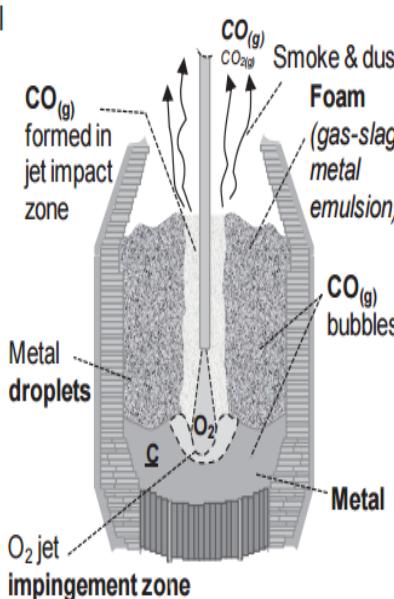
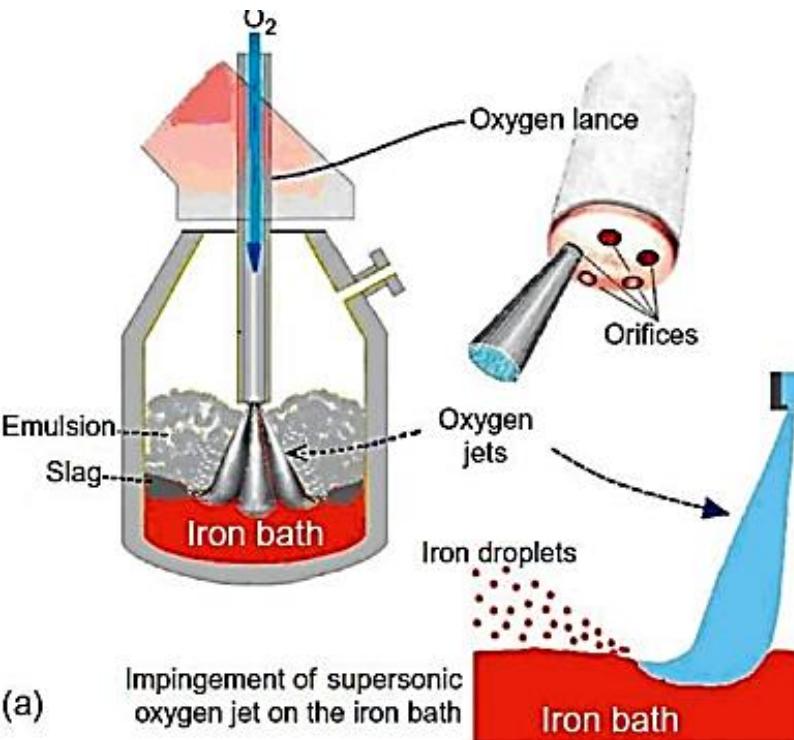
FOAMING IN THE LD PROCESS

A distinctive characteristic of the LD process is the formation of a **multi-phased foam, consisting of liquid slag, metal droplets, solid “second phase” particles such as undissolved fluxes and process gases**. This is because:

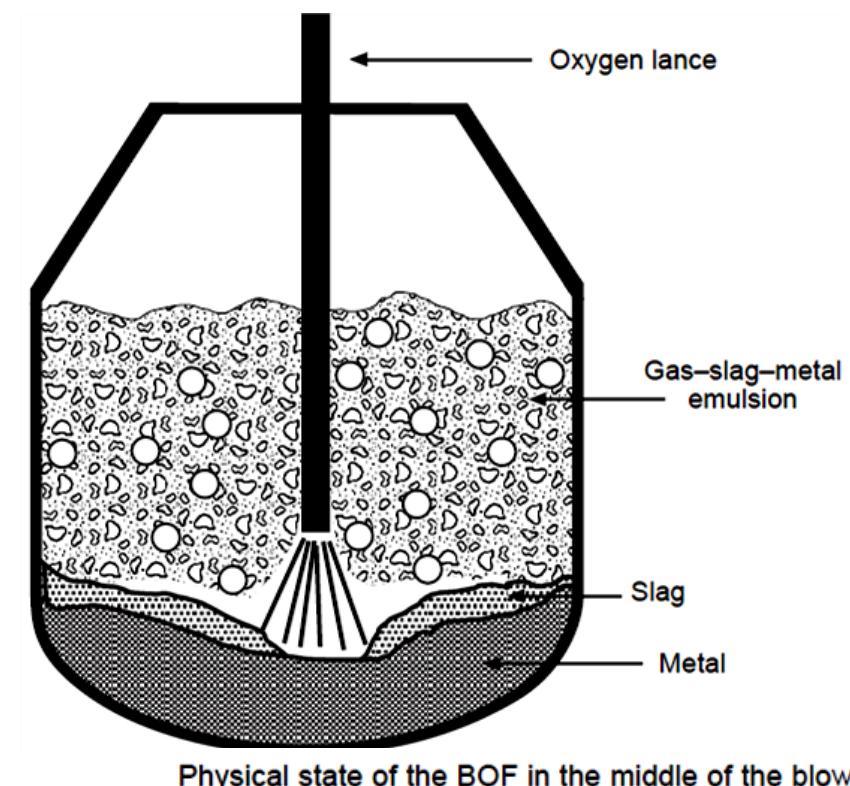
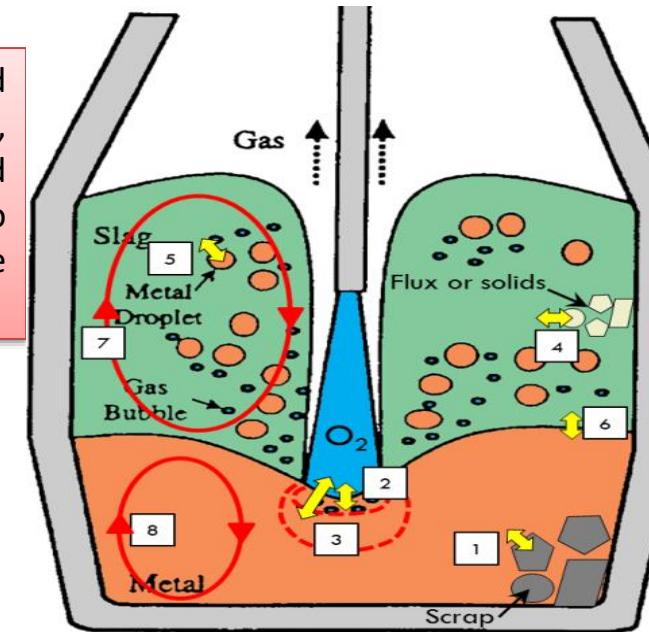
- i. the high-velocity oxygen jet impinges the melt, ejecting a considerable part of the melt in the form of metal droplets into the upper part of the vessel;
- ii. the lumpy fluxes are added in batches, resulting in a slow flux dissolution, and hence **a slow liquid slag formation**;
- iii. the liquid slag, undissolved fluxes and metal droplets form a more or less viscous emulsion, **intercepting the process gases on the way up towards the vessel mouth**;
- iv. **a large portion of the process gases is formed within the emulsion itself due to the reaction between the carbon in metal droplets and iron oxide** in the liquid slag.

basic principle of LD process is vertical high-velocity (super-sonic) blowing of pure oxygen via a water-cooled lance against the metal bath in order to oxidize the carbon. As in all BOS processes, the ferrous charge mainly consists of liquid hot metal and scrapped steel. The carbon in the charge will primarily form carbon monoxide gas, which exits through the vessel opening (mouth), after which

some degree of post combustion to carbon dioxide gas may occur.



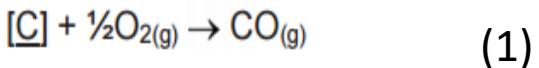
Fluxes are minerals added early in the oxygen blow, to control sulfur and phosphorous and to control erosion of the furnace refractory lining.



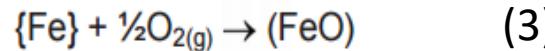
Foam index, is ratio between foam volume and gas flow rate [or foam height (cm)/superficial gas velocity (cm/s)]. **Gas generation rate plays a vital part in the formation and growth of the foam.** The gas is a product of the decarburization process .

Foam index: Measure of the time it takes for the process gases to vertically pass through foam. Higher the apparent viscosity of emulsion, the higher the foam index.

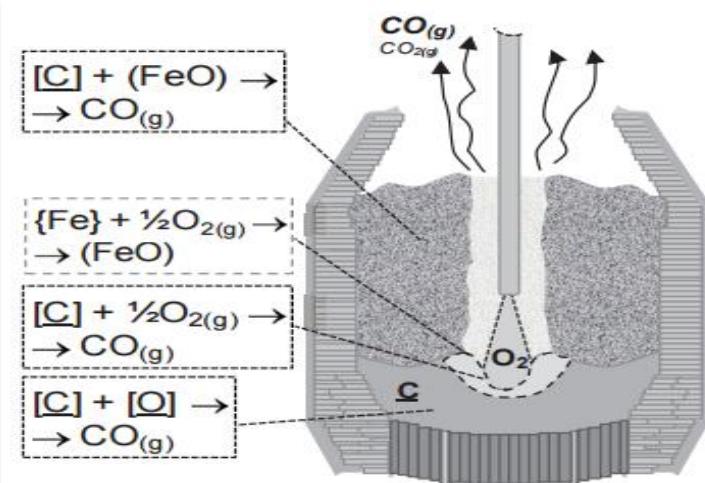
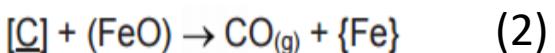
by direct oxidation at the metal surface in the hot spot:



where the (FeO) is a product of oxidation of iron by pure oxygen:



in the foam, indirect by iron oxide reacting with metal droplets: in the melt, by reaction between dissolved oxygen and carbon:



Decarburization (1), iron oxidation (3), will begin immediately and continue throughout the blow, although in the first case with a diminishing pace, due to the continuous decrease in carbon content at the metal surface. The rate of iron oxidation is more constant, but the resulting iron oxide content of the slag will eventually decrease due to an increased consumption according to reaction (2). At the end of the blowing period the iron oxide content in the slag will start to increase again as the participation of iron oxide in the decarburization process is reduced due to the low carbon content of the melt. At the very end of the blow the controlling decarburization reaction is the one in the melt between carbon and dissolved oxygen according to reaction (4). Therefore, the decarburization rate at the end of the blow will be dependent on mass transfer of carbon from the lower to the upper part of the melt and of dissolved oxygen in the opposite direction.

During the oxygen blow

The following observations can be made:

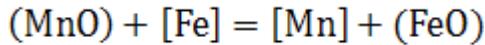
- Impurities like C, Si, Mn begin to oxidize simultaneously.
- Si and Mn oxidize faster relative to C. Also Fe oxidizes to FeO. Rate of carbon removal is low in the beginning.

Dissolution of lime increases during the blow. In the initial periods FeO helps lime dissolution.

Formation of basic and limy slag promotes removal of P. It may be noted that once slag is formed both C and P removal occur simultaneously.

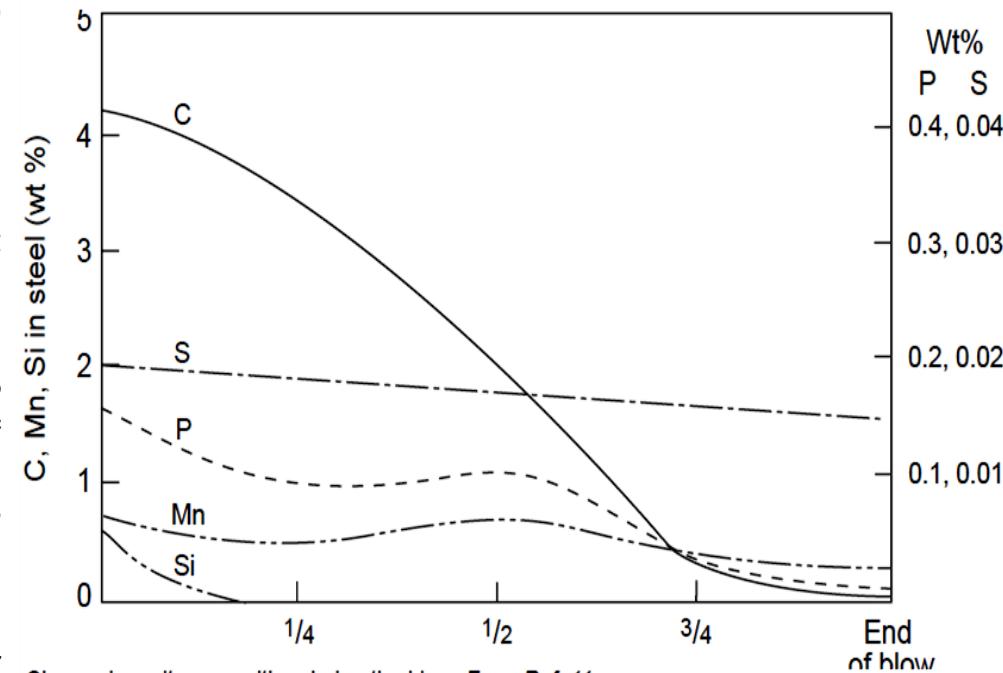
- In the initial stages, carbon removal rate is kept lower than P removal since P removal is favored at lower temperatures. If carbon is removed at a faster rate in the beginning bath temperature would increase which impedes dephosphorization. Once phosphorus removal is complete, carbon removal rate can be increased.

Note that Mn content of metal decreases initially but at later periods of blow Mn content of bath increases. This is due to the onset of the following reaction:



In the later stages of the blow bath temperature increases due to decrease in carbon content and at the same time FeO content of slag decreases. Both conditions are responsible for increase in Mn content of the bath. To overcome, sometimes iron ore additions are made to increase the FeO content of slag to adjust the Mn content of steel.

- Temperature of the bath increases continuously.



Change in melt composition during the blow. From Ref. 11.

Example of Oxygen Batches in a BOF.

Batch N°	Lance Height, in	Oxygen Vol., Nm ³	Purpose
1	150	850	Initiate oxidizing, heat generating reactions without touching solid scrap charge
2	120	1700	Increase reaction rates and control slag formation
3	90	11650	Promote optimum carbon removal rate and proper slag for the other reactions

During the beginning of the blow, the lance is kept high above the surface of the metal. During the first 3-4 minutes silicon from the metal rapidly oxidizes together with iron forming a slag rich in FeO and SiO₂. Significant amounts of lime and dolomitic lime are added into the furnace.

As the blow continues, solid lime continuously dissolves into the liquid slag increasing the slag mass and basicity. As decarburization continues, the slag starts to foam and the CO gas generated reduces the FeO content in the slag. Close to the end of the blow, the decarburization rate decreases and iron oxidation becomes significant again. Throughout the blow the metal temperature steadily increases from 1350°C to 1650°C and the slag temperature is usually 50°C higher than the metal at the end of the blow.

The blow of oxygen creates a three phase gas-slag-metal emulsion, which drastically increases the total interfacial area available for several chemical reactions to occur between the phases.

Metal droplets are continuously ejected from the bulk metal bath into the slag-gas mixture where they can react for a given amount of time. The generation and behavior of these metal droplets is important for refining processes

During periods of intense mass transfer of surface-active elements, such as oxygen, spontaneous emulsification can occur due to a very pronounced reduction in the interfacial tension between metal-slag systems.

In a normal LD operation the vessel is first charged with an appropriate quantity of scrap followed by lime and the hot unrefined metal is poured in. **The addition of lime is necessary as a neutralising medium, since the thermo-dynamics of the system are such that silicon will be one of the first elements oxidised and thus, without the presence of lime, an acidic slag would be produced in the initial stages of the conversion.** An acidic slag would result in serious damage to the basic lining of the converter. Oxygen is blown on to the melt surface at supersonic speeds (up to twice the velocity of sound at the nozzle) from a lance sited above the melt. It is important to avoid deep penetration of the bath by the oxygen jet, and multihole lances (3-8 holes) have been developed to produce a reasonable degree of uniformity over a large surface area.

When oxygen blowing is commenced, elements such as silicon and manganese rapidly form oxides, which flux with the lime, but the sulphur and phosphorus present in the melt are not removed until a later stage in the conversion. **The critical factor in the refining process is the oxidation of the carbon to form carbon monoxide.** This reaction is effectively the driving mechanism for the refining process since it is exothermic and sufficient thermal energy is generated to permit the oxidation process to self-propagate without additional external heating.

Flexible control of the blowing conditions (by control of lance position and oxygen consumption) is essential to maintain a suitably active and fluid slag during the period of rapid carbon removal. This reduces the problem arising from slag ejection and from metal build-up on the oxygen lance.

- In steelmaking, the impurities like carbon, silicon, manganese, phosphorus and sulphur are removed from hot metal through a combination of gas/metal, gas/slag and gas/metal/slag reactions to produce steel of desired chemistry and cleanliness (cleanliness refers to the inclusions). **Science of steelmaking involves equilibrium concentration of an impurity between the phases and the rate of transfer of an impurity from the hot metal.**

In the integrated steel plants, 130-200 kg slag is generated from Basic Oxygen furnace (BOF) per tonne of crude steel produced.

•The phases in steelmaking are hot metal, molten slag and gas. Hot metal is a multi-component solution in which impurities like carbon, silicon, manganese, phosphorus and sulphur are dissolved in very low amount (total concentration of all the impurities is approximately 5% to 6%) in iron. Slag is a solution of predominantly oxides with small amounts of sulphides, phosphides, silicates etc.

During the beginning of the oxygen blow, fluxes are added to promote phosphorus, sulfur and refractory erosion control. These fluxes are rich in CaO and MgO and the two most used are burnt lime and dolomitic lime. CaO is mainly added to aid sulfur and phosphorus control and MgO is responsible for saturating the slag to minimize refractory erosion. The dissolution of these fluxes, the oxidation of iron, manganese, sulfur and phosphorus results in highly basic slag.

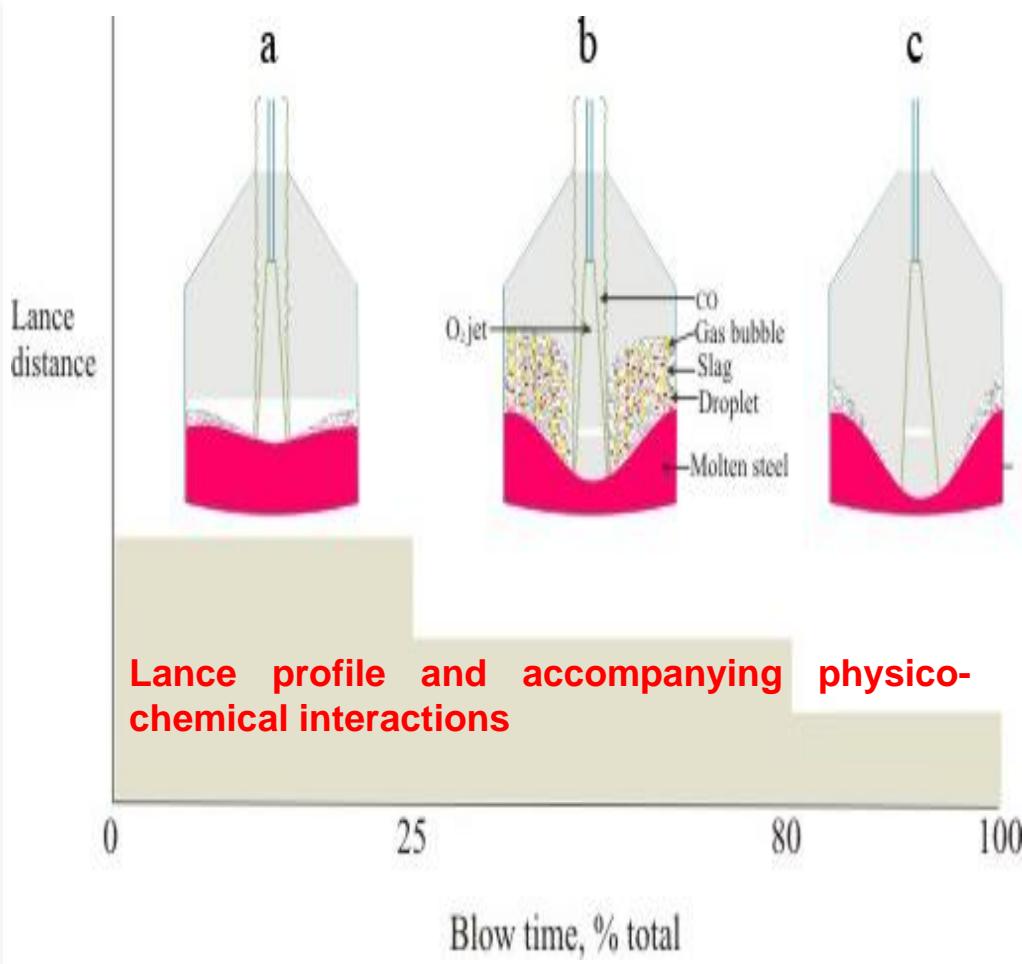
The use of scrap simultaneously imports tramp and alloying elements into the steelmaking.

Lime is not pure CaO. It contains impurities such as SiO₂ and Al₂O₃ which must be compensated for addition calculations. Also, its metallurgical efficiency is affected by the particle size and reactivity (or degree of burning). The normal particle size is 8 mm to 40 mm, as particles <6 mm are extracted from the converter, together with waste gas; up to 30 % in some cases. Since a large amount of calcined lime is charged into the converter within a short period of time, careful selection of the lime quality is important to improve its dissolution in the slag and to cope up with the speed of reactions. (Size, SiO₂ content etc), porosity (hygroscopic), reactivity)

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.
- Another flux addition sometimes used in high carbon heats is fluorspar (CaF_2 , or spar). This mineral is charged to dissolve the lime and to reduce the viscosity of the slag. It is used for making high carbon heats, (>0.30% C at the end of blow) because the iron oxide concentrations are low on these heats. Iron oxides help dissolve lime in lower carbon heats but these oxides are present in low concentrations in high carbon heats.
- To compensate for less FeO, use spar to dissolve the lime. However, spar is used very sparingly because it is very corrosive on refractory linings.
- Unfortunately there is no corrosion inhibiting practice or ingredient to stop the corrosive effects of spar. In addition, spar forms hydrofluoric acids in the gas cleaning system that seriously corrode any metal surfaces in the hood and cleaning systems.

- ✓ We note that at higher lance distance, oxygen jet penetration into bath is shallow and slag formation occurs. **(a)**
- ✓ As the lance distance is decreased, jet penetrates deep into the bath, carbon reaction commences, CO forms, droplets are produced which together leads to the formation of a three phase dispersion consisting of gas bubbles/slag/metal droplets **(b and c)**.
- ✓ In this state of blow, both carbon and phosphorus removal occur at a faster rate. Formation of three phase dispersion is a characteristic feature of the top blown steelmaking. Three phase dispersion creates conditions for faster removal rates of C and P. Foaming of slag has to be controlled to avoid expulsion of slag, which can be controlled by controlling C reaction with FeO in slag. Reaction between C and FeO of slag in slag will not allow CO bubbles to grow.
- ✓ Smaller size gas bubbles can be trapped easily in slag as compared to larger sizes. Slag may foam and may be expelled from the converter.



- Shallow jet penetration as obtained at **higher lance distance** is a “soft jet” as compared to deep penetrating jet as obtained at **lower distance** and is termed “hard jet”.
- Thus method of oxygen supply in converter steelmaking practice i.e. through “free jet” is very effective in terms of physico-chemical reactions.

Soft Jet	Hard Jet
<ul style="list-style-type: none"> • Oxidation of Fe • Shallow penetration • Slag/metal reaction • Slag formation is promoted. P removal is enhanced <p>Too long duration of soft let will promote sloping of slag due to overoxidation</p>	<ul style="list-style-type: none"> • O₂ available deep in bath • C oxidation is favoured. P removal is impaired • CO evolution occurs deep into bath and its escape through the bath agitates the bath • Droplets are produced which are then emulsified in the slag

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.

Physico-chemical interactions of molten bath with oxygen jet depends on the lance profile i.e. change of lance height during the blow. The lance profile is specific to each converter and depends on converter profile, hot metal composition, oxygen flow rate, hot metal chemistry and steel of desired composition.

Nevertheless, in all converters initial lance distance is such as to promote iron oxidation so that dissolution of CaO commences. The idea is to create a basic and limy slag at the early part of the blow to onset dephosphorization. Shallow jet penetration covers the larger bath surface and is favorable more for iron and silicon oxidation. Small amount of carbon may be removed. Once slag is formed, lance is lowered. Oxygen jet penetrates into the bath and carbon reaction favours because oxygen is available now deep into the bath. At the same time, force of the oxygen jet creates metal droplets and as a consequence three phase dispersion of gas/slag /metal droplets are formed which enhance the rate of decarburization.

Refining of hot metal

After the previous heat is tapped and slag is drained, lining is inspected. Scrap and hot metal are charged. Converter is tilted into the vertical position and the lance is lowered in the vessel to start the blowing. Selection of the starting lance distance is such that the concentration of the force at the bath level should not cause ejection of tiny iron particles (sparking) and at the same time maximum bath surface area is covered by the oxygen jet. **The starting lance (X_i) for specific oxygen blowing rate**

$$X_i = 0.541(d_b)^{1.04}$$

d_b is bath diameter in meter. For 150 Tons converter, $d_b = 4.87$ m and $X_i = 2.8$ m, when oxygen flow rate is approximately $450 \text{ Nm}^3/\text{min}$.

Initially oxygen is blown soft by keeping lance distance higher to promote slag formation and to avoid ejection of small particles, because hot metal is not covered by slag. Lime may be added either at the beginning of the blow or in portion during the blow. Oxygen is blown for nearly 15-20 minutes by progressively decreasing the lance distance such that slag foaming remains under control and oxidation reactions occur uninterruptedly. Slag and metal samples are analyzed.

Top blowing attributes

- Energetic supply of oxygen
- Control of slag formation
- Control of oxygen distribution.
- Simultaneous removal of C and P.
- Inadequate stirring of slag /metal phases.

In bottom blown steelmaking, all oxygen is injected through the bottom tuyeres. Though this technology provides efficient bath stirring and enhanced carbon removal, but it is difficult to distribute oxygen within the bath and also to control slag formation. As compared with top blowing, bottom blowing changes somewhat the course of reaction of carbon, manganese, phosphorous oxidation, resulting in a different degree of oxidation of bath.

Bottom blowing increases sharply the intensity of bath stirring and increases the gas/metal area by 10-20 times the values of typical of top blowing. Rate of decarburization is higher than that of top blowing.

As in top blowing the intensity of decarburization at higher concentration of carbon is determined by the rate of supply of the oxidant. With a carbon content of less than 0.1% in bath, mass transfers become rate controlling which favours iron oxidation. Since bottom blowing provides favourable conditions for decarburization reaction, the metal and slag have a lower degree of oxidation.

For example, concentration of FeO in slag is not less than 15-25% during the entire blow in top blown steel-making and increases even more by the end of blowing, whereas in the bottom blown converter process it does not exceed 5-7% and raises up to 15-25% at low concentration of carbon. Since the slag in bottom blown converter has a low degree of oxidation at most during the whole operation, condition are unfavourable for dephosphorization reaction. Only toward the end phosphorous removal occurs.

- Since the slag in the bottom blown converter oxidizes much less than in the top blowing, concentration of Mn in steel is higher in the course of a heat.
- The advantages of pure top and pure bottom are coupled and a new technology is developed under the name combined top blowing of oxygen and bottom stirring. The advantages of such a technology when compared with pure top blowing like reduced FeO content of slag and O content of steel etc. are obvious. Several process technologies for combined blowing were developed under different names. These technologies differ in
 - Amount of inert gas Type, number and arrangement of bottom tuyeres and porous plugs.

The most important development in top blown steelmaking practice is the simultaneous gas stirring of the bath from the bottom of the converter. This has resulted in combination blowing processes. These processes differ in terms of bottom gas rate, number and arrangement of bottom tuyeres and type of bottom injection elements and whether inert/oxidizing gas is used.

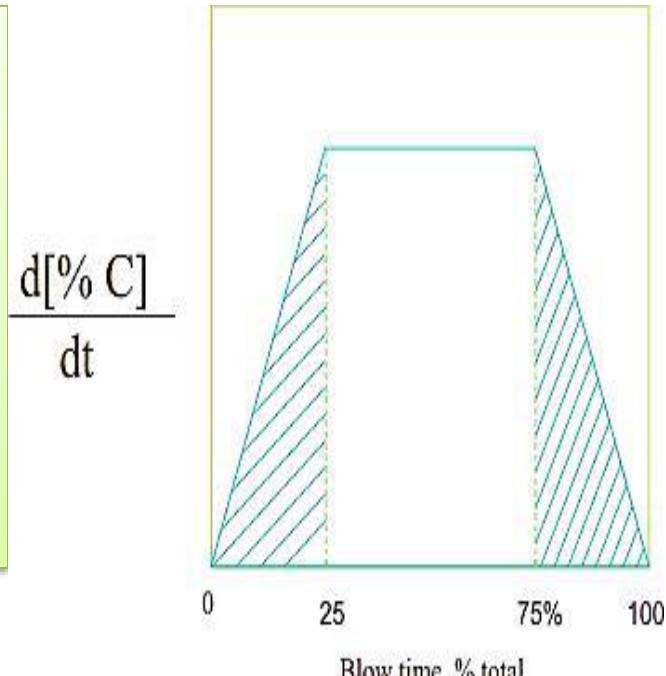
All processes which use top blowing of oxygen and bottom stirring by inert gas is known as bath stirred top blown processes. In another type, oxygen is blown from top and bottom and is called top and bottom blowing processes.

Concept of bottom stirring in top blowing

In pure top blown steelmaking, bath agitation is very weak particularly during the initial and final stages of the blow. In the initial stages Si and Mn removal delays carbon removal whereas in the final stages carbon removal rate decreases.

Rate of carbon removal with time of blow

- ✓ In the hatched regions, CO evolution in the bath is very low in pure top blown steelmaking; jet could not produce adequate bath stirring.
- ✓ **Evolution of CO is the principal cause of bath agitation.** Both in initial periods (silicon oxidation period) and in final periods (where rate of carbon removal is mass transfer controlled), evolution of CO is low.
- ✓ Slag analysis reveals higher rate of oxidation of Fe to FeO in both the periods which is due to weak stirring in the bath. In main part of the blow higher carbon removal rate produces higher amount of CO and produces enough bath stirring.
- ✓ It is considered appropriate to introduce bottom stirring gas in a top blowing converter to stir the bath.



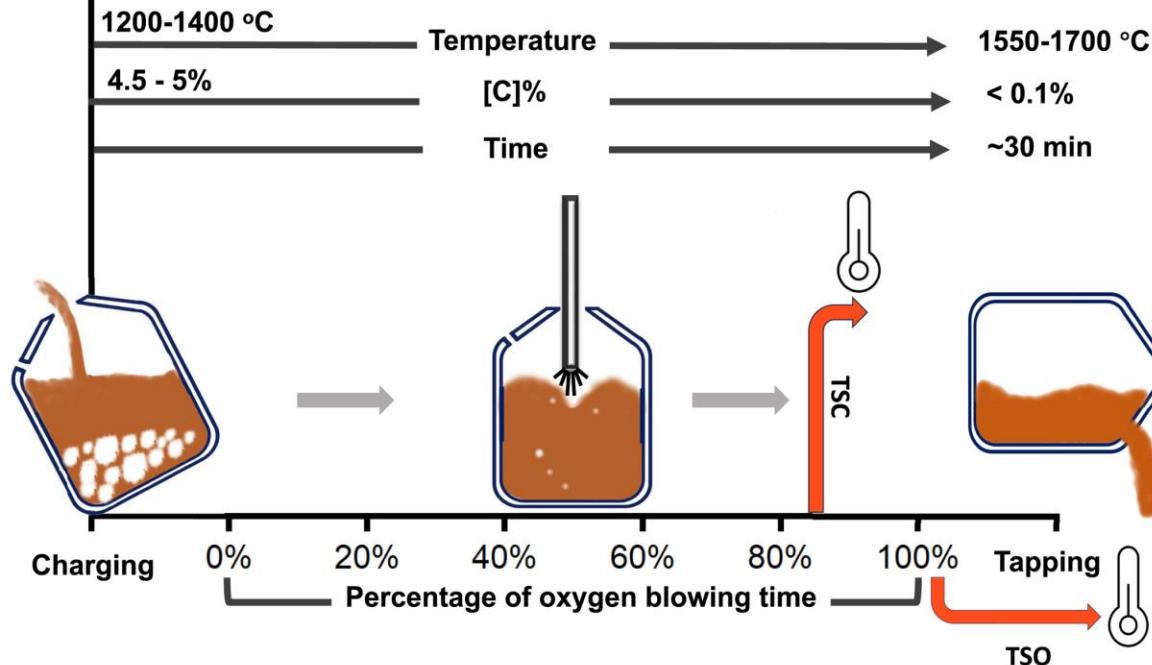
Bottom-blown basic vessels proved to be unsustainable due to the rapid deterioration of the refractory tuyere caused by the high temperatures attained during the process. On the other hand, blowing oxygen from the top was found to produce steel with high chemical and thermal efficiency

Slag formation, droplet formation, mass transfer, heat transfer and parallel chemical reactions are examples of key operational factors in the BOF

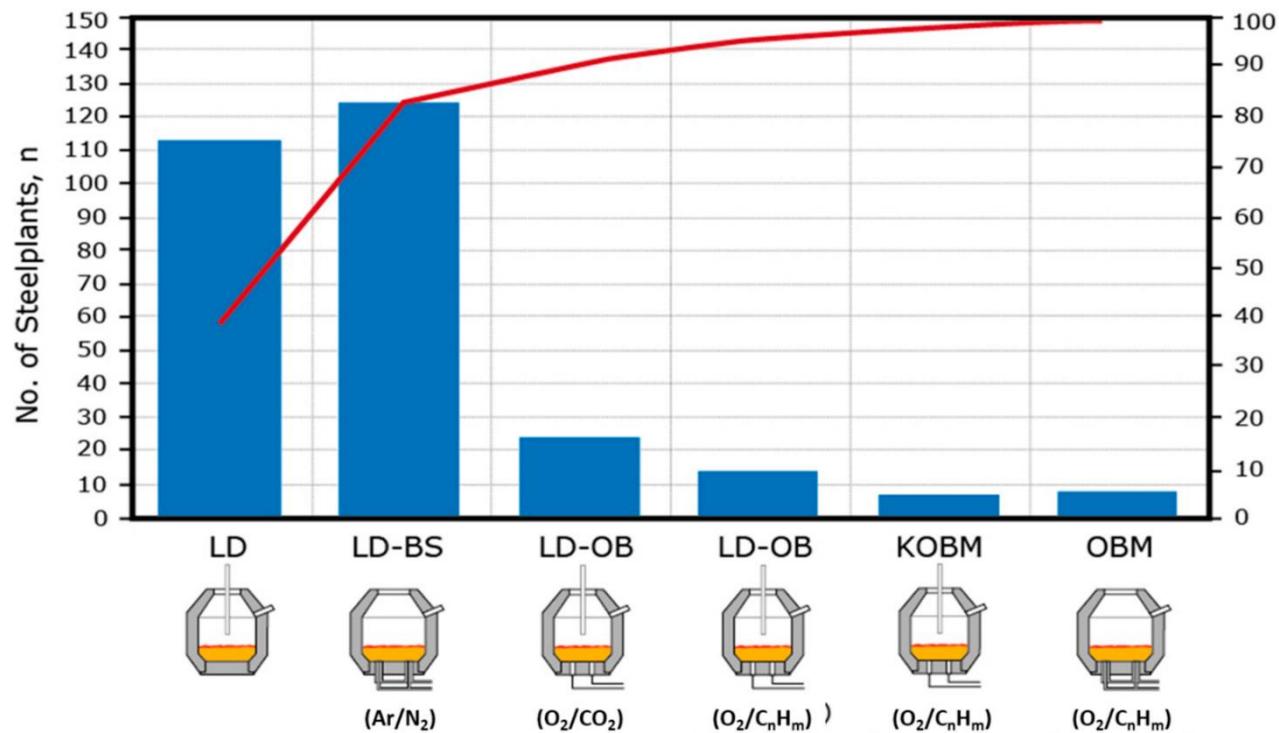
The rate of refining, during oxygen steelmaking, is not only a function of the chemical kinetics but also a function of the residence time that a given metal droplet spends in the slag.

Metal drops can be as small as a few tens or several hundreds of micrometers. As metal drops get smaller, they behave differently and changes in interfacial area can be dramatically higher

An emulsion is a mixture of two fluids (liquid or gas) that are immiscible. If two immiscible liquids are at thermodynamic equilibrium, the interfacial area and the system free energy are at a minimum. In this case, in order to promote emulsification, energy has to be supplied to the system and the emulsified state is not thermodynamically stable. However, if two immiscible liquids that are not initially at equilibrium are brought into contact, dynamic interfacial phenomena caused by temporary interfacial instabilities can promote the spontaneous emulsification of the system without external stirring



temperature sampling carbon (TSC), occurs between 80% and 90% of the oxygen blowing time, and the second sub-lance sampling, end-blown sampling—temperature sampling oxygen (TSO), occurs at the end of the blowing time.



In order to make steel from pig-iron, the following operations must be carried out.

- The carbon level must be reduced considerably and manipulated to a very tight specification.
- The levels of manganese and silicon need to be adjusted. Both must usually be reduced, but in some cases the manganese levels need to be increased.
- Deleterious impurities such as sulphur, phosphorus, hydrogen, and nitrogen need to be removed.
- Various metal alloying elements may need to be added.
- Oxygen may need to be removed. Oxygen is used extensively in steelmaking, and the level of oxygen in the metal at the end of these operations may be significant. When this happens, steps must be taken to reduce these levels in an operation known as **deoxidation**.

Elements	Concentration (%)	Positive aspects	Negative aspects
Al	0.95-1.30	Produces finer grains and improves toughness	
B	0.001-0.003	Added to small quantities to have a hardening effect	Lowers forging quality
C	0.003-0.42	Improves hardenability and strength	Reduces ductility, forgeability and machinability
Cr	0.5-18	Improves hardenability, strength, response to heat treatment and wear resistance	
Co	14 max	Strength and hardness at high temperatures and magnetic permeability	
Cu	0.1-0.4	Precipitation hardening properties and increase corrosion resistance.	
Mn	0.25-13	Improves hardenability, and wear resistance. Also increases machinability in combination with sulphur	Decreases ductility and may cause embrittlement at high conc. At too low conc. it may promote porosity and cracking
Mo	0.2-5.0	Increases hardenability and strength, particularly at high temperatures. Improves corrosion resistance and creep strength	
Ni	2-20	Increases strength, impact strength and toughness, corrosion resistance and hardenability	
P	0.03-0.10	Increases the tensile strength of steel along with improving machinability and corrosion resistance	May cause embrittlement at higher conc. and decrease toughness
S	0.08-0.35	Improves machinability	Lowers ductility, reduces toughness
Si	0.2-1	Improves strength and hardness and facilitates good galvanized layer formation	decreases ductility and may induce cracking
Ti	0.25-0.60	Improves both strength, toughness and corrosion and heat resistance	
V	0-0.15	Increase strength at high temperatures and ductility can be retained. Increases hardenability, fracture toughness, wear resistance and fatigue resistance	may cause embrittlement during thermal stress relief treatments

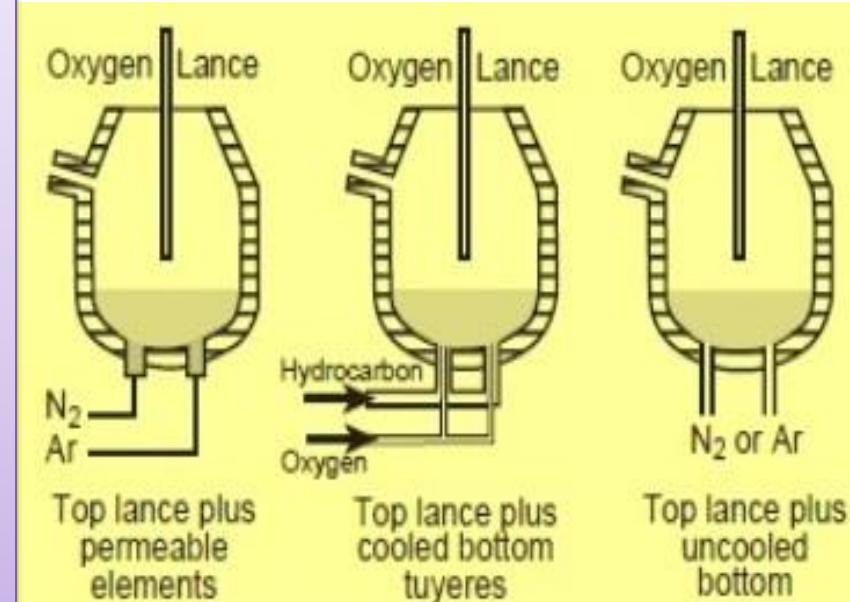
Combined blowing process in converter steel making

Inhomogeneities in chemical composition and temperature are created in the melt during the oxygen blow in the top blown converters due to the lack of the mixing in the metal bath. There is a relatively dead zone directly under the jet cavity in the converter.

The first combined blowing practice LBE (Lance Bubbling Equilibrium) is much more closely related to the BOF process in that all the oxygen is supplied from the top lance. The combined blowing aspect is achieved by a set of porous elements installed in the bottom of the converter through which argon or nitrogen is blown. In LBE process the nitrogen gas is typically used almost exclusively for blow in the range of 3 -11 N Cum/min. However in the later part of the blow when nitrogen absorption can create a problem, argon gas is used for stirring. In addition, argon is used almost exclusively as the inert gas for post blow stirring, at this time the rate is increased to 10-17 N Cum/min.

In the combined steel making process oxygen, required to refine the steel, is blown through the top mounted lance while the inert gas needed for improving the mixing of the metal bath is blown through the bottom mounted tuyeres or permeable elements.

Stirring is performed with nitrogen gas in the high carbon range of the melt in the bath and with argon gas once lower carbon levels have been reached. The bottom flow rates are normally lower than 0.2 N Cum/t minute. In typical practice nitrogen gas is introduced through the bottom 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 the CO gas in the first part of the oxygen flow prevents nitrogen pick up in the steel.



The advantages of combined blowing over top blowing in an LD converter are:

Acceleration of blowing cycle

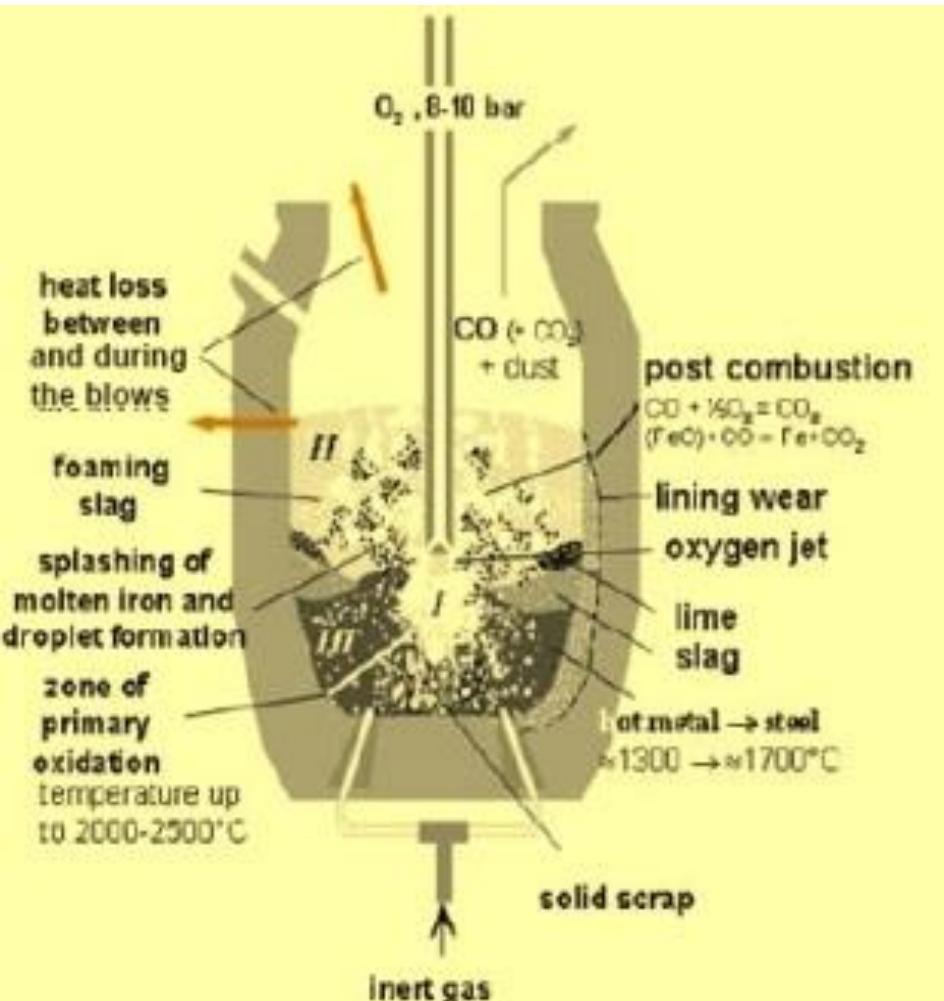
Higher yield

Less FeO in the slag

Improved converter lining life

Increased accuracy in achieving specific composition

Reduced splashing and spitting



Metallurgical effects of combined blowing

The following are the effects of the bottom stirring in the combined blowing process

Decreased FeO content in the slag – Better mixing conditions in the converter makes FeO content in the slag closer to the equilibrium conditions which results into lower percentage of FeO in the slag. It has been experienced in many plants that during production of low carbon heats, FeO levels in the slag have been reduced by around 5 %. This in turn results into better metallic yield, lower FeO level in the ladle slag and reduced slag attack on the refractories. Around 1.5 % of improvement in iron yield has been reported by many plants.

Reduced dissolved oxygen in the metal – It has been reported that bottom stirring can reduce the dissolved oxygen level in a low carbon heat by around 225 ppm. Lower oxygen level results in lower aluminum consumption. A saving of about 0.13 Kg of aluminum per ton of steel due to bottom stirring has been reported.

Higher manganese content in the steel during tapping – Manganese content in the steel at the time of turn down is about 0.03 % higher with bottom stirring. This means lower consumption of Fe-Mn or Si-Mn in the ladle.

Sulphur removal – Bottom stirring improves the mixing of the bath and hence enhances the desulphurization potential.

Phosphorus removal – It has been reported that dephosphorization is not substantially improved due to bottom stirring even though the bottom stirring drives the reaction towards the equilibrium. This is because the reduced level of FeO in the slag tends to decrease the equilibrium phosphorus partition ratio.

SLAG

The slag phase plays a crucial role in all metallurgical processes. For some, slag is just a “necessary evil”, but if slag is well taken care of it can be a vital tool in the manufacturing of high-quality metals.

If not, slag can cause severe and costly problems, both within the process vessel and on the outside.

Basic Oxygen Steelmaking (BOS) is in this regard no exception.

Fluxes combine with SiO_2 which is oxidized from hot metal to form a "basic" slag that is fluid at steelmaking temp. This slag absorbs and retains sulfur and phosphorus from the hot metal.

Early formation of a liquid slag phase is, for several reasons, of great importance in the BOS process. Together with metal droplets, undissolved additives and process gases, the slag will form a *foam*. *Incorrect slag phase properties in combination with certain process circumstances may cause the foam to grow excessively, forcing some of the foam out of the steelmaking vessel; i.e., the vessel and the melt will slop.*

Such an event causes not only damage to the vessel and its auxiliary equipment, but also loss of valuable metal (entrained in the foam), production disturbances and considerable dust emissions; hence the need for technical solutions and process control measures for slopping prevention.

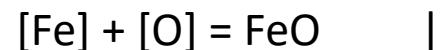
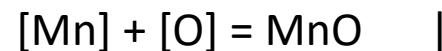
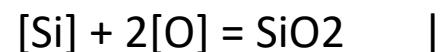
In steelmaking process, the slag is predominantly a mixture of oxides with small amounts of sulphides and phosphides. The oxides are either acidic or basic in nature. Slag is formed during refining of hot metal in which Si oxidizes to SiO_2 , Mn to MnO , Fe to FeO , and P to P_2O_5 etc., and addition of oxides such as CaO (lime), MgO (calcined dolomite), iron oxide, and others. The addition of oxides is done to obtain desired physico-chemical properties of slag like melting point, basicity, viscosity etc.

There are four primary sources for the slag during the steelmaking process in the converter.

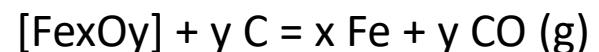
- (i) oxidation of metallic elements in the liquid steel (e.g. silicon, manganese, aluminum, titanium, chromium, and vanadium etc.),
- (ii) due to presence of non-metallics in the liquid bath (e.g. sulphur, and phosphorus),
- (iii) flux additions (e.g. lime, calcined dolomite, and fluorspar),
- and dissolved refractories (e.g. MgO , and $\text{CaO} + \text{MgO}$).

An acidic slag erodes the converter lining since the lining bricks are basic. The acidic slag contains high amounts of SiO_2 , Al_2O_3 which can make the slag thinner. A basic slag contains oxides like MgO and CaO , which makes the slag thicker. FeO is the most important part of the slag in that it causes lime to dissolve at lower temperatures which is called 'fluxing'. The melting temperature of CaO being 2570 deg C and MgO being 2800 deg C, it can be seen that it difficult without FeO lowering the melting point to get lime or magnesia into solution where steel tapping temperatures are generally below 1650 deg C.

Slag formation starts with the dissolution of oxygen in liquid iron and simultaneous oxidation of iron and other bath constituents in the oxygen jet impact zone. As the temperature of the liquid bath in the oxygen jet impact zone is very high (more than 2000 deg C), a large amount of oxygen (up to 1 %) can be dissolved by the iron. In this primary oxidation zone, Iron oxide is formed and the liquid iron with high oxygen content penetrates the bath and gets in contact with fresh bath liquid iron having with higher contents of carbon and other constituents oxidizing them. Part of the primary reaction products are splashed into the slag and furnace atmosphere. Iron oxide and other non-volatile oxidation products such as SiO₂, MnO, and P₂O₅ etc. mix with the existing slag and more lime and calcined dolomite is dissolved into the liquid slag. **Slag is, accordingly, formed by a complex chain of reactions.**



These reactions are followed by secondary oxidation-reduction reactions, especially by decarburization taking place on the surface of liquid iron droplets circulating in the slag.



In the start-up period of a converter blow, when the bath temperature is low, slag is usually saturated by di-calcium silicate (2CaO.SiO₂), but with the progress of hot metal oxidation the slag composition departs from the di-calcium silicate 'nose' returning in the later stage of the blow back to it and passing it to the tri-calcium silicate (3CaO.SiO₂) saturation or even lime saturation range. The evaluation of the slag path passing the high temperature liquidus surfaces such as the 2CaO.SiO₂ nose or liquidus surfaces of the 3CaO.SiO₂ or lime and corresponding precipitation of solid phases from the liquid bath, is somewhat obscured by the fact that slags are multicomponent phases and the slag temperatures have been reported to exceed, even by several hundred degrees, the average temperature of the liquid iron bath.

The role played by the slag in the oxygen converter steelmaking process is very important. Lime is critical to steelmaking. The science of how lime interact with the various components formed during the steelmaking is the basis for understanding the old phrase '**Make the slag and the steel will make itself**'. Slag is a generic name and in steelmaking it is mostly a solution of oxides and sulphides in the liquid state and the multi-crystalline phases in the solid state. Slag is a separate phase than liquid steel since (i) it is lighter than the liquid steel, and (ii) it is immiscible in the liquid steel.

Role of slag during steelmaking

- ✓ It acts as a sink for impurities during refining of steel.
- ✓ It controls oxidizing and reducing potential of the bath during refining through FeO content. Higher FeO content of the slag makes the slag oxidizing while the lower FeO content makes the slag reducing.
- ✓ It helps in dephosphorization and absorbs some sulphur.
- ✓ It prevents the passage of nitrogen and hydrogen from the atmosphere to the liquid steel in the bath.
- ✓ It absorbs oxide/sulphide inclusions.
- ✓ It insulates the liquid bath and reduces thermal losses. It provides a thermal barrier and thus prevents heat transfer from the liquid steel to the surrounding.
- ✓ It provides protection to the liquid steel from re-oxidation.
- ✓ It emulsifies the hot metal and promotes carbon oxidation.

The functions of slag as given above require the slag to possess certain chemical properties (basicity, oxidation potential) as well as physical properties (density, melting point, viscosity). Both of these properties are controlled by the composition and the structure of the slag.

There are four principles of **controlling slag** in steelmaking.

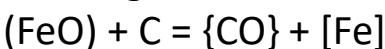
- (i) control of slag basicity which is the ratio of the basic oxides and the acidic oxides,
- (ii) saturation of slag with MgO,
- (iii) slag foaming control also known as slag viscosity control,
- (iv) balance of steel and slag in the steelmaking process for reaching an 'equilibrium state'.

Slag basicity: index how acidic or how basic a slag is in relationship to the basic refractory utilized in converter. If the slag is more acidic then it will erode the bricks, if it is more basic it will protect the bricks. The basicity of the slag is normally fixed by the amount of lime and calcined dolomite added, Si, Al of hot metal and steel scrap charged as well as ferro-alloys. The lower value of the ratio indicates that the slag is acidic and as the ratio increases the slag becomes more and more basic.

In addition to basicity, **MgO content** of the slag is also important. The slag contains dissolved calcium compounds and acidic compounds that cause MgO to dissolve from the refractory bricks of the lining into the slag. MgO dissolves into the slag based on relationships of FeO content, basicity and temperature. The lower the slag basicity, the higher the MgO requirement for the slag. An increase in FeO and temperature also increases the MgO requirement of the slag.

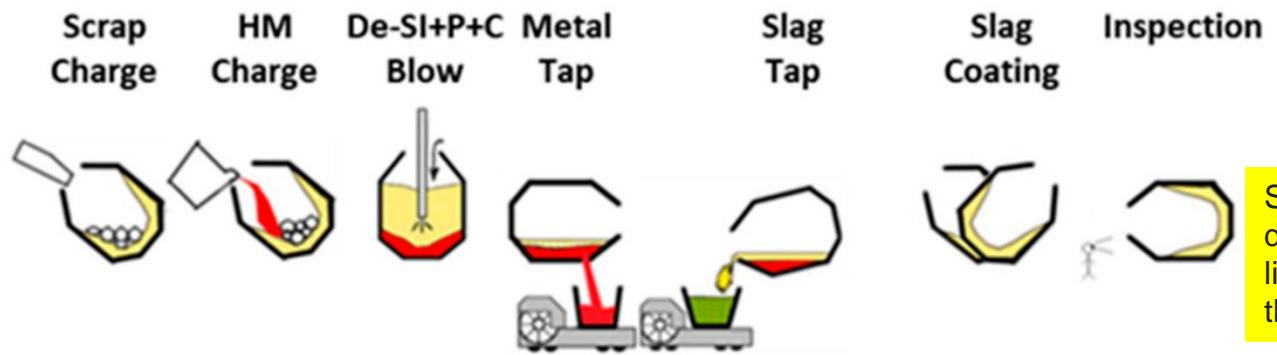
Foam height in the converter is a function of blowing time. The maximum height of the foam is reached when slag mass approaches 70 % of the end slag amount. The reactive converter dust is a source of iron oxides and assists rapid formation of foaming slag, even when the blow has started with low lance i.e. hard blow practice. The foaming slag decreases the post-combustion ratio and increases the heat transfer efficiency to the bath.

Slag foaming: Foam is a dispersion of gas bubbles in a liquid. A liquid is said to be foaming when gas bubbles could not escape through the liquid and as a result height of the liquid increases. In steelmaking, slag foaming can occur due to the following reactions:

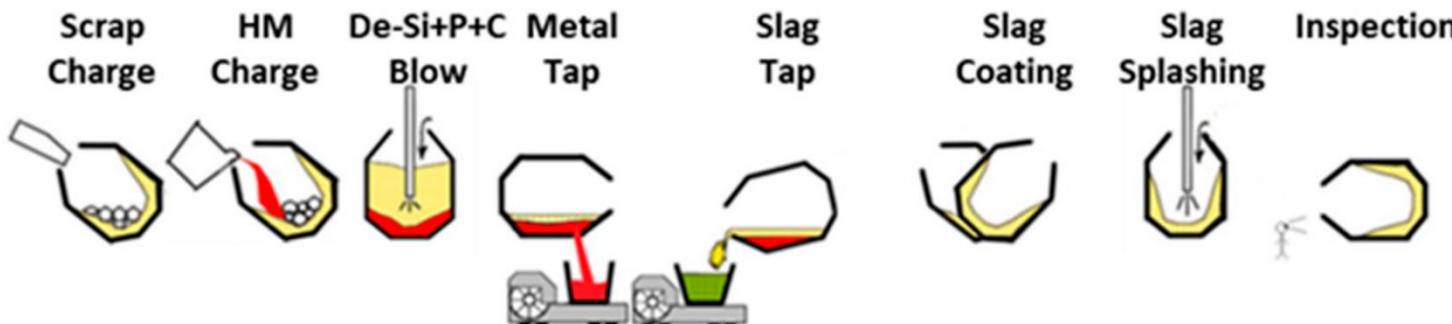


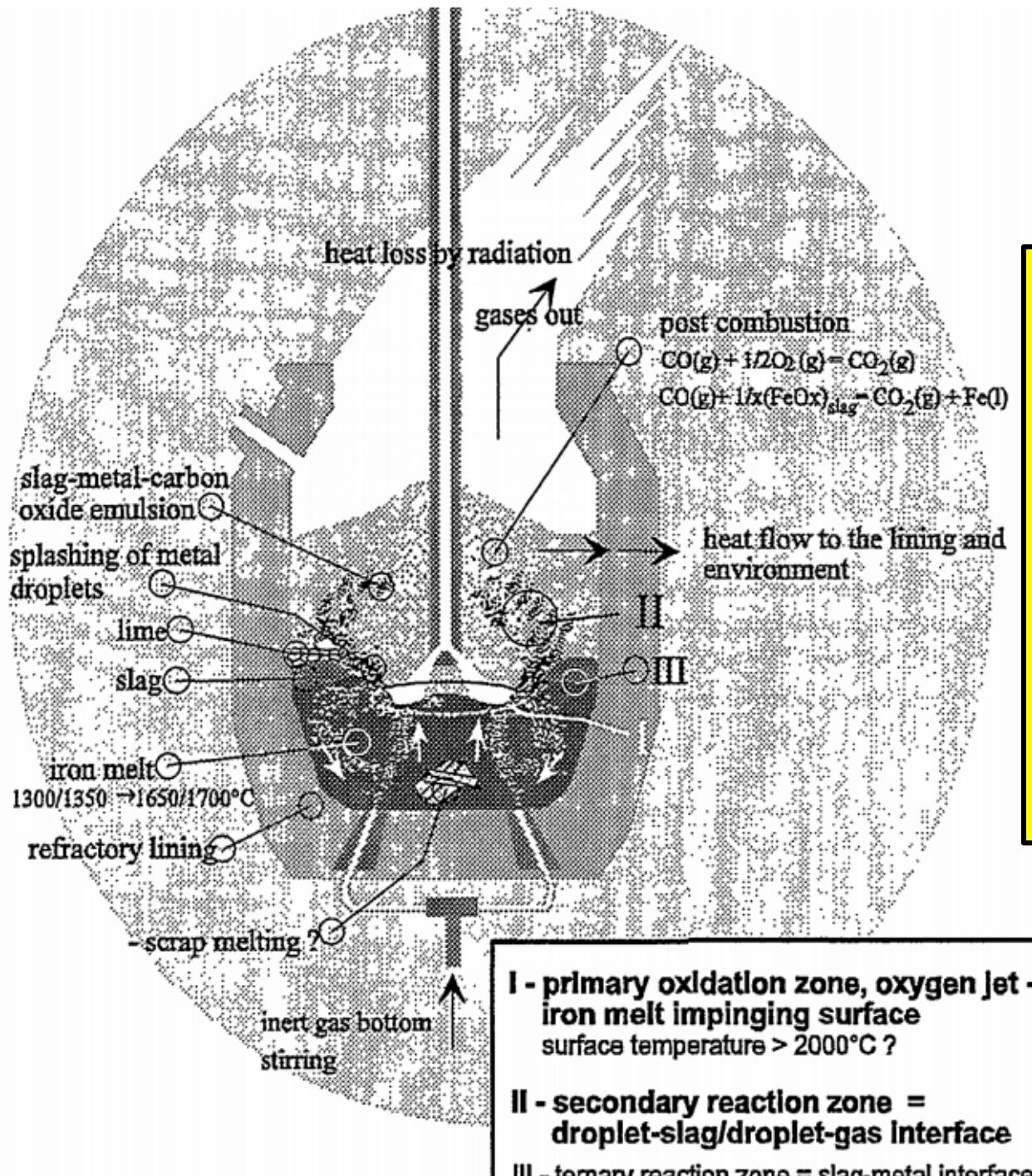
This reaction occurs within the slag. The other reaction $[C] + [O] = \{CO\}$ This reaction occurs at the gas/metal interface. In both the cases when the CO gas bubbles are unable to escape through the slag, the slag is said to be foaming. If the reaction between carbon and oxygen occurs deep into the bath i.e. reaction 2 then gas bubbles have enough time to grow in size and can easily escape through the slag layer as compared to when the gas bubbles are produced by reaction 2. The reaction 2 occurs within the slag

Is slag foaming desirable? Yes to the extent that slag should not flow out of the reactor. Slag foaming enhances the reaction area.



Slag splashing technology was developed to increase the vessel lining life significantly and to drastically reduce the downtime for relining



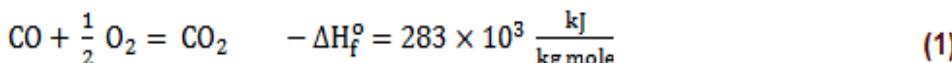


The lack of insufficient real-time information about the compositions of liquid metal and slag leads often to such measures like additional blows or additional coolings, which consume a lot of energy and raw materials. Major developments have included bottom and combined blowing, hot metal pretreatments, increased scrap melting and combustion

Post Combustion

The oxidation of carbon to CO in BOF steelmaking is the principle reaction. In converter steelmaking CO produced during refining exits the furnace in exhaust system where it is combusted with the ambient air.

Combustion of CO to CO₂ produces large amount of thermal energy



$$= 12634 \times 10^3 \frac{\text{kJ}}{\text{m}^3}$$

Thus post combustion of CO in BOF and transferring the heat of combustion to the slag and metal offers an additional amount of energy. The amount of post combustion taking place in the furnace can be represented by post combustion ratio (PCR)

$$\text{PCR} = \frac{\% \text{CO}_2}{\% \text{CO} + \text{CO}_2} \quad (2)$$

A technology is required which can inject oxygen in the converter just above the slag so that CO can be combusted to . The supply of oxygen for the post combustion must be well distributed above the slag surface for an efficient combustion of CO. Transfer of the heat to the slag and metal phase is also to be considered.

One possible way is to add several small orifices around the main supersonic nozzle tip. Lance distance has to be adjusted so that oxygen through the orifice is available for combustion of CO to above the slag surface.

Still another method could be a lance with double flow for oxygen. In the main oxygen lance, a separate oxygen inlet and oxygen control system can be provided which is solely dedicated to post combustion. This design may provide better control of oxygen for post combustion without affecting the oxygen flow through the main lance.

One of main requirement of oxygen flow for post combustion is that velocity and angle of oxygen flow should be low to avoid the refractory wear. Nozzle diameter, angle of oxygen flow and location of nozzle are the principle design issues.

Potential post combustion issues

1. Higher melting rates can be achieved
2. Reduced green house gas emission /ton of steel because more scrap can be used
3. Reduction in slopping. This is achieved by increase in slag temperature which helps dissolution of lime in slag and decrease in slag viscosity.
4. Development of high quality refractory would be required because high temperature would be generated in the post combustion zone.

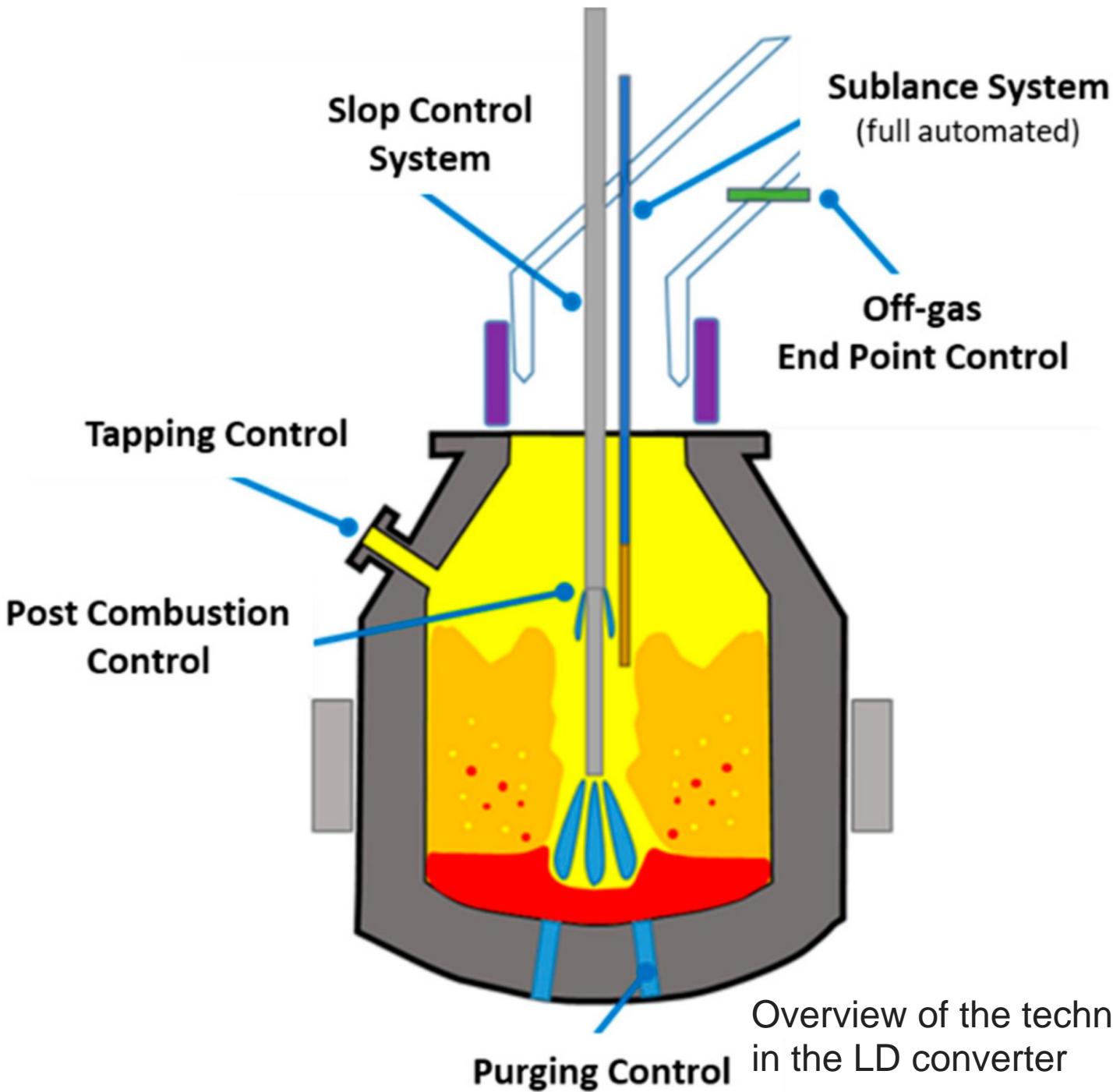


Table 1 : Effect of phosphorus in steel [2]

Property	Effect of phosphorus
Strength	++ (ferrite strengthener)
Bake hardenability	+
Ductility	--
Fe-Zn galvanneal	may improve resistance to powdering
Phosphatability	+
Enamelling steels	Fish-scaling
	Pickling
Weldability	Not harmful for < 0.1 mass%
Core loss in motor laminations	--
Fracture toughness	--

+ increase ++ strong increase - decrease -- strong decrease

Dephosphorization is not attractive because it requires desiliconization, causing temper. loss, which reduces scrap melting in the OSM, and additional costs

The only source of phosphorus in steel is from the raw materials

- Phosphorus is removed from steel by oxidation process i.e. in the form of held in combination with basic constituents in the slag generated in the steel refining process.
- Dephosphorization is governed by the equilibrium condition which is characterized not only by metal and slag composition but also by temperature.
- The operating parameters which affect dephosphorization of steel include temperature, basicity of slag, ferrous oxide activity or iron content of slag, activity, silica content of the slag, slag volume, the following operating parameters are desirable for dephosphorization of steel:
 - (a) low temperature,
 - (b) high basicity of slag,
 - (c) high ferrous oxide activity or iron content of slag,
 - (d) low activity or phosphorous content of slag,
 - (e) low silica content of slag, and
 - (f) high slag volume or double or multiple de-sludging.

For the dephosphorization slag plays an important role in the oxygen converter steelmaking. The balance of oxygen activity in the steel and slag can be related in the oxidation phase as well as materials being used for dephosphorization.



All this shows is that to remove phosphorous from the steel, lime (CaO) and oxygen (FeO) is needed to produce the product of $P_2O_5 \cdot CaO$ to trap in the slag. However, if the temperature goes over 1640 deg C the reaction gets reversed and rephosphorization takes place. Hence for the removal of phosphorous, slag containing $P_2O_5 \cdot CaO$ is to be removed by the deslagging of the converter in the middle of blow or it is necessary to add more lime, to blow the heat down more (oxygen activity) or to keep it cooler.

The dephosphorization mechanism in oxygen steelmaking can be summarized as:

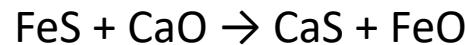
1. During the beginning of the blow, where the oxygen lance is kept high, good ejection of droplets is achieved and phosphorus removal happens fast.
2. As the blow continues and decarburization starts generating CO gas, FeO in the slag is reduced and the slag can become not oxidizing enough which can result in reversion of phosphorus into the melt as droplets are rephosphorized and return to the bulk metal. This is specially important if dissolution of lime is not optimum.
3. Closer to the end of the blow, decarburization slows down and the FeO content in the slag increases favoring dephosphorization once again. This however, may not be enough to compensate for the possible reversion that occurred earlier.
4. Optimum results can be achieved by closely monitoring FeO and CaO in the slag. Iron ore additions can be helpful to maintain ideal FeO content to continue phosphorus oxidation in parallel with decarburization.

Sulfur....

- BOF slag contains harmful P as well as useful CaO, MgO and iron oxides. To recover the useful components, the slag is recycled as an additive to sintering and resulting sinter is fed into BF.
- The recycling makes P in hot metal increased beyond the tolerable value for BOF blowing to meet low P, S for quality steels. Also, the blowing of high P hot metal necessitates increased use of CaO which in turn brings forth a large amount of slag.
- In BOF, thermodynamic requirements for deP are lower temperature and higher oxygen potential, contradictory to higher temperature and lower oxygen potential for deS.
- Therefore, it is difficult to achieve both deP and deS in single BOF vessel with single slag operation.
- In BOF, S originating from scrap is additional, and hence supplemental deS is required in RH, or LF for extra low S grades.
- In recent years, injection of 20%Mg–CaO mixture into hot metal has been practiced for its convenience and less amount of slag formation. MgS, formed from S in hot metal and injected Mg, combines with CaO, ascends and is absorbed into top slag, preventing the reversal of S to attain lower S.

Removing sulfur

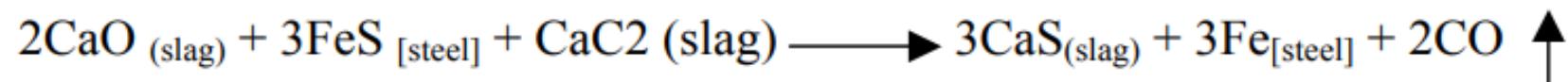
The majority of sulfur, present as ferrous sulfide (FeS), is removed from the melt not by oxidation but by the conversion of calcium oxide to calcium sulfide:



According to this equation, desulfurization is successful only when using a slag with plenty of calcium oxide—with a high basicity. A low iron oxide content is also essential, since oxygen and sulfur compete to combine with the calcium.

For this reason, many steel plants desulfurize blast-furnace iron before it is refined into steel, since at that stage it contains practically no dissolved oxygen, owing to its high silicon and carbon content.

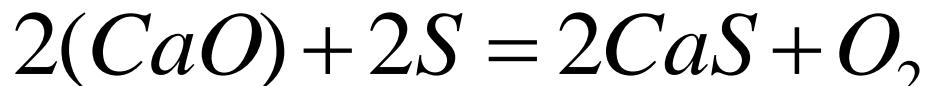
Nevertheless, sulfur is often introduced by scrap and flux during steelmaking, so that, in order to meet low sulfur specifications (for example, less than 0.008 %), it is necessary to desulfurize the steel as well.



Desulphurising Reagents

❑ Lime – Advantages

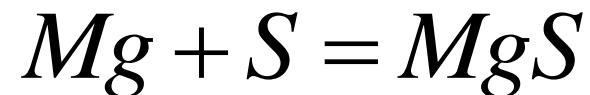
1. Low Cost



2. Easy Availability

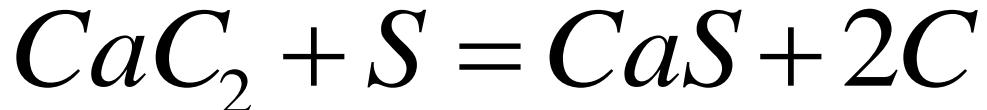
❑ Magnesium –

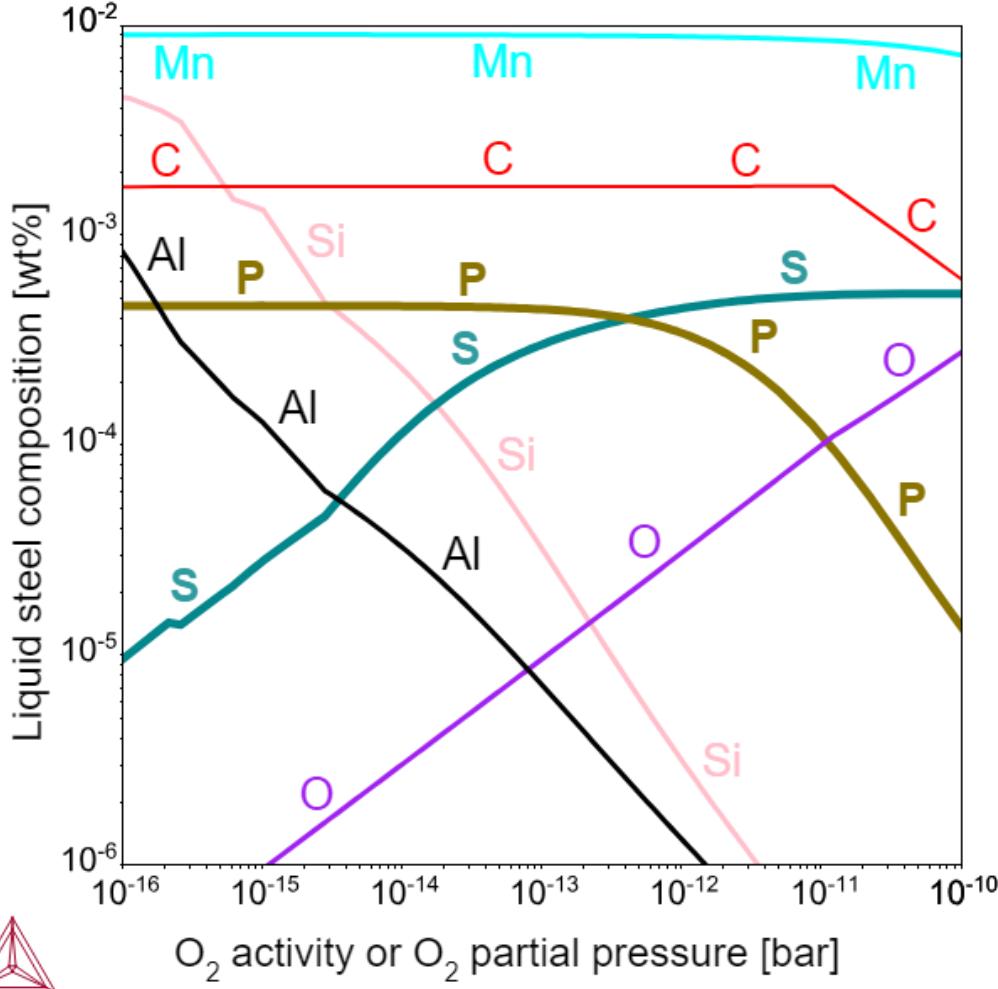
- Magnesium forms vapors as it enters the hot metal due to Low M.P.(1090°C)



Magnesium vapours form bubbles in ladle which rise up and react with sulphur in solution forming Magnesium Sulphide (MgS) which is skimmed off later as it settles at top as slag layer

❑ Calcium carbide - The use of this widely famous desulphurising agent is now less prevalent.





Composition of 100t of liquid steel in equilibrium with a CaO-rich slag phase at 1600°C, showing desulfurization at low oxygen partial pressure and dephosphorization at high oxygen partial pressure.

- Steelmaking slags have both a liquid and a solid fraction.
- Aluminum is one of the most common deoxidizers, being responsible to profoundly decrease dissolved oxygen on liquid steel.
- After addition of aluminum as deoxidizer, formation of alumina clusters is first observed and subsequently the formation of spinel ($\text{MgO}\cdot\text{Al}_2\text{O}_3$) takes place.

Oxygensteelmaking involves preferential oxidation of the solutes **C, Si and Mn** from the hot metal charged to the converter. Liquid iron oxide is formed at beginning of the oxygen blow and this fluxes the silica, formed by oxidation of the silicon. Lime, charged with the hot metal and the scrap, gradually replaces iron oxide as the flux. It produces a slag in the system $\text{CaO}-\text{FeO}-\text{SiO}_2$ which is simultaneously saturated with $3\text{CaO}\cdot\text{SiO}_2$ and CaO . The composition of this melt is used to calculate the amount of lime that should be charged with any amount of hot metal.

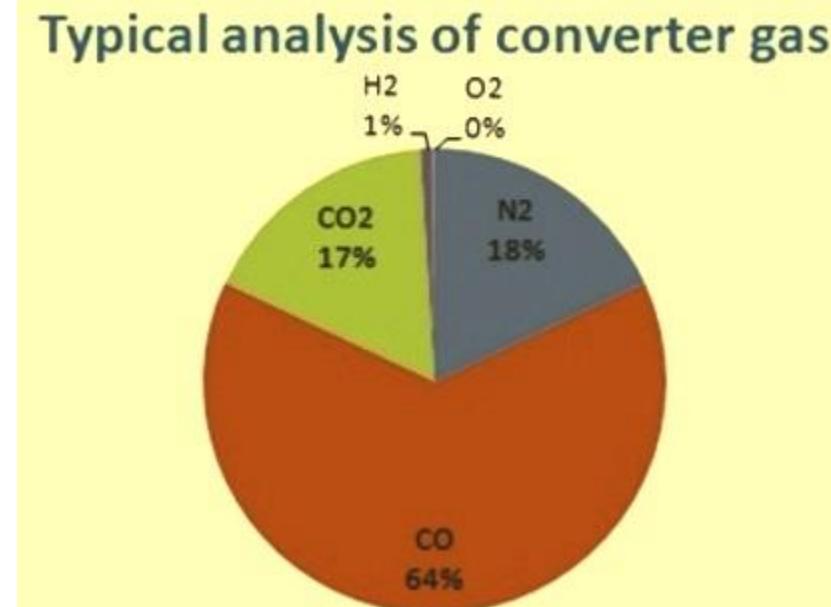


Gravel-size steel slag particle with a lime pocket

- During the process of steel making in the basic oxygen furnace (BOF), significant amount of gases, rich in carbon monoxide content, are generated during the blow time at a temperature of 950 deg C. This gas is termed as converter gas or BOF gas or LD gas.
- It is a byproduct gas produced during the production of liquid steel in a basic oxygen furnace (converter), where impurities of hot metal are oxidized with oxygen gas.
- The main constituents of converter gas are carbon mono oxide (CO), carbon di oxide (CO₂), oxygen (O₂) and nitrogen (N₂). Composition wise it is similar to blast furnace gas but with lesser percentage of nitrogen in it.
- Converter gas is dust laden at the converter mouth. The dust content is around 100 to 120 g/N cum. The recovered converter gas is cleaned in a venturi scrubber using water, followed by processing in the mist eliminators. The gas is then stored in gas holder for steady supply and cleaned further in the electrostatic precipitators (ESP) and finally fed to the gas distribution system. Wet type of gas cleaning plants have capabilities to reduce the dust content of the gas to a level of 5 mg/N cum.

Typical analysis of LD converter gas

H₂ 1%
O₂ 0
CO₂ 17%
CO 64%
N₂ 18%



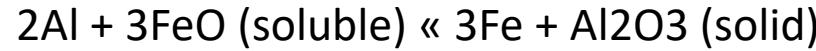
Sr. No.	Furnace	Refractory material
1.	Iron blast furnace	Entire lining consists of fireclay but of different qualities
	Hearth and Bosh	Coarsely ground fireclay
	Shaft or stock	Medium ground fireclay
	Top	Finely ground fireclay
	Hot blast stoves	Porous fireclay bricks
	Hot blast main	Fireclay
	Bustle pipe	Fireclay
2.	Acid open-hearth Furnace	
	Portions above the working floor	Silica bricks
	Regenerative walls	Fireclay bricks
3.	Basic Open-hearth Furnace	
	Roof	Silica bricks
	Side walls	Silica bricks
	Hearth	Dolomite or magnesite
4.	Acid Bessemer Converter	
	Body	Ganister
	Tyres	Fireclay
5.	Basic Bessemer Converter	Calcined dolomite or magnesite
6.	Basic Electric Furnace	
	Roof	Silica bricks
	Bottom and sides	A layer of fireclay bricks next to shell and upon this a layer of magnesite
7.	Cupola	Fireclay lining
8.	Reheating Furnace	
	Roof	Silica bricks
	Hearth	Chromite or magnesite bricks

The magnesia lime type refractories used in lining oxygen steelmaking vessels are selected mainly for their compatibility with the highly basic finishing slags required to remove and retain phosphorus in solution.

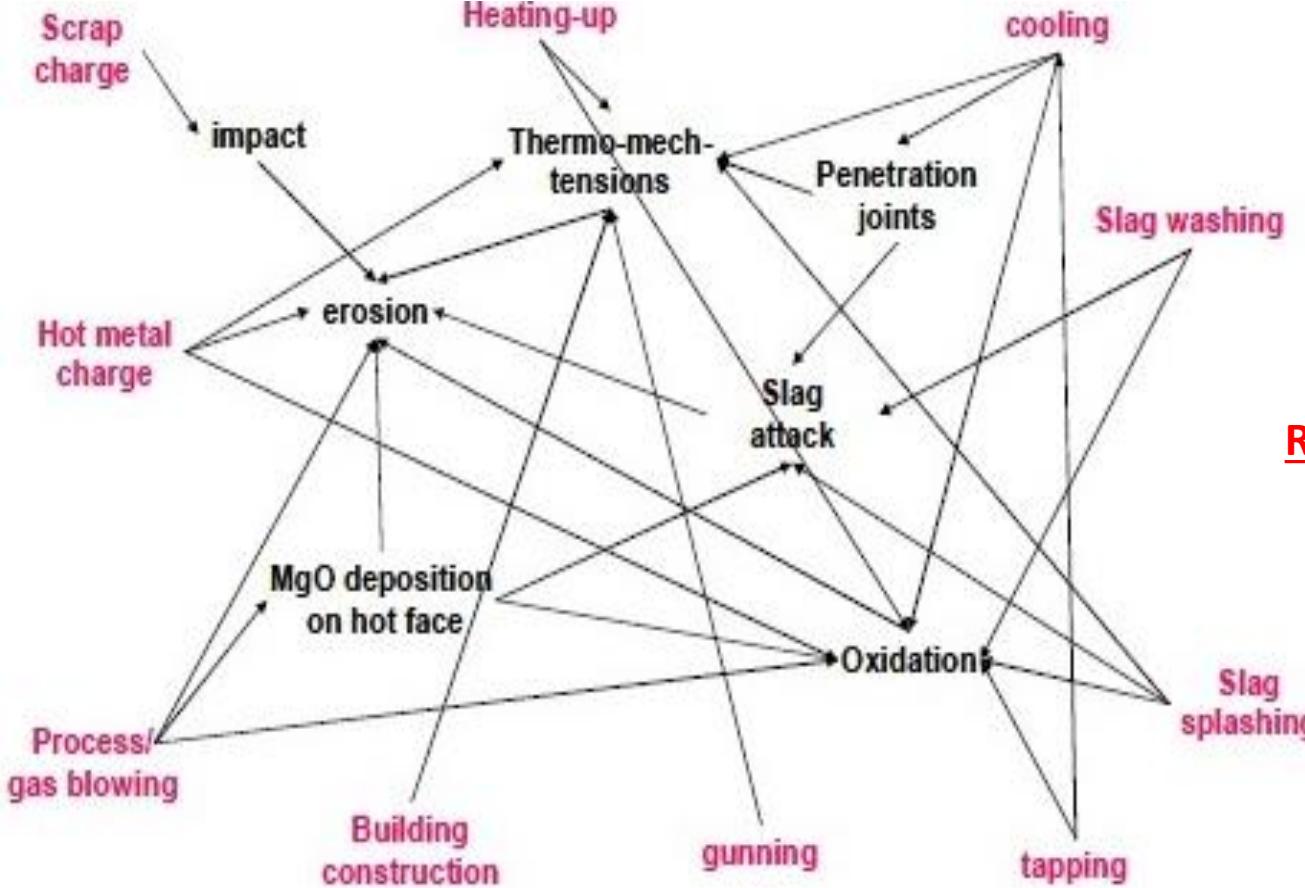
Acid and basic steels

The remaining methods for making steel do so by removing impurities from pig iron or a mixture of pig iron and steel scrap. The impurities removed, however, depend on whether an acid (siliceous) or basic (limey) slag is used. An acid slag necessitates the use of an acid furnace lining (silica); a basic slag, a basic lining of magnesite or dolomite, with lime in the charge. With an acid slag silicon, manganese and carbon only are removed by oxidation, consequently the raw material must not contain phosphorus and sulphur in amounts exceeding those permissible in the finished steel.

In the basic processes, silicon, manganese, carbon, phosphorus and sulphur can be removed from the charge, but normally the raw material contains low silicon and high phosphorus contents. To remove the phosphorus the bath of metal must be oxidised to a greater extent than in the corresponding acid process, and the final quality of the steel depends very largely on the degree of this oxidation, before deoxidisers-ferro-manganese, ferro-silicon, aluminium-remove the soluble iron oxide and form other insoluble oxides, which produce non-metallic inclusions if they are not removed from the melt:



In the acid processes, deoxidation can take place in the furnaces, leaving a reasonable time for the inclusions to rise into the slag and so be removed before casting. Whereas in the basic furnaces, deoxidation is rarely carried out in the presence of the slag, otherwise phosphorus would return to the metal. Deoxidation of the metal frequently takes place in the ladle, leaving only a short time for the deoxidation products to be removed. For these reasons acid steel is considered better than basic for certain purposes, such as large forging ingots and ball bearing steel. The introduction of vacuum degassing hastened the decline of the acid processes.



Relationship of the parameters affecting the lining life

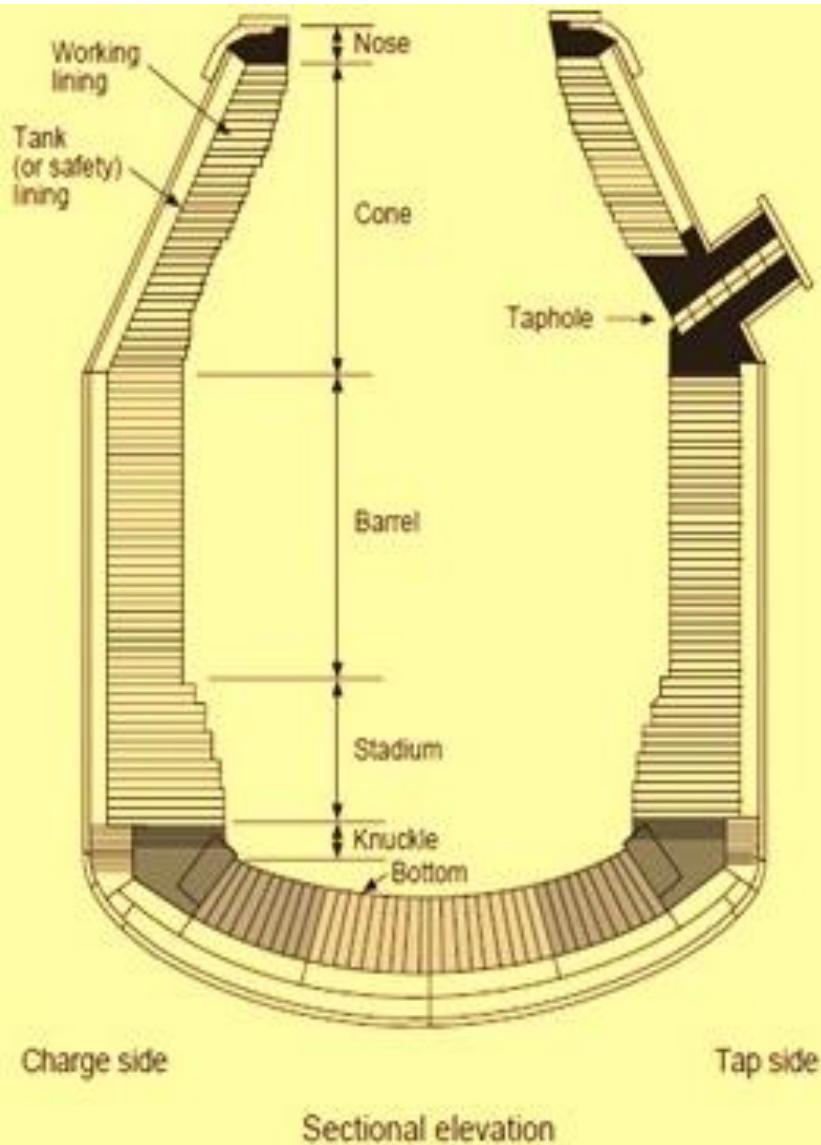
Some oxides are acidic in nature which can react with the basic refractories of the converter and hence a basic slag using lime and calcined dolomite is usually made for protecting the converter refractories.

Iron oxide is the principal corroding constituent for lining.

Injection of high-velocity oxygen jets in top blowing and combined blowing processes causes a lot of splashing of metal on refractory walls.

Refractory lining of a Basic Oxygen Furnace

The purpose of a refractory lining in a basic oxygen furnace is to provide maximum furnace availability during operation of the converter in order to meet production requirements and to ensure lowest possible specific refractory consumption.



Wear of refractory lining:

- i) Corrosion due to chemical attack of slag
- ii) Temperature
- iii) Oxidizing atmosphere
- iv) Impact and Abrasion
- v) Mechanical damage during deskulling

Refractories qualities normally used for converter lining ranges from tar bonded dolomite, pitch bonded dolomite and pitch bonded magnesia to the advanced refractories that are made with resin bonds, metallics, graphites and sintered and/or fused magnesia that can be 99% pure. Refractories should withstand high temperatures and rapid changing environment condition during a heat in a converter. A balance of properties such as hot strength, oxidation resistance and slag resistance are expected from converter refractories. Magnesia carbon (Mag-C) refractories are most popular refractories .

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 steel shell lined with refractory material. The inner volume enclosed by the refractory should be maximized to achieve an optimum metallurgical process without sloping of slag. A ratio of 3 m³ (internal volume/ ton) is typical.
- A modern LD-converter consists of a top cone with the lip ring a barrel section and a lower cone with a dished bottom.
- The nose diameter and angle are chosen with reference to problems of heat loss, erosion, skulling, and stability of nose lining. The vessel is supported by a suspension system which transmits the load to the trunion ring.
- Converter design requires knowing height of molten steel bath, diameter of bath, and working height of the converter

- **REFRACTORY LINING**
- **Up to 1 m thickness**
- **Errosion, abrasion, thermal cycling**
- **Losses 0.5-1 mm per run**
- **Laser controlled thickness**
- **Slower wall dissolution when CaO added**
- **Life more than 1000 runs (classical converters 100 runs)**
- **Regeneration of walls by slag spray ; (up to 10 000 runs)**

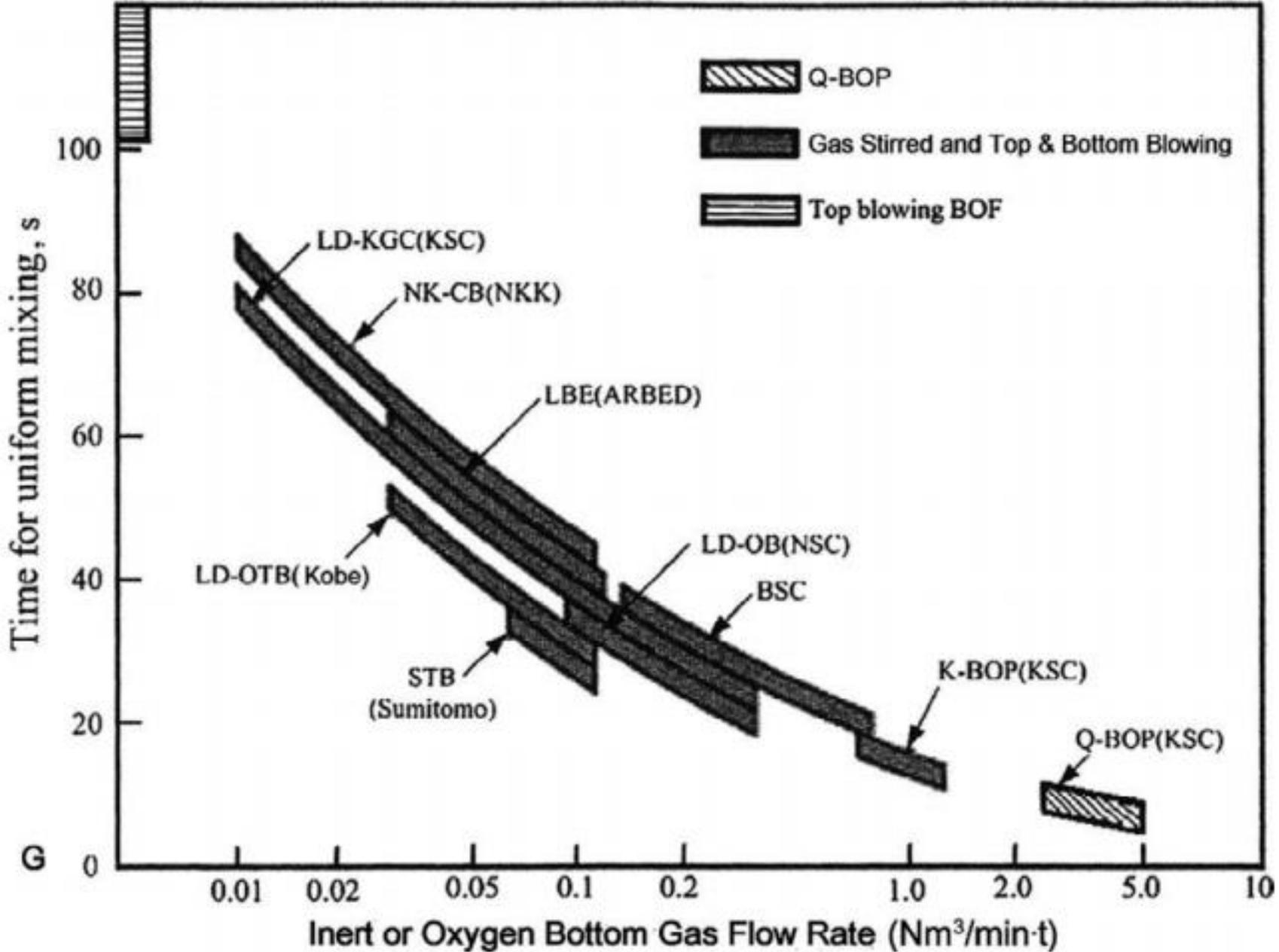
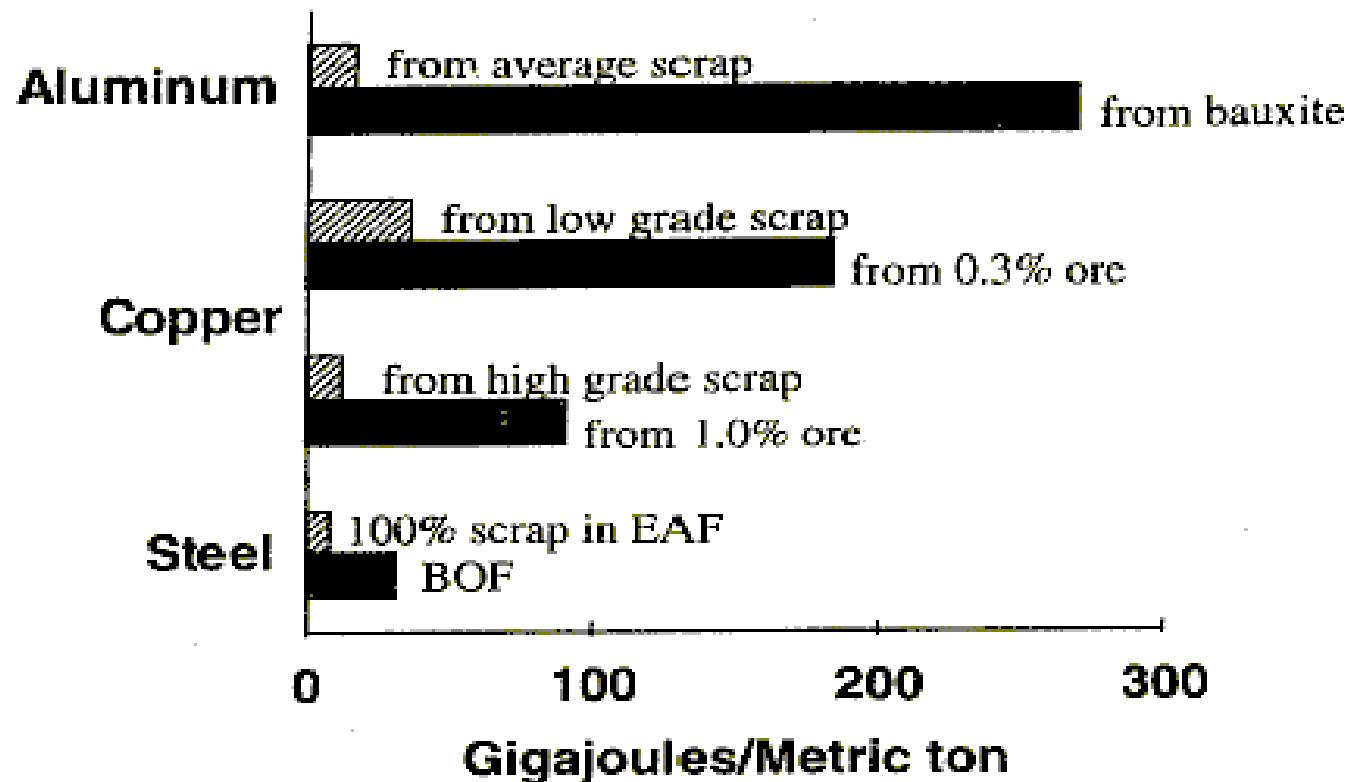


Fig. 3. Mixing Time of Melt in Various BOFs vs. Bottom Gas Flow Rate.²³⁾

ISP: Iron ore: Blast furnace

MSP: Steel scrap: Electric arc furnace

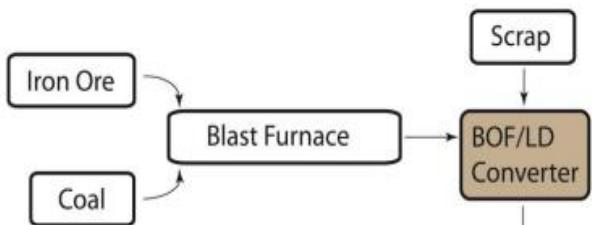


Approximately how much energy is required to make 1 ton of steel through BOF route?
40GJ/mt

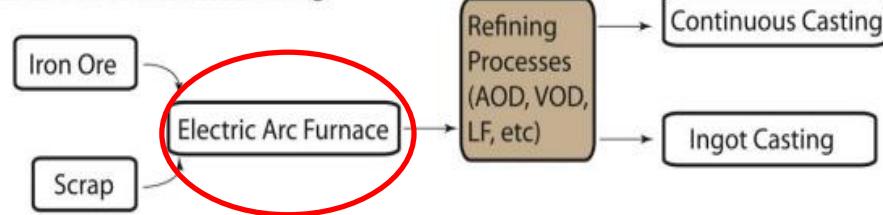


Although scrap is the preferred raw material but sponge iron and iron carbide are being used regularly in most plants because of shortage of steel scrap and to dilute the concentration of tramp elements. Several developments in the design and operation have made EAF steelmaking to contribute significantly to the overall total production of steel in the world.

Blast Furnace Steelmaking

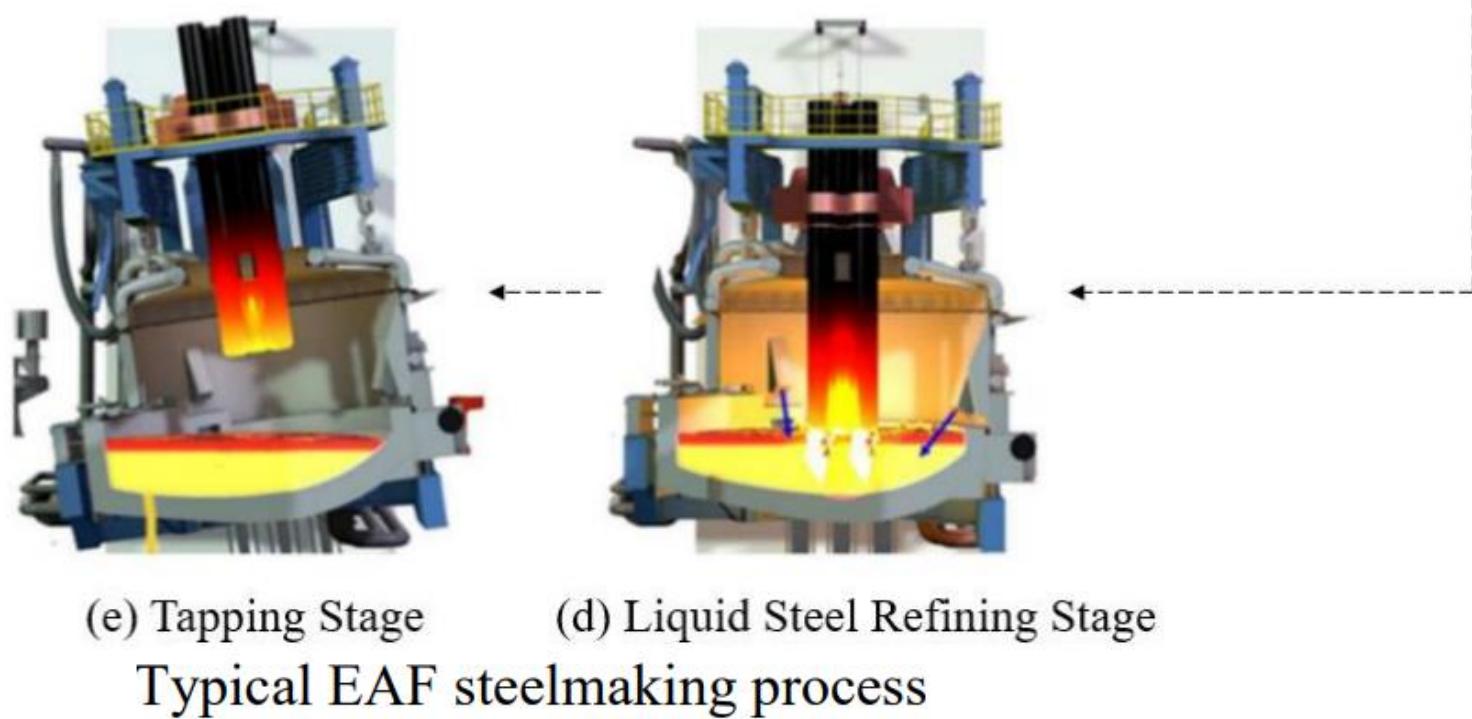
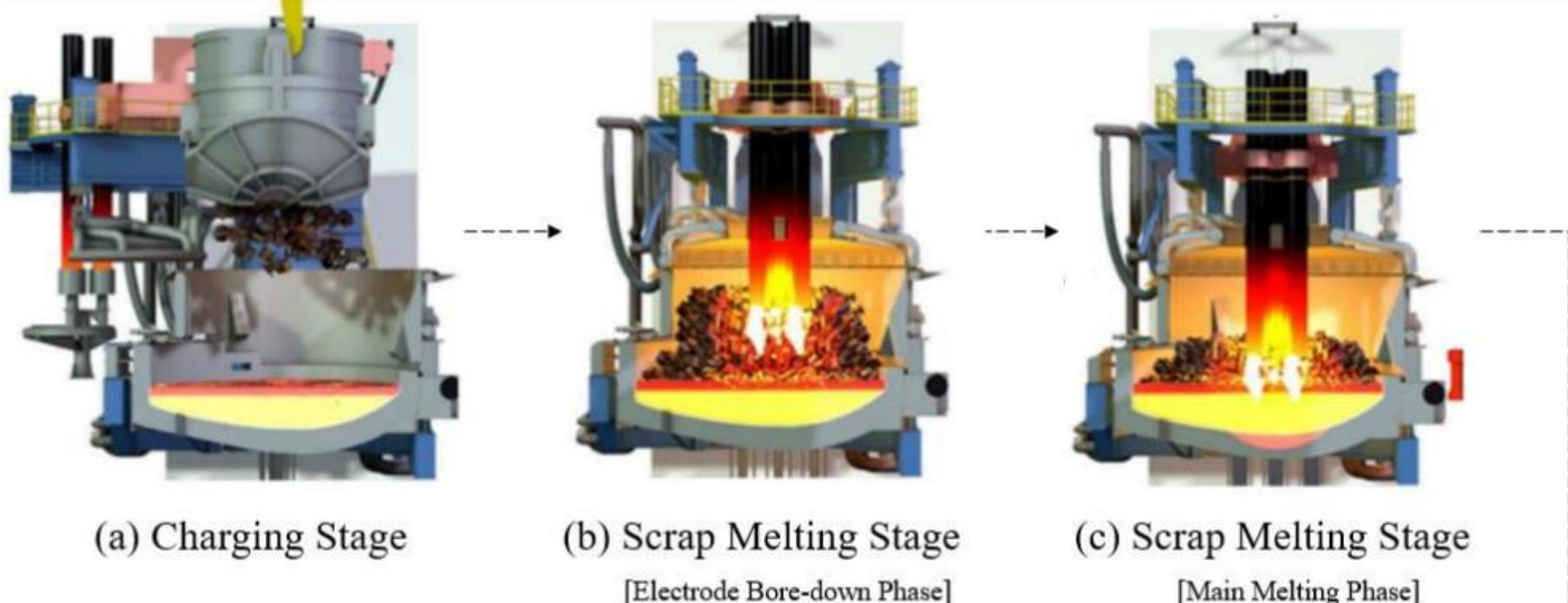


Electric Arc Furnace Steelmaking



The process of **steelmaking in an EAF** is very straightforward and consists of a few basic steps:

1. The furnace is charged with the material
2. The roof is lowered and closed
3. Electrodes are lowered onto the material to form the arc between the material and the electrodes
4. Arc is struck at a lower voltage which is thereafter increased to speed up the melting process. The arc heats the material to a molten state
5. While melting takes place the refining process starts with the oxidising of certain elements



Initially, EAF steelmaking was developed for producing special grades of steels using solid forms of feed such as scrap and ferro alloys. Solid material were firstly melted through direct arc melting, refined through the addition of the appropriate fluxes and tapped for further processing

In brief, these furnaces melt steel by **applying an AC current to a steel scrap charge by mean of graphite electrodes.** It requires a tremendous quantity of electricity. The melting process involves the use of large quantities of energy in a short time and in some instances the process has caused disturbances in power grids ('flicker' (brief irregularities in voltage) Until only around 30-35 years back, tap to tap times of over 3 hours were quite common and specific power usage was often well over 700 kWh/ton, nearly twice the thermodynamic requirement (350-370 kWh/ton).

The EAF operates as a batch melting process producing batches of liquid steel. EAF operating cycle is called tap to tap cycle or a heat and is made up of the components namely (i) charging of the furnace, (ii) melting phase, (iii) refining phase, (iv) deslagging operation, (v) tapping of liquid steel, and furnace turnaround.

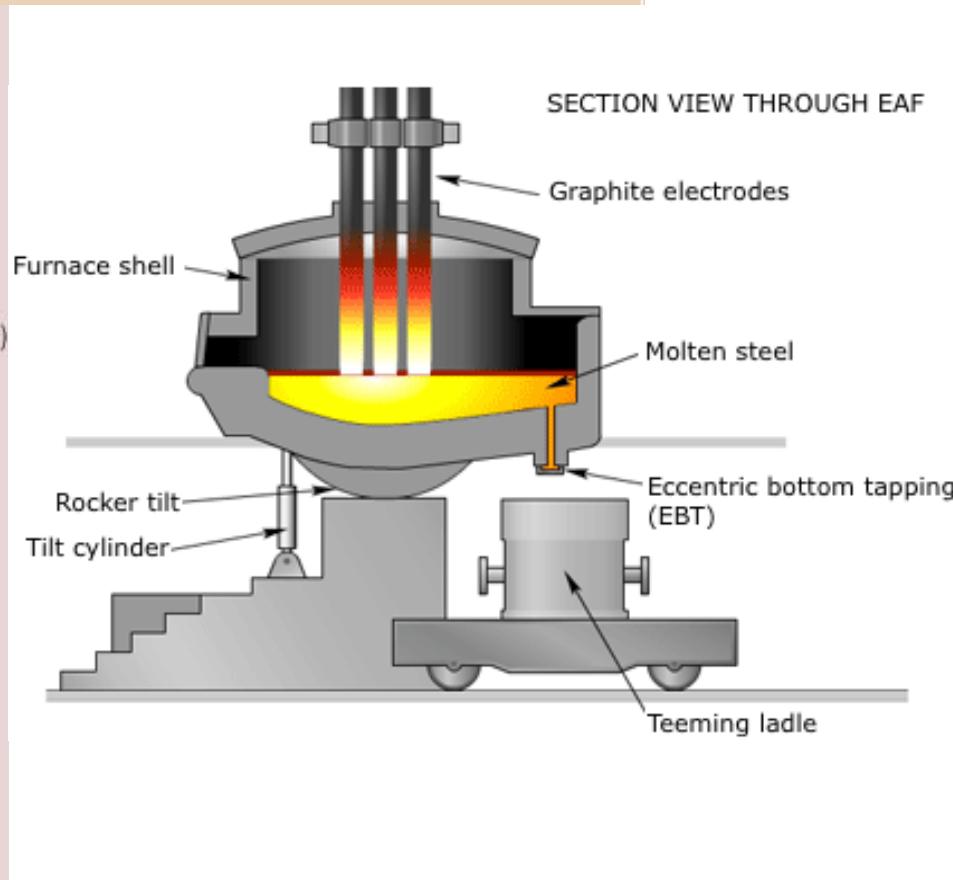
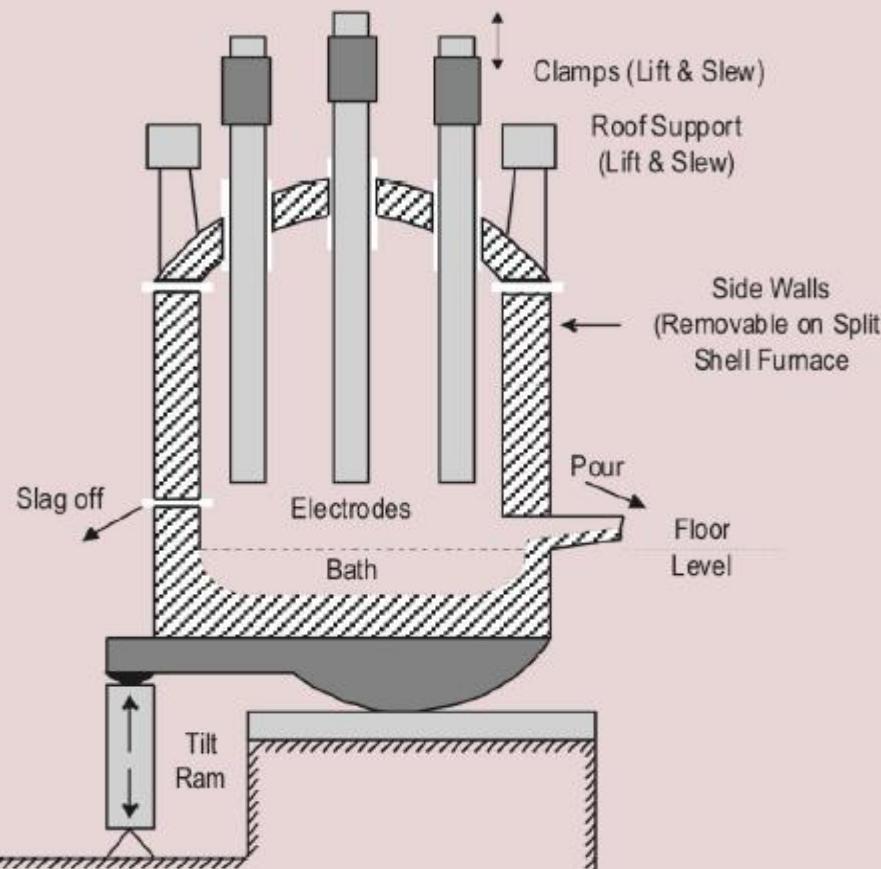
Tap to tap time is normally less than 60 minutes in modern EAFs (tap to tap times of 35 to 40 minutes).

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.

	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	

Above the roof of furnace there are electrode arms which support electrodes and also carry the conductors leading the current to the electrodes. The electrode arms are connected to busbar which are connected to transformer.

Electrodes are raised and lowered by means of motors, or hydraulic rams, to control the amount of power delivered in the furnace. For a given transformer voltage, lengthening the arc increases the resistance, so, reducing the current flowing and the corresponding power input. Conversely, shortening the arc will increase the current and power input. Normally in all modern arc furnaces, the control of the power input is affected by means of automatic regulation.



The casing of the furnace is lined with refractory material, acid or basic, depending on the chemistry of the steelmaking process which is to be carried out.

The Electric Arc Furnace (EAF), also coproduces between 15-25 kg of dust per ton of steel.

- furnace charging: the scrap and the additives (lime, coal, etc.) are loaded into special charging buckets which are then emptied into the furnace; - melting: an electric arc is created between the graphite electrodes and scrap which entails the charge melting and the formation of a steel bath covered by a slag layer, **volatile solute species (e.g.) zinc begin to be removed**; - refining: in this step of the process, phosphorus is removed from the steel bath by interfacial reactions between the slag and liquid metal, injection of oxygen promotes the decarburization reaction with dissolved carbon and bubbles of carbon monoxide (CO) are formed, which helps to remove other dissolved gases; - slag forming: the CO-bubbles crossing the slag layer make it foam, - casting: after the composition and the temperature of the bath have been controlled, the liquid steel is cast.

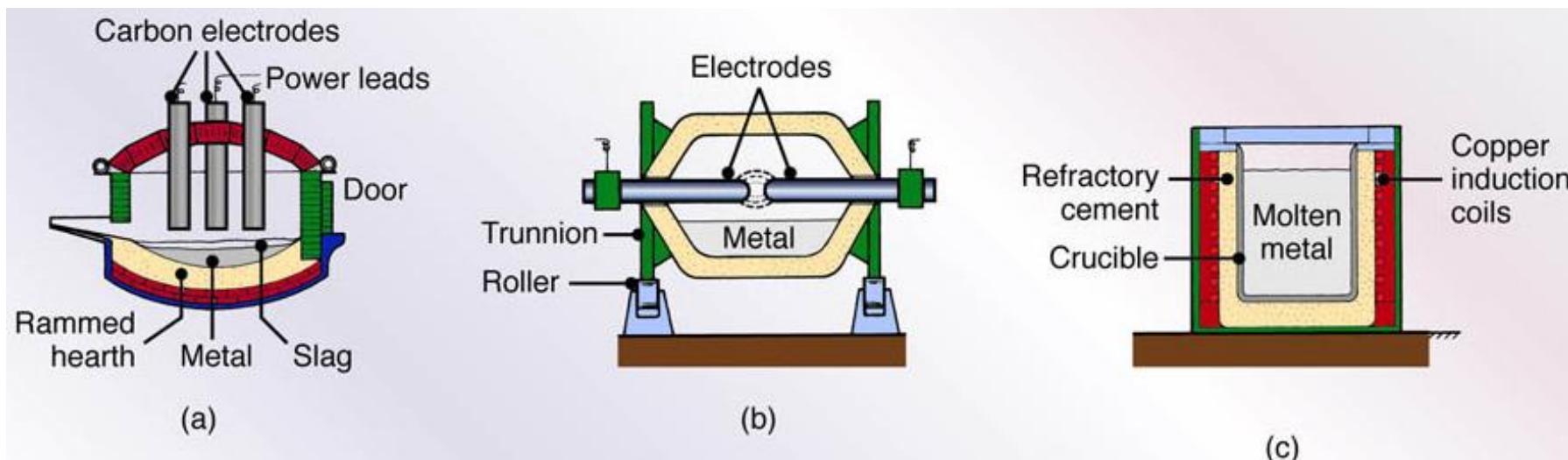
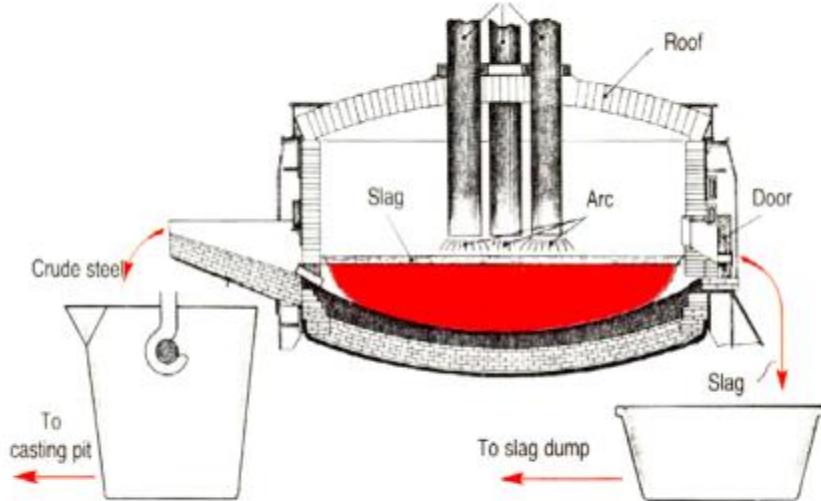
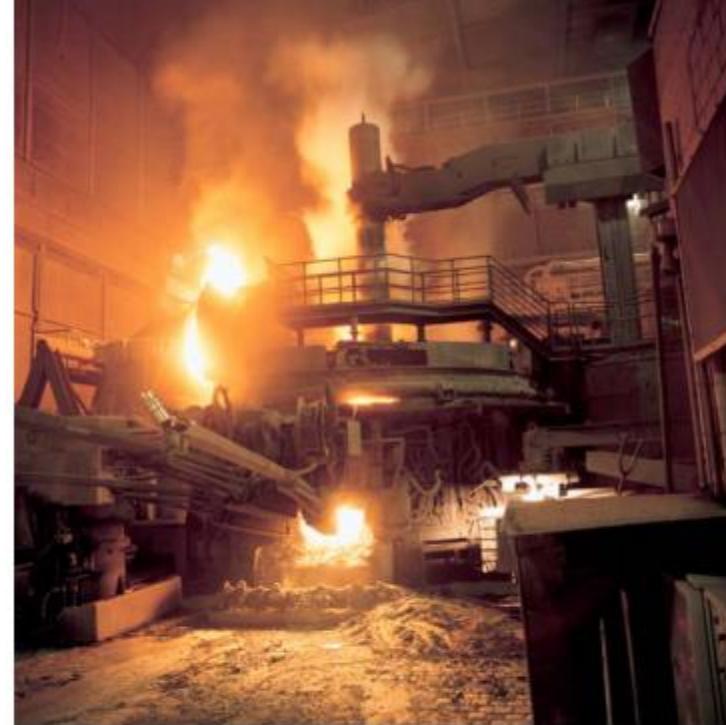


Figure: Schematic illustration of types of electric furnaces: (a) direct arc, (b) indirect arc, and (c) induction

Graphite Electrode



Scheme of an Electric Arc Furnace



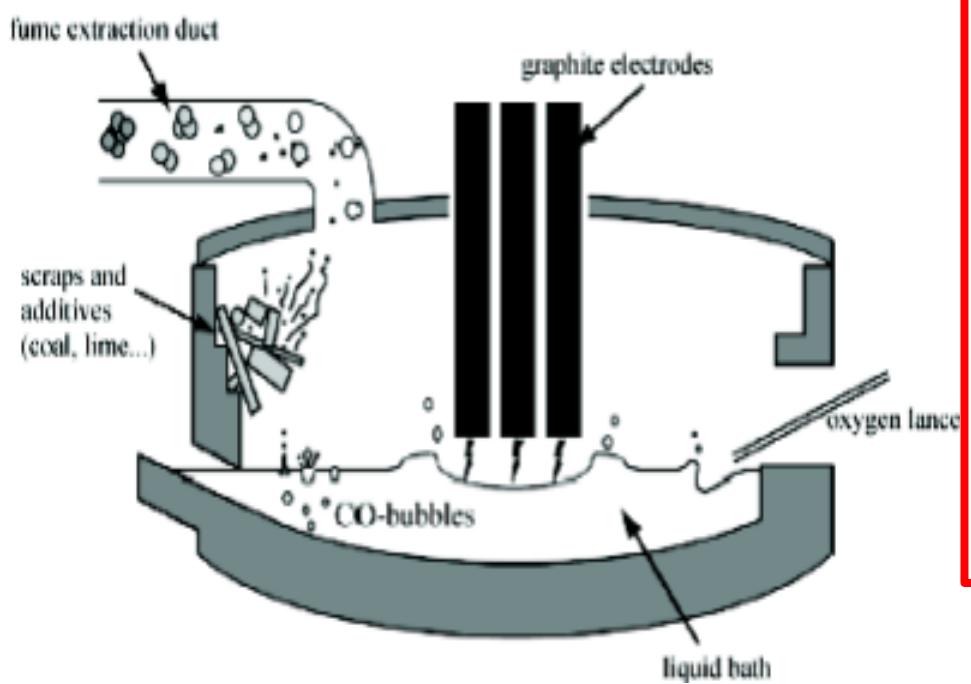
Electric Arc Furnace in use

Due to different wear mechanisms the length of the electrode is reduced during the process. In order to keep the arc (1) stable the height of the electrode has to be readjusted continuously.

Electrode should have

1. Good electrical conductivity in order to withstand the high current density required by the metallurgical process
2. High thermal conductivity to minimise the temperature differences inside the electrodes when in use and, consequently, to reduce internal stresses
3. Low thermal expansion resulting in high thermal stress resistance
4. Strength at high temperatures to withstand the stresses when in use
5. Chemical inertness

The Electric Arc Furnace (EAF), also coproduces between 15-25 kg of dust per ton of steel.
- furnace charging: the scrap and the additives (lime, coal, etc.) are loaded into special charging buckets which are then emptied into the furnace; - melting: an electric arc is created between the graphite electrodes and scrap which entails the charge melting and the formation of a steel bath covered by a slag of layer, **volatile solute species (e.g.) zinc begin to be removed**; - **refining:** in this step of the process, phosphorus is removed from the steel bath by interfacial reactions between the slag and liquid metal, injection of oxygen promotes the decarburization reaction with dissolved carbon and bubbles of carbon monoxide (CO) are formed, which helps to remove other dissolved gases; - slag forming: the CO-bubbles crossing the slag layer make it foam;; - casting: after the composition and the temperature of the bath have been controlled, the liquid steel is cast.



A point that must be taken in account is the fact that, at the end of the melting process, when most of the scrap is melted, the arcs can affect the walls of the furnace which can cause expensive repair work. To avoid this, oxygen is blown into the bath using the oxygen lance. The combination of carbon and oxygen produces a foaming slag which is used as the protection mechanism. Another advantage of the oxygen blowing is the fact that its reaction with the oxidizing elements, such as carbon and iron, provides additional energy.

In the furnace, there are also oil burners used to generate homogeneous heat. In fact, the heat generated by the arcs is not uniform in all the scrap.

The main advantage of EAFs lies in their ability to accept scrap, DRI, and molten hot metal in various proportions since whatever external energy is required, can always be provided by controlling the electrical power supplied. Furnace efficiency can be improved by the combined injection of carbon and oxygen through water-cooled supersonic lances at high rates. The aim is to complete cycle time for steel production in about 40 minutes thereby achieving around 40 heats per day (similar to BOF). The furnaces in the range of 30 to 200 tonnes are common.

EAFs can be of normal power or UHP (ultra high power) with one or two electrodes, single or twin-shell, as well as with and without a top shaft furnace (used for preheating the scrap before charging). However, a feature of all electric furnaces is that a considerable amount of noise is emitted; typical noise levels are between 125 and 139 dB(A). Moreover, their operation (particularly initial arcing) causes flickering in the grid.

Electrical Requirements: One of the most important consumable in electric steelmaking is the power. The power consumed in overcoming resistance is given by:

$$P = I^2R$$

The heat produced (H) in any circuit is given by:

$$H = I^2RT$$

1000

Where,

T = time during which the current flows Since one kilowatt hour (kWh) is equal to 860 k cal

$$H=0.860 I^2RT \text{ k cal.}$$

About 350 kWh of power is required to melt one tonne of steel.

Total theoretical energy required to melt the scrap and to superheat it to the typical tap temperatures requires around 350 – 370 kWh/t-steel. This energy can be provided by the electric arc, from fossil fuel injection or oxidation of the scrap feedstock. In practice, the energy use is highly dependent on product mix, local material and energy costs and is unique to the specific furnace operation. Factors such as raw material composition, power input rates and operating practices – such as post-combustion, scrap preheating – can greatly influence balance.

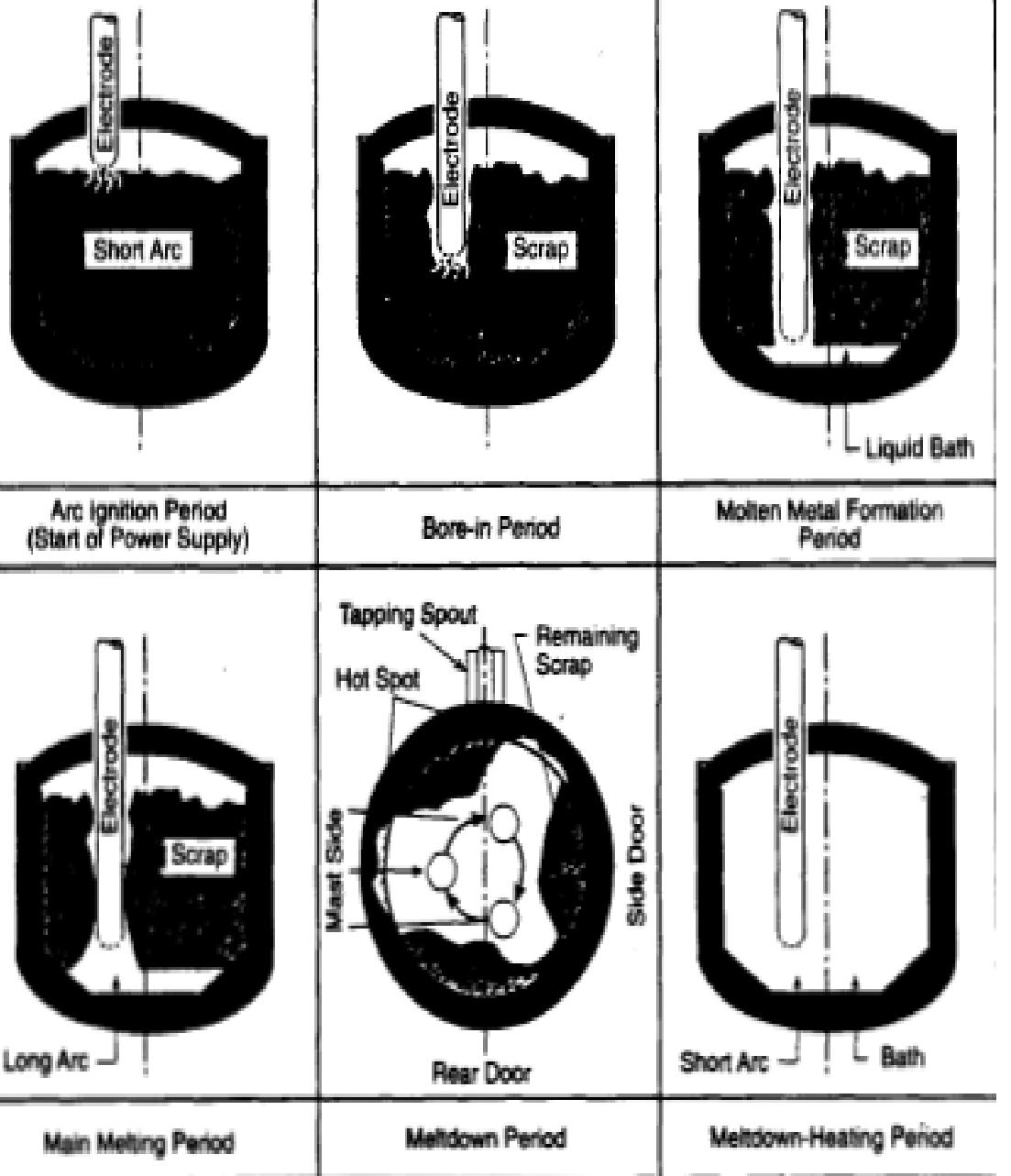
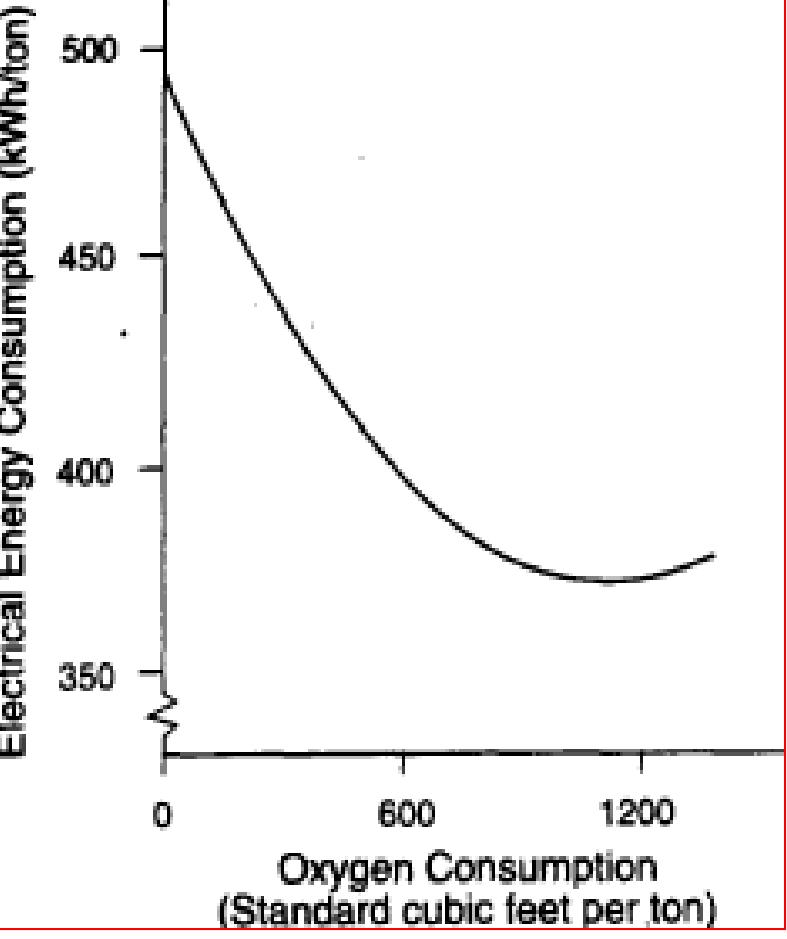


Figure 1. Steel Melting Cycle.

a typical heat cycle, commonly referred to as the "tap-to-tap cycle", for the EAF. The cycle starts with the charging of the furnace with steel scrap. After the furnace is charged and, the operator lowers the electrode or electrodes, each of which has its own regulator and mechanical drive. **Current is initiated and the electrodes bore through the scrap to form a pool of liquid metal.**

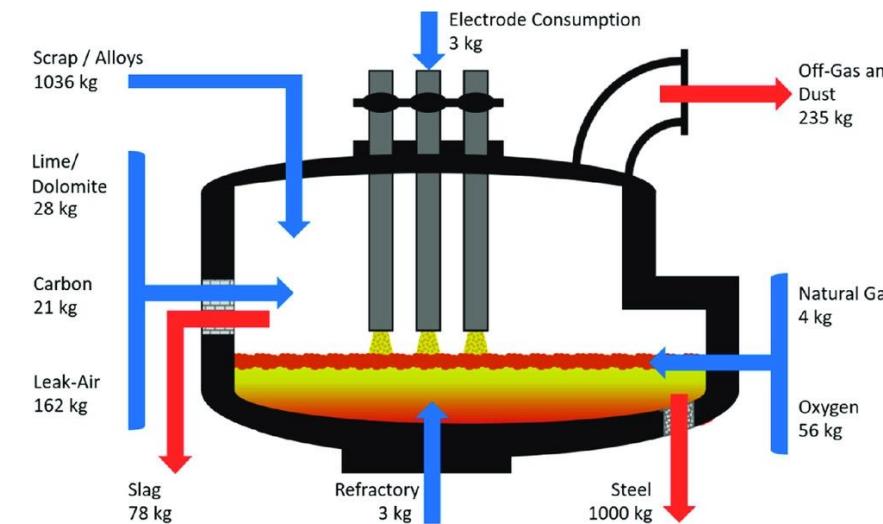
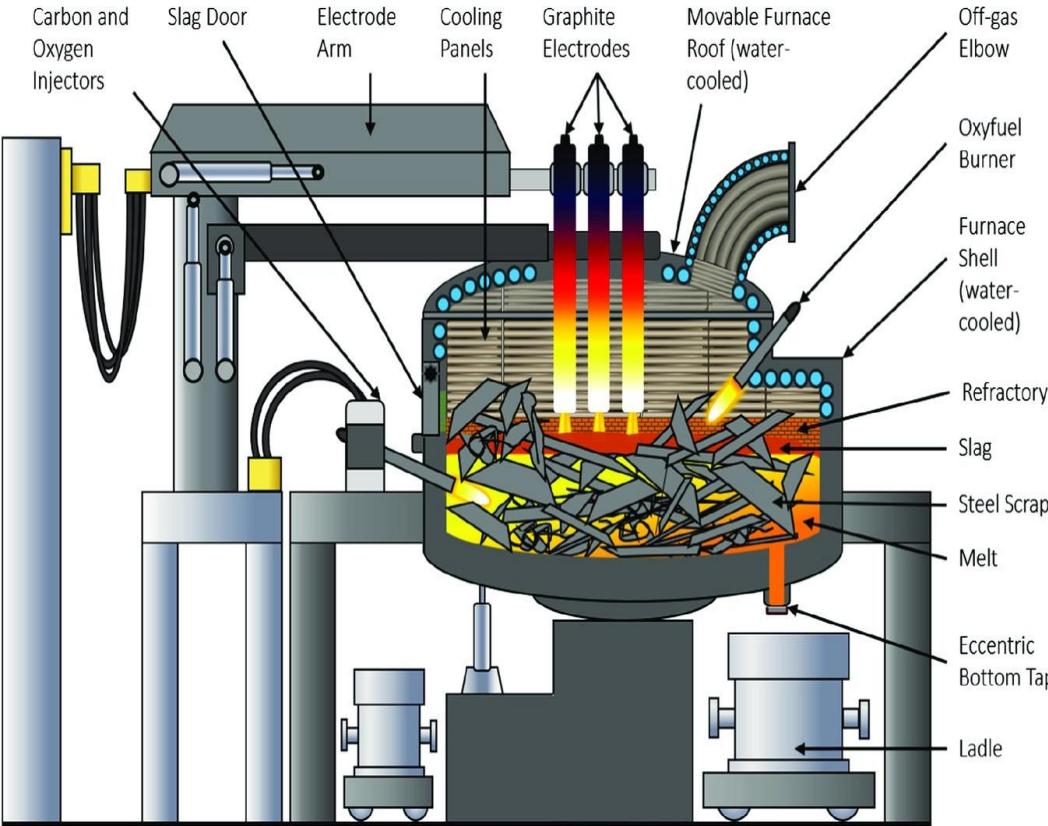
The scrap helps to protect the furnace lining from the high intensity arc during meltdown. Subsequently, the arc is lengthened **by increasing the voltage to maximum power**.

Most modern furnaces are equipped with water-cooled panels in the upper half of the sidewall, rather than refractories, which allow for longer arcs and higher energy input to the furnace. In the final stage age, when there is a nearly complete metal pool, the arc is shortened to reduce radiation heat losses and to avoid refractory damage and hot spots. After meltdown, oxygen is injected to oxidize the carbon in the steel or the charged carbon. In some operations, oxygen injection is started as soon as a liquid pool of metal is formed. The decarburization process is an important source of energy. In addition, the carbon monoxide that evolves to flush nitrogen and hydrogen out of the metal. It also foams the slag, which helps to minimize heat **loss** and shields the arc thereby reducing damage to refractories.



The relationship between electric energy and oxygen consumption for the EAF

- ✓ Much of the EAF productivity gain achieved in the past decade is related to increased oxygen use.
- ✓ With the increased availability of lower cost oxygen due to new air separation technologies, oxygen use in the EAF has grown. Oxygen usage has increased from about **300 scf/ton (8.8Nm³/tonne) in 1985** to as much as **37.4 Nm³/tonne**, saving **50-100 kwh** of electric energy per ton of steel produced and reducing tap-to-tap times by **3-6 minutes**.
- ✓ **It is now** common for between **30-40%** of the total energy input to the EAF to come from oxy-fuel burners and oxygen lancing.
- ✓ Oxy-fuel burners are currently standard equipment on EAFs. The first use of burners was for melting the scrap at the slag door where arc heating was fairly inefficient. In ultra-high-power (UHP) furnaces, it **is common for “cold spots” to exist**
 - ✓ in the areas lying between the electrodes on the periphery of the furnace bottom. Burners are often installed to help melt scrap in these cold spots. This results in more uniform melting and decreases the time required to reach a flat bath.



Mass balance of the EAF process

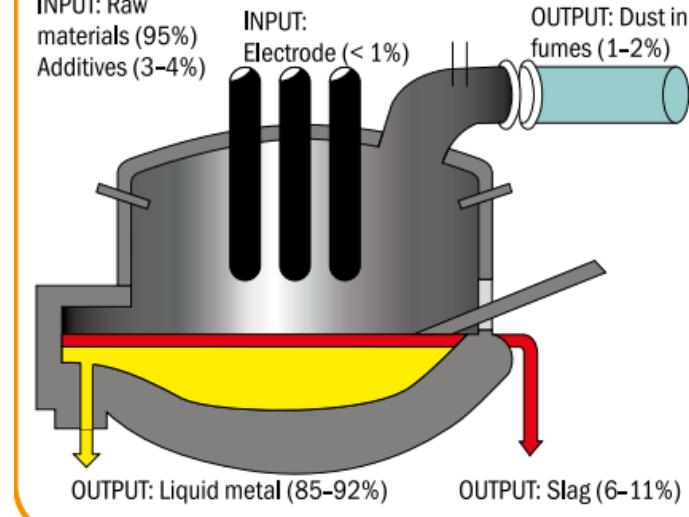
Heat of reactions inside EAF

Exothermic reaction

	Heat of reaction at 1650 °C (kWh per kg)
$\text{Fe} + \frac{1}{2} \text{O}_2 (\text{g}) \longrightarrow \text{FeO}$	1.275
$\text{Si} + \text{O}_2 (\text{g}) \longrightarrow \text{SiO}_2$	9.348
$4\text{Al} + 3 \text{O}_2 (\text{g}) \longrightarrow 2 \text{Al}_2\text{O}_3$	8.650
$\text{C} + \frac{1}{2} \text{O}_2 (\text{g}) \longrightarrow \text{CO} (\text{g})$	2.739
$\text{CO} (\text{g}) + \frac{1}{2} \text{O}_2 (\text{g}) \longrightarrow \text{CO}_2 (\text{g})$	2.763
$\text{C} + \text{O}_2 (\text{g}) \longrightarrow \text{CO}_2 (\text{g})$	9.184
$\text{Mn} + \frac{1}{2} \text{O}_2 (\text{g}) \longrightarrow \text{MnO}$	2.044
$\text{H}_2 (\text{g}) + \frac{1}{2} \text{O}_2 (\text{g}) \longrightarrow \text{H}_2\text{O} (\text{g})$	34.614
$\text{CH}_4 (\text{g}) + 2 \text{O}_2 \longrightarrow \text{CO}_2 (\text{g}) + 2 \text{H}_2\text{O}$	13.994

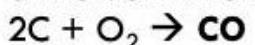
Material balance of EAF

INPUT: Raw materials (95%)
Additives (3-4%)

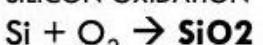


OXIDATIONS

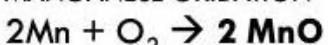
CARBON OXIDATION



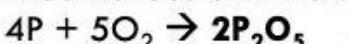
SILICON OXIDATION



MANGANESE OXIDATION



PHOSPHOROUS OXIDATION

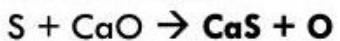


ELECTRIC ARC FURNACE (EAF)



DESULFURIZATION

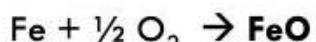
DESULFURIZATION



DESULFURIZATION



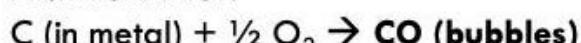
SLAG FOAMING REACTIONS



IRON OXIDE REDUCTION

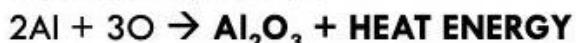


DECARBURIZATION

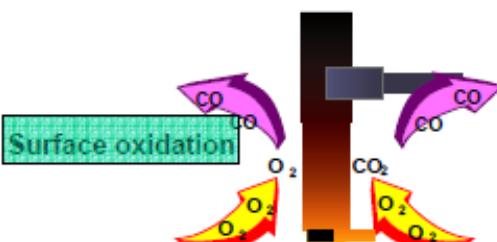


DEOXIDATION

ALUMINUM DEOXIDATION



Continuous Wear

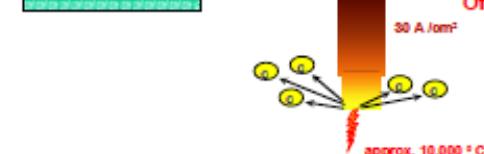


Discontinuous Wear

Stub end Loss



Tip
Sublimation



Wear Mechanisms for an Electrode in Use

Power is supplied to the furnace by a transformer and graphite electrodes. The electrodes are lowered into the furnace, touching the materials, and an electric arc is formed between the electrodes. The arc then melts the materials, resulting in a liquid bath.

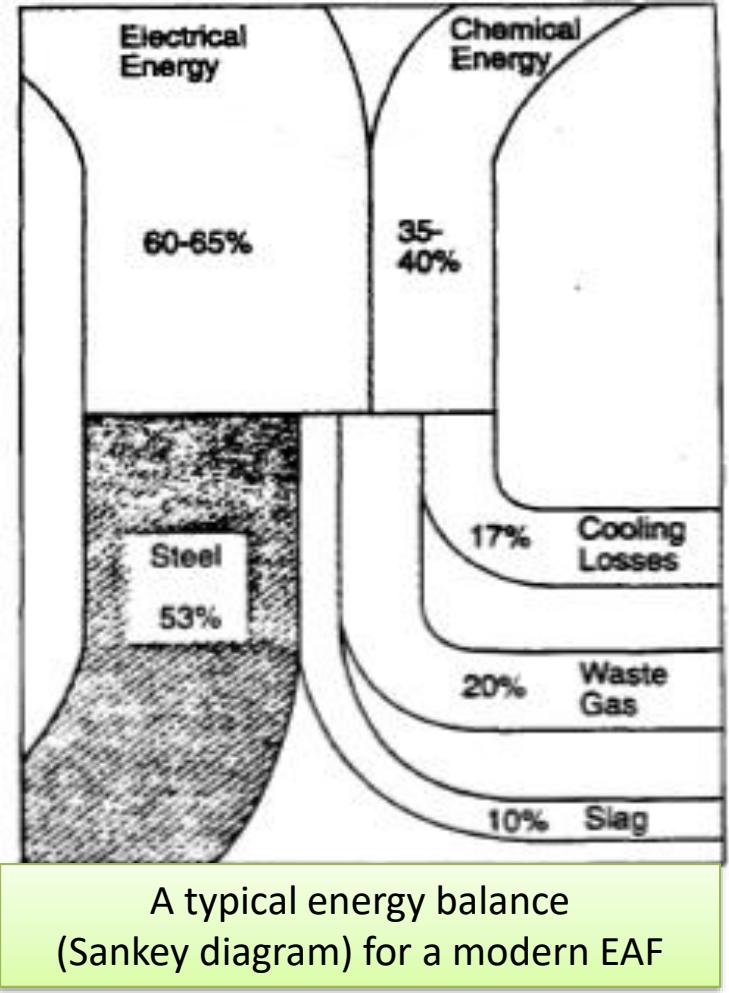
For sulphur removal a low oxygen activity and a basic slag are required.

The electric furnace steelmaking process mainly uses arc heat, and the temperature is up to 4000 °C in the arc action zone. The smelting process is generally divided into the melting period, oxidation period, and reduction period. In the furnace, not only oxidation atmosphere but also reduction atmosphere can be created, efficiency of dephosphorization and desulfurization is very high. EAF steelmaking process is a complex, high-temperature physicochemical process in which gas, solid, liquid, and arc plasma coexist, and momentum, mass, and heat transfer are coupled.

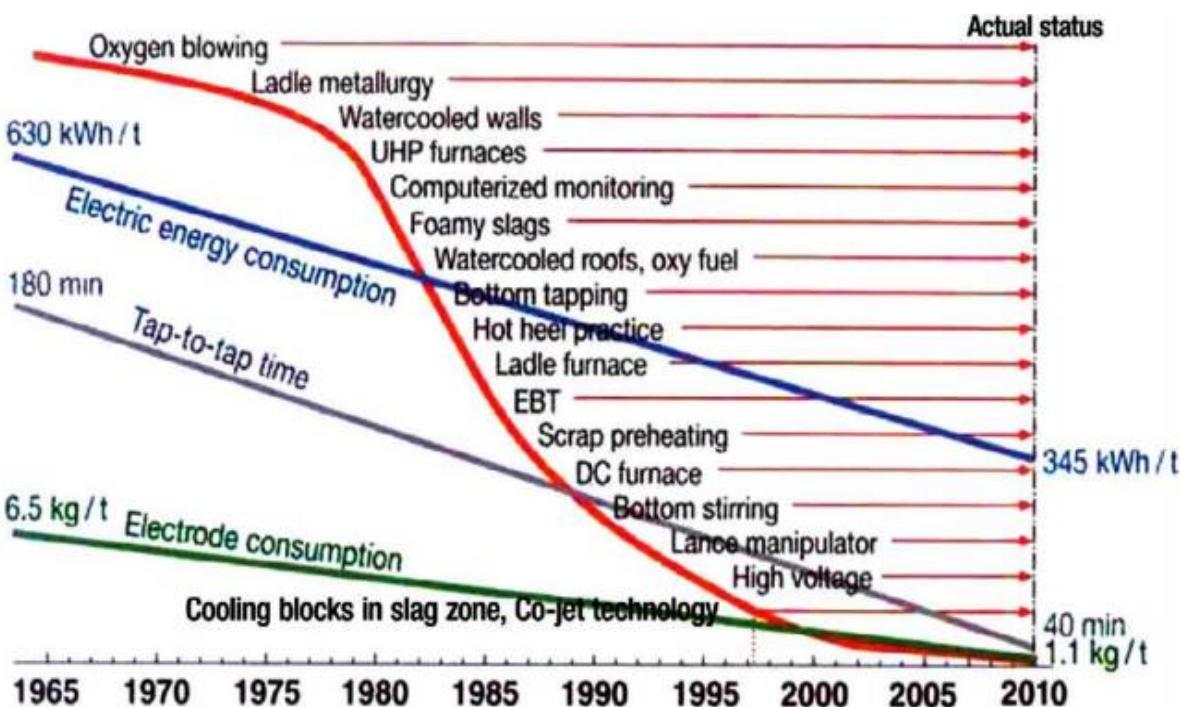
EAFs in countries with high electricity and scrap costs tend to use more chemical energy and to use more direct reduced iron (DRI) as raw material. Main differences in the operative practices between carbon and stainless steels is that in carbon steels, large quantities of oxygen and carbon are injected toward the end of the batch with the target of creating a foamy slag layer on the top of the liquid metal which can be sufficiently deep to cover the electric arc. On the other hand, stainless steel is produced without carbon injections, and the arc mostly remains uncovered throughout the batch time.

The EAF slag has been seen to have higher FeO% compared to oxygen converters. This is a direct consequence of lower stirring energy inherent in the EAF process

- The three phase alternating current is supplied by the low voltage side (300 - 700V) of a high-power transformer.
- The nominal transformer rating, expressed as KVA/t, extends from 300 to 500 KVA/t for high power furnaces and from 500 KVA/t upwards for Ultra High Power (UHP) furnaces.
- These furnaces have an inner diameter of 6 to 9 meters with a capacity of 100 to 200 tons of steel.
- The UHP furnace operates with only a lime based oxidising slag. The melt down of the scrap charge is accelerated by the use of oxy-fuel burners positioned to reach the cold spots of the large hearth furnace. Oxygen lancing and carbon additions are used to make a foaming slag which yields better energy input from the arcs and improves dephosphorisation.
- The 100% scrap charge makes the process more vulnerable to injurious 'tramp elements,' such as copper, nickel, and tin which cannot be removed by the process, their stability being higher than that of iron.
- To control these tramp elements, it is of great importance to identify the sources of the incoming



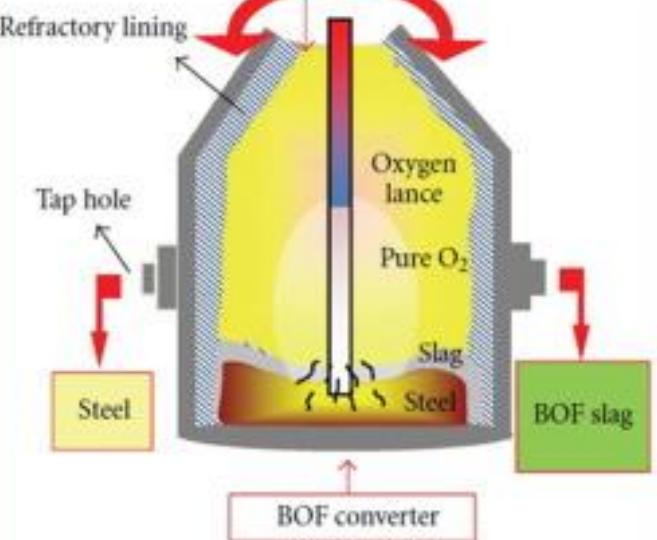
Depending upon the melt shop operation, about **60 to 65% of the total energy is electric**, the remainder being chemical energy arising from the oxidation of elements such as carbon, iron, and silicon and the burning of natural gas with oxy-fuel burners. About **53% of the total energy leaves the furnace** in the liquid steel, while the remainder is lost to the slag, waste gas, and cooling.



Basic-oxygen-furnace steelmaking

(Linz and Donawitz process)

Molten iron (70–75%) +
steel scraps (25–30%) +
lime/dolomite



Electric-arc-furnace steelmaking



Ladle furnace (refining center)

