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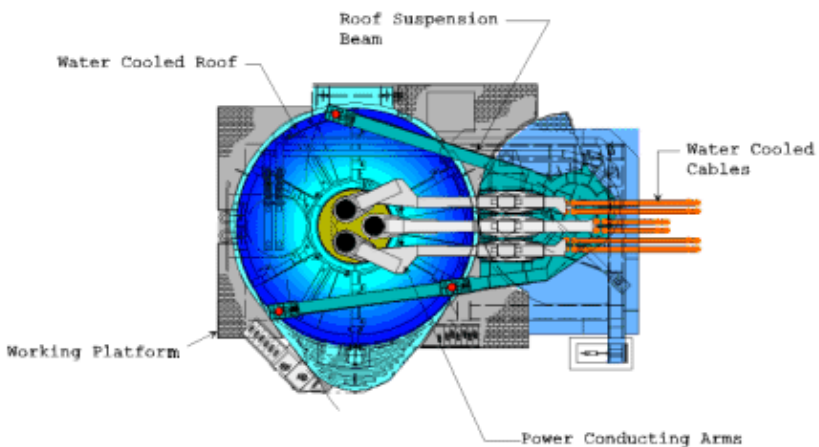
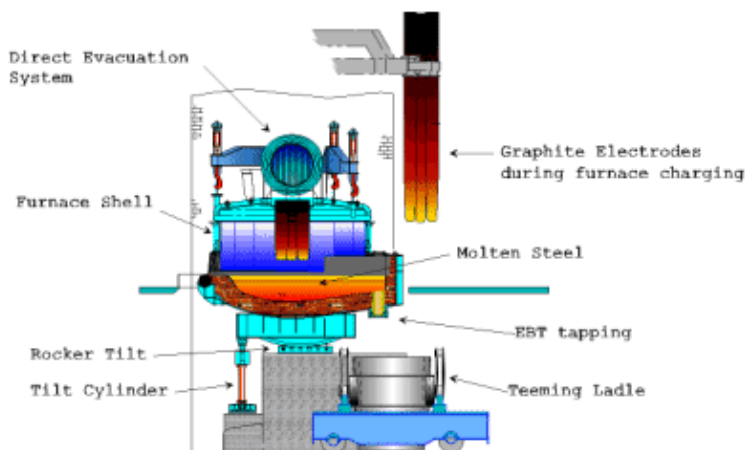
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### Electric Arc Furnace Steelmaking By Jeremy A. T. Jones, Nupro Corporation



Courtesy of Mannesmann Demag Corp.

#### FURNACE OPERATIONS

The electric arc furnace operates as a batch melting process producing batches of molten steel known "heats". The electric arc furnace operating cycle is called the tap-to-tap cycle and is made up of the following operations:

- Furnace charging
- Melting
- Refining
- De-slagging
- Tapping
- Furnace turn-around

Modern operations aim for a tap-to-tap time of less than 60 minutes. Some twin shell furnace operations are achieving tap-to-tap times of 35 to 40 minutes.

### Furnace Charging

The first step in the production of any heat is to select the grade of steel to be made. Usually a schedule is developed prior to each production shift. Thus the melter will know in advance the schedule for his shift. The scrap yard operator will prepare buckets of scrap according to the needs of the melter. Preparation of the charge bucket is an important operation, not only to ensure proper melt-in chemistry but also to ensure good melting conditions. The scrap must be layered in the bucket according to size and density to promote the rapid formation of a liquid pool of steel in the hearth while providing protection for the sidewalls and roof from electric arc radiation. Other considerations include minimization of scrap cave-ins which can break electrodes and ensuring that large heavy pieces of scrap do not lie directly in front of burner ports which would result in blow-back of the flame onto the water cooled panels. The charge can include lime and carbon or these can be injected into the furnace during the heat. Many operations add some lime and carbon in the scrap bucket and supplement this with injection.

The first step in any tap-to-tap cycle is "charging" into the scrap. The roof and electrodes are raised and are swung to the side of the furnace to allow the scrap charging crane to move a full bucket of scrap into place over the furnace. The bucket bottom is usually a clam shell design - i.e. the bucket opens up by retracting two segments on the bottom of the bucket. The scrap falls into the furnace and the scrap crane removes the scrap bucket. The roof and electrodes swing back into place over the furnace. The roof is lowered and then the electrodes are lowered to strike an arc on the scrap. This commences the melting portion of the cycle. The number of charge buckets of scrap required to produce a heat of steel is dependent primarily on the volume of the furnace and the scrap density. Most modern furnaces are designed to operate with a minimum of back-charges. This is advantageous because charging is a dead-time where the furnace does not have power on and therefore is not melting. Minimizing these dead-times helps to maximize the productivity of the furnace. In addition, energy is lost every time the furnace roof is opened. This can amount to 10 - 20 kWh/ton for each occurrence. Most operations aim for 2 to 3 buckets of scrap per heat and will attempt to blend their scrap to meet this requirement. Some operations achieve a single bucket charge. Continuous charging operations such as CONSTEEL and the Fuchs Shaft Furnace eliminate the charging cycle.

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### Melting

The melting period is the heart of EAF operations. The EAF has evolved into a highly efficient melting apparatus and modern designs are focused on maximizing the melting capacity of the EAF. Melting is accomplished by supplying energy to the furnace interior. This energy can be electrical or chemical. Electrical energy is supplied via the graphite electrodes and is usually the largest contributor in melting operations. Initially, an intermediate voltage tap is selected until the electrodes bore into the scrap. Usually, light scrap is placed on top of the charge to accelerate bore-in. Approximately 15 % of the scrap is melted during the initial bore-in period. After a few minutes, the electrodes will have penetrated the scrap sufficiently so that a long arc (high voltage) tap can be used without fear of radiation damage to the roof. The long arc maximizes the transfer of power to the scrap and a liquid pool of metal will form in the furnace hearth. At the start of melting the arc is erratic and unstable. Wide swings in current are observed accompanied by rapid movement of the electrodes. As the furnace atmosphere heats up the arc stabilizes and once the molten pool is formed, the arc becomes quite stable and the average power input increases.

Chemical energy is supplied via several sources including oxy-fuel burners and oxygen lances. Oxy-fuel burners burn natural gas using oxygen or a blend of oxygen and air. Heat is transferred to the scrap by flame radiation and convection by the hot products of combustion. Heat is transferred within the scrap by conduction. Large pieces of scrap take longer to melt into the bath than smaller pieces. In some operations, oxygen is injected via a consumable pipe lance to "cut" the scrap. The oxygen reacts with the hot scrap and burns iron to produce intense heat for cutting the scrap. Once a molten pool of steel is generated in the furnace, oxygen can be lanced directly into the bath. This oxygen will react with several components in the bath including, aluminum, silicon, manganese, phosphorus, carbon and iron. All of these reactions are exothermic (i.e. they generate heat) and supply additional energy to aid in the melting of the scrap. The metallic oxides that are formed will end up in the slag. The reaction of oxygen with carbon in the bath produces carbon monoxide, which either burns in the furnace if there is sufficient oxygen, and/or is exhausted through the direct evacuation system where it is burned and conveyed to the pollution control system. Auxiliary fuel operations are discussed in more detail in the section on EAF operations.

Once enough scrap has been melted to accommodate the second charge, the charging process is repeated. Once the final scrap charge is melted, the furnace sidewalls are exposed to intense radiation from the arc. As a result, the voltage must be reduced. Alternatively, creation of a foamy slag will allow the arc to be buried and will protect the furnace shell. In addition, a greater amount of energy will be retained in the slag and is transferred to the bath resulting in greater energy efficiency.

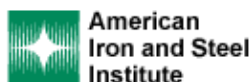
Once the final scrap charge is fully melted, flat bath conditions are reached. At this point, a bath temperature and sample will be taken. The analysis of the bath chemistry will allow the melter to determine the amount of oxygen to be blown during refining. At this point, the melter can also start to arrange for the bulk tap alloy additions to be made. These quantities are finalized after the refining period.

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### Electric Arc Furnace Steelmaking By Jeremy A. T. Jones, Nupro Corporation continued

- Furnace charging
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#### Refining

Refining operations in the electric arc furnace have traditionally involved the removal of phosphorus, sulfur, aluminum, silicon, manganese and carbon from the steel. In recent times, dissolved gases, especially hydrogen and nitrogen, been recognized as a concern. Traditionally, refining operations were carried out following meltdown i.e. once a flat bath was achieved. These refining reactions are all dependent on the availability of oxygen. Oxygen was lanced at the end of meltdown to lower the bath carbon content to the desired level for tapping. Most of the compounds which are to be removed during refining have a higher affinity for oxygen than the carbon. Thus the oxygen will preferentially react with these elements to form oxides which float out of the steel and into the slag.

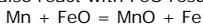
In modern EAF operations, especially those operating with a "hot heel" of molten steel and slag retained from the prior heat, oxygen may be blown into the bath throughout most of the heat. As a result, some of the melting and refining operations occur simultaneously.

Phosphorus and sulfur occur normally in the furnace charge in higher concentrations than are generally permitted in steel and must be removed. Unfortunately the conditions favorable for removing phosphorus are the opposite of those promoting the removal of sulfur. Therefore once these materials are pushed into the slag phase they may revert back into the steel. Phosphorus retention in the slag is a function of the bath temperature, the slag basicity and FeO levels in the slag. At higher temperature or low FeO levels, the phosphorus will revert from the slag back into the bath. Phosphorus removal is usually carried out as early as possible in the heat. Hot heel practice is very beneficial for phosphorus removal because oxygen can be lanced into the bath while its temperature is quite low. Early in the heat the slag will contain high FeO levels carried over from the previous heat thus aiding in phosphorus removal. High slag basicity (i.e. high lime content) is also beneficial for phosphorus removal but care must be taken not to saturate the slag with lime. This will lead to an increase in slag viscosity, which will make the slag less effective. Sometimes fluorspar is added to help fluidize the slag. Stirring the bath with inert gas is also beneficial because it renews the slag/metal interface thus improving the reaction kinetics.

In general, if low phosphorus levels are a requirement for a particular steel grade, the scrap is selected to give a low level at melt-in. The partition of phosphorus in the slag to phosphorus in the bath ranges from 5 to 15. Usually the phosphorus is reduced by 20 to 50 % in the EAF.

Sulfur is removed mainly as a sulfide dissolved in the slag. The sulfur partition between the slag and metal is dependent on slag chemistry and is favored at low steel oxidation levels. Removal of sulfur in the EAF is difficult especially given modern practices where the oxidation level of the bath is quite high. Generally the partition ratio is between 3 and 5 for EAF operations. Most operations find it more effective to carry out desulfurization during the reducing phase of steelmaking. This means that desulfurization is performed during tapping (where a calcium aluminate slag is built) and during ladle furnace operations. For reducing conditions where the bath has a much lower oxygen activity, distribution ratios for sulfur of between 20 and 100 can be achieved.

Control of the metallic constituents in the bath is important as it determines the properties of the final product. Usually, the melter will aim at lower levels in the bath than are specified for the final product. Oxygen reacts with aluminum, silicon and manganese to form metallic oxides, which are slag components. These metallics tend to react with oxygen before the carbon. They will also react with FeO resulting in a recovery of iron units to the bath. For example:



Manganese will typically be lowered to about 0.06 % in the bath.

The reaction of carbon with oxygen in the bath to produce CO is important as it supplies a less expensive form of energy to the bath, and performs several important refining reactions. In modern EAF operations, the combination of oxygen with carbon can supply between 30 and 40 % of the net heat input to the furnace. Evolution of carbon monoxide is very important for slag foaming. Coupled with a basic slag, CO bubbles are tapped in the slag causing it to "foam" and helping to bury the arc. This gives greatly improved thermal efficiency and allows the furnace to operate at high arc voltages even after a flat bath has been achieved. Burying the arc also helps to prevent nitrogen from being exposed to the arc where it can dissociate and enter into the steel.

If the CO is evolved within the steel bath, it helps to strip nitrogen and hydrogen from the steel. Nitrogen levels in steel as low as 50 ppm can be achieved in the furnace prior to tap. Bottom tapping is beneficial for maintaining low nitrogen levels because tapping is fast and a tight tap stream is maintained. A high oxygen potential in the steel is beneficial for low nitrogen levels and the heat should be tapped open as opposed to blocking the heat.

At 1600 C, the maximum solubility of nitrogen in pure iron is 450 ppm. Typically, the nitrogen levels in the steel following tapping are 80 - 100 ppm.

Decarburization is also beneficial for the removal of hydrogen. It has been demonstrated that decarburizing at a rate of 1 % per hour can lower hydrogen levels in the steel from 8 ppm down to 2 ppm in 10 minutes.

At the end of refining, a bath temperature measurement and a bath sample are taken. If the temperature is too low, power may be applied to the bath. This is not a big concern in modern meltshops where temperature adjustment is carried out in the ladle furnace.

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**De-Slagging**

De-slagging operations are carried out to remove impurities from the furnace. During melting and refining operations, some of the undesirable materials within the bath are oxidized and enter the slag phase.

It is advantageous to remove as much phosphorus into the slag as early in the heat as possible (i.e. while the bath temperature is still low). The furnace is tilted backwards and slag is poured out of the furnace through the slag door. Removal of the slag eliminates the possibility of phosphorus reversion.

During slag foaming operations, carbon may be injected into the slag where it will reduce FeO to metallic iron and in the process produce carbon monoxide which helps foam the slag. If the high phosphorus slag has not been removed prior to this operation, phosphorus reversion will occur. During slag foaming, slag may overflow the sill level in the EAF and flow out of the slag door.

The following table shows the typical constituents of an EAF slag :

Component	Source	Composition Range
CaO	Charged	40 - 60 %
SiO <sub>2</sub>	Oxidation product	5 - 15 %
FeO	Oxidation product	10 - 30 %
MgO	Charged as dolomite	3 - 8 %
CaF <sub>2</sub>	Charged - slag fluidizer	
MnO	Oxidation product	2 - 5%
S	Absorbed from steel	
P	Oxidation product	

**Tapping**

Once the desired steel composition and temperature are achieved in the furnace, the tap-hole is opened, the furnace is tilted, and the steel pours into a ladle for transfer to the next batch operation (usually a ladle furnace or ladle station). During the tapping process bulk alloy additions are made based on the bath analysis and the desired steel grade. De-oxidizers may be added to the steel to lower the oxygen content prior to further processing. This is commonly referred to as "blocking the heat" or "killing the steel". Common de-oxidizers are aluminum or silicon in the form of ferrosilicon or silicomanganese. Most carbon steel operations aim for minimal slag carry-over. A new slag cover is "built" during tapping. For ladle furnace operations, a calcium aluminate slag is a good choice for sulfur control. Slag forming compounds are added in the ladle at tap so that a slag cover is formed prior to transfer to the ladle furnace. Additional slag materials may be added at the ladle furnace if the slag cover is insufficient.

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**Furnace Turn-around**

Furnace turn-around is the period following completion of tapping until the furnace is recharged for the next heat. During this period, the electrodes and roof are raised and the furnace lining is inspected for refractory damage. If necessary, repairs are made to the hearth, slag-line, tap-hole and spout. In the case of a bottom-tapping furnace, the taphole is filled with sand. Repairs to the furnace are made using gunned refractories or mud slingers. In most modern furnaces, the increased use of water-cooled panels has reduced the amount of patching or "fettling" required between heats. Many operations now switch out the furnace bottom on a regular basis (2 to 6 weeks) and perform the hearth maintenance off-line. This reduces the power-off time for the EAF and maximizes furnace productivity. Furnace turn-around time is generally the largest dead time (i.e. power off) period in the tap-to-tap cycle. With advances in furnace practices this has been reduced from 20 minutes to less than 5 minutes in some newer operations.

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**Furnace Heat Balance**

To melt steel scrap, it takes a theoretical minimum of 300 kWh/ton. To provide superheat above the melting point of 2768 F requires additional energy and for typical tap temperature requirements, the total theoretical energy required usually lies in the range of 350 to 370 kWh/ton. However, EAF steelmaking is only 55 to 65 % efficient and as a result the total equivalent energy input is usually in the range of 560 to 680 kWh/ton for most modern operations. This energy can be supplied from a variety of sources as shown in the table below. The energy distribution is highly dependent on local material and consumable costs and is unique to the specific meltshop operation. A typical balance for both older and more modern EAFs is given in the following Table:

		<b>UHP FURNACE</b>	<b>Low to Medium Power Furnace</b>
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	Electrical Energy	50 - 60 %	75 - 85 %
<b>INPUTS</b>	Burners	5 - 10 %	
	Chemical Reactions	30 - 40 %	15 - 25 %
<b>TOTAL INPUT</b>		100%	100%
<b>OUTPUTS</b>	Steel	55 - 60 %	50 - 55 %
	Slag	8 - 10 %	8 - 12 %
	Cooling Water	8 - 10 %	5 - 6 %
	Miscellaneous	1 - 3 %	17 - 30 %
	Offgas	17 - 28 %	7 - 10 %

Of course the above figures are highly dependent on the individual operation and vary considerably from one facility to another. Factors such as raw material composition, power input rates and operating practices (e.g. post-combustion, scrap preheating) can greatly alter the above balance. In operations utilizing a large amount of charge carbon or high carbon feed materials, up to 60 % of the energy contained in the offgas may be calorific due to large quantities of un-combusted carbon monoxide. Recovery of this energy in the EAF could increase energy input by 8 to 10 %. Thus it is important to consider such factors when evaluating the energy balance for a given furnace operation.

The [International Iron and Steel Institute \(IISI\)](#), classifies EAFs based on the power supplied per ton of furnace capacity. For most modern operations, the design would allow for at least 500 kVA per ton of capacity. The IISI report "The Electric Furnace - 1990" indicates that most new installations allow 900 - 1000 kVA per ton of furnace capacity. Most furnaces operate at a maximum power factor of about 0.85. Thus the above transformer ratings would correspond to a maximum power input of about 0.75 to 0.85 MW per ton of furnace capacity.

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## MECHANICAL SYSTEMS

Mechanical systems are integral to the operation of the EAF and many are inter-related. To gain a better perspective of the importance of various systems in the furnace operation, it is good to step back and evaluate the function of the electric arc furnace itself. The EAF has several primary functions:

1. Containment of steel scrap
2. Heating and melting of steel scrap
3. Transfer of molten steel to the next processing stage

It is easy to see that the first function, scrap containment can only be properly carried out if the furnace shell is properly maintained. The furnace shell consists of a refractory lined bottom that helps contain the liquid steel and typically, a water-cooled upper section that only comes into contact with scrap and slag. Heating and melting of the scrap are accomplished by supplying electrical energy through the electrodes and chemical energy through the use of burners and oxygen lances. Transfer of the liquid steel to the ladle is accomplished by tilting the furnace and opening either a tapping spout or a bottom tap-hole to allow the steel to flow from the furnace. It is apparent that many sub-systems come into play throughout the tap-to-tap cycle. Many of these systems are dependent of the following systems in order to be able to function properly:

- [Hydraulic system](#)
- [Cooling water system](#)
- [Lubrication System](#)

### Hydraulic system

The hydraulic system provides motive power for almost all EAF movements including roof lower/raise, roof swing, electrode arms up/down/regulation/swing, furnace tilt forward/backward, slag door raise/lower and movement of any auxiliary systems such as the burner lance. The hydraulic system consists of a central reservoir, filters, an accumulator, hydraulic valves and hydraulic piping. As hydraulic fluid passes through valves in one of two directions within a given circuit, hydraulic cylinders are extended or contracted to provide movement of various mechanical components. Without sufficient fluid flow and pressure within a circuit, movement is impossible. Thus issues such as low fluid level, low accumulator pressure, system leaks, fluid degradation due to over-heating, solids build-up in valves or in hydraulic lines and wear in mechanical components can lead to poor system performance and in some cases, system failure.

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### Cooling water system

Another system that is integral to EAF operation is the cooling water system. Typically, there are several cooling systems. Some operations require extremely clean, high quality cooling water. Transformer cooling, delta closure cooling, bus tube cooling and electrode holder cooling are all such applications. Typically, these systems will consist of a closed loop circuit, which conducts water through these sensitive pieces of equipment. The water in the closed loop circuit passes through a heat exchanger to remove heat. The circuit on the open loop side of the heat exchanger typically flows to a cooling tower for energy dissipation. Other water cooled elements such as furnace side panels, roof panels, offgas system ducting, furnace cage etc. will typically receive cooling water from a cooling tower.

The cooling circuit typically consists of supply pumps, return pumps, filters, a cooling tower cell or cells and flow monitoring instrumentation. Sensitive pieces of equipment normally have instrumentation installed to monitor the cooling water flow rate and temperature. For most water-cooled equipment, interruption of the flow or inadequate water quantities can lead to severe thermal over loading and in some cases catastrophic failure.

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### Lubrication System

Many modern furnaces have an automatic system that provides lubrication to various moving parts based on various "events" occurring during the tap-to-tap cycle. For example, some parts are lubricated every three roof swings, following tapping, etc.

Some components such as roller bearings are critical to furnace operation and are lubricated periodically by hand. Some hard to reach locations are serviced using tubing and remote blocks.

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#### AUXILIARY SYSTEMS

In addition to the major mechanical systems associated with the EAF, there are also many auxiliary systems that are integral to furnace operation and performance.

##### **Oxygen lance system**

Over the past 20 years, the use of oxygen in EAF steelmaking has grown considerably. In the past when oxygen consumption of less than 300 cubic feet per ton of steel were common, lancing operations were carried out manually using a consumable pipe lance. Most modern operations now use automatic lances and most facilities now use a non-consumable, water-cooled lance for injecting oxygen into the steel. Many of these lances also have the capability to inject carbon as well.

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##### **Carbon injection system**

Carbon injection is critical to slag foaming operations, which are necessary for high power furnace operations. Carbon reacts with FeO to form CO and "foam" the slag.

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##### **Oxy-fuel burner system**

Oxy-fuel burners are now almost standard equipment on large high-powered furnaces. In operations with short tap-to-tap times, they provide an important function by ensuring rapid melting of the scrap in the cold spots. This ensures that scrap cave-ins are kept to a minimum and as a result, electrode breakage is minimized. In large diameter furnaces, burners are essential to ensure a uniform meltdown. Non-uniform scrap meltdowns may result in operating delays and lost productivity. The biggest maintenance issue for burners is to ensure that they do not get plugged with metal or slag. The closer burners are mounted to the bath, the greater the risk of them becoming plugged while in a low-fire mode. Some burners are mounted directly in the water-cooled panel while others are mounted in a copper block. If burners are fired at high rates against large pieces of scrap, the flame can blow back on the furnace shell damaging the water-cooled panel. Thus the panel area should be inspected for wear around the burner port. If a copper block is used, it will be more resistant to flame blow back but should still be inspected regularly for wear and cracks.

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##### **Electrode spray cooling system**

It is common for electrodes to have a spray cooling system in order to reduce electrode oxidation. Spray rings direct water sprays at the electrode below the electrode clamp and the water runs down the electrode thus cooling it. Sprays rings can reduce overall electrode consumption by as much as 10-20%. In addition, spray cooling usually results in improved electrode holder life and surrounding insulation. Due to the reduction in radiation from the electrode, power cable, air hose and hydraulic hose life is also greatly improved.

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##### **Temperature Sampling System**

The modern disposable thermocouple was introduced to steelmaking almost 40 years ago and temperature measurement had become an integral part of tracking progress throughout the tap-to-tap cycle in steelmaking. Expendable probes are also used for tracking bath carbon content and dissolved oxygen levels in the steel. These tools have enabled the tap-to-tap cycle to be accelerated by eliminating long waiting periods for lab results, thus increasing productivity. Disposable probes are typically mounted in cardboard sleeves that slide on to a steel probe (pole) which has internal electrical contacts. The disposable probe transmits an electrical signal to the steel pole, which in turn transmits the signal to an electronic unit for interpretation. Almost all probes rely on an accurate temperature measurement to precisely calculate carbon or oxygen levels. Most facilities keep several spare poles on hand so that they can be quickly replaced if they have reading problems.

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##### **Offgas Direct Evacuation System**

Early offgas evacuation systems were installed so that the furnace operators could better see what was happening in and around the furnace. Since the early days of EAF steelmaking, the offgas system has evolved considerably and most modern EAF shops now use a "fourth hole" direct furnace shell evacuation system (DES). The term fourth hole refers to an additional hole other than those for the electrodes, which is provided for offgas extraction. On DC furnaces with only one electrode, the fume extraction port is sometimes referred to as the "second hole". It is important to maintain sufficient draft on the furnace for the following reasons:

1. To provide adequate pollution control.
2. Excessive shop emissions make it difficult for the crane operator to charge the furnace.
3. Excessive emissions around the electrode ports can result in damage of hoses, cables, the electrode holder, the furnace delta, roof refractory, accelerated electrode wear, damage to the electrode spray cooler etc.
4. Emissions at the roof ring can result in warping of the roof ring structure.
5. Excessive emissions of carbon monoxide to the secondary canopy system may result in explosions in the ductwork downstream.
6. Excessive dust build-up may cause arcing between electrode phases.

Most DES systems consist of water-cooled duct, spray cooling, dry duct and may or may not have a dedicated DES booster fan.

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#### ELECTRICAL SYSTEMS

Electrical systems in an EAF meltshop usually consist of a primary system which supplies power from the electrical utility; and the secondary electrical system which steps down the voltage from the utility and supplies the power to the EAF. The primary system may include a yard step-down transformer as part of the steelmaker's facility and this transformer will feed several other transformers within the facility including the EAF transformer. Regardless, there will be a main breaker which isolates all of the steelmaking facility's electrical systems from the power utility. On the secondary side of the primary electrical system, a vacuum switch and motorized disconnect are used to isolate the secondary furnace transformer from the primary power supply.

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#### Vacuum Switch

The vacuum switch is a long life switch that is generally used in all electric furnace applications. The traditional vacuum switch allows for the secondary electrical circuit to be broken either under load or without load. Most vacuum switches are rated for 40,000 operations or four years. In practice, it is not unusual for such switches to achieve 200,000 operations without maintenance. The primary cause of failure in these units is a metallic bellows, which is used to provide a seal for the moving contact, which is enclosed in a vacuum. Once this seal begins to wear (typically after 100,000 operations), a vacuum leak will occur thus making it difficult to adequately isolate the primary power from the secondary.

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#### Motorized Disconnect Switch

The motorized disconnect switch (MDS) is typically a motorized knife gate switch which is capable of physically isolating the EAF from the primary power supply. The knife switches are retracted when the furnace is not under load (vacuum switch open, electrodes raised) so that arcing does not occur between the blades on either side of the switch. [Top](#)

#### EAF Transformer

The power flow from the utility's generators, through their network, arrives at the steel plant at very high voltage and must therefore be converted to low voltage suitable for the furnace arcs. Transformers perform this task. The EAF transformer receives the primary low current, high voltage power and transforms this to a high current, low voltage power for use in the EAF. Reliable operation of the EAF is totally dependent on reliable operation of the EAF transformer. Many large furnace transformers are rated 100MVA or greater.

Transforming the power from the kV level at the incoming utility line to the voltage level needed in the EAF is usually done in two stages. A first transformer (occasionally two transformers in parallel) steps the voltage down from the high-voltage line to a medium voltage level which is generally standardized for each country. In the USA this medium voltage is usually 34.5 kV, while in Europe, Japan and other areas the voltages are not very different, often 30 to 33 kV. From the 34.5 kV busbar, the arc furnace is powered by a special, heavy-duty furnace transformer. The secondary voltage of this furnace transformer is designed to allow operation of the arcs in the desired range of arc voltages and currents. Since there are varying requirements of arc voltage/current combinations through the heat it is necessary to have a choice of secondary voltages. The furnace transformer is equipped with a **tap-changer** for this purpose.

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#### Tap changer

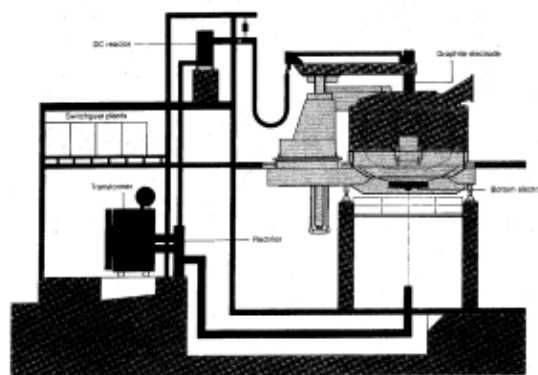
The purpose of a tap changer is to allow a choice of different combinations of volts and amps for different stages of a heat. This is achieved by changing the number of turns of primary coil. (The primary takes lower current so it is simpler to change the number of turns on this coil rather than the high current secondary coil). Basically the tap changer takes the form of a motorized box of contacts which switch the primary current to different parts of the coil around the iron core. Most tap changers are designed to operate "on-load" meaning switching the primary current, usually in 2 kA steps, at 34.5 kV. A 'make-before-break' contact movement is used to avoid current interruption. These contacts are subject to heavy erosion due to arcing and therefore require preventative maintenance.

Some steelmakers choose an 'off-load' tap changer in order to avoid the heavy duty of on-load switching. However, such a tap changer requires that the steelmaker break the arc by lifting the furnace electrodes and this procedure may take as long as one minute. Today such a delay each time a tap is changed is intolerable and such designs are becoming rare.

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### SECONDARY ELECTRICAL CIRCUIT

The secondary circuit of the EAF electrical system consists of five major components: delta closure, power cable, bus tube/conducting arm, electrode clamp/holder and the electrode.



**Typical DC EAF Arrangement – SMS-GHH**

#### Delta Closure

The secondary circuit of the EAF transformer terminates at low voltage bushings, which are attached to the delta closure, which consists of a series of copper plates, tubes or both. These are arranged so that the secondary windings of the transformer are joined to form a closed circuit. Most of this equipment is located within the transformer vault to assure a secure, clean environment. The delta closure protrudes through the wall of the vault adjacent to the EAF and connectors are provided to attach to one end of the furnace power cables; the other end being attached to either the current conducting arms of the furnace or the busbar.

In the case of the direct current EAF, the thyristor will have two copper terminations; one of which is attached to the EAF power cable, and other is attached to the bottom furnace electrode. The bottom furnace electrode is usually rigid, as no movement is required during operation of the furnace. In principle, the termination on the thyristor is analogous to the delta closure, though physically, it differs considerably. With respect to the maintenance issues for the delta closure, however, the

same concepts can be applied to the DC operation.

Bus systems are typically supported at the transformer vault wall and may also be supported from stainless steel hangers suspended from the vault ceiling. Suspension systems for secondary bus or delta closures are frequently supported at the vault wall with kiln dried timbers.

Secondary bus systems and delta closures are insulated in order to prevent arcing from phase to phase and from phase to ground especially at the support members.

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#### **Furnace Power Cables**

The water-cooled furnace power cables provide the only flexible connection in the secondary circuit. These cables must be flexible to permit movement of the electrode arms up and down and to allow swinging the electrode arms and roof when charging of the furnace. The connections from the delta closure, which are on the outside of the transformer vault, are silver plated to provide a clean contact for the power cables. The power cables consist of copper wire strandings forming a cylindrical construction, which is soldered to copper terminals at either end of the cable. A rubber jacket around the outside of the cable permits cooling water for the cable. The rubber hose is attached at either end of the cable using stainless steel clamps, vulcanized bumpers or an anti-chaffing hose. The cooling water hose is covered with a protective sleeve which may be fabricated of fiberglass, vulcanized material, and silicon or aluminum glass fiber sleeves. As cable design advanced, it was noted that due to the "skin effect" typical of AC operations, the current was carried predominantly by the outer portion of the copper strands. Therefore the center strands were replaced with a hollow rubber tube which reduced the cable weight, the reactance and the cost of the cable. At a later date, some operations used this inner channel for water cooling as well.

In DC furnace operations, the inner rubber tube in the cable is used for cooling because DC operations do not experience the "skin effect" and the whole cross section of the copper cable carries the current uniformly. However, DC cables are cooled more effectively from the center and cooling from the outside is not always used.

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#### **Bus Bar / Current Conducting Arm**

Several designs now exist for the electrode arm and bus-bar assembly. Many older furnaces utilize an arm structure that supports an electrically insulated bus-bar. The bus-bar provides the electrical connection between the power cables and the electrode holder. Bus-bars consist of a rigid, round, copper pipe. Typically the bus tube is supported by one or two bolted connections. Good insulation must be installed between the bus tube and its supporting members to ensure that arcing which could destroy the bus tube does not take place. Bus tubes are usually attached to the power cables using removable, cast copper terminals or in some cases, permanent fabricated copper terminal plates and pads.

Several configurations are available for the bus tube termination at the electrode holder and contact pad. These include flanged connection to the contact pad, flat blade joined to the tube for parallel connection with the holder and a round copper tube contact point with the connector. The bus tubes may be bolted to the holder or contact pad or a fused permanent joint may be used.

Many modern furnaces utilize current conducting arms in which the arm itself transmits electricity to the electrode holder and contact pad. Current conducting arms are usually fabricated from copper clad steel or aluminum alloys. Due to the reduced weight of conducting arms as opposed to conventional arm and bus tube assemblies there is somewhat less mechanical wear. However, many of the same maintenance issues apply both to bus tube assemblies and current conducting arms.

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#### **Electrode Heads/Contact pads**

The Electrode heads and contact pads provide the final connection between the power supply and the graphite electrode. They are exposed to extreme mechanical conditions (vibration, torsion etc.) and thermal cycling and as a result are the weakest link in the secondary circuit. Traditional electrode holders are either cast or fabricated from copper plates. Contact pads are smaller and incorporate only the electrode contact area. In traditional electrode holders, the electrode is pushed forward into the contact area. In the case of contact pads, the electrode is pulled back with steel housing equipment to make contact with the pad. The current transfer between the contact pad and the electrode occurs in the lower 3 or 4 inches. Proper clamping for is a necessity in order to prevent arcing between the electrode and the contact area. Any dirt build-up in this area will result in resistance to current flow and will cause over-heating and damage to the electrode holder/contact pad.

Typically cooling water requirements will vary from 2 to 40 gallons per minute depending on the electrode size, water quality, clamping force and maintenance of a clean contact area. The contact area should be cleaned regularly to remove oxidation, carbon build-up and other material build-up in this area.

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#### **Electrode Regulation**

Typically, the electrode/arm/mast/cable assembly weighs in the range of 20 tons. This is moved vertically for control purposes by a hydraulic cylinder incorporated in the mast. (In some older furnaces the movement is effected by an electric motor/cable winch arrangement). Since the arc length is dependent, amongst other things, on the ever changing level of scrap or liquid under the electrode it is necessary to have an automatic control over electrode position -- the regulation system.

The regulation system influences many important aspects of furnace performance, such as energy input, mean current, arc stability, scrap melting pattern, energy losses to water-cooled panels, energy, electrode and refractory consumption. All these parameters are interrelated in a complex manner and there are many differences of opinion on 'optimum' control strategies.

The accepted "standard" handling of the electrical signals is to form an "impedance control". This method attempts to hold the ratio of voltage to electrical current constant, hence its description as 'impedance' control. A voltage signal taken from the phase to ground and a current signal are each separately rectified and their dc values are compared "back-to back". If the voltage and current are each at a desired level - the set point, chosen by the steelmaker - the output from this comparison of signals is arranged to be zero. If however the current exceeds this level its signal increases and simultaneously the voltage decreases. Then the two back-to back voltages do not balance and an output voltage is generated. This signal goes to the regulating valve in such a way to command the electrode to raise, aimed at reducing current

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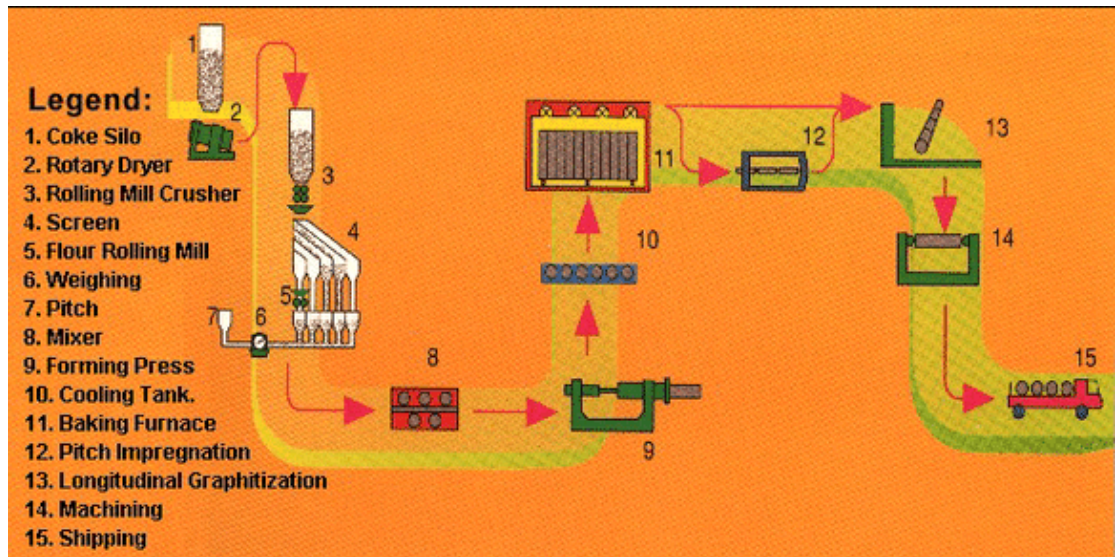
## **ELECTRODES**

(By William A. Obenchain, AISI and Steve Casto, UCAR Corp)

One of the most important elements in the electric circuit and consumable cost in electric furnace steelmaking are the electrodes. The electrodes deliver the power to the furnace in the form of an electric arc between the electrode and the furnace



charge. The arc itself is a plasma of hot, ionic gasses in excess of 6,000°F. Electrodes come in two forms: amorphous and graphitic carbon, or graphite. Since only graphite electrodes are used in steelmaking only they will be discussed here.



Courtesy of UCAR Corp.

Graphite electrodes are composed of a mixture of finely divided, calcined petroleum coke mixed with about 30% coal tar pitch as a binder, plus proprietary additives unique to each manufacturer. This mixture is extruded at approximately 220°F, the softening temperature of pitch, to form a cylindrical rod known as a "green electrode". The green electrode is now given a controlled bake in a reducing atmosphere at temperatures as high as 1800°F and again impregnated with pitch to increase its strength and density and lower the electrical resistivity. The electrodes are now ready to be graphitized, i.e. converting the amorphous carbon into crystalline graphite. This is accomplished by passing an electric current through them and heating them to as much as 5000°F. The graphitizing consumes as much as 3000-5000kWH/ton of electrode. The final product is strong, dense, and has a low electrical resistivity. Lastly the electrode is machined to its final shape. Into each end of the electrode is a recess in which threads are machined. These are used to accept a threaded nipple manufactured in the same way so that the electrode column can be lengthened as it is consumed.

Historically, electrode consumption has been as high as 12-14 pounds per tons of steel, but through continuous improvement in electrode manufacturing and steelmaking operations, this has been reduced to the neighborhood 3.5 to 4.5 pounds per ton. Most electrode consumption is through oxidation and tip sublimation, with some small pieces lost around the connecting joint. A considerable portion is also lost to mechanical breakage caused by scrap scrap cave-ins in the furnace or crushing the electrode into the charge.

Electrodes are commonly available in sizes from 15 - 30 inches in diameter varying lengths to 10 feet. They come in three grades: regular and premium and the newer DC grade.

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