

COMMENTARY

Understanding Electric Arc Furnace Operations

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Introduction

Over the past two decades the use of electric arc furnaces (EAFs) for the production of steel has grown dramatically in the United States. In 1975 EAFs accounted for 20% of the steel produced; by 1996 the figure had risen to 39% and by the year 2000 (or shortly thereafter) could approach 50%. There are two major reasons for this trend—lower capital cost for an EAF steel-making shop and significantly less energy required to produce steel by the EAF versus the blast furnace/basic oxygen furnace method of the integrated steelmaker. EAFs range in capacity from a few tons to as many as 400 tons, and a steelmaking shop can have from one to five furnaces. In brief, EAFs can be either ac or dc powered and they melt steel by applying current to a steel scrap charge by means of graphite electrodes. It requires about 360 to 400 kWh of electricity to melt a ton of steel; consequently, these furnaces use a tremendous quantity of power. Transformer loads may reach 150 MVA.

The features of EAFs are described in a prior CMP *TechCommentary* titled "Introduction to Electric Arc Furnace Steelmaking" (TC-107713). The purpose of this *TechCommentary* (TC-107714) is to give utilities a more comprehensive understanding of the electrical operations and energy usage, and to review some of the innovations that are making the EAF a very energy-efficient steel melter.

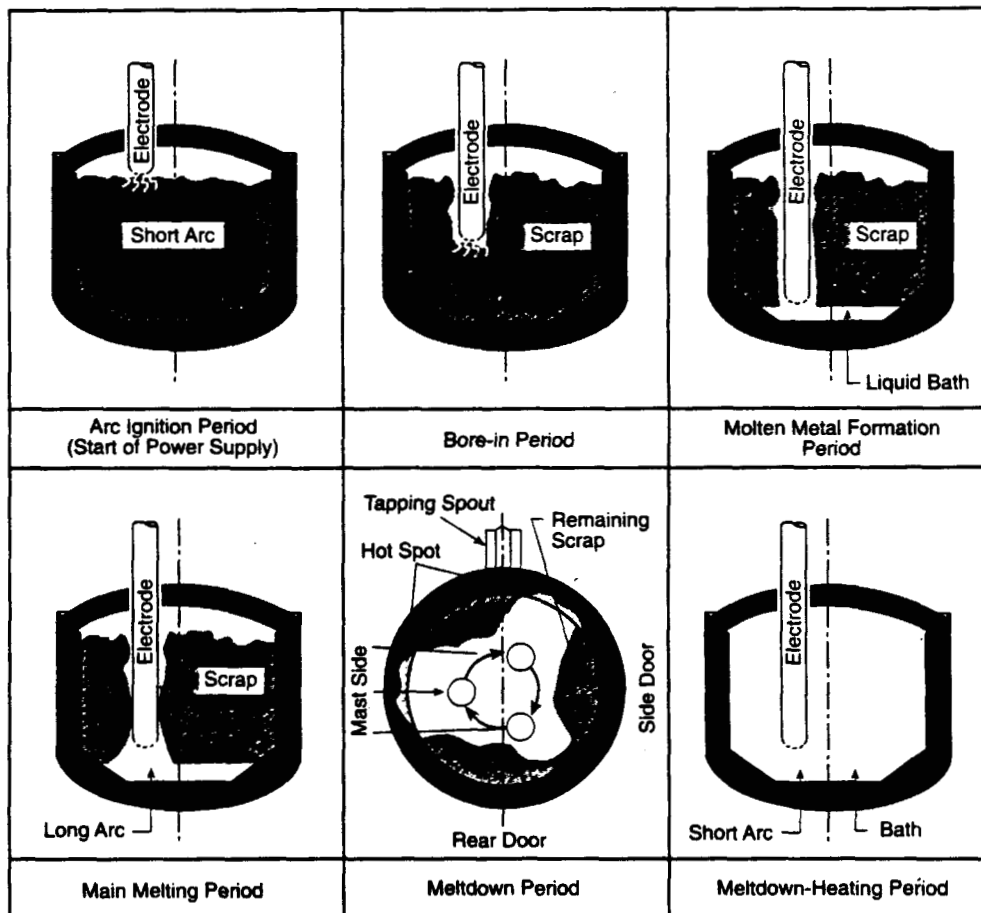


Figure 1. Steel Melting Cycle.

Typical Steelmaking Cycle

Figure 1 shows 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 roof is in place, 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, 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 opera-

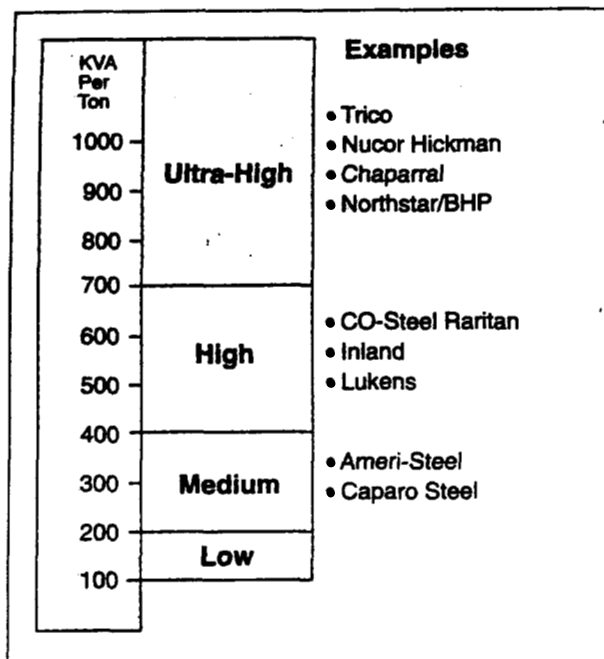


Figure 2. EAF Power Classifications.

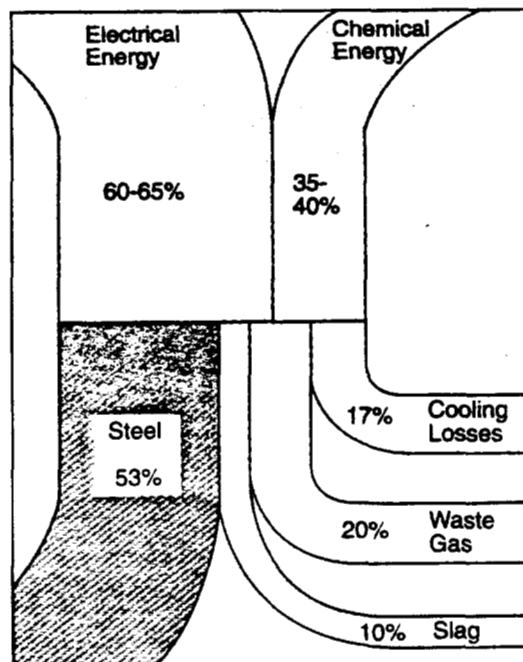


Figure 3. Energy Patterns in an Electric Arc Furnace.

tions, 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 helps 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.

Energy Needs

The International Iron and Steel Institute classifies EAFs based on the power supplied per ton of furnace capacity. The power classification ranges and some representative furnace installations are shown in Figure 2. Most modern EAFs found in steelmaking shops are at least 500 kVA per ton and the trend is toward ultra-high-power furnaces in the range of 900 to 1000 kVA per ton of furnace capacity.

A typical energy balance (Sankey diagram) for a modern EAF is shown in Figure 3. Depending upon the meltshop 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.

Just a decade ago tap-to-tap times had decreased from over 2

hours to 70-80 minutes for the efficient melt shops. Continuing advancements in EAF technology now make it possible to melt a heat of steel in less than one hour with electric energy consumption in the range of 360 to 400 kWh/ton. EAF operations utilizing scrap preheating such as the CONSTEEL® Process and the Fuchs Shaft furnace can achieve even lower cycle times. Most new EAF shops now aim for tap-to-tap times of between 50-60 minutes. These times are rapidly approaching those for basic oxygen furnace operations used in integrated steel mills.

Charge Materials

In the past, EAF shops essentially charged 100% scrap to the furnace. Although most EAF steelmakers producing long products, such as rebar and merchant bar, continue to use all scrap, some EAF shops today are supplementing the charge with other materials for producing higher quality products. This is the case for some producers of high-quality bars and highly formable sheet products for automobiles. These charge materials include direct reduced iron, iron carbide, and pig iron. For more information on scrap quality and direct reduced iron see CMP Report 95-1. The trend toward the use of direct-reduced materials will continue to grow as more high-quality scrap containing low levels of residuals or undesirable elements becomes scarce.

Oxygen Usage

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 1300 scf/ton (37.4 Nm³/tonne), saving 50 to 100 kWh of electric energy per ton of steel produced and reducing tap-to-tap times by 3 to 6 minutes. The relationship between electric energy and oxygen consumption for the EAF is shown in Figure 4. It is now common for between 30 to 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. Also, burners are beneficial for heating the cold spot around the tap hole of eccentric bottom tapping furnaces. Typically burners are installed in the side wall and roof of

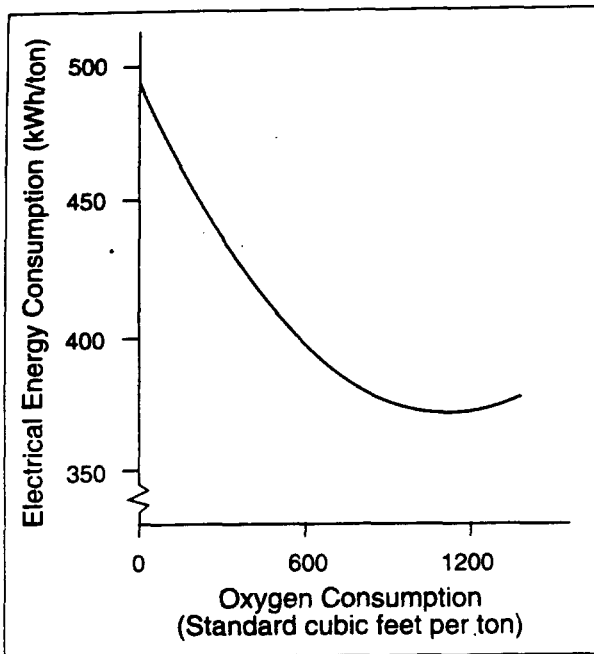


Figure 4. Electrical Energy vs. Oxygen Consumption.

the furnace as well as in the slag door. Productivity increases of 5 to 20% have been reported from the use of burners.

Oxygen lancing has also become an integral part of EAF melting operations over the past decade. Modern furnaces use oxygen lances to cut scrap, decarburize (refine) the bath, and foam the slag. Energy savings due to oxygen lancing arise from both exothermic reactions (oxidation of carbon and iron) and due to the stirring of the bath which leads to temperature and composition homogeneity of the bath. Oxygen lances can be of two forms, water cooled and consumable. Water-cooled lances are generally used for decarburizing; however, in some cases they are used for scrap cutting. The first consumable lances were operated manually through the slag door. Today, remote-controlled lance manipulators are available to optimize the injection process. These robotic units, Figure 5, can be used with multiple, individually controlled, consumable lances for scrap burning and decarburizing, as well as for injecting oxygen, carbon, and lime.

Foamy Slag Practice

At the start of meltdown the radiation from the arc to the side-walls is negligible because the electrodes are surrounded by the scrap. As melting proceeds, the efficiency of heat transfer to the scrap and

bath declines as more heat is radiated from the arc to the side-walls. By covering the arc in a layer of slag the arc is shielded and more energy is transferred to the bath. Oxygen injected with granular coal or carbon produces carbon monoxide (CO) which foams the slag. In some cases, only carbon is injected and it reacts with the iron oxide in the slag to produce CO. This is called a foamy slag practice and is now commonly used by EAF operators. When foamed, the slag cover normally increases from 4 inches (0.1 meter) to 12 inches (0.3 meter) thick.

Claims for thermal efficiency range from 60 to 90% with slag foaming compared to 40% without foamy slag. If a deep foamy slag is achieved, it is possible to increase the arc voltage considerably. This allows a greater rate of power input. Slag foaming is usually carried out once a flat bath is achieved. However, with hot heel operations (residual liquid steel in the furnace bottom) it is possible to start foaming much sooner.

Post Combustion

CO gas is produced in large quantities in the EAF both from oxygen lancing and slag foaming. If the CO is not combusted in the furnace freeboard then it must be

burned in the fourth hole evacuation system conveying the off-gases from the furnace to the baghouse. The heat of combustion of CO to CO₂ is three times greater than the heat of combustion of C to CO. Thus, this represents a very large potential energy source for the EAF. If the CO is burned in the EAF it is possible to recover the heat while reducing the heatload on the off-gas system. This is called post combustion. Results of studies have shown that by practicing post combustion, i.e., injecting oxygen into the EAF to burn the CO to CO₂, 35 to 60 percent of the heat in the off-gas can be recovered. EAF operators are now moving toward adopting this practice and typical electric energy savings are about 0.1 kWh/scf (4 kWh/Nm³) of oxygen injected).

EAF Bottom Stirring

For conventional ac furnaces there is little natural electrically induced turbulence within the bath compared to dc furnaces which have more convection stirring. If there is little bath movement, large pieces of scrap can take a long time to melt and may require oxygen lancing. The concept of stirring the bath is not a new one and records indicate that electromagnetic coils were used for stirring trials as early as 1933. Today most EAF stirring operations use inert gas as the stirring medium. The gas is introduced through the bottom of the furnace using porous plugs. In a conventional ac furnace, three plugs are used with a plug located midway between each of the three electrodes. Primarily argon or nitrogen gases are used; however, some trials have been conducted with

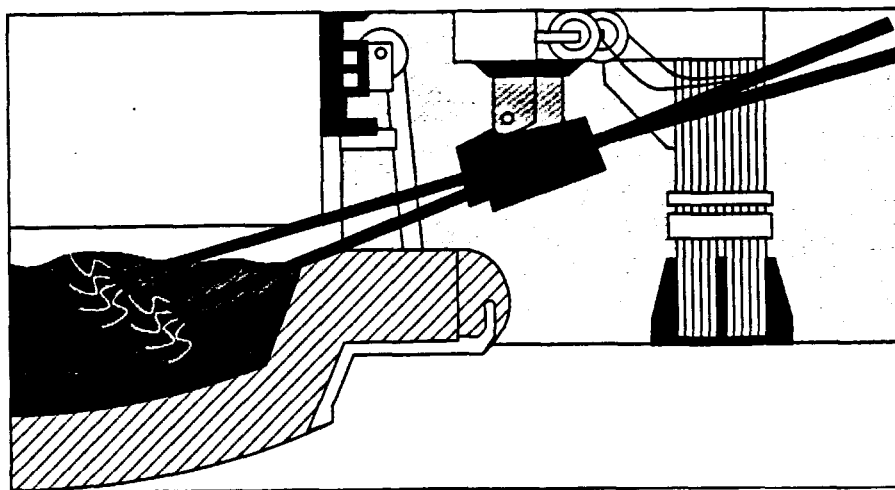


Figure 5. Lance Manipulator.

natural gas and carbon dioxide. Advantages for bottom stirring include yield increases of 0.5 to 1%, average tap-to-tap time savings of about 5 minutes, energy savings of about 10 to 20 kWh/ton, and reduced electrode consumption.

Scrap Preheating

Of the total energy consumed directly in EAF steelmaking, about 20% normally leaves the furnace in the waste gases, see Figure 3. The loss can exceed 130 kWh/ton of steel produced. A significant portion of this energy can be recaptured by using the off-gas to preheat the scrap. Two methods for preheating scrap, the CONSTEEL® process and the Fuchs shaft furnace have been installed on several new installations in recent years. The CONSTEEL® process utilizes a conveyor to continuously feed scrap into the EAF. Hot furnace gases leaving the EAF travel countercurrent to the scrap on the way to the baghouse thereby preheating the scrap. The Fuchs furnace has a shaft situated on top of the EAF which holds a scrap charge that is preheated by the off-gases rising up through the shaft. Energy usage has been reduced by 15 to 20% over conventional EAF operations using these technologies.

High Voltage AC Operations

Some EAF steelmakers have retrofitted their shops and installed new power supplies to obtain higher operating voltages. An ac furnace electrical circuit is shown in Figure 6. Energy losses in the secondary circuit are dependent on the secondary circuit reactance and to a greater extent on the secondary circuit current. If power can be supplied at a higher voltage, the current will be lower for the same power input rate. Operating with a lower secondary circuit current will also give lower electrode consumption. Thus, it is advantageous to operate at as high a secondary voltage as is practical. Of course, this is limited by arc flare to the furnace sidewall and the

existing furnace electrics. A good foamy slag practice can allow voltage increases of up to 100% without adversely affecting flare to the furnace sidewalls. Energy losses can be minimized when reactance is associated with the primary circuit.

Supplementary reactors are being used to increase the operating voltages on the EAF secondary circuit by connecting a reactor in

transformer secondary voltage is increased (sometimes to as high as 800 to 1100 volts) allowing operation at higher arc voltages and lower electrode currents. Some of the benefits attributed to ac operation with supplemental reactance are:

- More stable arc than for standard operations.
- Electrode consumption reduced by 10%.
 - Secondary voltage increased by 60 to 80%.

DC Furnaces

In recent years a number of dc furnaces have been installed. Essentially, the equipment needed for dc melting has the same configuration as that of a conventional ac furnace shown in Figure 7. The exceptions are the addition of a bottom electrode (anode), a dc reactor, and a thyristor rectifier all of which add to the cost of the dc furnace. These furnaces use only one graphite electrode with the return electrode installed in the bottom of the furnace and operate with a hot heel practice in order to ensure an electrical path to the return electrode. Figure 8 shows several types of return electrodes. These include conductive refractories with a copper external base plate and the multipin type made up of conductive rods passing through the hearth and connected to a bottom steel plate. A third type consists of one to four large diameter steel rods fitted in the furnace bottom, the steel rods being water cooled where they emerge from the furnace. During startup from cold conditions, a mixture of scrap and slag is used to provide an initial electrical path. Once this is melted in, the furnace can be charged with scrap. Advantages claimed for dc furnaces over ac furnaces include:

- 50% reduction in electrode consumption.
- 5 to 10% reduction in power consumption.
- Reduced refractory consumption.
- Uniform melting.
- 50% reduction in flicker.

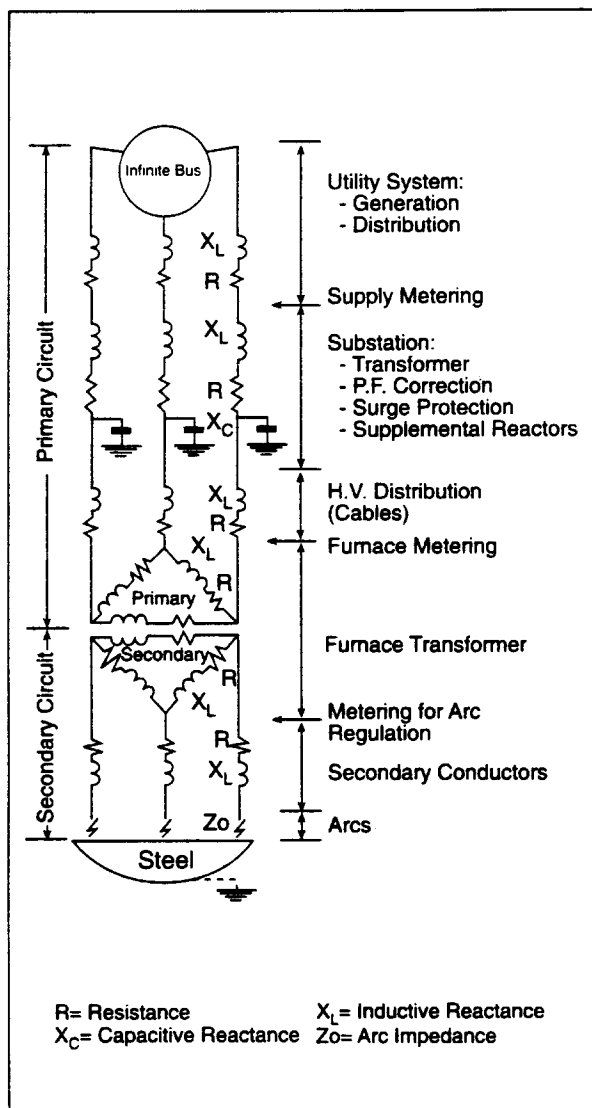
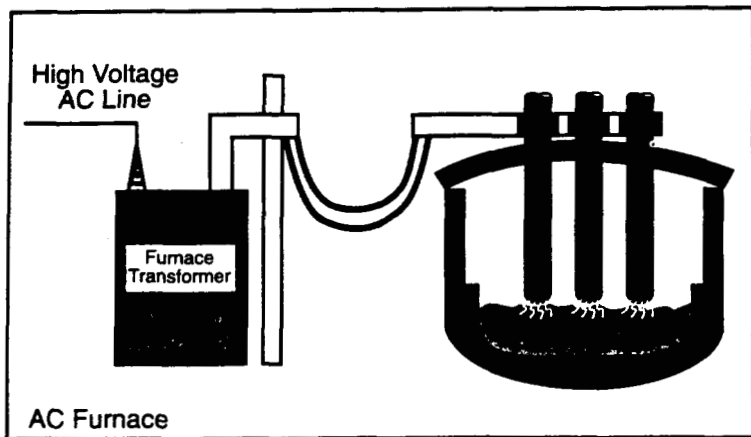
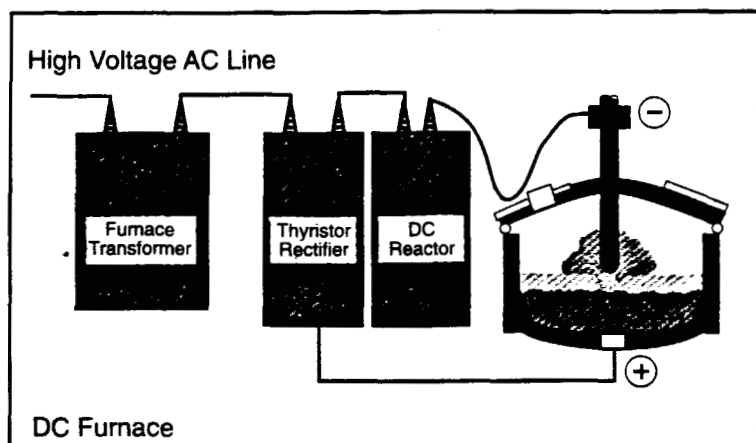


Figure 6. Simplified Schematic of the ac EAF Arc Circuit.

series with the primary windings of the EAF transformer. This allows operation at a power factor of approximately 0.707 which is the theoretical optimum for maximum circuit power. This is made possible because a large storage device is placed in the circuit, which in effect acts as an electrical flywheel during operation. The insertion of the series reactor drops the secondary voltage to limit the amount of power transferred to the arc. In order to compensate for this, the furnace



AC Furnace



DC Furnace

Figure 7. Layouts for ac and dc Furnaces.

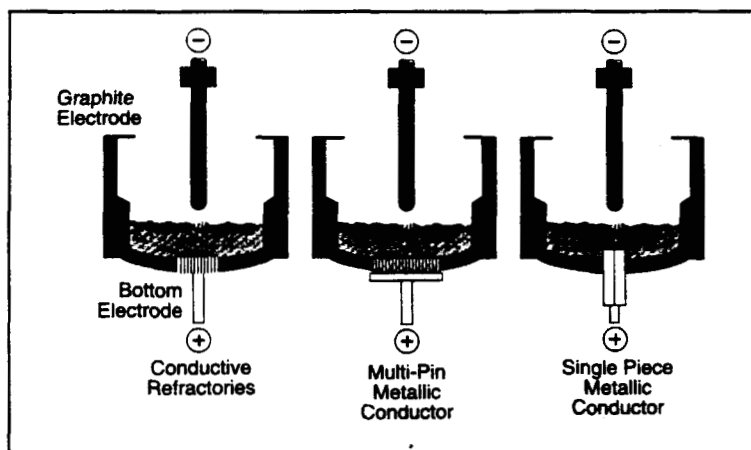


Figure 8. Bottom Electrode Designs for dc Furnaces.

Reducing Electrical Disturbances

The melting process involves the use of large quantities of energy in a short time (1-2 hr) and in some instances the process has caused disturbances (flicker & harmonics) in power grids but this problem is being minimized with the installation of modern furnaces and improved operating practices.

Many ways exist to reduce the effects of arc disturbances. These are determined by the utility system to which the furnace or furnaces are to be connected, and they are influenced mainly by the size and stability of the power grid. Some sizable shops require no particular flicker control equipment. It is quite possible that, if a furnace shop is fed from a 220 kV or higher system with a short-circuit capacity of 6500 MVA or more, the utility will experience

very little load disturbance, and the steelmaker can have considerable flexibility in configuring his internal plant power system. Most utilities require power factor correction. Shops with large EAFs would more than likely use static capacitors; synchronous condensers of sufficient capacity would be prohibitively expensive for a multifurnace shop. Before such systems are installed, transient analysis is required to determine:

- 1) Capacitor bank configuration.
- 2) Need for harmonic tuning of sections.
- 3) Switching procedure (This is important to avoid a power factor penalty and does not eliminate flicker).

As mentioned earlier, use of dc EAFs and improved operating practices such as scrap preheating, foamy slags, and use of hot heels all work to reduce flicker. If additional regulation is needed, installation of a static var control (SVC) may be required. Many EAF shops have installed SVC systems not only to minimize flicker problems but also to increase productivity.

Ladle Refining Furnace

During the past decade, the EAF has evolved into a fast and low-cost melter of scrap with the major objective being higher productivity in order to reduce fixed costs. In addition, refining operations to improve product quality are (for the most part) carried out in a ladle refining furnace (LRF). This allows the EAF to concentrate on melting the scrap and removing impurities via oxidation reactions. Temperature and chemistry adjustments are carried out more optimally in the LRF. For more information on the operation and role of the LRF see CMP *TechCommentary* CMP-071.

EAF Dust

The dust exiting the furnace with the off-gases has been classified as a hazardous waste (K061) by the Environmental Protection Agency (EPA) because it can contain lead, cadmium, chromium, and nickel. As a result, the dust must be treated prior to disposal in order to meet EPA requirements. There are various methods for treating the dust—for more information on these processes refer to CMP Report 93-1. □

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