FOREWORD

The induction furnace has always been an important metallurgical tool but it has only been in the last few years that high-capacity units which operate at line frequency have become available. This information circular has been prepared to review the recent development of this melting process and to project its possible field of application in the future. Consideration of this process is especially timely now that so-called "direct reduction" processes are being developed to reduce iron ore to the metallic state; the line frequency induction furnace may offer an attractive alternative to conventional processes for the subsequent steelmaking stage.

Mr. J.E. Rehder is a well-known consulting engineer with an extensive background in the foundry and allied metal industries and with special knowledge of this interesting process. He has been the author of many technical articles and holds several patents. His work on the development of charge preheating techniques, applicable to the induction furnace and to other melting processes, is especially noteworthy.

John Convey
Director

Ottawa, October 1971.

AVANT PROPOS

Le four à induction a toujours été un outil métallurgique important mais ce n'est que dans ces dernières années que les unités de haute capacité, qui fonctionnent à la fréquence de ligne, sont devenues accessibles. Ce bulletin d'information a été préparé pour reviser le développement recent de ce procédé de fusion et préparer son champ d'application dans l'avenir. Il est important de considérer ce procédé maintenant parce que les soi-disant procédés de "réduction directe" sont en train d'être développés pour réduire le minerai de fer à son état métallique; le four à induction à la fréquence de ligne peut offrir une bonne alternative aux procédés conventionnels pour la période subséquente d'aciérage.

M. J.E. Rehder est un ingénieur-conseil bien connu avec des connaissances considérables dans les industries de fonderie et d'alliages. Il a aussi une connaissance speciale de ce procédé intéressant. Il est l'auteur d'un bon nombre d'articles techniques et a plusieurs brevets d'invention. Son travail sur l'enfournement préchauffé, applicable au four à induction et aux autres procédés de fusion, est surtout remarquable.

John Convey

Directeur

Ottawa, octobre 1971.

APPLICATION IN THE STEEL INDUSTRY OF LARGE LINE-FREQUENCY INDUCTION FURNACES

by

J.E. Rehder*

ABSTRACT

Development of large induction furnaces has proceeded rapidly in the iron foundry industry, particularly in the United States. To-day, 65-ton 21,000-kW furnaces are operating, and a furnace 50 percent more powerful has been designed. These are heavy industrial furnaces that operate at line frequency and so are of reasonable capital cost, and there are many places in the steel industry where such powerful energy injectors can be valuable. Immediate application can be made, for example, to increasing blast furnace output by duplexing the hot metal with steel scrap, and to making synthetic hot metal for the basic oxygen furnace (BOF) from steel scrap or from reduced pellets. Synthetic hot metal so made is free of blast furnace operating restraints and can, for example, economically substitute temperature for silicon content, making practical the specification of hot metal for maximum BOF production rate and minimum total cost.

Induction furnaces of moderate size are being used to-day for minor steelmaking and in vacuum degassing equipment. However the large, high-powered induction furnace has some characteristic features that have not been adequately explored for tonnage steelmaking. Important among these are the ability to emulsify slag into the molten steel to obtain very high interface area and rate of reaction, the feasibility of handling considerable slag volume with maintenance of slag temperature, and the ease of obtaining nearly continuous production. Effective application of such factors will constitute new methods of steelmaking. Processing of solid-state reduced pellets seems particularly well suited to the induction furnace.

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L'APPLICATION DES GROS FOURNEAUX A INDUCTION DANS L'INDUSTRIE D'ACIER

par

J. E. Rehder*

RÉSUMÉ

Il y a eu un développement rapide des gros fourneaux à induction dans l'industrie de fonderie de fonte, particulièrement aux États Unis; a présent les fourneaux de 65 tonnes et de 21,000 kW sont en opération, et un fourneau avec 50 pourcent plus de force à été dessiné. Ce sont de lourds fourneaux qui fonctionnent à la fréquence de ligne qui sont par conséquent d'un coût raisonable, et il y a plusieurs endroits dans l'industrie d'acier où de tels injecteurs à énergie puissante peuvent être utilisés, par example, pour augmenter le rendement du haut fourneau en ajoutant les ferrailles au métal en fusion synthétique à l'usage de l'opération basique et oxidante (BOF) provenant de la ferraille ou des boulettes réduites un tel métal en fusion synthétique est libre des contraintes d'opération du haut fourneau et peut, par exemple, substituer économiquement la température pour le contenu de silicium, en rendant pratique la spécification du métal en fusion pour le rendement maximum de la BOF et pour le coût total minimum.

A présent, les fours à induction d'une grandeur modérée sont utilisés pour la fabrication mineure de l'acier, et dans l'équipement pour l'aspiration du gaz. Cependant, le fourneau à induction a quelques capacités caractéristiques qui n'ont pas été suffisamment explorées pour la fabrication par tonne de l'acier. En importance parmi celles-ci se trouvent - la capacité d'émulsionner la scorie dans l'acier pour obtenir plus de surface exposée et une réaction plus rapide, la practicabilité de maniement et de maintien de la température d'un volume considérable des scories, et la facilité d'obtenir presque continuelle production. Les applications efficaces de tels facteurs constitueront les nouvelles méthodes de faire l'acier. Le traitement des boulettes reduites et solides semble particuliérement convenable au fourneau à induction.

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APPLICATION IN THE STEEL INDUSTRY OF
LARGE LINE-FREQUENCY INDUCTION FURNACES

INDEX

INTRODUCTION

Major changes in the design, construction, and operation of coreless induction furnaces have taken place in the last few years. The driving force has been in demand from the American iron foundry industry, pressed by rising coke prices and by more stringent air pollution control requirements. Operating experience has now reached the point where a 65-ton furnace is operating very satisfactorily at 21,000 kW at line frequency, and a 100-ton 30,000-kW furnace has been designed.

Furnaces of such size and power input capabilities are of real interest to the steel industry and it is timely to review seriously their capabilities. Performance and costs in melting and processing hot metal are well established and it seems that some practical and economic changes in steelworks hot metal practice could be made immediately. It also appears that some marked and interesting changes in steelmaking practice can be effected if the operating characteristics of the furnaces are properly used. They have quite different capabilities from the basic oxygen furnace and from the arc furnace, and indeed from small induction furnaces, because of scale effects on heat losses and, so, will add to the choice of processing equipment available to the steelmaker. The objective in this paper is to review the design, performance, and application of large, coreless, line-frequency induction furnaces and to suggest what can be done in steelworks practice with existing technology and with moderate development.

Development and Use in Iron Foundries

In the late 1940's, several electrical equipment manufacturers in Europe built coreless induction furnaces to operate directly on line frequency and application was made to 2 to 5-ton furnaces in iron foundries. The combination of larger potential tonnage and a better price ratio between coke and electricity in North America resulted in a strong marketing entry on iron melting in the United States in about 1960. Replacement of cupolas and of air furnaces has become a strong growth industry which is still accelerating because of its demonstrated lower total costs. Demand grew rapidly for larger and more powerful furnaces, and the result has been rapid development based on extensive experience. Well over one million tons of iron per year is now melted in these furnaces in America.

Iron foundry melting practice is conditioned by the chemistry of the metal and by the nature of a foundry operation which requires final delivery of the iron to a continuous train of molds to be filled by relatively small portions. The total quantities however can be considerable, from 50 to over 200 tons per hour.

Carbon content is generally from 2.30 to 3.70 percent and silicon content 1.20 to 2.50 percent depending upon the type and grade of iron being made. Tapping temperature at the furnace must be 2800 to 2950^{o}F, depending on the type of iron and on the handling facilities. Close control of chemistry and temperature are essential to operating high-productivity molding lines at low rates of reject or scrap.

Multiple furnace installations are standard, to provide continuity of hot metal supply, flexibility in case of breakdown, and ready expansion. The practice nearly universally used is to tap about one third of the contents of a furnace into a series of distributing ladles, and then to refill with cold charge materials and additives. While this is being melted and superheated to tap temperature, another furnace is being tapped to maintain a continuous supply of hot metal. Two to five furnaces may be used depending on local conditions such as the number of varieties of iron to be poured. Four 21,000-kW, 70-ton furnaces will readily supply iron at the rate of 160 tons per hour.

The use of electric melting makes choice of raw materials one of price and availability, and the increased freedom is an important avenue to decreased costs. Steel scrap is commonly and widely used, constituting up to 100 percent of the charge, where price is attractive, with suitable additions of carbon and ferrosilicon. Very light-gauge scrap is readily melted with negligible loss. A widely used practice is to preheat charges with natural gas to between 800 and 1400^{o}F in order to decrease risks involved in charging wet scrap to a molten bath and to increase furnace output by up to 30 percent.

Cast iron is readily melted on acid, neutral, or basic refractories, but acid refractory is largely used because it is lowest in cost. It has been found that a rammed lining of high-purity silica with a controlled addition of boric acid as binder gives excellent life and is adequate to tapping temperatures of about 3000^{o}F. Lining life of five to six months is common, with total refractory cost in the order of one dollar per ton melted.

Slag formed in melting is from dirt on scrap and from sand on sprue and is not usually a necessary part of the metallurgy of cast iron. It is generally somewhat viscous and no flux is desired so that the slag can be removed with a mechanical skimmer or spoon just before each tapping period. If not removed, the slag layer will cause low and erratic recovery of carbon on the next addition of charge material.

Operation in iron foundries is usually two shifts per day five days per week. Furnaces are held full over the third shift at reduced temperature and over week-ends if no repairs are scheduled. For lining repair the furnace is emptied Friday night, forced-air cooled, repair made on Saturday, and sintered and filled on Sunday.

Furnace Description and Characteristics

The induction furnace has been made into a practical large-scale melter by a combination of the use of line frequency power and changes in construction. Performance may now be summarized as follows:

- operation on line frequency avoids conversion losses and capital costs;
- construction is robust in structural steel, and capacity as large as 100 tons 30,000 kW is practical;
- power density in kW per ton can be in the same range as for so-called ultra-high-power arc furnaces;
- stirring action can be made sufficient to emulsify slag into the metal and create slag/metal interface approaching that of the BOF;
- energy conversion efficiency from power transformer primary to metal temperature is 70 to 75 percent on both meltdown and superheating.

These and some other points will be elaborated in the following sections, at the risk of appearing to suggest that the induction furnace does everything well. There is obviously no ideal furnace, so operating experience will eventually determine the practical and economic place of every piece of equipment.

Construction -

The basic structure is familiar, that of a refractory container surrounded by a water cooled coil of copper tubing. A major design improvement is the use of magnetic yokes, which are bars of laminated transformer iron placed vertically against the outside of the coil, separated only by electrical insulation. The yokes contain most of the magnetic flux developed so that the furnace frame or body may be built of structural steel. The frame can then be made as simple and as stiff as desired and provides adequate support for yokes, coil, refractories, and furnace contents. Measures are taken to compensate for differences in thermal expansion so that no deformation occurs and the structure remains tight, the details varying with the furnace manufacturer.

The coil itself is straight-forward, the height usually being equal to the diameter. Since the molten content of the furnace frequently extends above the top of the coil and the lining subtracts from the diameter, the height of the molten content of a furnace is usually about 50 percent greater than its diameter.

Electrical insulation is placed between turns, the voltage drop from turn to turn being of the order of 100 volts. Power is introduced to the coil by hollow, water cooled, flexible power cables or tubes.

Cooling water for the coil is usually circulated in closed circuit with a heat exchanger so that there is negligible risk of internal deposit in the coil and of decrease in cooling capacity.

The furnace is normally arranged to pour over a lip or spout above the top of the coil and it is tilted hydraulically. Tapping through one or more tap-holes in the sidewall above or below the coil is practicable but so far has been little used commercially. A refractory lined cover is invariably used because heat losses from the surface of an open bath are considerable. The cover is lifted and rotated hydraulically.

Typical construction is shown in Figures 1 and 2 and an operating 65-ton furnace in Figure 3.

Electrical Circuit -

The coil is usually operated on single phase so a balancing network of a reactor and capacitors is applied in delta connection to present a three-phase load to the power supply. Balancing on a new lining is very good, altering to 8 to 10 percent unbalance as the lining approaches replacement. The load is of course highly inductive, power factor being about 0.17 lagging, and capacitors must be provided to correct power factor. Because the capacitance necessary depends partly on the amount of metal in the furnace and on the voltage applied, a portion must be switchable; therefore, in practice, the power factor is continuously and automatically corrected to unity. The total capacitance required is large, the kVAR required amounting to 6 to 10 times the furnace rating in kW, and constitutes an important item in the total equipment cost. Because of operation at unity power factor, furnace rating is in kW rather than in kVA.

Voltage applied to the coil is between 2,500 and 3,000 volts in larger furnaces. Power input is controlled by an on-load tap changer on the transformer which decreases incoming line voltage to that applied to the furnace network, and a very recent installation used thyristor stepless control. A starting resistor is in the circuit momentarily to control inrush current. A typical electrical diagram is shown in Figure 4.

Power density applied, measured at transformer primary, is from about 150 to 300 kW per ton, limited by meniscus height and intensity of stirring action. The lower figure gives adequate stirring for rapid absorption of charge materials, excellent uniformity, and a rate of temperature rise of about 17°F per minute. The higher figure gives very vigorous stirring and a temperature rise of about 34°F per minute.

It may be noted that an input power density of 300 kW per ton corresponds to a transformer input capacity on an arc furnace of about 400 kVA per ton, which is well into the so-called ultra-high-power category.

There are of course adequate interlocks on the electrical system, an important one being based on resistance between the coil and ground. This is to protect against water leakage or condensation on the coil; so, typically, the interlock is arranged to shut the furnace down when resistance to ground falls below about 5,000 ohms.

The electrical load presented by a line frequency induction furnace is markedly different and easier to deal with than is that of an arc furnace of the same power input. The load is smooth, free of flicker, and of consistent unity power factor. These characteristics make it practical to consider generating power for a large induction furnace from blast furnace or from other off-gas via a steam or a gas turbine. This can lead to considerable economies in equipment cost because in such case the alternator could be single phase to the coil and power input could be regulated by alternator field control. It would also permit use of frequencies below 60 Hz, which could be an advantage in very large furnaces.

Stirring Action -

A characteristic feature of coreless induction melting is a stirring action in the metal caused by electromotive forces. At line frequency this can, as noted above, be powerful enough to limit the power density that can be applied. In the top of the bath, the motion is down the walls and up the centre, creating a high centre or meniscus. In practice, the top of the power coil is placed somewhat below the normal top of the metal bath so that the upper layers of metal can partially suppress the meniscus. The stirring is desirable in that it promotes rapid mixing and uniformity in the metal, causes rapid solution of charge additions, and creates a large slag/metal interface. The ability to create a very large controllable interface with slag in terms of square feet per ton per minute is an important potential tool in steelmaking which has not been adequately explored. At power density of the order of 300 kW per ton, slag can be emulsified into the metal to create very large specific interface, approaching conditions in the BOF.

Principal limitations on violent motion in the bath are rapid wear of refractories and increased mechanical stresses. These can be compensated for if sufficient metallurgical advantage appears as was the case with the refractory problem in the BOF. For many applications however, such vigorous motion is not necessary and lower power density of the order to 200 kW per ton is adequate.

Refractories -

The refractory lining of a coreless induction furnace has always, with some justice, been considered the sensitive feature of the furnace as a tonnage melting unit. The lining thickness is a compromise between long life and good electrical coupling; so, in practice, a new lining occupies 30 to 35 percent of the cross section inside the coil, or its wall thickness is 10 to 12 percent of the diameter of the coil. A currently operating 65-ton furnace has a diameter inside the lining of 72 inches and the thickness of a new lining is 9 inches.

In the last four or five years, the growth in market and increase in size of furnaces has attracted the attention of refractory suppliers, and a considerable range of materials is now available in grain and in brick form. Various combinations of brick and rammed grain are in use, although rammed silica is still by far the most commonly used refractory simply because the largest tonnage melted is iron. There is much information available on magnesite linings but these are of minor interest in iron foundry practice, and experience on basic linings in large furnaces is therefore limited. For large furnaces, a rammed lining below the metal line has been found practical, the top few feet, where slag erosion and mechanical damage is more severe, being of alundum brick.

Maintenance of linings is based on visual appearance, measurement, and electrical load characteristics. The top of the lining, where slag erosion and impact from charging occur, has the shortest life and is assessed both visually and by physical measurement of internal diameter. Replacement of this portion of lining without disturbing the rest of the lining is not difficult.

As the main body of the refractory under the surface of the bath slowly wears, the electrical characteristics of the furnace change, the coil drawing more power at a given voltage as the lining becomes thinner and electrical coupling therefore better. This is a good measure of average lining thickness but of course a hollow spot resulting from faulty lining practice or raw material cannot be so detected. For this reason, it is good practice to empty a furnace about once a week to both inspect the lining visually and to make measurements of lining thickness from an established centre line. These measurements give an accurate measure of rate of lining wear and quickly show up thin spots.

New lining and repairs can be installed rapidly because the heat content of a lining is not large and a furnace can be cooled, after emptying, in about 12 hours. A "shave job" or a complete reline, dry, and sinter can readily be done on one day. A "shave job" on a lining is where the sintered and contaminated surface refractory is removed but not the clean backing grain before fresh lining material is rammed between a sheet steel form and the backing grain.

Efficiency -

The principal source of energy loss between power transformer primary and temperature in the metal is the coil efficiency, which is 75 to 80 percent, or 25 to 20 percent loss. Losses in power transformer and circuitry are small at two to three percent. Thermal losses are independent of the power supplied and are surprising small considering the fact that most of the crucible is surrounded by a water-cooled copper coil. Most of the loss is of course through the wall but there is some loss through the bottom of the furnace and the cover.

On a 70-ton furnace, total thermal losses with cover closed will be equivalent to 270 to 300 kW which is about 380 kW measured at the power transformer. This is the power input necessary to hold the furnace full of metal with no loss in temperature and amounts to only 5 to 6 kwh per ton contained. Similarly, rate of temperature drop with power off is low, amounting in a 70-ton furnace to about 40°F per hour. This means that delays are not technically serious, and that even major power failure leaves hours of leeway before the decision to empty the furnace must be taken.

Loss through the cover is about 10 percent of total thermal loss but, with the cover off, loss by radiation is appreciable, amounting to about eight times the total furnace thermal loss with cover closed. For this reason, furnaces are kept covered at all times except for charging or for slagging.

Combined electrical and thermal efficiencies, that is the percentage of energy coming into the power supply primary that appears as temperature in the metal, is 70 to 78 percent, varying somewhat depending on how the furnace is designed and used.

Most of the electrical and thermal losses are rejected to cooling water in the coil and determine the flow of water necessary. At 55°F temperature rise, this amounts to about 800 U.S. gpm on a 70-ton furnace at 21,000 kW input, or to about 1,100 U.S. gal per ton melted.

The amount of power that can be induced in the metal decreases as the amount of metal in the furnace decreases and, below about two-thirds full, starts to fall rapidly, as shown in Figure 5. This also means that an empty, line frequency furnace cannot be started in reasonable time on filling with ordinary steel scrap at 50 to 80 pcf bulk density. Either a denser charge, a heel of molten iron, or starter blocks previously cast from over-metal must be used, depending on circumstances and availability. Most furnaces are used on a continuous basis, but batch operation is entirely practical, for example in a roll foundry, where a scrap roll is an excellent charge which heats rapidly.

Charge Preheating -

Effective and reliable gas fired preheaters have been developed, and it is common practice to preheat charges to between 1000 and 1400°F. This not only gives a net saving in total energy cost but ensures that no wet or oily scrap can reach the molten bath. Another considerable advantage is an increase in output, in tons per hour from a given furnace and power supply, of from 20 to 30 percent. Preheaters must work very rapidly to be useful in induction furnaces; for example, a 65-ton 20,000-kW furnace using 1400°F charges will have a melting rate of about 55 tons per hour, hence 7-ton charges must be ready at 7-minute intervals.

Size of Furnaces -

The pace of development forced by iron foundry demands has resulted not only in larger furnaces than were believed practical five years ago but has made it clear that much larger ones are feasible. A considerable number of 35-ton furnaces have been operating for several years; a 65-ton furnace has been running a year and a half and four more are being installed; a 100-ton 30,000-kW furnace has been designed and early design is complete on a 40,000-kW furnace that will hold about 135 tons. For applications not needing high power density such as hot metal, a 150-ton coreless furnace powered at 15,000 to 20,000 kW is entirely practical. Various proportions are possible, depending on the application, and there is no apparent barrier to building a 200 to 250-ton furnace after experience on mechanical design has been accumulated.

Difficulties -

Water leaks, occasional run-outs of metal, and voltage flash-overs which caused coil leaks were the main practical problems on the early furnaces, especially because coil voltage had to be increased as furnaces became larger. Many design changes have been made and lining practices improved as a result of this education and such troubles are now manageable and have less serious effects.

Voltage flash-over is no longer a problem on a well-designed furnace, and water leaks come from poor joints in or to the coil. These can be checked out thoroughly before the furnace is put into operation. However, moisture from a new lining or patch must still be driven off carefully, and full working voltage not put on the coil until resistance to ground is suitably high.

Run-out through the wall of the crucible and the coil results only from a faulty lining or one whose wear rate is not checked sufficiently but it can occur. The effects depend on whether the iron reaches the coil as a fin through a crack in the lining, or over a larger area through a lining wash-out or failure. In the former case, little or no iron escapes and damage is not serious; in the latter case, a considerable amount of iron can run out. Experience has been that the meeting of molten iron and water is not as catastrophic as might be expected, and damage is generally localized. Necessary repairs vary from replacing a few turns on a coil to complete replacement of the coil and some magnetic yokes but these are inexpensive compared to the cost of the whole installation.

Power failure is not usually troublesome because a furnace can be held for some hours before it is necessary to empty it. Emergency power of some sort is necessary to drive the hydraulic pumps for tilting the furnace.

Water supply failure can be more serious and reaction must be immediate. Since heat exchangers are commonly used, the problem is one of cooling the exchanger. This can be with an ermergency water supply, or with an air-to-water exchanger on standby or permanent basis.

Future Development -

The large coreless induction furnace is available now in size and power capacity that makes it practical and useful in a major steelmaking context. Many of the requirements in a steel plant, expecially those dealing with making or handling hot metal, can be met immediately with well-established practices. Larger and more powerful furnaces are clearly practicable and steel industry demand will simply make them a reality sooner.

Steelmaking directly from solid-state reduced iron is of major importance and it is possible that this can be done more economically in an induction furnace than in any other. The main requirement from an equipment viewpoint is large-scale test work to establish the best refractory practice; this can be met rapidly.

A recent development is to turn a coreless furnace on its side, so that it is the base of a broad "U", permitting charging at one end and delivery of molten iron at the other end. A 12-ton 2,000-kW furnace of this design is operating in an automotive iron foundry. It is not clear at this writing whether the advantages outweigh the disadvantages nor is it clear what the size limitation may be.

It is a fact that current designs based on water cooled coils are effective and give only minor trouble. It is also a fact that water cooling is extensively and increasingly used on various types of furnace holding or processing molten iron or steel. However there is no doubt that, if air could be used at not greater cost for such cooling, it would be preferred by many users. Some calculation will show that the heat to be removed from an induction furnace coil can be carried by a reasonable amount of air at moderate temperature rise, but the design problem is a geometrical one of efficient air distribution. It does not seem insuperable but it will require ingenuity and motivation.

Almost no experience is available on handling thick layers of molten slag in induction furnaces. The problems involved are refractories to withstand the slag, which is not apparently serious, and the fact that, because all heat enters the slag from the metal below, the top of the slag is cooler than at the metal interface. Whether this is undesirable depends on whether the slag is simply to be disposed of or is a necessary working part of the steelmaking. The situation is thus the opposite of that in arc furnace steelmaking in which the slag can be considerably hotter than the metal, especially at depth.

Chilling of the surface of the slag can be decreased by simply increasing insulation in the furnace cover, and this will be sufficient in many cases. Heat loss through the cover can be compensated either by using a gas burner through the cover or by embedding an electrical resistance grid about half-way back in the cover refractory. Either method consumes only a small amount of energy, less than one percent of the total for melting. Of course when slag is emulsified into the metal it immediately acquires metal temperature.

Application to Production of Hot Metal

The large coreless induction furnace can be applied to refine and superheat hot metal from the blast furnace; and it can make synthetic hot metal of very uniform quality. Both of these applications can be made immediately with existing technology, and the economics or advantages can be determined by detailed study of specific cases. In the following discussion, the objective is to outline a few ways in which a blast furnace practice might be made more productive or the hot metal more uniform in properties and to outline methods by which a synthetic hot metal feed to a BOF can be economically made.

Duplexing Hot Metal -

Since blast furnaces are individual units, some with depraved personality, and operate under a wide variety of conditions in raw materials, tonnage output, and hot-metal requirements, exhaustive or even adequate treatment here is not practical. It is intended simply to spark or initiate thought, in new directions, made possible by the use of high-power treatment.

Areas in which blast furnace performance can be improved include uniformity in hot-metal composition and temperature, both short- and long-term; ability to include scrap and pre-reduced material; and ability to produce hot-metal quality that is not conditioned so closely by furnace operating requirements. Secondary treatment or duplexing of hot metal in coreless induction furnaces at high energy input can be very effective in each of these directions.

Use of active mixers for averaging hot-metal composition and temperature is common but this is of only moderate effectiveness and is sharply limited in versatility. Fuel firing is costly because thermal efficiency is low, from 12 to 15 percent, and increasing metal temperature to any degree is expensive. Recently channel inductors of 1,000 to 2,000-kW input have become available to replace fuel as energy source, but limitations such as relatively poor mixing effectiveness, small ability to accept cold additions, and relatively high capital cost per unit of energy input remain.

Temperature -

The only practical comment on the composition and temperature of hot metal is that they vary in ranges that depend on the particular furnace being discussed. In some cases, the variation in chemistry can be a severe trial for a BOF operator, and it is only fairly recently that close attention has been paid to accurate continuous temperature measurement.

Temperature is, of course, an excellent indicator of furnace condition but to obtain higher hot-metal temperature, as a specific objective in a blast furnace, is expensive aside from unwanted increase in silicon content. The blast furnace as a liquefier and superheater of molten iron performs physically in the same manner as a cupola and, very likely, has the same low efficiencies. This has been closely observed in cupola practice, and the cost of an increase of 100^{o}F in molten-iron temperature is well known to be an increase of 80 pounds of coke per net ton of hot metal (NTHM). Undoubtedly, this will apply in the blast furnace and extra carbon will be required as reductant for the increased silicon produced. In addition, the increased carbon to be burned will decrease the production rate of iron.

It requires about 15 kwh of electricity, measured at high-tension input, to heat one net ton of molten iron by 100°F in an induction furnace. At a power cost of \$0.008 per kwh, this is equivalent to about \$0.12 per ton. Increased coke in the burden to produce the same increase in the blast furnace, at \$25.00 per ton of coke, costs about \$1.00 per ton of iron. This is energy cost only, but it is well established in iron foundry practice that superheating by induction furnace is considerably cheaper than in the cupola. Other cost advantages accrue, to external superheating, such as those from avoidance of increased silica reduction and increased tonnage output from a given hearth.

Superheating consumes only moderate power, for example 3,000 NTHM per day can be increased in temperature by 200°F, including losses, with a 3,750-kW power input. For the physical size of induction furnace necessary for this tonnage, the resulting power density is too low for stirring that is really effective for composition levelling.

Composition -

Control of hot-metal composition is much more effective if positive additions can be made for large-scale and rapid correction. For example, steel scrap and/or pre-reduced pellets can be added to decrease carbon or other metalloid content by dilution, or carbon or ferro-alloys may be added to increase their concentration. When the hot metal is to go to a BOF, temperature can be accurately adjusted at the same time. A practical method would seem to be to always add some scrap to the induction furnace, varying the amount to adjust the composition. The extra power to melt and superheat the additions gives a much more effective power density in the charge, and the additions can be incorporated rapidly enough to effectively correct composition. An example is given in Appendix A.

Metallic Additions -

Scrap iron and steel are charged to some blast furnaces for a variety of reasons and extensive trials have been made with pre-reduced pellets in the burden. Operating results show clearly, as would be expected, that, in proportion to the amount of reduced iron charged, the furnace is being used as a cupola. The blast furnace as constituted for reduction is far too expensive to be used for simple melting, and there is little question that melting and composition adjustment of iron can be done at less capital and operating costs in other furnaces. The issue has not to the present time been serious or important because scrap has never been a major component of the burden and pre-reduced pellets have simply not been available in commercial quantity. However, these economics must be dealt with very soon.

With the availability of high-energy input equipment of adequate size for melting and handling metal, it is practical and economic to add scrap and pre-reduced material to the hot metal produced by the blast furnace, to make a combined product in increased quantity. The final hot-metal can be not only under close control of composition and temperature but can incorporate whatever proportion of metallic addition desired at the lowest-cost point in the system. There is a wide variety of ways in which this procedure can be applied, from simple duplexing for increase in total output and stabilization of results to systems that involve shutting down an obsolete furnace and considerable modification of steelmaking practice.

One result of using powerful duplexing equipment is to decrease the number of restraints on blast furnace practice because composition and temperature are readily corrected externally. This should make it easier to operate the furnace primarily for tonnage output or to operate under whatever modification that decreases the net cost of making steel.

Another result should be review of continuous tapping practice on the blast furnace. This is well developed in cupola practice at rates of up to 100 tons per hour and there seems to be no major obstacle to its use on the blast furnace. The main differences are twofold, more slag per ton of iron from the blast furnace and much higher blast pressure.

In continuous tap practice on cupolas, the tap hole is large enough to tap both iron and slag, and the two separate in a basin, constructed as part of the tapping trough, immediately in front of the furnace. The iron continues under a dam and the slag overflows to one side. Such "front-slagging" practice is now used on all cupolas operated for more than a few hours, therefore, the larger slag volume of blast furnace practice should not cause serious difficulty.

The blast pressure in the well or hearth must be balanced in order to carry a basin or pool of molten metal in which slag can separate and no blast be lost. In cupola practice with blast pressure of the order of 1½ pounds per square inch, an atmospheric leg with an iron level difference of about 5 inches balances the pressure. For blast furnace pressures of the order of 30 pounds, the difference in level must be about 9 feet. This is more awkward but is about that encountered in many bottom-pour ladles.

Operating a blast furnace with continuous tap is an unaccustomed idea, but the resulting more uniform material flows should markedly help both operating and product uniformity. The resulting much shorter residence time of hot molten iron and of slag in the hearth will very likely decrease the carbon content of the iron, and decrease the amount of silica that is reduced. It is unlikely that a perfectly smooth descent of burden will continue indefinitely, even in the best furnace with resulting changes in smelted iron composition and temperature, but the adjusting and levelling capacity of an external duplexing furnace should readily take care of even serious variations.

Hot Metal for the BOF -

The oxygen vessel was developed as a processor of blast furnace hot-metal and its operating practices are presently tied to the limitations of the blast furnace. Principal among these is the necessity for each blast furnace to be operated on its own terms on the ores available with hot-metal composition (always saturated with carbon) and temperature that are results of compromises. There is very little chance of a BOF operator being able to specify hot metal in his own terms.

The only economic alternative has been to melt scrap or reduced pellets in hot-blast, water cooled cupolas, of which a few installations have been made. However present and future capital costs, which must include extensive pollution control, and high prices for suitable coke make the cupola often uneconomic compared to the line frequency induction furnace. This has been shown in several recent feasibility studies. In addition the cupola is usually operated with a basic slag to control sulphur pickup from coke, hence the iron is nearly saturated with carbon as is blast furnace hot-metal.

The use of large induction furnaces for melting reduced pellets along with steel scrap, in whatever amount that is economic, to make hot metal for the BOF has several advantages that open new approaches to BOF operation. In addition to being able to accept hot reduced pellets and fully utilize their contained heat, the induction furnace can demonstrably make iron of any composition low or high in carbon content to close chemical tolerance and to within 10°F of specified temperature. Control over BOF operation is thus simplified and costs are decreased.

Since temperature of the hot metal can be accurately and inexpensively adjusted, silicon content can be compensated for readily and little or no silicon need be used while maintaining adequate ignitability. Carbon content can be similarly appreciably decreased, with a resulting decrease in oxygen requirement, off-gas volume to be cleaned, and blowing time and with an increase in productivity. Scrap can then either continue to be added to the vessel or replaced with ore as coolant. Almost as many variations are possible as there are individual plant circumstances but a simple example would be a practice using synthetic hot metal made from 60 percent hot, reduced pellets and 40 percent scrap to an analysis of 2.30% C and 0.10% Si and a temperature of 2750°F, with 6 percent oxide pellets to be added to the vessel as coolant. This specification could be held to a narrow range, with temperature the independent control variable. Blowing time could be reduced to about half of that necessary with usual hot metal, and finishing temperature would be more predictable.

Such a practice could in fact be set up immediately, since there is ample experience in using the line frequency induction furnace for making this analysis of metal in large quantity. Capital and operating costs are well known and all details of operation are predictable. An outline example is given in Appendix A.

The possibilities overlap into the region where the costs of synthetic hot-metal plus abbreviated BOF practice equal those of using the arc furnace or the induction furnace, solely and directly, for going from the same raw materials to finished steel. This is not readily assessed except for specific instances; in fact, the whole range would have to be explored to find the cost minimum, including capital charges.

Steelmaking in Large Induction Furnaces

The induction furnace is a means or tool, like the BOF or the arc furnace, for applying physical chemistry to make steel from hot metal or scrap at lowest possible cost. Rates of reaction and of energy input become paramount as labor and equipment costs increase, and this is exemplified by the progress of the BOF in the last 10 years.

The large, line frequency induction furnace can operate in ways that combine the advantages of both the BOF and the arc furnace, and this should lead to lower-cost steelmaking in many circumstances. The following notes are intended to serve not as a treatise on making steel in the induction furnace but as an outline of basic modes of operation and an indication of some of the possibilities that follow from them.

Direct mention must be made of the comparison that inevitably comes to mind between the induction furnace and the arc furnace. Both are electric, and arc furnace characteristics are well known. However, such comparison should be made cautiously because the two furnaces function quite differently, and to think of either one in terms of the other can be seriously misleading.

There are basic differences that may be outlined as follows. The line-frequency induction furnace contains a compact shape of metal, like a cup, in which heat is generated internally and with a strong stirring action; the arc furnace is a shallow bath or saucer into which heat is introduced, at the surface by radiation and by some conduction from high-temperature arcs, with very little stirring action. Power density comparison must take into account the very different methods of applying power, including power factor and duty cycles; a 100-ton induction furnace may have about 30,000 kW applied whereas a 100-ton arc furnace may have 25,000 to 50,000 kVA (i.e., about 18,000 to 35,000 kW). The arc furnace can accept larger-size charge material because of its shape but the induction furnace can readily melt large heavy pieces that are slow to melt in the arc furnace. Arc furnace refractories are robust but the induction furnace uses no electrodes. The list can be extended but these are illustrative. Each furnace must be examined strictly on its own merits for the work to be done, assessing performance by final cost and product quality.

Practice -

The most interesting operating characteristic of the large line-frequency induction furnace is its stirring action, and this is, as noted above, a function of power input per ton of metal. At moderate power input of 200 kW per ton, stirring is vigorous, and slag/metal interface, in terms of square feet per ton of steel per minute, is much larger than in an arc furnace and reaction rates are correspondingly faster. As noted earlier, it should not be difficult to keep such a slag layer as hot as the metal under it.

When power input rate is increased further, slag begins to be pulled down the furnace walls in quantity and, by the time the rate reaches 300 kW per ton, the slag is emulsified completely into the metal. This has been observed repeatedly on a 65-ton furnace. Very large specific slag metal interface is thereby created which approaches that obtaining in the BOF. This effect may be created, regulated, or stopped at will by adjustment of power input and need not be associated with evolution of gas.

Use of such a capability for decarburizing a bath must be considered carefully because, if the bath contains much carbon and a highly oxidizing slag is emulsified quickly by rapid increase in power input, the rate of reaction could make an almost explosive boil. Control will be by adjustment of the oxidizing potential and quantity of the slag and by regulating the rate and extent of emulsification. Of course very rapid oxidation of large amounts of carbon is best carried out in the BOF which has the necessary physical volume and refractory thickness.

It should be possible to rapidly carry out refining reactions such as removal of phosphorus or sulphur in a vigorously stirred bath under a suitable slag. This is clear from the results in arc furnaces using induction stirrers where the bath movement is relatively feeble. It should therefore be possible to dephosphorize or desulphurize very rapidly with a suitable emulsified slag. This would not only decrease furnace time and increase output but would appreciably decrease refractory wear because of the short times involved.

The main penalty of such high reaction rates is refractory wear which increases with stirring action. This becomes an equation involving factors such as cost of lining materials and labor, value of increased production rate, and costs of decreased slag volume and power consumption; at present, no such data are publicly available.

It should not be overlooked that a large induction furnace operates satisfactorily and independently of the amount of slag on the metal bath because slag is not a necessary part of the operation. This makes it practical in some cases to set up simple, rapid, low-cost melting procedures.

Another operating characteristic that affects application of coreless induction furnaces to steel plant is the ease of operation on a continuous or semi-continuous basis. This mode is commonly used in iron foundries, the furnaces being emptied to below about two-thirds full only on week-ends for lining inspection. The arc furnace normally operates in batch or heat fashion and is not commonly used for continuous steelmaking. This makes some rethinking of operating procedures worthwhile.

An incidental characteristic which affects capital cost is that fume and smoke produced by induction furnace steelmaking is relatively small in volume and sub-micron fume such as created by an arc is not produced. In most cases cleaning equipment can be relatively simple and moderately priced. Oily and galvanized scrap are the main offenders and, if these are preheated or low in amount, the fume problem is minor.

Comment may be made here on vacuum degassing experience. The increasing use of line frequency induction furnaces for vacuum degassing of steel is providing useful data but much of this is not readily applicable to normal steelmaking. Furnace size is limited, although one furnace holding 60 tons is operating, by the fact that voltage on the coil must be kept down to about 600 volts to control corona in vacuum. Also, refractories present more difficulty in vacuum than in air because there is a stronger tendency to reduction and decomposition. The main point of divergence, however, is that the objective is to degas, therefore as little true steelmaking or composition adjustment as possible should be done in such expensive equipment. The net result of these factors is that, except on refractories, the degassing furnace experience does not seem to be of major help to normal practice.

A considerable number of line frequency furnaces are making steel but none so far are known to be used in 60 to 100-ton sizes to make plain carbon steels. This is not surprising because coreless furnaces, holding more than about 35 tons, have been available for only a few years. Most product is killed steel but there seems to be no reason semi-killed or rimmed grades would not be practical. A list of such applications is not known to the writer but examples are: a steel foundry in Chicago that has been making ASTM Grade 80-40 steel for 6 years in a 9-ton 2,000-kW furnace, on acid refractories, tapping at 2,950 to 3,000^{o}F, with a refractory cost of about $1.50 per ton; an electric motor manufacturer who casts frames in an 0.05 to 0.08 carbon steel made in a similar furnace that has a magnesite lining which has a life of four weeks; in Sweden a 20-ton furnace, operating at 560 Hz from a motor generator set, is making silicon steel on a production basis; a major American steel producer is in a testing program of making similar steel in line frequency furnaces at what should be appreciably lower capital and operating costs.

The induction furnace is well suited to a continuous mode of operation, and it appears that a practice similar to that in iron foundries can be used. In such operation, taking a 100-ton, 30,000-kW furnace as example, after teeming approximately 30 tons of steel, the furnace would be refilled with 30 tons of fresh charge. Due to the low bulk density of scrap, there would not be room for 30 tons all at once so about three 10-ton charges would be made, adding each as the previous one is absorbed. Suitable slag-making additions would be made with the charges, and the power input necessary to melt each charge would emulsify the slag and permit it to react rapidly with the charge as it is absorbed. After all charges are in and the bath approaches tapping temperature, it should be nearly in equilibrium with the slag and fully refined. Then the slag can be flushed by back-tilting the furnace and 30 tons of steel can be tapped to a ladle to which suitable deoxidizers can be added.

If a double-slag practice is necessary, after flushing the first slag, a fresh slag can be added and emulsified by application of power. The slag will rapidly reach bath temperature, react, and in turn it can be flushed.

Alternatively two furnaces could be used and arranged for direct transfer of metal, one acting as melter and the other smaller one being used to refine, superheat, and finish. This would make changes in steel specification easier and permit different refractory practices in the two furnaces. There are many variations possible to suit particular conditions, raw materials, and grades of steel to be made.

Gas Content -

Gas content of steel made in an induction furnace is usually under good control due to the stirring action and to the ability to apply a carbon monoxide boil if desired. In small furnaces operated without a cover such as in a laboratory, nitrogen content can be a problem but in large furnaces which must be operated with a cover to control heat loss, nitrogen pick-up should be less than in an arc furnace because the space above the slag is smaller and can be made more gas tight.

Cleanliness -

When slag is actively stirred into steel in order to increase interface area and reaction rate, the steel is intentionally made "dirty" and the emulsified slag and other inclusions must be removed later as far as possible. The identical problem exists to a more intense degree in the BOF in which large quantities of satisfactory steel are made.

In this connection, experience in iron melting is interesting since it demonstrates removal of alumina. A plant is operating using 15-ton line-frequency furnaces to melt a steel scrap charge and to carburize it sufficiently to atomize it to iron powder. The lining is rammed magnesite and there is build-up of the lining with alumina to the extent that periodically the accretion must be chiselled off to maintain a good inductive coupling. The effect is apparently the same as that found in tundish nozzles.

Operating Costs -

Operating costs may be summarized in familiar categories for arc furnace practice and are outlined on a comparative basis for simplicity.

Electric power consumption per ton of steel made at a given slag: metal ratio will be very similar to that for an arc furnace of the same capacity in tons per month. This has been clearly shown by comparative experience on medium-sized furnaces melting iron. The slightly higher losses to water cooling in induction practice are about balanced by better efficiency of use of power during finishing. The electrical load is much more desirable because it is smooth and free of flicker and because the unity power factor would in some cases qualify for a lower rate or be acceptable to an in-plant generating station.

Refractory costs per ton are likely to be somewhat higher in induction practice than in arc furnace practice making the same steel. It is possible that with good practice the increased cost may be under one dollar per ton of steel.

Labour cost should be nearly identical on induction and on arc furnace practices. The same crew is necessary, but duty is lighter on the induction furnace because there are no electrodes to handle.

Electrode cost, a major item in arc furnace practice, amounts to about as much as the power cost. It is non-existent on an induction furnace.

Maintenance costs appear to be about the same on the induction as on the arc furnace. Power regulation equipment is simple on the induction furnace but more complicated, in the form of electrode controls, on the arc furnace. However, periodic attention must be given to the coil on an induction furnace and occasionally a capacitor must be replaced in the power factor correction circuit.

Overhead, including laboratory and supervision, should be no different on the two practices.

In summary, operating costs of the large induction furnace making steel should be the same or less than those of an arc furnace making the same steel, the difference being approximately that between electrode costs and increased refractory cost. In some cases, there will be types of raw material that are physically more economically handled in the arc furnace but this is also true in reverse, hence it is not believed to be an important general factor.

Capital Costs -

Since consideration of induction furnace steelmaking from steel scrap or reduced pellets will generally be given in a situation where arc furnaces have been used or are a reasonable alternative, direct comparison will frequently be made. Such comparison must be carefully done because the two types of furnace operate differently which can affect choice and cost of associated equipment. Any useful comparison must be specific and direct for the particular circumstances involved in a real situation, with full allowance for ancillary effects.

Considering furnaces, power supplies, all auxiliaries and controls, and using purchased power, capital cost of installed equipment per annual ton of steel made will currently be about the same for a large line-frequency induction furnace as for an arc furnace. The arc furnace installation must include efficient fume collection equipment but, as noted above, this either does not seem to be necessary on induction furnaces or much simpler equipment will serve.

If a supply of thermal energy such as off-gas from solid-state reduction from a blast furnace or coke oven is available and if the capital cost of steam or gas turbine generating equipment is written off against power cost, the capital cost of the induction furnace will be appreciably less than that of the arc furnace.

Melting Solid-State Reduced Iron

Iron produced by a solid-state reduction process must usually be melted and refined to be usable; hence, its handling presents some special problems.

The product is fairly readily re-oxidized, carries gangue in amount depending on the ore used, and must be cooled from final reduction temperature under reducing conditions. For storage or shipment, the pellets must be treated or covered or both, therefore, though experience is still limited, it appears that cost of treatment and of iron loss by oxidation may be appreciable. It seems unlikely that fully reduced iron pellets will become a large item of commercial shipping.

The most practical and economic use of reduced iron is to melt it directly after reduction or, ideally, to transfer it hot from reduction to melting. The latter step obviates awkward and costly cooling arrangements and conserves a considerable amount of energy. A good deal of development work has been done on melting reduced pellets on the arc furnace, and it seems clear that a satisfactory procedure can be worked out to use cold pellets that have not too high a content of gangue. A viable method of continuous charging of hot (1500^{o}F) pellets in an integrated arrangement is not as clear. There also seems to be an appreciable penalty on gangue content due partly to energy consumption and partly to electrode wear. The limitations may be related to the relatively thin metallic bath in an arc furnace and to the difficulty of distributing the charged material satisfactorily to both absorb maximum heat from the centre triangle where it is generated and to protect bank and side wall refractories.

The line frequency induction furnace appears well suited to the melting of reduced pellets for several reasons. A primary one is that continuous melting is readily done with added pellets being absorbed rapidly into the bath by the stirring action. Tests have been run in a 100-ton furnace with excellent results. Another advantage is ease of close physical association of reduction and melting equipment, with complete top accessibility of the latter so that hot pellets are readily transferred out of contact with air. Still another feature is the ability to melt and flush off slag resulting from melted gangue and flux. The furnace can be either stationary, using tap holes at two levels above the coil for flushing slag and tapping metal, or tilting forward to tap metal and backward to flush slag.

If hot metal is to be made from pellets for BOF processing, the low-carbon high-temperature practice suggested earlier would be well suited. There seems to be no serious practical bar to handling a considerable slag volume in the induction furnace, particularly if the slag is neutral or acidic in chemistry as it would be for most pellets.

Increased slag volume increases cost in an induction furnace mainly because of the extra power consumed and the proportionately decreased output capacity of a given, furnace power supply. A rough estimate of cost increase is that it would amount to about $0.15 per ton of steel for each one percent increase in slag volume; this is considerably less than current price extras paid for super-clean concentrates.

If steel is to be made in the induction furnace directly from reduced pellets, several modes of operation are possible as indicated above. If gangue content and slag volume are relatively heavy, two furnaces in series can be used; one to melt the pellets and slag and do such refining as the slag permits and the second to act as a batch refining or finishing unit.

SUMMARY

It seems clear that there is a considerable variety of practical applications, in tonnage steelmaking, of large line-frequency induction furnaces. Operating experience already obtained in the iron foundry industry shows that the economics are excellent whenever hot metal is to be handled and that the outlook for direct steelmaking is promising. None of the procedures discussed here could have been seriously considered as economic or practical only five years ago, so rapid has been the rate of change. The important fact is that a powerful energy injector is available in practical form, and this must open up thinking about metallurgical procedures to make some genuinely fresh approaches to lower-cost steelmaking.

ACKNOWLEDGEMENT

The courtesies of Ajax Magnethermic, ASEA, Brown Boveri, and Inductotherm Corporations in supplying illustrative material are appreciated.

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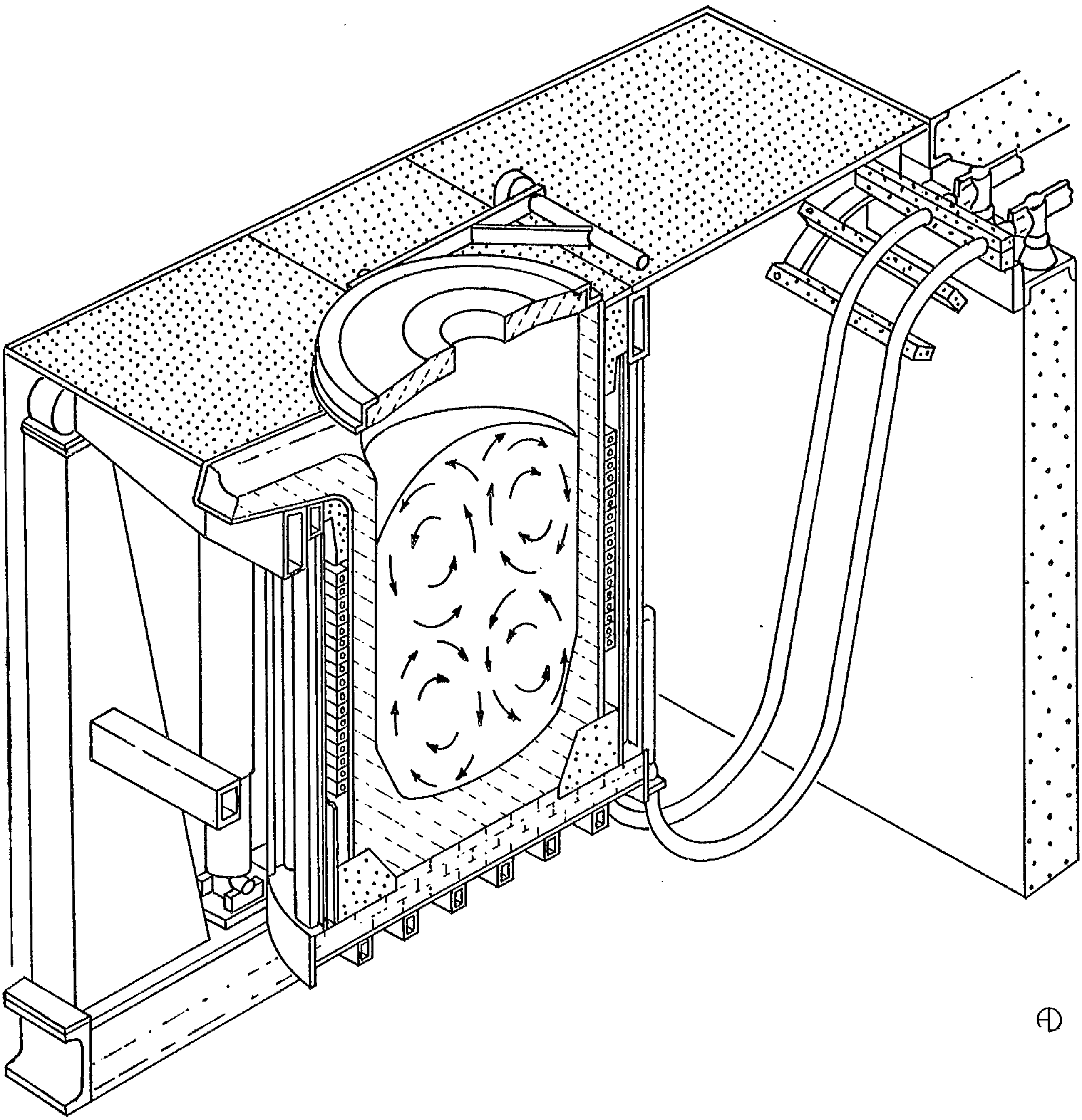

Figure 1. General Arrangement of Coreless Furnace Construction.

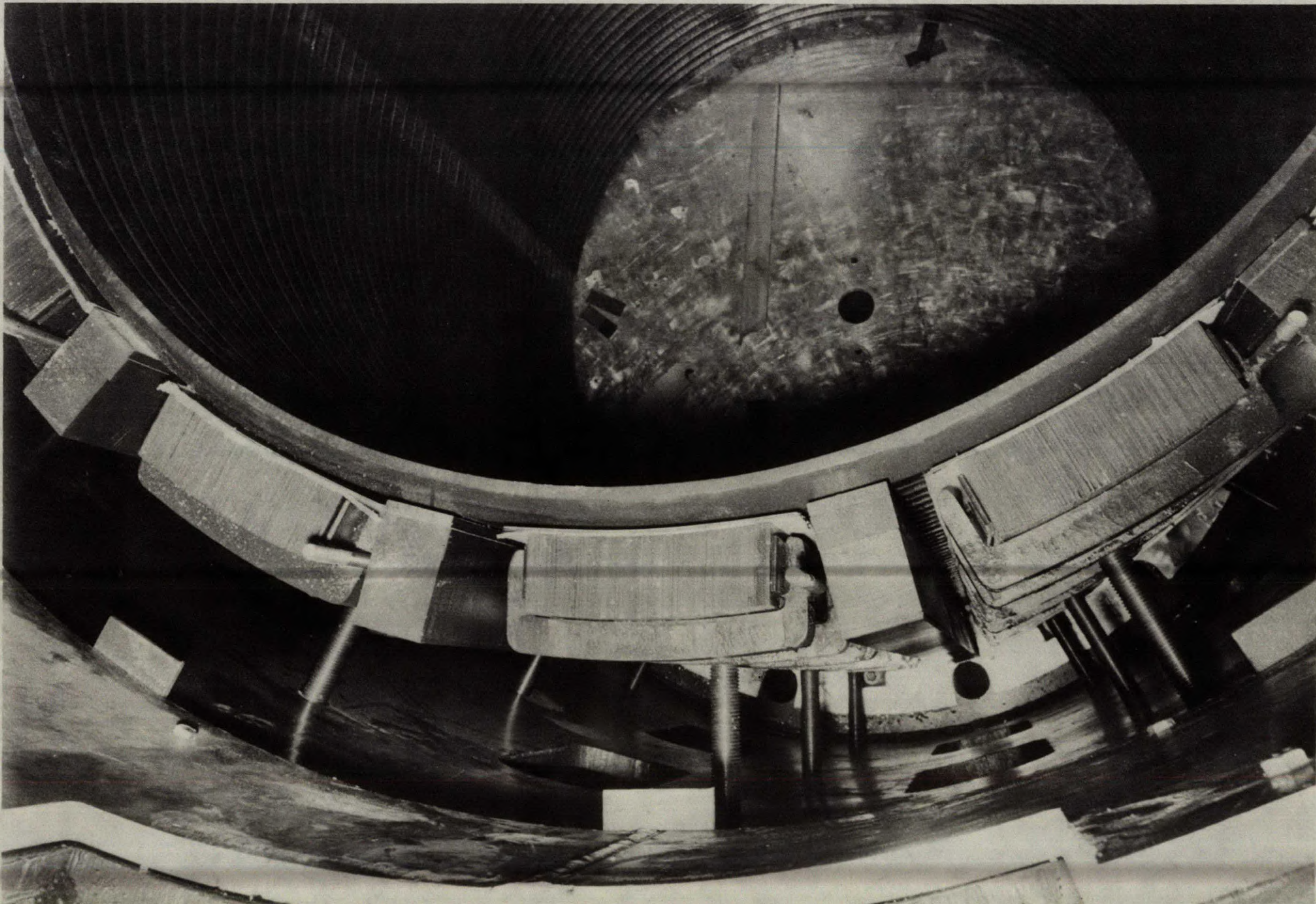

Figure 2. Furnace Construction Showing Coil, Insulation, Magnetic Yokes, Yoke Studs, and Furnace Frame.

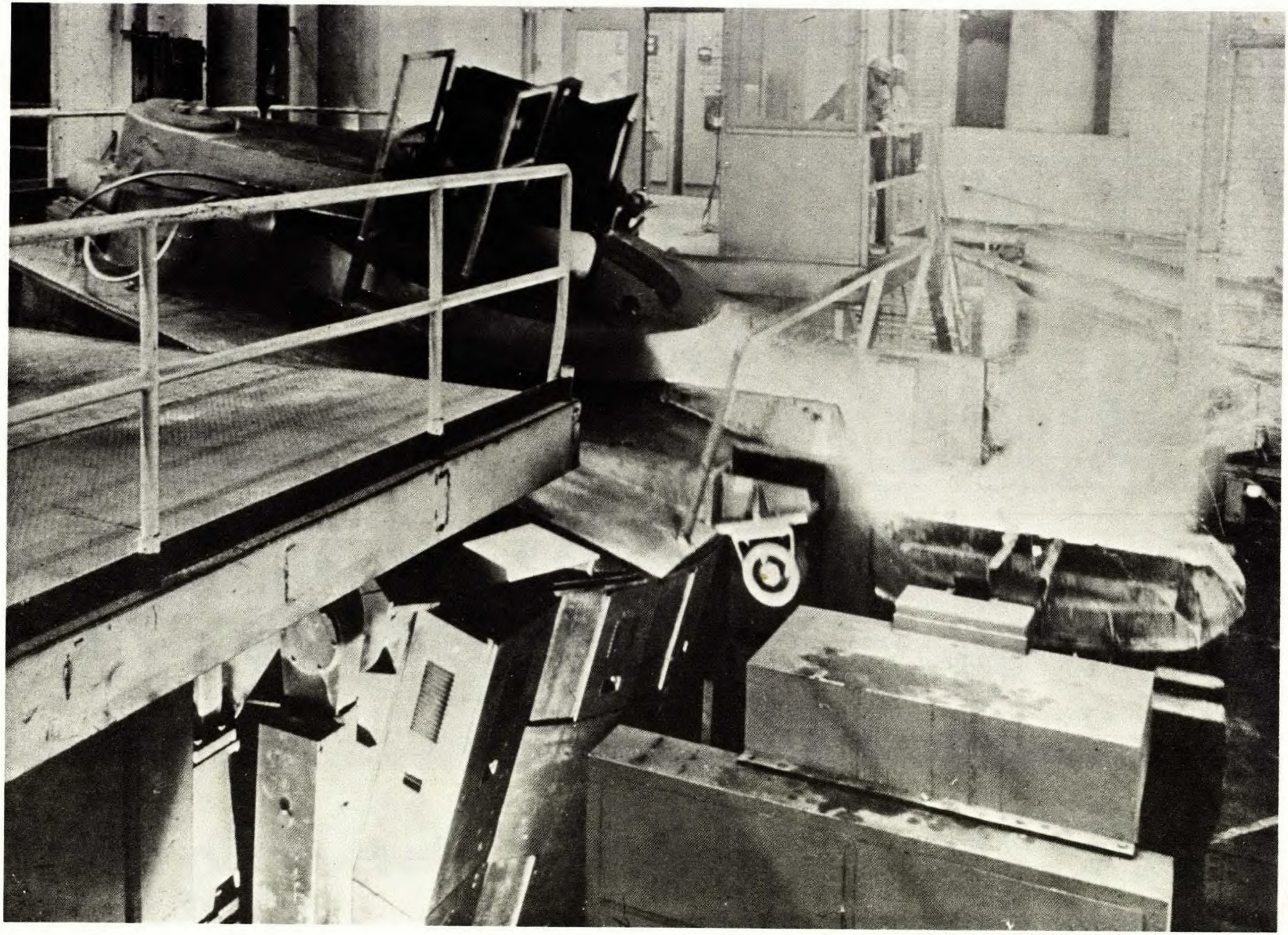

Figure 3. 65-ton 21,000-kW Furnace in Operation

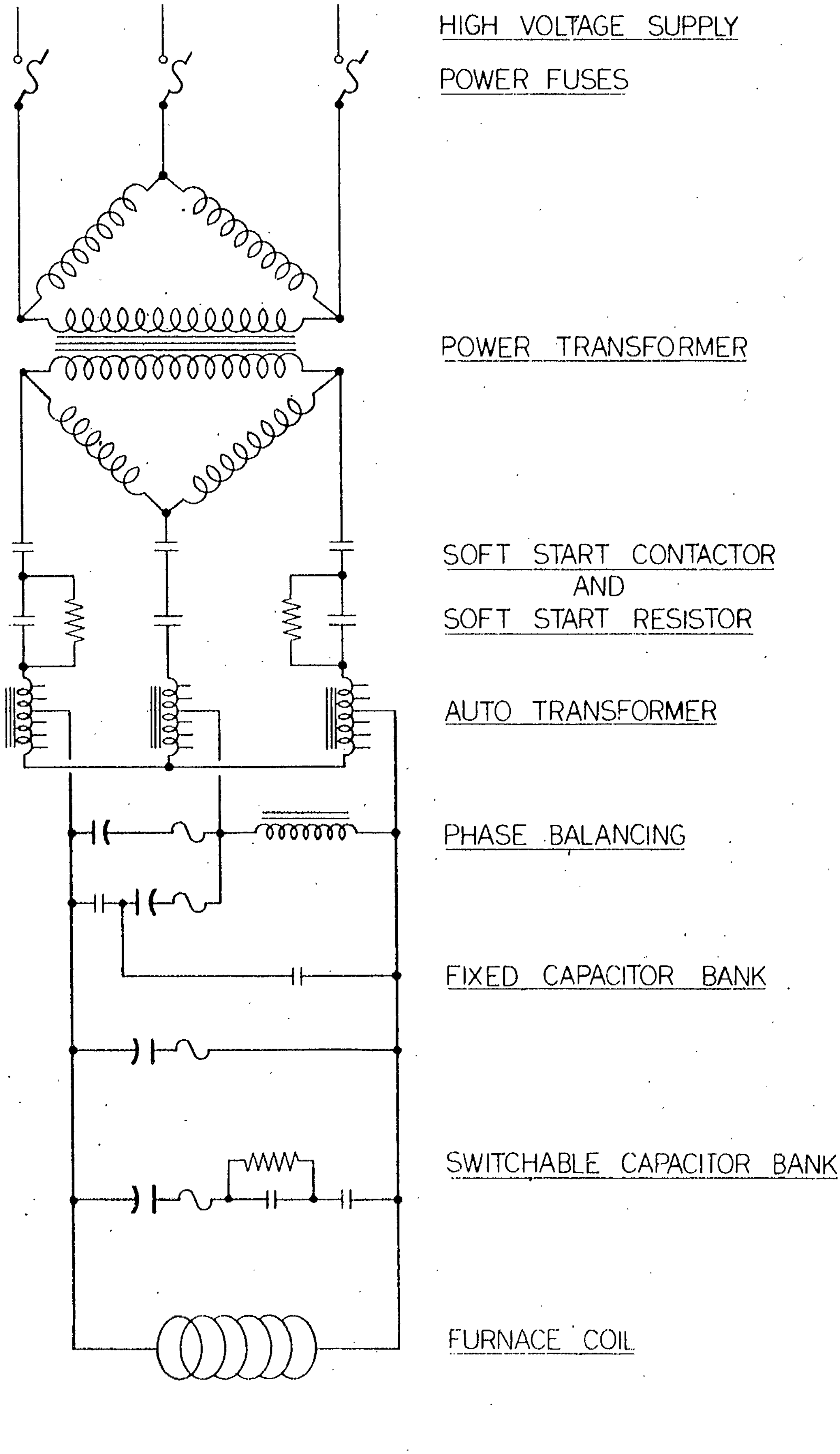

Figure 4. Typical 3-Phase Circuit Diagram

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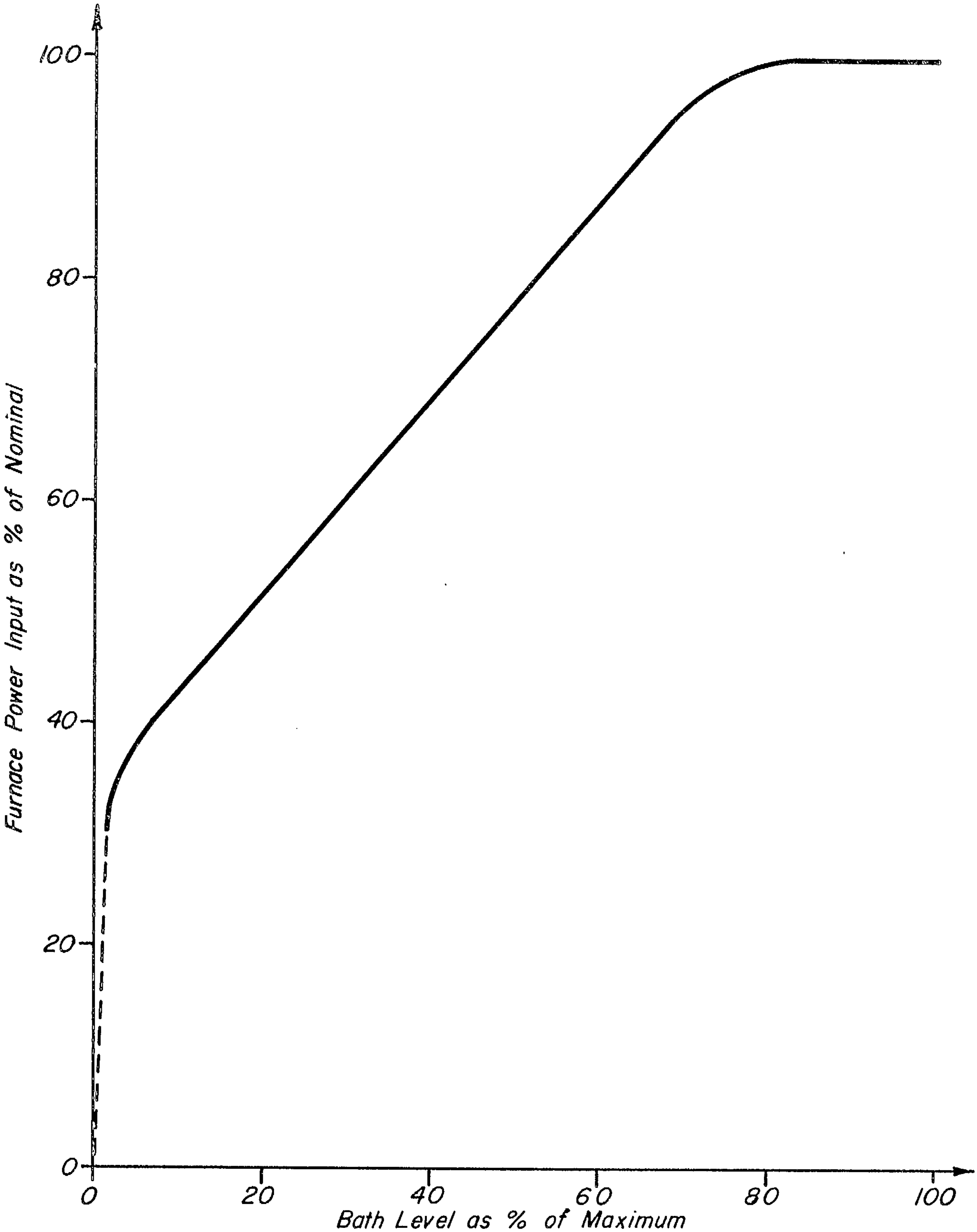

Figure 5. Induced Power as Function
of Height of Bath

APPENDIX A

Estimation of Furnace Size and Power

For illustrative purposes, outline estimates of furnace requirements for three different situations will be given here. These situations are:

steelmaking direct from solid-state reduced pellets;

duplexing blast furnace hot-metal with steel scrap;

synthetic feed for a BOF from pellets and scrap.

Much more detail must be included in an actual case but these are intended to show the approach involved, the order of size of equipment involved, and some operating parameters. The mode of operation suggested in each case is in skeleton form and is selected from many possible alternatives.

1. Steel Direct from Reduced Pellets -

The basis is 400,000 tons per year of reduced pellets plus 40 percent or 160,000 tons of steel scrap to be processed to steel to be continuously cast. The pellets contain 90 percent metallic iron and an acid gangue that requires addition of 6 percent of lime to make a slag basic enough to accomplish some desulphurization. The induction furnace is lined with magnesite. The pellets reach the furnace at a temperature of 1200°F and the scrap is preheated with gas to 1200°F. Operation is for 24 hours per day 330 days per year.

Two line-frequency coreless furnaces are used. The larger, of about 80-ton capacity, receives pellets, flux, and half of the steel scrap and melts these to 2850°F. The slag is flushed after sufficient desulphurization, and about one third of the steel is transferred by launder or by direct pour to a 25-ton furnace which has just been emptied. To this furnace is also added the remaining steel scrap. The contents are corrected in composition, heated to 2950°F, and blocked for tapping into a ladle for transfer to the continuous-casting machine or to a third holding furnace acting as continuous-casting ladle. While the steel is being finished in the second furnace, fresh charges of pellets, scrap, and flux have been made to the first furnace.

Material to first furnace -

Pellets incl. gangue	400,000 tpy	= 50.4 tph
20% of steel scrap	80,000 "	= 10.1 "
Flux	24,000 "	= 3.0 "
Total	504,000 tpy	= 63.5 tph

Material to second furnace -

Liquid steel	440,000 tpy	= 56.5 tph
Remaining scrap	80,000 "	= 10.1 "
Total	520,000 "	66.6 "

First furnace, per hour -

Heat content in metal and slag to 2850 = 63.5 x 258	= 16,400 kwh
Heat losses 80-ton furnace	400 "
Total	16,800 kwh

Furnace total efficiency 76% power input req'd = 22,100 kW

Furnace rating, 10% delays = 24,300 kW

Power density 276 kW per net ton

Second furnace, per hour -

Heat content molten steel 2850-2950^{o}F = 56.5 x 11	= 622 kwh
Remaining scrap 1200 to 2950^{o}F = 10.1 x 269	=2,717 "
Heat losses 25-ton furnace	120 "
Total	3,459 kwh
Furnace efficiency 76% power input required	=4,560 kW
Furnace rating, 10% delays	=5,050 kW

Power density 182 kW per net ton

Total power consumption 22,100 + 4,560 = 266,660

Steel produced 66.6 tons per hour.

Power consumption $\frac{26,660}{66.6}$ = 400 kwh per net ton

Gas required for preheating steel scrap at 40 percent thermal efficiency = 830,000 btu per net ton of scrap

= 252,000 btu per net ton of finished steel.

2. Duplexing BFHM with Steel Scrap -

A blast furnace makes 2,000 tons per day of hot metal to which 40 percent of steel scrap is to be added to give 2800 tons per day of final hot metal to supply a BOF. The scrap is not preheated. The original hot metal is 4.30% C, 0.80% Si, at 2650°F and final hot-metal will be 3.10% C, 0.60% Si, at 2800°F. The induction furnaces are acid lined. The blast furnace is tapped every two hours to give 167 tons. The BOF requires 98 tons every 50 minutes.

Two 100-ton coreless induction furnaces are used and there is one power supply and a small "Holding" supply. The blast furnace tap is taken on both furnaces. Steel scrap is added, composition and temperature are adjusted, and each furnace in turn is emptied to supply the BOF. There will be no difficulty in drawing full power in the induction furnace because it will be refilled to over half full from the next tap of the blast furnace.

2000 tpd blast furnace iron	= 83.3 tons per hr
800 tpd steel scrap	= 33.3 " " "
Total	116.6 tons per hr

Energy input to heat BFHM 2650 to 2800°F = 83.3 x 16.5 =	1,380 kwh
Energy required to melt scrap to 2800°F = 33.3 x 350 =	11,600 "
Heat losses from two 100-ton furnaces	800 "
Total	13,780 kwh

Furnace eff. 76%, power input req'd = 18,100 kW

Furnace rating, 10% delays = 19,900 kW

Power density 181 kW per net ton

Power consumption per net ton of final hot-metal = 156 kwh

3. Synthetic Hot-Metal for BOF -

Raw materials are reduced pellets and scrap in the ratio 60:40 both at 1200°F. Quantities are 800,000 tpy pellets, 320,000 tpy scrap, 48,000 tpy flux. Induction furnaces have basic linings, and desulphurization is to be done. The BOF is a 90-ton vessel on a 40-minute cycle. Hot metal is to be 2.00% C, 0.10% Si, at 2850°F.

Two 135-ton furnaces are operated in parallel so that, by tapping one third from each at same time, 90 tons can be taken to the BOF.

Material to furnaces -

Pellets incl. gangue	800,000 tpy	=	100.8 tph.
40% steel scrap	320,000 "	=	40.4 "
Flux	48,000 "	=	6.0 "
Carbon 1.5%	15,000 "	=	1.9 "
Total	1,183,000 tpy		149.1 tph

Hot metal produced -

From pellets at 90%	=	90.7 tph
From scrap at 95%	=	38.4 "
From carbon at 90%	=	1.4 "
Total		130.5 tph

= 1,035,000 tons per year.

Energy per hour -

Input to melt pellets 1200 - 2850°F	= 100.8 x 258	=	26,100 kwh
" " " scrap 1200 - 2850°F	= 40.4 x 258	=	10,400 kwh
" " heat flux and carbon	= 7.9 x 355	=	2,800 "
Heat losses from two 135-ton furnaces		=	1,000
Total			40,300 kwh

Furnace efficiency 76 % power input req'd. = 53,000 kW

Furnace rating, 10% delays, per furnace = 29,150 kW

Power density $= \frac{53,000}{2 \times 135} =$ 196 kW per net ton

Power consumption per net ton of hot metal = 405 kwh