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Agenda item 6

UTILIZATION OF DIRECT REDUCTION IRON
IN ELECTRIC STEELMAKING[1]

by

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SUMMARY

This paper on the utilization of direct reduction iron in electric steelmaking is an attempt to summarize the experience gained at Lukens Steel Co. in production trials over the last 8 years employing a variety of direct reduction iron products. In general, it was found that a steelmaking practice could be developed to accommodate any of these materials. However, steelmaking costs were found to be significantly affected by the characteristics of the direct reduction iron as well as the furnace practices employed. Some detailed analyses of the effects of these characteristics are presented with respect to physical and chemical properties.

A generalized economic consideration with respect to direct reduction iron as a commodity is given. It is indicated that a long-term world scrap shortage may be developing and that continued electric furnace expansion will create additional demand for suitable charge materials. The usage of direct reduction iron appears justified for both industrialized and undeveloped nations, but for different reasons. It has been demonstrated that this material is a metallurgically desirable alternate or substitute for steel scrap.

It is probable that direct reduction capacity will increase substantially during the next 10 years. The location of these plants will be limited to those world areas which can provide a stable energy supply with relative freedom from domestic demands.

The overall experience with the use of direct reduction iron has demonstrated to Lukens Steel Co., producing specialty plate products, that this material is metallurgically and economically attractive. Methods of usage have resulted in significant productivity improvements with a potential reduction in steelmaking cost.

INTRODUCTION

This paper on the utilization of direct reduction iron in electric steelmaking is an attempt to summarize the experience gained at Lukens Steel Company in production trials over the last 8 years employing a variety of direct reduction products.

The nomenclature with respect to the resultant products of direct reduction processes is currently diverse and subject to some degree of confusion. There has been a general tendency for each manufacturing process to be identified with a specific product name. For metallurgical considerations, it would be desirable to have a generically acceptable name for this new material.

Within this paper, the name "direct reduction iron" is used to indicate the product of any direct reduction process. The direct reduction iron materials used in these trials have represented a wide range of compositions with respect to metallization,* acid gangue, oxygen, carbon, sulfur, and phosphorus. There have also been several forms of the material including pellets, briquettes, and lump ore. These materials also represent the product of the most significant

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*"Metallization" is defined as the quotient of the metallic iron content and the total iron content of the direct reduction iron material expressed as a percent

direct reduction processes such as: rotary kiln -- solid reductant, batch type -- gaseous reductant, shaft furnace -- gaseous reductant, and fluidized bed -- gaseous reductant.

Along with the wide variety of directly reduced materials, there were also a wide variety of melting or furnace practices employed. These melting practices covered batch charging, continuous charging via three pipes, and continuous charging via a single pipe in the furnace roof. Aside from the material handling systems, wide variations in steelmaking practices were tried such as: maximum power, maximum continuous charging rate, slag flushing, no slag flushing, minimum amount of continuously charged material, maximum amount of continuously charged material, lime feeding, oxygen blowing, and carbon injection, etc.

As may be expected, some practices resulted in both a loss of productivity and increased steelmaking cost, some resulted in increased productivity but increased steelmaking cost, and some resulted in increased productivity and reduced steelmaking cost. The ability to obtain the desired results has been demonstrated to be a function of both the material characteristics and the steelmaking practice employed.

HISTORY

Interest in direct reduction iron at Lukens Steel Company was initiated in the late 1940's with laboratory experiments involving hydrogen reduction of various iron oxide pellets. Because steelmaking operations at Lukens are based upon a 100% scrap charge, we have maintained a continuing interest in direct reduction iron as an alternate to steel scrap. As trial quantities of direct reduction iron have become available, we have been eager to conduct experimental steelmaking trials to evaluate the potential benefits of these new materials.

The initial production trials with direct reduction iron were conducted during 1965 in a 90 metric ton electric furnace employing batch charging of the material with the steel scrap. The first major evaluation program was conducted in 1968 with 2700 metric tons of SL/RN pellets employing the continuous charging technique in a 135 metric ton furnace. Table 1 summarizes the history of the experimental programs through 1972.

The details of the electric furnace and the associated materials handling equipment have been previously reported. [1,2] Briefly stated, the arc furnace used in the experimental piograms, after 1968, is a 6.7 meter diameter furnace of 135 metric ton nominal capacity, equipped with 61 cm. diameter electrodes. Electrical power is supplied from a 56,000 kVA transformer providing a maximum power to the furnace of 39 megawatts. Water-cooled cables are used between the transformer and the electrode arms.

MATERIALS HANDLING

The system used initially for storing and supplying direct reduction iron materials to the furnace is similar in design to that used in the Stelco trials. [3]

TABLE 1

EXPERIMENTAL PROGRAMS WITH DIRECT REDUCTION IRON AT LUKENS STEEL CO.

DATE	IDENTIFICATION	DIRECT REDUCTION IRON (METRIC TONS)	NO. OF HEATS	STEEL PRODUCED (METRIC TONS)
1966	PICKANDS-MATHER	136	5	450
1967	FALCONBRIDGE NICKEL	182	6	545
1968	SL/RN HILTON PELLETS	2700	71	10000
1969	STEEL SCRAP	32	2	273
1964	ESSO FIOR BRIQUETTES	4800	178	23300
1969	HAMMERSLEY HI-met	39	3	410
1970	MEXICAN HYL PELLETS	82	5	710
1971	MIDREX PELLETS (Briquettes)	230	11	1450
1972	MIDREX PELLETS (and Lumps)	6700	357	49000

It consists of a silo storage hopper with holding capacity for 165 metric tons of material having a bulk density of 3.2 t/m^3. Material flow from the hopper is controlled by a vibratory feeder discharging onto a weigh-belt feeder that is calibrated to indicate the rate and total quantity of material entering the furnace. The weigh-belt feeds into a bucket elevator that carries the material to a distribution box 9 meters above the furnace roof. In the SL/RN trials a splitter box was used to distribute approximately equal quantities of the material to three 20 cm diameter stainless steel feed pipes. These pipes carried the pellets to the furnace roof openings where they dropped into the bath. The roof ports were positioned so as to introduce the pellets into the arc flare regions between the electrodes and furnace wall. For the FIOR test series utilizing briquetted material, the splitter box was removed and a single 25 cm diameter feed pipe was used to deliver the material to the center of the furnace roof. Here a 25 cm diameter roof port allowed the material to fall directly into the center of the electrode delta. A funnel on the feed pipe attached to the furnace roof support structure permitted the furnace to be tilted 2 degrees backward or forward during continuous charging to allow slag flushing.

Near the beginning of the first experimental trials, an auxiliary system for lime feeding was added. This bin, with a capacity of about 2500 Kg, supplies lime via a screw conveyor into the base of the bucket elevator. Lime feed rate can be regulated by means of a variable speed reducer.

MATERIAL PROPERTIES AND COMPOSITIONS

Table 2 lists the various materials used by Lukens in our direct reduction iron trials and some of their physical characteristics. Note particularly the effective density of the materials, determined by spraying a plastic coating over the material before determining density in water. It is believed that this density simulates the condition that occurs when the material falls into the slag and is coated by a chilled layer of slag. Whenever this density is close to the density of slag, there is a possibility for island formation, or a piling up of the material on the slag surface.

Table 3 lists the chemical composition of the materials used.

RESULTS OF TESTING

As indicated in Table 1, we have had limited experience with a wide variety of direct reduction products. Although it would appear attractive to compile a comparative table of the results obtained with each material, we feel that such a comparison would not be objective inasmuch as the steelmaking practices were subject to continuing improvements and the quantities of the test materials were greatly different. Detailed results of some of these trials have been previously reported.[1,2] For the broad base nature of this paper, we have chosen to describe the characteristics which are subject to variation with respect to both reduction process parameters and with respect to the compositional characterization of a given feed stock iron ore. Therefore, the following discussion is directed toward an understanding of the effects of direct reduction iron characteristics upon steelmaking.

TABLE 2
PHYSICAL CHARACTERISTICS OF DIRECT REDUCTION IRON

PRODUCT IDENTIFICATION	PROCESS TYPE	FORM	SIZE	AVG. PIECE WEIGHT	BULK DENSITY	PIECE DENSITY	*EFFECTIVE DENSITY
PICKANDS-MATHER	ROTARY KILN - SOLID REDUCTANT	PELLETS	N.R.	N.R.	N.R.	N.R.	N.R.
FALCONBRIDGE NICKEL	ROTARY KILN - SOLID REDUCTANT	PELLETS	5-22 mm	N.R.	3.05 t/m³	4.6 g/cc	N.R.
SL/RN HILTON PELLETS	ROTARY KILN - SOLID REDUCTANT	PELLETS	~15 mm	2.7 g	1.04 t/m³	5.3 g/cc	3.9 g/cc
STEEL SCRAP	NONE	PUNCHINGS & GRINDING BALLS	~75 mm	N.R.	N.R.	7.7 g/cc	7.7 g/cc
ESO FIOR	FLUIDIZED BED	BRIQUETTES	76x38x25 mm	236 g	3.05 t/m³	5.9 g/cc	5.35 g/cc
MIDREX DRI	ROTARY KILN - SOLID REDUCTANT	LUMP	~19 mm	3.2 g	3.51 t/m³	5.9 g/cc	1.6 g/cc
MIDREX HYL	SHAFT TYPE - GASEOUS REDUCTANT	PELLETS	3-25 mm	4.4 g	1.85 t/m³	4.4 g/cc	2.9 g/cc
MIDREX PELLETS (Briquetted)	SHAFT FURNACE - GASEOUS REDUCTION	BRIQUETTES	57x29x19 mm	128 g	N.R.	N.R.	N.R.
MIDREX PELLETS (and Lump)	SHAFT FURNACE - GASEOUS REDUCTION	PELLETS & LUMP	1-30 mm	3.3 g	2.16 t/m³	5.7 g/cc	4.8 g/cc

N.R.—NOT REPORTED
* MEASURED BY COATING WITH PLASTIC SPRAY MATERIAL AND DETERMINING DENSITY BY WATER DISPLACEMENT.

TABLE 3
CHEMICAL COMPOSITION OF DIRECT REDUCTION IRON MATERIALS

PRODUCT IDENTIFICATION	TOTAL Fe	METAL Fe	METALLIZATION	C	P	S	SiO_2	Al_2O_3	CaO	MgO
PROVISIONAL RANGE				.97/.18	.010/.020	.014/.015				
FALCONBRIDGE BRIQ.*	91	88.6	91.4	0.62	0.65	0.065	2.16	1.07	0.40	0.54
SL/RN HILTON PELLETS	86.6	77.6	89.9	0.29	N.D.	0.016	4.68	0.08	0.50	3.12
ESSO FIOR	92.1	84.3	92.1	0.57	0.057	0.024	2.04	0.63	0.08	1.01
HAMBURGER REEK	92.5	90.9	96.9	0.37	0.08	0.029	2.01	1.23	N.D.	N.D.
HPL PELLETS	87.6	82.6	94.1	2.10	0.270	0.087	3.98	1.06	1.12	0.80
MIDREX PELLETS (Briquetted)	92.5	90.0	96.5	2.50	0.010	0.011	2.50	0.08	0.51	0.56
MIDREX PELLETS	92.0	88.0	96.0	1.76	0.022	0.004	1.16	0.63	1.07	0.21

* THIS MATERIAL ALSO CONTAINED 1.57% N

GENERAL OBJECTIVES

Every steel company has a list of objectives to be fulfilled in order for a production process to proceed profitably. In the case of direct reduction iron usage, every company has a different situation with regard to scrap cost, size of furnace, product chemistry, amount of direct reduction iron to be used, power input, etc. Nevertheless, in utilizing this material, a series of common objectives has emerged which apply to Lukens as well as other steel producers. Specifically, the material characteristics and operating practices should be optimized to yield:

1. A high-quality steel product.
2. The highest productivity.
3. The lowest total cost of energy, refractories, electrodes, and auxiliary materials.
4. Low storage and handling costs.

At Lukens both continuous charging and batch charging have been tried, but no operating advantages were noted for batch charging. In fact, batch charging can be detrimental to productivity unless careful procedures are used to mix the direct reduction iron with scrap materials. Pellets, for instance, can sinter into a monolithic mass which will not fall into the molten metal pool as scrap does. This feature results in massive bridging and excessively long melt cycles.

Continuous charging can be utilized during the melting of scrap with some benefit in power stabilization, as also reported by others.[3,4] While this procedure has been tried numerous times, and some benefits appear to be attainable, Lukens economic situation has generally tended towards utilization of the amount of direct reduction iron that would maximize productivity while minimizing charge costs. This has resulted in a usage of about 10-25% direct reduction iron continuously charged during the refining cycle. The operating conditions and physical properties discussed in the following sections refer in all cases to continuous charging during the refining cycle, here defined as the time between the melting of the initial scrap charge, and the tapping of the furnace. The ideas set forth are considered valid for direct reduction iron usages up to 60% of the capacity of the electric furnace where continuous charging is accomplished with bath temperatures of 1550-1620°C.

OPERATING CONDITIONS DEVELOPED TO MEET OBJECTIVES

Of the four general objectives listed above, the first three depend on both operating conditions and physical properties, while the fourth depends solely on physical characteristics. The operating conditions that we consider vital in achieving these objectives are:

1. Refine and melt simultaneously (simultaneous oxygen, lime, and carbon additions as required.)
2. Control temperature carefully and achieve highest temperature (near tap temperature) at end of continuous charging.
3. Predict the end point of continuous charging by chemical sampling so that refining period ends when continuous charging ends.

4. Eliminate time losses for carbon injection or oxygen blowing by performing these operations during the continuous charging.

5. Use the minimum amount of lime to achieve desired sulfur level and/or neutralize the acid gangue in the direct reduction iron.

6. Shield refractories from arc damage by maintaining thick slag cover or a continuing carbon-oxygen boil. Use shortest arc possible to achieve desired power setting.

IMPORTANCE OF PHYSICAL PARAMETERS

Size - This factor assumes considerable importance in continuous charging any material. If the material is too fine, it can be oxidized in falling to the slag or lost in the fume exhaust system. If it is too large, the continuous charging system becomes costly and complex. In our experience pellets, or briquettes up to 10 cm maximum dimension are easily handled. The size fraction of the material less than 1 mm should be limited when continuously charging through the furnace roof.

Density - The effective density (determined as previously stated in Table 2) should lie between that of molten slag and molten steel (2.7-6.9g/cc). It is desirable for the material to reside at the slag-metal interface for effective heat transfer and chemical reactions. The effect of the material density has been observed during the various steelmaking trials. The lower-density materials had a tendency to float on the slag and to form islands or "icebergs". In contrast, the higher-density materials were readily absorbed into the bath. Therefore, a density in the range of 4.0-6.0g/cc was found to be desirable.

Mass or Unit Weight - Mass of an individual piece is obviously governed by density and size, but the momentum (mass x velocity) with which a direct reduced iron particle contacts the slag will determine the transition time through the slag. Obviously, a 500g briquette falling from three meters will not be impeded from penetrating the liquid metal by the presence of some slag; however, perhaps a 3 gram pellet will be impeded, and the density factor must then prevail to determine how long it will take the pellet to reach the liquid steel. It is believed that the long residence time of some pellets in the slag is responsible for a carbon oxygen boil in the slag, or "slag boil", as contrasted to the more deep-seated metal boiling accompanying an oxygen blow or chemically active briquettes.

Slag fluidity exerts a major effect on the behavior of the lower unit weight materials and the tendency to form "icebergs" or large floating masses of unmelted material. The heavier briquetted material does not require this close degree of slag control as it will penetrate directly through to the liquid steel.

Crushing Strength and Breakage Resistance - These parameters usually determine the amount of fines generated throughout the processing handling operations. Since fines are considered less desirable because of yield and oxidation considerations, the direct reduction iron should have good crushing strength and resistance to breakage.

Weather Resistance - It is desirable to be able to store materials outside and ship in open containers. The ability to do so without significant oxidation and heat buildup is governed by the density of the material, the effective surface area per Kg., and any surface conditioners or passivation procedures that have been applied. It is beyond the scope of this paper to deal with this subject. I should be mentioned, however, that a large particle size of high density is favored for best weather resistance. Briquetted material has been stored outside for 18 months with a loss of only 5% in metallization. Outdoor storage of direct reduced pellets is not anticipated because of their history of rapid oxidation sometimes leading to high temperatures and almost total reoxidation.

IMPORTANCE OF CHEMICAL PARAMETERS

Gangue Components - The importance of gangue components centers on five factors:

1. Cost of energy to heat gangue components.
2. Importance of desulfurization - if desulfurization is important, then lime additions must be made to obtain $\frac{CaO + MgO}{SiO_2}$ ratio of ~ 3, and the cost of this lime and the required energy to heat it becomes important.
3. Furnace lining considerations - if a basic furnace lining is used, acid gangue components must be neutralized by lime additions or the slag will dissolve the furnace lining.
4. Loss in productivity because of time required to heat lime and gangue constituents.
5. Cost of transporting the gangue materials with the direct reduction iron.

The cost of all of these factors will be considered in more detail in a later section.

Sulfur - At a time in steelmaking history when much emphasis is being placed on low sulfur levels in steel product, it is redundant to emphasize the importance of this element. The cost analysis following treats the cost of sulfur in terms of the amount of lime required and the cost of power to heat the lime. It is thus seen that, depending on the final aim sulfur level, money and time can be saved when sulfur is lower in the direct reduction iron than the final aim sulfur level. The actual savings resulting from the use of a low sulfur material, may be greater than the calculation indicates. A hypothetical material, for instance, of $\sim$ .010% S, might be the easiest and cheapest way of achieving very low-sulfur steel, when compared to a double slag practice or expensive ladle additions. For specialty steels of high quality, low-sulfur direct reduction iron could indeed be a viable alternative that is competitive in cost and which would not result in decreased productivity.

Phosphorus - There are indications that low phosphorus levels may be difficult to achieve when feeding greater than 30% of the charge as direct reduction iron. Since Lukens has not had experience at this level of usage, we cannot comment. At lower levels of usage, say, 10-30% of the furnace charge,

phosphorus levels up to .070% have been used with no noticeable effect on final product phosphorus content.

Oxygen and Carbon Contents - In order to operate in a manner suggested earlier in this discussion, the carbon and oxygen (as iron oxide) contents should be adjusted to provide:

1. Relatively stable and predictable carbon composition in the liquid steel bath during continuous charging so that only minor adjustments of carbon level need to be made. (These adjustments should be made during the continuous charging.)

2. An active carbon-oxygen boil. This boil is necessary to protect refractories from arc damage during the continuous charging.

These considerations become more acute the greater the percentage of direct reduction iron that is used.

Lukens experience and that of McCallum and Peters[4] indicates that there is a minimum carbon content in the direct reduction iron, probably around 0.6°, and dependent on bath carbon content, below which an active boil will not occur without using additional oxygen, regardless of the oxygen content in the material. If this minimum carbon content is provided, then a total carbon removal rate of about 1 point or 0.01% per minute seems to be enough to shield the arcs. One point must be stressed here. Shielding the arcs by a carbon-oxygen boil is a cost item, no matter how it is accomplished. If oxygen and carbon are present in the direct reduction iron, then a penalty in energy and consequently furnace time is taken, because of the endothermic reaction between FeO and C. If oxygen lancing is used, then the penalty is the cost of oxygen lancing and carbon, although the energy input into the furnace is effectively increased. In reality, Lukens experience indicates that a compromise must always be struck, since iron oxides are always present in the direct reduction iron.

Figure 1 indicates the "ideal" oxygen content (as iron oxide) in direct reduction iron as a function of furnace capacity and power. With this quantity of oxygen available, and the normal power and continuous charging rate, a reduction in carbon of 0.01%/min. (calculated on total furnace capacity) will be accomplished, and arc shielding should result. A generalized value of 28 Kg/min/MW has been assumed for the charging rate. Clearly, as charging rates are allowed to increase (higher power level for the same size furnace), the quantity of oxygen required in the direct reduction iron decreases. If it is assumed that Figure 1 represents ideal conditions for direct reduction iron, the graph can then be divided into two parts. If oxygen is less than ideal for a given furnace size and power, (point A in Figure 1) oxygen must be introduced in the amount of Δ0% x charging rate, and an appropriate cost is incurred, but extra energy is introduced into the furnace and productivity is increased. If oxygen content is greater than ideal (Point B), extra power, carbon, and furnace time are required (for endothermic reactions), thereby effectively decreasing productivity. The graph in Figure 1 is thus seen as "ideal" because it represents just enough oxygen to cause a boil for refractory protection.
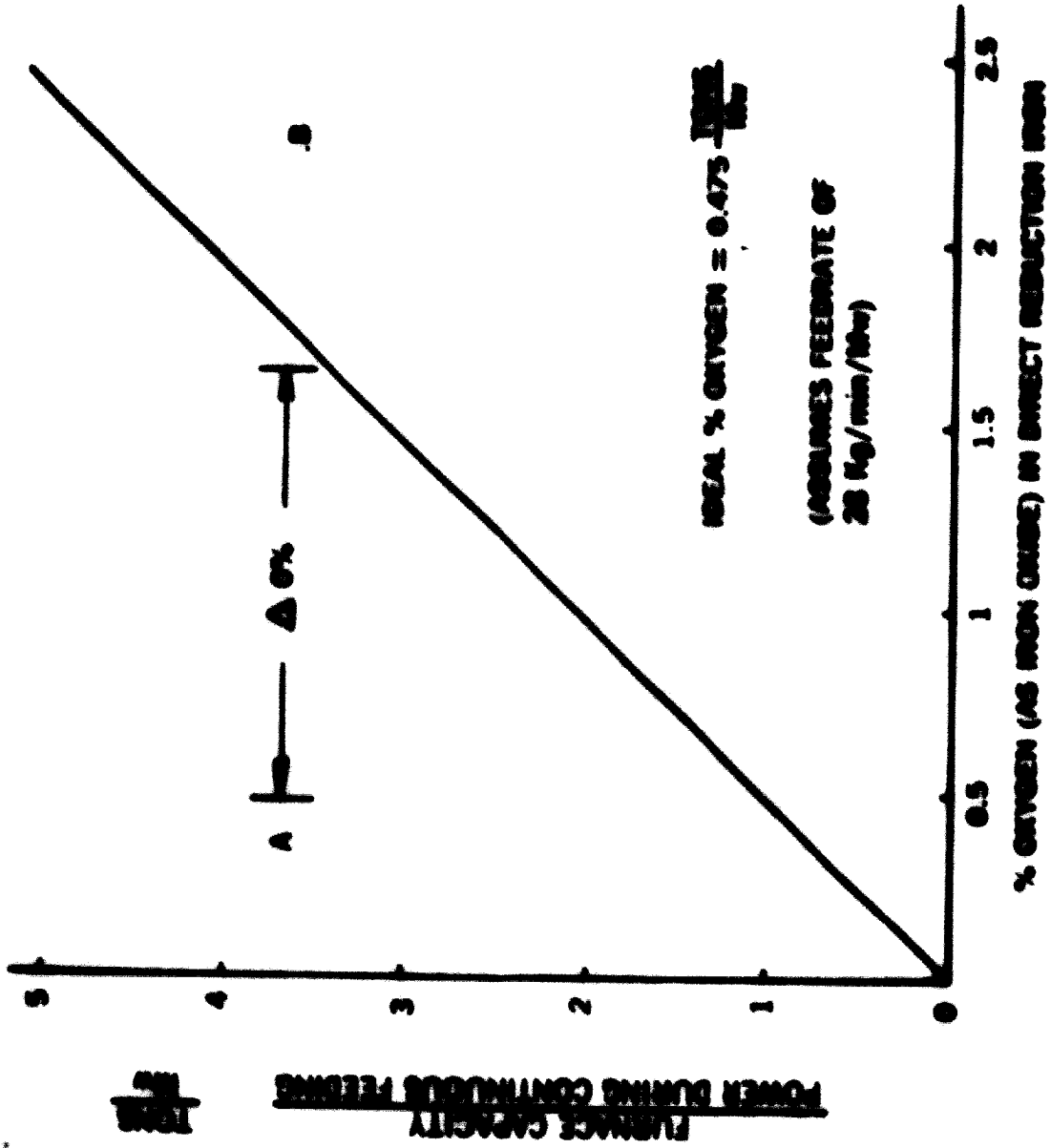
IDEAL OXYGEN CONTENT VS. FURNACE SIZE AND FURNACE CAPACITY
FOR CONTINUOUS FEEDING DIRECT REDUCTION IRON

FIGURE: 1

Figure 2 displays the carbon content required to just balance the necessary oxygen for refractory shielding. For example, if a direct reduction iron contains 1% oxygen and it is used in a furnace with 4 tons capacity/MW energy input, (Point C) 1.43% C is required to keep the bath carbon level constant but still maintain a carbon boil. Part of the carbon will be oxidized by the oxygen in the direct reduction iron, and oxygen blowing will be required to remove the remaining carbon.

In summary, it is Lukens' experience that shielded refractories are a requirement during continuous charging, and the C-O boil is the most expedient method of accomplishing this. The approximate levels of carbon and oxygen required in the direct reduction material to produce a sustained boil can be taken from Figures 1 and 2. As mentioned previously, physical characteristics also play a part in determining the effectiveness of this boil. It should be appreciated that this discussion is superfluous if the furnace size, powering, and slag depth, is such that exposed arcs do not occur. Our experience clearly deals with high powered furnaces where exposed arcs are the primary cause of sidewall refractory wear.

EFFECT OF COMPOSITION ON STEELMAKING COSTS

The composition of direct reduction iron is a critical factor in evaluating the economics of the process.[5] The effect of the following parameters has to be considered:

1. gangue materials (SiO_2, Al_2O_3, CaO, etc.)
2. sulfur
3. phosphorus
4. metallization
5. oxygen as iron oxides

Figure 3 shows a block diagram of the procedure adopted in evaluating the effect of direct reduction iron composition on steelmaking costs. The influence of electrode consumption rate, increase in productivity and the relative prices of scrap and direct reduction iron is not considered. A computer program was written to evaluate the relative effects of the different variables involved.

EFFECT OF GANGUE MATERIALS

The acidic components added to the charge have to be neutralized by appropriate amounts of lime, in a basic electric steelmaking operation, to obtain good desulfurisation and to protect the basic refractory lining. A high SiO_2 + Al_2O_3 content in the direct reduction iron increases the amount of lime to be charged in the furnace. Besides the cost of the extra lime to be charged, power consumption also increases. Extra electrical energy is required to melt the gangue materials, as well as the lime charged. Figure 4 gives the net effect of the increase in SiO_2 + Al_2O_3 content of the direct reduction iron on the
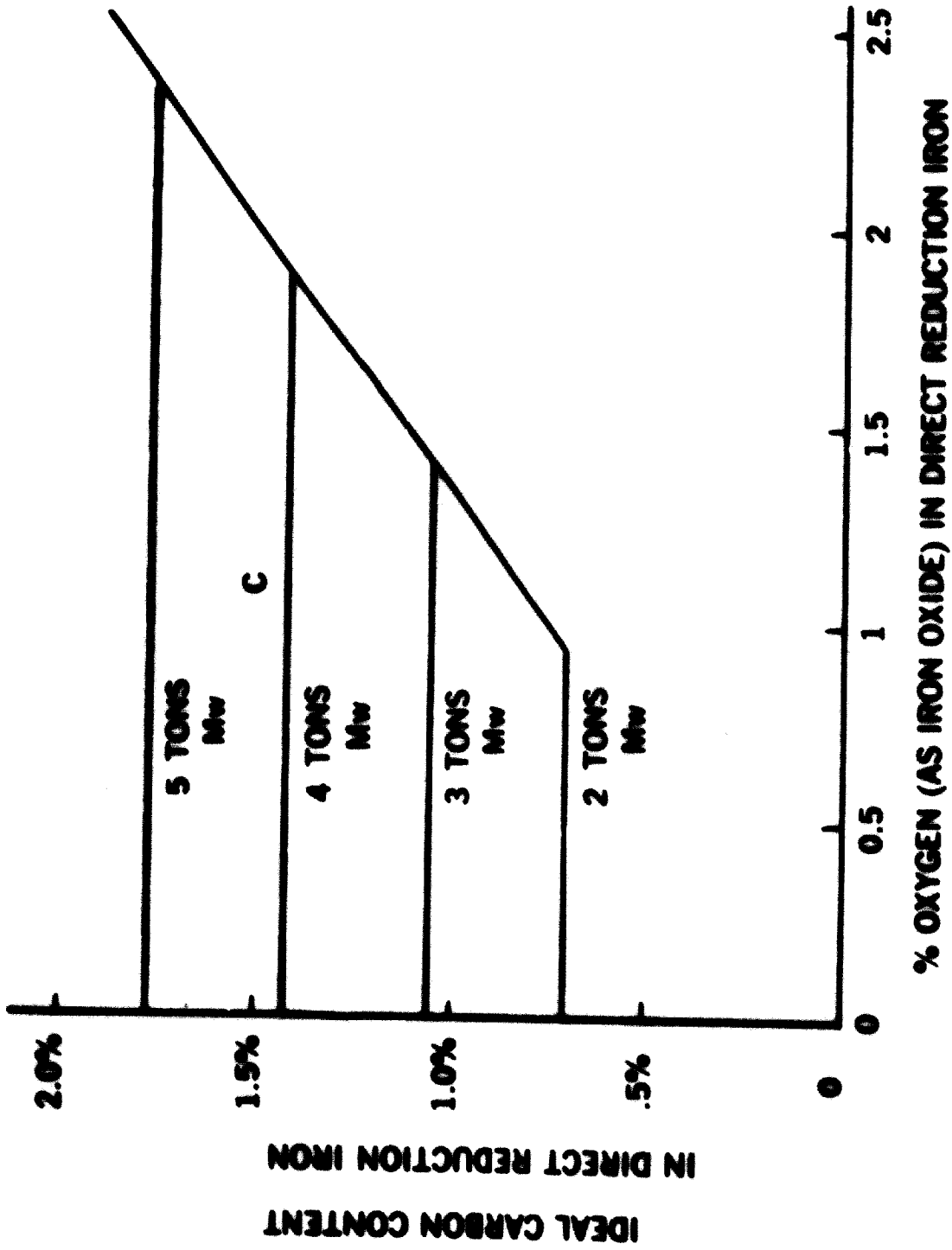
% OXYGEN (AS IRON OXIDE) IN DIRECT REDUCTION IRON

FIGURE: 2

IDEAL CARBON CONTENT VS
OXYGEN CONTENT IN DIRECT REDUCTION IRON
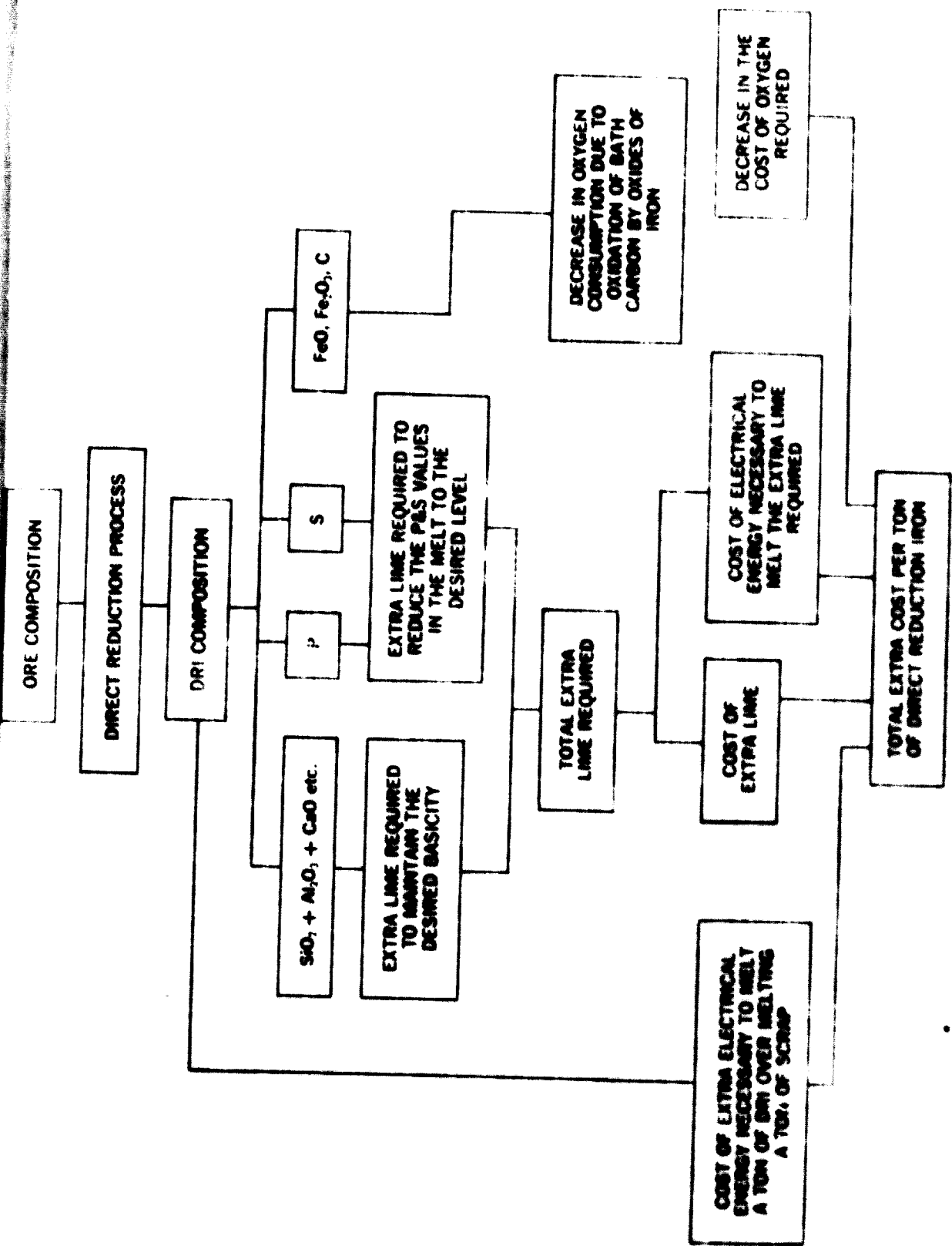
IDEAL CARBON CONTENT
IN DIRECT REDUCTION IRON

FIGURE 3:

METHOD OF EVALUATION OF EFFECT OF COMPOSITION UPON STEEL MAKING COST
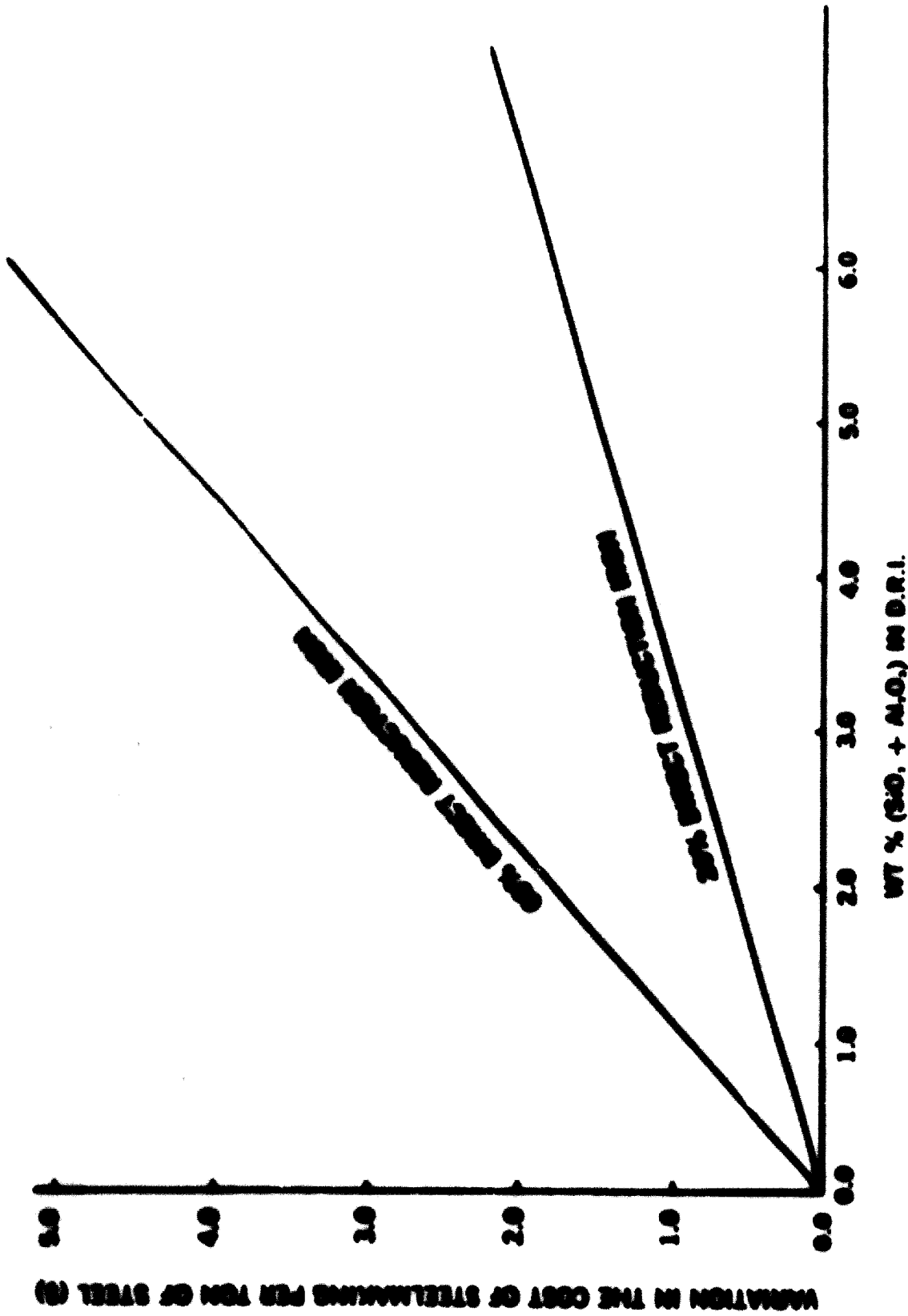(DRI USED AS ABBREVIATION FOR DIRECT REDUCTION IRON)

VARIATION IN THE COST OF STEEL MAKING PER TON OF STEEL DUE TO
SiO₂ + Al₂O₃ CONTENT OF DIRECT REDUCTION IRON

FIGURE: 4

processing cost of a ton of steel for two levels of usage. The calculation is based on a price of $22.00 per ton of lime, delivered at the furnace and $13.50 for 1000 KWH of electricity. The basic electric steelmaking slag has approximately a constant ($\sim$ 20%) amount of FeO present. With the increase in slag volume due to higher SiO_2 + Al_2O_3 content of direct reduction iron, the iron loss as FeO also increases and the yield correspondingly decreases. However, the effect of decrease in productivity and yield is not considered in the present quantitative analysis as their value may vary from one plant to another.

EFFECT OF SULFUR AND PHOSPHORUS

As discussed earlier, there is considerable attention being given to the tonnage production of very low sulfur content (0.010% S max.) steels within the industrialized countries. Lukens Steel Co. as "The Specialist" in plate steel products has recognized the importance of the sulfur content in direct reduction iron as being a sensitive item affecting the steelmaking costs on these grades. However, an economic analysis of the effect of the sulfur content of direct reduction iron with an orientation toward Lukens products would not be especially meaningful to the requirements of the developing nations.

Therefore, for developing countries a higher value of both sulfur and phosphorus would be generally acceptable. For this objective, a base value of 0.025% is assumed for both the sulfur and phosphorus content of the steel to be produced.

The Figures 5 and 6 show the effect of higher sulfur and phosphorus content of direct reduction iron on the cost of making a ton of steel at 20% and 60% usage levels. A base value of 0.025% is assumed for both the sulfur and phosphorus content of the steel produced. The present calculations consider only the cost of extra lime (material cost + melting cost) thermodynamically necessary to lower the sulfur and phosphorus values to the base level. Process kinetics may be improved by an active metal boil as evidenced by some trial experiences. However, as the amount of sulfur or phosphorus to be removed during the refining period becomes greater, there is a general reduction in productivity in order to provide the time required for this chemical work. The effect of this change in productivity is a significant factor in steelmaking cost, but because of widely variable costs from one plant to another, this term is not included in the costs shown in figures 5 and 6.

METALLIZATION AND OXYGEN AS IRON OXIDES

The evaluation of the effect of metallization and oxygen as iron oxides cannot be done on a similar quantitative basis. While higher metallization and lower iron oxide content will be desired on the basis of a unit of iron criteria, the negative effect of the higher metallization on the process in general must be considered.[6] A higher metallization severely reduces the bath activity (caused by carbon monoxide evolution) and the resulting flat bath condition is not favorable for the refractory life of the furnace.[7]
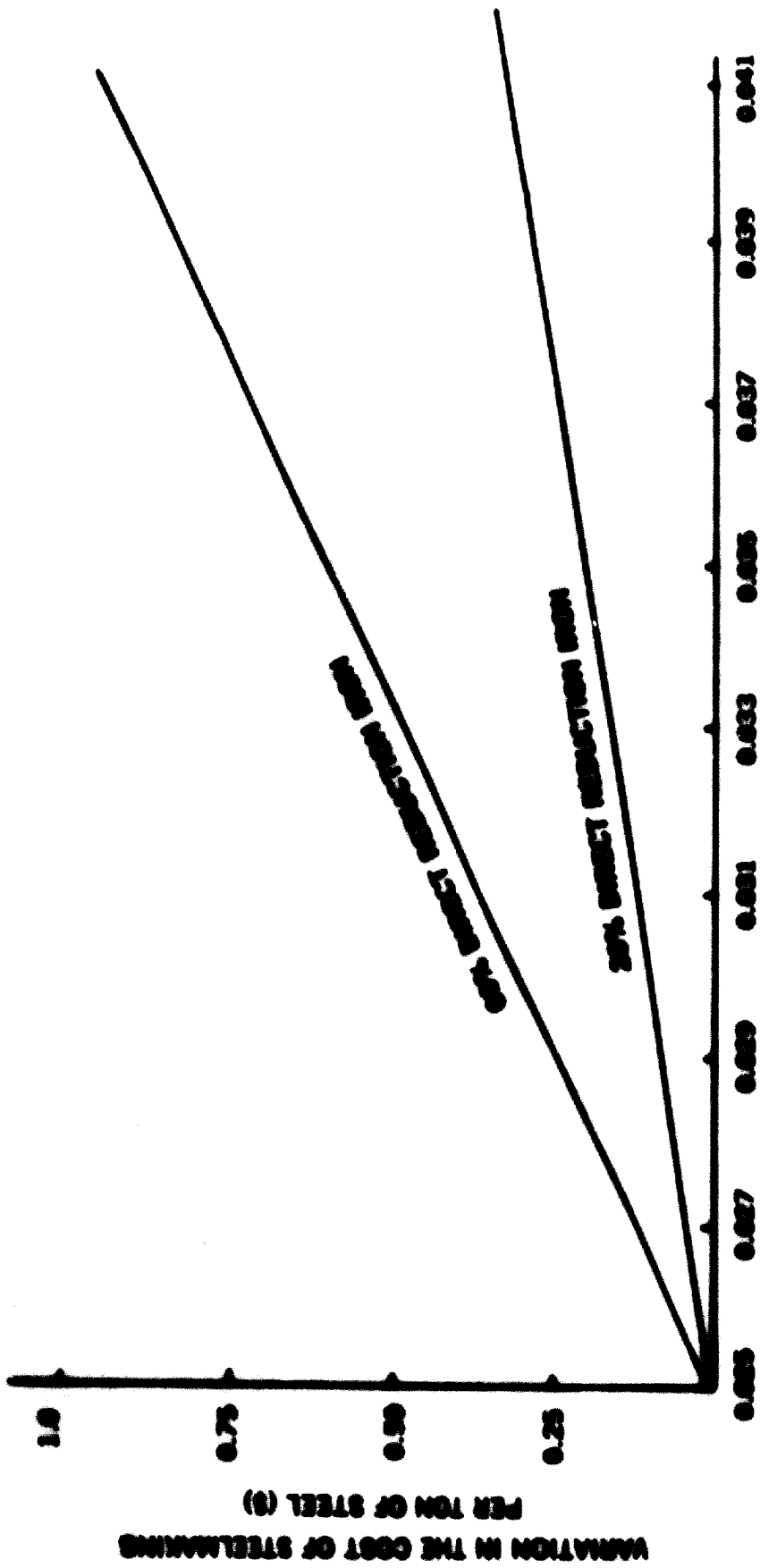
VARIATION IN THE COST OF STEELMAKING PER TON OF STEEL (S)

WT % SULPHUR IN DRI

FIGURE: 5

VARIATION IN THE COST OF STEELMAKING PER TON OF STEEL DUE TO SULPHUR CONTENT OF DIRECT REDUCTION IRON
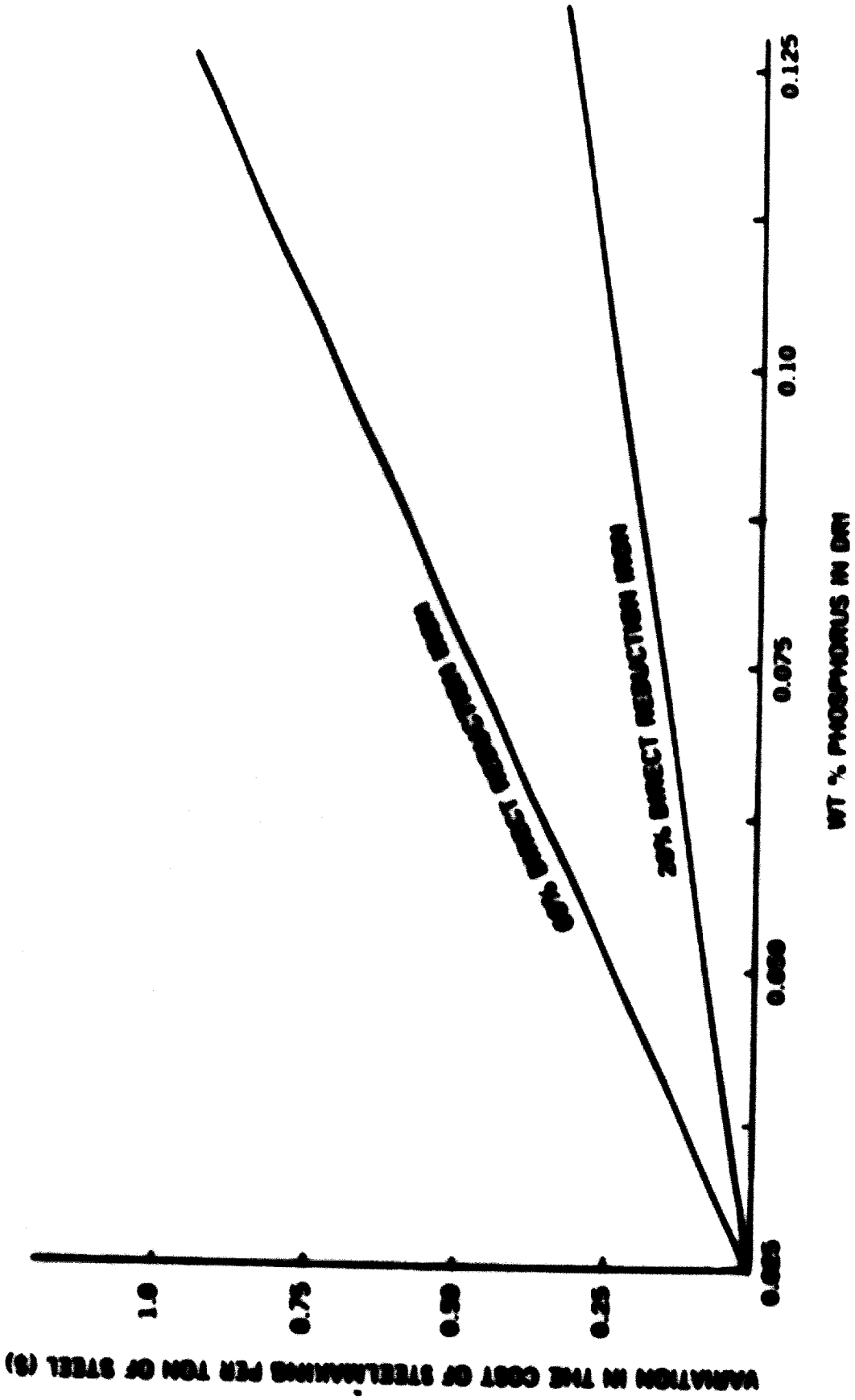
WT % PHOSPHORUS IN DRI

FIGURE: 6

VARIATION IN THE COST OF STEELMAKING PER TON OF STEEL DUE TO
PHOSPHORUS CONTENT OF DIRECT REDUCTION IRON

ECONOMIC CONSIDERATIONS FOR DIRECT REDUCTION IRON

Direct reduction iron is being used and will continue to be used in making
steel. World production capacity for direct reduction iron at this time
is approximately 5,000,000 metric tons. When those additional plants under
construction start producing, the world capacity figure will exceed 8,000,000
metric tons. The extent or significance of this material in the future world
steelmaking picture is a complex economic, as well as political question.

It has been generally agreed that the blast furnace/BOF steelmaking route is
more economical than the direct reduction iron/electric furnace route if a
facility producing 2,000,000 metric tons or more were built. For under
2,000,000 metric tons facilities, the direct reduction iron should be con-
sidered as a substitute for iron and steel scrap and decisions based upon
the relative availability, cost,and quality considered, of the two materials.

For the economics of the large installation - over 2,000,000 metric tons -
the key elements may well be political. It is undeniable that the costs of
making molten pig iron by blast furnaces have been sharply escalating in the
industrial countries of the world. While these costs are normally highly
confidential, the Kaiser Steel Corporation stated in their annual report for
1972 that "Including the costs of mining, processing and shipping iron ore,
coal and limestone, and the costs of operating coke ovens and blast furnaces,
the cost per ton of hot metal was approximately 63% higher in 1972 than in
1968."

In these same industrial countries the costs of direct reduction iron have
also been sharply escalating. The process itself has become impossible in
some of these countries simply because of the shortage of natural gas.

But in those areas of the world where natural gas or coals, suitable iron ore,
inexpensive electric power,and adequate international transportation facil-
ities are available, large steel-producing complexes using direct reduction
iron and electric furnaces may well offer an advantage over blast furnaces.
In such areas, gas is often surplus so its economic cost is simply that price
at which someone will use it. Iron ore is somewhat similar as its "cost" is
more determined by what someone will pay rather than its cost of production.

These two -- gas and iron ore -- are the principal cost items for direct re-
duction iron. If the area also has inexpensive electric power, it would
appear indisputable that the "costs" of direct reduction/electric furnace
semi-finished steel can be made more than competitive with blast furnace/BOF
costs. There should be an increasing tendency to locate semi-finished steel
facilities in areas where gas, iron,and electric power are both plentiful
and inexpensive in terms of production costs. This would most likely result
in direct reduction iron becoming a world commodity. But the question becomes
essentially political - can these areas attract the necessary capital to
build the facilities and will the consuming sectors of the world be confident
enough of the stability of the availability and price of the material to
depend upon the area for a continuing supply of semi-finished steel?

SCRAP AVAILABILITY

Current trends in the processes by which steel is being made appear to
make inevitable a world-wide shortage of iron and steel scrap. The year
1973 is a year of critical shortage and the trends that produced that
shortage have not changed.

In 1970, the United States produced 18,330,000 metric tons of steel by
electric furnaces. In March of 1973, steel was produced in electric fur-
naces at an annualized rate of 25,450,000 metric tons, a 38% increase if
that rate continues. The following are estimated installations of additional
electric furnace capacity in the United States as estimated by a compilation
of recently announced installations:

            1973 - 1,500,000 Metric Tons
            1974 - 1,978,000 Metric Tons
            1975 - 5,180,000 Metric Tons
            1976 - 3,501,000 Metric Tons

It does not appear that the United States can continue to supply the quantity
of scrap iron and steel to scrap deficient countries that it has in the past.
Many scrap-consuming areas and facilities will have no choice but to turn
to direct reduction iron as a replacement for scrap. A near-term worldwide
scrap shortage is highly probable. This shortage will push up the price of
scrap to an extent that large quantities of direct reduction iron will be
produced, sold, and exported at prices advantageous to the producers.

DIRECT REDUCTION IRON AS A COMMODITY

All direct reduction facilities operating today produce a metallized iron
pellet or lump and are located adjacent to a steel-producing facility. This
is not feasible for many locations that will require direct reduction iron.
There have been questions and problems in the economic transporting of this
product form over long distances relating to degradation and stability. It
is expected that these problems will be solved.

It has been demonstrated that direct reduction iron in the briquetted form
is very stable, suitable for long hauls and outdoor storage. The recently
announced FIOR process reduction plant in Venezuela will produce such a
product and is the first plant designed to export direct reduction materials,
other than the nearby U. S. Steel HIB plant that will produce and export a
partially reduced iron briquette for blast furnaces. The resources in
Venezuela are substantial and successful operation of the FIOR process plant
will do much to make direct reduction iron a regular item of commerce.

While direct reduction iron will be a significant raw material for world
steel production, it will not necessarily be the most economic material, in
whole or in part, for all electric furnace facilities.

ECONOMIC EVALUATION

Economic evaluation of the use of direct reduction iron is highly individual as to location and to facility. The economics between companies and even between plant locations within a company can be quite different. Transportation cost is an important factor in steelmaking and the location of the consuming mill will affect the cost of the direct reduction iron. It also makes a difference whether added steelmaking capacity at a particular location is needed. Is a 15% increase in steelmaking capacity worth anything? Are there old facilities that could be shut down if capacity in existing electric furnace facilities could be increased?

The local scrap situation is an important factor. Are the area scrap prices subject to violent fluctuation that could be stabilized by the availability or use of direct reduction iron? Is the mill a dominant factor in the local scrap market and would the addition of direct reduction iron have a favorable effect on scrap prices and availability? Is there scrap available locally?

These and many other questions must be answered in making the decision whether or not to use direct reduction iron. This is a major decision for any company because it appears, at least for the near term future, that a company must either commit substantial capital for the erection of a direct reduction plant or must commit for a long-term supply contract if it is to use direct reduction iron materials. The only specific economic question that will be examined in this paper concern the use of direct reduction iron as a partial alternative to scrap.

The continuous charging of direct reduction iron will also result in cost savings in the following areas:

1. Electrode consumption
2. Materials handling
3. Better predictability of heat times permitting improved facility utilization in subsequent operations (e.g. continuous casting)
4. Reduced demands on the furnace emission control systems
5. Reduction in the number of off-analysis heats because of better process control
6. Increased potential of closed-loop computer control
7. Assurance that a portion of the charge is maintained at a relatively stable cost.

The most difficult item to predict accurately is the effect of direct reduction iron on metallic charge costs since this requires a forecast of future scrap prices. For illustrative purposes, Table 4 shows relative price estimates and yield factors for commonly used charge materials. Since charge balances are usually constrained by residual alloy limits in the final product and on the desired bath sulfur level at melt-down, copper and sulfur values for the various charge commodities are also shown in the table. This information was used to calculate relative costs for two charges; one consisting of an all-scrap mixture and the other containing 11% direct reduction iron. The actual

TABLE 4
COMPARISON OF VARIOUS CHARGE MATERIALS

	RELATIVE YIELD FACTOR	RELATIVE PRICE	COPPER CONTENT, %	SULFUR CONTENT, %
DIRECT REDUCTION IRON	1.00	1.20	.02	.020
NO. 1 DEALER BUNDLES	1.00	1.15	.10	.020
NO. 1 HEAVY MELTING	1.00	1.00	.20	.030
NO. 2 HEAVY MELTING	0.98	0.88	.35	.045
S. S. TURNINGS	0.92	0.70	.20	.07

price of No. 1 heavy melting scrap at a given time is not required in this analysis as it has been observed that the dollar difference between the scrap grades is nearly constant over long time periods as well as the location of use. The price relationship in Table 5 between direct reduction iron and No. 1 heavy melting scrap was experienced during 1969 to 1972. If the assumed scrap shortage becomes a reality, the present differential cost may well become reversed.

The percentages of the various commodities needed to meet a charge specification of 0.20% maximum copper and 0.032% maximum sulfur (at melt down) are listed in Table 5. Also shown in the table are the relative costs for these two charge balances.

Obviously the comparative economics depend strongly upon the assumed material price relationships, particularly as they relate to the price of the directly reduced material. In the example used, the cost for a charge containing direct reduction iron is shown to be economically competitive with that for an all-scrap charge.

FUTURE ACTIVITIES

For several years there has been an interest at Lukens in securing a long term supply of direct reduction iron for continuous charging to the electric furnaces. Because there has generally been an available supply of steel scrap in our area, the basic requirements for direct reduction iron are to use the minimum amount which will result in substantial productivity increases. It has also been assumed that the delivered price of this material would be greater than steel scrap. The usage level for direct reduction iron under these guidelines represents a minor portion of the furnace charge. However, if the relative values should economically favor direct reduction iron, then it would be desirable to increase the usage level to a major portion of the furnace charge. The accomplishment of this objective is the basis for Lukens' participation in a newly formed company located in Venezuela to produce direct reduction iron.

Initial operations of this Venezuelan company are planned for a 400,000 metric ton per year pilot plant with an anticipated start-up in 1975. This plant would use Cerro Bolivar iron ore for direct reduction by reformed natural gas in a fluidized bed reactor process. Iron-ore fines will be used as feed stock with the metallized product compacted by briquetting.

It is expected that a complete materials handling system for all four electric furnaces will be available for continuously charging this briquetted direct reduction iron product into the furnaces. Each furnace will be equipped to maintain charging rate control into the furnace via a water-cooled pipe through the roof.

TABLE 1

RELATIVE CHARGE BALANCE AND ECONOMICS

	ALL-SCRAP CHARGE		SCRAP & DIRECT REDUCTION IRON	
	PERCENTAGE	RELATIVE COST*	PERCENTAGE	RELATIVE COST*
DIRECT REDUCTION IRON	-	-	10.0	.131
NO. 1 DEALER BUNDLES	0.6	.007	-	-
NO. 1 HEAVY MELTING	94.1	.941	76.6	.776
NO. 2 HEAVY MELTING	-	-	11.2	.069
S. S. TURNINGS	5.0	.045	2.3	.016
	100.0	.993	100.0	.993

*COST RELATIVE TO NO. 1 HEAVY MELTING SCRAP

CONCLUSION

The overall results of our experimental programs have demonstrated that a wide variety of direct reduction iron products may be used in electric furnace steelmaking. There are also a variety of steelmaking practices which may be employed. It has been our intention in the preparation of this paper to provide guidance and information with respect to an optimization of the use of direct reduction iron. We have experienced substantial differences in steelmaking costs with respect to both the characteristics of the direct reduction iron and the steelmaking practices employed. As we have shown, the quality of the iron ore exerts a significant effect upon the steelmaking costs. With the use of high-power electric furnaces, the maintenance of a carbon-oxygen boil is necessary to minimize refractory wear.
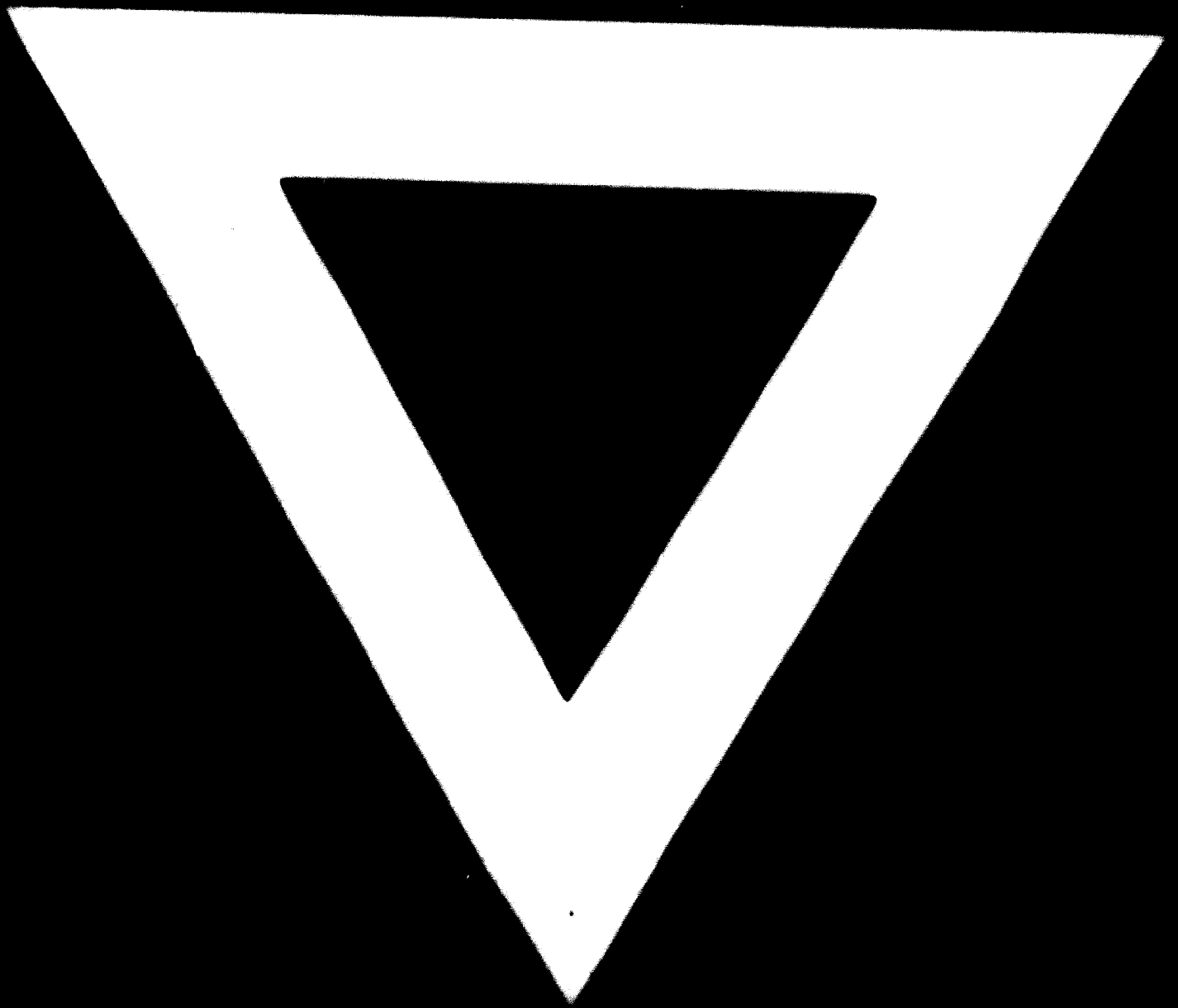
The composition of the direct reduction iron with respect to carbon and oxygen has been found to control the behavior of the molten bath during continuous charging. The steelmaking process becomes very dynamic when continuously charging direct reduction iron, blowing oxygen, and feeding lime with power on. However, it is the effect of these simultaneous operations which results in increased productivity.

The utilization of direct reduction iron in electric furnaces appears to be economically justified for both industrialized and undeveloped nations, but for different reasons. In the case of industrialized countries this material may compete with higher-cost premium scrap to provide a means of reducing harmful residual elements in non-integrated steelmaking facilities, and result in productivity benefits. For the developing countries, direct reduction iron may be a suitable alternate to steel scrap for small steel plants.

BIBLIOGRAPHY

1. R. M. Smailer and J. A. Price, Proc. 53rd NOH and BOSC Conf., AIME, 53(1970), pp. 38-43.

2. E. L. Fogleman, D. O. Gloven, and H. B. Jensen, Blast Furn. Steel Plant, 58(1970), pp. 733-43.

3. J. G. Sibakin, P. H. Hookings, and G. A. Roeder, J. Iron Steel Inst. 205(1967), pp. 1005-17.
    and same authors in J. Metals 20(1968) No. 5, pp. 108-14.

4. N. McCallum and R. J. W. Peters, 28th Electric Furn. Conf. 28(1970), pp. 198-205

5. G. Post, "The Optimum Method for Converting Sponge Iron to Steel in Arc Furnaces", Presented at Symposium on Science and Technology of Sponge Iron, Jamshedpur, India, Feb. 1973.

6. T. R. Meadowcroft, J. of Metals, 25(1973), pp. 67-8.

7. T. A. Williams, N. Donaghy, and P. D. Dastur, Ind. Heat. 39(1972), pp. 285-88, 298, 481-86, 498.

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