OCCASION

This publication has been made available to the public on the occasion of the 50th anniversary of the United Nations Industrial Development Organisation.

DISCLAIMER

This document has been produced without formal United Nations editing. The designations employed and the presentation of the material in this document do not imply the expression of any opinion whatsoever on the part of the Secretariat of the United Nations Industrial Development Organization (UNIDO) concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries, or its economic system or degree of development. Designations such as "developed", "industrialized" and "developing" are intended for statistical convenience and do not necessarily express a judgment about the stage reached by a particular country or area in the development process. Mention of firm names or commercial products does not constitute an endorsement by UNIDO.

FAIR USE POLICY

Any part of this publication may be quoted and referenced for educational and research purposes without additional permission from UNIDO. However, those who make use of quoting and referencing this publication are requested to follow the Fair Use Policy of giving due credit to UNIDO.

CONTACT

Please contact publications@unido.org for further information concerning UNIDO publications.

For more information about UNIDO, please visit us at www.unido.org

UNITED NATIONS INDUSTRIAL DEVELOPMENT ORGANIZATION
Vienna International Centre, P.O. Box 300, 1400 Vienna, Austria
Tel: (+43-1) 26026-0 · www.unido.org · unido@unido.org

UNITED NATIONS

INTERREGIONAL SYMPOSIUM ON THE APPLICATION OF MODERN TECHNICAL PRACTICES IN THE IRON AND STEEL INDUSTRY TO DEVELOPING COUNTRIES

11-26 NOVEMBER 1963

STEEL SYMP. 1963/
Technical Paper/B.4
3 October 1963
Original: ENGLISH

COMPARATIVE EVALUATION OF DIRECT REDUCTION PROCESSES

by

H. Poblete, Head Metallurgical Dpt.
Chilean Steel Institute

I. Summary

An analysis is made of the most important selection criteria to be borne in mind when contemplating direct reduction as a solution for a specific problem concerning iron ore utilisation.

The influence of these criteria is discussed, and the application of the proposed selection method to one specific case is considered.

II. Introduction

Blast Furnace iron making may be disadvantageous for our countries, due to the great investment involved to insure an economical operation and to the need of having good coking coals. Although the coke blast furnace is still the most economic way of reducing iron ore in large size operations, specially if the latest improvements in blast furnace design are applied, there are many instances in Latin America where high transport cost and small size of the market make other reductions methods more advantageous.

The characteristics of our raw materials and fuels are somewhat different from those in other countries. Ores with an iron content over 63% and a very low impurities content, are available, but most of the local coals have very poor coking properties. Nevertheless, there are plenty of natural gas fields, with possibilities for iron ore reduction, and wood resources that are still being used in several charcoal blast furnaces. These facts, added to the small size of the local markets, poor transportation facilities and the great investment needed for coke blast furnace plants, force us to search for new processes that could better fit the aforementioned local conditions.

Direct reduction processes would not involve these disadvantages, as they can be adapted for plants of various capacities and investment costs. These could be quite small size units, which could be adapted to the local demand. According to the costs and availability of energy and fuels, we can find processes using electric power, non coking coals, coke fines, natural gas, etc. Most direct reduction processes could use iron ore fines, by-product of iron ore mining, very abundant in our countries.

As a good example of non traditional iron making solutions in our countries, we could mention the Hojalata y Lámina sponge iron plant in Mexico the Strategic Udy and the Tysland-Hole electric reduction furnaces in Venezuela, and Peru and the Belgo-Mineira and Acesita charcoal blast furnaces in Brazil, known as the biggest of this kind in the world.

III. Direct Reduction Products

Depending upon its working temperature a direct reduction process would yield:

1. An unmolten solid mass, sponge iron, which retains the iron ore structure and chemical analysis minus the oxygen. Considered as a steel-making material, this sponge iron could be classified as steel scrap, so its production cost must be lower than the local scrap price in order to replace it. Nevertheless, there is no sponge iron trade, due to the limited production, so that the small amount available has only a domestic use.

Sponge iron must be charged into electric steel-making furnaces due to slag and impurities trapped in. As it has no tramp elements, it is good for quality steel producing, and it could obtain in certain cases a higher price than that of common scrap. Handling, storage and melting of sponge iron may lead to trouble, due to its great specific volume and tendency to oxidation.

Another typical use of sponge iron is the precipitation of copper from leaching solutions, with the advantage over steel scrap of its spongy structure and great specific surface, which makes it very reactive. Due to these conditions, it would again justify a higher price over that of steel scrap.

2. A low carbon molten iron, similar to a blast furnace pig iron, which is low in silicon, manganese and sulphur, and may have non reduced iron oxide. The slag produced by impurities has been separated by fusion, so that this product can be charged as hot or as blown metal into any steel making furnace. Because of its purity and absence of tramp elements it would be fit for quality steel making and castings, thus justifying a price similar to that of the low phosphorus and sulphur pig iron. Furthermore, the melting of this iron has been achieved using a cheap and abundant fuel or energy, instead of consuming blast furnace coke, which is not always available at a convenient price. Nevertheless, as the direct reduction processes yielding molten iron are among the youngest, there is no wide experience about the matter.

3. Semi-molten 92% iron "luppen", produced by Krupp-Renn process, that have their slag trapped in, and are somewhat high in sulphur. Those "luppen" can be charged into steel-making furnaces, with the same disadvantages already mentioned for sponge iron. That is why in Czechoslovakia they charge them into a blast furnace, as an uncompletely reduced, slag containing solid material.

4. Iron powder, by very low temperature direct reduction processes which is briquetted for using as scrap. If very pure iron ore fines are available, iron powder for sintering in powder metallurgy can be produced.

IV. Description of the problem

Iron ore beneficiation by direct reduction, in an under-industrialized country, has as many solutions as direct reduction processes have reached a reasonable stage of industrial development. Nevertheless, some of these solutions may have advantages, but many of them will prove to be, in some respect, inadequate to local conditions.

Bodies or individuals, in charge of selecting the process, are often inclined to consider one particular process simply because they have heard more about it, but as the technical and economic studies proceed, they find out that the practical application of this process to their case may involve serious difficulties. In other cases, the disadvantages may not be so obvious and the project may even be completed based on a mistaken solution.

All direct reduction processes having been devised and developed to make better use of some specific local conditions, when considering their adoption in any particular case, it is necessary to have a thorough knowledge of the problem involved, in order to be able to select only such direct reduction processes as could be best adapted to our particular circumstances.

V. Selection criteria

An analysis is made of the most important selection criteria to be borne in mind when contemplating direct reduction as a solution for a specific problem concerning iron ore utilization.

Such criteria could be the following:

5. Specific local or area demand, its amount and characteristics

This would determine projects capacity, and the choice between iron powder, sponge iron, luppen or molten iron production. In some cases, as when we need sponge iron to precipitate copper from leaching solutions, the active surface and purity requisites of the sponge iron may be so important that they could even determine the reduction temperature, thereby discarding some of the sponge iron processes. The required purity would determine also the degree of reduction needed, and thus would exclude the use of some low grade ores.

Whether the demand expected in the near future, be over some 150,000 tons per year, it would also be indispensable to consider the alternative of the blast furnace or the electric reduction furnace in the economic evaluation, as the project is coming into the range where the investment and operation costs of these furnaces becomes low enough to compete with that of direct reduction processes. Furthermore, there are only a few among direct reduction processes which have been developed over 50,000 tons per year. To produce 100,000 TPY multiple units would have to be used, which would increase investment and operation costs.

6. Local energy cost, Price and quality of available fuels

The availability and cost of electric power and fuels is one of the most important factors in process selection. The transportation of electric power and natural gas to a great distance being very difficult, the adoption of direct reduction processes using either one of them limits the location. Non coking coals, charcoal and coke fines can be shipped anywhere, provided that the freight would not make their use uneconomical. Power and fuel prices are important items in the final cost of reduced products, specially in Latin America, where they are more expensive than in industrialized countries. The amount and type of energy and fuels needed by the most important processes is shown on Table 12.

7. Iron ore and fluxes

Most Latin American countries have plenty of high quality iron ores which sometimes can be acquired at mining cost, and very often also unexpensive iron ore fines; if not, they can be bought from neighbouring countries at standard prices plus freight. This is vital, as iron ore is the other important component in reduced products cost. However, some of the reduction processes have been developed abroad to use ores unsuitable for the Blast Furnace due, for instance, to their low grade or high silicon content. Such special processes could not be adapted to reduce the high grade iron ores available in Latin America.

Latin America has plenty of limestone, spar and other type of fluxes, and the refractories industry is just starting.

Generally when evaluating iron ores, the main emphasis is given to its grade and to low content of impurities, but increasing attention has been given lately to its geo-morphologic and physico-chemical characteristics, which affect the "reducibility" of the ore. It has been found that in direct reduction processes, in which the reducing power is limited, these factors are of highest importance and several well known research centres are devoting considerable efforts to the study of ores coming from different sources.

This new tendency, born from the limited kinetics of direct reduction processes, is now also being considered by blast furnace operators and designers as they have learned that more "reducible" ores would increase production and lower the coke rate of their furnace.

Once such ore characteristics are known, the performance and efficiency of various processes, when using different ores, can be predicted without the need of an expensive pilot plant test, which would involve shipping to an experimental plant several hundred tons of the ore. For instance, the H & L process was developed at Monterrey, where they have very "reducible" hematites. The Chilean ores are a mixture 1 : 3 hematite-magnetite and are slower to reduce due to their smaller "reducibility". Were we to know the "reducibility index" of both, the Chilean and the Mexican ores, tested according to the same standards, it would permit to make an estimate of the probable production and efficiency of an H & L plant in Chile.

In Appendix A the influence of these properties is discussed in detail, and methods for their laboratory testing are proposed.

8. Capacity and location of the plant

Considering the aforementioned facts, it is realized that the size of the plant is determined by area demand of reduced products; availability of electric power, fuels and raw materials, considering the limitations mentioned in 2; and capital availability.

Location of the plant will be influenced by location of the market and of the iron ore, power and fuel supply.

When considering minimum freight expenses, we must remember that electric power and natural gas cannot be easily transported, while ores and non gaseous fuels have very low charge by boat, as compared with higher cost by train or truck. Other factors that would influence the choice of location are proximity to a port or railway system, to a town or industrial city, or to water resources.

9. Pre-selected methods

After studying and weighing all the above mentioned facts, it will probably be found that only a few direct reduction methods actually fit the particular requirements of the specific problem. It may happen that one of these methods has not been developed yet to a commercial stage for the project's plant capacity, and must therefore be discarded, no matter how sound it may seem. That is why only the industrially developed and reliable methods are mentioned in Tables 11 and 12.

If a critical pre-selection among the approved methods is made, only three or four of them will be worth subjecting to an economic evaluation, in order to get an estimate of the investment needed and the product cost.

10. Economic evaluations

Having the tentative location and size of the plant, the comparative evaluation of the pre-selected methods can be started. As there are in the available literature some reference figures about the initial investment, energy, fuel, raw materials and labour needed for each process, a rough estimate can be made of the capital needed and product cost. This information, corresponding to the industrially developed and reliable processes, is given in Tables 11 and 12.

No matter whether the tentative location and capacity stated for the project looks very sound, it is worth considering other solutions, for a good evaluation, such as, two or three smaller plants better adapted to local conditions. It could happen that the most economical solution is given by a very sophisticated alternative.

The economic evaluation will permit to select the process that is able to yield, at the lowest cost, the particular reduced product needed. Should this cost seem high, as compared to scrap or pig iron prices, even if the facts stated at 2 are considered, still direct reduction might be a sound solution for the problem. Limited capital availability, a small market, and/or the convenience of giving to an existing integrated plant a small production increase, until the installation of a Blast Furnace is justified, could be mandatory for the final decision. Shortage of selected scrap for quality steelmaking, light scrap for copper precipitation, or pig iron suitable for high grade castings may be important arguments too.

VI. The case of the Dominican Republic

As an application of the proposed selection method, the case of the Dominican Republic will be considered, in which the solution of direct reduction is particularly interesting, due to local conditions.

11. The Dominican Republic by itself, or considered as a unit with Haiti is an insular country (Isla Hispaniola), which is just starting its economic and technical development. Its chief source of employment is agriculture, but due to its having the highest rate of population increase in all Latin America, the Dominican Republic must widen its field of employment.

As this nation needs a certain number of goods from foreign markets, it would have to be able to get the corresponding foreign exchange by exporting its own agricultural and mineral resources, in rather processed condition. They must try also to replace imported goods by local manufacture. That is why the Dominican Republic government is deeply interested in promoting any enterprise for industrialization, and particularly those projects that could result in employment and foreign exchange.

The principal economic and demographic characteristics of the Dominican Republic and Haiti are shown in Table 1.

Table 1

Economic and Demographic Data

Nation	Population 1962	Area Sq.M.	Per capita income US$	Apparent Steel consumption per capita
Dominican Republic	3,200,000	19,325	203	7.5 kg
Haiti	4,346,000	10,700	98.60	2.3 kg

Steel consumption per capita is extremely low, corresponding to the degree of industrialization. But it is necessary to remember that when a country like this one is going through the first steps of industrialization steel consumption increases very rapidly.

The Dominican Republic has three iron ore mines. Their high iron content and low sulphur and phosphorous content are quite unusual.

The information available about these mines is given in Table 2.

Table 2

Iron ore Mines at the Dominican Republic (a)

Mine and location	Ore analysis	Reserves in million tons
La Laguna (18°52'N; 70°05'W)	Magnetite 62 - 72% Fe	2
Duarte Hatillo (18°55'N; 70°10'W)	Magnetite 67% Fe; 1.5% SiO_2; 0.03% P; 0.03% S; Al_2O_3 0.27-1.07%; MnO 0.10-0.33% CuO 0.15-0.80%; TiO_2 0.03-0.90%; Cr_2O_3 0.01-0.05%	Indicated r. 8.5 calculated 41.5 Total res. 50.0
Sabana Grande (18°58'N; 70°15'W)	Magnetite 62 - 72% Fe	6

According to the aforementioned selection method, the following data must be considered:

12. Amount and characteristics of local or area demand

Due to the limited industrialization of these countries, their steel products imports, shown in Table 3, are rather small and diversified.

Table 3

Steel products imports. Thousand Metric tons (b)

Steel product	Country				Total per product both countries	
	Dominican Republic		Haiti			
	1960	1961	1960	1961	1960	1961
Railway track material	3.3	5.4	0.2	0.2	3.5	5.6
Light and heavy sections	6.9	7.7	5.2	2.4	12.1	10.1
Strip	0.1	0.1	—	0.1	0.1	0.2
Plates	0.5	0.6	0.1	0.1	0.6	0.7
Sheets	3.9	3.7	2.8	2.7	6.7	6.4
Pipe and fittings	1.8	2.9	0.9	0.5	2.7	3.4
Wire	4.1	2.1	0.5	—	4.1	2.1
Tin plate	1.4	0.9	0.1	0.1	1.5	1.0
Wheels and axles	0.1	0.1	—	—	0.1	0.1
Total	23.5	22.1	6.1	9.8	29.6	31.9

Nevertheless, considering that the Dominican Republic is just starting its industrialization, we can realize that these figures are much smaller than the needs in the near future. Necessary data for a future demand projection are not available, but estimates can be made, based on what happened in similar countries under the same circumstances.

According to Table 3, the most important items, among those that could be made locally, are Light and Heavy Sections and Wire. According to the United Nations classification, Sections includes round and square bars and light structural shapes. As there are no big fabricating shops in the area, it can be assumed that no heavy sections are imported.

Based on the corresponding figures, it can be stated that in 1963 the imported sections and wire amounted to 25,000 tons. It is assumed that 66% of these products, that is 16,000 tons, could have been rolled locally with a small bar rolling mill.

As the ores are extremely pure, it would be of advantage to make ingot iron bars for export. That very pure iron product, similar to the Swedish iron, would get a fairly good price in the American Market.

The export market must be considered for the surplus of production which could not be absorbed by domestic consumption, knowing that the plant capacity must be increased as soon as possible in order to avoid the high costs pertaining to a very low scale production economy.

When considering the production of ingot iron, the very low sulphur and phosphorous content is going to be mandatory, not only in the direct reduction process selection, but also in the reduced product melting and refining furnace selection.

13. Price and quality of available fuels

Due to the proximity to the American industry, it is possible to assume that any kind of solid or liquid fuel would be available at international price for this project. There is also plenty of electric power from a new hydro-electric plant, Yague del Norte. It is assumed that this power could be delivered at the project at a lower rate than that of the United States, partly because the government is interested in its promotion, and also because this would be a regulation factor for the plant load curve. A price of US $0.0065 per kWh seems to be possible, by comparison with Chimbote (Peru).

When calculating the items "energy and fuel", for evaluating the different solutions, it will be seen that electric power is less expensive for this case than other sources of energy, having the advantage that it must not be imported. Furthermore, electric power is the only kind of energy that would not carry in the least any sulphur and phosphorous into the smelting furnace.

14. Iron ore, fluxes and alloying elements

According to Table 2, there is plenty of high grade low impurities ore. The three mines are 6 km apart from each other, placed on a mountainous country, about 30 miles from Santo Domingo. There is now a little mining done in the area, as proven by some 200,000 ton/year exported through this port, but roads are very poor, and mining facilities would have to be improved.

Limestone and other fluxes could be imported from the States, if not available in the country. No alloying elements are needed to make this pure iron, but some ferro-silicon and ferro-manganese would have to be imported for the low carbon steel heats. For special uses some nickel alloying is needed, but the country is an important nickel producer.

15. Capacity and location of the plant

Considering the estimated internal demand of 16,000 tons per year merchant bars, the probability of a rapid increase in steel consumption, and the possibility of exporting high purity iron bars to the American Market, it is advantageous to plan the project capacity in three stages:

(a) The plant must have an initial capacity of 25,000 tons per year steel billets (22,000 tpy. finished products).

(b) When the necessary technical experience to produce high quality ingot iron bars has been achieved, and the American Market requests this product, the capacity can be increased to 50,000 tons per year steel billets (44,000 tpy. finished products).

(c) When the internal demand will have grown in the same proportion, the capacity can be increased to 75,000 tons per year steel billets (66,000 tpy. finished products).

The melt shop would have to be able to produce 25,000, 50,000 and 75,000 tons per year steel billets, in the three stages. But the Direct Reduction plant will have 20,000 tons per year capacity in the first stage, and 40,000 and 60,000 tons per year in the second and third stages. 20% purchased scrap is considered, aside from the circulating scrap, to be charged into the melting furnaces. Purchased scrap could be charged into heats for internal market merchant bars, saving the circulating scrap for the ingot iron heats.

As the production must be brought into Santo Domingo for domestic use or export, the plant must be located near the city. With that location electric power, water supply, railway siding, housing for the people, and other necessary facilities will be available.

16. Pre-selected methods

Looking at Table 12 considering that electric power is available, and that coal, coke or oil can be imported, it is found that Wiberg, R-N and S-L processes are the only ones that suit the particular conditions of this problem. In fact, all of them are developed up to the industrial scale needed, and they have been in operation successfully.

17. Comparative evaluation

Among the three pre-selected methods, Wiberg's is the one which needs the lowest initial investment, and S-L the highest.

If S-L and R-N methods are compared, it is realised that S-L needs more fuel and labour, therefore it must be more expensive to operate than R-N.

Accordingly, the operating cost comparative evaluation must be made between the R-N and the Wiberg processes. Tables 4 and 5 show the pertinent calculations (c).

Table 4

R-N Process Operating Cost per Metric Ton of Iron

Cost Factor	Unit Cost US$	Quantity	US$/ton
Iron ore	8.00/ton	1.5 ton	12.00
Coque	20/ton	0.380 ton	7.60
Oil	20/ton	0.100 ton	2.00
Limestone	4/ton	0.080 ton	0.32
Electric power	0.005/kWh	110 kWh	0.55
Operating labour	0.8/manhour	1.3 MH	1.04
Supervision	1.4/manhour	0.7 Mh	1.00
Maintenance			2.30
R-N net operating cost per metric ton of iron		US$	26.81

Table 5

Wiberg Process Operating Cost per Metric Ton of Iron

Cost Factor	Unit Cost US$	Quantity	US$/ton
Iron ore	8.00/ton	1.5 ton	12.00
Coque	20/ton	0.111 ton	2.22
Oil	20/ton	0.063 ton	1.26
Electric power	0.005/KWh	940 KWh	4.70
Electrodes Söderberg	0.5/kg	1.5 kg	0.75
Raw dolomite	4/ton	0.06 ton	0.24
Operating labour	0.8/Manhour	1.3 MH	1.04
Supervision	1.4/Manhour	0.7 MH	1.00
Maintenance			2.60
Wiberg net operating cost per metric ton of iron		US$	25.81

From the operating costs figures it can be deducted that a Wiberg plant is the most convenient of the two. Its initial investment is also the lowest and is the only one using domestic energy. Furthermore, it has the important advantage of producing a very pure sponge iron, as it can be provided with a desulphurizing tower.

18. **Initial investment**

According to Stalhed (d), a 20,000 tons per year Wiberg unit, similar to the one at the Sandviken Works, would cost about US$ 800,000. It is assumed that this cost would have to be increased by 25% if the same plant were to be installed in the Dominican Republic, that is US$ 1,000,000.

For the three stage increase of capacity planned for the project, three different Wiberg units must be installed. For the second and third units an additional cost of US$ 900,000 would have to be considered. Table 6 shows the necessary investment for the sponge iron plant.

Table 6

Investment per stage for sponge iron plant

Stage of increase Tons per year capacity	1st 20,000	2nd 40,000	3rd 60,000
Wiberg units US$	1,000,000	1,900,000	2,800,000
Buildings and facilities US$	600,000	800,000	1,000,000
Total investment US$	1,600,000	2,700,000	3,800,000

The melt shop would be integrated by three 20 ton capacity electric furnaces, corresponding to the Wiberg units. The cost of each furnace complete and installed would be US$ 500,000.

The casting plant would have a continuous casting installation, producing up to 80,000 ton per year of 4" x 4" billets. The cost of this plant, including building and necessary facilities, would be about US$ 900,000.

Table 7 shows the necessary investment for the melt shop and casting plant.

Table 7

Investment per stage for melt shop and casting plant

Stage of increase		1st	2nd	3rd
Tons steel billets per year		25,000	50,000	75,000
20 ton electric furnaces	$	500,000	1,000,000	1,500,000
Scrap yard and cranes	$	270,000	300,000	340,000
Building and facilities	$	320,000	360,000	400,000
Continuous casting inst.	$	900,000	900,000	900,000
Total investment	US$	1,990,000	2,560,000	3,140,000

The merchant bar rolling mill could be integrated by a 400 mm two high 6 stands mill and a 270 mm two high 6 stands mill. In order to avoid high investment this equipment could be a second hand one, costing some US$ 1,200,000. The rolling mill would then cost, including installation, buildings and facilities, about US$ 2,000,000.

19. Operating costs

Calculations will be made to work out production costs for each stage. As production scale is low, these costs would be too high and the whole project would become uneconomical. Pertinent calculations are shown in Tables 8, 9 and 10.

Table 8

Wiberg Plant. Operating costs per metric ton of sponge iron

Cost Factor			Production Scale: ton per year		
			20,000 US$	40,000 US$	60,000 US$
Iron ore	1.5 ton	$ 8/ton	12.00	12.00	12.00
Coque and oil	0.174 ton	$ 20/ton	3.48	3.48	3.48
Electric power	940 kWh	$ 0.005/kWh	4.70	4.70	4.70
Electrodes	1.5 kg	$ 0.5/kg	0.75	0.75	0.75
Raw dolomite	0.06 ton	$ 4/ton	0.24	0.24	0.24
Operating labour			1.10	0.95	0.75
Supervision			1.00	0.50	0.40
Maintenance and miscellaneous			11.00	7.50	6.00
Capital charges, 9% investment			5.75	4.86	4.70
Operating costs per ton of sponge iron		$	40.02	34.89	33.02

Table 9

Melt Shop and Casting Plant. Operating cost per ton of Steel Billets

Cost Factor			Production scale: ton per year		
			25,000 US$	50,000 US$	75,000 US$
Sponge iron	0.8 ton		32.02	27.98	26.41
Scrap	0.25 ton	$ 25/ton	6.25	6.25	6.25
Ferro alloys			2.25	2.25	2.25
Refractories	0.012 ton	$ 140/ton	1.68	1.68	1.68
Electric power	710 kWh	$ 0.005/kWh	3.55	3.55	3.55
Electrodes	8 kg	$ 0.6/kg	4.80	4.80	4.80
Lime	0.05 ton	$ 12/ton	0.60	0.60	0.60
Operating labour			6.50	5.00	4.30
Supervision			4.0	3.0	2.40
Maintenance			5.50	5.0	4.80
Miscellaneous			10.80	10.50	10.00
Capital charges, 9% investment			7.15	4.61	3.76
Operating cost per ton of steel billets			85.10	75.22	70.80

Table 10

Merchant Mill. Operating Cost per ton of Finished Products

Cost Factor		Production scale: ton per year		
		22,000	44,000	66,000
		US$	US$	US$
Steel billets	1.150 ton	97.98	86.50	81.42
Credit for scrap		-4.00	-3.60	-3.40
Refractories and spare parts		2.40	2.30	2.20
Maintenance		4.00	3.40	3.10
Electric power		1.90	1.90	1.90
Operating labour		9.00	8.10	7.00
Supervision		2.30	1.80	1.30
Capital charges, 10% of investment		8.00	4.00	2.66
Operating cost per ton of finished product		121.58	104.40	96.18

20. Conclusions

(a) Direct Reduction gives a good solution for small scale steel-making in this little country, where steel consumption per capita is still low because of the newly begun industrialisation. The necessary initial investment and production costs are fairly reasonable, and the production capacity can be increased by stages, as the market grows.

(b) This plant would give employment to the Dominican people, and would save and even produce foreign currency from domestic resources. The foreign currency expended for the initial investment in the plant could be recovered within 4 to 6 years, through the plant production, which could be exported or could replace imports.

(c) In order to lower mining and ore transportation costs, bigger lumps of this pure ore could be exported for Open Hearth and the range of 25 to 80 mm could be used in the Wiberg units. It is advisable to consider the installation of a pellets plant in the future, which could use the range of 25 mm down to fines. These pellets could be used in the Wiberg units or exported.

(d) The aforementioned calculations and statements have been made according to the general information available, and for the purpose of this paper. It would be interesting to make a complete study of this case, considering the local conditions with more detail.

In order to study the performance of a Wiberg unit when using this ore, a proper sample would have to be sent to Söderfors, in Sweden, where tests could be made as recommended in Appendix A.

Table 11

Data on commercially developed Direct Reduction Processes

Process	Scale of commercial development ton per day/unit	Initial investment for same scale. US$/ton	Labour per ton reduced product Manhour/ton	Maintenance cost US$/ton
	Molten Metal Processes			
Strategic Udy (e)	200	60–70	3.0	2.30
	Solid Sponge Iron Processes			
Shaft Furnace Processes				
Wiberg (d)	60	50	2.0	2.60
Retort Processes				
H y L (f, g)	500	45	0.80	1.60
Rotary Kiln Processes				
R – N (h)	50–75	65	2.0	2.30
S – L (i)	50	70	2.5	2.00
Krupp-Renn	300	62.5	2.3	2.50
Fluidized Bed Processes. Iron Powder				
Nu-Iron (j)	5	100	0.5	4.00
H-Iron (k)	150	80	0.35	3.20

Remarks: A critical selection had to be made from the available information, as there were some differences in the data given for the same process by the various reference papers.

Table 12

Energy and Fuel consumed per Metric ton of Iron (1. m)

Process	Kilograms Coal	 Coke	 Oil	m^3 N. Gas	KWh Power	Million Kcal/ton
Molten Metal Processes						
Strategic Udy	500				1,100	4.5
Solid Sponge Iron Processes						
Shaft Furnace Processes						
Wiberg (d)		110	63		940	3.0
Retort Processes						
H y L				530		4.8
Rotary Kiln Processes						
R - N (h)		380	100		110	3.7
S - L (i)	450			103	110	4.2
Krupp-Renn	275	925			80	8.5
Fluidised Bed Processes, Iron Powder						
Nu-Iron				330 or 395	375	3.8
H-Iron				375 or 450	375	4.3

REFERENCES

a. *Estudio de los Recursos Minerales de Hierro del Mundo*. Naciones Unidas 1955.

b. *Importaciones Latinoamericanas de Productos Siderúrgicos*. Revista ILAFA 15-16; (June 1963)

c. Pfeifor, H.C. *Processes de Reduçao Direta: Análise Comparativa de diversos Procesos do Ponto de Vista Ecónómico*. ABM Boletim; 5-64; (January 1963).

d. Stålbed, J., *Production of Sponge Iron According to the Wiberg-Söderfors Method*; Söderfors Bruk; Sweden (1955).

e. Koppers Co. Inc., *The Strategic-Udy Universal Smelting-Refining Process*. (1959).

f. *H & L Direct Reduction Process*; New Iron Ore Reduction Techniques; Corporación Venezoland de Guayana; Caracas (January 1962)

g. Kellog Co., *Steelmaking with Gas, From Ore to Ingot Via the H & L Direct Reduction Process*. (1962).

h. Smith R.P., *R-N Rotary Kiln for the Direct Reduction of Iron Ores*. Paper presented at the Fifty-Fifth Annual Meeting of American Institutes of Chemical Engineers. Chicago (December 1962).

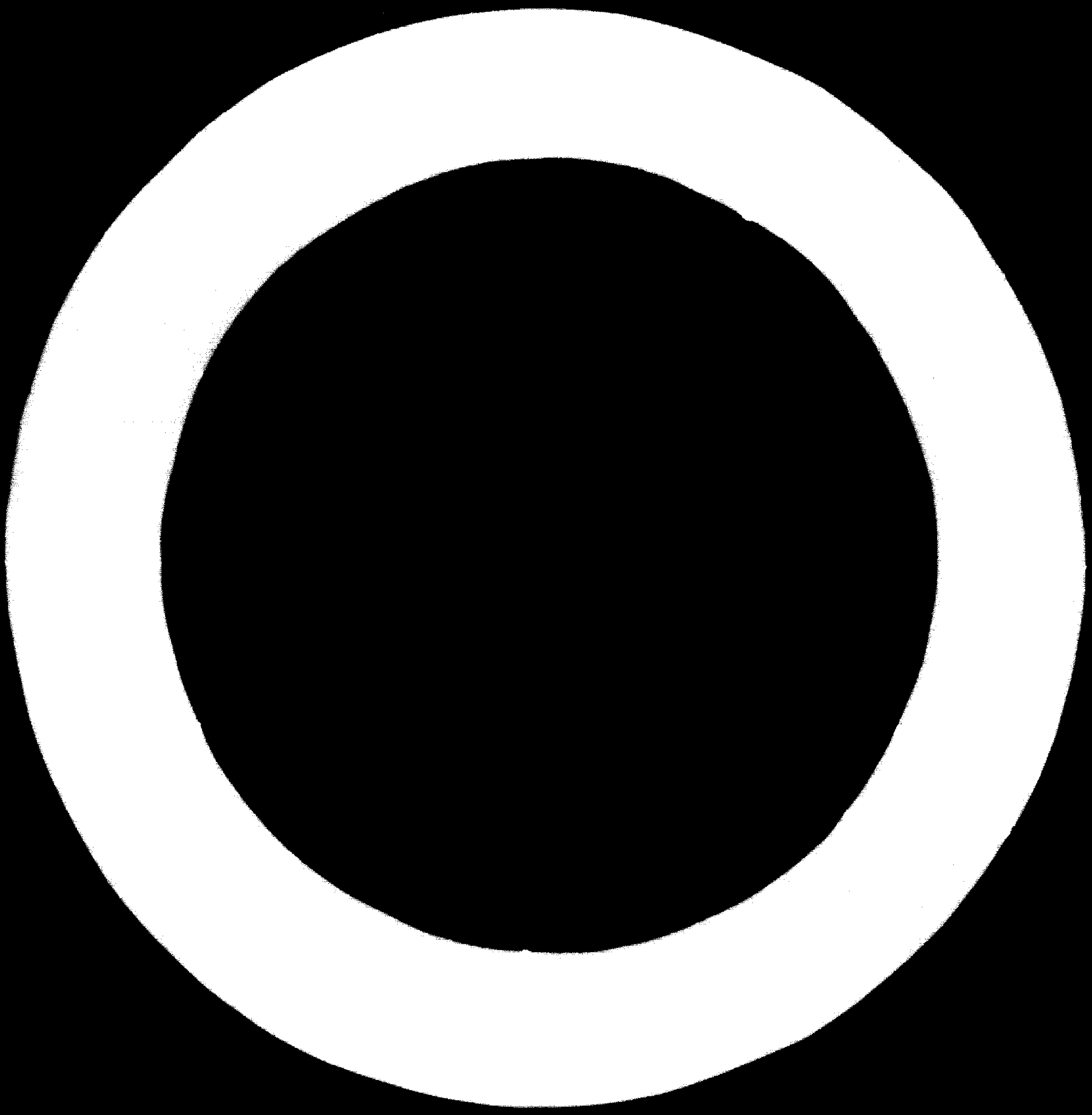
i. Sibakin, J.G., *Development of the S-L Direct Reduction Process*, Yearbook American Iron and Steel Institute; 187 - 228 (1962).

j. Agarwal J.C., and others; *The Nu-Iron Process, a Fluidized Bed Reduction Process*. Lecture presented at the 100 Anniversary Congress of the Colegio de Ingenieros de Venezuela, Caracas (October 1962).

k. Stotler H.H. and others. *Direct Reduction of Iron Ores by the H-Iron Process*. Lecture presented at the 100 Anniversary Congress of the Colegio de Ingenieros de Venezuela, Caracas (October 1962).

l. McBride D.L. and Chase R.J., *Present and Future of Direct Reduction Processes in Latin America*. Paper presented at the III Latin-American Steel and Iron Congress; Caracas, Venezuela (July 1963).

m. Wild R., *Energy Requirements for Iron Ore Reduction*. Journal of the Institute of Fuel; 381 - 392; London (September 1961).



Appendix A

PHYSICO-CHEMICAL PROPERTIES OF AN IRON ORE THAT MUST BE STUDIED TO PREDICT ITS PERFORMANCE IN REDUCTION PROCESSES

A discussion is made of those properties, and their effect on reduction kinetics, and methods for laboratory testing are proposed. We are considering those characteristics that are important not only for direct reduction process, but for any iron making furnace.

VII. Discussion of the properties and their effect

21. Chemical analysis

This analysis must report the following:

Total iron content, which would give a first technical qualification of the ore.

Separate ferrous and ferric iron content, which would be connected with the Hematite/magnetite ratio in the ore. That ratio has effect on the ore behaviour in reduction phenomena, as it is related with the mineralogical structure, and the fast reducing hematite or slow reducing magnetite content.

Impurities and slag forming elements content, as S, P, SiO_2, Al_2O_3, CaO, etc. which could affect the analysis of reduced products, or the burden characteristics when heated to the high reduction temperature. As they establish the slag composition, they can determine the type of refractory lining to be used. Also through their influence on the melting and softening point, they can exclude some of the reduction processes because of their working temperature, or type of furnace used.

Uncommon elements, like Cu, Ti, V, Ni, Cr, etc., which must be analyzed, as they can affect the reduced product analysis and the development of a process.

22. Softening and melting points

Increasing attention is being given to the softening and melting point of iron ores. These properties determine the temperature limits between which an ore can be reduced to a solid, semi-molten or liquid phase. The importance of these limits is increasing, because they determine whether we are going to get sponge iron, lumps, or molten iron. Sometimes, if the softening point is too low, the ore reducing mass may become sticky and make the process inoperative. As new direct reduction methods are increasing their working temperatures in order to improve the reduction kinetics, this fact is becoming more important.

23. Load resistance at high temperature

The behaviour of an ore sample under a constant load at increasing temperatures, could be plotted as "dimensional changes/temperature curves" at various loads, until the final collapse temperature of the sample. Those curves show the dimensional stability and load resistance of the ore when charged into the furnace, thus they furnish very useful information to predict its behaviour in a direct reduction or blast furnace.

Those curves would show the dimensional variations of the sample caused by structural changes, and would be connected with its dilatometric test. In reality, they are "dilatometric curves under load" reproducing the actual working conditions of the ore in the furnace. The no-load curve would be close to the standard dilatometric curve, but could be altered by cracks, which may occur in the sample by structural changes. In order to report about those cracks, it is necessary to be able to observe at the sample under test, and photograph it at various magnifications.

The same load test may be conducted under a reducing gas atmosphere, but using a fixed load and maintaining the same temperature at which the ore would be commercially reduced. The reducing gas could be CO, H_2, a mixture of both, or a mixture similar to the one existing in the reducing furnace. That test would give extremely useful data about the dimensional changes of the ore when submitted to a particular reduction process. These changes could increase the reduction kinetics markedly by causing cracks and pores which would provide a better reaction surface. This is actually a change in the "reducibility" of the ore.

24. "Reactivity of the ore under reducing media, or reducibility"

This property can be studied in two ways:

a. Laboratory testing of the physico-chemical characteristics of the ore that affect reduction kinetics -

The most important of these characteristics are: open porosity, dimensional stability under heat and load, and mineralogic structure. It is necessary to try to evaluate the effect that each of the above factors has on the reduction kinetics. This evaluation could be based on theoretical deductions, or upon checking with the laboratory "reducibility test" proposed later.

i. Porosity -

Reactivity of an ore sample depends upon its specific surface, which is the limiting factor to the mass transfer between the sample and the reducing media.

That it is proposed to test the open porosity, corresponding to the pores open to the outer face of the sample.

It is felt that it would be also of advantage to measure the variation of porosity in a sample, which has been heated in a neutral or reducing media, according to a pre-established cycle or which has been load tested under the same conditions. This test would measure the changes reported in 23.

ii. Mineralogic structure -

This test shows us not only the structure and type of the ore, but also tells about the compacity and irregularities of the specimen. The application of this test to partially reduced specimens is reported in divers papers. Thus the intermediate and final phases through the reduction process can be seen. A valuable information about reactions and migration of oxygen in the solid ore phase during reduction has been obtained with this test.

b. Reducibility test -

Laboratory testing for reducibility is intended to measure the reduction rate of representative specimens, under controlled and reproducible conditions. This test consists of reproducing the reduction phenomena to which the iron ore is actually subjected in Direct Reduction or in the Blast Furnace.

There are two tendencies how to make this test:

Using small pure mineralogic specimens, in pure gases reduction atmosphere, working at constant temperature. These ideal conditions, and the information obtained, must be considered solely under a physico-chemical point of view. In fact, the reduction of a pure and static piece of ore, under very reactive uncontaminated media, at a fixed temperature, would be very useful in studying the reduction kinetics and subsequent phenomena. But these testing conditions are quite different from what is actually happening to an heterogeneous iron ore lump passing through a direct reduction kiln or placed in a Blast Furnace.

Natural ores to be used in direct reduction processes must be tested under conditions resembling the ones existing in the considered reduction process; i.e. if the use of an ore in the H & L process is being considered, the specimen must be a regular sample, and the testing conditions should be such as to reproduce the operating conditions of H & L process. And the same idea would have to be kept in mind if the intended procedure were a kiln or a fluidized bed process.

Blast Furnace ores must be tested under conditions similar to the ones existing in the furnace, but as this method, due to its high kinetics, has been the last in getting "reducibility" conscious, the author does not know of a reducibility test specially developed for this case. That is why it is suggested to choose among the various tests, developed for direct reduction.

The "reducibility index" is applicable only in predicting the behaviour of an ore when used in a direct reduction method operating on principles similar to the test.

If the wrong test is used, one may get a "reducibility" figure which will classify this ore as unsuitable for direct reduction. It is necessary to be able to discriminate which processes are excluded by this test. For instance, if this particular ore is intended to be used in a traditional Blast Furnace. If the testing method chosen is good only for fluidification processes, one may obtain a low reducibility index. However, it has to be remembered that, with the proper testing method, the right index would be obtained, which may prove that this ore is good for Blast Furnace. And both tests may have been perfectly well carried out, according to their peculiar methods.

So, it is of vital importance to study all the existing tests, in order to have a complete knowledge of their basic principles, and corresponding fields of use. Unfortunately, most of the papers about reducibility refer only to the theoretical test, and the few publications dealing with technical testing are incomplete. That is why pertinent information and criteria should be obtained from the men and research centres who have developed these technical methods.

According to M. Pierre Coheur, Director of C.N.R.M. at Liege, his own research centre was intending to reach an agreement with the other important centres in the world regarding standardization of these testing methods. Battelle Memorial Institute, in U.S., and Krupp Research Laboratories, in Germany, have already adopted the same methods as C.N.R.M.

Prof. Martin Wiberg, during the second ILAFA meeting at Buenos Aires was asked about the selection of the proper reducibility test in particular cases, and he answered that in Sweden they have developed different tests for each case, but the most used when considering direct reduction was his own, similar to the one used in Liege. When discussing these tests, some details about the proper procedure and equipment will be furnished.

25. X-ray diffraction analysis

As a complementary information, it would be advisable to investigate the ores Cristalization in order to identify the various mineralogic structures by X-ray diffraction components. This test would be very useful to predict the reducibility of an ore, establishing a correlation between mineralogic structure and "reducibility index". The information thus obtained would be more complete than that from the mineralogic structure obtained by microscope.

26. Differential cooling curves analysis

"Dimensional changes/temperature curves", according to 23, show structural changes occuring at the specimen, provided they can be detected by tilatometry. There may be some structural changes that are not associated with volumetric changes, so "differential cooling curves analysis" are very interesting. If this analysis could be made on specimens under various reducing media, it would permit to measure the variation in enthalpy (H), at a given temperature, when submitting the ore to a certain chemical reaction. These parameters would be extremely useful when changing the standard design of a direct reduction furnace or reactor, or when designing special equipment for the ore. Differential cooling curves would also detect the time and temperature at which the reduction reactions are taking place.

VIII. Recommended testing methods and apparatus

27. Chemical analysis

It could be made according to A.S.T.M. Standards, or any other method.

28. Softening and melting points

Softening and melting points could be tested with a standard refractories fusion point furnace, using test cones. But, as we will be shown later, the fusion microscope is the best instrument for that test. A well known optical instrument manufacturer has a very good model, provided with special attachments to make these, and some of the following tests.

29. Load resistance at high temperature

According to M. Coheur's suggestions, Leitz-Wetzlar has designed and built the necessary attachments for its fusion microscope, specially fitted to make all the measurements described at 23, exactly as recommended.

30. Reducibility

Physico-chemical characteristics affecting reducibility.

a. Porosity.

Open or external porosity could be tested by introducing an ore specimen in vacuum, and then filling with CO_2. The CO_2 absorbed could be measured by standard chemical methods.

A more accurate method would be to fill with freon gas, and then measuring the absorbed gas with a mass spectrograph.

b. Mineralogic structure

Could be observed with a mineralogic microscope, according to standard techniques.

c. Reducibility test

Reducibility test on pure mineralogic specimens could be made according to Wiberg and Edström techniques, or any other variation of the methods recommended by them.

When considering direct reduction, Prof. Wiberg suggests testing ore samples by his method similar to that of the U.S. Bureau of Mines and that of C.N.R.M. This method uses a 2.5 kg. specimen electrically heated in a small vertical vessel. Reducing medium is obtained by gas reforming at a small electric carburator. The curve reduction/time is plotted by analysis of the percentage of oxide reduced after 1, 2 and 5 hours of testing.

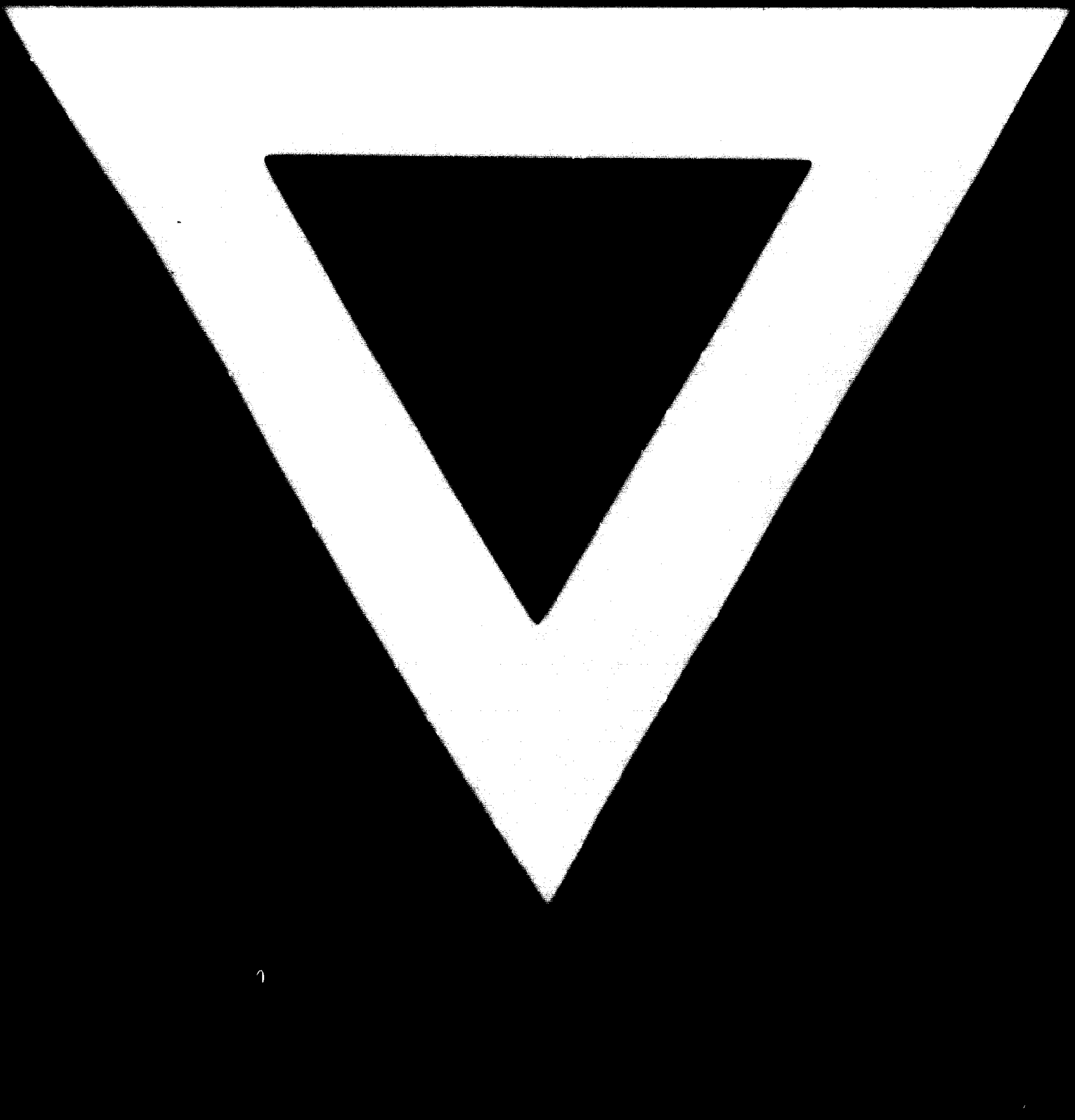
Blast Furnace ores are usually tested by Linder's Method, with a tiny rotary kiln fired in standard conditions.

31. X-ray diffraction analysis

The ores crystal structure could be investigated according to standard techniques for X-ray diffraction.

32. Differential cooling curve analysis

This analysis could be made using the standard methods and equipment. The thermo-analyser used must have the necessary attachments to fill it with a reducing or neutral medium.



4. 4. 74