

Pelletizing of Iron Ores

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With 146 Figures

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Preface

After the Second World War, there was in many countries a great backlog demand in nearly all branches of life, which resulted i. a. in a world-wide upswing in the iron and steel industry. Many damaged or destroyed production facilities had to be replaced, reconstructed and extended. This was a good opportunity of revising the production concept of the iron and steel industry and introducing innovations where it was possible and promising.

This renewal covered i. a. two important sectors. On the one hand, the dimensions of the production units and auxiliary equipment were extended to such a degree that considerably higher capacities were achieved. An interesting example is the extension of the blast furnace volume and hearth diameters up to 15 m at a pig iron production of about 10,000 tons per day.

In addition, remarkable progress was made by improving existing process parameters and introducing new technologies. Some of these innovations had already been formerly known, but not yet applied. A few examples of such developments in connection with ore preparation and particularly with the agglomeration technology are given below:

1. Physical Preparation of Blast Furnace Burden by Crushing, Screening and Classification of Constituents

Already in the thirties, it was known to many experts that it is advisable to classify the blast furnace burden before it is used ²⁾. However, this idea was not consistently realized until about 1950. From this date onwards, raw ores, coke and other burden constituents were crushed, screened and supplied to the blast furnace in a narrow size range. Increasing amounts of fine ores emerged from this operation and required a strong *extension of sinter plant* capacity, as shown in *Figures 9 and 10*, chapter 1. As a result of these measures, by using a physically prepared burden with rising sinter portions, the gas permeability of the blast furnace burden greatly improved the pig iron capacity increased and the coke consumption decreased.

2. Thermal Separation of Volatile Ballast Materials from Raw Materials

A further improvement of the blast furnace operation was achieved by removal of volatile ballast material, such as H_2O or CO_2 , from raw ores during sintering or pelletizing before they enter the blast furnace. Such an ore preparation is of particular importance when Minette or limonite ores have to be treated. There are plants in which the blast furnace burden consists of 100% sinter.

3. Mechanical Beneficiation of Ores by Separation of Mineral Ballast Materials

By mechanical beneficiation, it is possible to remove a great portion of mineral ballast components from the iron ores before they enter the blast furnace. But the concentrates so produced are very fine-grained, and agglomeration is thus necessary. This agglomeration is achieved by sintering and pelletizing. The *pelletizing* process was introduced on an industrial scale as a new agglomeration method and an alternative to sintering.

4. Change of Chemical Composition of Ores During Agglomeration

The possibility of modifying the chemical composition of the ores by using corresponding additives during agglomeration leads to the desired change or improvement of metallurgical properties of the agglomerates.

From this procedure resulted the production of basic or even over-basic agglomerates, as already proposed in 1938²⁾. The development of the agglomeration technology in the form of sintering or pelletizing is closely connected with the promotion of the blast furnace technology.

Pellets offer additional advantages due to their good transportability. With the introduction of pellets into the world market, the hope of many metallurgists – to produce steel from ores by direct reduction and bypass the blast furnace – came closer to realisation.

The increasing and successful efforts to improve the direct reduction processes were one of the most important consequences of the newly developed pelletizing technology.

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* Frankfurt/Main, Federal Republic of Germany

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Introduction

In contrast to sintering, for which the *down-draft sintering* method is only successfully employed, pellets are today indurated according to three methods: in the *shaft furnace*, in *grate-kilns* and on *travelling grates*.

The greatly varying properties of ores resulting from their origin, genesis, shape, crystal form and chemical composition are to be taken into account for ore preparation and pelletizing in order to produce at any time pellets of uniform and good quality. Nowadays, measures are known, by which the differences in the ore properties can be compensated. However, the corresponding parameters have to be variable and selected according to the nature of ores involved. In practice, this means that the design of new plants or the conversion of existing ones to other ore types cannot be based on generalized programmes. In each particular case, it is practically unavoidable to find out the optimum parameters by the performance of tests. This is a decisive factor for the concept and composition of this book, which virtually relies on experimental knowledge and comprises the following chapters:

- The most important development phases for pelletizing and the underlying causes are described in *Chapter 1*.
- The fundamentals for successful green ball formation and induration are described in *Chapter 2*.
- *Chapter 3* deals with the utilizable ores and additives as well as their preparation for processing into pellets.
- In *Chapter 4* adequately equipped laboratories and the testing of pellet quality according to different test standards are described.
- The efficiency and kind of the individual influencing factors are to be found out in adequate tests for obtaining a uniform pellet quality. These considerations are the subject of *Chapter 5*.
- The decisive quality criterion is the behaviour of pellets during reduction, *Chapter 6*. Experiments and considerations in connection with oxygen removal are described although despite many efforts some questions have not yet been fully clarified.

- Special processes for pellet induration and the possibilities of utilizing unusual raw materials are dealt with in *Chapter 7*.
- A survey of the main equipment and furnaces used is given in *Chapters 8 and 9*. At the same time, these chapters show the importance of the cooperation of process engineers, mechanical engineers and designers for ensuring a successful process application.
- Furthermore, some comments on plant design and automatic process control are made. A direct conversion of the collected data to other conditions should be considered carefully to avoid misinterpretation, *Chapter 10*.
- The behaviour of pellets in the blast furnace or in direct reduction plants is very essential for justifying the application of the pelletizing process and its future importance, *Chapters 11 and 12*.
- In order not to interrupt the continuity of the various chapters by theoretical or mathematical considerations, some interesting formulae and equations are compiled in *Chapter 13* and simultaneously references are made to relevant literature.

This book will neither be a manual for the construction of industrial pelletizing plants nor gives it precise instructions for pellet production since the underlying conditions considerably differ due to the great variety of raw material characteristics.

The purpose of this book is rather to investigate and to describe the possibilities and methods to produce pellets of good and uniform quality irrespective of the varying properties of raw materials.

The existing and ever increasing amount of literature was considered insofar as it was useful for the confirmation and support of relevant theories, parameters and correlations.

1 Definition and Development of Pelletizing Process

1.1 Definition

Pellets are balls produced from concentrates and natural iron ores of different mineralogical and chemical composition with some remarkable properties such as:

- uniform size distribution within a main range of 9–15 mm diameter
- high and even porosity of 25–30%
- high iron content of more than 63% iron
- practically no loss on ignition or volatiles
- uniform mineralogical composition in the form of an easily reducible hematite or hematite-bearing compounds
- high and uniform mechanical strength
- low tendency to abrasion and good behaviour during transportation
- sufficient mechanical strength even at thermal stress under reducing atmosphere.

1.1.1 Differentiation Against Other Iron Ore Agglomerates

The simplest and earliest process for agglomerating fine-grained raw materials is *briquetting*. Fine-grained iron ores, for example, are pressed into briquettes with the addition of some water or another binder under high mechanical pressure. These briquettes may undergo direct further treatment or thermal processing before their use. Although their metallurgical behaviour in melting or reduction furnaces is very good, the iron ore briquetting could not make headway since the processing costs are relatively high and, above all, the production capacity of briquetting units is limited when compared with the enormous quantities of fine ores or concentrates to be agglomerated.

The briquetting process is still utilized to agglomerate small quantities of dust or other circulating materials. This process has, of late, acquired growing importance for briquetting of fine-grained sponge iron.

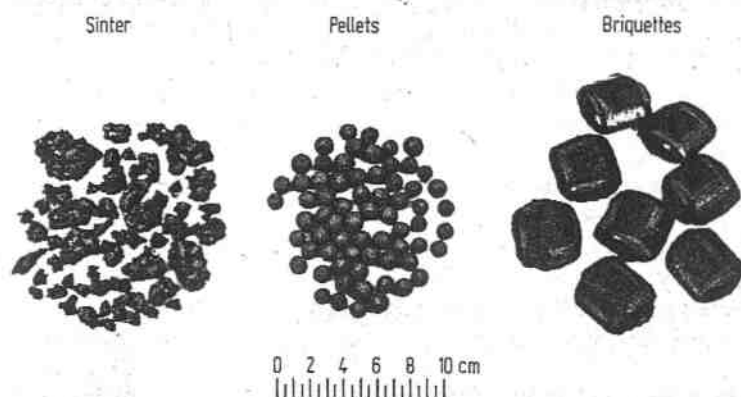


Fig. 1. Comparison of Briquettes, Pellets and Sinter

The second and presently most important agglomeration process is *down-draught sintering*. It differs from pelletizing by various characteristics, such as:

- feed of coarser-grained ore particles up to a diameter of 8 mm
- coke breeze as main energy source
- heating up of the granulated mix to slightly above the softening temperature
- the final product consists of a spongy sinter cake, partly molten, which by crushing, grinding and screening, is brought to the necessary grain size of 5–30 or 5–50 mm. Fig. 1 shows the different outer shape of the agglomerates produced according to the three processes.

1.1.2 Principal Process Steps for the Production of Pellets

The first stage is the formation of green balls. Fine-grained iron ores having adequate size distribution are rolled with the addition of a wetting liquid, usually water, in suitable devices such as drums or discs. In this way, wet balls are formed, the so-called *green pellets*. During the ball formation, it is also possible to use other additives for improving the properties of green and fired pellets, e.g. bentonite, and for changing the metallurgical properties of the indurated pellets, e.g. limestone or dolomite.

In a second step the green pellets are dried and indurated to obtain the typical features of pellets. This is achieved, in most cases, by careful heating under oxidizing atmosphere to just *below* the softening point of the

ores used. During this heating, not only the crystalline structure is changed but also other bonds appear, such as reactions between slag-forming constituents – both between each other and with iron oxides.

The hot pellets are carefully cooled in order to maintain as far as possible the resulting crystalline structures and other bonds as well as to avoid tension cracks.

Green pellets can also be indurated by hydraulically acting binders, e.g. cement or calcium hydroxide, possibly by using steam under high pressure. However, some properties of such pellets differ from thermally indurated pellets (see Chap. 7).

1.2 Development of Pelletizing Process

Iron ore agglomerates, be they briquettes, sinter or pellets, are not the final products. They are formed from such fine-grained iron ores which, in this physical shape, cannot be utilized and serve as an intermediate product on the way from the ore mine to the blast furnace or direct reduction plant. The sole purpose of agglomerate production is to keep the cost price of pig iron or steel at the lowest level. For many years until about the turn of the century, the iron ores charged to blast furnaces had been crushed and partly classified either at the mine or at the iron and steel works. In this case lump ores were preferred although small portions of fine ores could be tolerated.

As a result the fines which were not utilised formed continuously growing dumps with no economic use. They could only be employed to a limited extent in the blast furnace since they decreased the gas permeability of the blast furnace burden in an irregular manner and disturbed the blast furnace operation.

Moreover, a great part of these fines was blown out of the blast furnace and had to be recovered as flue dust. These dust quantities represented a considerable iron value which, like the unused fine ore dumps, was lost; this was of lesser importance in countries with great iron reserves than in those with small iron reserves. The amount of the accumulating dust depends largely on the ore type treated. In the case of Minette or other ores with a high loss of ignition, it is substantially greater than in the case of high-grade, dense ores with a small loss on ignition.

Possibilities were examined and tests to agglomerate the flue dust by *sintering* or *briquetting* and to recycle it to the blast furnace were started at approximately the turn of the century in various industrialised countries although with differing intensities. Countries with important iron reserves were less interested in this agglomeration. They considered sintering as a

“necessary evil”). The situation was quite different in countries with small ore reserves. Here the development of the sinter process continued intensively and not only flue dust but also other iron-bearing secondary raw materials such as pyrite cinders, mill scale or red mud were of great interest. The sintering of fines, obtained during the crushing and screening of unclassified lump ores, was also gaining significance.

At about the same time, some researchers were looking for an alternative process to sintering, especially in areas in which very fine ores or concentrates were available. This was the beginning of the pelletizing process.

1.2.1 First Phase, Alternative to Sintering

The different stages of development, progress and speed of introduction of the sintering process, especially if very fine iron ores were to be treated, led to considerations for improving the process and finally for developing an alternative to sintering, namely pelletizing.

Above all, countries such as Sweden or Germany²⁾, which in the very early days had already been compelled to give particular attention to sintering, had to solve the problem of processing increasing amounts of very fine concentrates. Upon using major portions of such fines in the sinter mix, limits on the specific production capacity of sinter plants became evident. This brought about, first in Sweden, the development of pelletizing. Concentrates were no longer added to the sinter mix but were separately formed into *balls* with the addition of water and then indurated by using binders or in a thermal way. Such a patent had already been granted in 1912 under No. 35124 to the Swede A. G. Andersson. Unfortunately, no further details or metallurgical results were published³⁾. Almost simultaneously, similar research and development work was started in Germany. In 1913, a German patent No. 289606 was granted to the inventor C. A. Brackelsberg. This patent protects a process according to which ore fines were mixed with water or binders, formed into balls and indurated at low temperatures.

No consequences resulted from the Swedish patent whereas Brackelsberg continued his work⁴⁾. One of the most interesting test results was the knowledge that the pellets (referred to as “GEROELL” derived from rolling) could be more quickly reduced than lump ore or sinter made of the same raw material. In the course of this work, a pilot plant⁵⁾ with a capacity of 120 tons per day “GEROELL” was built in 1926 for Krupp at the Rheinhausen steel plant. This plant was reconstructed in 1935, and already showed essential features of the pelletizing process. This pilot plant was dismantled in 1937 to make available the area required for the construction of a large sinter plant.

In this way, the first development phase came to an abrupt end. The pelletizing was forgotten. Sintering spread as the only important agglomeration process throughout the entire world. The pelletizing know-how was practically lost until the way was paved for the second phase, especially in the USA and again in Sweden.

1.2.2 Second Phase, Pellets from Concentrates

The second phase was initiated by the problem of securing the ore supply from the Lake Superior region, especially from the Mesabi Range. From there, many iron and steel works in the United States had hitherto been supplied with high-grade lump ores and coarse-grained concentrates with an iron content of 50% and more, demanding no further treatment. During and at the end of the Second World War, the reserves of such high-grade ores were on the decline so that other sources had to be opened up. One of the richest deposits in the Mesabi Range contained large ore reserves, the well-known "taconites" which have a low iron content, about 30% total iron, almost exclusively in the form of magnetite. These taconites are mechanically very hard. To liberate the magnetite, very finely disseminated through the ore, a very fine grinding was necessary which, after magnetite separation, yielded concentrates with more than 85% fines minus 325 mesh (0.044 mm).

A typical analysis of such a concentrate, having been treated in the plant of Reserve Mining Comp., Silver Bay Minnesota, is shown in Table 1^a).

Table 1. Chemical composition and grain structure of magnetite concentrate in pellet plant of Reserve Mining Company ^a)

Chemical analysis, dry		Structure		
	%	mesh	wt-%	Cumulative wt-%
Fe	65.5	+ 100	0.1	0.1
SiO ₂	7.8	+ 150	0.6	0.7
Al ₂ O ₃	0.5	+ 200	1.5	2.2
CaO	0.5	+ 270	4.0	6.2
MgO	0.6	+ 325	3.5	9.7
Mn	0.25	+ 400	9.0	18.7
P	0.032	+ 500	8.4	27.1
S	0.003	- 500	72.9	100.0
TiO ₂	0.10			
Fe ²⁺	21.75	Specific		
Moisture,	10.00	Surface Area		
% H ₂ O of Pellet Feed		1700 cm ² /g		

The high fine ore portion of above 96% minus 325 mesh is too fine-grained for efficient sintering due to the low permeability of the sinter mix.

Around 1943 intensive development of the pelletizing process for taconite concentrates was started under guidance of and at the MINES EXPERIMENTAL STATION OF THE UNIVERSITY OF MINNESOTA.

When this development work became known in Sweden, the Jernkontoret (Swedish iron and steel institute) in Stockholm founded a committee in 1946 to apply concentrates⁷⁾, a historical curiosity in remembrance of the patent specification by Andersson.

The work of the Swedish researchers, under the direction of Magnus Tiegerschiöld, soon led to the construction of several small industrial plants. The pellets produced in these plants were, inter alia, used for direct reduction of iron ores according to the Wiberg process with remarkable success⁸⁾. This was a *first indication* that pellets were particularly suitable for *direct reduction* and it was a decisive impulse for the further development of direct reduction processes. At first, pellet production and further development of corresponding processes were limited to the two above regions where particularly favourable conditions prevailed. The concentrates produced there were so *fine-grained* that they could be *formed into green pellets without further grinding*. Even if pelletizing initiated an interesting development, other alternative processes for the agglomeration of taconite concentrates were also tested. At almost the same time that the first major publication on the development progress of the new pelletizing process was made in 1944⁹⁾, the Oliver Mining Division of U. S. Steel Corporation in Extaca, Virginia, Minnesota decided to develop further, on a large scale, another agglomeration method, the so-called "nodulizing process" for the production of nodules from fine-grained taconite concentrates in a duff coal fired rotary kiln¹⁰⁾. At the same site a sintering plant was built although normally such plants had hitherto been erected near the blast furnaces. After a period of initial troubles, both plants were started up and operated. However, after a few years, they were shut down. The production of pellets – whose qualities were increasingly gaining recognition – advanced so rapidly that from then onwards pelletizing plants were *exclusively* built. In these plants, the ever-growing quantities of concentrates produced could be processed successfully so that the original goal of also opening up deposits with a low iron content was fully achieved. Around 1955, the second phase of the pelletizing process development was terminated with the start-up of the two large pelletizing plants of Reserve Mining Co. and Erie Mining Co. with an annual capacity of 12 million tons. The successful development of the different pelletizing processes in the Mesabi Range is the result of intensive cooperation between big *mining companies*, e.g. Erie and Reserve Mining Co. with *science*, the University of Minnesota as well as important *engineering com-*

panies, contractors and suppliers. The latter could partly use machinery, equipment and structures already known and approved. Two firing systems for the induration of green pellets were employed on a large-scale. Erie Mining used the shaft furnace ¹¹⁾, and Reserve Mining a modified sintering machine ¹²⁾. In Sweden, the shaft furnace was exclusively used during this period.

Without the intention or compulsion of securing the future ore supply from the Mesabi Range, development of the pelletizing process would probably not have been started at this location.

1.2.3 Third Phase, Pellets from Ores

The close correlations between sintering and pelletizing became explicit during both the first and second development phases. Since there was no compulsion at that time to develop further the ingenious knowledge of Andersson and Brackelsberg, the first promising steps to pelletizing were soon forgotten.

In the second phase of development the sinter process was exclusively confronted with ever-increasing quantities of very fine-grained *magnetite concentrates*, so that the production capacity was closely limited. The enormous quantities of concentrates and the necessity of finding a solution to the problem gave the impetus to develop pelletizing up to a process applicable to industrial operation. At that time, neither in the USA nor in Sweden was there a need for pelletizing other ores than concentrates. The third phase started from quite another situation.

Various newly developed steps for improving the *sinter process* were modified and successfully combined to form the basis for a new pelletizing process variant for iron ores and mixtures. This process was developed in parallel to the knowledge derived from the pelletizing of concentrates. The sintering of iron ores had a very different importance in various countries according to the availability of ore reserves. Consequently, the readiness to give this process an adequate position within the context of pig iron production in conjunction with the operation of the blast furnace differed greatly. This was apparent at the end of the First World War as well as at the beginning of and during the Second World War.

The necessity also to produce pig iron from low-grade fine-grained ores resulted in intensified development work in the sintering field ¹³⁾. This development work referred both to process parameters and constructional improvements of the necessary machinery and equipment. The most recent development progress in sintering is described in a book by F. Cappel and H. B. Wendeborn ²⁾. Again after the Second World War in a varied raw material situation highest production rates of the sinter

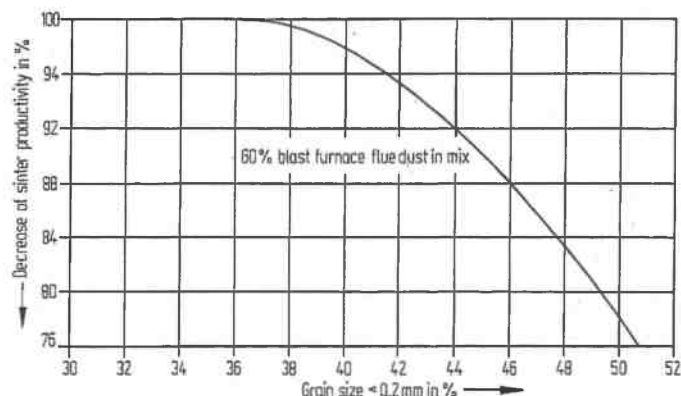


Fig. 2. Influence of particle size on sinter productivity

machine at minimum fuel consumption for the production of agglomerate were the conditions to be fulfilled. Flotation pyrite cinders and Swedish concentrates constituted growing portions of the ore mix. The greater fineness resulted in a reduced specific output (in tons sinter/m² area in 24 hours) as is clearly demonstrated in Fig. 2. With a rising proportion of fines -0.2 mm a considerable output decrease was observed ¹³⁾.

From this resulted the demand to keep the fines portion approximately -0.2 mm as low as possible. For example, in Germany it was expected that the portion -0.125 mm should not exceed 10% ²⁾. The fine ores at present available on the world market generally contain a much higher percentage of fines. According to experience, a corresponding decrease of output of sinter plants in operation throughout the world would be unavoidable. For the owners of such sinter plants supplied with ores from mines all over the world and not from their own mines, this would mean higher prime costs for sinter and thus for pig iron.

The designers and suppliers of such sinter plants were also confronted with the above problem. It was obvious that this unavoidable deficiency of *fine ores* had to be compensated for. The separation of fines from the sinter mix could be theoretically conceivable (but difficult to realise) as is demonstrated by the test described below ¹⁴⁾.

A sinter mix consisting of 11 different ore components with a grain size portion of about 40% -0.5 mm was sintered at a capacity of X tons/m² per day after careful preparation. The same ore was screened at 0.5 mm and only the coarser fraction was sintered. In this case, the capacity rose by about 35% compared to the first test.

A second method of compensating the reduced capacity to be expected would be the enlargement of the suction area of the sinter strand. How-

ever, a sinter strand with a suction area designed for specific ores would not be sufficiently flexible to compensate for the capacity fluctuations resulting from varying ore mixtures and the correspondingly different fines portions. Nor would the separation of the very fine particles or the extension of the suction area be considered suitable measures to solve this problem.

1.2.3.1 The Two-Stage Granulation of the Sinter Mix

Finally, the introduction of a new process stage brought the expected solution. After the detrimental effect that excessive fines portion has on the sinter output became known, the sinter mix permeability was improved in intensive laboratory tests by further treatment of the prepared sinter mix. In these tests the prepared mix was conveyed to a second mixer in which it was additionally rolled. This process variant is known as *two-stage granulation (rerolling)* and now forms part of most of modern sinter plants in operation throughout the world. By rerolling, the very fine particles adhere to coarser particles. The ore mix now contains small balls and ore particles with a size distribution of about 0.5–8 mm. Micro-pellets are formed as can be seen from the comparison shown in Fig. 3. A normal sinter mix and a sinter mix subjected to this after-treatment show distinct differences in the size distribution and shape.

The rerolling apparatus, e.g. a drum, is equipped in a different way to a normal mixing drum. It is practically identical to a balling drum.

The rolling effect and the different sintering time for some high-grade iron ores with good sintering properties are shown in some tests described

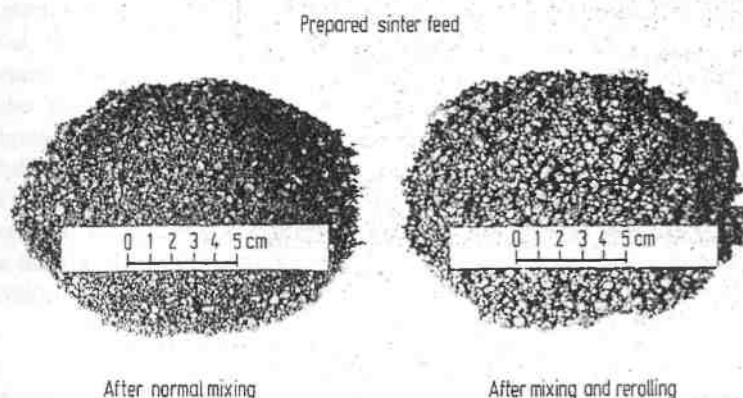


Fig. 3. Piles of sinter mix with and without re-rolling

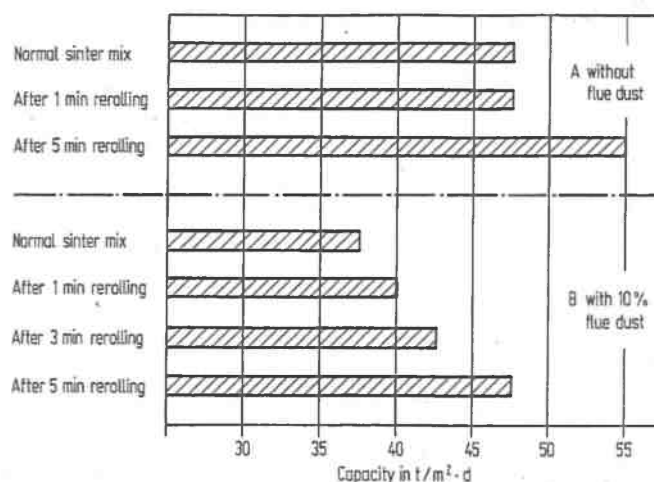


Fig. 4. Influence of re-rolling of a Venezuelan ore feed on sinter plant capacity

below which were carried out with and without portions of fine-grained flue dust¹⁵).

Venezuelan fine ores (mix A) are mixed with coke breeze, return fines and water and are sintered at a production rate of 48 t/m²/24 h. During rerolling, only a very slight output increase is observed. By the addition of 10% flue dust (mix B), the output drops to about 38 tons. By rerolling over 5 minutes the output is re-increased to the previous value (see Fig. 4). A substantially lower specific output (about 22 t/m²/24 h) is obtained with another ore mix having a high proportion of grains -0.2 mm. If this mix is rerolled before sintering, the output can be gradually raised to more than 30 tons, which represents an increase of almost 38% (Fig. 5).

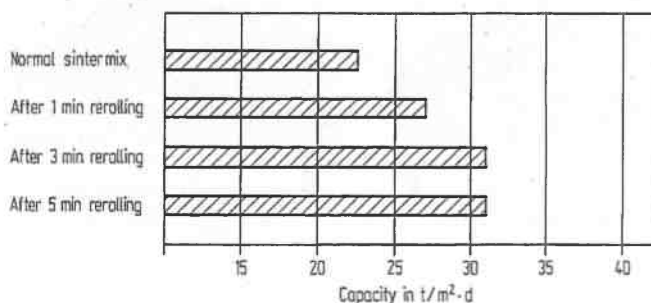


Fig. 5. Influence of re-rolling of a sinter mix (magnetite concentrate, flue dust, pyrite cinders) on sinter plant capacity

By this simple process variant, which is at present applied throughout the world, it is possible to improve the sinter mix permeability and thus the sinter process in such a way that today portions of more than 10% fines – 0.2 mm can be used. The result of this improved sintering method was that in industrialised countries purchasing a high percentage of extraneous ores (Japan, Great Britain, Germany), there was but little incentive to introduce the pelletizing process.

Nevertheless, the production of micro-pellets was the first step towards pelletizing in these countries. This method of producing micro-pellets, virtually developed in Germany, was, in one particular case, adopted to 100% flotation pyrite cinders without the expected success.

1.2.3.2 Pellet Sintering

The sinter process was then modified in such a way that not the total mix but only the fine raw material was formed into balls of 3–6 mm diameter which were mixed with return fines and coke breeze and sintered. This process has become known as *pellet sintering* and is an intermediate process between normal sintering and pelletizing. The final product is a sinter cake in which the pellet structure of the raw mix can still be recognised in the finished sinter product. Such a pelletizing plant was operated for several years by COMINCO in Trail, Canada. Similar results were obtained in an up-draught pelletizing plant erected by Cleveland Cliffs Iron Company near Ishpeming, Michigan, called “Eagle Mill” plant “). In this plant the total heat required was supplied in a solid state. The final product obtained consisted largely of sinter lumps and not, as expected, of pellets. However, neither of the process variants was further developed. These plants are no longer in operation.

In many countries which exclusively used the sinter process for iron ore agglomeration, another problem arose, namely to supply the necessary solid, lean fuel, mainly coke breeze. There was a scarcity of this fuel in certain countries because due to the considerably increasing number of sinter plants being built, the necessary amounts of coke breeze, chiefly originating from coke screening, were no longer sufficient to meet the requirements. It was necessary to crush high-grade, expensive metallurgical coke for sintering. The search for cheap replacement fuel led to an increased use of blast furnace gas from which another process variant of the normal down-draught sintering, namely the *mixed firing method*, was developed.

1.2.3.3 Mixed Firing Method

Normally, the coke breeze on the surface of the sinter bed is ignited by the combustion of flue gas in an ignition hood. The ignition hood length

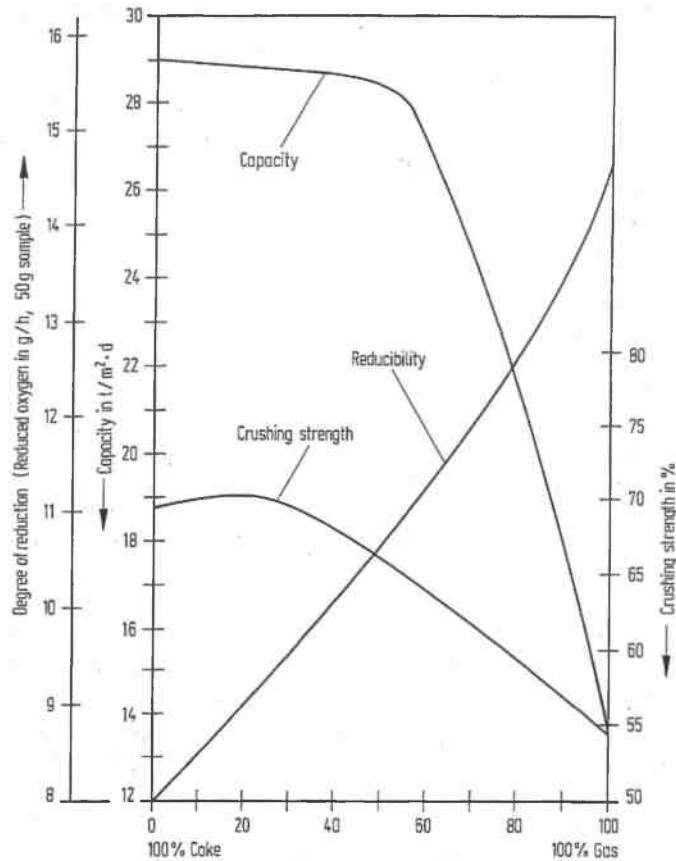


Fig. 6. Influence of mixed firing on sintering of iron ores

and the duration of the influence of the hot combustion gases is accordingly limited. The heat amount developing inside the ignition hood is insignificant compared with the solid fuel amount contained in the sinter bed. When adopting the mixed firing method, the ignition hood is substantially extended in order that a higher gas volume can be burned and greater heat quantities can be sucked into the sinter bed. With such extended ignition hoods it is possible to decrease the coke consumption remarkably.

Flue gas can be replaced by other heat sources, such as hot air of about 800 °C, oil or natural gas, according to their availability. Coke breeze cannot be replaced by hot gas to an unlimited extent, without impairing the plant output and sinter strength, as shown in Fig. 6. An advantage of this method is the better reducibility with increasing portion of hot gas ¹⁷⁾.

The mixed firing method is nowadays often adopted particularly in countries where coke breeze is expensive. Once it had been possible to produce micro-pellets from fine-grained mixtures by rolling of balls of 3–6 mm for pellet sintering, it was not very difficult to produce green pellets of a greater diameter and of a uniform, close size range (9–15 mm). However, it was not yet possible to indurate these pellets exclusively with coke breeze or by adopting the mixed firing method in order to meet the pertinent requirements. A consistent further development of this firing technology by the exclusive use of gas or oil leads to the application of the pelletizing process. This firing technology applicable to the firing of green pellets from iron ores was adopted inter alia to ceramic mass, glass constituents, burning of limestone ¹⁸⁾.

The three development phases of pelletizing are summarized below:

First Phase – Alternative to Sintering: 1910–1927. Besides the sintering process under development, an alternative becomes apparent, to agglomerate very fine-grained ores by pelletizing without any consequences ensuing.

Second Phase – Pellets from Concentrates: 1940–1955. Production of very fine-grained concentrates increasing considerably in some regions, such as in the Mesabi Range/USA, compels development of the pelletizing process as an alternative to sintering. The state of development at that time did not yet allow for the use of high portions of fines in the ore mix.

Third Phase – Pellets from Ores: 1948 up to the present date. In various countries the sinter process is further developed intensively to adapt it to the varying supply of ores of different fineness. As a result of this development work, the application range of the pelletizing process was also extended, beyond the use of concentrates as only components, to other ores and, moreover, with considerable success to ore mixtures, see item 9.3.5.

1.3 Pelletizing, a Contribution to Ore Preparation

For economic reasons, the treatment of iron ores in the blast furnace or in direct reduction plants is nowadays no longer possible without intensive *ore preparation*. Even if individual process stages involve high prime costs, these are accepted, provided that the total production costs of pig iron or sponge iron can, in this way, be kept at lowest level. The purpose of iron

ore preparation is the qualitative improvement of different features of raw materials:

- (a) Mechanical crushing, grinding, screening, *classification*.
- (b) Physical separation of various mineral constituents for the *elimination* of gangue from the lean ores and preparation of concentrates with high iron content.
- (c) Thermal or chemical treatment for the *elimination* of volatile energy-consuming constituents such as H_2O , CO_2 , SO_4 , S or conversion of hematite to magnetite.
- (d) Metallurgical change by basic additives which decrease the energy consumption of the succeeding process stages.

In all four steps pelletizing plays a significant role, such as:

- *Agglomeration of the finest ore particles or concentrates* [(a) and (b)]
- *Volatilisation of components, such as H_2O , CO_2 , SO_4 , S* [(c)]
- *Changing to the chemical composition by basic additives*.

The entire complex of present-day iron ore preparation is shown in Fig. 7.

Since the significance of “physical mixing” is recognised throughout the world and accepted, even iron-rich ores are crushed to a maximum lump size, for the blast furnace to approx. 30–50 mm, for direct reduction to approx. 20–30 mm. The eliminated fine ore can either be sintered or after further fine grinding pelletized. Low-grade ores with an iron content of less than 50% are upgraded, the solid gangue constituents separated and in so

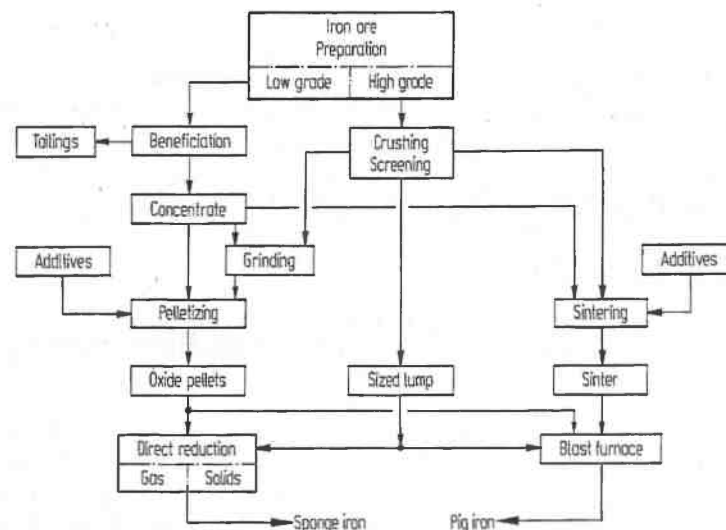


Fig. 7. Alternatives for iron ore preparation

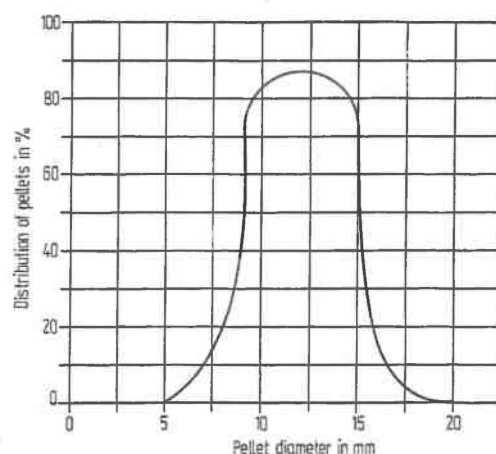


Fig. 8. Size distribution of pellets

doing the iron content in the concentrate increased. According to its fineness the concentrate can be pelletized immediately or following further grinding. In certain proportions concentrates can also be incorporated in sinter mixes. During thermal treatment the separation of volatile components takes place in both pelletizing and sintering. Because of their defined properties, high iron content together with uniform size distribution and close size range pellets are an important charge constituent for blast furnaces and direct reduction plants.

The size distribution, shown in Fig. 8, as an average of three commercial samples¹⁹⁾ is remarkable. The conditions are very strict: 80–90% of the pellets should have a diameter of 9–15 mm, the major part of which a diameter of 9–12 mm. The charge should, if possible, contain neither fines –5 mm nor pellets of a diameter exceeding 25 mm. This is also an important size range for use with other iron-bearing components in, for example, the blast furnace. The feed should consist of grains 5 to max. 50 mm, preferably 30 mm; Fig. 9 schematically shows the various operations leading to this desired size distribution: crushing of coarse ores and sinter cake, screening and separation into 3 fractions. The oversize is recycled to the grinding plant, the *product of 5–50 mm or 30 mm goes into the blast furnace* and the undersize is conveyed to agglomeration, either sintering or pelletizing plant. The undersize also includes concentrates, pyrite cinders, mill scale, flue dust and possibly additives. Pellets, crushed sinter and classified raw ore constitute, either alone or in the form of mixtures, the blast furnace burden.

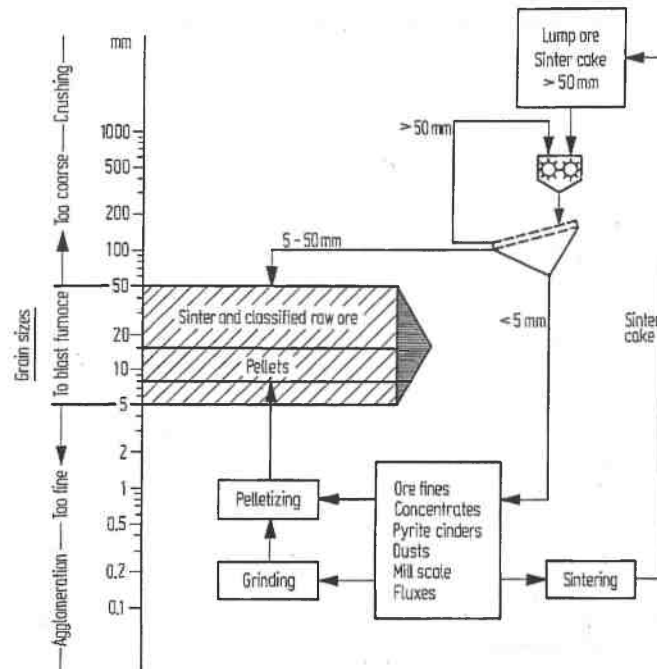


Fig. 9. Scheme of preparation and size distribution of blast furnace feed

Besides sinter, still the most important type of agglomerates for blast furnace burdens, pellet portions are, compared to lump ores, of growing importance for pig iron and sponge iron production. In Fig. 10 the development of pig iron production from 1960 to 1978 is compared with sinter and pellet production. From 1974 the curves for sinter and pig iron decline, the latter caused by economic reasons. The pellet curve remains steep up to an estimated average pellet portion of 25% in the *blast furnace burden*.

In the pellet production curve, Fig. 10, the amount of pellets as feed material for *direct reduction processes* is included but the portion is remarkably higher by up to 100%. In shaft furnaces efforts are made to replace a part of the pellets by cheaper, carefully selected and screened lump ores. A mixture of 55–75% pellets and 45–25% lump ores has recently proved to be suitable for optimum productivity, as shown in Fig. 11.

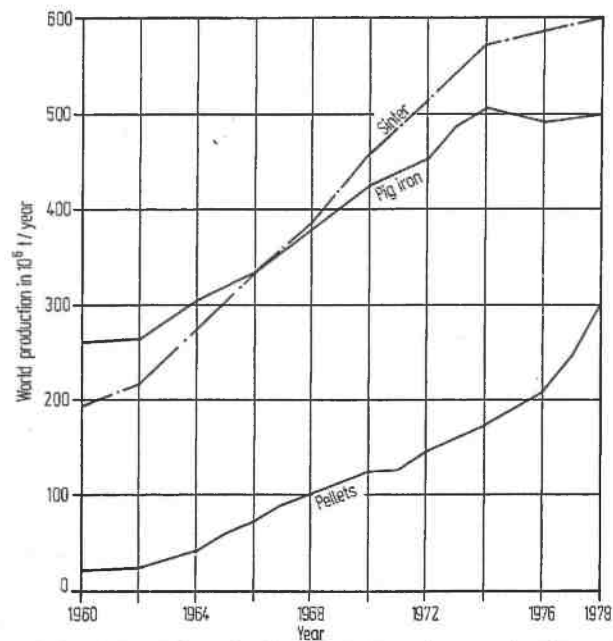


Fig. 10. World production of pig iron, sinter and pellets

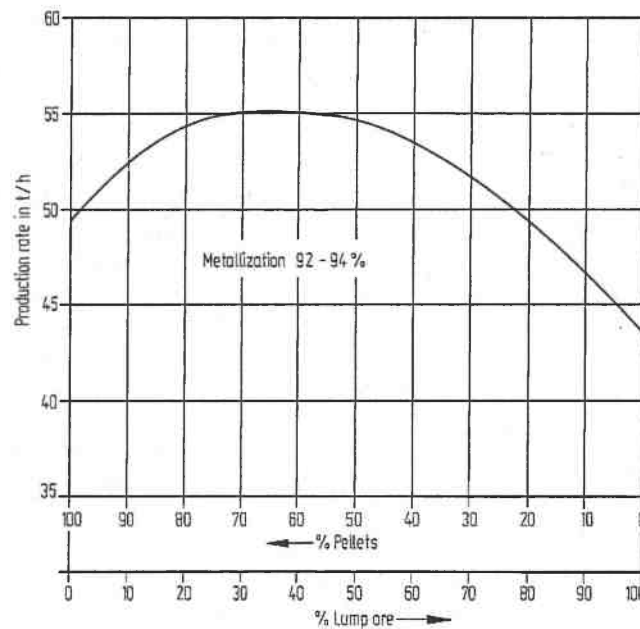


Fig. 11. Influence of a mixture of pellets and sized lump ores on direct reduction shaft furnace capacity

1.4 Sites of Pelletizing Plants and Transportability of Pellets

As already mentioned above, pellet production and the development of appropriate processes is directly connected with the beneficiation of low-grade iron ores – originally chiefly magnetites to produce (very fine-grained) concentrates.

In the first place, it was necessary to convert these concentrates into agglomerates ready for the blast furnace. At the same time the question arose regarding the optimum site of such a pelletizing plant. The very fine-grained, wet concentrates are unsuitable for storage, especially in regions with long and cold winters because they freeze during this time and can neither be loaded nor transported. These problems were solved by erecting the pelletizing plant in the close vicinity of the beneficiation plant and thus practically *at the ore mine*. Pellets are resistant to the influences of storage and winter conditions. They withstand long transportation routes with several trans-shipments better than lump ores or even sinter.

During the first years, pellets were produced, mainly in the USA, to supply blast furnaces within a controlled market. Their transportability was accepted but no special controls were instituted. Only after major pellet quantities had appeared on the world market and had reached other blast furnaces, was greater importance attached to the behaviour of pellets during transport. Thus, the preparation of a large-scale test (1963), run on about 150,000 tons pellets from the Reserve Mining Company in a blast furnace of the Federal Republic of Germany, also included, e.g. the study of the abrasion behaviour, compression strength and variation of pellet size²⁰⁾. From Port Silver Bay to the works port situated on the river Rhine, the pellets were subjected to six trans-shipments, a water transport and an 18 month storage period at the port area of Amsterdam during two winters. The fines portion –6 mm, contained in the pellets, was used as a reference value.

This fines portion was at Lake Superior 8.0% and increased during transportation via the Port of Amsterdam to the Duisburg-Huckingen Works, and after screening before the blast furnace to about 18%. The portion of 10–15 mm diameter varied from 85% to 82% and, after screening, rose again to 88% at the blast furnace. In this way, proof was furnished that pellets can be transported satisfactorily. This large-scale test – successfully carried out in an independent steel plant with high pellet proportions in the blast furnace burden – became known publicly and aroused increased interest in these new agglomerates also at those works where pellets had hitherto not been used at all.

Table 2. Countries leading in iron ore production and export ^{1,3)}

Countries	10 ⁶ t/year			
	1966		1976	
	Production	Export	Production	Export
Africa				
Liberia ^a	17.0	16.6	35.0	20.8
Rep. South Africa	6.8	3.1	15.7	5.0
America				
Brazil ^a	23.3	11.8	70.0	47.3
Venezuela ^a	17.9	17.0	23.0	15.6
Canada ^a	36.6	31.2	56.0	44.5
USA	91.6	9.9	81.2	2.9
Asia				
India ^a	26.8	13.4	42.6	24.0
Australia ^a	11.0	2.0	93.1	81.1
Europe				
France ^a	55.7	18.2	45.5	15.8
Great Britain	13.9	—	4.6	—
Sweden ^a	28.0	22.3	30.5	22.0
USSR ^a	160.2	26.1	239.0	43.1

^a Leading Exporters

Pellet production was initially always linked with a beneficiation plant, usually located at the mine where sufficient quantities of very fine-grained concentrates were available without any intermediate treatment.

The increasing world-wide demand for high-grade iron ores led to the discovery of new deposits with iron ores of different mineralogical and chemical composition. Their quality could also be improved by beneficiation as in the case of Marcona in Peru. However, many of these deposits were located in countries with little domestic demand for pellets so that their exploitation could only be secured by exportation.

Some countries have adapted themselves particularly to this situation so that a considerable change of ore suppliers has occurred during the last ten years, as is shown in Table 2 for the years 1966–1975. Firstly, it indicates the increase in production within a ten-year period by 170 million tpy or 50% compared to 1966. In some instances there were even more important changes as, for example, in Australia and Brazil. A further remarkable phenomenon is the production decrease of low-grade ore in France (minette) and in Great Britain (home ores). These countries now import the corresponding iron units in the form of high-grade ores. Other countries, such as Japan and the Federal Republic of Germany as well as nearly all other E. E. C. countries meet their requirements almost exclusively by imports.

Table 3. Screen analysis of exported fine ores²⁾

Screen Undersize in mm	Liberia (Bomi Hill)	Mano River washed	Kiruna B weight %	Hamersley (cumulative)	CVRD Common Fines	CVRD Sinter Feed B	Nimba
- 11.2							
- 8				1.0	21.5		
- 5.6	15.5	13.5	9	11	34	3	8
- 4	22	24	18.5	24.5	42	10	16
- 2.8	29	35	27	35	47	19	24
- 2	35.5	44	35	43.5	51.5	26.5	31
- 1.4	42	53.5	41.5	49	54	32	35.5
- 1	49	61	47	54.5	55.5	36	39
- 0.71	56.5	68	51.5	60.5	57.5	40.5	42.5
- 0.5	64	75	55	65	59.5	45	46
- 0.355	72	80.5	58.5	69.5	61	49	50.5
- 0.25	80.5	85	63	75	62.6	52	55
- 0.18	89.5	88.5	67.5	79	64.5	57	68
- 0.125			73.5	84.5	67	63	73.5
- 0.09			80	87.5	70	74	80.5
- 0.063				90.5	75	85.5	84.5
- 0.045				92.5			

The fine ores to be shipped from port to customer frequently contain a very high and different portion of fines as is apparent from some examples given in Table 3. Transportation difficulties as a result of dust arising during loading, trans-shipment and unloading of such ores as well as difficulties during sintering led to the production of pellets at the port and to the exportation of pellets instead of fine ores. This was the beginning of the construction of new pelletizing plants in shipping ports, e.g. CVRD, Tubarao/Brazil, Hamersley, Port Dampier/Australia, Marcona, San Nicolas/Peru, Wabush, Quebec/Canada. Such plants treat the fine ores and concentrates supplied from various mines; they can be designated as *pelletizing plants located at the port*. After pelletizing technology had been sufficiently developed, blended ore pellets consisting of varying ore types were also produced²¹⁾. As a result of this it became possible to build pelletizing plants in direct connection with the blast furnace.

Only this latter combination would have the advantage of being able to pelletize very fine-grained ores and concentrates as well as waste oxides and thus release the sinter plant. A typical example of such a combination is the pelletizing plant of the Koninklijke Nederlandsche Hoogovens en Staalfabrieken N. V. in IJmuiden/Netherlands²²⁾, where, besides the pellet plant (3.5 million tpy) three sinter plants, altogether having the same capacity, are in operation. Further plants are operating at the Japanese Iron & Steel Works Kawasaki-Chiba, Kobe-Nakahama and Kobe-Kakogawa. This third type of plant can be designated as *pelletizing plant located near the blast furnace*.

2 Fundamentals of Pelletizing

Pellets differ from lump ore and, to a certain extent, also from sinter by several properties which are predetermined and definable. Despite the great variety of raw materials used, the pellets produced must have the *same* properties which are judged in accordance with internationally accepted standards. Due to their importance and great variety, the properties demanded from pellets are specified under item 1.1.

According to today's technology, nearly all iron ores with a correspondingly high iron content can be pelletized: magnetite, hematite, limonite and their concentrates as well as purposely prepared mixtures, waste oxides, pyrite cinders or pertinent by-products from other industries.

To obtain the required properties and taking the great variety of raw materials into account, adequate production methods are to be adopted which are described and discussed below:

Three process stages are involved to produce the pellet from raw material:

- Stage 1: Raw material preparation
- Stage 2: Formation of green balls
- Stage 3: Induration of green balls.

Successful pellet production calls for an optimum efficiency and harmony between all three process steps with the preceding stage highly influencing the subsequent one. An error made in the preceding stage can only be corrected to a limited extent in the subsequent process stages. Even during induration, no first-class pellet can be produced from a defective green ball. The purpose of the green ball formation is to obtain balls of the desired size range and having a mechanical strength which enables them to be safely transported from the balling equipment to the induration facilities.

During the formation of green balls from solid fine-grained particles, many different forces co-act, which are designated as *bonding mechanisms*.

2.1 Bonding Mechanisms for Green Ball Formation

At an early stage, both experimental and theoretical considerations were made with regard to the bonding mechanisms underlying the green ball formation. Some of the theories developed in this connection were already known from other processes, e.g. those of the fertilizer industry, food-stuffs industry, pharmaceutical and refractory industries. Similar bonding mechanisms also play a great part in the granulation and crumbling of the sinter mix. The rapid progress of pelletizing technology was achieved particularly by almost *simultaneous* experimental and theoretical progress in contrast to other process developments, e.g. in the blast furnace technology.

2.1.1 Important Bonding Factors

The decisive factors for the green ball formation and green ball properties can be divided into the following groups ²³⁾:

- (a) *physical forces*, such as van der Waals', magnetic or electrostatic forces
- (b) *surface-dependent factors*, such as particle size, particle size distribution, particle shape and crystalline structure
- (c) *material-dependent factors*, such as wettability, absorptive capacity due to porous structure, availability of swelling components, chemical properties in primary ores or by-products after previous treatment
- (d) *capillary forces and surface tension* during the addition of liquid binders, such as water or others.

Some of these factors, mainly the raw material-dependent factors are *not* variable. However, they influence the green ball formation to a great extent. Other forces also acting on the green ball properties are variable. By utilizing such forces, the raw materials to be pelletized can be adapted to the relevant requirements.

Variable factors are, for example the quantity of wetting agent added, the particle fineness and shape, the balling equipment used for green ball formation, the forces arising in such equipment as well as the movement of raw materials in these units.

2.1.2 Ball Formation Alternatives

Green balls can be formed in different ways. In each particular case, the various bonding mechanisms act at different intensity.

2.1.2.1 Compacting Method

The solids are pressed into briquettes only by the application of high mechanical forces. Sharp-edged briquettes may be rounded off by re-rolling. The individual grains are held together by adhesive and cohesive forces which, in turn, determine the mechanical strength of the briquettes.

The solid particles, mixed either with or without binders are packed randomly without any relative movement. The location of the various grain faces to each other is at random – it does not have to be the optimum location for the formation of the greatest adhesive forces.

The compacting technique – well known for briquetting and tablet compressing – is nowadays applied to ore preparation only in specific cases.

2.1.2.2 Green Ball Formation

Besides the solid phase, a *liquid* phase is, in each case, required for green ball formation. The interface forces arising have a cohesive effect on the solid particles, liquid and air. These interface forces consist, on the one hand, of the surface tension of the binder, usually water, and on the other, of capillary forces developing in the liquid bridges between the individual ore particle faces, the surfaces of which are of *concave* shape. Under these conditions, a certain *tensile strength* occurs. The forces resulting from the surface tension form a *concave* liquid surface whereby compression strength becomes active.

For the formation of green balls from solid particles and liquid, there are two possibilities:

- The solid particles are without any *active relative movement*. They are mixed in suitable equipment, so-called mix granulators, by the rotation of the vessel and the mixing devices arranged inside without having to perform their own rolling movement as in the case of a drum. At the same time, they are pushed together by a pushing movement and slight mechanical forces and are compacted. The ore particles are brought to such a favourable position to each other that the agglomerate forms a tight packing. Capillary and surface forces co-act with adhesive forces²⁴). The liquid bridges and surfaces between the individual ore particles form automatically. In most cases the relevant balling facilities operate intermittently. They are less suitable for the throughput of big ore quantities which are nowadays processed in pelletizing plants. However, in many industries with lower throughput, they are used with great success.

- In the second case, the ball formation is mainly achieved by *rolling* of solids/liquid mix in well-known balling units, such as drums or discs. The green ball formation is similar to snow-ball growth by layering. The liquid surface is freely movable which is advantageous for the contact between the ore particles and the formation of capillary bridges.

2.1.2.3 Mechanism of Ball Formation

The feed material may consist, according to its preparation, of either a conglomerate of dry grains or a wet filter cake. In the one case, the ores were subjected to dry grinding, in the other, to wet grinding. Most concentrates are available as filter cake. If dry solid particles come into contact with water, the ore surface is wetted. The ore particle is coated with a water film, as is schematically shown in Fig. 12, phase A. In many places, the wet particles touch each other. Due to the surface tension of the water film, liquid bridges are formed, phase B. As a result of the movement of the particles inside the balling unit and of the combination of individual water droplets, each containing one or several ore grains, the first agglomerates are formed, phase C. In the interior of the loose agglomerate, the first liquid bridges appear among a large number of voids still existing. These liquid bridges hold the particles together as in a network. Loose balls are formed. With the further supply of water the agglomerates condense. More and more water is layered in the interior and the agglomerates become more dense, phase D. At this stage of green ball formation the capillary forces of the individual liquid bridges are essentially active. The optimum of this ball-formation phase is attained when all pores inside the balls are filled with liquid but the latter does not yet uniformly coat the whole agglomerate, phase E. The effect of the capillary forces is clearly shown by Ilmoni and Tigerschiöld in Fig. 13²⁴). Concave liquid surfaces form on the outer pores and capillary suction is holding the ore particles together.

The final stage is exceeded, when the solid particles are fully coated with a water film. Now, the surface tension of the water droplets

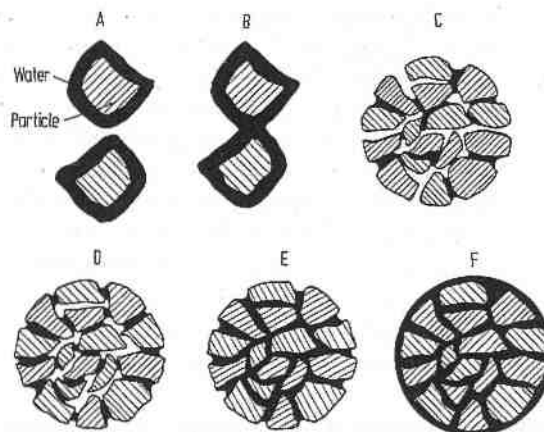


Fig. 12. Influence of water addition on green ball formation

containing the solid particles becomes fully active, Fig. 12, phase F, and the effect of the capillary forces drops sharply, see Fig. 135.

Besides this effect, the rolling movement of the grains and the movement or shifting of the particles relative to each other plays an important role too. They increase adhesion by the great number of contact points at a simultaneous compression strength due to the load of the rolling material.

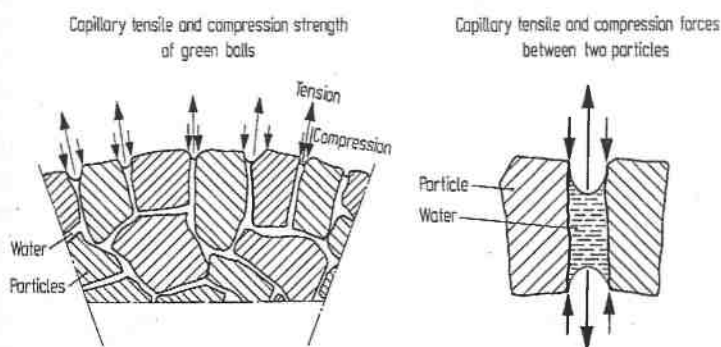


Fig. 13. Influence of capillary forces on bonding mechanism

Apart from the compacting and solidification of agglomerates due to pressure and movement, these factors may also have a negative influence. They damage mechanically weak granules which have not yet attained a sufficient adhesive strength. The damage resulting is that the weak green balls may either crumble into minor fragments or disintegrate into even finer particles. During green ball formation, these fractions may be layered onto moist stable green balls and be incorporated into the latter.

Besides the ideal ball formation from fine-grained individual solid particles initially described, various other possibilities exist more or less simultaneously in practical operation. This also applies to loose agglomerates as in the case of wet filter cake. According to Sastry and Fuerstenau²⁵⁾ the following methods, as shown in Fig. 14, can be adopted:

- A) Layering of very fine particles to others and thus formation of an agglomerate.
- B) Conglomerating of smaller balls already existing resulting from relative motion and a certain pressure.
- C) Layering on and incorporation of minor fragments from damaged green balls into existing sound ones.
- D) Incorporation of fine-grained abraded material from weak pellets into the surface of stronger pellets.

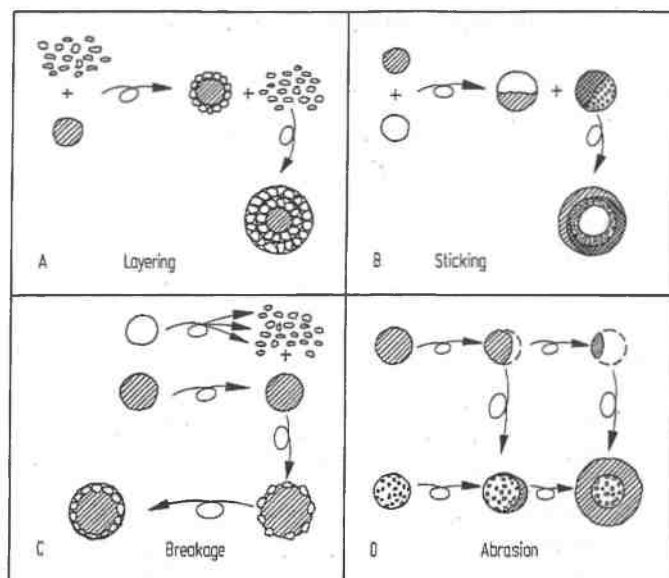


Fig. 14. Alternatives for green pellet formation

During green ball production, their formation proceeds parallel to the disintegration of a certain number of balls. Only such balls which can withstand the dividing or destructive forces during rolling survive. A selection of the best balls takes place. The contest of the constructive and destructive forces favours the formation of astonishingly uniform, dense and stable green balls²¹⁾.

As set forth under item 2.1.1, various factors may co-act during green ball formation, either dependently on raw materials or independently thereof. Much development and research work has been performed to investigate the raw material independent factors. In this connection, some of the researchers who have played an important role are mentioned²²⁾.

The theory and the mathematical formula resulting therefrom are dealt with under item 13.1. These investigations are based, for the most part, on the use of exactly defined particle shapes, such as balls or on specific raw materials, such as quartz, limestone or glass. The laws discovered can thus only serve as a guide since each ore – even of the same size – has its typical size distribution or particle shape. This again requires an individual investigation of each ore or mixture.

2.2 Induration of Green Balls

In a very few cases it has been possible to use green balls directly in a metallurgical process despite their low mechanical strength. Pellets must have a substantially higher strength primarily to withstand their transportation and the stresses occurring in metallurgical operations. Such a strength can be achieved by thermal treatment under a controlled atmosphere or by utilizing hydraulically-acting binders.

The most widely-spread thermal green ball induration on an industrial scale, namely firing to directly below the softening point of the respective ore, is carried out in two stages: *drying* of the balls followed by heating and *firing*. Just as for green ball formation, optimum conditions must also be aimed at for drying to ensure maximum achievable final properties.

Therefore, the green ball strength must not deteriorate during drying. However, should this be the case due to the ore properties, adequate action should be taken.

2.2.1 Drying of Green Balls

During drying, the moisture contained in the green balls is evaporated by warm gases. In this connection, it should be noted that the water may be contained in the green balls in a variety of combinations:

- (a) There is water in the *interstices* between the particles, i.e. in the pores and capillaries.
- (b) In the case of a porous ore, water may also be *in the* pores of the individual ore grain.
- (c) Water may be *chemically combined* as hydrate, e.g. in limonite or in other minerals accompanying the iron oxide.
- (d) Water may be *incorporated* into such binders which tend towards the formation of gels, e.g. clays or bentonite.
- (e) Water may be *chemically combined* as *hydrate* in such binders which leads to hydrate formation, e.g. Ca(OH)_2 , Mg(OH)_2 .
- (f) Water may be present as *crystal components* in existing or added salts.

The moisture content in the green ball may thus be composed of water, contained in the ore, or by such being added during pelletizing.

Only part of the water contained in the green balls evaporates at 100 °C. Salts and hydrate combinations loose their water at higher temperatures only. The drying speed, therefore, must be adapted to the different combinations to avoid a weakening of the pellet structure due to cracks or splintering of fragments. During drying of a pellet layer or a pellet bed at a certain depth, two operations can be observed. Drying starts in the individual ball and uniformly proceeds in the pellet layer.

2.2.1.1 Drying Procedure of Individual Balls

This drying commences when heated air or combustion gases flow over wet green balls. In this connection, the gas temperature, dew point, quantity and drying velocity play an important role. The moisture contained in the green pellets starts to evaporate evenly on the entire surface. After this evaporation, water from the pellet interior is emitted by capillary forces to the surface. As long as this procedure continues, the drying velocity remains constant. However, if the drying velocity on the surface is greater than the water emission from the pellet interior, the drying front travels down into the pellet interior. The water vapour thus arising has to cover an ever increasing distance through the capillaries which are already dried out until it reaches the pellet surface from where it can escape together with the air flow. During this drying phase, the drying velocity is no longer constant but decreases. As soon as the capillary water evaporates, the drying procedure is terminated. However, if the pellet contains hygroscopic or chemically-combined water, the drying procedure only continues when the temperature of the drying medium is high enough to dissociate the compounds. The velocity of this third drying phase is again lower. The drying procedure of such a green ball, which also contains hygroscopic water, was described by Krischer and Jaeschke ¹¹⁾ in a curve shown in Fig. 15.

On the ordinate, the drying velocity is plotted. It is measured by the evaporated water amount, referred to the drying surface, during a given period.

$$g = \frac{\text{evaporated water amount}}{\text{surface of material to be dried} \times \text{unit of time}} \quad \text{in kg/m}^2 \cdot \text{h}$$

On the abscissa, the time is plotted which is needed for the various drying phases.

There are three different drying velocity ranges which are indicated by three breaks of the curve:

Range I: The water evaporates at constant velocity on the entire pellet surface. This procedure continues as long as humidity from the pellet interior is emitted at a sufficient speed by capillary forces or diffusion to the ball surface. The constant drying velocity is influenced by the following factors:

- Temperature and moisture content (dew point) of the drying gas,
- Volume and speed of the drying gas which flow, per unit of time, over the ball surface,
- Surface of ball.

This range I is thus characterized by the *evaporation of surface water*.

Range II: If the moisture from the interior of the pellet is emitted to the surface more slowly than water evaporates there, the evaporation level

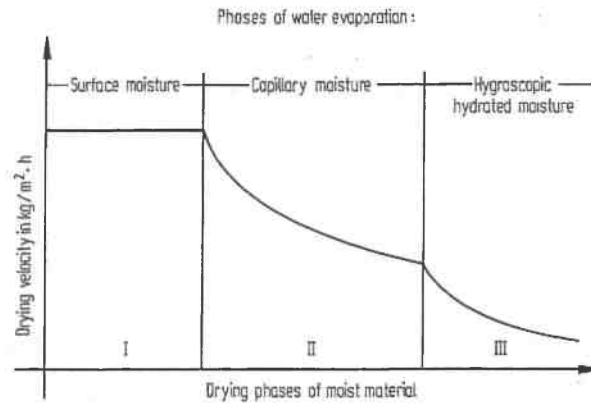


Fig. 15. Drying stages of moist material

(drying level) moves further towards the pellet core. The water evaporates inside the pellet, the diffusion distance to be covered by water vapour becomes longer and the drying velocity diminishes. It is now determined by the :

- Diffusion resistance
- Depth of drying level below the ball surface
- Diffusion index expressed in m/h.

Range II is characterized by the *evaporation of capillary water* from the pellet interior. After this stage, the pellets are normally dry.

Range III: If the pellet contains moisture other than surface and capillary water, the drying procedure continues under other conditions,

In this case, the temperature of drying gas is important for the dissociation of the water compounds. Besides the longer diffusion distance, this dissociation has to be considered and consequently the drying velocity decreases even more. It is virtually determined by the operations proceeding in the pellet core and by the ambience of the pellet.

In Range III, the *evaporation of the hygroscopic or chemically combined water* mainly takes place.

The term “moisture” is not uniformly defined in literature. One version refers to the water amount of the dry substance. In practice, the wet substance is frequently used as reference value on which the data given below are also based. Moisture is thus defined according to the following formula:

$$y = \frac{\text{water content}}{\text{wet substance}} = \frac{G_F - G_{Tr}}{G_F}$$

G_F = weight of wet substance

G_{Tr} = weight of dry substance

The drying procedure determined with one individual pellet on a thermoscale is shown in Fig. 16. The ore, a hematite with 67.5% Fe, 1.2% Al_2O_3 and 0.7% SiO_2 , as well as 1.2% loss on ignition, was pelletized with 0.8% Wyoming bentonite and 8.2% water and slowly dried in a laboratory-scale drying oven at a temperature of 400 °C under air flow.

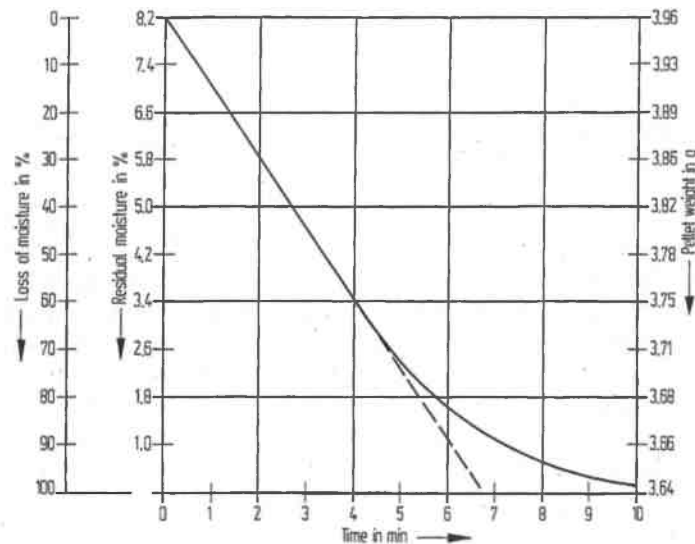


Fig. 16. Drying of an individual green pellet

The left ordinate shows the remaining water content of the pellet as well as the moisture decrease in percent while the right ordinate indicates the loss of weight. Up to a moisture loss of about 67% during a drying period of 4.5 mins. — plotted on the abscissa — the drying curve proceeds linearly. The drying velocity up to this moisture content is constant. About $\frac{2}{3}$ of the water evaporates from the pellet surface. From now on, the drying proceeds more slowly and asymptotically until the residual moisture content of the pellet core has evaporated.

By volume and temperature of the drying gas the heat supply for water evaporation *has to be adapted* to the relevant heat consumption in such a way that during the capillary movement of water and diffusion of water vapour, the relative position of the individual ore grains to each other *is not changed*.

If the heat supply and thus the formation of water vapour proceed too quickly, cracking or even decrepitation may occur (shock temperature).

The *material-dependent* properties of the ore, the grain size, size distribution, dense or loose packing of grains play such an important role that it is advisable to find out the drying conditions by tests with the ore to be pelletized. Although the drying procedure of the individual pellet can still be surveyed the drying conditions of green balls in layers are more complicated.

In industrial plants, green pellets are always thermally treated in layers of a different depth, either in shaft furnaces, on travelling grates or in grate-kiln plants.

The behaviour of green balls in layers of different thickness is thus of interest for all three processes.

In view of the great number of factors affecting the drying technology, it is difficult to describe precisely each of these factors. On the other hand, it is possible to ascertain qualitative dependencies. For this purpose, experiments furnish, for the present, more reliable results than mathematical calculations do.

2.2.1.2 Drying of Pellets in a Layer

Therefore, it is worthwhile to look into this matter more closely. The equipment and measurements required for the drying are described under items 4.5–4.5.2.3.

During drying, the drying gases may be sucked through the pellet layer in a downward direction. This process is called *down-draught drying*. However, the gas flow may also be forced in an upward direction through the pellet bed. In this case, an *up-draught drying* is involved.

A combination of the above methods is also possible and is, in practice, adopted.

When the drying air flows through the first pellet layer, it absorbs a certain moisture volume from the pellets up to their saturation (dew point). During this operation, the drying air cools from its inlet temperature down to its evaporation temperature.

This water-vapour saturated air consecutively impinges onto wet and cold pellet layers. On this occasion, part of the water absorbed by the first pellet layer is condensed out and this condensation heat is transferred to the second pellet layer which is thus also heated to evaporation temperature.

The energy required for the evaporation of the water from pellets of the directly adjacent layers is supplied from the incoming hot drying gases. In this case the gas again cools down to evaporation temperature as long as water is to be evaporated.

However, in the course of this interplay between heat and material exchange, an over-wetting may occur so that a weakening of the pellet structure and hence a decrease of pellet strength may temporarily take

place. During down-draught drying, the lower pellet layers can be weakened and compressed in such a way that the pellet bed may become impermeable to gas. During up-draught drying, the drying air flows through the pellet bed in an upward direction. On this occasion, water droplets may condense on the surface of the pellet bed.

Although the drying should be carefully carried out in one single direction to save energy, a combined up-draught and down-draught drying is frequently applied. In this way, it is possible to render the lower layers more resistant to pressure.

Some tests²⁸⁾ are described below in which uni-directional drying as well as the up-draught and down-draught drying with change in direction were qualitatively tested. The pellet diameter was between 10 and 12 mm and the moisture content of green balls 6.50% H_2O .

2.2.1.2.1 Unidirectional Drying. To avoid a weakening of the pellet structure, the drying gas temperature is kept below the shock temperature at the beginning of the drying process. The temperature gradient of drying is shown in Fig. 17 by way of example of up-draught drying. For this purpose, a pot grate as represented in Fig. 39 was used. The charge consisted of 10 cm hearth layer and 30 cm pellet bed. The drying was achieved with hot air of 240–330 °C. The temperature gradient was measured with 7 thermocouples.

First, part of the heat amount is consumed for the heating of grate and hearth layer. The first curve shows the temperature gradient after a drying time of 1 1/4 minutes (curve I); about 25% of the layer has been dried. After 5 minutes about 3/4 of the pellets are dry (curve II). The pellet top layer still shows an evaporation temperature of approx. 42 °C although the bottom

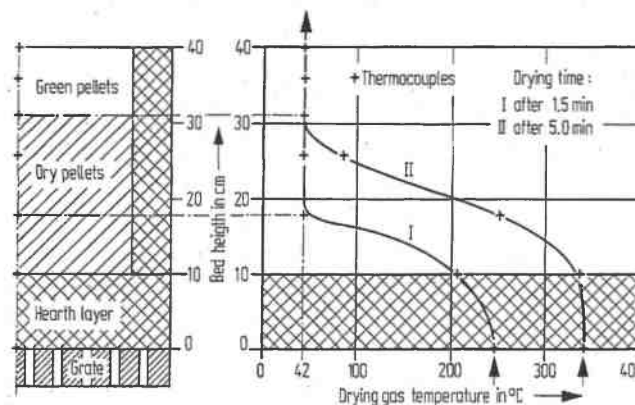


Fig. 17. Updraught drying of a green pellet layer

layer has already a temperature of around 310 °C. With a further supply of drying air, the moisture level moves upwards.

In the case of the shaft furnace, the drying zone is kept at a specific furnace level because the dried pellets moving downwards, are replaced from above by wet pellets.

2.2.1.2.2 Up-Draught – Down-Draught Drying. After 5 minutes the up-draught drying was terminated in this demonstration test and replaced by down-draught drying. The recorded temperature gradient is shown in Fig. 18. Curve I indicates the end of up-draught, curves II and III represent the down-draught procedure after $\frac{1}{2}$ and 3 minutes, corresponding to a total drying of 8 minutes. This period was selected for a particular project for which a longer total drying time on the pellet indurating machine was not available.

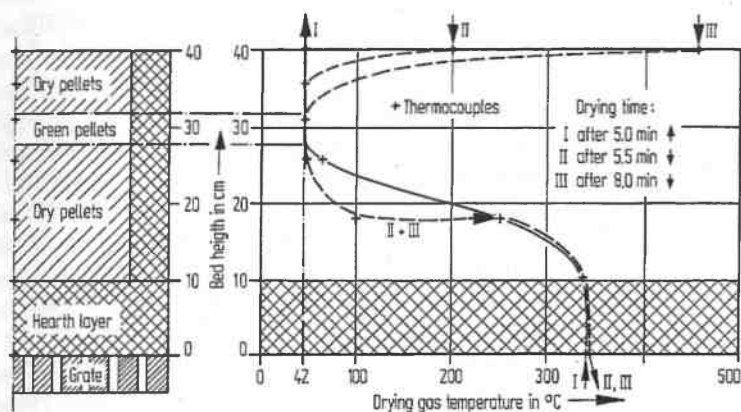


Fig. 18. Up- and down-draught drying of a green pellet layer

As can be seen from this diagram, about 15% of the pellet bed in the middle of the layer had not yet been dried after 8 minutes although the drying air had already reached a temperature of 450 °C. Part of the lower layers was temporarily slightly cooler (curves II and III).

2.2.1.3 Dry Pellet Strength

Like green pellets, dry pellets have a short life which often is only a matter of minutes. However, during this time, a minimum dry pellet strength is necessary to ensure that the pellets withstand, for example, the movement of the charge during its migration through the shaft furnace, without damage. In other burning systems, for example in the case of a travelling grate, a minimum dry pellet strength is also needed so that the

pellets withstand the load of the layers located above or the pressure of gases flowing through the charge.

* The mechanical strength of green pellets is chiefly dependent on the superficial tension and capillary tensile forces of the wetting agent whereas other bonding mechanisms are of great importance for the dry pellets.

Even if, according to Rumpf²³), no bridges exist between the individual solid particles, adhesion and tensile forces may become active. Molecular adhesion forces are always effective when the distance between the individual grains is sufficiently short. Van de Waals' forces are also to be considered as possible bonding forces. Electrostatic forces may, in principle, be acting if particles with a positive and negative load participate – though it be to a very small extent – in the granulate formation.

These physical factors, being independent of the specific materials, become active but their natural bonding force is insufficient for many ores (e.g. high-grade magnetite or hematite concentrates) to attain the strength of green pellets. In the case of such ores, binders have to be added. A few other ores already contain components, similar to binders, which enable a sufficient pellet dry strength to be obtained.

Table 4 shows the green and dry strength of pellets produced from different ores, see items 3.1.4 and 5.3. The dry strength of pellets 1–3 (concentrates) is insufficient while that of ore 4 is satisfactory. The dry strength of pellets 1–3 can be improved by the addition of bentonite. In practical operation, a dry pellet strength of about 10 Newton is required. These values can be obtained either directly or by the addition of binders. The gel-containing constituents in the ore or in the added binders – seemingly soluble in water or reacting with water – concentrate in the ever shrinking liquid bridges during drying. These processes can be compared with the solidification of drying loam or clay. The dehydration of the gels is accompanied by a shrinkage whereby the adhesion forces are increased.

Table 4. Compressive strength of green and dry pellets from various ore types

No.	Types of ore	Compressive Strength in N/Pellet					
		without binder		with 0.5% bentonite		with 1.0% bentonite	
		wet	dry	wet	dry	wet	dry
1	Magnetite Concentrate	11	7	12	20	13	33
2	Artif Magnetite Concentrate	11	4	10	23	–	–
3	Spec. Hematite	12	4	10	20	11	35
4	Earthy Hematite	14	30	16	70	–	–

Rumpf²³⁾ even designates this phenomenon as “mortar bridges”. Crystallizing “salt bridges”²⁴⁾ can also contribute to the dry pellet strength. Even if, nowadays, for metallurgical or ecological reasons, the direct addition of salts has been abandoned, the formation of such bridges may, nevertheless, occur when ores are pelletized with sea water.

2.2.1.4 Shock Resistance

Apart from many influences which are connected with the nature of each individual ore, the *initial temperature* of the drying gases is of decisive importance for the dry pellet strength. The heat supply has to be so controlled that the arising water vapour and the air inclusions still existing in the pores can escape or expand from the pellet cores through the capillaries without any ensuing over-pressure. An overpressure would weaken the pellet structure and, thus, its strength by the formation of cracks or by splintering of fragments³⁰⁾. The admissible drying gas temperature, at which the pellet structure is not yet damaged, is called “shock temperature”, something which was already found out very early, e.g. by Tigerschiold⁷⁾. The shock temperature can be raised by the addition of binders, see item 5.4.1.1.2, Fig. 72.

Since a sufficiently high dry strength can be obtained with all types of ores by using suitable binders, it is still important to adjust or, better, to determine the drying velocity in tests in such a way that the formation of cracks is avoided and the conglomerates, formed during green pellet production, are not damaged.

Green ball formation and pellet drying are essential preparatory steps leading to the production of pellets, ready for reduction. However, the decisive step is the thermal treatment by controlled heating of a pellet bed.

2.2.2 Pellet Firing

The last processing step before utilizable pellets are obtained, is the thermal induration of dried pellets. The induration imparts such characteristics to the pellets, as are imperative both for their transportation and metallurgical treatment, provided the preceding steps were made under optimum conditions.

During the first years, when production was carried out on a smaller scale and the portion of pellets in the blast furnace burden was low, few features were sufficient for the determination of the pellet quality. With rising pellet quantities, it was possible and necessary to study more precisely the influence of the pellets on the blast furnace operation. As a result, the quality specifications have become more rigorous. In addition, special conditions had to be considered for the use of pellets in the direct

reduction processes. Not only the sound transportability but primarily the behaviour of pellets during the different reduction stages was given particular attention. To meet the more severe requirements, various process parameters are to be taken into account, such as:

- (a) Influence of metallurgically-effective additives
- (b) Harmonization of heating velocity and firing period
- (c) Observation of close temperature ranges and precise control of the firing temperature
- (d) Elaboration of heating programmes especially adapted to specific ores or ore mixtures.

In connection with these factors, the question arises regarding the type and importance of efficient bonding mechanisms which have to differ from those for the green and dry pellet strength. In numerous tests carried out primarily with pellets from industrial plants, it was found that two thermal bonding types are decisive for the quality of indurated pellets:

(a) Change of the *crystalline structure* during firing either by crystal transformation and growth upon oxidation of magnetite to hematite or by crystal growth when hematite is used only.

(b) The reaction of *slag-forming constituents* which are either present as gangue in ores or concentrates or added before the ball formation, such as bentonite, quartz or basic additives. Basic components react with acid components and — under certain conditions — also with iron oxides.

Since the ores or concentrates to be pelletized always have a certain gangue content and since additives are used to an increasing extent, both bonding mechanisms simultaneously occur under normal operating conditions. Additives are used because it is intended thereby to improve the pellet quality. The importance and effect of the additives are in close relation with the ore to be treated, see items 3.1.4 and 5.3.

The thermal treatment by heat supply with hot combustion gases proceeds in two stages. The first stage, the *preheating stage*, directly follows the temperatures of the drying zone. According to the ore type involved, the temperature is raised from 300–350 °C to 1250–1340 °C by a continuous and controlled heat supply.

In the second, the final *induration stage*, the pellet charge is heated to an optimum temperature for each ore type, and this temperature is maintained for a controlled period. The said temperature is to be below the melting temperature but within the reactivity range of gangue components and additives. In general, the induration is achieved under a defined, oxidizing atmosphere.

During preheating, various reactions proceed in parallel and successively according to the component composition.

- Evaporation of crystal water
- Decomposition of hydrates, carbonates, sulphates

- Roasting of sulphur from sulphide components
- Conversion of iron oxides from siderite, limonite, pyrite as well as mainly magnetite into the highest oxidation stage, the hematite.

The preheating velocity depends, inter alia, on the composition and quantity of the combinations to be decomposed and also on the oxidation velocity required for magnetite.

The bonding types decisive for obtaining the desired pellet characteristics finally arise in the induration zone.

2.2.2.1 Bonding by Change of the Crystalline Structure

As a rule, the ores or concentrates to be pelletized contain a certain percentage of gangue or additives which – even at minimum portions – react with each other by the formation of intergranular melting phases. As transport medium, these phases may play an important part for the growth of iron oxide crystals. However, the behaviour of pure iron oxide phases should be considered first.

The conglomerates, arising during the formation of green pellets and their drying, are stabilized by thermal treatment and are further consolidated. The consolidation is achieved by energy supply during preheating and induration. The solids react with each other in conformity with natural laws. The reaction proceeds below the melting temperature while new solid phases are formed. Such reactions of fine crystalline and pulverous materials develop in dependence on the energy supplied during the temperature rise in various stages:

- First, an activation occurs in the crystal lattice which can be recognized in the interfaces. A re-arrangement of the molecules takes place. The particles draw closer together with strength beginning to increase.
- During the further temperature rise, the mobility of the ions in the lattice increases. A lattice diffusion occurs which leads to re-arrangements, vacancies are occupied and inclusions are eliminated.
- The dislocations intensify and involve adjacent crystals in the diffusion.
- Crystal bridges are formed between the individual ore grains. These bridges lead to a consolidation of the conglomerate.
- A re-arrangement of the crystal lattice and a re-crystallization occur. The bridge formation changes to a bridge bonding. The re-crystallization intensifies the latter.
- A further energy supply causes the rounding of the grains. The pores between the ore grains become smaller.

The latest phase would be melting which, however, has to be avoided because, in this case, individual pellets would no longer exist.

This reaction development is well-known from solid-state chemistry and physics. It depends on many factors, with the genesis of the ores being of a

certain importance. Due to their small crystal size, fine crystalline ores of sedimentary origin are more reactive than coarse crystalline ores which require higher temperatures or more time for crystal growth.

The incentive of the crystal growth and consolidation reaction in a solid state consists of the free energy of a system. On account of the tendency to a thermo-dynamic equilibrium, the very fine particles with the greatest interface energy lie on greater particles while the energy potential diminishes. At a sufficient reaction time and adequate temperature as well as at a further decrease of the interface energy, these particles would draw near to a spherical shape.

The consolidation of the conglomerates is exclusively caused by recrystallization and crystal growth. The oxidation of magnetite during heating is a special case insofar as the oxidation energy is additionally available and from a crystallographic viewpoint, a crystal transformation from the cubic magnetite to the hexagonal hematite lattice takes place first. These newly formed very fine hematite crystals now start to grow intensively according to the further temperature rise.

2.2.2.1.1 Crystal Change During the Induration of Pellets from Magnetite Concentrate. The structure of a green ball is determined by its shape, size and location of magnetite grains to each other, in a similar way to that

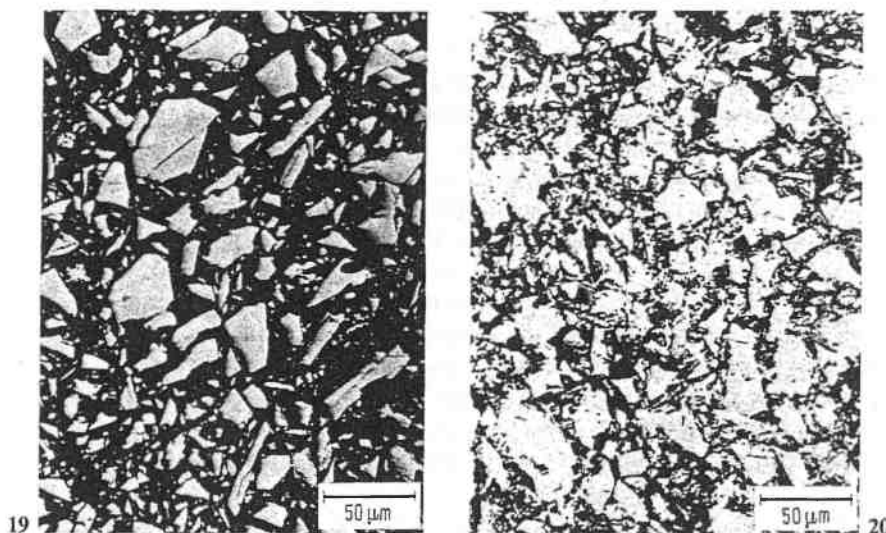


Fig. 19. Grain structure of green pellets from magnetite concentrate. 1 cm = 0.025 mm

Fig. 20. End of oxidation, crystal growth and first bridging. Temperature 1150 °C, 1 cm = 0.025 mm

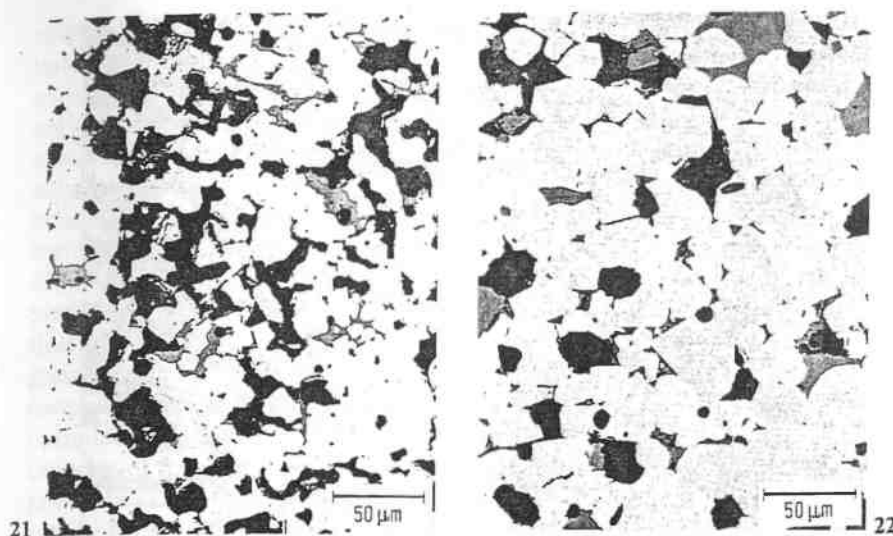


Fig. 21. Intensified bridging, crystal growth. Temperature 1250 °C, 1 cm = 0.025 mm

Fig. 22. Crystal growth after further temperature rise to 1320 °C, 1 cm = 0.025 mm

shown in Fig. 19³¹). The concentrate indicated in this plate contains about 71% iron and less than 1% gangue.

During heating under oxidizing atmosphere, the magnetite oxidizes into hematite at a simultaneous conversion of the cubic magnetite into the hexagonal hematite lattice. According to the genesis of magnetite, the oxidation starts at about 300–600 °C and is to be terminated at a temperature of 1100 °C. It begins on the crystal and grain surfaces, as represented in Fig. 20. The first very small crystals simultaneously form first bridges between the grains. At a temperature of 1150 °C, the oxidation is finished and all the magnetite should be converted into hematite. At the grain edges, numerous small new crystals have formed, which simultaneously intensify the formation of bridges between the individual grains.

Already at a temperature of 1250 °C (Fig. 21), the bridges have intensified and the re-crystallization has brought about a growth and the rounding-off of crystals. The optimum strength has been reached. Further heating would result in further crystal growth and rounding off at temperatures of about 1320 °C, Fig. 22, but dissociation of hematite would start.

2.2.2.1.2 Crystal Change During Induration of Hematite Pellets. Hematite ores and concentrates are being used to an ever increasing extent for pellet production. Hematite is present, according to its genesis, in the form of

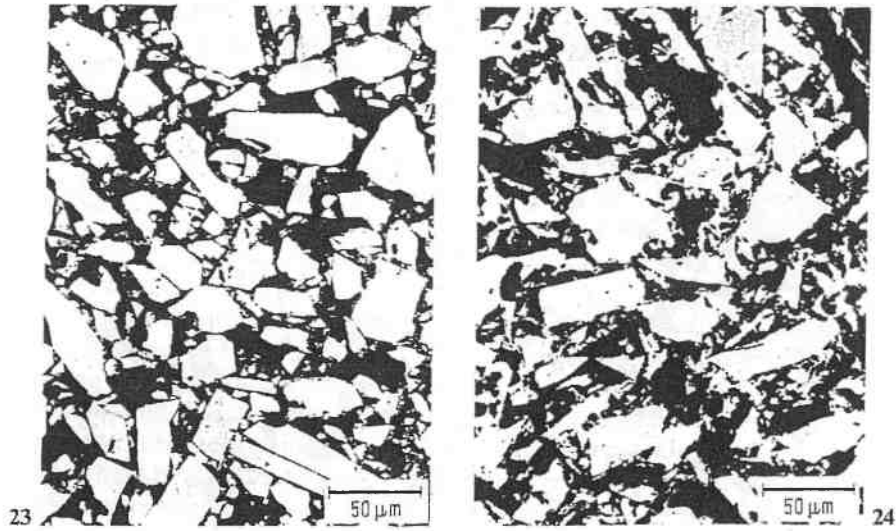


Fig. 23. Crystal structure in a hematite pellet at 1200 °C, 1 cm = 0.025 mm

Fig. 24. First bridging via fine-grained hematite crystals at 1300 °C, 1 cm = 0.025 mm

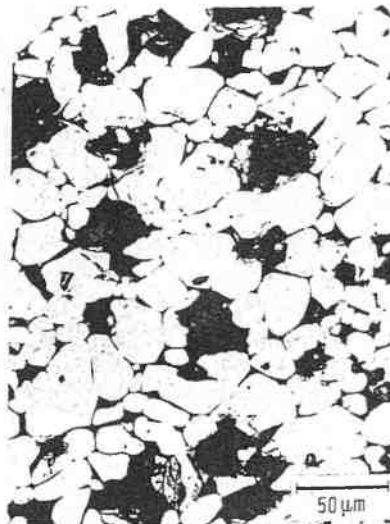


Fig. 25. Crystal bridges and strong recrystallization at 1350 °C, 1 cm = 0.025 mm

many crystalline variants as set forth under item 3.1.1.1. During the induration the strength increase is only achieved – in contrast to magnetite pellets – through crystal growth and recrystallization. This growth can only be measured at temperatures of above 1200 °C. Up to this temperature, the individual ore grains and the pellet structure maintain their original shape as shown in Fig. 23. The various grains lie side by side without any bond. Only at higher temperatures of 1300 °C the small ore particles form the first crystal bridges, Fig. 24, and recrystallization can be observed at 1350 °C as is apparent from Fig. 25. Fig. 24 also shows how important the presence of sufficiently fine-grained ore particles is for crystal growth and thus for creating pellet strength. There is a direct relationship between grain size and crushing strength of pellets³²⁾. To ensure that a sufficient formation of bridges occurs in the hematite, a longer induration time at an optimum induration temperature is necessary. This is reflecting the capacity of industrial pellet induration plants. For example, in travelling grate plants, 28–30 t of pellets can be produced from magnetite per m² suction area and day, but only 22–25 t of pellets from hematite.

The theoretically possible acceleration of crystal growth by higher induration temperatures cannot be realised³³⁾. At temperatures above 1350 °C hematite starts to dissociate into magnetite and oxygen, resulting in a weakening of pellet strength.

2.2.2.2 The Reaction of Slag-Forming Components

Usually, high-grade iron ores and concentrates are used for pelletizing only. Therefore, the gangue portion, mostly consisting of acid components, is correspondingly low. In spite of a great variety of ore types the pellets have to be of uniform mechanical and metallurgical condition. It was investigated early which methods should be adopted to equalize any different ore properties. A very efficient method proved to be the addition of certain substances such as basic earthy compounds, silicates, quartz, bentonite and others. Inorganic additives, or such which do not volatilize during induration, participate in the reactions. They can react either with the gangue constituents or with the iron oxides. When they react with the gangue, they can form part of the intergranular melting phase which, besides the crystalline phase, contributes to pellet solidification although this phase is qualitatively insignificant compared to the crystalline phase. This can be seen from the phase triangle, Fig. 26, which is composed of the principal basic constituents such as CaO/MgO, the acid constituents SiO₂/Al₂O₃ and hematite (Fe₂O₃). The analyses of some well-known pellet types are plotted on the phase diagram. The dominating role of the iron oxide phase is apparent. Although the intergranular phase is qualitatively insignificant, it plays an important part

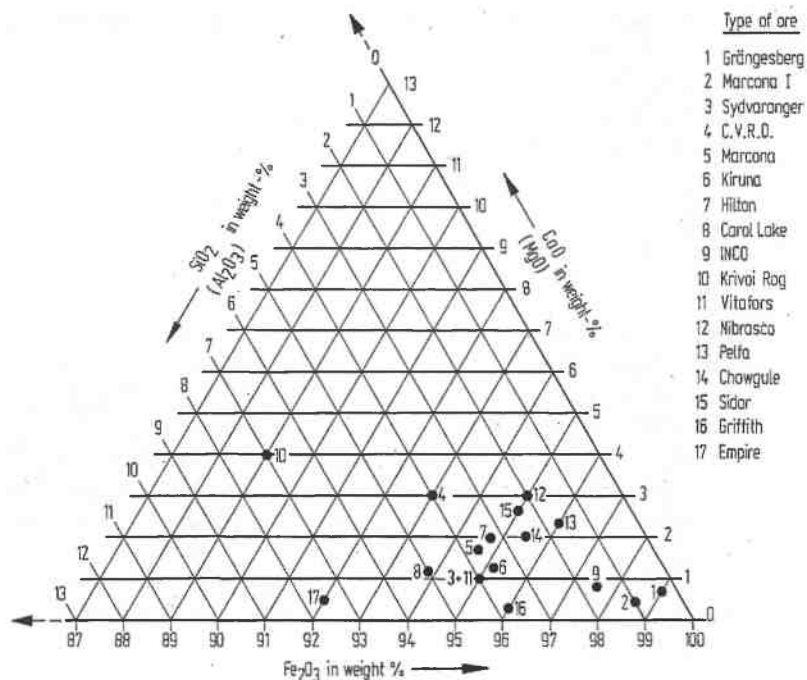


Fig. 26. Iron oxide corner in phase triangle Fe_2O_3 – CaO – SiO_2 composition of various pellet types

for the crystal growth primarily of hematite. For example, CaO reacts with Fe_2O_3 at a simultaneous formation of different calcium ferrites which substantially accelerate the crystal growth particularly at temperatures of above 1250°C . This is due to the fact that these ferrites melting at lower temperatures speed up the diffusion of individual crystal ions in such a way that the crystal growth proceeds more rapidly than in crystal structures free from any melting phase. Even low CaO additions are sufficient to produce this effect, as is shown in Fig. 27³⁴). After the addition of one or two percent CaO , a concentrate with 99.1% magnetite is pelletized and indurated at different temperatures. An addition of as low as 1% CaO is sufficient to make the hematite crystals grow more intensively than the sample free of lime from temperatures of 1300°C onward. SiO_2 in the form of quartz does not react with hematite during induration. SiO_2 in the form of reactive silicates, which are partially or completely converted to glassy or crystalline compounds can be combined with ore grains to form silicate bridges.

As mentioned at the beginning of this section, certain additives are of great importance for pellet production. Nowadays, in many pelletizing

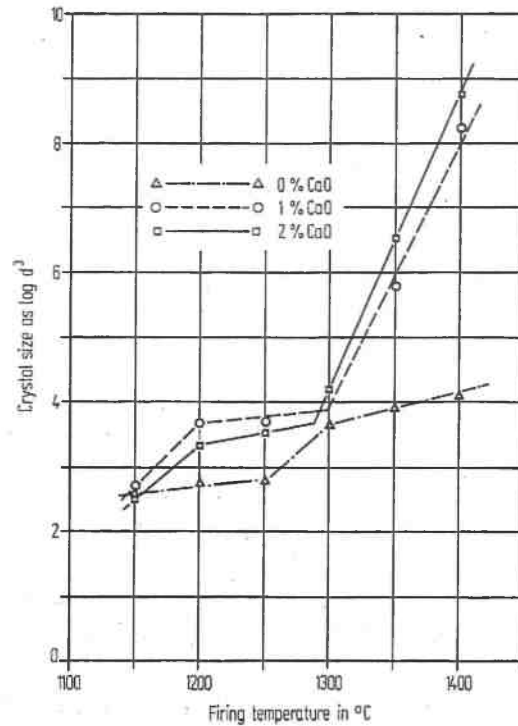


Fig. 27. Influence of CaO and firing temperature on crystal formation of hematite

plants, additives are increasingly used which serve not only for the original purpose to improve the pellet strength, but go beyond that. In a similar way, as in the production of self-fluxing sinter, the additives are selected in such a way that the acid gangue components are neutralized to improve to a large extent the slag formation in succeeding melting units or reduction furnaces. The type and quantity of these additives depend on the analysis of ores to be treated (see item 5.3).

2.2.3 Cooling of Indurated Pellets

There are two reasons why the pellet cooling is an important step in the final pellet production.

On the one hand, the hot pellets have a certain heat content which, with a view to a favourable heat balance, should be recycled, if possible with small losses, to the heating process. In all pellet firing systems presently applied on an industrial scale, corresponding technological and constructional measures are taken.

However, it is also important that the crystalline and glassy compounds arising during induration are not damaged by a too rapid cooling. Relevant tests have demonstrated¹⁸⁾ that pellets, which were carefully cooled by air to 300 °C, will not be damaged if their further cooling is achieved in water. However, during cooling pellets having a temperature of 600 °C, almost at 50% crumbled into smaller fragments. Other tests yielded similar results. In these tests, it was found that the crushing strength of pellets having been quenched in water at a temperature of about 700 °C diminished to less than half of their initial crushing strength. Careful pellet cooling for maintaining pellet strength in conjunction with extensive heat recovery are demands which must be considered for the dimensioning of the cooling units.

If, finally, the various processing steps from the raw ore to the finished pellets are reviewed, it is found, that several bonding mechanisms are responsible for the formation of sound pellets.

- *Liquid bridges* between the individual grains of the conglomerate to be pelletized are responsible for the strength of the *green balls* during their formation.
- *Solid bridges* in the form of “mortar bonds” arising through gels, hydrates and inter-facial forces are responsible for the strength of *dry pellets*.
- The final strength of *indurated pellets* is again due to *solid bridges* arising by crystal change, crystal growth and sintering of the inter-granular melting phases.

3 Raw Materials and Their Preparation for Pellet Production

3.1 Raw Materials

According to their intended use for pelletizing and their chemical composition, there are two different groups of raw materials. One of them consists of the iron-bearing minerals and represents the pellet matrix. The other one comprises mostly raw materials low in or free from iron, which are exclusively used for:

- facilitating the pellet production (binders)
- improving the physical-mechanical quality (binders and additives)
- modifying the metallurgical properties of pellets (additives).

3.1.1 Iron-Bearing Materials

The by far greatest quantity of iron-bearing materials consists of natural ores either in the form of high-grade ores or concentrates originating from the beneficiation of low-grade ores. When high-grade ores are used, the iron content of the pellets is mostly higher than 65%. The concentrates generally contain more than 64% iron. Occasionally, small quantities of high-grade secondary materials such as calcines from pyrite roasting plants are used. Some of these secondary materials may contain other impurities either in the form of detrimental constituents to be separated such as phosphorus, non-ferrous metals or utilizable components, e.g. vanadium or copper. For the separation of such impurities, special process variants are to be applied which are described in Chap. 7.

3.1.1.1 Natural Iron Ores

Natural high-grade iron ores and concentrates complying with the demands made on the chemical composition of pellets are forming the basis of the pellet feed. Natural ores with low iron contents which cannot be upgraded, such as iron silicates, are insignificant for pellet production. The iron ores which are nowadays industrially utilized originate primarily

from highly metamorphic, initially sedimentary deposits with the pre-cambrian era dominating as geological formation. A high portion of ores from these deposits originates from weathering zones in which the iron content was enriched. According to the climatic zone in which the weathering took place, alumina minerals such as bauxite materials or lateritic weathered products predominate as gangue constituents of the iron ores in tropic zones. In cooler zones, silicate minerals or quartz are dominating. In the original parts of these deposits, the quartz-banded iron ores occur as itabirite, locally designated also as taconite or jaspilite, predominantly in the form of magnetite ore. Other deposits in the perimagmatic area, mostly pneumatolitic ore replacement deposits, often contain the ore in two different forms: as carbonate and magnetite, and also in the form of pyrite as accessory mineral.

The great quantities of geologically younger sedimentary deposits consisting of cretaceous and dogger formations are of great importance for many geographically limited areas but not as ore supplies to pelletizing plants. The principal iron minerals used for pellet production are described below:

3.1.1.1.1 Magnetite. Magnetite is the main iron-bearing mineral in unweathered and non-oxidized metamorphic sedimentary deposits or in replacement ore deposits in the magmatic area. The iron contents of these ores range from 20 to 50% for itabirites and up to 65% in the magmatic deposits.

Its chemical composition is Fe_3O_4 , frequently also designated as $\text{FeO} \cdot \text{Fe}_2\text{O}_3$ with a theoretical iron content of 72.4%. A replacement of the bivalent iron by manganese or calcium ions, of the trivalent iron by aluminium ions can be observed in ore replacement deposits. In deposits with a high formation temperature, TiO_2 contents are found which are mostly present in the form of segregated ilmenite lamellae within the magnetite crystals. Vanadium-pentoxide incorporated into magnetite lattices, occurs in mineralized gabbro massifs mostly together with titanium. Other undesirable accompanying minerals are apatite (Northern Sweden) or metal sulphides (Peru, Marcona). Magnetite, being of the spinel type, crystallizes as double oxide with the iron occurring in bivalent form as FeO and in trivalent form as Fe_2O_3 . The predominant crystal shape is the octahedron or the rhombic dodecahedron.

In general, magnetite ores are beneficiated to achieve a chemical composition suitable for smelting. As the best-known process, magnetic separation is applied and sometimes, in addition, flotation is also used. During pellet induration, the magnetite oxidizes to hematite. During this reaction about 498 kJ per kg magnetite are liberated which, as additional energy, positively influence the induration process.

3.1.1.1.2 Hematite. Hematite is the iron ore which occurs most frequently and in the greatest quantities. According to its genesis, it is available in coarse to medium crystalline structure designated as iron glance or specular iron ore, in fine crystalline structure or in earthy condition as earthy hematite. Its chemical composition is Fe_2O_3 with a theoretical iron content of 70.0%. Hematite is also the final oxidation stage of indurated pellets. From a crystallographical viewpoint, it pertains to the corundum group and predominantly crystallizes in the hexagonal system with a great number of shapes in different combinations up to micaceous scales. Due to weathering of magnetite to hematite, the cubic crystalline shape is often maintained. This type of hematite is known as martite.

The primary itabirites mostly contain 30–45% iron with quartz and silicates as gangue. More important are the weathering zones of itabirite deposits in which the iron is enriched to contents of 50 up to almost 70%. The iron content is mainly present as specular iron ore or earthy hematite, in lower percentages also as magnetite or martite and – dependent on the weathering degree – as iron hydroxide (“limonite”, FeOOH). The major part of the iron ores used at present originates from tropical and subtropical zones and represents lateritic weathering products. The caps of such lateritic ore deposits generally consist of a hard ore layer of up to 20 m depth with high iron and alumina contents. Soft to brittle fine iron ores (mostly iron glance) with iron contents diminishing with increasing depth are situated underneath. The hematite ores and their concentrates seldom contain metallurgically detrimental constituents except for the unfavourable ratio of alumina to silica in some ores.

3.1.1.1.3 Weathered Ores. These ores deserve some additional lines since, quantitatively, they are of very great importance as feed materials for pelletizing plants. The best-known deposits are at present situated in Canada, West Africa, Brazil, Venezuela, India and Western Australia. In all cases, the original materials consist of itabirite deposits of the Precambrian Era with magnetite and iron glance as basic minerals. By weathering, gangue minerals, quartz and silicates are decomposed and removed to a greater extent due to their higher solubility whereby the iron content in the residual ore is increased. The gangue content is locally decreased to less than 1% e.g. in some parts of Minas Gerais/Brazil.

The iron minerals are also subjected to atmospheric influences and are thus partly converted to a high degree. A typical feature of the weathering deposits is their *heterogeneous* composition and their considerable variations at shortest distances. The ratio of the individual iron minerals to each other such as specular iron ore, earthy hematite, limonite and magnetite changes within wide limits. Pelletizing plants for such ores can only be operated with great difficulties unless they are preceded by homogenizing

systems. The very close intergrowth of alumina minerals and limonite is typical for the weathered lateritic ores.

3.1.1.1.4 Limonite. Limonite can be considered as a typical example of weathered ore. This somewhat inexact collective term covers the iron hydroxide minerals. Mineralogically, they occur in the modifications "needle-iron-ore" and "pyrrhosiderite" whose structural formula is FeOOH . Other mineralogical designations are "goethite" or "lepidocrocite". The intermediate grades with undefined hydration degree are also specified as "hydrohematite". Iron hydroxide is the basic mineral of nearly all sedimentary as well as metamorphic deposits. Economically important limonite deposits originate from weathering zones of the itabirite and siderite deposits as well as from deposits with oolitic and fragmental iron ores (Mesozoic Era). In the former itabirite deposits limonite deposits occur together with specular iron ore and earthy hematite. During the pellet induration process, limonite is converted into trivalent iron oxide, Fe_2O_3 . This process is endothermic and therefore increases additionally the heat consumption. After drying and preheating, limonite leaves a very fluffy porous structure which calls for a rather long induration time at high temperatures. Primary limonite ores sometimes contain phosphorus at a percentage necessitating special steelmaking processes such as Thomas and LDAC processes because separation of the phosphorous minerals by mining methods is very difficult or only possible to a limited extent (Minette) due to their dissemination with the iron minerals.

At present limonite is an important ore constituent in several pelletizing plants, e.g. Robe River, Western Australia, Sidor, Venezuela.

From all ores used for pelletizing, hematite is the final oxidation stage after induration, as shown in Table 5. Table 6 gives some data of ores nowadays utilized without previous beneficiation.

Table 5. Conversion of iron compounds into hematite during induration

Types of compounds	Formula	% Iron content	
		before Induration	after Induration
Hematite	Fe_2O_3	70	70
Martite			
Magnetite	Fe_3O_4	72.4	70
Goethite/Limonite	$\text{FeO}(\text{OH})$	62.9	70
(Hydro-Hematite)	$(\text{Fe}_2\text{O}_3 \cdot \text{H}_2\text{O})$		
Siderite	FeCO_3	48.3	70*
Pyrite	FeS_2	46.6	70*

* After intermediate roasting

Table 6. Type, chemical analysis and specific surface area of rich iron ores directly used in pellet plants

Plants	Types of ores Spec surface area cm ² /g	Fe tot.	Fe ⁺⁺	SiO ₂	Al ₂ O ₃	CaO	MgO	L.O.I.
		in % about						
CVRD Brazil	Hematite 1600 – 1800	66	–	2.7	1.0	0.2	0.2	1.0
Samarco/ Brazil	Hematite 1500 – 1700	66.5/ 67.5	–	2.5/ 3.6	0.4/ 0.7	0.1	0.2	
Hamersley/ West-Austr.	Hematite/ Limonite 1200 – 2700	63.4 68.7	0.7	4.5/ 1.2	2.6/ 1.0	0.4	0.1	3.5 – 1.0
Robe River West- Australia	Limonite	57.5		n. d.	3.0			9.5
Chowgule/ Goa India	Hematite/ Limonite	63/64	–	1.5	1.5		4.0	
Sidor/ Venezuela	Hematite/ Limonite 3400	62.9	–	1.6	1.2			6.0

3.1.2 Beneficiation Products

Ores having a metallurgically unsuitable composition undergo beneficiation processes before pelletizing in which the undesirable constituents are largely separated. The concentrates to be pelletized are often sufficiently fine-grained for green ball formation as in the case of magnetite.

Apart from the gangue, the contents of deleterious substances such as phosphorus, arsenic, titanium, chromium, chlorides, fluorides and non-ferrous metals, which are partly detrimental during smelting and partly affect adversely the quality of finished products, should be decreased by beneficiation. Mineralogically, the beneficiation products mostly conform – as far as the iron minerals are concerned – to the raw ores. Particular reference should be made to the artificial magnetite arising from limonite or hematite-containing ores by roasting under reducing conditions and which is separated as magnetite by low-intensity magnetic separation and occasionally by flotation. Owing to its high porosity and crystalline structure, its reactivity to oxygen is very high. The beginning of its oxidation is markedly lower than that of natural magnetite.

The iron content of concentrates, irrespective of the process according to which they are obtained, is at least 64%, with few exceptions.

3.1.3 Secondary Raw Materials

In some cases, apart from iron ores and their concentrates, materials are pelletized alone or mixed with ores originating from other thermal or chemical processes. Such materials cover pyrite cinders, leaching residues and inplant fines. The cinders are produced during the roasting of iron sulphides, such as pyrite (FeS_2) or pyrrhotite (FeS). Their use is limited due to the often existing non-ferrous metal (Cu, Pb, Zn), or arsenic impurities. However, in some countries, there are exceptions. Pelletizing plants for these ore types are under construction or in operation in Japan, in the United States, Canada, Italy and Rumania.

During the roasting of iron sulphides (oxidation of sulphur to gaseous SO_2), the iron is oxidized to either Fe_2O_3 or Fe_3O_4 according to the adjusted roasting atmosphere. In these cases, highly porous oxides are involved. Residual sulphur contents of 0.5–2% are usual. Residues from the leaching of copper or nickel-bearing sulphides such as chalcopyrite or pentlandite, which are roasted before leaching, are also used as ores, for example artificial magnetite concentrates from the Inco plant at Copper Cliff, Ontario, Canada.

In pelletizing plants located in iron and steel works, nowadays attempts are made to add in-plant fines to the ore mix to be pelletized. In this case, materials are involved which are either obtained as waste materials with a high iron content or are tolerated as basic materials. These materials consist of BOF dust, mill scale, blast furnace dust and slag and BOF slag. Examples of analyses are given in Table 7. The dusts have a high fineness degree at a great specific surface area whereas slag and mill scale have to be ground before pelletizing. The presence of mill scale calls for special attention. The oil adhering may adversely affect the pelletizing process and is to be carefully considered during the dedusting of the pelletizing plant waste gases.

Table 7. Chemical composition of inplant fines²⁾

	Fe total	SiO_2	Al_2O_3	CaO	MgO	MnO	S
	in % about						
Blast furnace dust	34.8	10.2	2.7	1.1	1.2	1.2	0.4
Blast furnace slag	0.3	34.6	14.8	41.8	4.3	0.9	1.5
BOF dust	64.1	1.8	0.2	5.2	0.6	1.5	0.1
BOF slag	12.0	20.5	6.4	42.5	3.5	4.2	0.6
Mill scale	64.0	3.0	1.9	3.2	0.3	1.3	0.1
Pellet undersize	64.8	4.3	0.8	0.6	0.9	0.1	0.02

3.1.4 Binders and Additives

3.1.4.1 Binders

Binders, in conjunction with the finely-ground ore particles, serve to improve the properties of pellets in wet, dried or indurated condition. The most important binding reagents, namely water and iron ore particles are not considered here since they will be discussed in chapter 5. During the development of the pelletizing process, a great number of organic and inorganic substances were tested with regard to their suitability as binders. However, nowadays only bentonite, slaked lime, limestone and dolomite are used. Binders which are deleterious or which give off pollutants to the waste gas of pellet plants are no longer taken into consideration. Although some binders are simultaneously used as additives, bentonite serves as a binder only.

3.1.4.2 Additives

Additives are provided for modifying the chemical composition of pellets, especially their slag-forming constituents. Some of them have binding properties too:

- (a) Lime and lime-magnesium compounds,
- (b) Recycling materials,
- (c) Ores with a particularly high bonding ability,
- (d) Siliciferous substances such as quartz, quartzite or rocks with a high quartz content.

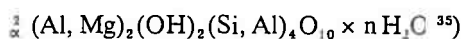
Siliceous material is sometimes utilized if the gangue content of the ore to be pelletized is too low for obtaining an intergranular phase. Thus, in some beneficiation plants the separation is, due to the elimination of metal sulphides (Marcona) or phosphorous minerals (Northern Sweden), accomplished to such a degree that, subsequently, the insufficient gangue content in the concentrate has to be increased by addition of ground silica.

Besides binders and additives, ground pellet return fines (fines from the screening of indurated pellets) or ground sponge iron can be added to the material to be pelletized. Return fines show an inert behaviour whereas sponge iron improves the quality and raises the productivity (see items 5.3.1.6–8).

3.1.4.3 Bentonite

In this case, a clayey rock is involved originating as a result of weathering from glassy, magmatic masses and occurring in cretaceous and tertiary layers. The principal mineral component is montmorillonite. Besides this main mineral, small quantities of quartz, mica, feldspar and

kaoline are present. As concerns montmorillonite, the following structural formula is given:



It has a lattice structure arranged in layers which is capable of absorbing great water quantities between the individual layers; this is represented by $n\text{H}_2\text{O}$ in the formula. On such occasions the distances between the lattice layers increase considerably. The mineral swells. This swelling property and the high thixotropic behaviour are the most important characteristics for its bonding capacity. The tetrahedral crystalline structure of silica can incorporate calcium and magnesium cations in an exchangeable manner with the Ca ions frequently being replaced by Na ions. These ions are responsible for water bonding in the intermediate area between lattice layers. There are two large groups, the calcium bentonites, predominantly occurring in the Mediterranean area, and the more active sodium bentonites in the United States. One of the bentonites with the highest swelling capacity is the Wyoming bentonite. It is possible also to introduce sodium ions into the calcium bentonite and such a bentonite is then designated as activated bentonite. The swelling capacity is characterized by the *Enslin value*. It is a typical coefficient for the swelling behaviour of the montmorillonite group with intercrystalline swelling property. The water absorption of a predetermined bentonite quantity is ascertained at intervals of 30 minutes up to 24 hours altogether.

The *Enslin value* is calculated according to the formula:

$$E_w = \frac{V \times 100}{P}$$

E_w = Enslin value in %

V = absorbed water quantity in cm^3

P = bentonite quantity in g.

The *bentonite index* indicating the swelling capacity and the *emptying index* characterizing the viscosity of bentonite suspensions are used as further data. There is a certain proportionality between these three indices.

The chemical composition of some bentonites is shown in Table 8³⁵⁾.

Without taking the interstitial water into account, the typical components are as follows³¹⁾:

SiO_2 66.7%, Al_2O_3 28.3%, H_2O 5%.

Bentonite beneficiation mostly consists of crushing or extrusion followed by drying from an average natural moisture content of 30% (25–50%) to 7–8%. To maintain the bentonite activity, the drying temperature should

Table 8. Specifications of various Bentonite types

Chemical analysis	A Ca.-B.	B Ca.-B.	C act. B.	D act. B.	E act. B.	F Na.-B.	H Na.-B.	I act. B.
Fe ges.	14.02	0.67	1.42	4.47	1.14	2.70	2.55	4.20
SiO ₂	42.70	56.80	72.76	56.56	72.08	60.50	60.64	56.90
Al ₂ O ₃	17.40	3.37	11.72	19.10	13.96	21.18	21.70	19.52
CaO	1.79	1.34	1.51	1.79	1.00	1.48	1.12	1.06
MgO	2.74	26.37	3.06	3.39	2.12	2.24	2.58	3.26
Na ₂ O	0.04	0.25	2.14	2.31	3.00	2.25	2.56	3.20
K ₂ O	0.11	0.44	0.70	1.70	0.58	0.62	0.44	0.99
L.O.I.	11.83	9.88	5.38	7.84	4.88	6.10	5.80	7.48
Spec. surface area cm ² /g	6502	4340	8480	7056	7350	2900	3380	4610
Permea- bility methods								
Enslin values in %	200	280	480	610	620	800	900	900

act. = activated

not exceed 150 °C. Subsequently or during drying, the bentonite is ground to at least 90%–0.044 mm corresponding to a specific surface area of up to 8000 cm²/g. The transportation is achieved in closed containers such as tank cars or bags.

3.1.4.4 Lime Compounds

Limestone, CaCO₃, and hydroxide, Ca(OH)₂, are preferably used. In nature, limestone is sometimes contaminated by quartz or silicates such as clay. Limestone is sedimentary stratified rock or of compact coralline nature. The lime mineral consists mostly of calcite and more seldom of aragonite. Both differ by their crystal form. Their chemical composition is CaCO₃. They are beneficiated by crushing, classification, washing and grinding, if necessary. Excessively contaminated limestone and especially limestone with a high clay content (marl) is not used for pelletizing.

Before limestone is added to the ore to be pelletized, it is ground to a fineness corresponding to a specific surface area of about 2500–4000 cm²/g. The dry grinding method is usually adopted. In most cases, roller mills or comparable mill types are used. Limestone is mainly employed for modifying the pellet gangue basicity.

As a binder, calcium hydrate $\text{Ca}(\text{OH})_2$ is preferred, which is produced from CaO by slaking with water. Calcium oxide is obtained by calcination of limestone, CaCO_3 , at a temperature of above 900°C in several reactor types such as shaft furnaces, rotary kilns or fluid bed reactors. The selection of the reactor type depends on the size and tendency to degradation of CaCO_3 during heat treatment.

The oxide is continuously converted to hydroxide at a slightly over-stoichiometrical water amount in quenching units similar to mixing screws and is then ground in order to pulverize any remaining coarse-grained constituents. As in the case of bentonite, transport is carried out in closed containers.

Lime hydrate is both binder and basic additive. *Dolomite* or dolomite-containing limestone is occasionally used as further basic additive. Dolomite is a mixed crystal isomorphous to calcite. Its formula is $(\text{Ca}, \text{Mg})\text{CO}_3$ and it is prepared like limestone.

During pellet induration, the basic additives react first with the “acid” gangue constituents whereby a neutral or basic matrix between the iron oxide grains is formed.

3.1.4.5 Other Additives

If, apart from pellet induration, other reactions are to be carried out, corresponding reagents can be used. *Calcium chloride* (CaCl_2) is employed for the volatilization of non-ferrous metals such as copper, lead and zinc of the pellet mix. Sodium carbonate or sodium sulphate is added if vanadium is to be dissolved as sodium vanadate from vanadium-containing ores, see Chap. 7.

3.2 Preparation of Raw Materials for Pelletizing

Many of the natural ores, secondary raw materials, additives or binders are naturally not suitable for direct processing into pellets. In these cases, a preparation adapted to the raw materials involved is required. This refers to the

- increase of iron content in the low-grade raw ore,
- separation of undesirable constituents,
- grinding to the fineness required for pelletizing.

The methods adopted for this purpose are described in the following items as far as they are of importance in conjunction with pellet production. In this connection, it is also recommended that the facilities required for the performance of adequate tests (see item 4.2) should be provided in the pelletizing laboratory.

3.2.1 Separation

Separation methods cover all beneficiation processes which are necessary for obtaining a suitable chemical-mineralogical composition of the materials to be pelletized. Depending on the properties of the ores, several methods are available for this purpose:

3.2.1.1 Washing

Washing is mainly used to decrease the portion of clayey constituents in high-grade lateritic ores. Ores can be subjected to the washing process as screened natural fine ores or after additional grinding. By washing, the clayey constituents of the weathered ores are slurried with water and the dissolved particles are separated. In this case very fine-grained alumina compounds as well as some iron minerals, preponderantly limonite, go into the tailings. For this reason, the concentrate always has a higher ratio of magnetite or specularite to limonite than the raw ore. From a physical viewpoint, this washing process is a classification process (separation according to grain size). Due to the higher specific gravity of the ore minerals compared with that of the gangue, an additional up-grading effect occurs. The equipment used for washing consists of washing troughs or washing drums, spiral classifiers, hydro-cyclones and tumble mills. The iron concentration is not very high. But the iron losses are considerable in the very fine tailing particles. Fig. 33, item 4.2.1 shows a beneficiation flow-sheet for an earthy, limonite containing ore.

3.2.1.2 Gravity Separation

The gravity methods are based on differences in specific gravity between gangue ($2.8-3 \text{ g/cm}^3$) and iron minerals ($4.5-5.1 \text{ g/cm}^3$). These methods are adopted for fine-grained ores with specular hematite or magnetite as iron-bearing material and quartz-silicate gangue. Before separation, the ores are ground to such a degree that the iron-containing constituents are mechanically liberated from the gangue. The optimum size range is between 1.5 and 0.1 mm. In the finer size range, the iron recovery drops considerably. The most important unit which is often used on an industrial scale is the spiral separator, known as *Humphrey's Spiral*, which has an acceptable throughput.

Other apparatus, having in principle the same or even a better separation efficiency such as shaking tables are hardly used due to their great space requirements and insufficient throughput. In future, the cone separator according to Reichert, which within a short time has gained a dominating position for preconcentrating heavy mineral sands, may partly supplant the spiral separator. Humphrey's spirals are used for example in

the Carol Lake and Wabush Lake plants producing concentrates with an iron content of above 63%.

3.2.1.3 Flotation

This process which has proved to be suitable for the concentration of many sulphide ores has also gained a certain importance for oxidized iron ores within the last 30 years. The separation is achieved on the basis of the different physical-chemical surface properties of the individual mineral constituents, particularly on the basis of their wettability by water. The ore surface properties are influenced by several reagents which, owing to their polar – nonpolar structure, are surface-active. Other reagents are employed to provide favourable conditions in the circulating liquid phase. Such reagents are designated as modifiers. The water-repellent particles and those difficult to wet accumulate on the air bubbles produced in the ore pulp. They are discharged by foam formed by these and separated from the pulp surface. In many cases, a reagent favouring the foam formation is necessary. The wettable grains of the gangue remain in the pulp.

When this separating method is adopted, it is understood that the mineral particles separated by flotation must not exceed a definite upper grain size diameter which is of the order of 0.1 mm and dependent on the specific weight. The optimum size range seems to be 0.01–0.06 mm. Initially, the flotation method was adopted in two plants in North America for the direct concentration of itabirite specular iron ore in which concentrates with about 65% iron were produced from raw ore with about 50% iron. In one of the two plants, the flotation was temporarily carried out at about 45 °C when concentrates with an iron content of 68–69% were required. In this way, a more intensive influence of the reagents and a more efficient separation were achieved due to a lower viscosity of the liquid phase.

In the meantime, the flotation method is adopted to a much greater extent for the separation of residual gangue from concentrates and of metal sulphides or phosphorous minerals from concentrates already produced otherwise. In the case of this “inverse flotation”, the iron-bearing minerals are thus hydrophilized or “depressed” and the remaining gangue particles are hydrophobized and float in the foam. The concentrates produced by inverse or indirect flotation contain 63–67% iron. The iron losses in the tailings are mostly below 10%.

3.2.1.4 Magnetic Separation

According to the magnetic properties of the iron-bearing minerals, two different magnetic separator types are used (see item 4.3.1). The *low-intensity magnetic separator* is employed for highly magnetic ores such as

magnetite. According to the necessary liberation grain size, the separation is carried out in dry manner (above 2 mm grain size) or in wet manner when a finer grinding is required. Drum separators with permanent magnets are utilized as separators. The size of recently developed units is 3000 mm width and 1200 mm diameter at a capacity of 250 m³/h feed pulp containing 20–50 weight % solids.

The Alnico magnets formerly used are at present being supplanted to a high degree by ferrite magnets. The magnetic induction (field intensity) measured on the drum surface or at a distance of 50 mm is 0.04–0.2 tesla.

In many cases, magnetite ores are so finely ground for liberation that the concentrates produced already have the grain size required for pelletizing. The low-intensity wet magnetic separation allows a high iron concentration to 65–72% at a recovery of 95–97% referred to the highly magnetic ore portion. In some cases, it is possible to upgrade martite ores with a high residual magnetite content by using drums of a stronger field intensity.

Dry high-intensity magnetic separators with a field intensity of up to 2.4 tesla are sometimes used for weakly magnetic ores, primarily for those with a mean size range of 0.05–2 mm. Under favourable conditions, a concentration to 65–66% iron is possible. An important development of the past twenty years is the high-intensity *wet magnetic separator*. It permits the upgrading of relatively finely ground specular iron ores in units having a capacity of 100–150 t/h. As regards the fineness of the ores to be treated, its application range is partly identical with that of flotation. In some cases the flotation concentrate processing problems can thus be obviated when this separator type is used. Up to now, this separator type is being largely employed for the beneficiation of Brazilian low-grade itabirite weathered ores.

3.2.1.5 Magnetizing Roasting

Even at a very early stage, attempts were made to beneficiate hematite-bearing ores by converting the hematite first to magnetite by reduction and by separating the magnetite from the gangue in magnetic separators. Shaft furnaces, rotary kilns and fluid-bed roasters can be used for reduction. According to the density and porosity of the ore to be treated, the ore is charged at a grain size of up to 20 mm. Gaseous, liquid and solid fuels are usable as heating and reduction energy. Solid fuels can be employed when they are sufficiently reactive, e.g. lignite. Due to the relatively high fuel costs, this process is preferably used when cheap energy is available or in conjunction with other processes.

Up to the fifties, a plant for the treatment of dogger ores with a throughput of 10 000 tpd³⁷⁾ was in operation in the Salzgitter district in Germany. Large-sized plants are presently operating in the Soviet Union and Australia. In a plant for the processing of nickel-containing ores,

operated in Canada, artificial magnetite is obtained as is also the case in a plant for the roasting of pyrite cinders in Italy.

Large-sized pilot plants were operated by Oliver Mining and Hanna Mining Co. in the Mesabi range for several years.

However, owing to excessive costs, no industrial plants were erected in this area.

According to this process, very high-grade concentrates with an iron content of up to 70% could be produced. On account of its high reactivity, the artificial magnetite already oxidizes at very low temperatures of around 300 °C. The fact that it reacts very quickly must be considered during heating and oxidation of green pellets from artificial magnetite.

3.2.1.6 Electrostatic Separation

In the magnetic field, mineral mixtures may show a different behaviour according to their magnetizability so that the separation of magnetic and non-magnetic solids is based on this property. Similar tendencies can also be observed in an electrically-loaded field when electrically conductive and non-conductive mineral mixtures are introduced. By charging the mineral surfaces and subsequently discharging the conductive particles, migration of the conductors in one direction and of the non-conductors in the opposite direction can be achieved in an electric field. Conductors and non-conductors can thus be separated from each other. This principle is also applicable to iron-containing minerals of different conductivity or to a mixture of the same with other iron-free minerals.

This process is particularly suitable for secondary cleaning of magnetic concentrates which are contaminated by iron-containing minerals, such as hornblende, garnet and mica or for secondary cleaning of gravimetrically produced concentrates. A typical example is the Wabush Lake beneficiation plant. In this plant, spiral concentrates are subjected to secondary electrostatic cleaning after previous drying. Also in the case of magnetic concentrates, as for example in a plant built in Northern Sweden, a secondary electrostatic cleaning is carried out. Table 9 shows the results of the principal beneficiation processes, analyses of raw ores and their concentrates.

According to this table, several suitable processes are available in which a high iron content of the beneficiation products is obtained.

A second important task of pellet preparation is to ensure a suitable size distribution of the raw materials for ball formation.

3.2.1.7 Proportion of Different Ores in Pellet Production

Up to about 1962, magnetite had almost exclusively been processed into pellets and this primarily in the Mesabi Range. Only from that date on

Table 9. Chemical composition of pellets and concentrates produced from crude ores according to various beneficiation methods

Methods of Benefication Types of Ores Plant/Location	Stage of Beneficiation	Analysis *		SiO ₂	Al ₂ O ₃	CaO	MgO	L.O.I.
		Fe total	bivalent					
<i>Washing</i>	Crude	62.7	1.8	2.4	2.7	n.d.	n.d.	4.0
Hematite/Limonite	Concentr.	64.2	1.9	1.8	2.0	n.d.	n.d.	3.7
(Goa India)	Pellet	66.0	0.3	1.9	2.2	0.5	n.d.	—
<i>Gravimetry</i>	Crude	38.0	n.d.	40.5	n.d.	n.d.	n.d.	n.d.
Hematite	Spiral Concentr.	64.93	n.d.	5.62	0.21	0.20	0.18	0.34
(Lac Jeanine Canada)	Pellet	65.05		5.64	0.30	0.20	0.17	0.11
<i>Flotation and flocculation</i>	Crude	36.0	n.d.	45.0	n.d.	n.d.	n.d.	
Hematite (Tilden Mine USA)	Concentr.	66.0		5.0				
	Pellet	65.0		5.7	0.7	n.d.	n.d.	
<i>Magnetic separation</i>	Crude	42.1	12.5	14.7	4.4	2.8	2.3	
(Low-intensity)	Concentr.	69.4	22.1	1.1	0.5	0.5	0.1	
Magnetite	Pellet	66.8	0.5	1.0	0.5	0.5	0.0	
<i>Magnetizing roasting</i>	Crude	36.4	1.0	45.9	n.d.	n.d.	n.d.	0.26
<i>Low-intensity separation</i>	Concentr.	66.9	20.2	5.6	0.8	n.d.	n.d.	
Jaspilite (Whyalla Australia)	Pellet	65.0	1.0	5.4	0.7	0.35		
<i>Wet magnetic separation</i>	Crude	56.4	0.2	15.4	1.3	n.d.	n.d.	1.8
<i>High-intensity</i>	Concentr.	68.3	0.2	0.6	0.7	n.d.	n.d.	1.2
Hematite (CVRD Brasil)	Pellet	Used in mixture with other ores						
<i>Gravimetry</i>	Crude	36.0	n.d.	41.4	n.d.	n.d.	n.d.	n.d.
and	Concentr. I	61.4	n.d.	5.8	n.d.	n.d.	n.d.	n.d.
<i>Electrostatic separation</i> Magnetite/	Concentr. II	66.3	n.d.	2.8	n.d.	n.d.	n.d.	n.d.
Hematite (Wabush Mine Canada)	Pellet	65.4	n.d.	2.97	0.27	0.1	0.1	

* Analysis of pellets incl. additives or binders

were other ores increasingly used for pellet production, such as hematite concentrates (Marquette Range, USA), magnetite-hematite mixtures (USA and Canada) or hematite containing high-grade ores (Brazil, Australia). Limonite-containing hematite was successfully pelletized on an industrial scale even at a later date, from about 1966. (Goa, Robe River, Western Australia.)

Table 10. Proportion of main ore types used in pellet plants in 1978

Ore types	10 ⁶ tons/year	%
Magnetite	156.0	53.4
Hematite	62.0	21.1
Magnetite/Hematite	47.0	16.0
Hematite/Limonite	28.0	9.5
	293.0	100.0

Ore mixtures were treated as late as about 1968–70. For this purpose, the technological conditions had first to be elaborated. Table 10 gives a survey of the ore supply for pellet plants throughout the world. It also contains already the figures for the plants whose start-up is scheduled for 1978. Furthermore, this table represents the percentages of the various ore types being used for pellet production up to this date.

✓ 3.2.2 Physical Properties of Fine-Grained Iron Ores

The physical properties of fine-grained iron ores are the most influencing factors for green ball formation, see items 2.1, 4.3.1, and 5.1.1. Some of them are variable, others not. By controlling and influencing the variable factors the pellet quality can be improved.

Such variable factors are the following:

- grain size and size distribution
- grain shape
- surface condition (e.g. peak – to – valley height, specific surface area)
- porosity
- pore types.

✕ 3.2.2.1 Size Distribution – Specific Surface Area

There is no definite information available on the ideal physical properties for green ball formation. In practical operation, a suitable size distribution is *empirically* ascertained. Subsequently, one attempts to make this size distribution reproducible by a precise description. With certain

limitations this leads to the desired success. An immense difficulty is that the ore to be pelletized undergoes fluctuations due to its raw material-dependent properties. In many cases, homogenizing processes are at present applied to equalize the ore properties to maximum extent.

A further problem is caused by the difficulty in performing an accurate measurement of size distribution. This is comprehensible because the major part of the grains of a pelletizable ground product is below the usual size range of test screens. To avoid an excessive amount of work and time, only the coarse grain size portion down to 0.037 or 0.045 mm is determined by dry or wet screening, and the portion below this size range which may cover 65–95% by weight is ascertained by adopting another method.

A rather suitable criterion for this purpose is the determination of the specific surface area (see item 4.3.2.). However, in this case also, the measurement problems have to be taken into account. The usual methods are those in which the permeability of a sample prepared according to exact specifications is measured. By comparison with standard samples, the size of the specific surface area of the sample is inferred and this size is indicated in cm^2/cm^3 or cm^2/g or more seldom in m^2/kg . A comparison of different measuring methods, particularly when the gas adsorption processes (e.g. B. E. T.) are included, shows considerable differences between the measured values which may be up to multiple values of other methods. However, in practical operation, it has proved that simple permeability measurements, which can be quickly carried out, can be standardized to such an extent that their reproducibility is sufficient for process control. According to experience the specific surface area almost exclusively depends on the proportion of particles, primarily of those around 0.001 mm.

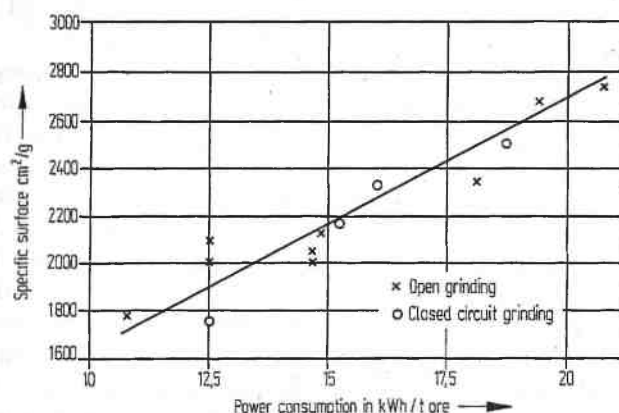


Fig. 28. Grinding energy consumption versus specific surface

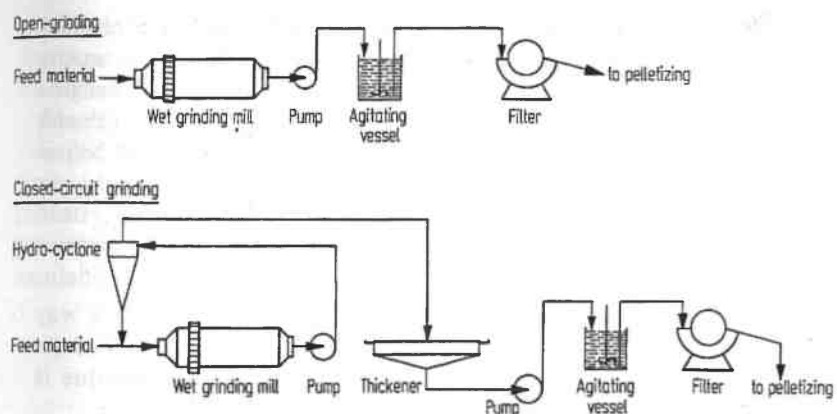
Ore “grinding” should be carried out as “surface grinding” in contrast to “liberation grinding” used for upgrading. The values found out by measuring the specific surface are dependent on the type of iron minerals. The usual values for specular iron ores are 1600–1800 cm²/g and 1600–2300 cm²/g for magnetite concentrates. If limonite portions are included in these ores, a surface area of up to 4000 cm²/g may be found. Pyrite cinders are of a similar order of magnitude. However, the measured values for magnetite and specular iron ore are dependent on the surface shape. Magnetite tends to disintegrate into cubic particles during grinding while specular iron ore often yields flat, mica-like fragments. In the case of specular iron ore, the surface values measured according to the permeability method thus differ much more from the real surface than for magnetite. The size of the specific surface area highly influences the grinding energy consumption as can be seen from Fig. 28.

3.2.3 Grinding

Concentrates from disseminated magnetite ores are, in most cases, already obtained at a grain size suitable for pelletizing whereas in other cases this grain size has to be achieved by grinding. The grinding units used consist of tumble mills with a grinding media charge composed of steel balls, except for some cases in which grinding rods or ore fragments (“pebbles”) are used.

Normally, the ore is fed to the mills as a pulp with a solids content of 60–80% by weight (wet grinding). Nowadays the *dry grinding method* is adopted for about 15–20% of the capacity of plants under construction and in operation. This grinding process is applied if wet ground ore cannot be dewatered or not sufficiently by vacuum filtration. Particularly in those cases in which purchased ores predominate the dry grinding method is recommended to ensure a flexible ore supply.

The grinding can be achieved in an open circuit (single passage through the mill) or in a closed circuit. In the latter case, hydrocyclones (wet grinding) or air classifiers (dry grinding) are almost exclusively used for classification of mill discharge. The decision as to whether the closed-circuit or open-circuit grinding method is to be adopted is taken empirically on the basis of grinding and pelletizing tests. Figs. 29 and 30 diagrammatically illustrate the differences between the two systems. In most cases, the amount of energy required for grinding is, referring to the same ore type, the lowest for wet closed-circuit grinding and the highest for dry open-circuit grinding. The ratio of these values to each other differs from one ore type to the other. No definite rule can be given. As regards the capital costs, the wet open-circuit grinding is the cheapest while the dry closed – circuit grinding necessitates the greatest expense.



Figs. 29/30. Wet grinding in open and closed circuit

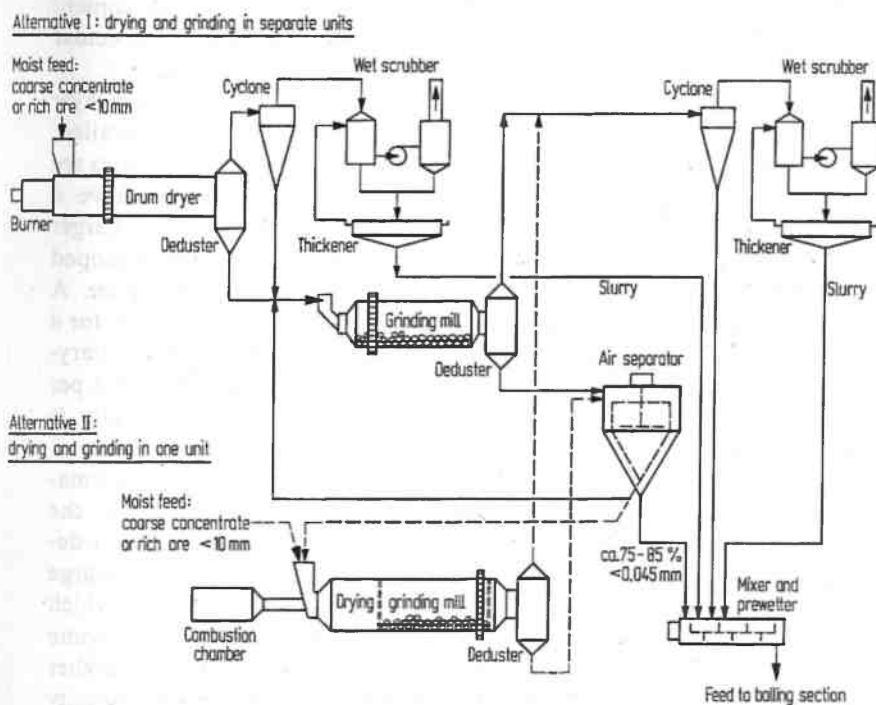


Fig. 31. Two alternatives for dry grinding

However, when considering the total grinding costs, including capital investment, the dry grinding method, Fig. 31, is more suitable for earthy hematite ores since, in this case, the wear costs are substantially lower due to the lower consumption of ball pebbles and mill lining than for wet grinding. In this way, the costs for ore drying, which is carried out before or during grinding, are more than compensated.

3.2.3.1 Dewatering

Wet ground ores must be dewatered before pelletizing in such a way that their moisture content is identical, with, or slightly below, that of the moisture required for green ball formation. The corresponding value is about 8.5–10% moisture, according to ore type and grinding fineness.

Ores which are wet ground in closed-circuit are first obtained as a pulp with about 15–20% solids by weight. In circular thickeners, the solids content is raised to about 60–65% by weight.

Rotary vacuum filters, predominantly disc-type filters are used for further dewatering to ensure a maximum capacity at a minimum space. Before the ore pulp is fed to the filter, it is adjusted to an empirically ascertained optimum density. This density corresponds to a solids content of about 50–55% by weight for magnetite and 55–65% for specular iron ore.

Filter discs made from metal, hard rubber, or plastic, have a fabric layer as filter medium. Up to now, monofil plastic fabrics have prevailed. Nowadays, relatively dense multifiles and partly felt-like plastic fabrics are increasingly preferred. The filters comprising up to 12 discs have a maximum suction area of 100 m² at a disc diameter of about 3 m. Larger filters with a maximum diameter of 5.3 m have meanwhile been developed and will possibly be used in commercial plants in the near future. A vacuum of about 85%, referred to atmospheric pressure, is necessary for a sufficient dewatering. This vacuum is produced in water-ring or rotary-piston-type-pumps. A capacity of about 140–200 m³/h air is required per m² filter area. In the case of iron ore, the vacuum filter capacity is 0.4–1.5 t/h per m² filter area.

Some ores cannot be sufficiently dewatered by filtration for ball formation due to their mineralogical composition. In some former plants, the filter cake is, therefore, subjected to *drying in drum dryers*. This has detrimental consequences for the pellet quality because the drum discharge consists almost completely of micro-pellets of about 0.5–3 mm from which perfect green balls can hardly be produced. For this reason, in some modern plants the filter cake formed on the filter disc is heated to a higher temperature by using steam instead of air. The decrease of water viscosity resulting therefrom is sufficient to improve satisfactorily the filtration. In

principle, the same effect could also be achieved by a corresponding temperature increase of the pulp but the relevant heat consumption would be higher.

Finally, the endeavours to improve filtration by filter aids should be referred to. Former attempts failed because the reagents known at that time adversely affected the green ball formation. Today the chemical industry seems to have reagents which do not show such undesirable secondary effects so that an alternative to steam filtration may soon be available.

4 The Pelletizing Laboratory and its Tasks

The fundamental demand for indurated pellets is their uniformly good quality irrespective of the raw material from which they were produced, of the purpose for which they are used and of the system according to which they are made. Due to different raw material properties it is necessary to ensure in tests the required pellet quality. This can be done in laboratories adequately equipped. Above all, in the design of new pelletizing plants it is imperative to convert the results of tests obtained in the laboratories into technological and constructional basic data.

Combined with sufficient experience available from industrial plants, one can establish reliable and convertible data in the laboratory.

4.1 Application Range of Laboratories

Laboratories in which the stages starting from the ore up to the testing of indurated pellets can be investigated are important for:

(a) *Pelletizing Plant Constructors.* For engineering companies building pelletizing plants, a well-equipped pelletizing research center is imperative. Careful test and research work is important for a reliable plant design and for the guarantees regarding quality, capacity and energy consumption.

(b) *Pellet Producers.* The greatest number of pelletizing plants is located near the ore deposit. However, it is seldom that an orebody is so homogeneous that the original design data remains valid forever.

When the orebody undergoes any changes (particularly hematite-limonite ores) other technological parameters are required for grinding, possible beneficiation and for the induration process. These parameters can be found out beforehand in laboratory tests so that necessary process variations can be quickly made at a constant quality without great production losses. Such investigations are also important if the pellet quality has to be changed from for example blast furnace to direct

reduction pellets for which other metallurgical properties are often demanded. Such laboratory tests are of particular importance for pelletizing plants in which mixed ores are treated.

(c) *Pellet Consumers.* Purchasers of pellets are primarily the blast furnace and the direct reduction plant operators. They often have laboratories in which mostly indurated pellets are tested.

(d) *Universities, Mining Schools as well as Independent and Public Research Institutions.* According to the tasks to be performed, such institutes often have only specialized equipment. The laboratories can be adapted and equipped according to and in conformity with the purpose of the tests required. The institutions referred to under a and b should have the complete scope of relevant facilities.

4.2 The Tasks of a Laboratory

From the processing of the ore up to the production of the finished indurated pellet, the following functions are in general to be fulfilled:

- Choice of suitable beneficiation processes for different ores
- Determination of the optimum grinding of all raw materials
- Choice and use of binders or metallurgically efficient additives
- Optimum green pellet composition
- Elaboration of suitable firing patterns for determination of the necessary pellet quality
- Dimensioning of the most important process units
- Data on the energy consumption to be expected.

Essential prerequisites to the determination of all the necessary data are:

- (a) the use of *representative* raw materials. According to the purpose of tests, some hundreds of kilograms to several tons of testing material may be required;
- (b) furthermore, such equipment, facilities and furnaces which allow a conversion of the results thus ascertained to industrial plants are to be used.

Fig. 32 shows a testing programme according to which various iron ores and additives can be processed up to the finished indurated pellet. According to the preparation stage of the ore, some process steps may be omitted. Above all, for the design and construction of a complete plant beginning with the raw ore and ending with the finished pellet, it is advisable to incorporate the beneficiation, particularly the fine grinding, into the laboratory cycle.

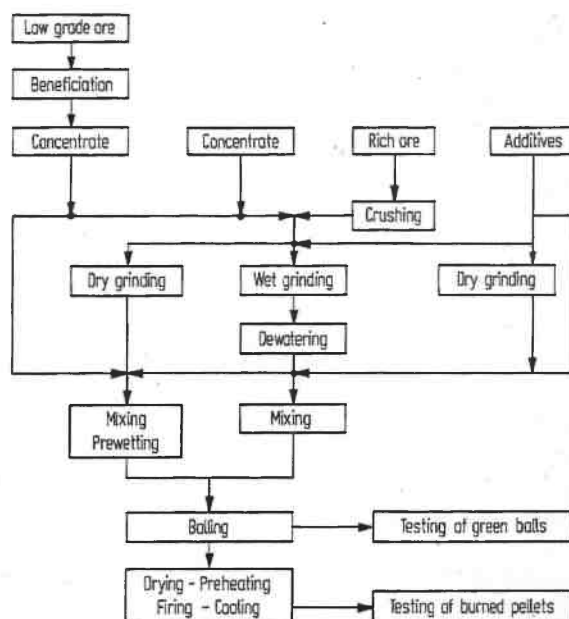


Fig. 32. Process flow sheet from ore to burned pellets

4.3 Raw Material Preparation and Pellet Production

4.3.1 Raw Material Preparation

Analogously to the comments given under item 3.2, an adequately equipped pelletizing laboratory should also include the most important facilities and equipment for the beneficiation of ores.

(a) *Washing of Ores.* Finely disseminated ores should be ground to minus 0.5 mm. In a preliminary test, a small quantity of ore is slurried in an agitating tank and its suspension behaviour is examined. After a certain settling time, the suspension is separated from the sedimented solids. After weighing and chemical analysis of the separated solids portion, a metal balance is to be established. In semi-industrial tests for the production of major concentrate amounts washing apparatus of types which are generally used in industrial plants, such as washing drums, spiral classifiers, wet screens and hydrocyclones are utilised. A flowsheet based on a test with an earthy, limonite-containing hematite from Goa is described in Fig. 33. In this case the iron concentration effect was of secondary interest while the decrease of the alumina content was more important.

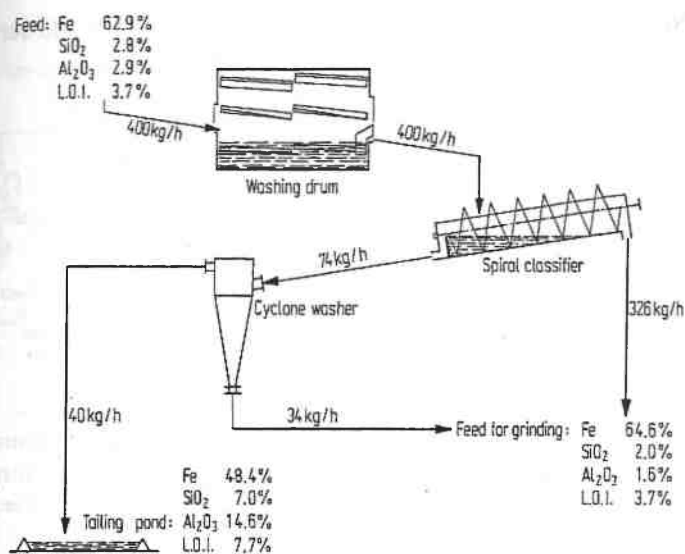


Fig. 33. Flow sheet and material balance in a pilot-scale washing plant for earthy hematite

(b) *Gravity Methods.* The characteristics of the ores are firstly ascertained with only minor quantities. By heavy-media separation in organic liquids of a higher density than water, the gangue is separated from the iron-bearing material. The density of the heavy media – generally around 2.8 g/cm³ for iron ores – is adjusted to optimum selectivity. These laboratory tests are to be confirmed by experiments on a semi-industrial scale. Suitable equipment for such tests is available on the market.

(c) *Flotation.* During flotation the ore surface is, in different ways, altered by using specific chemicals. The effect of individual chemicals is studied. Since, in contrast to many physical beneficiation processes, the time factor plays a certain role during flotation, the next testing phase is carried out in a continuously operating pilot plant. On this occasion, not only the time factor but also the influence of middlings in internal circuits on the process are investigated. Such tests on a larger scale are the prerequisites to the elaboration of a suitable flowsheet. With a view to a good filtrability of the concentrates and, if necessary, an efficient wettability of the grain surfaces during pellet production, the choice of reagents is of importance.

(d) *Magnetic Separation.* According to their behaviour in a magnetic field, the minerals can be divided into three classes, namely highly-, weakly-, and non-magnetic minerals. Some minerals important for pelletizing are

specified below³⁸⁾, with the behaviour of iron in a magnetic field serving as a criterion:

iron	= 100	highly magnetic
magnetite	= 40.2	
titanomagnetite	= 24.7	
pyrrhotite	= 6.7	weakly magnetic
siderite	= 1.8	
hematite	= 1.3	
limonite	= 0.8	
quartz	= 0.37	non magnetic
dolomite	= 0.22	
calcite	= 0.03	

In conformity with these properties, low-intensity magnetic separators are used for highly magnetic ores and high-intensity magnetic separators for weakly magnetic ores. For the determination of the liberation size, the ores are ground to different fineness.

The Davis tube, which already with a few grams of material gives representative results and guide values for further tests on a larger scale, is suitable for *highly magnetic* ores.

Such tests are carried out with equipment having a capacity of about 1–3 t/hour. Mostly drum separators are used. These separators are normally equipped with permanent magnetic systems whose field intensity, measured on the magnet surface, is about 0.2 Tesla.

A drum separator is used for dry separation while a liftout separator is employed for wet separation. Both types can be arranged in a mass flow circuit so that the data thus obtained is already valid for the design of industrial plants. Subsequently, representative pelletizing tests are run on the major concentrate quantities thus produced.

Fig. 34 shows, for example, the beneficiation flowsheet for a magnetite ore.

However, if weakly magnetic ores (hematites, limonites) are to be upgraded, substantially stronger magnetic fields of up to 2.5 Tesla are necessary. These separators are, therefore, called *high-intensity magnetic separators*. In this case, a test with small amounts of material can yield first data on the field intensity required. For the preparation of flowsheets, apparatus on a semi-industrial scale with a throughput of several hundred kilograms per hour are used. In the event of disseminated ores with an adequate grinding degree, wet separators are most suitable. Dry separators are employed for more coarsely intergrown ores.

(c) *Magnetizing Roasting*. Lean hematite bearing ores are reduced to magnetite under a weakly reducing atmosphere. This process calls for

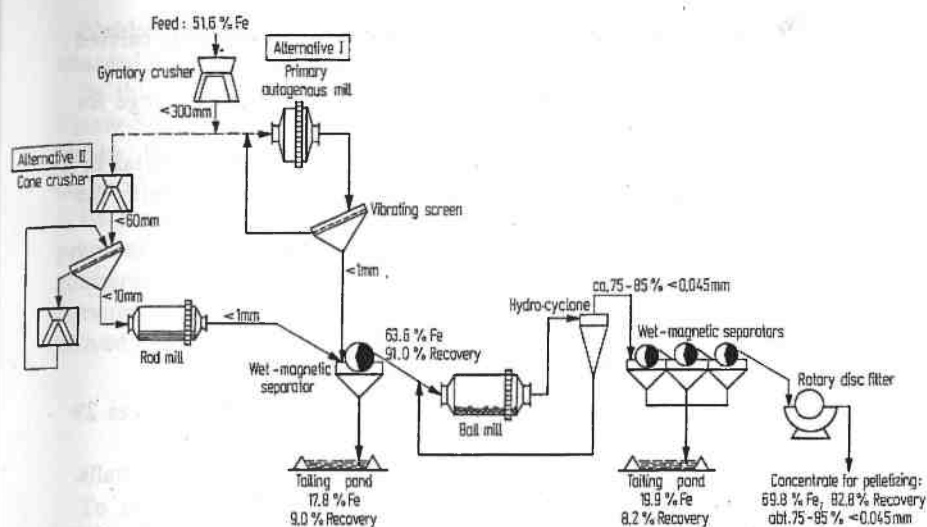


Fig. 34. Alternative routes for wet magnetic separation of magnetite ore in a pilot plant

relatively high processing costs so that it is only used rarely on an industrial scale. Intermittently operating small rotary kilns or fluid-bed reactors are employed for the performance of orienting tests in which the principal characteristics are to be determined. Before the construction of an industrial plant, pilot plants are generally erected and operated over a period of at least several months.

(f) *Electrostatics.* If this process is taken into consideration, the behaviour of the minerals in an electric field is first tested with small quantities. With this process, the corresponding parameters must be closely observed. The operating conditions must only vary within very narrow limits, they have to be precisely ascertained in previous tests. It is also possible to condition the ore grain surface in order to increase the differences in the conductivity of the various minerals.

4.3.2 Grinding

The most important prerequisite to green ball formation is a sufficient fineness and a suitable size distribution of the raw materials. With the exception of concentrates, which often are already obtained in a sufficient fineness from the beneficiation plant, natural ores, coarser concentrates

and additives have to be ground or re-ground. The grinding tests carried out in the laboratory have virtually two purposes:

- (a) Preparation of grinding samples with a representative size range for the performance of pelletizing tests.
- (b) Determination of the most economic method taking the capital investment, energy consumption and wear into consideration with the demand for high-grade pellets being of greatest importance.

There are four variants for the performance of fine grinding:

- Open-circuit dry grinding in ball mills,
- Closed-circuit dry grinding,
- Open-circuit wet grinding,
- Closed-circuit wet grinding (see item 3.2.2.2).

In all cases precrushing to minus 6 mm is recommendable, Figures 29 and 30.

Grinding rods or pebbles may also be used instead of grinding balls. Pebbles are ore fragments having a diameter of 40–80 mm.

In the case of earthy hematite and particularly limonite, only the dry grinding method should be adopted because after wet grinding, these ores cannot be sufficiently dewatered by filtration for green ball formation. An adequately equipped laboratory should comprise sufficiently dimensioned grinding test facilities for this purpose. This particularly applies to pelletizing plant constructors.

In order to limit the scope of test work accordingly it is advisable to run pellet firing tests in parallel to the grinding tests since often after a few tests preliminary decisions can already be taken. Moreover, the fineness has, of course, to be determined in all grinding tests. Two methods have proved to be successful but it is recommended to ascertain the fineness according to both methods:

(a) *Screen Analyses.* Normally, the screening is achieved in a dry manner. In this connection, a screen cut of 0.045 mm = 325 mesh has become usual. In principle, the screen cut may also be lower, down to 0.032 mm. In this regard, the use of air-blown screens has proved to be suitable. After dry grinding, some ores tend to form loose agglomerates. In such cases, the wet screening method is preferable. A screen analysis is reliable for the particle size range below 0.02 mm. For the precise determination of these very fine fractions in connection with the grinding degree, it is additionally necessary to ascertain the specific surface area (see item 3.2.2.1).

(b) *Surface Determination.* For this purpose, the method according to Blaine, known from the cement industry, was first taken over and is nowadays adopted for pelletizing also. In some laboratories, the Svenson method is preferred.

Neither method is quite independent of human errors, i.e. of the person charged with the performance of the pertinent test.

In this respect, the more mechanised surface determination with the Fisher-Subsieve-Sizer is less sensitive. Each method yields reproducible results. However, the absolute values obtained, indicated in cm^2/g or in cm^2/cm^3 , are not always identical.

Before the performance of screen analyses and surface determinations, a preparatory treatment of the samples for the destruction of pseudo-agglomerates by gentle grinding with rubber balls is often required. A previous repulping in alcohol for dissolving the agglomerates has also proved to be successful³⁹⁾.

4.3.3 Grinding Equipment and Grinding Energy

To obtain a size range required for practical operation in the grinding tests, it is recommended to use mills with a minimum diameter of 0.6 m where the ratio of length to diameter should be about 1.5:1. Furthermore, continuous grinding is to be given preference. In the case of closed-circuit grinding, care should be taken that the classifiers be sufficiently dimensioned since often they only ensure a representative classification from a certain capacity onward which may involve the use of correspondingly greater mills. This detail should be particularly considered for wet grinding with hydrocyclones as classifiers.

The performance of large-scale tests in mills with e.g. 1.0 m diameter at a throughput of 1–3 t/h is recommended for ascertaining the exact energy consumption. The throughput is dependent on the grindability of the ore and of the required fineness. Consequently a larger ore quantity of up to 50–100 t is recommended for such tests. In the event of a closed circuit, it takes about 3 hours for wet grinding and about 4 hours for dry grinding until the system is in balance. Normally, several tests have to be run to obtain dependable results. The specific energy consumption for grinding can be determined by:

Measuring the torque at the shaft before the main drive pinion or stopping the mill rotation by using a prony brake or determining the active power consumption of the mill motor.

Such measurements especially the torque metering yield very reliable data for dimensioning the grinding equipment and for the determination of the energy consumption. Table 11 shows test results which were obtained during grinding tests in large-scale pilot mills.

In these tests, the ore was ground in various grinding systems to the same fineness. Consequently, the quality of green and indurated pellets is roughly identical within the scope of test accuracy.

Table 11. Influence of various grinding methods on grinding energy and properties of hematite pellets

	Wet grinding		Dry grinding		
	Ball mill		Pebble mill	Ball mill	
	Circuit			Circuit	
	open	closed		open	closed
1. Specific surface area (cm ² /g)	1600	1600	1600	1600	1600
2. Grinding energy (Kwh/t)	18.0	14.5	16.5	21.0	15.5
3. Wet compression strength (N/pellet)	7.0	7.0	7.0	8.0	8.0
4. Drop number at 46 cm distance	4.0	3.5	4.4	3.6	3.6
5. Green pellet moisture content (%)	8.5	8.2	8.2	7.4	7.5
6. Dry compr. strength (N/pellet)	14	14	9.0	9.0	9.0
7. Compression strength of fired pellets (N/pellet)	3000	3500	3200	3600	3400
8. Tumbler index 0.6 mm (%)	3.5	3.2	3.4	3.5	4.3
9. Swelling rates (JIS) (%)	15	14	16	14	21
10. Specific capacity of a travelling grate (t/m ² 24 h)	24	25	23	26.5	24

As regards the energy consumption, closed-circuit wet grinding yields the lowest values. In the case of closed-circuit dry grinding, the energy consumption is almost the same ⁴⁰⁾.

In some cases, the specific power consumption for grinding may be determined with a certain precision by adopting the Bond method ⁴¹⁾. But often, in the case of surface grinding, this method is not precise enough.

4.3.4 Filtration

Wet grinding is followed by filtration in all cases in order to achieve a moisture content of the filter cake which is at or better below the optimum green pellet moisture content. As concerns the filter cake moisture content to be attained, small-scale tests with filter plates give indications. However, continuous filtration tests with the corresponding filter type, such as disc or drum-type filters are recommended for dimensioning the filter plant.

In the event that the filter cake is difficult to dewater, hot steam filtration may be advantageous. A thermal secondary drying is not only expensive but also often leads, primarily when drum-type dryers are used, to undesirable agglomerates which may bring about great difficulties during green ball formation. These agglomerates hinder:

- (a) the desired close size range of green pellets from being achieved;
- (b) a homogeneous mixture, particularly with additives after drying.

A further possibility for the subsequent regulation of the filter cake moisture content is the use of drying additives. In this connection, the highly water-bonding bentonite has, in particular, a considerable influence as has also calcium oxide (CaO) when special measures are taken.

4.4 Mix Preparation for Ball Formation

4.4.1 Mix Preparation

All fine-grained components for the pellet mix, binders or additives are previously mixed intensively. An optimum mixing is, of course, achieved during the common grinding of raw materials. However, possibly existing great differences in the grindability of ores or additives must be considered. In the case of wet grinding, no bentonite can be added since the swelling of bentonite would adversely affect the filtrability. To ensure a homogeneous mix, different mixer types are used. Small-sized experimental units of some of these types exist. In laboratories batch-type positive mixers have proved to be suitable. Since they operate intermittently, the charge components and mixing time can be precisely controlled. In these mixers, a pre-wetting of the complete mix to a moisture content being about 1–2% below the optimum pellet humidity is also achieved.

The testing material to be pelletized is then to be *continuously* and *uniformly* charged to the balling equipment preferably by using a variable speed belt. In the event of mixtures tending to the formation of lumps, it is recommended to insert a fluffer for fluffing any undesirable conglomerates before the mix is fed to the disc.

4.4.2 Green Ball Formation

The balling drum and the balling disc have for many years proved to be equally suitable for green ball formation.

Löfgren⁴⁵⁾ compared the quality of green balls produced from Malmberget magnetite concentrate both in drums and in discs of industrial

plants and detected practically no differences. When choosing a balling unit for the laboratory, in most cases the disc was selected. However, this decision has nothing to do with the choice of the unit to be used in the industrial plant to be designed. A main reason for the preference of a disc is its easy handling. Discs operate practically without circulating undersize load or with only a small amount. Consequently, no recirculation of undersize is required, and the disc quickly comes into balance, i.e. the quantity of pelletizing material supplied corresponds to the same amount of green balls discharged. Within a shorter time and with smaller quantities of testing material satisfactory results are obtained more quickly in the disc than in the drum. The question regarding the convertibility of laboratory test results to an industrial plant is positively answered by opera-

Table 12. Comparison of green pellet properties produced in discs on pilot and industrial scale

Equipment	Discs- No. 2	Discs- No. 3	Pilot- disc	Airplane- tire
Size ($\varnothing$ m)	6	6	1.0	—
Spec surface area (cm^2/g)	1500	1500	1500	1500
Green-strength (N/pellet)	7.8	7.3	7.6	7.0
Drop number (46 cm)	5.8	5.1	4.6	2.6
Moisture (% H_2O)	9.3	9.3	8.9	7.9
Size (mm $\varnothing$)	12 – 15	12 – 15	12 – 15	12 – 15

tional values of industrial plants, as can be seen from Table 12. The results obtained in a disc having a diameter of one meter are comparable with those reached in discs with a diameter of six meters. Consequently, it is justified to use a balling disc of smaller diameter for the work performed in the laboratory.

The last column of Table 12 gives the results obtained with another unit, the so-called "airplane-tire". This simple balling unit consists of an adequately supported, rotating tire. Testing material is intermittently introduced into the interior of the tire and green balls are produced in batches. The tire primarily serves for determining the green ball quality while it is not suitable for capacity determination.

The green ball formation in an experimental disc serves for the determination of:

- optimum moisture content
- conditions for the formation of green balls of different diameter
- possible capacity in dependence on the shape and fineness of grains and other ore characteristics.

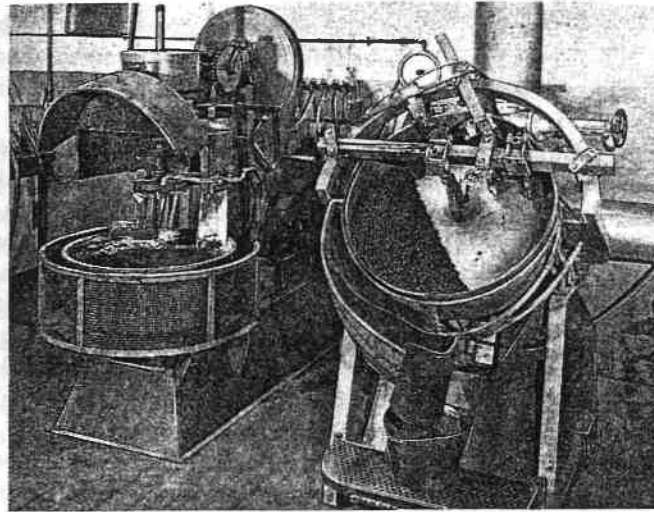


Fig. 35. Experimental disc and pre-mixer

In order that the experimental disc can fulfil these functions, it must meet the following requirements:

- disc diameter: 60–80 cm
- rim height: about 20 cm (to be varied)
- disc slope: adjustable between 45–55°
- rotating speed: adjustable between 10–18 R P M.
- adjustable location of ore and water supply.

The material supply is to be achieved steadily and evenly spread.

Fig. 35 shows such an experimental disc and a premixer arranged beside.

4.4.2.1 Green Ball Formation and Testing Methods

Green balls *cannot be* stored during their transportation from the balling to the indurating unit due to their low mechanical strength.

The pelletizing plant constructors intend, therefore, to keep the transportation route as short as possible with a minimum number of transfer points and low drop heights.

In modern travelling grate plants, for example, the transportation times are between two and maximum four minutes with about four to five transfer points and drop heights of 60 to a maximum of 100 cm. The testing methods adopted at present were established according to these practical requirements.

4.4.2.1.1 Pellet Moisture Determination. About 100 g of green balls are dried in a drying oven at a temperature of 105–110 °C.

4.4.2.1.2 Crushing Strength. A certain minimum crushing strength is necessary in order that the pellets can withstand the compression load in the pellet bed on a belt conveyor, drying grate, indurating grate, or in a shaft furnace.

The average crushing strength of green and dried pellets is controlled by compressing at least 10 pellets between parallel steel plates up to their breaking. The mean value of the tested pellets gives their crushing strength. In a simple manner, this test is carried out on a platform balance with weight indication by means of a pointer. The pellet to be tested is placed on the lower steel plate of the balance and is gradually compressed with a steel plate while the pointer position is observed. The pellet breakage is indicated by the jumping back of the pointer. The maximum weight load observed corresponds to the crushing strength measured in N/pellet. Often, mechanically operating testing units are recommended. If the crushing strengths ascertained with a platform balance are compared with the results of a mechanized test press, there are practically no differences for pellets of the same diameter, as can be seen from the following data:

	<i>Crushing strength:</i> Green Pellet	<i>N/pellet</i> Dried Pellet
Hand press	11.1	40.6
Automatic press	11.6	46.9

This method of determining the crushing strength is scientifically incorrect since pressure is always referred to a plane surface which is not the case with a pellet. A point load, represented by a point crushing strength, is also not correct for the spherical surface of a pellet. However, the measurements result in practically comparable values as reference values if the examination is carried out with pellets of approximately the same diameter. Consequently, small pellets must yield a lower strength than those of a greater diameter⁴³). Control measurements with the same earthy hematite as described above confirmed this assumption. Pellets having a diameter of 10 mm, 12 mm and 15 mm yielded the strength specified below both for green and dry pellets:

<i>Pellet diameter</i> in mm	10	12	15
Green pellets N/P	8.0	9.3	11.1
Dry pellets N/P	33.6	39.0	40.6

The pellets must withstand a further load during the drops in the course of their transportation. Two values are ascertained for these drops.

4.4.2.1.3 Drop Number. The drop number indicates how often green balls can be dropped from a height of 46 cm = 18" before they show perceptible cracks or crumble. Ten green balls are individually dropped on to a steel plate. The number of drops is determined for each ball. The arithmetical average values of the crumbling behaviour of the ten balls yield the drop number. According to experience, the minimum value is four. As a result, a pellet is to withstand, without any damage, four drops from a height of 46 cm. Comparative values are given in Table 13. If the necessary values are not achieved with the ore alone, binders are added. The ball diameter is also to be indicated for the determination of the drop number because, in this case, also correlations exist.

4.4.2.1.4 Drop Resistance. This testing method is only occasionally adopted today. By using this method, the crushing strength of green balls is found out after three drops from different heights. This value is an indication of the admissible height difference at various transfer points during green ball transportation. About 7 Newton are required as minimum strength for three drops from a height of 46 cm.

Desired values for the mechanical properties of green, dry and indurated pellets have to be ascertained in laboratory tests, 4.6.1–4.6.1.2 and shown in table 13, first column. For comparison, measured values of pellets produced from various ore types in industrial plants are also indicated.

4.4.3 Capacity Determination

Although pellet plant constructors have been gaining experience in industrial plants with different ores for several years, it is recommended that capacity determinations be carried out on an experimental balling disc. The maximum capacity can be recognized by the decreasing quality, particularly by an extension of the size range of the pellets produced.

Optically too, the capacity limit can be recognized by an increasing pellet surface roughness. From the considerable number of publications dealing with the question regarding the dimensioning of pelletizing plants, the article issued by Bhrany ⁴⁾ is to be noted. He has set forth a theory which permits the design of industrial balling discs on the basis of laboratory experiments.

Table 13. Mechanical properties of pellets, desired and obtained in industrial plants

Test specifications according to standard methods	Desired values	Results in commercial plants (examples)			
		Magnetite	Hematite	Limonite Hematite	Mixture of ores
Additives	Variable	Bentonite 0.7%	Lime hydrate 1% (Ca/OH) ₂	0.5% Bentonite 3.0% CaCO ₃ Lime stone	2% CaCO ₃ Lime stone
Grinding -0.045 mm in % spec surface area (cm ² /g)	Variable	72 1900	98 1900	67 2630	58 2200
Green pellets compression strength (N/pellet)	10	11	13	16	16
Drop numbers at 46 cm distance	Minimum 4	7	5	7	10
Dry pellets compression strength (N/pellet)	10	33	15	32	39
Indurated pellets compression strength (N/pellet)	2000	3100	3600	2800	4100
Tumbler index (% + 6.3 mm)	94	97.5	97.0	95	96
Abrasion index (% - 0.5 mm)	5	2.2	2.8	4.2	3.5

4.4.4 Bulk Density

The determination of bulk densities of ores, concentrates and additives is important for the dimensioning of bins and handling equipment. In addition, this determination gives indications of the capacity of ball forming units, which is decisively influenced by the bulk densities.

4.5 Green Ball Induration

The induration of green balls means their thermal treatment in the following stages:

- Drying of green balls
- Heating of dried pellets and oxidation of magnetite pellets up to induration temperature
- Firing at induration temperature
- Cooling of indurated pellets.

Depending on the intended purpose, the various trials are carried out with testing materials in furnaces having a different thermal capacity and volume. Orienting tests are run on quantities of individual pellets of up to one kilogram. Tests performed with quantities of up to 80 kg are performed in pot grates, which serve to:

- ascertain the quality of the pellets produced as a dependence on the raw material properties,
- determine the oxygen required for the most complete oxidation of magnetite to hematite,
- determine the temperature profile for the ore types involved,
- determine the capacity of e.g. travelling grate plants expressed in tons of pellets produced per sq.m. grate area and day,
- obtain data for gas flow and heating balances.

4.5.1 Furnaces for Orienting Tests

(a) In an *orienting test* the *shock sensitivity* during green ball drying is determined. For this purpose, shock tests are carried out in a muffle furnace which can be heated from 100 °C to 1000 °C. Ten wet pellets are, for example, introduced into such preheated muffles to find out the number of pellets which burst at a predetermined temperature. The admissible shock temperature is that at which all pellets remain undamaged. More precise measurements are made in a pellet layer through which gas is flowing. For this purpose, pellets are charged in a basket to a tube furnace as shown in Fig. 36.

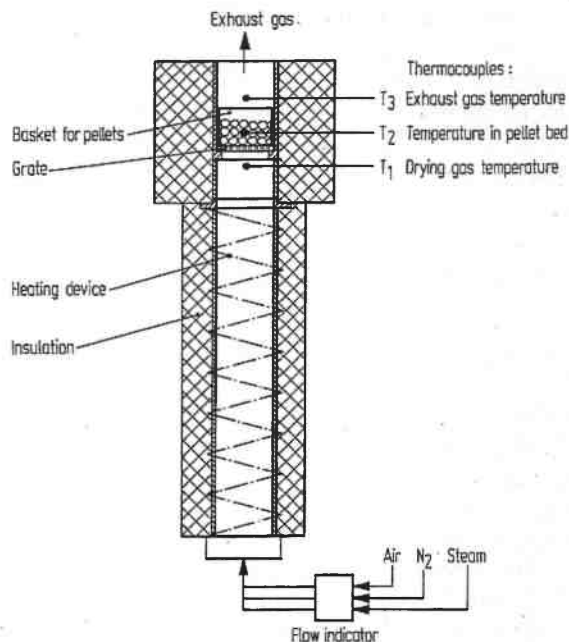


Fig. 36. Tube furnace for drying tests with green balls in a gas stream

(b) Orienting *pellet induration tests* are run in *conventional* laboratory furnaces, e.g. muffle furnaces, which can be heated up to a temperature of about 1350 °C. In these tests, small pellet quantities are used mainly to ascertain the optimum firing temperature.

4.5.2 Stationary Pot Grate for Principal Tests

The above two furnace types can be found in every metallurgical laboratory while the principal tests are performed in special equipment developed for pellet firing, the so-called *pot grate*. In these pot grates, representative tests for firing according to the travelling grate, grate-kiln and shaft furnace process can be carried out. Irrespective of special pelletizing processes this pot grate is often used for general investigations also those of a scientific nature. The drying, preheating, firing and cooling are achieved in the same pot grate with the process gases being sucked or forced through the pellet layer. According to the firing system applied, the bed height varies between 20 cm for the grate-kiln process and about 40 cm for the travelling grate process.

The pot grate was developed on the basis of down-draught sintering technology. It was then adapted to the special thermal conditions of pellet firing. In particular, the so-called side wall effect initially caused troubles in the course of the process. This effect brought about two phenomena:

(a) The gas flow is faster along the wall than in the pellet bed. As a result, the measured waste gas volume is greater than in industrial plants.

(b) The heating gases in the zone near the wall give off a considerable part of their heat energy to the wall. In this way, the pellets placed on the wall area are not heated to the necessary temperature and their quality is thus correspondingly lower. Two possibilities for avoiding or diminishing this effect are used in practical operation.

4.5.2.1 Pot Grate with Side Walls and Hearth Layer

Fired pellets of a smaller diameter than that of green balls or screened fired pellet fragments are placed between the stationary side wall and the green ball feed. This intermediate layer represents an insulating zone which dams heat convection and holds off the hot gases from the stationary smooth side wall. This side wall material can be separated by simple screening from the fired pellets after termination of the test. The main portion of the sample can be used for quality determination.

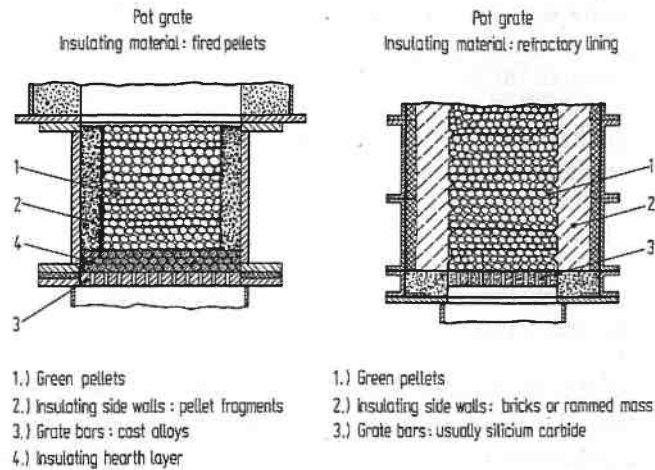
Since the pot grate bottom is composed of *metallic* grate bars, it needs to be protected against overheating. This is achieved with a layer of indurated pellets of 6–10 cm thickness.

The green pellet bed is thus protected by a “refractory envelope” consisting of the same material as the pellets. Smaller pellet samples from different ore types could also be embedded in one or several baskets of stainless steel into the middle of the green pellet layer. After termination of the test, these baskets can be separately withdrawn. Fig. 37 shows the section of such a pot grate with side wall protecting zone, hearth layer and pellet filling.

4.5.2.2 Pot Grate with Corrugated Side Walls

Attempts were also made to avoid air-in-leakage by using a refractory brick lining of an inside corrugated shape. In this case it is recommended that any finished pellets should be preferably withdrawn from the middle of the bed or for relevant tests baskets be employed. The section of such a pot grate is represented in Fig. 38 *). In both cases hearth layer can be used. Instead of side layer or refractory ramming mass a newly developed refractory fiber mat is nowadays used which is resistant to temperatures up to 1600 °C. This material has the following characteristics:

- high temperature resistance
- low heat capacity
- good insulating effect



Figs. 37/38. Alternative pot grate systems for heat treatment of pellets

4.5.2.3 Control Scheme of Pot Grate Tests

In the firing tests, different test conditions can be varied and checked, such as:

- air flow direction, drying method
- gas volume, suction and pressure in the wind box
- preheating rate and temperature profile
- fuel type: oil or gas
- heating gas atmosphere by using additional oxygen, if necessary.

Above all, temperature control is decisive for the quality of fired pellets and process development so that in all important locations thermocouples are installed. The side view of such an equipped stationary pot grate as it is frequently employed for pellet firing is shown in Fig. 39.

4.5.2.4 Movable Pot Grate

In the pot grate, the consecutive process stages develop in a stationary state in contrast to the travelling grate in which the individual process steps proceed locally and separately from each other.

When the necessary flow direction of the process gases is reversed, the test conditions are impaired in the stationary pot grate by the fact that the ancillary equipment connected with the pot grate, such as wind box and firing hood, cannot be brought so quickly to the temperatures required for the process. This has detrimental consequences primarily at the end of the firing process. During the change-over to cooling, the air is first preheated on the hot walls of the wind box and then passes in preheated condition to

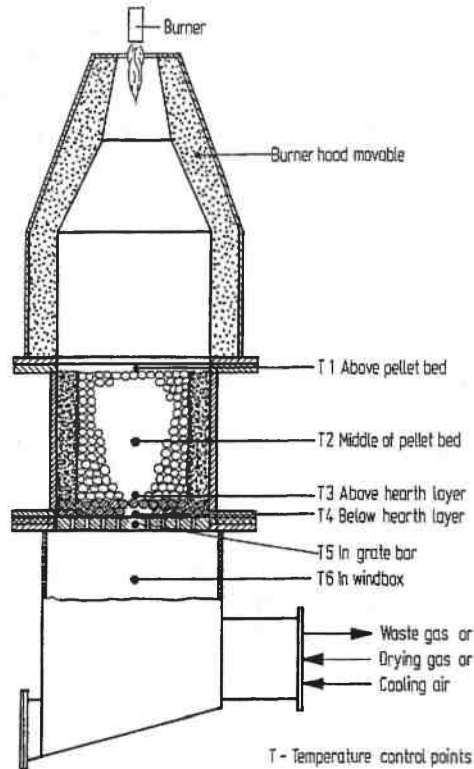


Fig. 39. Temperature control in pot grate tests

the pellet charge. However, in an industrial plant, cool air can immediately flow through the pellet bed. Also during preheating, delays which are caused by the heat consumption of the burner hood brickwork must be considered. Learning from this experience one proceeded to render the pot grate movable. It is, as in an industrial plant, brought into another position during each of the various process stages. Fig. 40 shows the scheme for such a pot grate which is moved from the right side to the left side during the heating operation. In position I, green balls are fed to the pot grate. In position II, the updraught drying is achieved while in position III the final drying, preheating, magnetite oxidation, firing and after-firing are accomplished. In position IV, the hot charge is cooled with an updraught air flow. The pot grate is emptied in position V.

The arrangement of the measuring device, particularly that for measuring the temperature in the pellet layer corresponds to the scheme shown in Fig. 39. Fig. 41 is a photograph of a laboratory equipment with various pots, heating device and instrument panel. From the three pots shown in

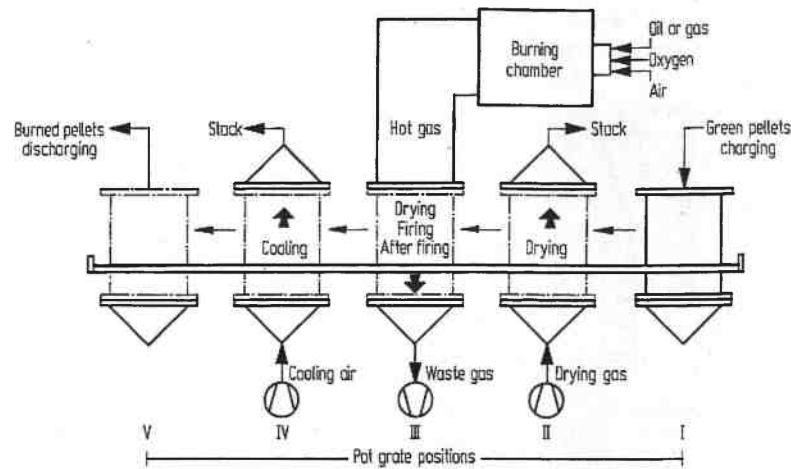


Fig. 40. Movable pot grate system for heat treatment tests

the plate, the pot in the centre serves for testing, the two others are stand-by pots. The data logged during the measurement is automatically recorded. The measuring instruments can be directly connected to a computer.

All data is logged, stored and is at any time available for renewed evaluations. These data can also be directly utilized through the computer for the design of industrial plants.

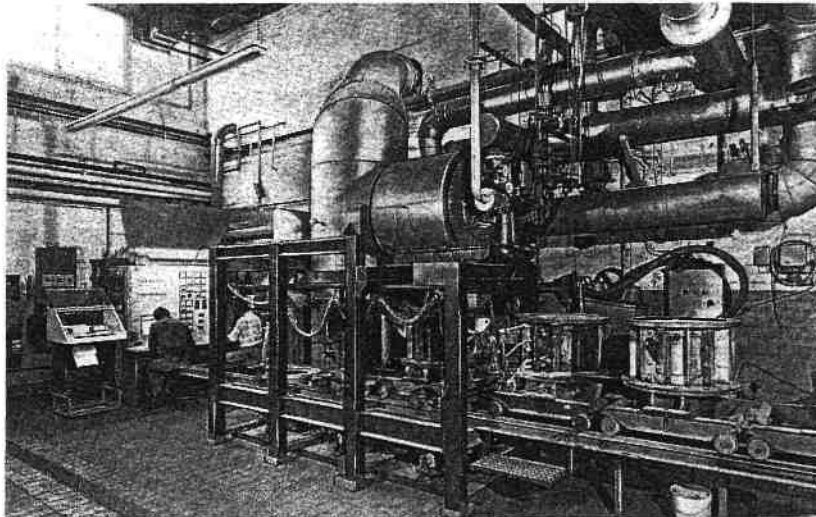


Fig. 41. Photograph of a movable pot grate system

4.5.3 Pilot Plants

Reference is made to Table 13 which shows the minimum demands on pellet properties empirically ascertained and the values measured in industrial plants, which were originally established on the basis of test results obtained in laboratories. In this way, proof has been furnished that it is possible to design and construct pelletizing plants on the basis of laboratory results. In some cases, it will, nevertheless, be advisable to operate a pilot plant having a capacity of 10–20 tpd pellets.

The purpose of such a pilot plant is:

- to provide major quantities of pellets for specific reduction tests in pilot plants of different direct reduction systems,
- to test new firing systems,
- to investigate new process variants for trying out different fuels, e.g. coal alone or mixed with gaseous or liquid fuel.

However, results from pilot plants are no longer needed for the design of conventional plants.

4.6 The Properties of Indurated Pellets and Their Testing Methods

From the indurated pellets such properties are demanded which are necessary for their behaviour during transportation (physical properties) and primarily during metallurgical treatment either in the blast furnace or in direct reduction plants (metallurgical properties). The pellet quality is evaluated by adopting appropriate testing methods, which were developed from experience gained mainly in industrial plants. Attempts are successively being made to develop and introduce international standards, called ISO Standards. These standards are elaborated and proposed by the International Organization for Standardization. Countries with a high pellet import rate, such as Japan, are using in parallel, their own testing methods. Laboratories of pellet exporters should be equipped for the use of all important testing methods.

4.6.1 The Physical Properties

Testing methods were initially taken over from those used for other products, as for example from the cement industry for testing the crushing strength as well as from coking plants for testing the tumbling behaviour. At an early stage W. E. Marshal⁴⁶⁾ pointed out the importance of the

mechanical strength of pellets in the blast furnace. He found clear correlations between the quantity of flue dust and the tumbling behaviour of pellets charged.

4.6.1.1 Crushing Strength, According to ISO TC 102/SC 3 DP 4700

It is apparent from practical operation, that the pellet consumers demand a minimum strength of an average sample of about 2000 N/pellet.

In order to determine the crushing strength, one individual pellet is placed between two steel plates in a similar manner as for green balls and the compression load is increased according to a specified time schedule. Pellets of an optimum roundness and most uniform diameter are selected to ensure an even point load. A minimum of ten pellets is used for each test. In the case of travelling grate plants, the examination is carried out for the upper, middle and bottom layer of pellets. The average strength of ten individual pellets is then regarded as crushing strength.

Nowadays, various testing methods are applied:

- (a) Hand press: It is operated by hand the power being hydraulically transmitted.
- (b) Hydraulic press with motorized drive.
- (c) Electrically operated press with a weight placed on a movable lever arm.

4.6.1.2 Tumbler Resistance

Although the abrasion test according to ISO Standard 3271 1975 E has been standardized internationally, a pelletizing laboratory should comprise facilities which will allow different examinations to be made according to the customer's wish. There exists in parallel to ISO, the ASTM (American Society for Testing and Materials) as well as the JIS (Tumble Test Japanese Industrial Standards). The ISO Test, according to ISO Standard 3271 1975 E is, for example, carried out as follows:

From a representative sample, 15 kg of pellets with a grain size of above 8 mm are introduced into a drum having the following dimensions:

$$\begin{aligned}\text{diameter} &= 1 \text{ m} \\ \text{length} &= 0.5 \text{ m}\end{aligned}$$

Two lifters, each 5 cm high, are located inside the drum which is rotated for eight minutes at a speed of 25 rpm, i.e. 200 revolutions. Subsequently, the pellets are screened and the fractions + 6.3 mm and - 0.5 mm are ascertained. The percentage of the separated fractions in proportion to the feed weight is the value of the Tumbler Index (+ 6.3 mm) and Abrasion Index (- 0.5 mm). All values should be checked by repetition of the test.

Since for each measurement a relatively large pellet amount is consumed, ISO developed a method for a 3 kg pellet charge.

A comparison of physical and mechanical quality of green and indurated pellets between desired and measured values in industrial plants is given in Table 13.

4.6.1.3 Microporosity

Nowadays, no great importance is attached to the determination of the microporosity, which was temporarily considered as important for the evaluation of the reduction velocity in pellets. According to experience, this velocity is in practice always so high that even porosity variations between about 10–30% hardly cause great differences and the major part of pellet qualities is within the upper part of this range. Only pellets of a very glassy structure can be more dense but such pellets are exceptions.

The porosity (P) is determined by measuring the true specific density (D) with benzene or kerosene in a pycnometer.

The apparent specific density is measured with mercury according to the replacement method.

The porosity is $\frac{D-d}{D} \times 100$ in %.

4.6.2 Behaviour of Indurated Pellets During Reduction

The demands hitherto made on the pellet quality exclusively referred to the mechanical behaviour of pellets during storage and transportation. With the beginning of reduction, additional properties are required such as:

- good reducibility which corresponds to a high throughput and an economic energy consumption,
- low tendency to swelling, correspondingly good gas permeability of pellet charge,
- good mechanical resistance in all reduction stages at low and high reduction temperature, which means little degradation, little abrasion, minimum strength and good gas permeability,
- low tendency to sticking under operating conditions, no cluster formation and no uneven gas permeability,
- softening and melting behaviour in accordance with other blast furnace burden components.

The necessity of knowing these properties before the pellets are used in the reduction furnaces was recognized in good time. Consequently, methods for testing the blast furnace charge components were developed accordingly. Some of them were taken over unchanged or, in some cases,

in a modified manner for direct reduction. From early knowledge of the behaviour of natural lump ores, sinter and pellets, it is essential to influence the charge in such a way that during reduction no difficulty occurs. In the case of natural lump ores, this is not possible. Their properties are determined by nature. The situation is different for sinter and pellets. By the selection of adequate additives and by a variable firing pattern, the behaviour of pellets during reduction can be largely influenced in advance. As a result, the testing methods are of increasing importance.

They shall be practicable in a laboratory, most simply applicable and imitate the effect of important parameters. However, they cannot simulate, in all details, the reduction procedure neither in the blast furnace nor in the direct reduction plant, but a similar correlation between the process in an industrial plant and the laboratory investigations shall be ensured.

The great importance of such testing procedures can be recognized by their large number nowadays being applied. An adequately equipped pelletizing laboratory should, therefore, comprise a maximum number of the principal testing facilities. In view of the worldwide interest the establishing of internationally valid and recognised testing methods is intensively pushed forward. The ISO Standards are right now receiving more and more attention, but the JIS, Japanese Industrial Standards, must be considered if pellets are supplied to Japan. LKAB in Sweden as an important pellet and ore supplier, are attempting, together with international organisations, such as the British and German Steel Industry, to develop adequate standards. However, the endeavours of all organisations are increasingly concentrated on international cooperation⁴⁷). Special testing methods still exist in plant complexes where pellets are produced for internal blast furnaces.

The reduction conditions in blast furnaces are, in the first phase, very similar to those of shaft furnace reduction processes if the differences in the reducing gas atmosphere are neglected. The temperature profile is also similar at the beginning but changes at about 800 °–1000 °C. In this temperature range, the oxygen removal during direct reduction ends. *Sponge iron* is cooled and available for melting to steel in other furnaces. For this purpose, it is necessary that sponge iron has a certain mechanical strength and a good tumbling behaviour.

The final reduction in the blast furnace proceeds differently. The partially reduced material remains in the same furnace and is heated to higher temperatures up to the liquid phase. In this phase, the gangue separates as slag from the metallic iron in the form of *liquid* pig iron. In this case, the pellets must have a softening and melting behaviour which adapts to the properties of the other burden components.

In direct reduction, a softening of the charge is, in any case, to be avoided during reduction. Consequently, great value is attached to the

knowledge of the softening behaviour (sticking). According to the different demands made on the charge properties, tests are carried out by adopting various methods.

4.6.2.1 Testing Methods for Reduction

These methods serve to find out the behaviour of pellets during reduction compared with natural lump ores and classified sinter.

4.6.2.1.1 Mechanical Strength. Sufficient mechanical strength of fired pellets is an important prerequisite to their optimum behaviour during transportation and reduction. The corresponding testing methods are described under item 4.6.1.

4.6.2.1.2 Examination of Fired Pellets for Blast Furnace Operation. During reduction, highly oxidized pellets of good quality pass through several process stages while a structural change occurs. It is imperative that in these phases the pellet quality is maintained as far as possible. Such changes may already occur at a relatively low temperature of 500 ° to 600 °C resulting in a certain degradation and thus impairing the gas permeability of the pellet charge.

At rising temperatures of up to 1000 °C, the pellet volume may increase beyond the initial volume. This volume increase, known as "swelling", decreases the voids in the charge accordingly and thus impedes the gas flow.

With swelling, the strength may diminish so that the pellets may even crumble whereby the gas permeability is further impaired. According to the chemical composition of the pellets, they start to deform plastically at a relatively early stage and can thus also impede the gas flow. Various methods are adopted for examination of pellet quality during the reduction stages conforming to existing standards. However, some pellet consumers are still using other, similar methods.

Mr. R. Linder⁴¹⁾, as one of the first researchers developed a rotary kiln method in which, during the kiln rotation, the behaviour of ores, sinter or pellets is studied under a changing atmosphere in the presence of coke of a size roughly the same as that of pellets and at a temperature ranging from ambient temperature to 1000 °C. The accumulating fines portion, reduction degree and crushing strength of the discharge were ascertained. This method was applied for several years. In some cases the rotary kiln proposed by Linder is in a similar form used for dynamic testing methods.

4.6.2.1.2.1 Low-Temperature Disintegration Test (Static Test). [ISO/TC 102/SC 3 (Sect. 98) July 76 341 E Fourth Draft Proposal ISO/DP 4696]. The purpose of this test is the determination of degradation under condi-

tions as they prevail in the upper part of the blast furnace. Pellets screened at 10–12.5 mm remain for one hour at a temperature of 500 °C under a weakly reducing atmosphere in a vertical tube furnace. After careful cooling under a nitrogen atmosphere, the kiln discharge undergoes a special tumble test according to ISO/TC 24–75 and is then screened. As a result, the reduction disintegration degree is indicated by the percentage of fractions plus 6.3 mm, plus 3.15 mm and minus 0.5 mm.

4.6.2.1.2.2 Low-Temperature Disintegration Test (Dynamic Test). [ISO/TC 102/SC 3 (Section 87) 286 E April 1974]. Under equal conditions, the reduction is carried out in a rotary kiln (similar to that used by Linder) with the disintegration behaviour during rotation being tested. After cooling under a nitrogen atmosphere to ambient temperature, the discharge is then screened as in the previous test. Fig. 42 shows the scheme of such a testing unit conforming to the ISO Standards.

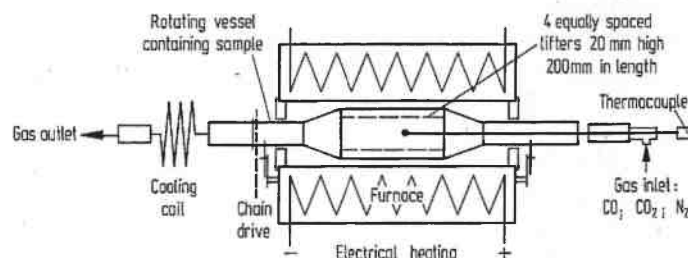


Fig. 42. Externally heated rotary kiln for low-temperature breakdown test (LTBT) according to ISO TC 102/SC 3 286 E (1974)

4.6.2.1.2.3 Swelling Test. [ISO/TC 102/SC 3 (Section 89) 288 E August 1974]. The purpose of this test is limited to the study of the swelling behaviour of pellets. They are placed in a tube furnace so that each pellet has, after swelling, sufficient space without coming in contact with other pellets. The temperature is 1000 °C ± 10 °C. The atmosphere consists of 40% CO and 60% N₂. The test is achieved by four single determinations at: 15, 40, 75 and 120 minutes with a reduction of 25–80% being attained.

The volume of a certain number of pellets is measured before and after the test.

4.6.2.1.2.4 Reduction under Load Test (RuL). [ISO/TC 102/SC 3 430 E]. The purpose of this test is the control of the gas permeability of a pellet bed of 1.2 kg (10–12.5 mm diameter) at a temperature of 1050 °C with 40% CO, 60% N₂ and at a pressure of 0.5 bar (da N/cm²).

The differential pressure above and below the charge is continuously measured at a predetermined gas volume per unit of time. This pressure

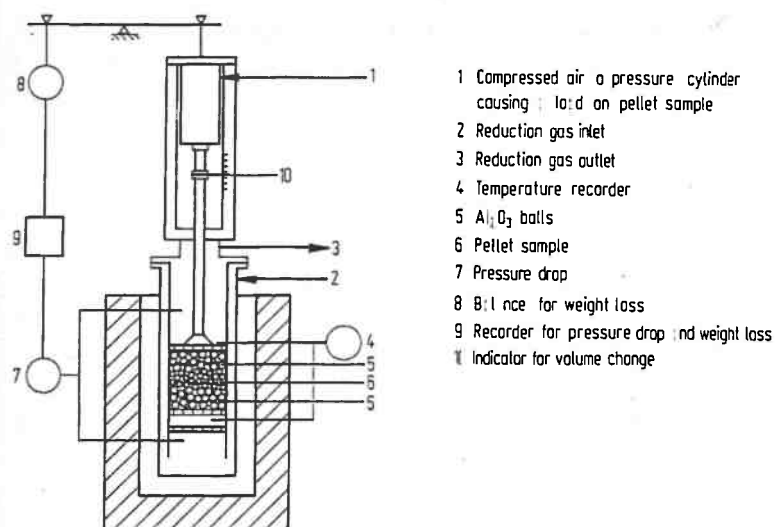


Fig. 43. Equipment for reduction test under load (RUL) ISO TC102/SC3 430E (1978)

changes when the gas permeability varies. If the pellets are deformed or disintegrate under test conditions, the permeability of the bed decreases and the differential pressure rises. Apart from the differential pressure, the pellet weight is permanently checked. In this way, the oxygen removal is measured. Fig. 43 diagrammatically illustrates equipment designed as per the ISO Standard.

4.6.2.1.2.5 Other Testing Methods. As already mentioned at the beginning of this chapter, still other testing methods are used by pellet consumers. This particularly applies to the Japanese steel industry because it imports great pellet quantities from different countries such as Australia, Chile, India, Brazil and Peru.

– Standard JIS M 8713 – 1972.

Method for Measuring the Reducibility of Iron Ores serves for testing the reducibility, reduction velocity and strength of reduced pellets.

This standard was developed from different versions of the “Gakushin” method which was adopted at the beginning of the sixties.

– Standard JIS M 8715 – 1968.

Method for Measuring the Swelling Index is used for testing the swelling behaviour of pellets.

– The ISO Standard TC 102/SC 3 357 E of the draft proposal ISO/DP 4695 “Iron Ores Determination of Relative Reducibility”, is sometimes applied additionally.

4.6.2.1.3 Examination of Pellets for the Direct Reduction. In principle, similar conditions apply to direct reduction processes as prevail in the top part of the blast furnace. However, the gas composition is different and the reduction potential is greater. Moreover, the pellets should not soften prematurely (sticking) and form lumps but are to be discharged as individual pellets.

After reduction a minimum strength is required for their transportation.

Although several industrial plants have already been successfully operating for some years, no generally valid standards, similar to the ISO Standards have as yet been established. Nevertheless, it is already known which pellet properties are most important.

4.6.2.1.3.1 Low-Temperature Disintegration Test (Dynamic). Standard ISO/TC 102/SC 3 (Section 87) 286 E April 1974 (item 4.7.1.2.2) is used for this test at a temperature of 600 °C.

4.6.2.1.3.2 Swelling Test It is suggested to perform swelling tests similar to ISO/TC 102/SC 3 (Section 89) 288 E August 1974 at other gas compositions. In the case of the Hojalata y Lamina Process the sample is treated for 30, 60 and 90 minutes at a temperature of 1000 °C with a reduction gas containing 74% H₂, 13% CO, 8% CO₂ and 5% N₂. After cooling, the volume increase, reduction efficiency, crushing strength and metallization degree are measured, see item 4.6.2.1.2.3.

4.6.2.1.3.3 Sticking Test. [ISO/TC 102/SC 3/429 E, RMC = "Reducibility Metallisation and Clustering Test"] In this test, the sticking is to be studied at different temperatures from 760 °C to 870 °C and at a gas composition of 55% H₂, 35% CO, 6% CO₂ and 4% CH₄. After cooling the furnace discharge is screened at 25, 20, 16 mm and the percentage + 16 mm is considered as sticking criterion.

4.6.2.1.3.4 Direct Reduction Disintegration Stability Test (DRDS). [ISO/TC 102/SC 3/428 E]. During direct reduction with gaseous reductants it is important to determine the stability of iron ores and pellets. This determination has to be carried out in a rotary kiln under the following conditions:

- temperature: 750 °C or 800 °C,
- gas composition: 55% H₂, 35% CO, 6% CO₂ and 4% CH₄,
- time: 3 hours.

After careful cooling, the kiln discharge is screened at + 6.3 mm and - 0.5 mm. Subsequently the crushing strength of the particles + 6.3 mm is ascertained. A tumble test is performed with the fraction + 6.3 mm. After

Table 14. Desired properties of reduced pellets, values obtainable in industrial plants^a

Test specifications according to standard methods	Values	Minimum requirement		Results obtainable
		Blast furnace	Gaseous (direct) ^a reduction	
<i>Low-temperature disintegration (dyn.)</i>				
ISO TC 102 SC 3 sect. 87 286 E	in % +6.3 mm	+80	—	—10 and —5
500 °C blast furnace	—0.5 mm	—20%	—	
600 °C direct reduction	+6.3 mm	—	+80	
	in % —0.5 mm	—	—10	
<i>Free swelling</i>				
ISO TC 102 SC3 sect. 89 288E 1000 °C				
Swelling index	%	—20%	not required	10 — 15%
Compression strength	N/pellet	ca. 450	—16% HyL	450
Degree of reduction (depending on given time)	%	60%	not required	70 — 75%
<i>Rul test</i>				
<i>Reduction under load</i>				aprox.
ISO TC 102/SC 3 430 E, R = Reducibility				
Pressure drop 80% red. deg. (differential pressure)	(dR)/(dt) 40	0.8% min	not required	1 — 1.1%/min
Bed height at 80% reduction in % of the initial height	mbar	2 mbar		1 mbar

^a In Connection with table 13^b Depending on special Reduction Process

tumbling, the tested material is screened at + 6.3 mm and - 0.5 mm. Finally, the metallization degree is defined.

In this connection reference is made to an article issued by D. Kanedo and his colleagues which was elaborated for shaft furnace processes in the central research laboratory of Kobe Steel Ltd., Kobe, Japan ⁴⁹⁾.

4.6.2.1.4 Present State of Testing Methods. Although several testing methods have been finally elaborated, some others are still under preparation. In this connection it should be noted that all these methods might be improved in future. Table 14 shows the test standards which nowadays are preferably utilized.

5 Process-Influencing Factors

Due to the nature and often varying properties of the ores it is difficult to predict the pellet quality. Therefore, it is of great importance to have necessary instruments at hand to compensate for these variations. There are many factors available for influencing the pellet quality and for securing good properties of indurated pellets irrespective of the ore nature.

The various factors can be classified into two groups:

(a) The first group is raw material dependent and *not variable*. They consist mainly of the ore nature, e.g. magnetite, hematite or others, and of the crystalline form in which they appear. If they have a positive influence, they ensure a good pellet quality. If they have a negative influence, attempts must be made to counteract this effect by other factors.

(b) The second group is independent of raw material properties and *variable*. They allow an efficient correction of negative factors of the first group and contribute to a uniformly good pellet quality. Some of the factors affect chiefly the green ball formation whereas others influence the thermal treatment. These factors mostly react in combination with others. Most important are the factors of the second group, which will be dealt with below.

5.1 Factors Influencing Green Ball Formation

Evenly formed green balls serve as a basis for the mechanical strength and other properties of the indurated pellets. Sufficient fineness and surface properties of the ores and the optimum quantity of water are the principal factors for green ball formation. For most ores, the addition of a binder is, nevertheless, unavoidable in order to ensure the necessary strength of green balls.

Three of these factors play an important role:

- granulometric properties
- optimum moisture content
- efficiency of binders.

However, the influence of one of the factors without the others is insufficient, but their simultaneous co-action is advantageous.

5.1.1 Granulometric Properties of Raw Materials

This term covers all properties in connection with the ore grain shape, such as: grain size, size distribution, shape and form of surface of the various grains, for example crystalline form, rugosity, porosity and, in this conjunction, wettability and adsorptive capacity as well as pore volume in the conglomerates. A further important factor is the so-called specific surface area of grains. It gives some information about the fines portion in the lower range of 5 microns – which is difficult to ascertain by screen analysis – as well as about the porosity and rugosity of the particle surface. The grain size is found out by screen analysis with the fraction ($-0,045$ mm) (-325 mesh) playing a decisive role. The specific surface (see item 4.1.1) is defined as the ratio of surface to weight or volume in cm^2/g or cm^2/cm^3 .

5.1.1.1 Grain Size, Size Distribution and Specific Surface Area

Out of the great number of factors, the grain size and size distribution play an important part. As early as 1912/13^{3,4} the fine-grained Norwegian and Swedish magnetite concentrates gave the incentive for the first tests for the development of the pelletizing process. For the formation of pellets the decisive value was found to be the portion -0.045 mm which is generally used as a criterion for the fineness of grains.

In most cases, particularly for the magnetic separation of magnetite, the liberation fineness is sufficient for direct green ball formation. For magnetites containing impurities, further grinding may be required, e.g. phosphorous compounds (Northern Sweden) or sulphides (Marcona) for their separation.

For some raw ores, it is possible to reach already the intended iron oxide concentration at a coarser grinding degree, e.g. in spiral concentrates. However, further grinding is needed for their pelletization. To save grinding costs, the material is only ground until the size distribution required for optimum green ball formation and quality of indurated pellets has been reached.

Nowadays, large quantities of high-grade iron ores are already processed into pellets without previous beneficiation. In such cases, the grinding is *only* undertaken for green ball formation, and only up to the fineness required. As far as grain size is concerned, the raw materials to be pelletized can be classified into three categories:

- (a) During beneficiation, the raw ore is already so finely ground that the concentrate can be directly formed into green balls.

Table 15. Chemical composition and screen analysis of pellet feed from various ore sources

	I Magnetite concentrate Vitafors (Sweden)	II Spiral concentrate Wabush (Canada)	III Hematite crude ore – CVRD Tubarao (Brazil)		
Chemical analysis Values in % (about)					
Fe tot.	68.9	66.9 – 69.3	68.5		
Fe''	21.7	0.3 – 1.6	0.2		
SiO ₂	3.8	2.4 – 1.6	1.3		
Al ₂ O ₃	0.47	n.d.	0.5		
CaO	0.15	n.d.	0.1		
MgO	0.27	n.d.	0.1		
L.O.I.	–	n.d.	0.3		
Screen analysis					
mm	I	II	III		
	Delivered as concentrate	Coarse concentrate	Pellet feed	Crude fines	Pellet feed
+ 1				14.9	
+ 0.5		7.0		6.4	
+ 0.25		42.8		7.0	
+ 0.125					0.7
+ 0.063	13.9	50.2	11.8	32.6	6.0
+ 0.045	8.3	–	5.2	12.4	6.7
– 0.045	77.8	–	83.0	26.7	86.6
Spec. surface area cm ² /g	≈ 1.765		≈ 1.920		≈ 1.820

(b) During beneficiation, a coarser-grained concentrate is obtained. Further grinding is required for green ball formation.

(c) Fine ores or mixtures have naturally such a high iron content that their beneficiation is superfluous.

The raw ore has then to be ground. The relevant costs are to the expense of pelletizing.

Table 15 shows some data of different raw materials which correspond to the above description and may serve as an example of the raw materials treated in a great number of pelletizing plants. Due to many test results and data from industrial plants, it is known that a high portion of

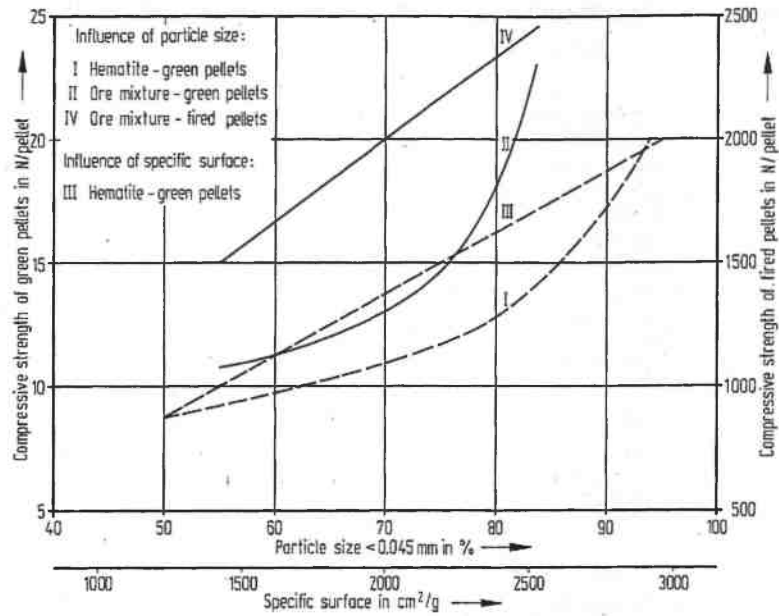


Fig. 44. Influence of particle size and specific surface area on compressive strength of green and indurated hematite pellets

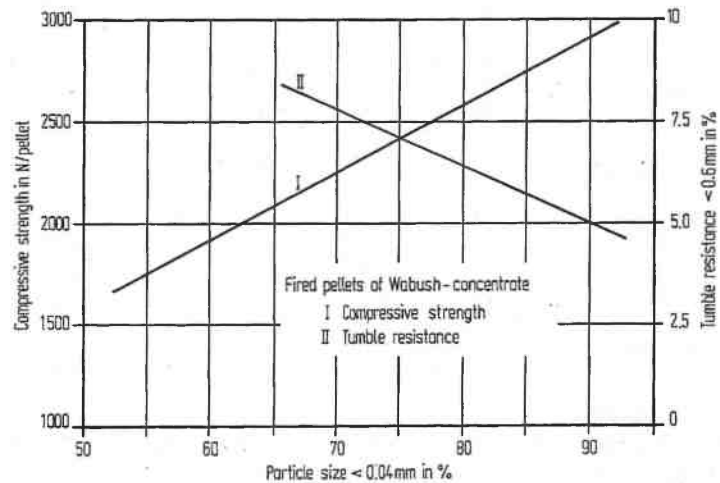


Fig. 45. Influence of particle size on compressive strength and tumble resistance of indurated pellets

very fine particles is a decisive factor to achieve the optimum effect of the capillary adhesion forces.

Fig. 44⁵⁰⁾ demonstrates the influence of the fine particles on compression strength for green and indurated pellets.

Curves I and II confirm the increase of strength with rising portions of fines. Above a certain fineness the curves become steeper. From this results that besides the size distribution other factors such as specific surface are active. Curve III shows a linear correlation between specific surface and pellet strength. Curves I and III are based on the same ore mixture. The specific surface provides more reliable information about the pelletizability of fine-grained ores. As can be seen from curve IV, the strength of indurated pellets is also dependent on the fineness and specific surface of ore.

The interdependence between curve II for green balls and curve IV for indurated pellets produced from the same ore mixture is obvious. The decisive influence of the rising fines portion on the strength of fired pellets and their close relation to the abrasion behaviour are shown in Fig. 45. After the correlation between pellet quality and fines portion had been determined in laboratories and pilot plants, the question regarding the results obtained in industrial plants was of interest. For this purpose, and as far as it could be used, pertinent data from 16 industrial plants, which were commissioned during a period from 1956 to 1978, was compiled.

In those plants still operating, pellets from different raw materials are produced.

Five plants are based on magnetite — four on hematite — in three plants a magnetite-hematite mixture is treated, in three plants a hematite-limonite mixture is processed — and the operation of one plant is based on a mixture of ores — purchased on the world market. The results are indicated in Fig. 46. In the lower part A, the portions of fine particles (curve 1) and the specific surface area (curve 2) are plotted. In part B the green ball strength (curve 3) and in part C (curve 4) the strength of fired pellets are represented. The vertical columns correspond to various groups of ores used:

- Group I: magnetites
- Group II: hematites
- Group III: magnetite-hematite mixtures
- Group IV: hematite-limonite mixtures

and an ore mix comprising various constituents, V.

A comparison of the two curves in part A shows some interesting differences. At first, the relative uniformity of the specific surface area of the ground ores between 1500–2000 cm²/g is striking. On the other hand, the fraction –0.045 mm undergoes much greater variations (70–95%). The

reversion of the values for ores No. 13 (Goa) and No. 14 (Venezuela) containing relatively small fine grain portions at high specific surface area is remarkable.

The green ball strengths recorded in part B are more in parallel with the values of the corresponding specific surface area than with those of fraction -0.045 mm. This would be a confirmation of the correlations found in previous tests. The relatively wide variations of fired pellet strength (part C) are dependent on the prevailing operating conditions, and particularly on the use of additives and the market situation so that they do not have to tally absolutely with the values of parts A and B.

Fig. 46 also allows a statement on the technology of the ore preparation. According to this technique, the ore can be ground to such a degree that a largely uniform specific surface area is obtained despite different raw ore properties. However, the recorded details are rather of a qualitative nature than of a quantitative one. Therefore, it will always be necessary to carry out grinding tests for each particular ore to be pelletized to avoid unnecessary grinding expenses. For this reason, one should indicate the efforts often made to produce suitable pellets by a coarser grinding⁵) and the attempts to adapt the proper grinding process (see item

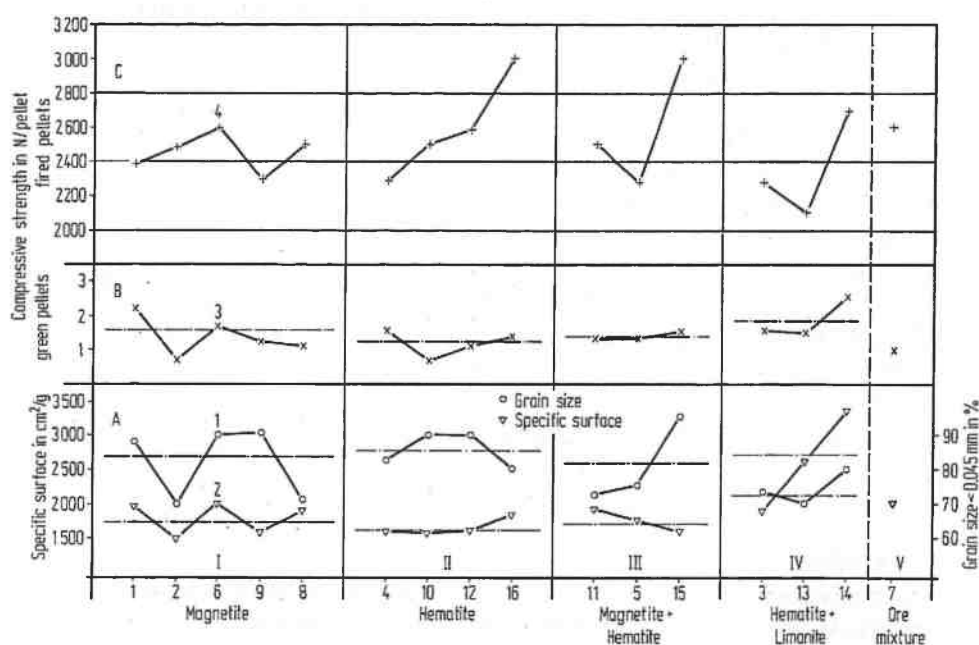


Fig. 46. Properties of pellets from 16 pellet plants comparison between grain size, specific surface area and compressive strength

3.2.2) to the ore type involved should be pointed out. Considerable expenditure was made to define the influences of the principal factors in mathematical terms. Corresponding remarks are made under item 13.1.

5.2 Influence of Water Addition on Green Ball Formation

During green ball formation, the effect of water as a binder is of decisive importance. Provided that sufficient granulometric properties are ensured, it largely depends on the amount of water added whether green pellets can be formed. The ore fines or concentrates to be pelletized may already have a certain moisture content according to their previous preparation. If the ore originates from dry grinding, it is available as a dry conglomerate. In the case of wet separation or wet grinding, a filter cake is obtained which, according to the ore nature, may be more or less moist. This results in different starting conditions for ball formation referred to the optimum moisture content required, namely:

- (a) The grain mix is dry. The full amount of water required is added.
- (b) The filter cake does not yet contain the optimum amount of water. The lacking quantity of water is added.
- (c) The filter cake has the optimum moisture content.
- (d) The filter cake is too wet. It has either to be predried or a drying additive may be used.

5.2.1 Optimum Moisture Content

The influence of the *granulometric properties* on the green ball strength can only become effective with an *optimum water content*. These are the two decisive factors for *green ball formation*.

The green ball quality can be influenced by further factors. Their effect often overlaps so much that it is hardly possible to identify the role of each individual factor.

Thus, the question regarding the optimum moisture content cannot be clearly defined. It is desired to use a minimum water addition due to the heat required for evaporation and owing to the specific capacity of the firing equipment.

Particular attention should be given to two important green ball properties: high compression strength and drop resistance which are complementary. A high crushing strength is achieved at a slightly lower water addition, but better drop numbers with pellets of a higher moisture con-

tent. The green pellet growth from individual grains or conglomerates proceeds, as shown in Fig. 12, through different phases under the influence of a rising water addition and rolling movement of material, item 2.1.2.3.

5.2.1.1 Optimum Moisture Content and Specific Surface Area

The correlation of optimum moisture content and the granulometric properties of a specific ore is shown by data taken from records²⁾ in Fig. 47 A and B. Green balls were produced from a magnetite concentrate with an iron content of 68.0% which was ground to different fineness and corresponding specific surface areas between 1100 and 3370 cm²/g. The water content was varied up to the optimum range. Crushing strength and drop resistance were ascertained in dependence on the specific surface and water content. Fig. 47 shows maximum strength at different moisture contents and varying specific surface areas. The green ball strength decreases at values below and above optimum moisture content whereas

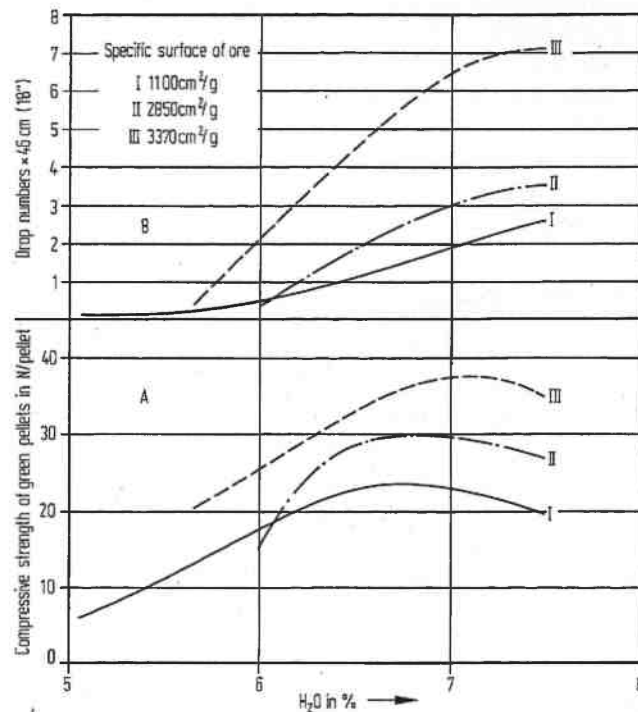


Fig. 47. Combined effect of moisture content and specific surface area on green pellet properties

the drop resistance further increases at higher values, see Fig. 47 B. During green ball transportation, the drop resistance is of greater importance than the crushing strength. In practical operation, it can therefore be observed that the green balls are slightly overwetted. The optimum moisture content should be determined for each particular ore.

Dry ground material should be prewetted to improve the balling operation as is shown in Fig. 48. Pellets of 12 mm diameter are produced from a magnetite concentrate with a different initial moisture content and

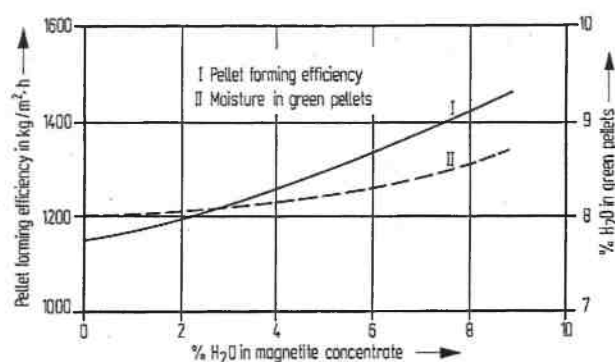


Fig. 48. Influence of original moisture content in concentrate on pelletizing disc efficiency

the balling capacity is ascertained at optimum moisture content. This capacity is the lowest for a dry ore and reaches its maximum value at optimum moisture content of incoming ground material or filter cake. The filtration technology after wet grinding is nowadays developed to such a degree that the filter cake can be supplied at optimum moisture content.

5.2.1.2 Optimum Moisture Content and Surface Condition of Ore Particles

Besides the grain size and specific surface area the shape and surface conditions of the individual ore grains play an important role in green ball formation. The green ball porosity is influenced by the quantity and type of connecting bridges due to the surface of the grain structure. A substantial contribution to green ball formation is made by the wettability of the grains. Glossy crystal surfaces have a lower absorption power than rough surface and micro-pores. From a good wettability of the grain surface, a higher moisture consumption results. Table 16 shows data of some ores with different wettability in conjunction with their specific surface area, optimum moisture content and crushing strength.

Table 16. Moisture content for optimum green pellet strength of different ore types

No.	Type of ore	% Fe about	Degree of grinding		% H ₂ O	Crushing strength pellet		Pellet ϕ
			% -0.045 mm	spec. surface area/cm ² /g		wet	dry	
1	Magnetite	68.3	70	2000	7.1	11	7	12 – 15
2	Hematite	66	90	1900	9.0	13	3	12 – 15
3	Earthy Hematite	65	74	2050	10.5	14	30	12 – 15
4	Artificial Magnetite from Pyrite-cinders	69	90	1900	15.0	11	4	abt. 20
5	Flotation Pyrite-cinders	61	60	2800	14.2	23	45	18 – 20

In the case of ore 1, the green balls consist of cubical magnetite crystals with glossy fracture surfaces, the water consumption is relatively low. Similar remarks apply to ore 2, pellets from specularite crystals. An earthy hematite, raw material No. 3, has a higher water consumption. The wettability of this ore is better than that of the magnetites. The two ores, 4 and 5, artificial magnetite and flotation pyrite cinders need a higher water addition for green ball formation. Both raw materials originate from roasting processes – in the case of one raw material, oxygen and in the other, sulphur was removed. Part of the water is absorbed by the micropores of the individual ore grains. This water does not directly contribute to the formation of capillary forces which is demonstrated by the water consumption of 15% for artificial magnetite although the green and dry pellet strength is roughly identical with that of natural magnetite. The flotation pyrite cinders show a slightly different behaviour. The green and dry pellet strength is higher. Apart from the great specific surface area, bonding by salt bridges may constitute a favourable factor.

The influence of the granulometric properties of ores in combination with water for green ball formation is very often insufficient since only few ores can be formed into suitable green balls without additional binders. Only ores already containing natural constituents which, for instance, tend to gel formation can be formed into green balls. In practical operation, additives are normally used, see Table 13.

5.3 Influence of Binders and Additives

Andersson already considered it very advantageous to use water and additionally binders for ball formation. Thus, he mentioned in the third of his patent claims ³⁾, molasses, sulphite waste liquor, sulphates, chlorides and slaked lime. Brackelsberg ⁴⁾ used soluble sodium silicates as special hardening agent which brought about solidifying salt bridges during drying and heating of pellets.

It has thus been proved that, during the *first* development phase of the pelletizing process, binders already played an important part besides water. During the *second* development phase in which mainly concentrates were treated, binders were already tested in the very first experiments and in particular bentonite played an important part. During the *third* development phase in which concentrates, natural ores and mixtures were pelletized, there was a greater number of possibilities for improving the pellet properties. In case of mixtures a combination of the properties of various ores may be advantageous for bonding purposes. Normally this bonding is achieved by using additives which can be so selected that they change the chemical composition of the pellets compared to that of crude ore to improve the metallurgical behaviour of the indurated pellets.

The purpose, efficiency and nature of additives used may vary in the following manner:

- (a) They improve only the mechanical-physical properties of green, dry and fired pellets.
- (b) In addition, chemical composition and metallurgical properties are influenced.
- (c) The additives serve only for metallurgical purposes.
- (d) The additives may be liquid, solid, soluble or insoluble.
- (e) They can react with water either by hydrate, salt bridges or gel formation with a simultaneous influencing of moisture content.
- (f) They can evaporate, burn or volatilize during heat treatment.
- (g) They can also form compounds with the ore constituents, both with gangue and iron oxides.
- (h) They can prove advantageous or detrimental from a metallurgical viewpoint according to their chemical composition.

The type and quantity of additives depend on the purpose for which they are used. They are classified as follows:

- (a) Additives are only used for improving green ball formation as well as green, dry and indurated pellet properties. The amount of additives is limited to this purpose and is independent of the chemical structure of the pellet feed. These additives are designated as *binders*. Their prototype is bentonite.

(b) Additives may react as binders, according to (a) but they may also be used for influencing the chemical composition of the pellet feed such as lime hydrate. They can be designated as binders or additives.

(c) Additives have no influence on the bonding mechanisms. They must be prepared like other constituents of the pellet feed. Their main purpose is, in principle, the change of the chemical composition of the indurated pellets. A typical example is limestone or dolomite which are designated as additives only.

The effect of a great number of additives is compiled in a wide-spread, extensive literature. The most frequently used and most efficient additives are discussed below.

5.3.1 Factors for Improving the Mechanical Properties

The life span of green balls and the transportation route from the pelletizing to the firing unit are relatively short.

According to the arrangement of the equipment involved, some transfer points are unavoidable in this route where the pellets drop from a higher to a lower level. On account of the low drop resistance of green balls, design engineers endeavour in pelletizing plants to reduce the transfer points to a minimum and to provide small drop heights. In modern travelling grate plants, for example, the transportation time is 2–4 minutes and the pellets may drop four or five times from a height of 60 to a maximum of 100 cm.

On the basis of such experience, corresponding testing methods for pellet quality were developed and described in chapter 4. If the desired values for green or dry pellets produced from different pelletizing raw materials are *not* reached, the use of a *binder* is imperative.

5.3.1.1 Bentonite as Binder

Bentonite, described as a mineral under item 3.2 has some remarkable properties. It combines with water and forms a gel at about five to six times its weight with its volume increasing to approximately tenfold. Bentonite envelops the ore grains together with water and can thus only become active in connection with water.

Due to its high water bonding power, it can also bring about an apparent drying of filter cake which is too wet without variation of the total moisture content.

5.3.1.1.1 Influence of Bentonite on Green Pellet Strength and Drop Resistance. The effect of bentonite is studied below on the basis of the influence of the granulometric properties and optimum water addition.

Here too, only guide lines can be given for different ore types. By way of example, for a hematite with a specific surface area of $1700 \text{ cm}^2/\text{g}$ and a magnetite with a specific surface area of $2100 \text{ cm}^2/\text{g}$, the influence of different bentonite additions on the properties of green and dry pellets at optimum moisture content was investigated⁵⁾. The result is shown in Fig. 49. The green pellet strength changes only insignificantly (Curves I), while the dry strength is highly influenced (Curves II).

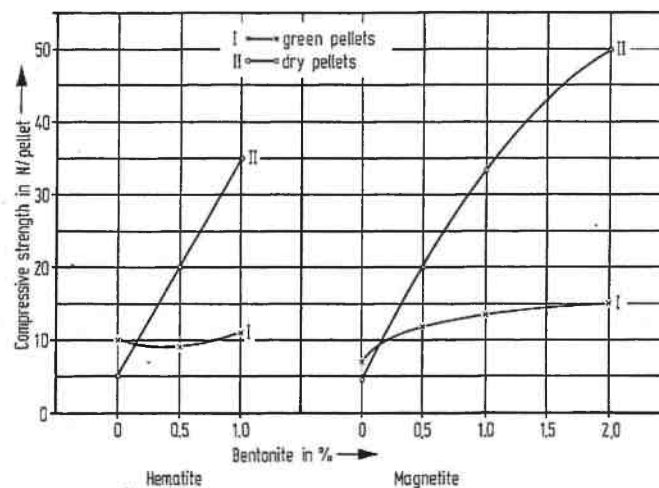


Fig. 49. Influence of bentonite on green and dry pellet compressive strength

Since bentonite is one of the most frequently used binders, values from industrial plants treating very different ores with and without about 0.7% bentonite addition are shown in Fig. 50, A, B, C. For green balls produced from magnetite (M), artificial magnetite (A. M.), crystalline hematite (H), earthy hematite (EA. H.) and an ore mix consisting of various components, the following data are compared:

green pellet strength A
drop numbers B and
dry pellet strength C.

No notable influence on the green pellet strength was observed.

- The plasticity is considerably improved. All ores have higher drop numbers when bentonite is added.
- The drop indices thus obtained are sufficient both for further transportation and for different transfer points.

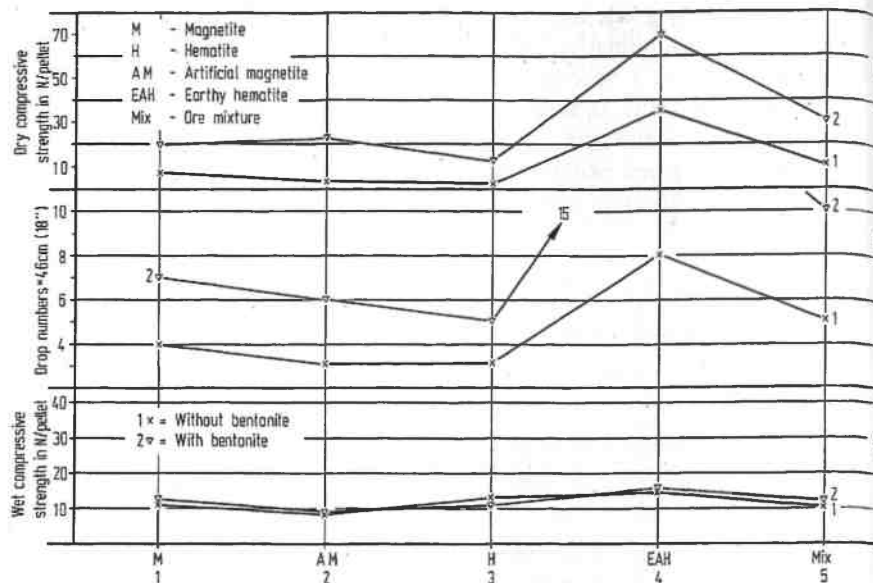


Fig. 50. Influence of 0.7% bentonite on properties of green and dry pellets from various ore types

5.3.1.1.2 Influence of Bentonite on Dry Pellet Strength. As already shown in Curves II of Fig. 49, the use of bentonite has a great influence on dry pellet strength. The bentonite, finely distributed in the water, concentrates during drying particularly in the residual liquid, especially at the contact points and on the contact surfaces of the ore grains. During final evaporation of water, the gels concentrated there dry up and form solid mortar bridges the influence of which can be recognized by the increased dry pellet strength. The influence of gels is also clearly shown in Fig. 50, B, and C with the pellets from earthy hematite and ore mix reacting most intensively. Those operations proceeding during drying also have an influence on the *shock temperature*. At a bentonite addition of 0.7% the amount of gelatinously combined water may be up to 2.5 – three times the bentonite weight. This is about one third of the total moisture content which only escapes slowly in the third drying phase, as shown in Fig. 15. In this way, the drying proceeds gradually and not abruptly – and at a higher drying temperature. In all pelletizing plants, the drying and heating cycle is adjusted to a gradual heating velocity to avoid the negative influence occurring at an excessive heating velocity.

5.3.1.1.3 Influence of Bentonite on Crushing Strength and Abrasion Resistance of Fired Pellets. The crushing strength of fired pellets is chiefly

attributable to crystallization processes and reactions of gangue constituents. For high-grade concentrates, crystallization processes and for ores with a major gangue content, glassy slag formations additionally play an important role. Neither in the one nor in the other case are the bentonite additions of decisive importance. In connection with investigations on the optimum fines portion, pellets with and without 0.62% bentonite addition were indurated⁵³). The result is shown in Fig. 51. The strength increase

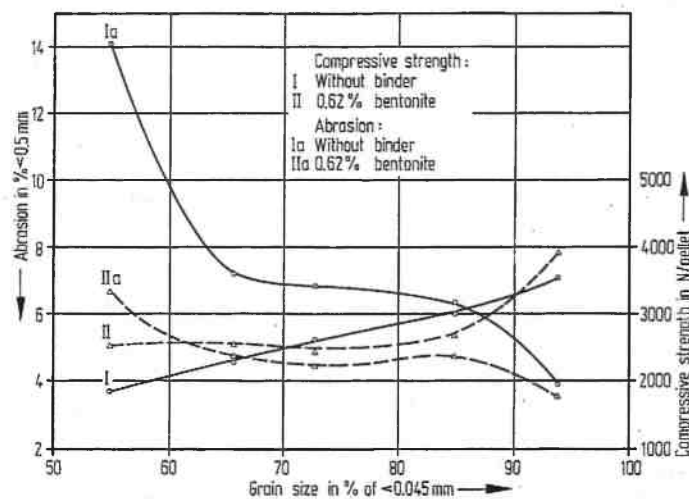


Fig. 51. Combined effect of 0.62% bentonite and grain size on compressive strength and abrasion resistance of indurated pellets from hematite at 1300 °C

at a rising fineness degree is obvious. However, the bentonite addition is of minor importance. The effect on the pellet transportation is more favourable since the tumbling behaviour is particularly improved at a coarser grain size (Curves Ia and IIa). During micrograph studies, a slightly stronger bridge formation between the finest ore particles -0.02 mm was observed when bentonite was added; this improves the abrasion behaviour.

5.3.1.1.4 Different Bentonite Types. The most important bentonite property is its swelling capacity, see item 3.1.4.3. The swelling capacity differs for various bentonite types so that its suitability as a binder has to be examined before the bentonite type is selected. Fig. 52 shows the green and dry pellet strength as well as the drop resistance of pellets produced from a magnetite-hematite mix with 65.3% iron content, 6.0% SiO_2 and an

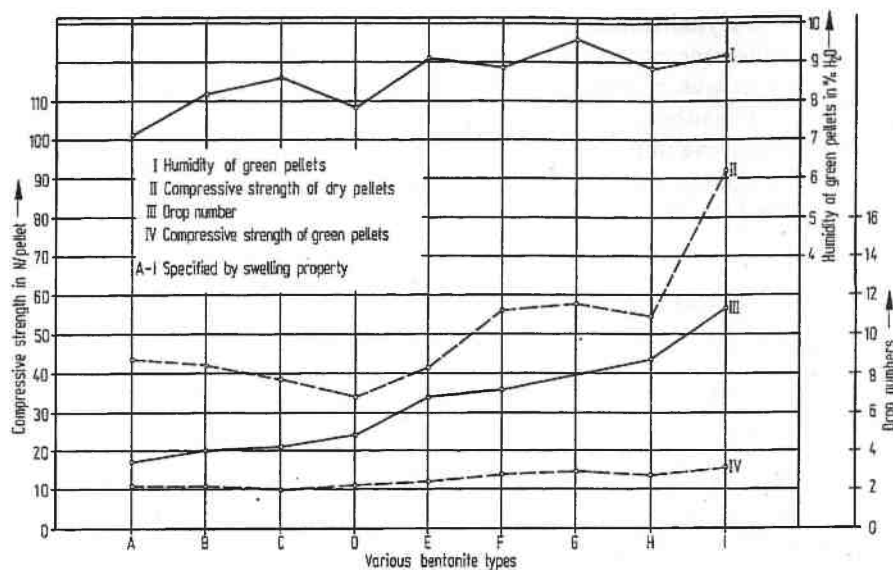


Fig. 52. Influence of various bentonite types on green and dry pellet properties

addition of 0.7% bentonite, according to Kortmann and Mai³⁵⁾, with 7 different bentonite qualities (A–I) having been used and arranged in conformity with their rising swelling property (see also Table 8, item 3.1.4.3). Certain variations occur in the pellet humidity (I). The green pellet strength practically does not change (IV) while the drop indices (III) and dry pellet strength (II) rise with the addition of bentonite of a higher swelling capacity.

5.3.1.1.5 Influence of Bentonite on the Chemical Composition of Pellets.

In many ores and concentrates to be pelletized, the acid constituents SiO_2 (and Al_2O_3), are preponderant in the gangue. During the subsequent metallurgical treatment, they have to be neutralized by basic components which can also be achieved during pelletizing. Bentonite consists of about 60–70% SiO_2 and of 15–20% Al_2O_3 . According to the quantity of bentonite added, the portion of acid constituents which are to be compensated rises proportionately. In the case of ores or concentrates with a high iron and low gangue content, the percentage of acid constituents originating from bentonite is much higher than for ores or concentrates with a high gangue content as is shown by way of example in Fig. 53. 0.5, 1.0 and 2.0% bentonite is added to three concentrates with 1.7, 4.4 and 7.1% SiO_2 and Al_2O_3 . The acid gangue portion then rises by 100% for the concentrate with the highest iron content and by as low as

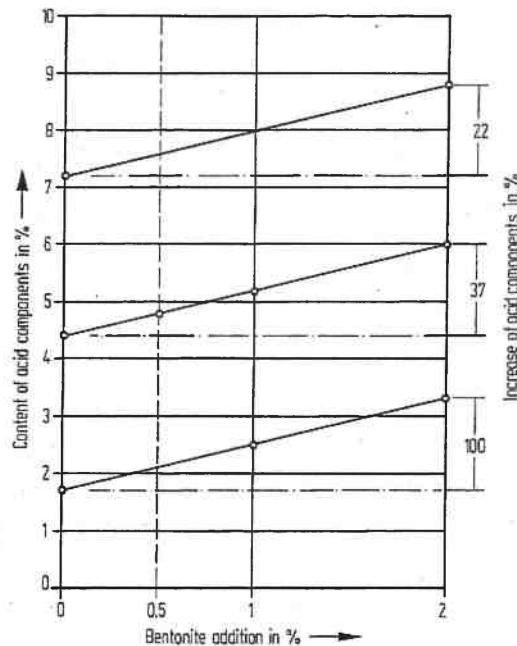


Fig. 53. Influence of bentonite on acid gangue components

22% for concentrate with a high gangue content. From a metallurgical-chemical view-point, bentonite is, in any case, a detrimental constituent the scorification of which is a cost increasing factor. Therefore, it is advisable to keep the bentonite rate as low as possible, which is also done in practice. In the major part of the plants, the bentonite rate is below 0.7% and mostly below 0.5%, irrespective of the ore nature.

5.3.1.2 Influence of Alkaline Earth Compounds

As a consequence of the foregoing those additives are more advantageous which both improve the mechanical properties of pellets and have a positive metallurgical effect. Such additives are, in any case, basic minerals, e.g. calcium compounds which react with the acid gangue constituents during induration. They can be used in different forms, namely as:

- | | |
|--|------------------------------|
| (a) calcium oxide | CaO |
| (b) calcium hydroxide | $\text{Ca}(\text{OH})_2$ |
| (c) calcium chloride | CaCl_2 |
| (d) calcium carbonate | CaCO_3 |
| (e) calcium magnesium carbonate (dolomite) | $(\text{Ca, Mg})\text{CO}_3$ |

According to their properties, these compounds may, as binders, influence the green and dry pellet strength as well as the drop resistance of pellets. At a sufficient firing temperature, they bring about, in most cases, an improvement in final pellet strength. The first two compounds can be used as binders. The compounds Nos. 4 and 5 virtually serve as basic additives for neutralization of acid constituents in the ore and are adapted to it. They only have little influence on green ball formation. Calcium chloride is only employed in special cases if it is necessary to volatilize impurities of non-ferrous metals, such as copper, lead, zinc. The use of lime compounds (see item 3.2.2) has been known for pelletizing almost as long as that of bentonite.

5.3.1.2.1 The Influence of Calcium Oxide [CaO] and Calcium Hydroxide [Ca(OH)₂]. If, during moistening, CaO is added, it reacts with water and calcium hydroxide thus formed becomes effective as a binder. According to the equation $\text{CaO} + \text{H}_2\text{O} = \text{Ca}(\text{OH})_2$, a stoichiometric water amount is combined. The reaction is highly exothermic. During hydration, the volume expands threefold.

Due to the considerable volume increase, the slaking process has to be completely terminated and the hydroxide be thoroughly mixed with ore before green balls are formed. If this is not the case, the burnt lime is only slaked during green ball formation which, at the beginning of the drying process at the latest, inevitably causes a local volume increase and damage to the pellet structure. To avoid such difficulties, only hydroxide is employed in practical operation which is ready for use without any pre-treatment. Published values on the influence of CaO thus refer to the effect of Ca(OH)₂. In the course of hydration and simultaneous volume increase, a very great specific surface area is obtained which may be 10 000 cm²/g and over according to the adjustable conditions. A higher water amount adheres to this big surface than corresponds to the stoichiometry of hydrate formation. This excessive water in conjunction with the great surface even imparts the character of a hydrogel to the hydroxide; the colloidal properties of the hydrogel improve the plasticity of the ore mix and, above all, strengthen the bonding mechanisms during drying. If Ca(OH)₂ is chiefly added to improve the mechanical-physical properties, the corresponding amount can be low and independent of the acid gangue constituents of ore.

5.3.1.2.1.1 Influence of Calcium Hydroxide [Ca(OH)₂] on Green Pellet Strength and Drop Resistance. During the firing of pellets to the temperature required, all the aforesaid lime compounds are dissociated to CaO which, at firing temperatures, reacts with the acid gangue or with Fe₂O₃. The lime addition has, in any case, a neutralizing effect during slag

formation. Lime compounds are normally cheaper as additives than bentonite even if they are less effective. Therefore, it is worthwhile to ascertain the influence of $\text{Ca}(\text{OH})_2$ on the physical properties of pellets which is illustrated in the following example^[4/28]:

An Itabira-type hematite was used and mixed with slaked lime both having the following characteristics:

Itabira ore	Lime hydrate
Fe tot. = 64.5%	$\text{Ca}(\text{OH})_2$ 94.4%
F = 0.3%	CaCO_3 2.7%
SiO_2 = 4.4%	CaO 1.0%
Al_2O_3 = n. d.	H_2O
CaO = 0.3%	$(\text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3)$ 1.7%
MgO = 0.1%	spec surface approx. 10 000 cm^2/g

At first, the influence of the great specific surface area of lime hydrate on the mix to be pelletized was ascertained. For this purpose, ore of three different sizes was used. The result is shown in Fig. 54. The specific surface area of the mix composed of ore and lime hydrate does not greatly

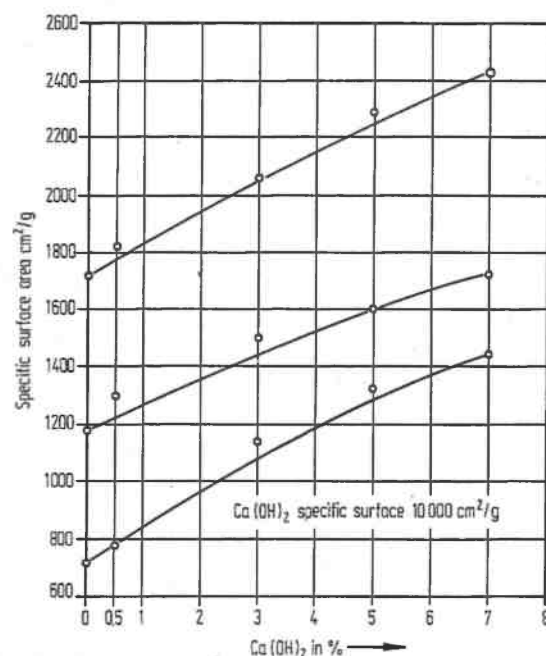


Fig. 54. Influence of $\text{Ca}(\text{OH})_2$ on specific surface area of ore

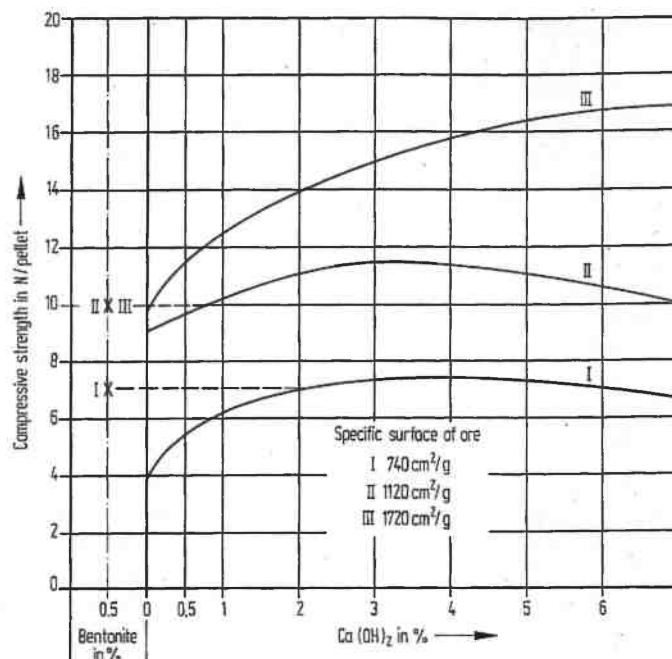


Fig. 55. Combined effect of specific surface area and $\text{Ca}(\text{OH})_2$ on compressive strength of green pellets

vary according to the mixing rule. At greater fineness degrees, a certain grain size increase depending on ore property may occur, due to a certain coagulation.

By the addition of very fine-grained material, like hydrated lime, the improved specific surface area of the mix could allow the use of ores with coarser fineness.

In all the subsequent tests, 0.5, 3.5 and 7% $\text{Ca}(\text{OH})_2$ were used. A trial with 0.5 bentonite addition was performed for comparison. The pellet size was uniformly kept between 10 and 12 mm diameter. The influence on the green pellet strength is shown in Fig. 55. As expected, the influence of bentonite is insignificant. The strength of green pellets produced from coarse-grained ores (740–1120 cm^2/g – Curves I, II) remains at or below 10 N/pellet even at higher amounts of $\text{Ca}(\text{OH})_2$ additions. Only when the ore has a higher Blaine index of 1720 cm^2/g the hydrate addition becomes effective. $\text{Ca}(\text{OH})_2$ has a positive influence on the drop resistance, Fig. 56, similarly to the more efficient bentonite.

5.3.1.2.1.2 Influence of $[\text{Ca}(\text{OH})_2]$ on Dry Pellet Strength. A good bonding power of hydrated lime in dry pellets is shown in Fig. 57. The

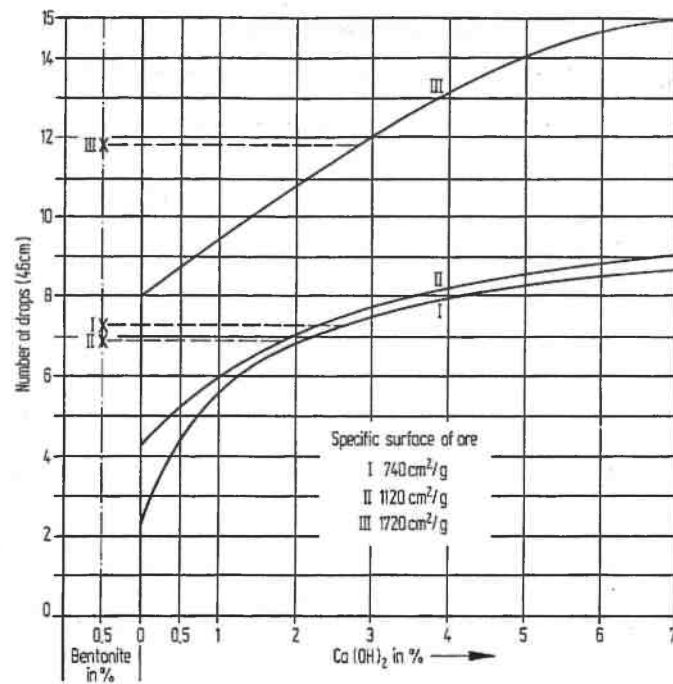


Fig. 56. Influence of Ca(OH)₂ on drop resistance of green pellets

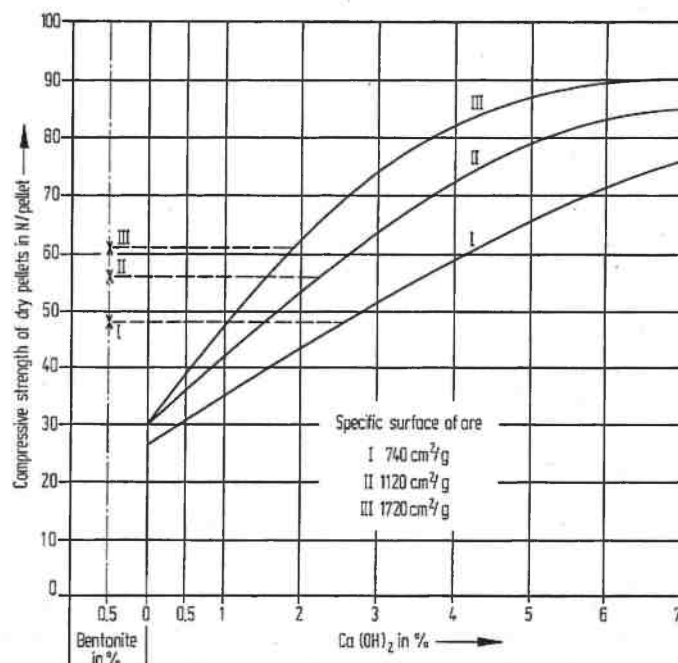


Fig. 57. Influence of Ca(OH)₂ on compressive strength of dry pellets

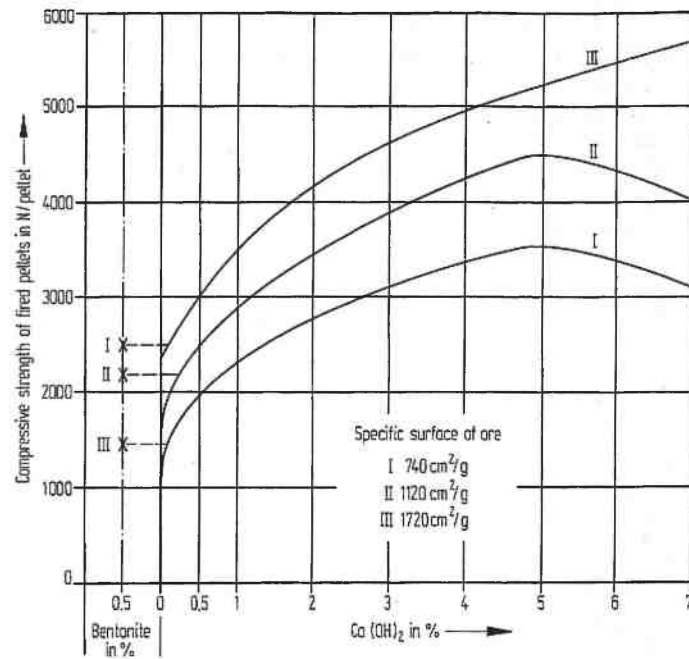


Fig. 58. Influence of $\text{Ca}(\text{OH})_2$ on compressive strength of indurated pellets

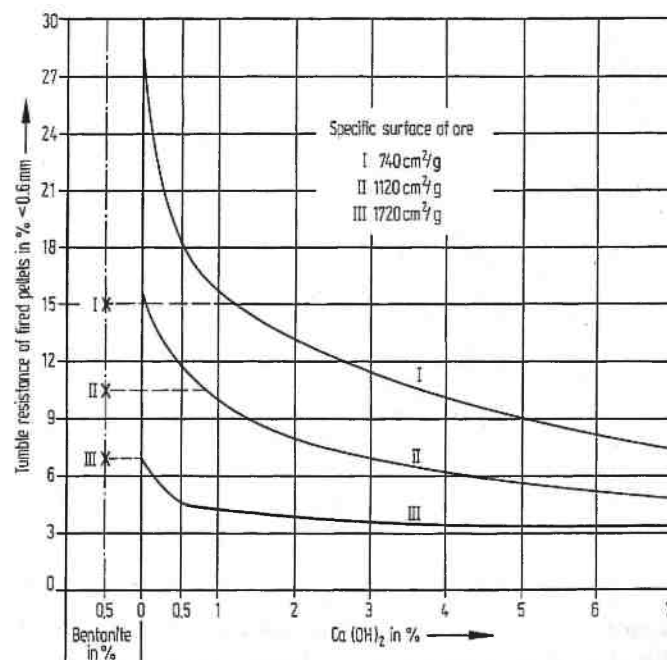


Fig. 59. Influence of $\text{Ca}(\text{OH})_2$ on tumble resistance of indurated pellets

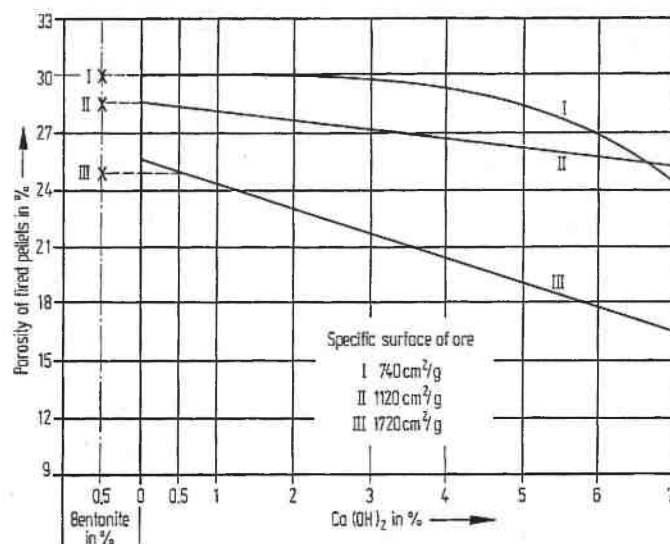


Fig. 60. Influence of $\text{Ca}(\text{OH})_2$ on porosity of indurated pellets

bonding power of bentonite is higher and comparable to about 2% lime addition. Since, as appears from the results, the influence of lime hydrate should mainly be considered in connection with the specific surface area of ore, the observations made with *hematite* ore are also valid for pellets from *magnetite* concentrates.

5.3.1.2.1.3 Influence of $[\text{Ca}(\text{OH})_2]$ on Crushing Strength, Tumbling Resistance and Porosity of Indurated Pellets. The influence of calcium hydrate on the final strength of fired pellets is remarkable, Fig. 58. Even the more coarsely ground ore already shows strengths of more than 2000 N/pellet with an addition of 0.5% $\text{Ca}(\text{OH})_2$. These strengths rise up to an addition of 5%. At a higher addition of 7%, the strength diminishes. It may be that a glassy structure is formed which is indicated by the relatively low porosity of these pellets, as shown in Fig. 60. The abrasion values improve with rising hydrate addition as can be seen in Fig. 59. The porosity of fired pellets produced from the coarse-grained ore, Fig. 60, Curves I and II only changes slightly with higher hydrate additions. However, the ore with the greater specific surface area, Curve III, reacts more intensively and the porosity decreases, but its reducibility is still sufficient.

5.3.1.2.2 Influence of Calcium Carbonate (CaCO_3) and Dolomite $[(\text{Ca}, \text{Mg})\text{CO}_3]$ on the Strength of Indurated Pellets. As described under item 3.2, carbonate is a natural mineral which is insoluble in water and is,

therefore, ineffective as a binder during green ball formation. Limestone is used rather for neutralizing the acid gangue. Consequently, no great influence on the green and dry pellet strength is to be expected. Limestone is liable to the same conditions for green ball formation as the ore itself. It should have at least the same fineness to ensure that after the carbonate has previously been dissociated calcium oxide completely reacts with gangue and hematite. Free CaO should not be present in the indurated pellets because, after a certain time, it hydrates and then causes a weakening of the pellet structure, see Fig. 62. Since limestone is ineffective as a binder for improving the green ball properties, only its influence on fired pellets will be described^{55 28}). An acid magnetite concentrate was pelletized with very pure limestone. Table 17 shows the chemical composition and size distribution.

Table 17. Chemical composition and screen analysis of a magnetite concentrate and limestone for special pelletizing tests

	Concentrate in % (about)	Limestone in % (about)
Fe total	63.5	—
SiO ₂	8.4	1.0
Al ₂ O ₃	0.5	—
CaO	0.1	55.0
CO ₂	—	43.2
Screen analysis		
+0.1 mm	9.3	21.0
+0.045 mm	9.9	70.5
−0.045 mm	80.8	8.5

During the formation of green balls having a diameter of about 15 mm, the lime addition was varied between 7 and 12% and the firing temperature between 1150 and 1300 °C. The green ball strength was practically not influenced. In the case of dry pellets, only small differences were found. For comparison the optimum indurating temperature was first ascertained without limestone addition as shown in Fig. 61. For this concentrate, a maximum strength was obtained at 1250 °C which results from its chemical composition. Subsequently, the influence of a rising amount of limestone addition was ascertained at 1150 °C and 1200 °C first of all directly after firing and again after a storage of 6 weeks in a protected room, Fig. 62. At the higher firing temperature (1200 °C) a substantially higher strength was obtained which reached its maximum at

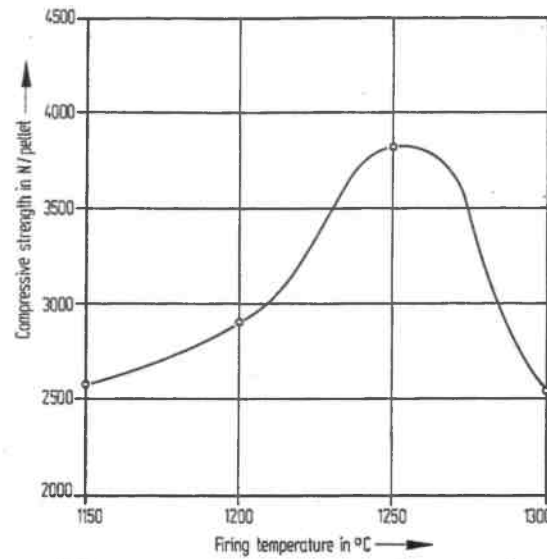


Fig. 61. Influence of firing temperature on compressive strength of pellets from magnetite concentrate without binders

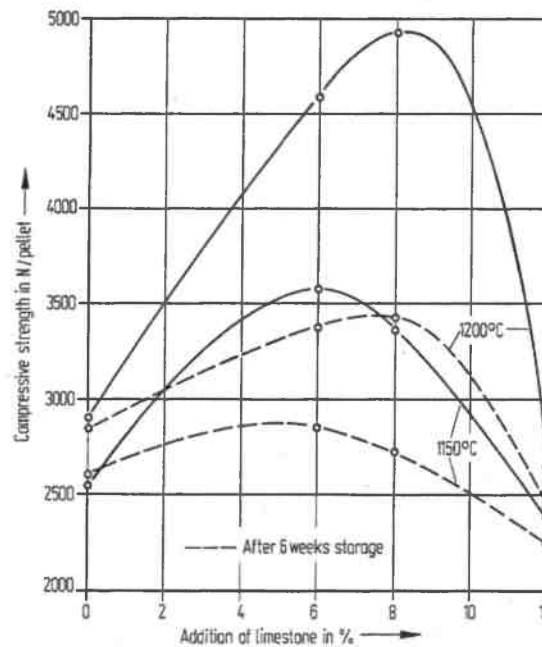


Fig. 62. Influence of limestone and firing temperature on compressive strength of indurated pellets from magnetite concentrate, before and after 6 weeks of storage

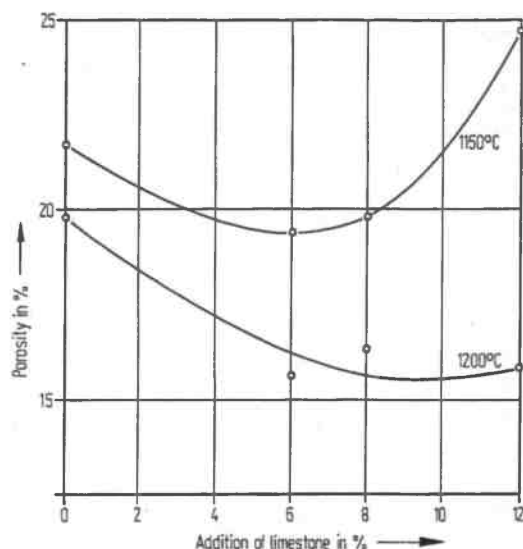


Fig. 63. Combined effect of limestone and firing temperature on porosity of indurated pellets from magnetite concentrate

a CaCO_3 addition of about 8% while at 1150 °C the maximum was at 6% CaCO_3 . After a storage of 6 weeks, the strengths of both samples considerably diminished. White spots of lime hydrate were observed in the pellets which did originate from not scorified free CaO. The screen analysis of limestone showed some portions of too coarse particles. The maximum strength which, for all samples was around 2500 N/pellet, is remarkable and indicates the great influence of slag bond. As can be seen from Fig. 63, the porosity of fired pellets is highly dependent on their CaO content. Up to a certain CaO amount it decreases and the micro-structure becomes more dense. At a higher CaO addition, it rises again, a fact which can be explained by the formation of a greater number of macro-pores, as can be demonstrated by micrographs. In each case, the porosity was sufficiently high so that it would not adversely affect the behaviour during reduction. Merklin and De Vaney observed similar results with another magnetite and increasing additions of limestone or dolomite. In view of the great economic importance of limestone addition, many researchers have dealt with this problem ^{*)}, chiefly in conjunction with the production of self-fluxing pellets. The main reason for the addition of limestone or dolomite is the production of pellets with a rising portion of basic constituents and thus with increasing basicity.

5.3.1.2.3 Influence of a Mixture of Different Additives on Pellet Properties.

In tests for the production of self-fluxing pellets from a magnetite concentrate with 71.3% Fe, 0.7% SiO₂, 0.1% Al₂O₃, 0.38% CaO and 0.14% MgO, increasing and different quantities of finely-ground limestone, dolomite and for a time sand, for raising the total slag portion were added. Inter alia, the mechanical pellet properties were ascertained. Due to the low bonding power of the alkaline earth carbonates in green and dry pellets, bentonite was added. The results of some of these tests are compiled in Table 18. The concentrate had a specific surface area of 1810 cm²/g and the pellet diameter was adjusted to 9–15 mm. As was to be expected, the green pellet strength did not differ markedly. As concerns the dry pellet strength and drop resistance, only the bentonite influence was perceptible. The strengths of fired pellets were quite different. Pellets without lime and dolomite addition showed the lowest value (test 1). A higher lime addition resulted in a higher strength (tests 2–5 and 7). When limestone was replaced by dolomite alone (tests 6 and 8), the crushing strengths were slightly lower. The main purpose of this test series was to

Table 18. Influence of additives on properties of indurated pellets from magnetite

Test specification		1	2	3	4	5	6	7	8
Additives									
Bentonite	%	0.6	0.6	0.6	–	0.6	0.6	0.6	0.6
Limestone	%	–	1.35	3.7	3.7	8.1	–	0.9	–
Dolomite	%	–	1.35	3.7	3.7	–	7.4	0.9	4.1
Quartzite	%	–	1.0	2.7	2.7	2.7	2.7	–	–
Basicity CaO/SiO ₂		0.36	0.90	0.94	0.94	1.18	0.75	1.0	0.5
Basicity CaO + MgO/ SiO ₂ + Al ₂ O ₃		0.40	1.0	1.1	1.1	1.1	1.1	1.1	2.0
Green pellet Compression strength	N/pellet	13	16	11	11	17	13	11	14
Green pellet drop number	Times	6.2	6.8	4.6	3.6	5.0	7.8	3.6	4.6
Dry pellet strength	N/pellet	33	33	18	8.0	30	38	18	29
Fired pellet strength	N/pellet	2630	3410	3830	3500	3830	3340	3480	3440

* Grain size –0.045 mm = 85.8%; Spec surface = 1810 cm²/g; Pellet size = 9–15 mm; Moisture = 8.4–8.9% H₂O, optimum firing temperature.

indicate the influence of the mechanical properties of green, dry and fired pellets by mixing the pellet feed with various additives.

Similarly as with magnetite, the addition of basic carbonates and mixtures of other additives also has an effect on *hematite ore*. The pertinent results are shown in Table 19. As always, bentonite increases the dry pellet strength more intensively than does calcium hydroxide. A combination with limestone results even at a lower temperature in a high strength of fired pellets. Moreover, it is known that ores with a lower fines portion can also be processed into suitable pellets. This knowledge is utilized in many industrial plants where mixtures of bentonite, lime hydrate or carbonates are used. As regards the correlations between basic additives and optimum firing temperature, reference should be made to items 5.4.3.1.2 and 6.1.2.3.5 for the effect of additives on the pellet behaviour during reduction.

Table 19. Influence of additives on properties of pellets from hematite ore*

Test No.	1	2	3
Firing temp in °C	1300	1300	1280
Additives	Ca(OH) ₂ 0.5%	Bentonite 0.5%	Bentonite 0.5% Limestone 4.5%
Compression strength in N/pellet (about)			
Green	11	14	14
Dry	7	46	32
Fired	4250	2300	5240
Abrasion in % 0.5 mm	4.6	6.8	3.5

* Fe = 66.2%; SiO₂ = 3.3%; CaO = 1.0%

5.3.1.2.4 Influence of Calcium Chloride [CaCl₂] on Pellet Properties. If additives are employed to improve the pellet properties any inherent unavoidable detrimental influences should be reduced to a minimum. When calcium chloride is used, the basic constituent has, at corresponding temperatures, the same effect as other lime compounds. However, chlorine liberated during firing may cause corrosion. Nevertheless, such an additive can still be successfully employed if, by a chemical reaction between chlorine and impurities in the ore such as non-ferrous metals, copper, lead and zinc are to be removed or possibly recovered as valuable substances. Nowadays, calcium chloride is used in several industrial plants, above all for processing pyrite cinders containing non-ferrous metals. Relevant details are described under item 7.2.

5.3.1.3 Influence of Alkali Compounds

For a similar reason alkali salts are also employed during pelletizing, e.g. when vanadium-containing ores are treated. Alkali forms a soluble vanadium salt. This can be dissolved from the pellet. The influence of alkali salts is thus discussed under item 7.3. The detrimental effect of alkali salts particularly during reduction of pellets has been known for a long time and is the subject of many studies, see item 6.1.2.3. This effect is so enormous that every endeavour is made to eliminate alkali salts to the maximum possible extent from the mix to be pelletized.

Concentrates beneficiated with sea water are sometimes rewashed with water containing a low percentage of salt as, for example, in the case of Marcona concentrates.

5.3.1.4 Influence of Ores with Good Bonding Properties

The grinding expenses for obtaining the fineness required for pelletizing represent an important cost factor in pellet production. This fineness largely depends on the properties of the various ores. Crystalline ores demand a higher fineness degree than those of an earthy character, as is shown in Table 16. Consequently, one can conceivably improve the pelletizability of a crystalline ore by mixing with another ore having a greater bonding power. Such combination is possible, for instance in plants treating different ores.

For the design of a pelletizing plant at a North Sea port, this possibility was once studied. In this case, Itabira hematite was used, see item 5.3.1.2.1.1. An earthy Dogger ore with a rough, porous surface and a fines portion of 36% below 0.045 mm was used as additive; its specific surface area was 2400 cm²/g. Its chemical analysis showed the following approximate values:

Fe tot.	=22–34%
SiO ₂	=11–20%
CaO	= 8–12%
Al ₂ O ₃	= 6– 8%
MgO	= 1– 2%
Loss on ignition	=20–22%.

For many years, the above ore had been processed in German blast furnaces. The Itabira hematite had been ground to different fineness degrees between 740 cm²/g and 1720 cm²/g specific surface area. 5 and 10% of earthy ore was added to the coarser hematite ²¹). The results thus obtained are given in Table 20. From the addition of 5 or 10% of earthy ore, satisfactory pellet properties (tests Nos. 3 and 4) were already obtained with a relatively coarse grinding of crystalline ore. The addition

Table 20. Influence of earthy iron ore as additive on properties of hematite pellets

Test conditions	Mixture			
	1	2	3	4
<i>Rich hematite ore</i> (Brasil)	100%	100%	95%	90%
0.045 mm in %	67	30	30	30
Specific surface area (cm ² /g)	1720	740	740	740
Earthy low-grade ore specific surface area (cm ² /g)			830	910
Addition of earthy ore to Hematite in %	—	—	5	10
Pellet quality				
Compression strength in N/pellet				
Green	9	4	11	15
Dry	28	13	38	56
Fired	2400	1100	2500	3720
Drop number of green pellets	8	2	9	11
Abrasion index of fired pellets -0.5 mm in %	6.8	28.3	10.5	7.7

of an earthy ore from Cerro Bolivar (Venezuela) to the crystalline Kiruna magnetite concentrate exerts a similar influence.

5.3.1.5 Behaviour of Ore Mixtures

After demonstrating that the behaviour of ores during pelletizing can be improved by the addition of another ore — which need not be the rule — the question soon presents itself regarding the behaviour of several ore mixtures during pelletizing and the properties of such pellets. The treatment of ore mixtures became acute when the construction of pelletizing plants in the vicinity of blast furnaces similar to sinter plants was considered.

In such a case, it was necessary to treat ores of different origin and morphology in the form of varying mixtures, and nevertheless to produce pellets of uniform quality. Countries covering their raw ore demand mainly by imports, such as Great Britain, the European continent and above all Japan are particularly interested in the construction of such pelletizing plants. The operation of these plants which may be installed in the vicinity of sinter plants already existing offers the advantage that the ores can be processed, according to their composition, either in a sinter or pelletizing plant. The simultaneous availability of both agglomeration systems allows the application of a more flexible import strategy. First

investigations were carried out at an early date the purpose of which sometimes was the treatment of domestic ores¹¹⁾ Systematic investigations with ore mixtures from sinter plants, which were pelletized after fine grinding, were reported in 1962¹⁴⁾. At the suggestion of a German steel plant, studies regarding the erection of a pelletizing plant on the basis of imported ores in the European continent were started around 1962²¹⁾. For this purpose, seven ores and concentrates available in the European market were chosen. The pelletizing properties of some of these raw materials were already known, those of others were not. Ores especially prepared for sinter plants (sinter feed) were partly involved. The ore types, hematite and magnetite, the chemical analysis and the size portion minus 0.045 mm as well as the portions of the various ore mix constituents are compiled in Table 21. The amount of bivalent iron indicates the endeavour to maintain a uniform portion of magnetite in the mix. Similarly as for individual ores, the portion of fines minus 0.045 mm was at first varied and the green balls of 9–15 mm were fired at 1300 °C, see Fig. 64. The behaviour of mixtures is similar to that of individual ores, see Figs. 44, 45, 51, sometimes even better, see Table 20. The results of tests run on mix 2, Table 21, were not shown in the above figures, since only an insufficient number of measured values was available. However, these figures correspond with the other values.

Table 21. Chemical composition and size of various ores, concentrates and mixtures for pellet feed

Ores of various origin	Type	Size -0.045 mm	% Fe	% Portions in mixture				
				I	II	III	IV	
Sydvaranger	M ^a	57.6	66.3	6	3	4	3	
Mano river	H ^b	1.7	54.7	18	9	13	12	
Brazil fines	H	26.7	66.5	18	27	40		
Marcona (sinter feed)	M	2.6	63.0	18	9	13	12	
Krivoj rog	M	73.0	63.3	9	9	7	6	
Kiruna	M	41.7	71.9	18	37	13	47	
Bomi hill	M	2.4	65.6	13	6	10	8	
				100	100	100	100	
Chemical composition of mixtures								
				Fe tot	64.5	67.5	65.4	67.0
				Fe''	12.4	14.1	9.4	15.4
				SiO ₂	5.6	4.1	4.9	3.6
				CaO	0.3	0.3	0.2	0.2

^a M = Magnetite

^b H = Hematite

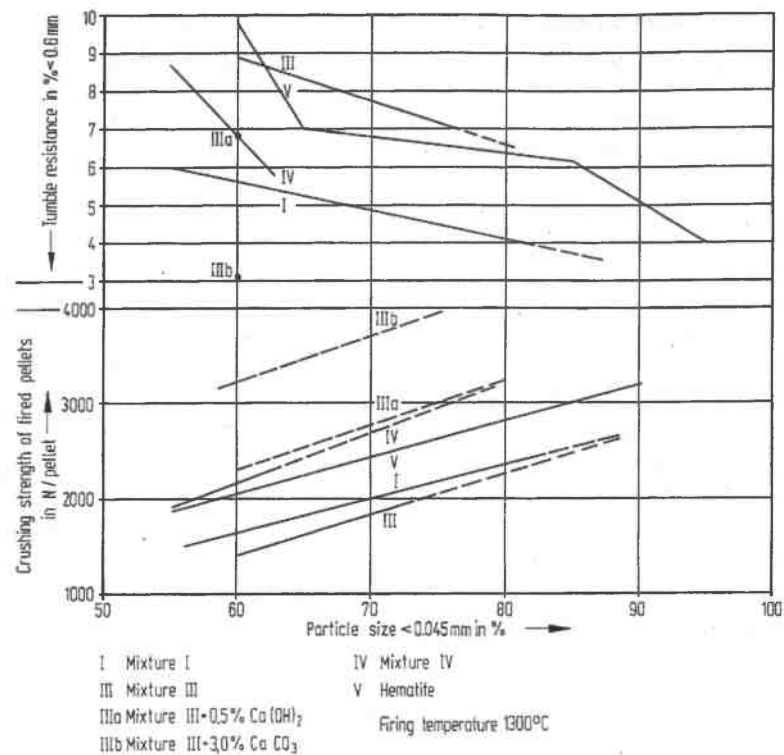


Fig. 64. Influence of particle size on properties of indurated pellets from ore mixtures

For comparison, Curve V was additionally introduced from Fig. 51 (Curve I). The difference in crushing strength between Curve V (hematite) and Curves I, IV, (mixtures) is not significant. In view of the relatively low slag portion, the formation of crystals is more important. Basic additives also have a favourable influence on mixtures, as can be seen from Curves III, IIIa, IIIb. Finally, it can be stated, that *ore mixtures* with sufficient grain size distribution or with additives can be formed into pellets of good quality, similarly as for individual ore types without any difficulties. The mix is ground to about 67% minus 0.045 mm at a specific surface area of approx. 2600 cm^2/g . Less than 0.5% bentonite is used as binder. The pellets produced meet the requirements of the blast furnace operation.

The knowledge thus acquired in the laboratory tests was realized in a commercial plant at the IJmuiden steel plant in Holland. There, a pellet plant with an annual capacity of 3.5 million tons based on imported ores⁵⁸⁾ has been operating since 1970 beside a sinter plant of equal

capacity for the production of a highly basic sinter. The combination of the two agglomeration plants can be considered as a typical example for an optimum preparation of imported ores for blast furnace operation. Bragard and Matthieu ⁵⁹⁾ reported on the construction and operation of a small pellet plant in Belgium with an annual capacity of 0.5 million tons of basic pellets from mixtures of calcareous minette, Swedish concentrate and Venezuelan hematite in different proportions. Due to the good bonding power of minette, no extraneous binders were necessary. Here also the quality of the pellets produced met the requirements of the blast furnace operation. The considerations leading to the construction of pellet plants are very interesting although at both works sinter plants were already in operation. In both cases, the extension of the agglomeration capacity was under discussion. The decision was taken in favour of the erection of a pellet plant due to the greater flexibility which was expected, and also achieved, with regard to ore import and the equally high demands made by the blast furnace operation on the quality of agglomerates. In Japan, the conditions for the construction of pelletizing plants near blast furnaces are also favourable, a fact which is confirmed by the erection of several plants with an annual capacity of about 6 million tons of pellets ⁶⁰⁾. Here, as well as in Great Britain, further plants with an annual capacity of 3 million and 5 million tons are under construction or will shortly be started up.

In this way, it has been demonstrated that based on ore mixtures pelletizing plants can be built advantageously near the blast furnaces.

5.3.1.6 Influence of Oxidized and Prereduced Return Fines

The question arises whether an influencing factor both important and necessary for down-draught sintering, namely the use of return fines, might also be of interest for pelletizing. During sintering, a high portion of 40–100% by weight of the sinter mix is continuously circulated as return fines. These return fines virtually consist of fine-grained sinter obtained during different process and transport phases. The conditions for pellet production are quite different. Pellets consist of individual balls of prescribed dimensions. The amount of fine-grained abrasive material arising during transport of indurated pellets is correspondingly low and hardly exceeds 3% in commercial plants. This low quantity is returned, normally after separate intermediate grinding, to the circulating pellet load without producing a special effect. From the process-technological viewpoint, there is thus in contrast to sintering no reason to attach great importance to the return fines problem. Nevertheless, H. W. Gudenau and W. Wenzel ¹²⁾ investigated the influence of greater return fines amounts on the properties of indurated pellets produced from different ores with the

return fines normally being present as oxidized fines. Tests with up to 35% prereduced return fines were also carried out. The results of such tests run on hematite ore with 64% iron and with a rising return fines quantity having a fineness degree of 40% -0.045 mm at optimum firing temperature are shown in Fig. 65. Curve I only shows a slight influence of oxidized return fines addition while Curve II indicates a substantial improvement of crushing strength when prereduced return fines are used.

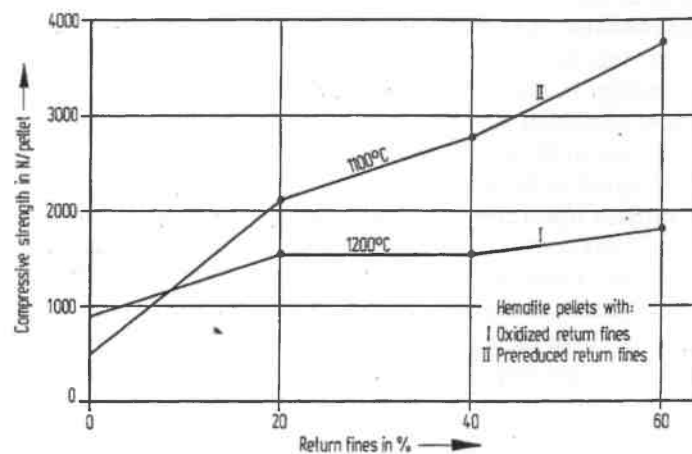


Fig. 65. Influence of oxidized and reduced return fines on compressive strength of indurated pellets

During careful firing and with a sufficient oxygen content of burning gas, reoxidation and recrystallization of the crystalline structure occurs.

Under equal oxidizing conditions, prereduced return fines could be replaced by sponge iron with the total iron being finally present as hematite in the pellet. However, it would also be imaginable to allow the metallic iron of sponge iron to react directly with iron oxides under a controlled, non-oxidizing atmosphere.

5.3.1.7 Influence of Sponge Iron on Pellet Properties

This question was thoroughly studied by the author^{62,28}. High-grade specially prepared concentrates from hematite and magnetite with iron contents of 68.9% and 70%, and SiO_2 values of 0.68 and 0.1% were ground to 2040 and 2280 cm^2/g specific surface area. Increasing quantities of sponge iron with iron contents of 96–98% at a specific surface area of 600–700 cm^2/g were added during green ball formation. Pellets of 10–12 mm diameter were produced.

5.3.1.7.1 Influence of Sponge Iron on Green and Dry Pellet Strength. It would have been possible that sponge iron could react with the moistening water during green ball formation. This *woud* have resulted in a loss of metallic iron by corrosion. However, the sponge iron used, which was produced from the concentrate involved at temperatures of 1150–1200 °C, showed a low reactivity against water during the short time of contact. In addition, the sponge iron had a relatively coarse grain size with a specific surface area as low as about 600–700 cm²/g so that after pellet drying no change of the amount of metallic iron previously added was observed. The strength of green balls formed from magnetite concentrate and sponge iron with and without bentonite addition was compared. The result is shown in Fig. 66. Without bentonite, the green and dry pellet

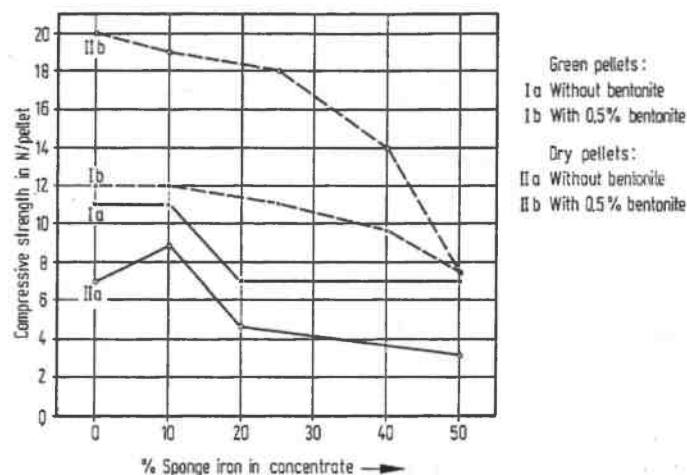


Fig. 66. Effect of sponge iron and bentonite on compressive strength of green and dry pellets

strength is very low irrespective of whether sponge iron is added or not. The rising rate of sponge iron added even decreases the strength, probably due to the coarser grain size resulting from sponge iron addition. Only bentonite raises the strength. The measurements made with hematite concentrate were similar, but lower values were obtained. The tests did not show any reaction of sponge iron. Thus, there was no danger of metallic iron being lost in this phase of pellet production.

5.3.1.7.2 Influence of Sponge Iron on the Strength of Indurated Pellets.

The purpose of these tests was to produce pellets low in gangue with a

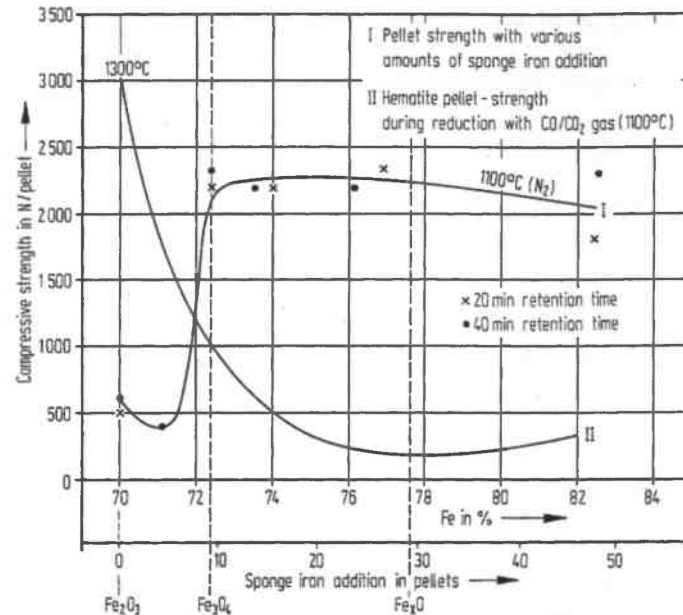


Fig. 67. Effect of sponge iron on compressive strength of indurated hematite pellets

high iron content by sponge iron addition in order to avoid the disintegration which would otherwise be expected during reduction. The metallic iron of sponge iron was to react with Fe_2O_3 and Fe_3O_4 to form lower oxides while the new crystal combinations and crystalline structures arising were to bring about the pellet strength. To avoid undesirable reactions between oxidizing heating gas atmosphere and metallic iron, the basic tests were carried out with nitrogen at temperatures between 950 and 1150 °C and an induration time of 15–40 minutes. The temperature of 1100 °C was found to be sufficient and further tests were performed at this temperature. Fig. 67 represents the influence of a rising sponge iron portion on the crushing strength, Curve I, in contrast to a decreasing pellet strength during reduction of fired pellets without sponge iron addition by using reducing gas, Curve II. When adding approx. 10 parts of sponge iron, the hematite phase is converted to magnetite, and a crushing strength of 2200 N/pellet is already achieved with no further change at higher sponge iron rates. The reaction of metallic iron with oxides is already terminated at 1100 °C after 20 minutes. Metallic iron similarly reacts with magnetite pellets having a strength of almost 3500 N/pellet, Fig. 68.

The two Figs. 67 and 68 indicate an interesting possibility for substantially improving the quality of indurated pellets which was particularly observed during their reduction, as described under item 6.2.

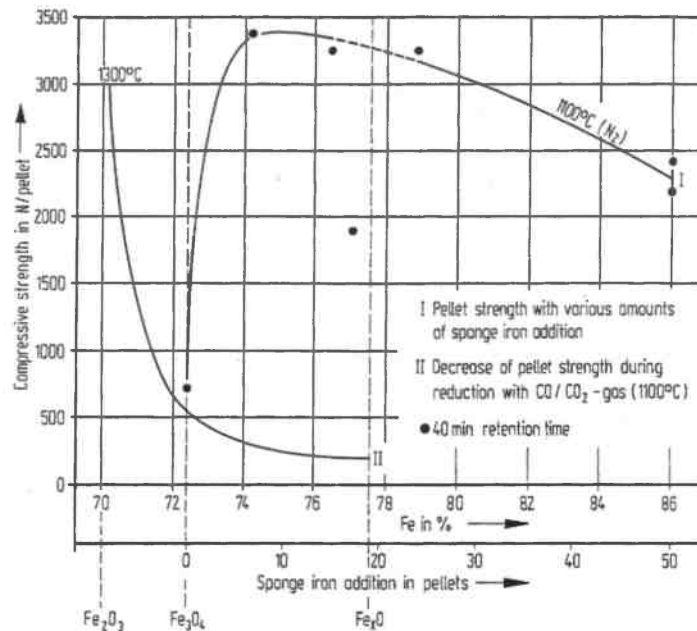


Fig. 68. Influence of sponge iron on compressive strength of pellets from magnetite concentrate

5.3.1.8 Influence of Inplant Fines on Pellet Properties

Since a growing number of pelletizing plants are erected within a steel plant complex, it is possible to incorporate a part of the inplant fines daily accumulating at the iron and steel works into the pellet feed. This refers, for example, to dust and slurries from gas cleaning installations of blast oxygen furnaces and blast furnaces, mill scale, calcareous B. O. F. slag as well as pellet fines screened out before entering the blast furnace. Above all, products with a high lime content are interesting as additives. In a pelletizing plant in Mexico, the use of such inplant fines in the mix is envisaged⁶³). Magnetite concentrates, hematite ore and inplant fines are used as iron-bearing materials. Lime compounds are added in order to produce basic pellets with a basicity of more than one. The recycled materials consist of six different constituents which have to be ground to the required fineness before they are mixed. The chemical analysis of the recycled materials is shown in Table 22. Out of a large number of tests carried out for design work, the behaviour of three mixtures is described below with the basicity having been uniformly adjusted to 1.3. The composition of mixtures is given in Table 23.

Table 22. Mixture and chemical composition of inplant fines as components of pellet feed ⁶³⁾

	Fe tot.	SiO ₂	Al ₂ O ₃	CaO	MgO	MnO	S	Composition in %
Blast furnace dust	34.8	10.2	2.7	1.1	1.2	1.2	0.4	3.7
Blast furnace slag	0.3	34.6	14.8	41.8	4.3	0.9	1.5	40.4
BOF dust	64.1	1.8	0.2	5.2	0.6	1.5	0.1	5.2
BOF slag	12.0	20.5	6.4	42.5	3.5	4.2	0.6	21.1
Mill scale	64.0	3.0	1.9	3.2	0.3	1.3	0.1	8.5
Pellet	64.8	4.3	0.8	0.6	0.9	0.1	0.02	21.1

Granulometric properties of mixture $-0.045 \text{ mm} = 55.6\%$; Spec. surf area cm^2/g 2200

Table 23. Mixture of pellet feed: ores, inplant fines, limestone and hydrated lime ³⁷⁾

	I	II	III
Magnetite	95.5	82.4	65.9
Hematite	—	—	16.5
Inplant fines	—	16.6	16.1
Limestone	3.5	—	—
Lime hydrate	1.0	1.0	1.5

The mixtures were uniformly ground to 68–71% minus 0.045 mm and a specific surface area of about 1680–1750 cm^2/g . The incorporated recycled materials have no notable negative influence on the strength of green nor on dry or indurated pellets (Fig. 69).

The abrasion resistance of all pellets has to be regarded as very good. To sum up, it can be stated that, after an adequate preparation, recycled materials can be added to the pellet mix without impairing the pellet quality – provided that they do not contain any detrimental metallurgical constituents.

This is an important contribution to the integration of pelletizing plants into the blast furnace area.

5.3.1.9 Influence of Organic Binders

Inorganic or mineralic binders additionally change the chemical composition of the indurated pellets and may influence the metallurgical

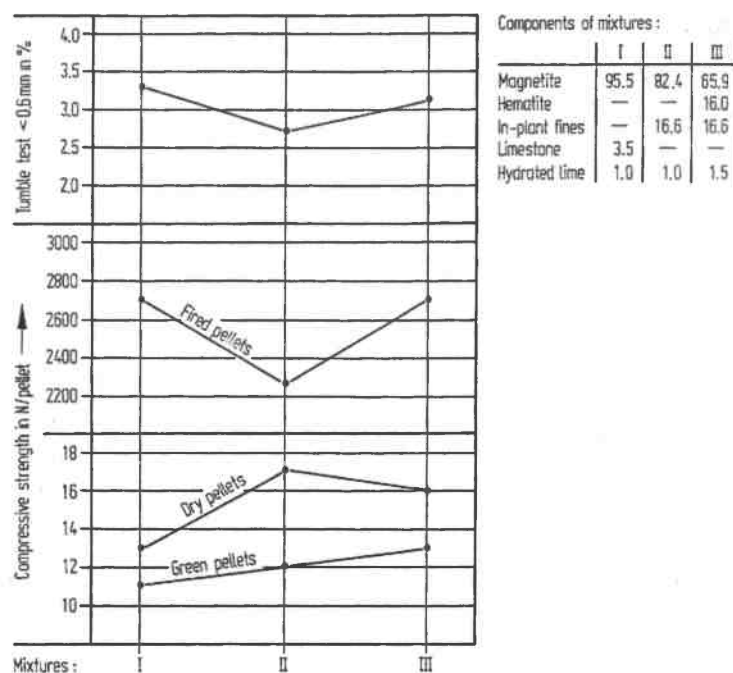


Fig. 69. Influence of in-plant fines on pellet properties

behaviour during further treatment. On the other hand, organic binders burn or volatilize at the latest during pellet firing. Consequently, they do not change the chemical composition of the pellets. At a very early stage organic binders were already tested at least on a laboratory scale. In this connection, reference should be made to the afore-mentioned patent of Andersson³⁾.

Due to the comparatively high prices of such substances, there was and is, for the most part, interest only in waste products of other industries, such as bitumen and spent sulphite liquor. In view of the considerable quantities which can possibly be added during pelletizing of iron ores, the mineral oil industry is interested in rendering such products attractive⁶⁴⁾.

Since the efficiency of organic binders is limited by the temperature, any influence on the final strength of indurated pellets is hardly to be expected. Some of such types of binders are mentioned below:

Starch is a frequently tested binder, which was added in quantities of 0.45–2.3 kg/t concentrate by Erie Mining Company during pelletizing of magnetite. Apart from an improvement of plasticity, starch primarily increased the dry pellet strength⁶⁵⁾.

Spent sulphite liquor, obtained as a by-product in the pulp and paper industry, is a product which is relatively cheap in some places. Spent sulphite liquor contributed to an improvement of the green and dry pellet strength during pelletizing of Sierra Leone concentrate. After firing, no further influence was observed.

Bitumen, a by-product accumulating during mineral oil processing, is often used as emulsion which also improves the green and dry pellet strength.

5.3.1.10 Influence of Coal Addition

In the past, the shaft furnace, as burning unit, played an important role⁴⁶⁾. However, it was difficult to ensure uniform heating of pellet feed over the whole furnace section. To achieve this goal, 1.0–1.5% anthracite was added to the concentrate or the green balls were coated with finely-ground coal. This method was previously adopted in all shaft furnace plants and also initially, even at lower coal rates, in some travelling grate plants. In the course of the years, the incorporation of solid fuel into green balls was abandoned because the difficulties during induration and above all the varying quality of indurated pellets experienced at that time outweighed the expected advantages.

Nowadays, the shortage and increasing prices of fuel oil suggest the use of coal again. Two possibilities were investigated, the addition of coal to fine particles during balling and the burning of coal in separate burning chambers. Detailed studies of coal addition are described by B. Hütter⁴⁷⁾.

Up to 2% of coals of different reactivity was added to five different ores ground to the fineness required for green ball formation. The pellet diameter was uniformly 10–12 mm. Neither the green nor the dried pellet strength changed as compared with that of pellets without coal addition. However, the crushing strength of indurated pellets decreases with coal addition of more than 0.5% for magnetite pellets and the resistance to abrasion diminishes at a coal addition of above 1%. On the other hand, it was possible to raise considerably the capacity of the pelletizing travelling grate for hematite pellets. Therefore, the negative and positive influences are to be outweighed for each particular case.

Fig. 70 shows the influence of increasing coal additions on hematite and magnetite pellets. In the case of hematite, the strength rises up to about 0.5% coal addition. The strength then decreases but is still sufficient up to 1.5% coal addition. This influence is explained by partial reduction of hematite to magnetite and subsequent incomplete reoxidation of magnetite to hematite. Higher coal additions may even result in a further reduction towards the formation of wüstite which, within the time available, does not reoxidize again and forms fayalite with the silica

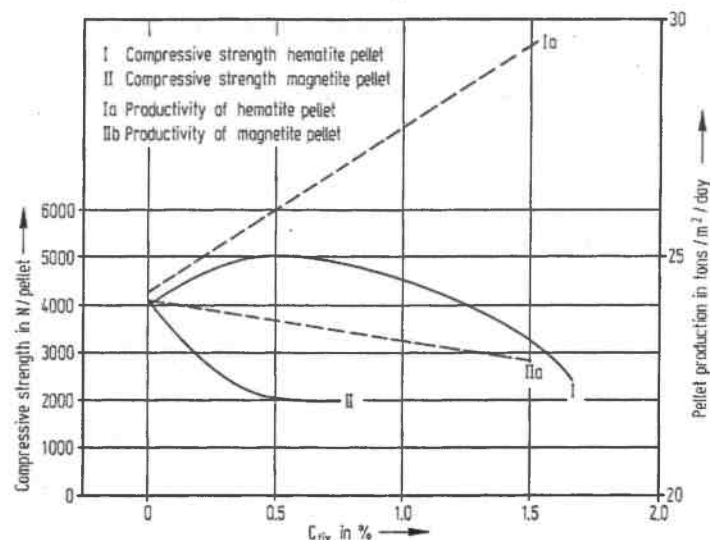


Fig. 70. Influence of coal addition on pellet strength and productivity of travelling grate

present. At present, the pelletizing plant at Ijmuiden is being operated with low addition of ground coke which allows a reduction of natural gas consumption without impairing the pellet quality.

Other travelling grate plants are using meanwhile also coal addition successfully.

Development work was recently started to burn the coal in suitable combustion chambers and to introduce hot combustion gases exclusively into the burner hood. A detailed description of this interesting application of firing technology to pelletizing plants is given in the Skillings Mining Review⁶¹⁾.

5.3.1.11 Summarizing Considerations

Binders were already used in the first pelletizing tests. Water-soluble salts were preferred which form salt bridges during drying thus improving the mechanical strength of pellets. Nowadays, salts are used in few special cases only.

Binders and additives are at present selected according to the following aspects:

- Improvement of green ball properties, above all better plasticity for increasing the drop resistance during transportation.
- Increase of dry pellet strength for the subsequent heat treatment stages.

- (c) Improvement of indurated pellet properties, in principle, their behaviour during reduction.
- (d) Binders should be cheap and not adversely affecting the chemical composition of pellets and operation.
- (e) Nowadays, alkaline earth compounds of different mixtures are preferred. One attempts to keep the bentonite addition at a minimum.

In all plants at present in operation, binders and additives are used. In the meantime, a separate industry has developed for providing additives and binders.

5.4 Influence of Thermal Treatment on Pellet Properties

The considerations relating to the fundamentals of pellet production (item 2.2) already demonstrated the great importance of thermal treatment for the final pellet quality. Furthermore most binders and additives only become fully effective in conjunction with heating and firing. The treatment can be divided into three (thermal) phases:

- (a) Drying at 250–400 °C
- (b) Preheating up to 1100–1200 °C
- (c) Firing at 1200–1350 °C.

The time and velocity of the necessary temperature rise depend on the properties of the individual ores and mixtures. The importance of the drying phase and its bases were already explained under item 2.2.1. In this connection, the various factors were indicated which become effective and influence the pellet quality. The principal factors are described below. In view of the complexity of this procedure, mathematical considerations have additionally been made for interested readers and set forth under item 13.3.

5.4.1 Factors Influencing Green Ball Drying

For clarification of the drying procedure, it appeared advisable – to consider further aspects⁶⁹⁾. The most important factor influencing the drying procedure is the drying medium: drying air or drying gas. Variable factors are temperature, velocity of gas flow, and drying time. They not only determine the pellet quality but also influence the time of total thermal treatment and thus, the burning unit capacity, see Figs. 83 and 84. These three factors are interdependent. The effect of one should only be considered in conjunction with others. For the relevant tests a tube

furnace, shown in Fig. 36²⁾), item 4.5.1, was used. Pellets of 10–12 mm diameter produced from a magnetite-hematite concentrate with 67.5% iron and optimum size distribution were tested. The bed height applied in the tests was 6 cm. The criterion for the drying progress is the drying degree “ τ ” which can be represented by the following formula:

$$\tau = \frac{\text{Initial-final moisture}}{\text{initial moisture}}$$

When “ τ ” reaches the value one, the drying is terminated. The following parameters were varied.

5.4.1.1 Temperature of Drying Gases

5.4.1.1.1 Influence of Drying Gas Temperature on Drying Time. The greater the temperature difference between drying medium and green ball feed, the shorter is the period required for drying. The temperature of the medium should therefore be as high as possible. The temperature influence at a predetermined velocity of flow of drying gas is shown in Fig. 71. For reasons set forth in Figs. 15 and 16, item 2.2.1 the drying velocity is not in parallel with the temperature. From a temperature of about 250 °C, the drying slows down more and more. The time for water evaporation and steam diffusion in the pellets are limiting factors. The drying temperature is further limited by another pellet property, viz. the shock behaviour of green balls.

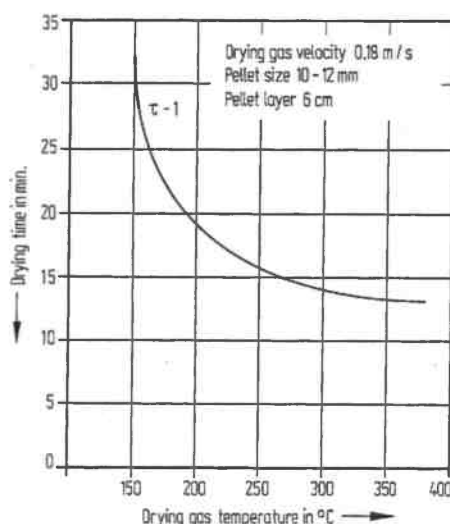


Fig. 71. Effect of drying gas temperature on drying time

5.4.1.1.2 Influence of Temperature on Shock Resistance of Pellets During Drying. As indicated under item 2.2.1.4, the shock temperature is of decisive importance for the pellet quality. The shock behaviour of each individual ore is a limiting factor for the drying temperature and drying speed. It is virtually determined by the type of ore, granulometric properties of ore, porosity of the green balls and binders. Owing to the effect of drying temperature on the drying time, one attempts to improve the shock temperature possibly by the addition of binders as explained in the following test ²⁸⁾. The shock temperature of green balls of 10–12 mm

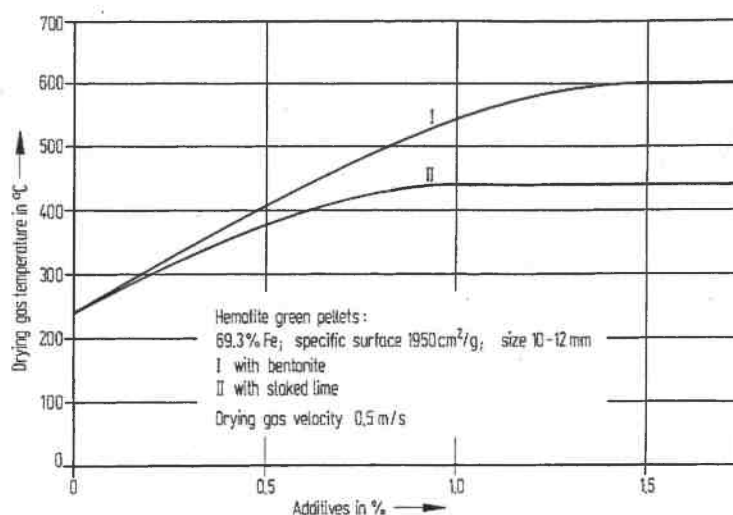


Fig. 72. Influence of drying gas temperature on shock behaviour of pellets with and without additives

diameter produced from Itabira blue dust with 69.3% iron was ascertained with and without the addition of bentonite and lime hydrate. The results obtained are shown in Fig. 72. Depending on the green ball structure the maximum permissible shock temperature of 240 °C without binders can be raised up to 600 °C with bentonite and up to 440 °C with lime hydrate addition before the pellets start to be damaged. The result refers to this specific ore, but can be regarded as typical for the drying procedure and shock temperature of green balls from other ores.

5.4.1.2 Influence of Velocity of Drying Gas Flow on Drying Degree

The velocity of flow is measured in meters per second at 0 °C and 1.0 bar referred to the free sectional area of the furnace as $W_0 = \text{Nm/s}$.

This velocity of gas flow is an important factor for the dimensioning of fans in the drying zone and for the size of reaction surface of travelling grates or the volume of shaft furnaces or rotary kilns. Optimum design data are obtained by pot grate tests.

Three different air velocities of $W_0=0.045$, 0.27 and 1.29 m/s were applied. The latter value is already within the range of velocities occurring in a travelling grate pelletizing plant. Fig. 73 very clearly shows the influence of air velocity. At a velocity of 1.29 m/s the drying is already terminated after five minutes while the drying takes 14 minutes at an air velocity of 0.27 m/s. Consequently, an optimum velocity of flow is to be aimed at.

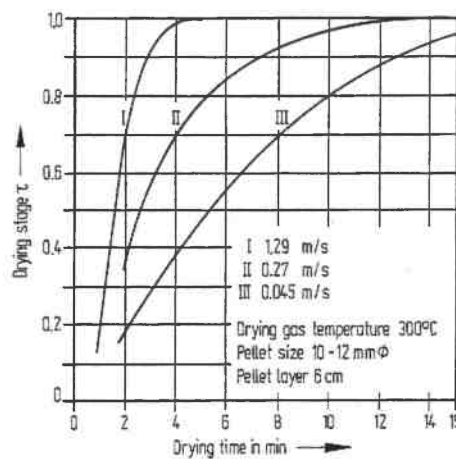


Fig. 73. Effect of drying gas velocity and time on drying stage

5.4.1.3 Change of Pellet Strength During Drying

The basic conditions for the green and dry pellet strength are very different. The crushing strength of *green* balls is chiefly determined by the capillary forces of water. It reaches its maximum value when the liquid filling degree in the capillaries is about $0.8-0.9$. During drying, the liquid bonds are reduced and gradually replaced by others. In the case of dry pellets, solid bonds are virtually effective between the ore particles. It is important that the pellets retain sufficient strength even in this intermediate stage to withstand the mechanical stress both in the shaft furnace and on the travelling grate. D. F. Ball⁶⁹⁾ studied the strength of magnetite and hematite pellets with and without the addition of bentonite and iron sulphate during drying. At the beginning of moisture removal, he

observed a slight strength increase and, shortly before the final drying, a minimum strength. Gudenau, Wenzel und Izgiz⁷⁰⁾ found an intermediate strength increase during drying for different ores, and this strength increase was far above the green and dry pellet strength. From this it follows that the capillary forces become more effective during drying than during moistening and green ball formation.

If drying is achieved in a pellet layer, the strength indices vary according to the progress of the drying front, so that the strength is slightly different in the various pellet layers. In a test²¹⁾ run on pellets of 10–12 mm diameter and with a moisture content of 7.5%, the drying progress and the corresponding pellet strength were investigated in two layers each of 6 cm height. To ensure that a measurable dry pellet strength can be achieved, 0.7% bentonite was added to the mix. The variation of the moisture content of the bed as well as the strength of the upper and lower layer were ascertained. The measurements were made every minute. The results obtained are shown in Fig. 74. A greater top layer strength as opposed to bottom layer strength can be clearly observed which means that the pellet strength varies with the moisture content during drying. Towards the end of the test, the strength curves approach each other.

The observation made with a 12 cm bed height can be analogously applied to greater bed heights. As can be seen from Fig. 18, item 2.2.1, it may happen that the drying zone is already overlapped by the preheating zone which directly follows. As is apparent from Table 4, item 2.2.1, the

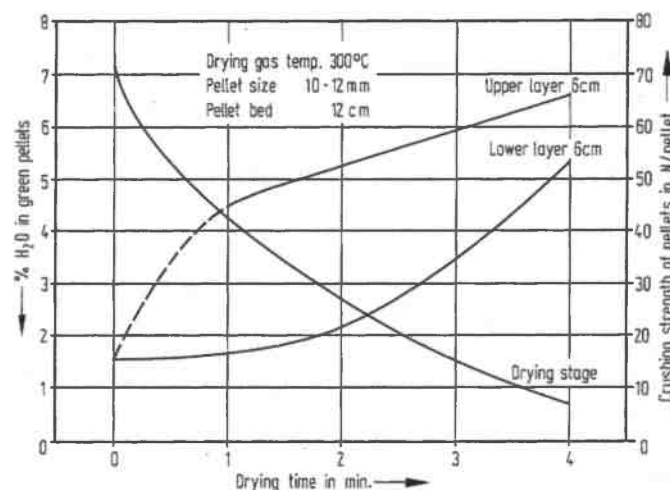


Fig. 74. Difference of compressive strength in two layers of a green pellet bed during drying

drying strength of pellets without binder addition is often insufficient to meet the mechanical requirements. Since nowadays practically all pelletizing plants are operated with binders as is described under item 5.3, a sufficient dry pellet strength is ensured in industrial plants.

5.4.2 Preheating of Dried Pellets

The preheating zone is the thermal link between the drying and firing of pellets. It ranges from 300/400 °C up to 1200 °C. As already indicated under item 2.2.2, different reactions may develop simultaneously or consecutively during preheating. These reactions such as decomposition of hydrates, carbonates or sulphates as well as roasting of sulphidic constituents may be important both for the final pellet quality and for the capacity of pelletizing plants. Last but not least all iron oxides besides hematites are converted into the highest oxidation stage, namely hematite. The preheating velocity in this zone must be harmonized with the compounds to be decomposed and oxidized.

The oxidation of magnetite is most important since it has a decisive influence on both the mechanical strength and the behaviour during reduction. During magnetite oxidation, the bivalent iron is converted to trivalent iron (see item 5.4.3.1). The progress of oxidation is normally analytically ascertained through the remaining part of bivalent iron. After complete oxidation, bivalent iron should no longer be present. However, it is also possible to analyse the progress of oxidation through the change of weight during magnetite preheating under oxidizing atmosphere ⁷¹⁾).

5.4.2.1 Change of Weight and Strength During Drying and Preheating of Green Balls

During drying, the weight of green balls diminishes by the quantity of moistening water evaporated until a constant weight is reached.

Ores with decomposable compounds containing hydration or crystallization water or carbonates vary their weight in accordance with the new compounds thus arising. For instance, in the case of magnetite pellets, the weight again rises when the oxidation starts. Here and also in the other compounds, a constant weight is only achieved when the iron oxides have finally been converted into hematite. At the same time, a different increase of pellet strength may occur during drying and, above all, during heating. The different behaviour of magnetite and hematite green balls was comparably investigated ²⁸⁾ and the results obtained are shown in Fig. 75. The principal test data were as follows: Magnetite pellets with 71.3% iron and 6.8% water, pellet diameter: 10–12 mm, specific surface area of concentrate: 1810 cm²/g.

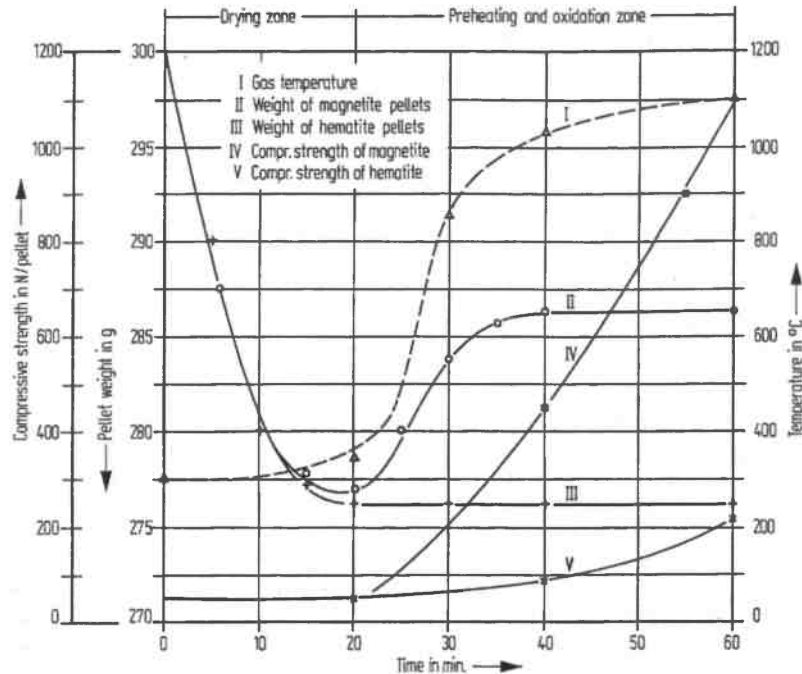


Fig. 75. Combined effect of drying gas temperature and time on green pellet weight and compressive strength

Hematite pellets with 64.6% iron, 7.1% water, pellet diameter 10–12 mm, specific surface area: 1845 cm²/g, pellet bed height: 6 cm, weight of wet pellets: 300 g, initial temperature of heating air: 300 °C, relative heating air velocity: 0.09 m/sec.

The measurements were made in the tube furnace represented in Fig. 36, item 4.5.1. The low air velocity was intentionally chosen in order to avoid too rapid a heating and to extend the heating procedure. Both ore samples had practically no loss on ignition. In this way, the drying and heating could be carried out speedily.

Curve I of Fig. 75 shows the average temperature gradient in the pellet layer.

After the drying of magnetite pellets (Curve II) had been terminated – after 20 minutes, the minimum weight had been reached – the oxidation started at 400 °C with weight increase. The oxidation is terminated at about 1000 °C and constant weight. During oxidation, the crushing strength continuously rose and reached about 1100 N/pellet at 1100 °C (Curve IV). The arising hematite crystals (see Fig. 20) formed the first crystal compounds.

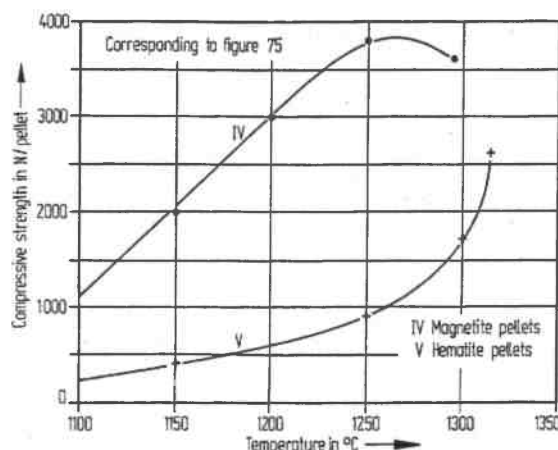


Fig. 76. Effect of rising gas temperature on pellet strength, supplement to Fig. 75

The corresponding curves for hematite pellets develop quite differently. After drying, a constant weight is obtained which is maintained during induration (*Curve III*). In the case of hematite, a bridge formation occurs only at higher temperatures so that up to 1100 °C a low crushing strength of about 200 N/pellet is observed, (*Curve V*). The different strength development in curves IV and V shows that the hematite produced from oxidized magnetite has a much higher reactivity and that crystal growth already occurs at lower temperatures, as is further apparent from the complementary curves IV and V in Fig. 76.

5.4.3 Firing and Cooling of Pellets

During firing as well as cooling, those pellet properties should be obtained which are required for their further treatment. The firing directly follows the preheating. According to the ore type, quantity and composition of additives, it is carried out at temperatures up to 1250 °C and 1350 °C under an oxidizing atmosphere. A certain minimum temperature has to be attained in order to enable the necessary crystal transformations and the reactions of oxidic gangue constituents. The maximum temperature is limited by the beginning dissociation of hematite and sticking of pellets because of softening of constituents. The optimum firing temperature and cycle in conjunction with the corresponding firing period is the *decisive influencing factor* for pellet induration.

Practically all the other influencing factors either granulometric properties or the various additives only become fully effective at the optimum

thermal treatment. Besides the strength increasing reactions others occur in parallel which have partly begun already in the preheating zone, such as decomposition of carbonates or sulphates and the rest of hydrates. Exothermic reactions too, mainly the oxidation of magnetite, may play a certain role at the beginning of the firing zone. It is necessary to control these partly opposed reactions by the speed of heat supply so that a decrease of pellet quality is avoided. The smaller the number of influencing thermal factors to be adapted to each other, the simpler is the control of preheating and firing temperature. From this comes the attempt to use, if possible, *one single* outer heating source, such as oil or gas, but not simultaneously coal. The heat supply has to be so proportioned that the temperature steadily rises. Too slow a heating has no negative influence on the pellet quality but the firing time is extended which results in a capacity decrease of firing units. Too rapid a heating can bring about a heat accumulation in the pellet surface which causes overheating and, thus, a quality decrease. The greatest additional influencing factor is the oxidation of magnetite which has to be incorporated into the firing pattern during preheating and firing.

5.4.3.1 Heat-Hardening of Magnetite Green Pellets

Magnetite is almost exclusively processed as concentrate. The concentrate can originate either from natural magnetite-containing ores or

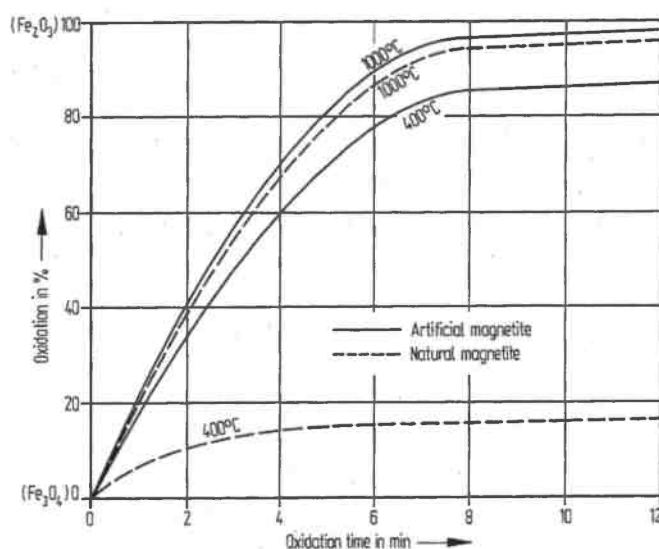
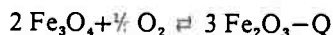


Fig. 77. Oxidation of natural and artificial magnetite during thermal treatment under oxidizing atmosphere

from other ores as a result of magnetizing roasting followed by magnetic separation. The artificial magnetite has a much higher reactivity than natural magnetite. This is particularly demonstrated by the oxidation to hematite, which in the case of artificial magnetite already starts at lower temperatures and proceeds more quickly than with natural magnetite. Fig. 77 shows the considerable difference. For example, the oxidation degree of artificial magnetite is at 400 °C nearly identical with that of natural magnetite at 1000 °C.

During this oxidation, magnetite is converted to hematite. The mechanism of this oxidation was the subject of intensive investigations¹¹⁾ and does not yet appear to be fully clarified. The following factors are of importance during oxidation: temperature, gas flow, velocity and oxygen partial pressure of heating gases, grain shape and grain size of concentrates. The porosity of dry pellets plays a certain role. According to the present state of knowledge, the oxidation proceeds in two subsequent partial phases to $\gamma\text{-Fe}_2\text{O}_3$.

The first phase proceeds much more quickly than the second. The oxidation is an exothermic reaction according to the formula:



The Q value is approximately 260 kJ/Mole. This additional heat source has to be considered and used accordingly during preheating and firing.

Due to oxidation heat, the pellet core is heated to a higher temperature than the pellet surface. This involves the risk of a more intensive sintering or even melting of pellet core and due to shrinkage its separation from the pellet shell which results in a considerable pellet quality impairment¹²⁾. The adaptation of oxidation velocity to firing velocity has a positive effect during firing of magnetite pellets. At a constant pellet quality, the heat consumption, firing unit capacity and firing temperature are more favourable than during firing of hematite pellets.

During the oxidation of magnetite to hematite, first hematite crystals are already formed at low temperatures on the edges and surfaces of ore grains and crystals. These crystals simultaneously cause the formation of the first bridges as shown in Fig. 20, item 2.2.2.1.1. At 1150 °C magnetite pellets already reach a strength of 1100 N/pellet while the hematite pellets only have a strength of about 200 N/pellet. When the firing temperature is further raised, the strength increases, as can be seen from Fig. 76. This figure is to be considered as a supplement to Fig. 75. Curve IV shows the further strength development of magnetite pellets and Curve V that of hematite pellets. The corresponding variation of crystalline structure, shown in Figs. 21 and 24 of item 2.2.2.1.1/2 should be noted.

Callender¹³⁾ studied the influence of the preheating and firing temperature on pellets produced from artificial magnetite concentrate with and

without additives. The crushing strength of pellets produced without additives rises up to a temperature of 1300 °C. The influence of 1% lime hydrate was clearly perceptible by temperature decrease.

5.4.3.2 Influence of Firing Temperature and Basic Additives on the Strength of Pellets from Magnetite Ores

According to the chemical composition of ore or concentrates and the intended use of pellets, the basic additives are varied. Quantity and type of additives determine the optimum firing temperature.

Interdependence between these two factors and time can be observed from Figs. 61 and 62 of item 5.3.1.2.2. Without additives, a specific maximum strength is achieved, Fig. 61. This strength can be substantially increased with the use of additives, Fig. 62. For an equal pellet strength, it should be possible to lower the firing temperature accordingly when basic additives are used. The result of such test series²⁸⁾ is represented in Fig. 78. Two magnetite concentrates with portions of 10% SiO₂ and 1% SiO₂ were fired with different amounts of basic additives at such temperatures which are permissible for the highest pellet strength *without* additives. The concentrate with a high gangue content (*Curve I*) had reached its optimum strength of 3500 N/pellet at a temperature of 1250 °C, whereas the concentrate low in gangue had achieved its maximum strength of 2500 N/pellet at 1350 °C. With an increasing rate of

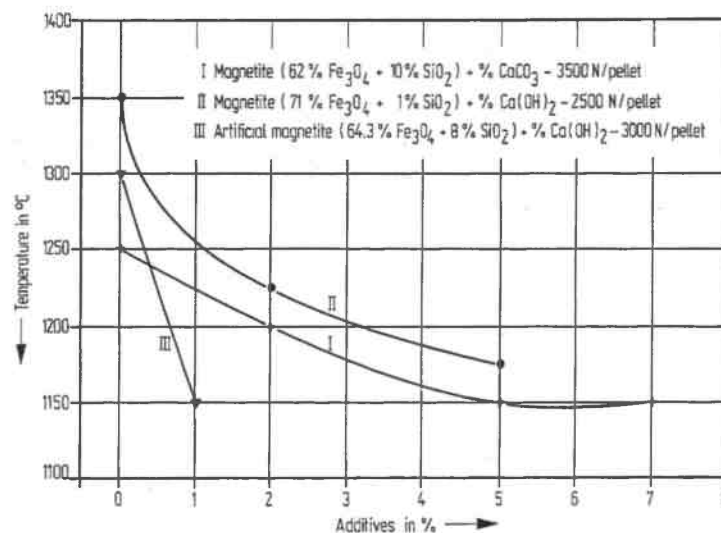


Fig. 78. Effect of additives on induration temperature of pellets from magnetite at equal strength

additives both concentrates can be indurated at much lower temperatures for obtaining constant strength. $\text{Ca}(\text{OH})_2$ (*Curve II*) or CaCO_3 (*Curve I*) have a similar influence. Artificial magnetite with 64.3% Fe and 9% SiO_2 reacts more sensitively to lime hydrate addition (*Curve III*).

5.4.3.3 Firing of Hematite Green Pellets

In the case of magnetite and natural hematite, the pellet strength is virtually determined by crystal modifications. In contrast to pellets from magnetite concentrates the solidification of hematite pellets has to be

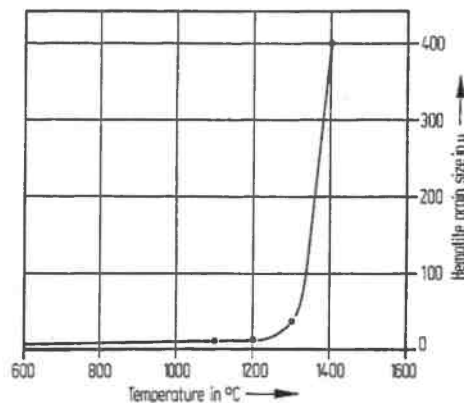


Fig. 79. Influence of firing temperature on grain growth in hematite pellets

achieved by crystal growth in one step only. This requires a higher induration temperature and longer firing time as already explained under item 2.2.2. The importance of the temperature for the growth of crystals from hematite pellets with 99.5% Fe_2O_3 is shown in Fig. 79³²⁾. Only from 1300 °C onward was a notable change of particle size observed. In parallel to this growth and bridge formation, the strength increases with rising temperatures, as is apparent from Curve V of Fig. 76 referring to pellets produced from natural hematite ores. Only at temperatures above 1250 °C is an appreciable increase of crushing strength obvious, which reaches its optimum value at 1320 °C. In this connection the visible crystal changes on micrographs Nos. 24/25 of item 2.2.2.1.2 which occurred at rising temperatures are informative. The crystal growth is not only dependent on the temperature but also on the time, as shown in Fig. 80³⁴⁾. At a firing temperature of 1250 °C, 30 minutes are needed in order to obtain a specific crystal size, but only five minutes at a temperature of 1350 °C.

5.4.3.4 Influence of Temperature and Basic Additives on Hematite Pellet Quality

Basic constituents reacting with hematite should also have a temperature-decreasing effect as demonstrated by Fig. 81. For pellets from magnetite, a similar influence is shown in Fig. 78.

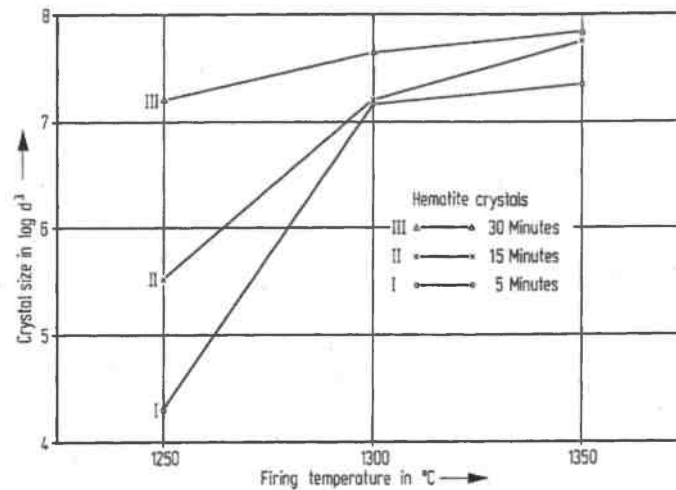


Fig. 80. Crystal growth as function of firing temperature and time

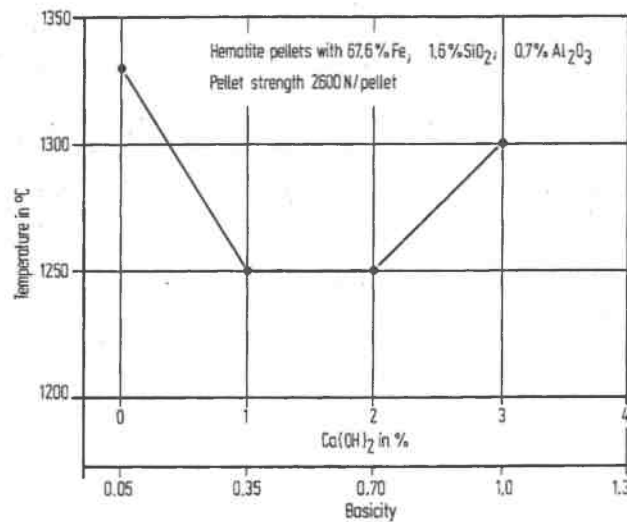


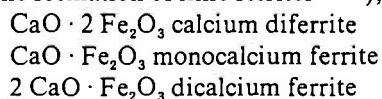
Fig. 81. Influence of additives on firing temperature of hematite pellets of equal strength

5.4.4 Reactions of Additives with Iron Oxides and Gangue Constituents

During the thermal treatment of pellets containing basic additives, the latter should form compounds with the gangue minerals or iron oxides at appropriate firing temperature. During induration, primarily Fe_2O_3 , CaO and SiO_2 react with each other with the iron portion greatly dominating, Fig. 26, item 2.2.2.2. The iron oxides Fe_2O_3 , Fe_3O_4 and FeO influence the type of the new arising compounds. In view of the short firing period at optimum temperatures, balances according to the phase theory can hardly be expected. Nevertheless, the study of the correlations between the individual constituents shown in the equilibrium diagram indicates the direction in which the mineralogical compounds to be expected may develop. The kinetics of the formation of individual phases due to reaction in a solid phase play an important role. The equilibrium relations of the three constituents $\text{Fe}_2\text{O}_3 - \text{CaO} - \text{SiO}_2$, which may also be influenced by other factors, have been repeatedly investigated ⁷⁴⁾.

For a better explication of these correlations, it is advisable to consider the system $\text{Fe}_2\text{O}_3 - \text{SiO}_2$, $\text{CaO} - \text{SiO}_2$ and $\text{Fe}_2\text{O}_3 - \text{CaO}$. The low reactivity of SiO_2 with Fe_2O_3 is known ⁷⁵⁾.

At adequate firing temperatures, Fe_2O_3 reacts, according to the CaO concentrations, by the formation of lime ferrites ^{76/77)}, such as:

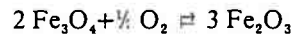


of which $\text{CaO} \cdot \text{Fe}_2\text{O}_3$ is most interesting for pellet production. CaO and SiO_2 already react at 1000°C in a solid state to form orthosilicate, $\text{CaO} \cdot \text{SiO}_2$.

When all the three constituents react under an oxidizing atmosphere, a glassy slag phase is virtually formed up to a basicity ($\text{CaO} : \text{SiO}_2$) of 0.8 from which it is difficult to identify clearly a defined mineralogical phase, such as $\text{CaO} \cdot \text{SiO}_2$ ³¹⁾. Apart from the matrix of Fe_2O_3 , the glassy phase contains $\text{CaO} - \text{SiO}_2$ and varying quantities of Fe_2O_3 . As soon as the system approaches reducing atmosphere, iron-containing olivines with different melting points are formed ⁷¹⁾, as set forth under item 6.1.2.3, and the following items, with the pellet properties being highly influenced during reduction. At a basicity higher than 0.8, lime ferrites may be additionally present which have a positive effect on the reduction behaviour.

5.4.5 Thermal Dissociation of Hematite in Pellets

After the usual firing, the iron oxides should always be present as hematite in the indurated pellets. The following considerations thus refer to all pellet qualities. The equilibrium of the reaction:



shifts to the right up to a temperature of about 1400 °C. However, at a higher temperature, a dissociation of hematite (see item 2.2.2.1.2) begins. The equilibrium again shifts to the left causing once more the formation of Fe_3O_4 and, thus, an impairment of the pellet quality. This hematite dissociation starts at lower temperatures if the pellets contain basic additives. According to the quantity of these additives, the dissociation temperature lowers and the magnetite portion in the pellet rises, as shown in Fig. 82³⁴⁾. By magnetometric measurements, the Fe_3O_4 portion in the pellet was ascertained at different temperatures and with different additives. Without additives, the hematite pellet practically remains without magnetite portion even at a temperature of 1400 °C (Curve I). An increasing CaO content in pellets favours the hematite dissociation (Curves II, III and IV). This phenomenon is explained by a temperature rise inside the pellets, due to the exothermic heat of formation of calcium ferrites and their additional melting heat which brings about an overheating in the pellet core to temperatures exceeding 1400 °C and thus hematite dissociation. The exothermic heat caused by the formation of ferrite may lead to an overheating and softening of the pellet core and to

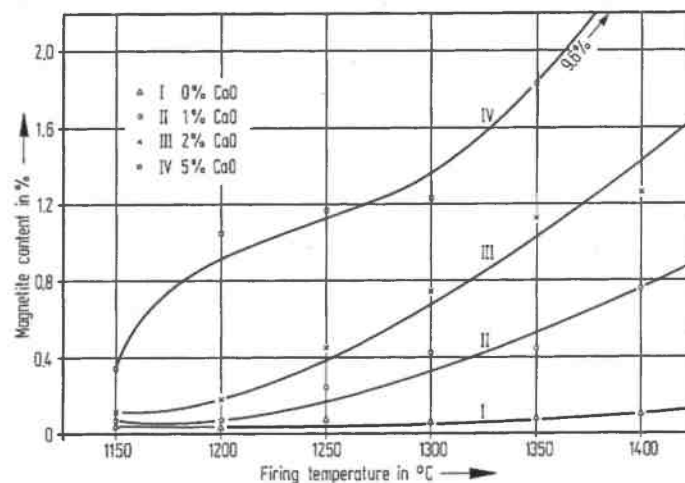


Fig. 82. Effect of additives on dissociation temperature of hematite in pellets

the formation of a glassy structure whereby reoxidation during cooling is hindered. The dissociation tendency of CaO-containing pellets can only be reduced by a drastic lowering of firing temperature.

As regards pellets produced in industrial plants, the question regarding hematite dissociation always arises so that great attention is given to the upper limit of firing temperature and the necessary firing time in each pelletizing plant. In relevant investigations, it has not yet been possible to clarify all questions since various authors are still of different opinion concerning temperature and dissociation⁷⁹⁾.

5.4.6 Scheme of Thermal Treatment

All phases of thermal treatment are consecutive irrespective of the firing system applied. In this connection, various influencing factors should be adapted to each other:

- (a) The *temperature* is different for each reaction,
- (b) The *time* is needed for the development of the individual reactions,
- (c) The *heat supply*, by means of heating gases, provides the various stages with the heat energy required. It is controlled by the heating gas flow.

The combination of these three process parameters represents the firing pattern according to which the optimum pellet quality and the burning capacity can be predetermined in the laboratory irrespective of the type of raw materials used. According to the characteristics of ores, binders and additives, firing patterns have been developed which proceed differently in the various process stages. For the principal ore properties, typical firing patterns are described below by way of example of the travelling grate pelletizing system²¹⁾ since in this system the temporal and local thermal treatment phases can be clearly overlooked. In principle, the succession in thermal steps is similar in other firing systems.

5.4.6.1 Heating Pattern for Pellets from Magnetite

The tests for elaboration of the firing pattern can be carried out in the pot grate and measuring devices described under item 4.5. According to the process stage involved, the direction of flow of the process gases is changed. Up-draught and down-draught is applied for drying, down-draught for preheating, firing and after-firing and again up-draught for cooling. The temperatures above the pellet bed are measured (T_1) as well as those between pellet bed and hearth layer (T_3), in the middle of the bed (T_2) and in the windbox (T_6). Pressure, suction and gas volumes are also recorded. A typical firing pattern for magnetite pellets of 10–15 mm diameter is shown in Fig. 83.

Side wall layer and hearth layer were used. The tests were performed in the equipment shown in Figs. 39 and 40, item 4.5. Temperature and pressure are indicated on the ordinates, time on the abscissa. The drying is achieved below the shock temperature e.g. of about 300 °C. During heating, the oxidation of magnetite with the simultaneous beginning of the relatively short firing time at induration temperatures of about 1300 °C is sufficient. As the heat front proceeds in the pellet bed, the bottom layers are heated accordingly, as is seen from rising temperatures T_2 and T_3 . After a certain firing period controlled by the individual temperature measurements the heat supply is stopped. The sensible heat from the upper layer is now sucked into the layers underneath. In the case of magnetite pellets, it may serve to oxidize any still remaining magnetite and, generally, to terminate the crystal change. The succeeding cooling is achieved at constant cooling air pressure.

The firing progress is also controlled by the temperature change of waste gas inside the windbox (T_6). The pressures or suction are adjusted to the pertinent process stage in order to control the gas and heat flow. Thus, the pressure applied for up-draught drying and cooling is relatively high since, here, no damage to the pellet structure is to be feared whereas

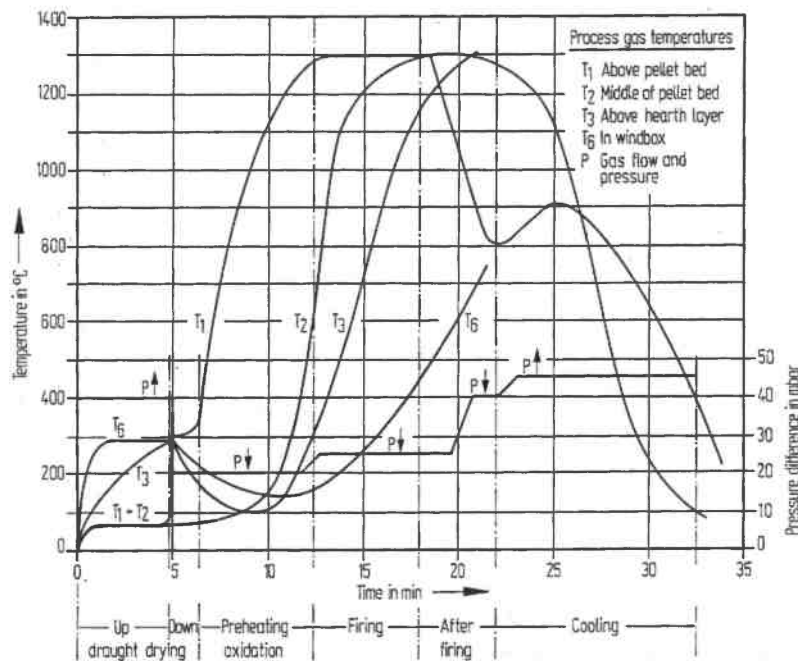


Fig. 83. Pattern of thermal treatment for pellets from magnetite concentrate

during down-draught drying and preheating low pressure differences are maintained.

Even though this firing pattern is typical for magnetite pellets – longer preheating time, shorter firing period – the principle is also applicable to pellets with other chemical compositions. The various process stages and periods can be adapted to each other according to the ore types involved as well as the nature and quantity of the additives used.

5.4.6.2 Firing Pattern for Pellets from Other Ores

For the following ore types, firing patterns have been developed by computer calculation, (Fig. 84):

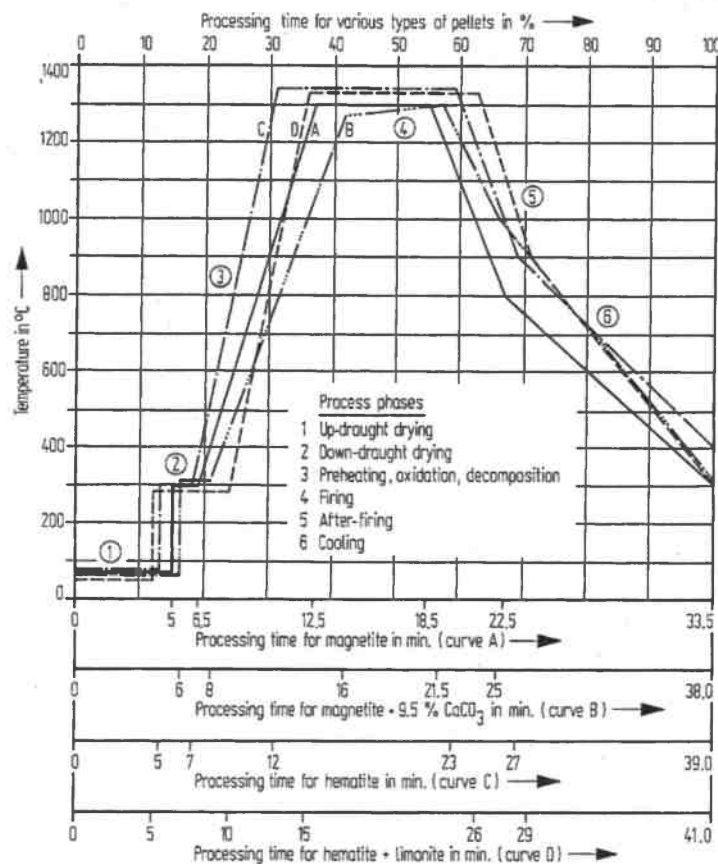


Fig. 84. Pattern of thermal treatment of pellets from various ores, relationship between time and induration temperature

- (A) magnetite concentrate
- (B) magnetite concentrate + 9% CaCO_3 (0.64 basicity)
- (C) hematite ore (itabirite)
- (D) hematite-limonite mix.

The different periods of thermal treatment were equalized to 100% for all pellets. In this way, the various process stages can be directly compared with each other. The firing temperatures (ordinate), the periods in minutes required for the individual process stages and the percentages were plotted on the diagram. The various process stages are marked by 1–6. The *drying* periods 1 and 2 resulted from the pertinent moisture content of green balls.

During preheating 3, considerable differences were found. The two magnetite pellet types A and B need a relatively long preheating time because the oxidation to hematite takes place simultaneously; the difference between A and B results additionally from the carbonate dissociation, Curve B. The two hematite curves, C and D, are steeper since in this case only the preheating of hematite crystals is achieved and no reaction takes place.

Nevertheless, there is a small difference between C and D since additionally in the case of D, a small amount of combined water from the limonite portion is to be liberated.

Marked differences exist during pellet firing. The magnetite pellets A necessitate shorter firing periods since, during oxidation, the solidification has already started intensively in the preheating phase. In the case of B, the positive influence of the basic additives, due to temperature decrease, is still perceptible. For hematite pellets, the firing periods are considerably longer in order to ensure hematite crystal growth. For this purpose, higher firing temperatures are also required. In the *after-firing* zone, no marked differences occur.

During *cooling*, there are hardly any differences. In this case, uniform cooling of hematite pellets produced from all ores during firing is achieved. If the real firing periods on the abscissa are compared with each other, very considerable differences of 33–41 minutes are observed. These differences are decisive for determining the throughput of the various firing units during induration of different ores.

6 Behaviour of Indurated Pellets During Reduction

Since it is possible to produce pellets of uniform quality by – suitable preparation of raw materials – use of quality-improving additives and optimum firing technique, the goal which was aimed at to make a satisfactory reduction charge from fine-grained, high-grade iron ores or concentrates has been achieved.

Good reducibility and sufficient mechanical strength during reduction are the most important properties demanded from pellets. Due to the high iron content, the uniformly high porosity and easy reducibility of hematite, as well as due to the spherical shape of pellets, a good behaviour in the blast furnace can be expected. This expectation was confirmed as early as 1916 by C. Brackelsberg *) who produced pellets from Sydvaranger magnetite concentrate with water glass as binder. He compared them with sinter and briquettes produced from the same raw material and found a better reducibility of pellets. To a greater extent, it was the mechanical strength during reduction which demanded special attention from the date when major pellet quantities were available for industrial processing. As was soon apparent, different demands resulted from the intended purpose:

- In the *blast furnace*, the most important demand was the stability and sufficient gas permeability of the whole charge during its passage through all reduction phases, especially in the upper part, despite a long retention time under a slightly reducing atmosphere at a relatively low temperature of 500–700 °C, an increasing reduction potential, a rising pressure and rising temperatures up to the molten phase in the lower level of the blast furnaces.

- During *direct reduction*, pellets are completely reduced to sponge iron in the solid state. They must maintain their shape and sufficient strength for their further transport to melting furnaces.

Initially, opinion was that a high mechanical strength of indurated pellets would be sufficient for their behaviour during reduction. This opinion was above all maintained in the USA where particularly favourable conditions prevailed. In the USA, the pellets were mainly produced and tested in pilot plants or laboratories all belonging to the

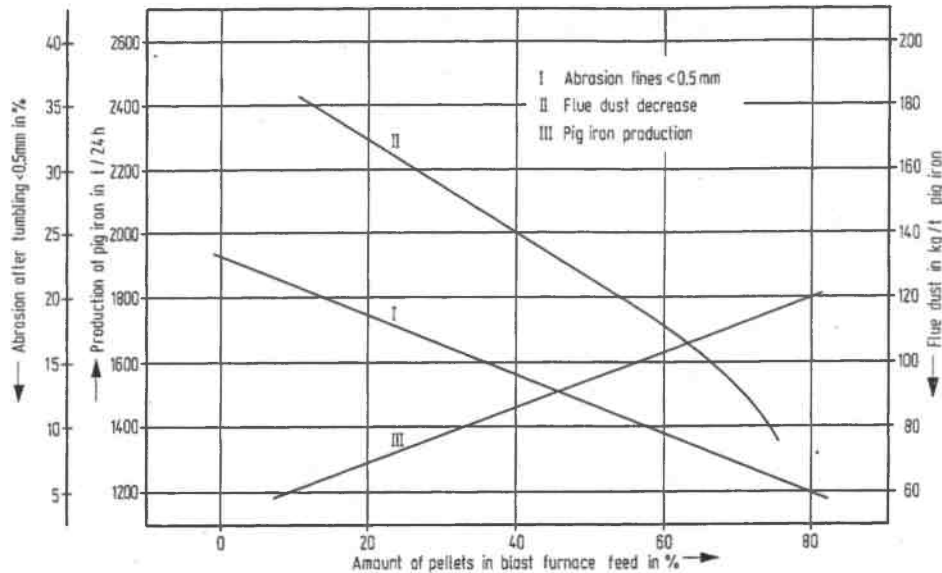


Fig. 85. Effect of pellets in blast furnace operation

same concerns, as is reported by W. E. Marshall ⁴⁶). He found that the mechanical strength of indurated pellets, especially their good abrasion behaviour, was the essential criterion for the increasing success and widespread use of pellets in the blast furnace, as is apparent from Fig. 85. Pellets with a higher resistance to abrasion (Curve I) allow a higher portion of pellets in the burden. From this results a lower flue dust accumulation (Curve II) and, owing to the better gas permeability of the charge, an increase in production (Curve III). These first favourable operational results obtained in blast furnaces of the relevant concerns were confirmed in a large-scale test run on 150,000 t pellets from the plant of Reserve Mining Company in a blast furnace outside the USA ²⁰). A high mechanical cold crushing strength of pellets was afterwards – and is up to the present day – the main criterion for the behaviour of pellets from the Mesabi Range in the blast furnaces of USA.

Almost simultaneously with the USA, first operational experience was also made with pellets in Sweden. However, from the conditions prevailing there resulted two fundamentally different starting positions compared with the USA:

– In Sweden, the pellets serve, besides for export, almost exclusively as charge for *direct reduction furnaces* operating according to the Wiberg process, as reported by Stahlhed ⁸).

Table 24. Analysis and basicity of pellets from two types of magnetite concentrates with high and low gangue content

Concen- trates	Fe tot	Fe"	SiO ₂	Al ₂ O ₃	CaO	MgO	Gangue content in %	Basicity CaO + MgO SiO ₂ + Al ₂ O ₃
Reserve mining	63.3	1.8	8.0	0.5	0.4	0.6	9.5	about 0.12
Malm- berget	68.5	n.b.	0.7	0.4	0.5	0.25	1.85	about 0.7

— In addition — and this was the second great difference — the Swedish Malmberget pellets had another chemical composition as can be seen from the following Table 24. Consequently, the two kinds of pellets differ considerably by their iron content, slag amount and basicity. Less favourable experience was made with the Malmberget pellets, low in gangue, during reduction. Despite high mechanical strength of indurated pellets, a considerable volume increase and crushing strength decrease were observed.

Tigerschiöld already reported on this phenomenon of "swelling" during reduction of such pellets with a high iron content. He investigated this problem together with his colleagues. It was found that the volume of these pellets increased by up to 60%. At the same time, it could also be demonstrated that additives can decisively influence this behaviour without finding exhaustive explanations for this. Even by the addition of 1% CaO, the volume increase could be lowered to 8% of the initial volume. On the other hand, the addition of 0.25% NaCl intensified swelling up to 110%.

A check test run on Malmberget pellets with 68.5% iron in a blast furnace yielded, contrary to the statement made by Marshall for Mesabi Range pellets, no positive results⁸⁰⁾. Opinion was that the hot crushing strength of Malmberget pellets was insufficient to withstand reduction. The reason for this behaviour was not yet known at that time. These two controversial results obtained with Malmberget and Reserve Mining pellets were, for a long time, the subject of discussions primarily between experts and pellet consumers. The "failure" encountered with the Malmberget pellets in the blast furnace at first had no important consequences as only small quantities of such pellets low in gangue were available at that time for processing in the blast furnace. In Sweden, however, the question of pellet swelling, and especially the cause of it, was thoroughly investigated by J. O. Edström⁸¹⁾.

The discussion of the behaviour of pellets low in gangue received a fresh impetus when, in 1963/64, major quantities of the first Marcona pel-

lets with 68.9% iron were available primarily for Japanese blast furnaces. The surprisingly negative initial behaviour of Marcona pellets, despite a high mechanical strength, was the subject of intensive investigations particularly in Japan, which was reflected in numerous publications⁸¹). Such investigations were continued especially in those places where pellet consumers had to cover their demand in the world market.

Owing to the supply situation in the USA with pellets of the well-known composition with high acid gangue content, swelling was only of secondary importance. There was no direct compulsion to deal so thoroughly as in other places with the problem of swelling which was confirmed by M. Chang⁸³) and his colleagues in 1967 by test results with a great number of pellet types originating from North America.

6.1 Change of Pellet Structure During Reduction

Two important basic theories were found at a very early stage which, in principle, are also valid today, viz.:

(a) Insufficiently-fired pellets with a low mechanical initial strength swell and disintegrate during reduction *irrespective* of the ore type and additives used.

(b) Pellets both high and low in gangue have a different behaviour during reduction. Pellets with a high gangue content are more resistant to swelling and disintegration, whereas pellets with a low gangue content swell and disintegrate intensively if no counteraction is taken. Despite numerous investigations, the reasons for this pellet behaviour during reduction have not yet been fully clarified. Nevertheless, parameters are nowadays known according to which pellets can be produced from different raw materials and have the quality required for the blast furnace and direct reduction plant. This knowledge, at first empirically acquired, was also the basis on which test methods adopted on an industrial scale could be developed.

The importance of satisfactory mechanical pellet properties before reduction is demonstrated by a test in which pellets of high-grade hematite ore with 65.9% Fe, 2.9% SiO₂ and 5% Ca(OH)₂ addition had been fired at temperatures between 1000 °C and 1300 °C under otherwise equal conditions. The individual samples were subjected to the relevant reduction test methods, and the results are shown in Fig. 86⁸¹). A definite dependence of crushing strength on firing temperature is apparent. The crushing strength of reduced pellets shows the same tendency (Curves I and II). Despite the high lime addition, the pellets disintegrate almost completely during reduction (Curve III). The portion of fragments and

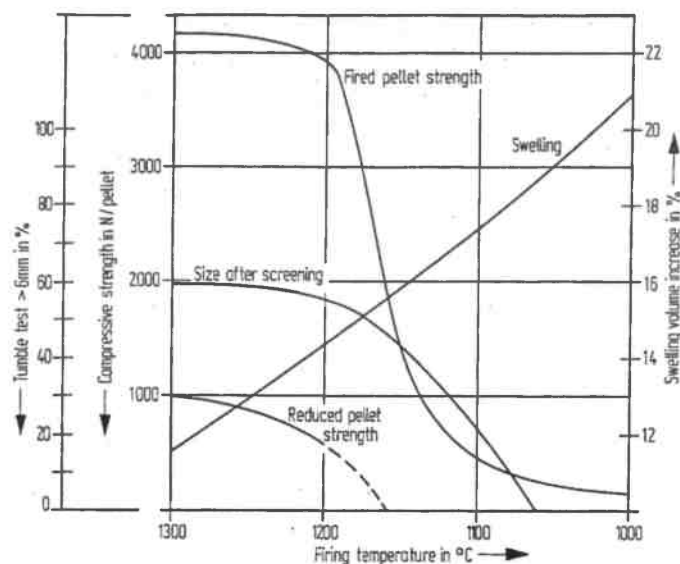


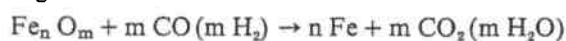
Fig. 86. Influence of oxide pellet strength on pellet properties after reduction

pellets plus 6 mm also decreases and the volume increase (swelling) rises continuously (Curve IV).

This knowledge is generally valid and confirmed by numerous passages in literature. The following considerations are therefore based only on *indurated pellets having satisfactory mechanical properties*.

6.1.1 Reduction Mechanisms

An extensive survey of the kinetics of iron oxide reduction by reducing gases is given by L. v. Bogdandy and H. J. Engell⁸⁴). The reduction proceeds according to the formula:



As regards kinetics, the reduction is a series of consecutively proceeding individual reactions which can be influenced by physical and chemical factors. Such factors may be connected with the raw material and with the properties of reduction gas. Factors dependent on the *raw material* are, for instance:

Chemical and mineralogical composition, oxidation degree of iron, mechanical strength before reduction, pellet porosity as well as gas permeability of the charge.

As concerns the *reducing gas* the following factors are important:

Reduction potential, gas volume, gas pressure, gas velocity and temperature.

Of these, the latter influences the reaction in both the gaseous and solid phases. For each individual step, there is a specific equilibrium position which can be varied by changing the concentration of the reactants.

In this connection, two mechanisms play a decisive role, namely:

- The phase border reaction on the phase border between solids and gas
- The solids reaction on the border and within the solid reactants by diffusion of metallic iron into the zones with a higher oxygen content. This reaction is only dependent on the iron concentration $^{14)}$.

The reaction itself proceeds in three steps:

- Oxygen removal on the oxide grain surface up to metallic iron from the wüstite phase
- Diffusion of metallic iron towards the oxides to be reduced
- Conversion of the higher oxides at their grain limits into lower oxides.

The following formulae describe these reactions:

- $\text{FeO} + \text{CO}(\text{H}_2) \rightarrow \text{Fe} + \text{CO}_2(\text{H}_2\text{O})$
Wüstite is reduced by gas to metallic iron
- $\text{Fe}_3\text{O}_4 + \text{Fe} \rightarrow 4 \text{FeO}$
Wüstite is resupplied by metallic iron from magnetite
- $4 \text{Fe}_2\text{O}_3 + \text{Fe} \rightarrow 3 \text{Fe}_3\text{O}_4$

According to the supply of metallic iron, hematite is converted to magnetite.

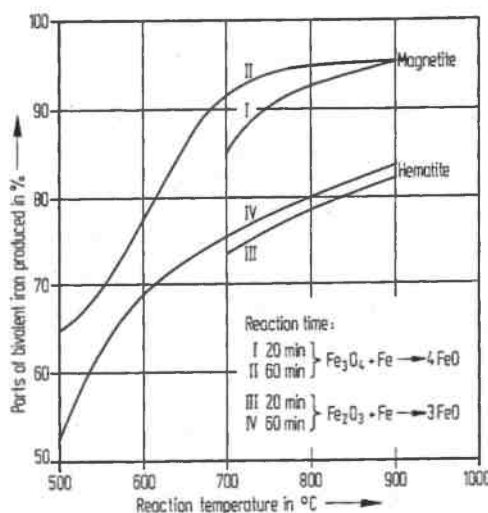


Fig. 87. Influence of temperature and time on reaction between metallic iron and iron oxides

The conversion is shown by way of different reaction examples, Fig. 87⁸⁶). Metallic iron was mixed and heated both with magnetite and hematite under vacuum at different temperatures and for various periods. The reaction progress was checked by the rising portion of bivalent iron. The beginning of the reaction at a relatively low temperature should be noted. When starting with magnetite, the reaction proceeds more quickly than with hematite. This is due to the different crystalline structure of both iron oxides.

6.1.2 Structural Change During Reduction

The components to be reduced react differently according to the prevailing conditions. As already indicated under item 6.1.1, many factors may influence the reaction. Thus, some apparently somewhat contradictory results were published because the underlying conditions had not been sufficiently known or considered. It may also happen that some results are influenced by factors which were not known. To be able to interpret results comparably, all given conditions must be considered exactly. As and when new experience is gained, the test methods become more and more sophisticated and tailored to operating conditions.

6.1.2.1 Volume Variation by Crystal Change

In conjunction with difficulties encountered during the operation of Wiberg furnaces with pellets low in gangue, Edström⁸¹) first attempted to find out whether and to what extent as well as at which degree of oxygen removal a volume change occurs. For this purpose, he reduced a cube of pure hematite ore with a defined edge length at a temperature of 1000 °C by using CO. The reduction potential was varied by mixing with CO₂ in order to adjust specific stages of oxygen removal. Edström's measuring data are comparatively as well as diagrammatically shown in Fig. 88. The reduction stages of iron with diminishing oxidation degree up to metallic iron are shown on the abscissa. The volume variations measured at each stage are represented on the ordinate with the volume being based on the hematite cube as 100% and the variation in percent being indicated. During reduction of hematite, a volume increase, in any case, takes place (Curves 1–4). After a close examination, it was found that the most intensive swelling occurs during the conversion of hematite to magnetite (Curves 1 and 2). However, it continues up to the formation of wüstite (Curves 1–3), and according to the prevailing reduction conditions, up to metallic iron (Curve 4). Except for the conditions referring to the latter curve, a volume shrinkage is observed at 1, 2 and 3 as soon as the first metallic iron has been formed from the wüstite phase. The volume

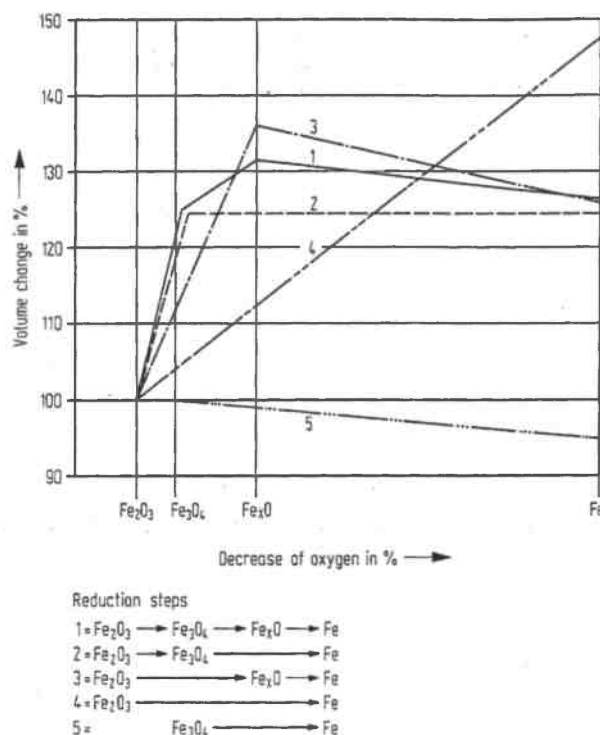


Fig. 88. Influence of reduction degree on volume change of a hematite cube

variation proceeds quite differently during reduction of a magnetite cube (Curve 5). In this case, a shrinkage immediately occurs from which it can be deduced that during magnetite reduction, no volume increase takes place.

The volume increase is explained by Edström as the result of a rising gas pressure in the pellet core. It occurs at a high reduction velocity when the arising gases of CO_2 and H_2O are more quickly formed than they can outwardly diffuse through the pores. But the reduction velocity is dependent on various factors, such as different pore structure of different shape of hematite crystals.

In other tests ⁸⁷⁾, a varying crushing strength decrease was found during reduction of pellet types with iron contents of 64 to 68%. The crushing strength decrease more or less reaches a minimum value for all samples in the wüstite phase. When those values are combined with the volume increase observed by Edström, the curves shown in Fig. 89 are obtained. The iron oxides with decreasing oxygen content, down to metallic iron, are represented on the abscissa. Curve 1 shows the volume variation and

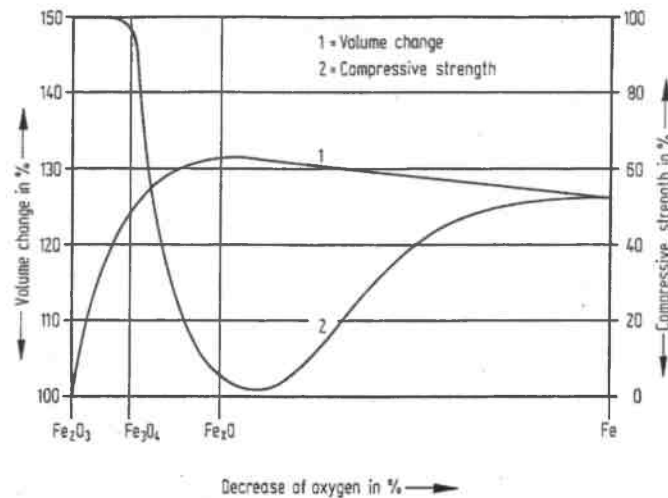


Fig. 89. Relationship between volume change and compressive strength during oxygen removal

curve 2 the corresponding crushing strength of the pellets in percent during the individual reduction phases. Based on an initial strength of unreduced hematite, equal 100, the strength drops almost as far as to zero near the wüstite phase and then improves with a rising portion of metallic iron. In principle, swelling and decrease of crushing strength of reduced pellets occur in opposite direction. This means a high swelling is connected with a low mechanical strength.

Besides Edström's theory on swelling during reduction, there are still other theories, such as:

- Incorporation of carbon at the phase limit between iron and wüstite⁸⁸⁾,
- Separation of fibrous iron needles, so-called whiskers, or iron droplets at preferred places of wüstite interfaces and thus displacement of the surrounding particles⁸⁹⁾,
- Intensification of iron separations when alkalines are present⁹⁰⁾.

This additional volume increase results in an intensified or "catastrophic" swelling.

An important contribution to the explanation of the structural change is made by Ottow⁹¹⁾. At first, he confirms the volume increase during reduction of hematite to magnetite as being about 11%. The magnetite layer has become thicker by this amount than the previous hematite layer. However, according to Ottow's theory, a second, crystallographic factor plays an important role. Ottow studied the *anisotropic* behaviour of hematite crystals during reduction. Substances like hematite crystallize in

the hexagonal system⁹²⁾ and, with regard to vectorial properties, often show a directionality. This is called anisotropic behaviour.

The reduction velocity in hematite grains, which, in parallel to the main axis, proceeds more slowly than in vertical direction to this axis, is also anisotropic. Apart from the volume increase, magnetite layers of different thickness are formed which, at the individual interfaces, bring about tensions and a tearing of crystalline structure. In a pellet the hematite phase is present as polycrystalline agglomerate, arranged at random. Therefore the crystalline destruction is highly intensified by the anisotropic effect on many crystallites. The three phases of structural destruction in conjunction with the anisotropic behaviour are shown by Ottow on the sketches of Fig. 90.

- (A) shows a hematite cube being partially reduced uniformly in all directions according to Edström. Due to volume increase, the initial volume rose according to section s' to the new section s . At the calculated volume increase of 11%, an angle of $\beta = 6^\circ$ arises by which the structure is damaged. Edström measured an angle of $8-10^\circ$.
- (B) shows the anisotropically different thickness of magnetite layers formed.
- (C) diagrammatically shows the different reduction velocity prevailing in one ore grain with two crystallites each of which has its c-axes in a different position.

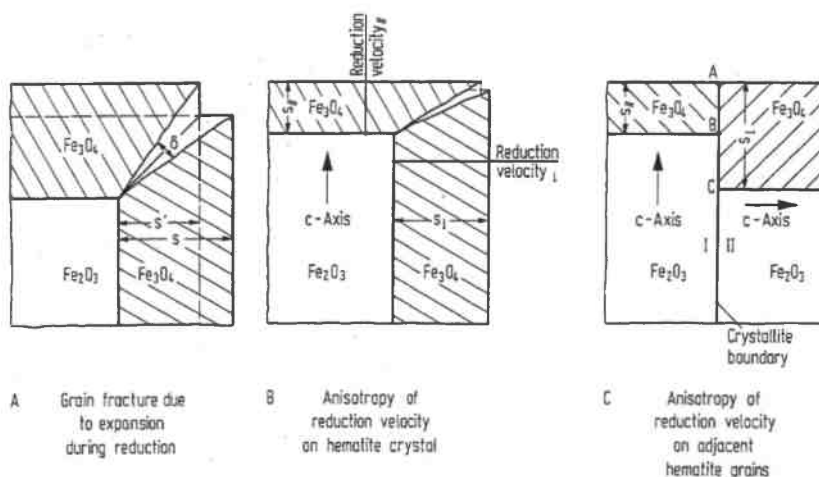


Fig. 90. Influence of volume increase and anisotropic behaviour on the structure of a hematite cube during reduction

Thus, the great drop in structural strength of pellets low in gangue during reduction can be attributed to the effect of the following mechanisms:

- (a) Volume increase during conversion from hematite to the lower oxide stages, mainly magnetite,
- (b) Anisotropism of reduction velocity resulting in the formation of magnetite layers of different thickness.

Both mechanisms proceed if corresponding reaction conditions allow this. In such a case, the structural damage cannot be avoided. New – even if intermediary – phases arise which demand a greater volume causing a growth pressure. To what extent this pressure may cause damage to or destruction of pellet structure is dependent on the prevailing conditions or those to be provided in order to counteract a structural damage. Some of the factors prohibiting a growth pressure as referred to under item 6.1.1 and having a specific effect are indicated below:

- (a) During pellet induration no *hematite crystals* are formed but other structures (e.g. magnetite) which, during reduction, do not have an anisotropic behaviour and are not notably weakened.
- (b) The bonding forces of the gangue portions are strong enough to withstand the growth pressure.
- (c) The gangue is changed both chemically and quantitatively until sufficiently strong reacting forces become active by the reaction of gangue components with each other or with iron oxides.

Since factors (b) and (c) in conjunction with gangue can be most simply varied, their influence is first discussed.

6.1.2.2 Structural Change by Reaction of Gangue Components with Iron Oxides and with Each Other

From the operational results obtained in North American blast furnaces it is well-known that only pellets with a great portion of highly acid gangue show a low tendency to swelling. There is also no longer any doubt about the positive influence of basic additives. Since Tigerschiöld, it has been known that other additives such as alkaline compounds have a detrimental effect on the swelling behaviour.

Since ever-increasing pellet quantities with a low gangue portion are produced as well as processed in blast furnaces, the importance of the chemical composition of gangue, like that of sinter, has become a significant factor in pellet production. In a large number of pelletizing plants, basic additives are nowadays used. In this connection, it had been observed that at a specific ratio of basic to acid gangue the swelling behaviour changes remarkably. At a basicity of 0.1–0.7 particularly high swelling indices were found ⁹³).

The experience acquired in blast furnaces has meanwhile demonstrated that a volume increase of up to 20% still does not adversely affect the blast furnace operation. However, if a greater volume increase occurs, it is considered as abnormal or even as a "catastrophic" swelling which has, in any case, to be avoided.

The importance of additives and especially their composition is well-known from publications often dealing with quite specific conditions which cannot be generalized. The results of such publications, which were often insufficiently described or based on different test conditions, sometimes brought about different and even controversial interpretations. Therefore, it was understandable that in other places basic research with clearly defined raw materials and additives was also carried out. The purpose of such tests was to investigate the influence of quantity and chemical composition of additives in connection with the ore characteristics on the pellet behaviour during reduction under controlled conditions. Some of such investigations with generally applicable results are discussed below. Many of them were jointly achieved by pellet consumers and pellet producers.

6.1.2.3 Influence of Additives on Pellet Swelling

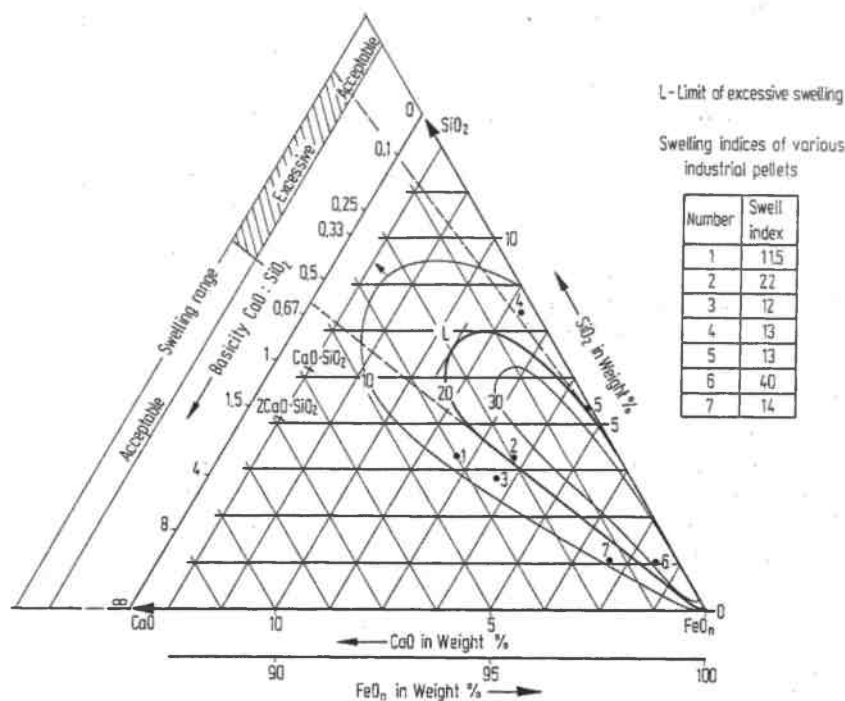
Under items 5–5.3 the influence of additives and, under item 5.4, the influence of thermal treatment on the mechanical properties of fired pellets was discussed in detail. It had been anticipated that these influences would also be similar during reduction.

In an extensive study, H. Kortmann*) dealt with the reactions of additives with gangue constituents and with iron oxides during reduction.

A high-grade Brazilian ore having the following chemical composition was used in his tests:

$$\text{Fe}_2\text{O}_3 = 99.15\%; \text{SiO}_2 = 0.30\%; \text{Al}_2\text{O}_3 = 0.20\%$$

The total gangue content of this ore was as low as 0.50% and its basicity was zero. According to the quantity and composition of gangue, the optimum firing temperatures ranged from 1300 to 1360 °C. Silica, limestone, dolomite, magnesium oxide, sodium and potassium carbonate and potassium feldspar served as additives. From the reduction tests carried out at temperatures of 900, 1000 and 1100 °C, those performed at 1000 °C were chosen for further consideration. The reaction time was sufficient in order to achieve full reduction by using a reduction gas containing 40% CO and 60% N₂. Because the results obtained are of practical value, they are discussed below, in particular the influence of silica and limestone, alone and in mixtures. The ratio $\frac{\text{CaO}}{\text{SiO}_2}$ was selected as basis for the basicity.

Fig. 91. Ternary phase diagram of $\text{CaO-SiO}_2\text{-FeO}_x$

The pellets were indurated at optimum conditions for various levels of different additives. The swelling behaviour of 33 pellet types thus found was tested during reduction. The different swelling values obtained under specific conditions were plotted on a triangle diagram, Fig. 91. The corners of the triangle are formed by the reactants: CaO , SiO_2 and FeO_x . Only the iron corner of the triangle is of interest. Swelling values of equal volume increase are connected with each other. Thus, isochores of pellets of equal volume increase but of varying chemical composition and of different basicity were derived. The isochore with 20% volume increase is especially marked as this value is generally regarded as the maximum permissible swelling degree in practice. Consequently this range of acceptable swelling with volume increases of less than 20% is outside the critical boundary whereas inside this boundary are located the pellet swelling values which are considered to be unacceptably high. The zones of higher swelling values become considerably narrower towards the iron corner. In this area, very small variations in the proportions of gangue, their chemical composition or basicity are sufficient to bring about great fluctuations of volume change. The greater the gangue

proportion on the highly calcareous side, the broader the range of acceptable swelling becomes and, in a corresponding manner, the less sensitive the pellets react during reduction. The extent and shape of isochores tend to a range varying around an average value of about 0.33 basicity. By lengthening the longitudinal side of the critical swelling zone, the basicity line is cut at about 0.1 and 0.6. Thus, three ranges of different basicity are formed. At the same time, the swelling range running in parallel is divided into three corresponding sections which mark the different swelling indices. These three ranges represent the following zones:

- (a) acid gangue with a basicity of -0.1 ;
acceptable swelling values of -20% ;
- (b) gangue with a basicity of $0.1-0.6$;
critical swelling values of $+20\%$;
- (c) basic gangue with basicity increasing to $+0.6$
acceptable swelling values of -20% .

The influence of basicity on the swelling behaviour decreases with rising gangue portion and loses its efficiency at about 10% of gangue amount as marked by "L" in Fig. 91. The isochores established on the basis of laboratory tests were compared with the swelling values of seven pellet types produced in industrial plants which were plotted on the

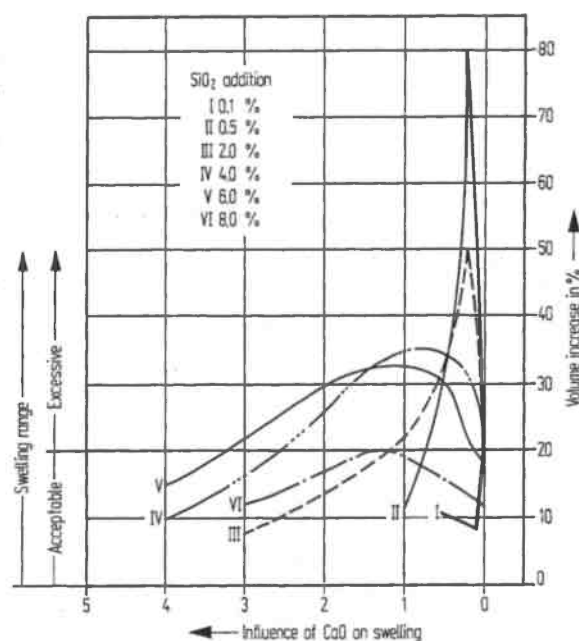


Fig. 92. Swelling rate of pellets during reduction with varying CaO and SiO₂ content

diagram. These show good conformity between the laboratory and industrial pellets.

From this it can be deduced that by varying the basicity pellets can be produced from different raw materials, which fulfill the operational demands of blast furnaces and direct reduction plants with regard to the swelling behaviour. The swelling values ascertained in dependence on the changed SiO_2 and CaO content, as per Fig. 91 are separately shown in Fig. 92. The swelling values first rise with increasing lime addition at low SiO_2 contents (Curves I–VI). They then exceed a maximum value and after this, diminish with further lime addition. As SiO_2 levels increase, the position of the swelling maximum moves and the maximum level decreases. At 8% SiO_2 and about 1.2% CaO corresponding to a basicity of approx. 0.15, the swelling maximum remains below the critical swelling line. At lower lime contents with the basicity approaching zero, favourable swelling values can also be achieved when the gangue proportion exceeds 5% as is shown in Fig. 93. Thus 5% gangue at a basicity of zero is sufficient to keep the swelling value below the critical limit of 20% (Curve IV). However, at basicities in the range of 0.1 to 0.6, increased gangue contents of up to about 10% are required (Curves I–III). As basicities increase above 0.6, the gangue proportions required to remain below the critical swelling line gradually diminish (Curves V–VIII).

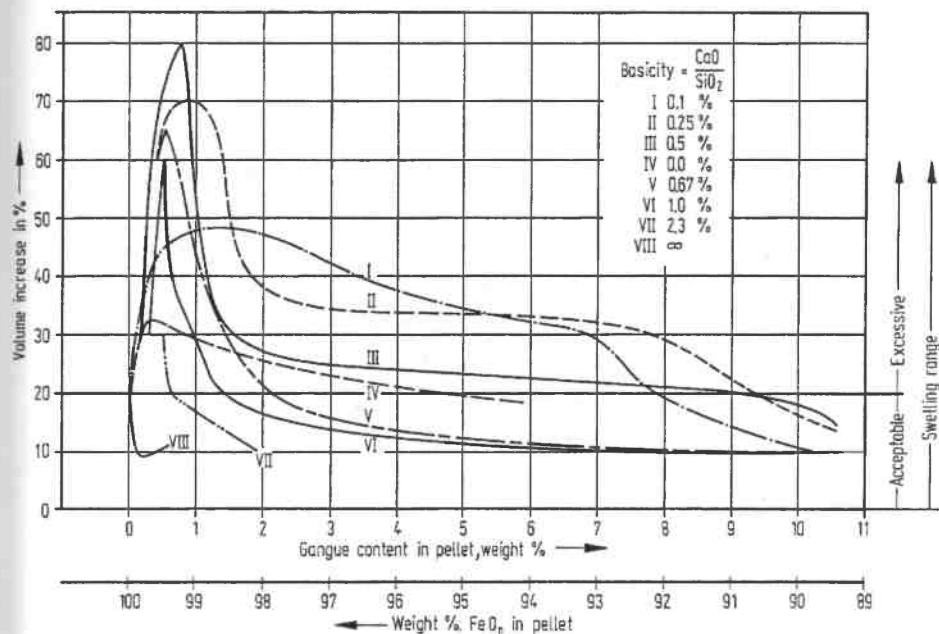


Fig. 93. Influence of basicity and gangue content on swelling

In general, there are three different ranges depending on the basicity:

- (a) Basicity range from 0 to about 0.1, gangue amount required: about 5% by weight;
- (b) Basicity range from 0.1 to about 0.6, gangue amount required: about 5–10% by weight;
- (c) Basicity range of more than 0.6, gangue amount required: less than 5% approximately.

The above values are guide lines in conjunction with the influence of basicity which are also confirmed by other authors⁹⁵), even if the interpretations of the data still greatly differ. Variations due to other conditions are also possible. During reduction, there is, in any case, a correlation between the gangue and the varying oxygen content of iron oxides at which mineralogical formations existing before reduction may change or even new ones may arise.

6.1.2.3.1 Properties of Acid Pellets with a Basicity of less than 0.1. In the case of *highly acid pellets* with a basicity of less than 0.1, the gangue is predominantly present as silica which partly reacts with hematite under a seam-like cristobalite formation³¹). The fired pellet strength is, to a certain degree, due to hematite bridges of polycrystalline structure. These pellets contain a large amount of open pores. The reduction gas can quickly penetrate through these pores into the pellet core and simultaneously attack the structure in many places. The structural change begins very early at low temperatures over the whole pellet volume. However, the structure can be held together primarily at high SiO_2 contents by the seam-like compounds between Fe_2O_3 and SiO_2 . As soon as the first wüstite arises, fayalite may be formed with silica of solid state, $2\text{FeO} \cdot \text{SiO}_2$. Due to low reducibility, at high SiO_2 contents the pellet structure only changes slightly. In this way, the total reduction velocity is also decreased. Moreover, fayalite with a melting point: 1217°C may act as a binder whereby a further swelling and degradation is diminished. Consequently, fayalite is to be considered as a stabilizing component during reduction of highly acid pellets. However, the gangue portion should exceed 5% (Fig. 93) and impede the degradation at lower reduction temperature.

6.1.2.3.2 Properties of Pellets with a Basicity of 0.1 to 0.6. During the firing of pellets with low CaO proportions at a basicity of 0.1 to about 0.6, a glassy slag phase consisting of SiO_2 , CaO, Fe_2O_3 of varying composition is formed from which, under suitable conditions, calcareous olivines may arise during reduction. These, with fayalite, form mixed crystals whose minimum melting point is about 1117°C and corresponds to a basicity of approximately 0.35. At this temperature and consistency, the mechanical strength of the gangue reaches a minimum so that a

stabilizing effect cannot be expected from the slag phase. In addition, the slag structure may vary if metallic iron separates from mixed crystals and the silicate structure tends to fall apart⁹⁷). In this basicity range of 0.35, the highest swelling values are observed. In Fig. 94 Fraser⁹⁸) showed the correlations between the melting behaviour of mixed crystals and the swelling of such pellets in conjunction with basicity. The lowest melting temperature corresponds with the highest swelling degree. A rising and decreasing basicity raises the melting point and the swelling behaviour changes accordingly. If very high gangue portions are present, see Fig. 93, the structural damage is avoided, and the swelling degree can be kept below 20%.

If, in olivines, other constituents, such as MgO, replace part of the CaO and the melting temperature in the mixed crystals rises correspondingly, this results in a decrease of swelling⁹⁷). However, it may also happen that alkaline compounds enter the olivine structure which causes a lowering of the melting temperature and intensifies the swelling⁹⁸). It can be stated that, within a basicity range of 0.1 to about 0.6 of the gangue constituents, low-melting olivine crystals are formed which do not impede pellet swelling during reduction but, under certain circumstances, can intensify such swelling. However, gangue portions of about 10% and over are capable of reducing the structural destruction because this gangue is still solid or plastic and holds the pellet structure together like a supporting frame.

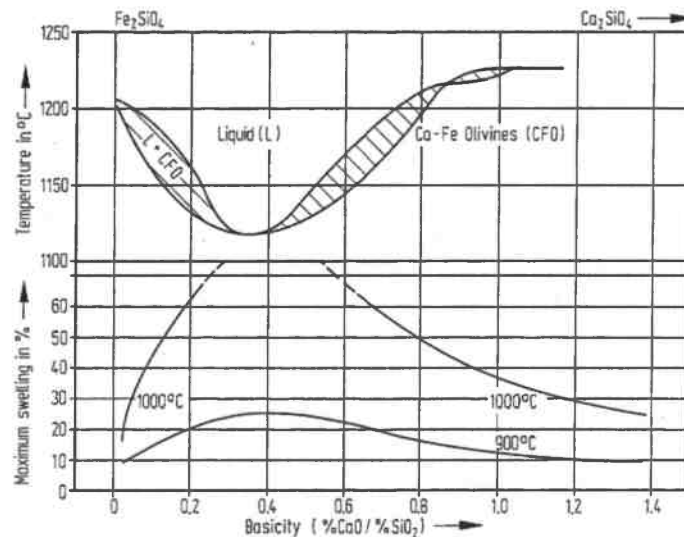


Fig. 94. Relationship between swelling degree, pellet basicity and phase diagram of Fe₂SiO₄ to Ca₂Si₄

6.1.2.3.3 Properties of Pellets with a Basicity of Higher than 0.7. If the pellet gangue contains more CaO than corresponds to a basicity of about 0.7, not only the glassy slag phase, consisting of CaO, SiO₂ and Fe₂O₃, but also calcium ferrites, CaO · Fe₂O₃, are formed which may cause a different structure of partially closed pores. During pellet firing, the availability of CaO considerably favours the crystal growth of hematite as is shown in Fig. 27³⁴). During reduction of CaO · Fe₂O₃, metallic iron arises on the entire surface of calcium wüstite as a skin without formation of needles. This iron forms concentric seams around the ferrite grains and impedes further swelling. It should be noted that pellets with a high CaO content and a basicity exceeding about 0.6 have a high mechanical strength after pellet firing and also after reduction.

The adaptation of the chemical composition of the acid gangue constituents contained in the ore or concentrate by means of CaO addition is thus an efficient technique for pellet production.

A further increase in the lime addition leads to neutralization of all the acid constituents and to the production of self-fluxing or over-fluxed pellets. Ilmoni and other Swedish authors dealt with this problem and additionally with the use of dolomite³⁵). Another purpose of these studies was to increase the total slag amount with a high basicity since some Swedish concentrates have a very low gangue content. During these studies, the necessity to maintain an optimum basicity was recognized. Consideration was given to the production of basic or over-basic pellets in a similar way to over-basic sinter. This possibility was successfully investigated in tests run on an industrial scale¹⁰). In this connection the overall economics of this procedure need to be studied.

The methods for measuring the swelling behaviour have, for a long time, been the most important ones for testing the pellet quality during reduction. However, the importance of this method decreases because it is too general and only informs about the structural change at about 1000 °C as can be seen from the test method for measuring the swelling index (item 4.6.1.2.3). At lower reduction temperatures of 400–600 °C and under a gas atmosphere with a low reduction potential – as exists in the upper part of the blast furnace – insufficient information is given on the structural change.

6.1.2.4 Influence of Gangue Bonds on Pellet Structure at Temperatures of 400–600 °C Under Reducing Atmosphere

In this temperature range, almost all gangue phases are still in a solid state. They act as a supporting frame against the destroying pressure forces during the conversion from hematite to magnetite, which is connected with a major volume increase, see Fig. 88. About 75% of the total

Table 25. Properties of reduced pellets depending on varying basicity and gangue contents measured in industrial plants

Pellets from	Chemical composition			Gangue		Low-temperature disintegration 500° C – 0.5 mm % – 20%	Swelling degree in % (Required – 20%)	Comments
	Fe _a	CaO	SiO ₂	Basicity	Portion %			
Magnetite concentrate	63.1	0.3	8.4	– 0.1	8.7	16.3	13.4	High gangue content
Magnetite concentrate	68.9	0.2	1.3	– 0.2	1.5	17.8	40.0	Low gangue content
Magnetite concentrate	63.2	3.9	4.1	0.95	8.0	19.5	12.4	Basicity 0.7
Magnetite concentrate	62.9	4.0	4.0	1.0	8.0	17.7	11.3	Basicity 0.7
Hematite	65.8	2.1	2.4	0.9	4.5	12.1	13.7	Basicity 0.7

volume increase already takes place during the conversion to the magnetite phase and only about 25% during the wüstite phase. Consequently, great importance must also be attached to the structural destruction at low temperatures.

As was found by Edström, Ottow and others, a transformation of *crystalline structure*, which automatically proceeds under given conditions, occurs during reduction of hematite to magnetite and wüstite. This transformation means a weakening and destruction of crystalline structure which is indicated by a shattering of the entire pellets into fragments and by an increase of the fines proportion below 0.5 mm.

Under blast furnace conditions, with low reduction temperature and gases with low reduction potential, this zone with its inevitable change of crystalline structure cannot be avoided. Table 25 shows test results obtained with pellets produced in industrial plants.

6.1.2.5 Influence of Gangue Bonds at About 1000 °C on Pellet Structure Under Reducing Atmosphere

As set forth under item 6.1.2.3.2, softening phenomena may primarily occur at a gangue composition with a basicity of 0.1–0.6 at which the pellets are deformed under pressure and thus the gas flow is impeded. As at these temperatures, the volume increase may simultaneously reach a maximum, both factors may jointly influence decisively the gas permeability of a pellet bed. The pellet behaviour under these reduction conditions is tested by adopting the pressure softening method described under item 4.7.1.2.4.

6.2 Behaviour of Indurated Pellets Consisting of Magnetite and Wüstite During Reduction

The structural destruction observed during reduction of pellets low in gangue can be prevented by varying the chemical composition and the quantity of gangue constituents. However, the increasing amount of gangue is detrimental when high-grade pellets are required from a metallurgical viewpoint. In particular, during steel production from sponge iron in the electric furnace, a small slag quantity would be advantageous as far as energy consumption is concerned.

Therefore, considerations to prevent the structural destruction without gangue variation are justified. Both Edström and Ottow observed that, under certain circumstances, magnetite crystals are not destroyed during reduction. The reduction of magnetite to metallic iron, see Fig. 88,

curve 5, is even connected with a volume decrease. If it were possible to produce only magnetite pellets instead of hematite, the structural destruction might be avoided. It is already known that magnetite pellets can be produced from magnetite ore under a neutral atmosphere. However, for hematite ores this is only possible by first converting to magnetite and then indurating under a neutral atmosphere. Pellets with a lower oxygen content than that corresponding to hematite can also be produced by the mixing of finely ground sponge iron with ores or concentrates as shown in Fig. 87 and as described under items 5.3.1.8–5.3.1.8.2 as well as in Figs. 67 and 68. For comparison, it should be noted that the strength of high-grade hematite pellets drops sharply during reduction with gas down to a minimum value in the wüstite stage.

On the other hand, small quantities of sponge iron addition already result in a very high strength. In a similar way, the strength of magnetite pellets can be improved by sponge iron addition. Also during the reduction of such pellets with gas containing 80% CO and 20% N₂ at a temperature of 1000 °C and during a period of 60 minutes, remarkable differences compared to hematite pellets can be observed, as is shown in Fig. 95.

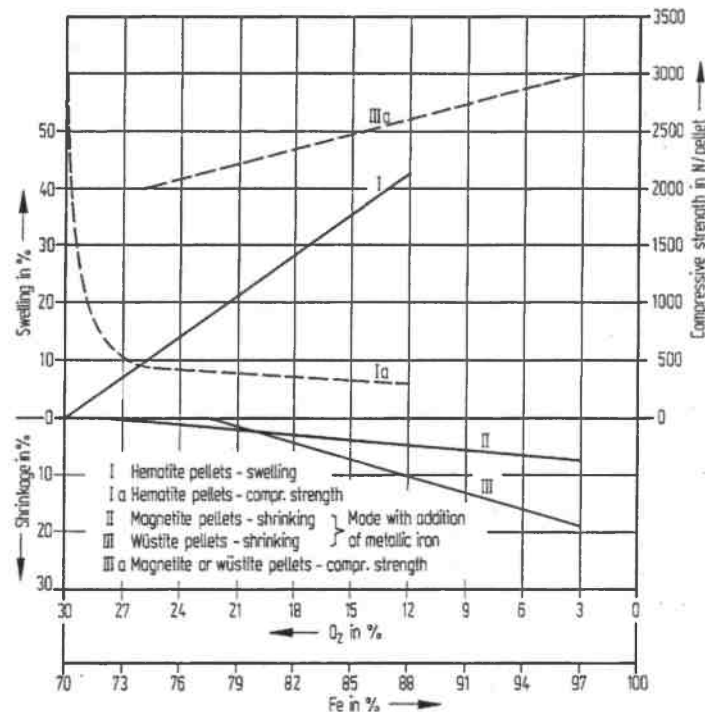


Fig. 95. Comparison of behaviour of various pellet types during reduction

During reduction of hematite pellets, curve I, a swelling of 43% is found whereas pellets produced from sponge iron show a clear shrinkage at different oxygen contents, curves II and III. The different strength development represented on curves Ia and IIIa is particularly striking. The abrasion values of less than 0.5% were correspondingly low. As can further be seen from the diagram, the pellets produced with sponge iron addition were practically reduced completely after 60 minutes while the reduced hematite pellet still contains 12% oxygen.

6.3 Conclusions

The following summarizing comments can be given on this important section in which the behaviour of pellets during reduction is dealt with:

- (a) Only pellets with optimum firing strength, irrespective of their chemical composition or origin of the ores from which they are produced, fulfill the conditions required for maintaining the necessary mechanical strength.
- (b) By a variation of the chemical composition of gangue constituents adapted to the ore composition, a potentially damaging structural change can be compensated for.
- (c) Pellets with a low gangue content are also resistant to swelling and degradation without variation of chemical composition of gangue, if the hematite crystalline structure is replaced by a structure of iron oxide crystals with a lower oxygen proportion, e.g. magnetite.

7 Special Processes for Pellet Production

In this chapter, alternative pelletizing methods are described which deviate from the conventional ones.

- (a) Besides *heat treatment* of green pellets for induration, the hardening is achieved by *additives* with *high bonding properties*.
- (b) Some iron ores containing detrimental or valuable ingredients can be cleaned during heat treatment whereby these ingredients are either eliminated by volatilisation or made soluble. The residual pellets are available for ironmaking.

7.1 Pellet Hardening by Using Binders

The pellets are produced according to such processes designated as cold bond pelletizing ¹⁰¹). They differ from thermally indurated pellets by other bonding mechanisms which are based on hydraulic or hydrothermal reactions from normal temperatures up to about 250 °C. The binders used should have such a chemical composition that no negative influence on the pellet properties is to be expected. Some processes, mostly known from the literature are described below: The most significant stages of such processes are shown as simplified flowsheets in Fig. 96.

7.1.1 Grangcold Process ¹⁰²)

The purpose of the development of this process was the intention to lower the pelletizing costs both for capital investment and energy consumption. It was developed by Grängesberg A. B. in Sweden. The quantity of cement used as binder varies between 8 and 12% by weight. According to the normal setting process for cement, a storage time of about 28 days is necessary to achieve an optimum strength within a justifiable hardening period. The strength as function of hardening time is shown in Fig. 97. At the beginning of the hydraulic reaction the green pellets have to be protected against abrasion and excessive pressure load. This is done in a

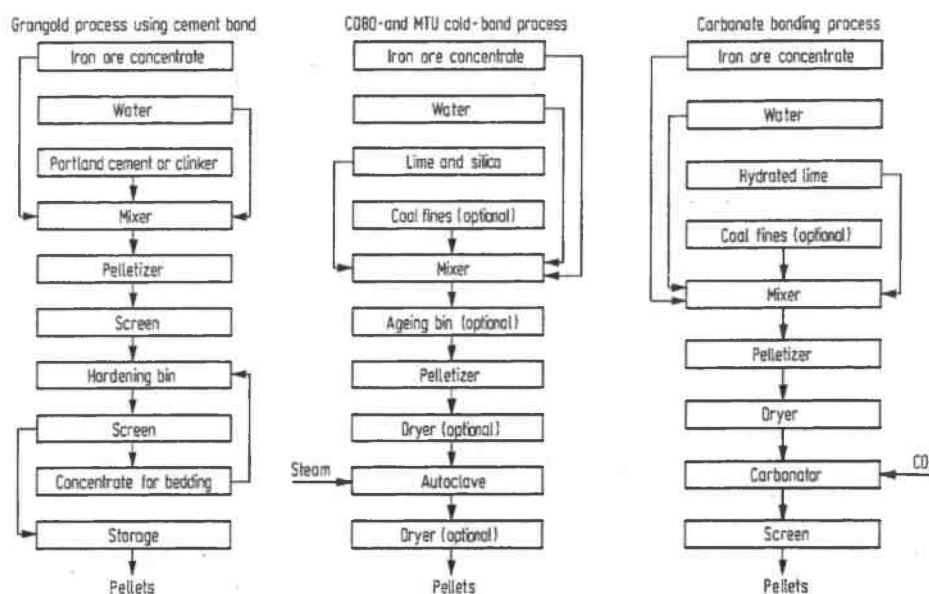


Fig. 96. Other pellet hardening methods without firing

bed of fine-grained concentrates. When a minimum strength is reached, these concentrates are separated from the pellets by smooth screening and recirculated. The final hardening is then accomplished in a stockyard or in an adequately dimensioned storage plant. The crushing strength of Grangold pellets is lower than that of thermally treated pellets. The hydraulic bonds disintegrate at about 600 °C, i.e. from this temperature onward, the pellets lose the greatest part of their mechanical strength. For this reason, the pellets should quickly pass through this temperature range during reduction. The swelling behaviour and other properties of pellets are sufficient during reduction. A plant in Japan ¹⁰³⁾ is producing about 45 000 tons of cold bond pellets per month.

7.1.2 COBO and MTU Process ^{104/101)}

The COBO – “COLD BOUND” Process was developed in the Division of Metal Processing of the Royal Institute of Technology in Stockholm. First publications date from 1967. The raw materials must physically conform to the conditions for green ball formation. Lime hydrate and possibly other additives are used as binders. The pellets are formed in well-known facilities and, after predrying, are indurated for about 1–5

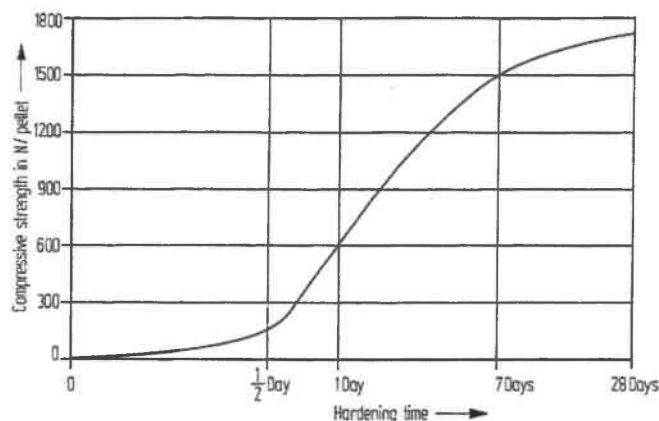


Fig. 97. Influence of time on hardening of Grang-cold pellets

hours at approx. 16 bar pressure in a steam autoclave at temperatures of 150–250 °C. The crushing strength of hardened pellets ranges from 750–1300 N/pellet and is less than the corresponding values of approx. 2000 N/pellet required for blast furnace operation. The reduction properties are good. The COBO process is also suitable for the pelletizing of other metal oxides, such as chromite ores, pyrite cinders and in-plant fines.

The MTU¹⁰¹) process is advertised especially in the USA for the recirculation of in-plant fines in steel plants. This process as well as the COBO process correspond to the simplified flowsheet of Fig. 96.

7.2 Chloridizing Volatilization of Non-Ferrous Metal Oxides and Pellet Production

Since pyrite – as the sulphur basis for sulphuric acid production – has mostly been replaced by elemental sulphur from other sources, the supply of pyrite cinders (calcines) as iron-bearing raw material for pig-iron production has drastically diminished. Nowadays, the mining of pyrite is no longer of primary interest. However, pyrite is often obtained as byproduct during flotation of zinc, lead or copper-bearing sulphides. However, this pyrite separated by flotation is normally not free from non-ferrous metal sulphides. Today, such pyrites are still of interest, especially in countries with great pyrite deposits, e.g. Scandinavia, Spain, Portugal, Greece, Soviet Union. These countries are interested in the separation of

non-ferrous metal oxides as chlorides from pyrite cinders by chloridizing at a temperature of about 1200–1250 °C. For this purpose, the pyrite cinders are formed into green balls after adequate grinding. As chlorinating agent CaCl_2 can be added to the pellet mix. It is also possible to pass chlorine gas at appropriate temperature through the hot pellet bed. The thermal treatment and chlorination can be achieved either in a shaft furnace or in a rotary kiln. Non-ferrous metal chlorides are volatilized and can be recovered from the waste gas stream by scrubbing. However, it is also possible to chlorinate the fine-grained calcines in a circulating fluid bed or in multiple hearth roasters in which sodium chloride is often used as chlorinating agent. Subsequently, the soluble chlorides are leached and thus separated from the calcines. These cleaned calcines, called purple ore, are mixed with other ores and agglomerated in sinter or pelletizing plants.

Since, pyrites are mostly obtained by flotation, they are already very fine-grained which is favourable for pellet production.

7.2.1 Chloridizing Volatilization and Pelletizing in the Shaft Furnace

A shaft furnace plant of Vuoksenniska OY in Imatra, Finland was operated for several years¹⁰⁵). The necessary quantity of CaCl_2 , corresponding to the amount of the non-ferrous metal oxides to be removed, had already been added to the pellet feed. To prevent premature dissociation of CaCl_2 in the presence of steam during pellet drying and heating, air dried by using silica gel was regeneratively heated to about 1200 °C and passed into the pellet charge in the shaft furnace. The cleaned pellets were cooled and processed into pig-iron in electric reduction furnaces. The chlorides contained in the waste gases were electrostatically precipitated, which was connected with many corrosion problems and high operating costs. This process was only used on a pilot plant scale of about 150 tons/day.

The shaft furnace process was further developed and CaCl_2 was replaced by chlorine gas. A corresponding pilot plant with about 120 tpd capacity was operated for some years at the Duisburger Kupferhütte, West Germany. The construction of an industrial plant and a wider application of this process failed owing to the changed market situation when the consumption of pyrites abruptly decreased. This process repeatedly described in literature under the name "*LDK Process*" (*Lurgi Duisburger Kupferhütte*)¹⁰⁶) is shown in the flowsheet, Fig. 98. In order to achieve a uniform size distribution, the calcines from various origins are subjected to dry grinding, mixed with bentonite and formed into green balls. Before the green balls enter the shaft furnace, they are largely dried

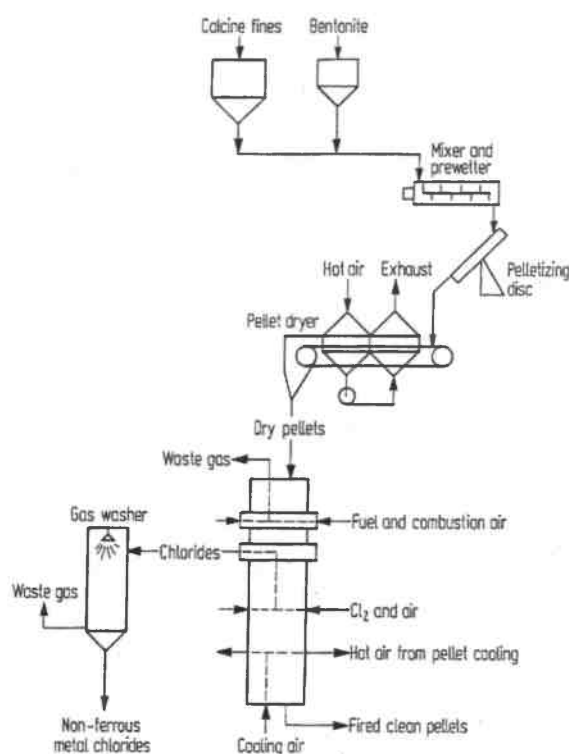


Fig. 98. Chlorination and pellet hardening of pyrite cinders in shaft furnace (LKD process)

on a belt dryer with drying gases low in steam. The shaft furnace, especially designed for this type of thermal treatment in the presence of chlorine gas, was divided into three zones, as shown in Fig. 99.

The dried pellets are indurated by hot combustion gases in the upper part of the shaft. The waste gas from this operation is withdrawn at the shaft furnace feed end. The hot charge is then treated with a chlorine gas-air mix in the chlorination zone, where the non-ferrous metal chlorides are formed. The gas arising in this zone and containing the volatile chlorides is treated separately. The heat content of the indurated and chlorinated pellets is recovered by fresh air in the cooling zone and separately exhausted.

The chemical analysis and mechanical quality of the pellets produced by chlorination met the pellet consumers' requirements. However, the additional consumption of chemicals and higher operating costs compared with normally produced pellets can only be justified if the non-

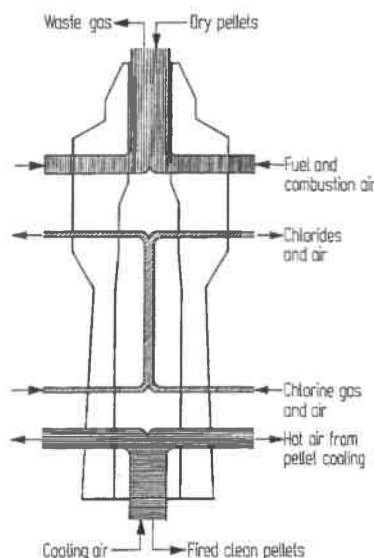


Fig. 99. Gas flow in LKD shaft furnace

ferrous metals can be used economically. This gas flow pattern, Fig. 99, can be analogously utilized for treating other ores.

7.2.2 Chloridizing Volatilization and Pellet Production in a Rotary Kiln

On the basis of the Vuoksenniska process, the Kowa-Seiko process was developed in Japan ⁽⁹⁷⁾, according to which the volatilization and pellet induration are achieved in a rotary kiln. CaCl_2 is added to the pellet feed. The process is represented in Fig. 100. The finely-ground calcines are mixed with a CaCl_2 solution in a special device, the green balls are dried on a belt dryer and heated up to about 1250°C in a rotary kiln. The chlorides are washed out from the waste gas and can be recovered. The pellets are of an excellent mechanical quality. Several plants with an overall capacity of about 1 million tons of pellets per year are in operation in Japan. In the USA, a plant with the same annual capacity is also in operation; further plants are under construction or in the design stage. The today's market situation is not favouring this process.

Table 26 shows the chemical analyses of pyrite cinders and of the corresponding oxide pellets produced with indication of physical-metal-

Table 26. Chemical composition of pyrite cinders and indurated pellets after chlorination and properties of pellets

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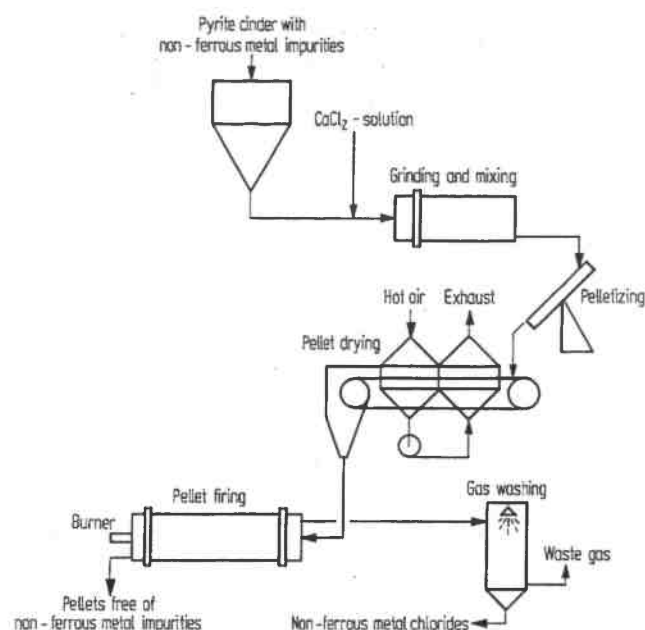


Fig. 100. Kowa Seiko chlorination and pelletizing process applied in a rotary kiln

lurgical properties. As can be seen from this table, pellets from a chloridizing process can indeed compete with marketable pellets.

7.3 Recovery of Vanadium Pentoxide from Vanadium-Bearing Iron Ores

Vanadium is an important alloying element in steel production and as catalyst basis in the chemical industry. The largest reserves are available in vanadium-bearing magnetites or titanomagnetites from which the metal is pyrometallurgically recovered as ferro-vanadium or as pentoxide, V_2O_5 , by a combination of pyro- or hydrometallurgical steps. A slag, high in vanadium, traded as intermediate product, is often used as raw material. This slag is roasted under oxidizing atmosphere, together with alkaline salts and the calcines obtained are leached. However, it is also possible to form a mixture of vanadium-containing magnetite concentrates and alkaline salts into green balls, which are indurated under an oxidizing atmosphere. The water-soluble vanadate is separated by leaching

from the pellets. By using these process variables, not only vanadium salts processed into V_2O_5 result, but also indurated pellets for iron production are obtained. Up to now, two variants are industrially applied.

7.3.1 Thermal Treatment of Vanadium-Bearing Pellets in a Shaft Furnace⁸⁸⁾

Since 1953, such a process has been applied by Rautaruuki Oy, Finland. The ore used contains about:

38–40% magnetite
28–31% ilmenite
1–2% pyrite

with about 0.25% vanadium.

From the raw ore, the following concentrates are produced by beneficiation:

about 64% vanadium-containing magnetite concentrate,
about 35% ilmenite concentrate,
as well as small amounts of pyrite concentrate

The magnetite concentrate for vanadium recovery has the following approximate composition

Fe tot. = 68.5%, TiO_2 = 3.1%, SiO_2 = 0.4%,
 CaO = 0.06%, MgO = 0.2%, Al_2O_3 = 0.7%,
V as V_2O_5 = 1.14%.

The concentrate is very finely ground to about 85% -0.037 mm (400 mesh) and the specific surface area is indicated as 10 000–11 500 cm^2/cm^3 . According to the portion of V_2O_5 , corresponding quantities of sodium carbonate are added to this concentrate. The following parameters are specified:

pellet diameter	16–19 mm
moisture content	8.5% H_2O
crushing strength of green pellets	about 22 N/pellet
drop number	4×46 cm
crushing strength of dry pellet	50–70 N/pellet
hot gas temperature	1100–1150 °C
pellet temperature	approx. 1250 °C

crushing strength of indurated pellet 1000–1300 N/pellet. After cooling, the pellets are leached in water, with the vanadium recovery approximating 85–90%, and are then used for the blast furnace burden.

7.3.2 Thermal Treatment of Vanadium-Bearing Pellets According to the Grate-Kiln Process

Transvaal Alloys (Pty) Ltd. in the South African Republic also produces V_2O_5 from a natural titanomagnetite without previous beneficiation. The ore has the following composition ¹⁰⁹⁾:

Fe tot.	55.6
TiO ₂	12.7
SiO ₂	2.2
V	0.9

The ore was ground to about 50%—0.09 mm and a specific surface area of about 2300 cm²/g and mixed with Na₂SO₄ as digesting agent. The following pellet crushing strength was ascertained in the preheating stage on the travelling grate:

green pellet strength	about 30 N/pellet
dry pellet strength	about 50 N/pellet
pellet strength at 900 °C	about 400 N/pellet

The prehardened pellets enter the rotary kiln in which they are heated up to temperatures of approx. 1270 °C for about 60–110 minutes. After cooling the pellets are leached in water. The liquor still contaminated by other constituents is cleaned and then processed through ammonium vanadate into molten V_2O_5 scales. The pellets can, as far as their TiO₂ content allows, be further treated.

7.4 Dearsenification and Pelletizing of Iron Ores

Some iron ores, above all pyrite cinders, contain arsenic as a detrimental substance which has to be removed before iron production. During pyrite oxidation, arsenic sulphide oxidizes to As₂O₃, which, in this oxidation stage, cannot be volatilized and, under certain circumstances, has a tendency to form calcium arsenate. However, it is possible to convert the arsenic compound to As₂O₃ which is volatile, and, in this state, can be eliminated from iron oxides. Such reactions are carried out either in a rotary kiln, e.g. during magnetizing roasting, or in a shaft furnace as shown in Fig. 99 in which a neutral to slightly reducing atmosphere, required for the reaction, can be provided.

A calcine with the following composition:

Fe tot.	= 53.70%
Fe ⁺⁺	= 6.60%
S	= 2.10%
As	= 0.22%

was finely ground, together with 2% coal corresponding to 1% fixed carbon and pelletized. At a temperature of about 950–1000 °C and an oxygen content of less than 3% in heating gas, it was possible to lower the arsenic content down to about 0.01–0.02% and the sulphur content to 0.02% (11). Such iron ore pellets, largely liberated from arsenic impurities can be utilized for iron production.

8 Balling Equipment

Raw material preparation, green ball formation and pellet hardening are the decisive factors for the production of pellets with the characteristics required for their handling and reduction. For the performance of these process parameters special equipment is used. In order to obtain pellets of uniform and optimum quality, the design and function of the pertinent apparatus must be sufficiently flexible for compensating for all of the very different properties related to the raw materials involved. Many of the devices used were already known. For many years some of them have been successfully utilized for similar purposes, which was advantageous for the introduction of pelletizing on an industrial scale. Nevertheless, it was necessary to adapt some of these devices to the conditions required for pelletizing. During the design and layout of the whole pelletizing plant, these varieties of apparatus have to be so dimensioned and combined with each other that an optimum performance and economy is ensured.

8.1 Homogeneity of Components for Pelletizing Mixtures

A uniform chemical composition of the raw material constituents is one of the principal conditions for the quality of the pellets produced. As long as only one concentrate or one single ore is treated in a plant, there is no risk of an irregular composition. However, even in such a case, good mixing of bentonite is problematic to some extent.

Therefore, at a very early stage attempts were made to premix the small bentonite portions of approximately 0.7% with the great ore mass. These attempts were not very successful at that time. The question regarding the sufficient homogeneity of the mass to be pelletized becomes very acute and important if several solid constituents, either ores or additives have to be treated and to be uniformly distributed over each individual pellet.

During the preparation of mixtures and green ball formation two functions have to be fulfilled:

- 1) Compensation of differences in the chemical composition of the various constituents and
- 2) Formation of green balls which is only done according to strict physical laws and is more or less independent of the chemical composition. Once several solid constituents are to be evenly incorporated into the pellets, *suitable mixers* should precede the balling devices for their release.

It was already recognized at a very early stage that it is difficult to distribute uniformly the small bentonite amount of 0.7% over a great quantity of magnetite concentrate. Formerly, the Pekay mixer was mounted as mixing unit on the belt conveyor. This mixer was equipped with plough-like blades with which the bentonite, charged on to the concentrate surface, was to be blended during transportation. This system was not very effective. The difficulties increased when mixtures of different ores, concentrates and additives with different chemical compositions were processed. Instead of the mixers arranged above the belt conveyor, passage mixers were developed capable of homogenizing large quantities of up to 150 tph⁽¹⁾. Before the design of the pelletizing plant for ore mixtures at Ijmuiden in Holland, mixing tests were carried out and different mixing systems were carefully investigated. On this occasion, it was found that the bentonite addition could be lowered from 0.7 to 0.3% if the mix were well homogenized. LKAB also performed extensive relevant tests and ascertained that good blending of the feed before pelletizing results in a reduction of bentonite consumption of up to 50%. In this way, it has been demonstrated that it is expedient to supply the balling units with a homogeneous mix.

8.2 Demands on the Mode of Operation of Balling Units

To ensure that the ball formation alternatives and bonding mechanisms, described under items 2–2.1.2.3, as well as the influencing factors, specified under items 5–5.3, become active, it is necessary to use adequate pelletizing equipment. In these units, the prepared loose pellet feed including binders and other additives as well as water are to be formed into green balls. All the conditions for obtaining a good pellet quality are to be fulfilled for a good mechanical procedure of ball formation. In this connection, all movements and compression forces should become active in

optimum harmony with each other. The following demands are made on the balling equipment:

- Good mixing effect to ensure – as far as possible – a uniform distribution of all constituents and additives,
- continuous and smooth movements,
- intensive relative movements of conglomerates due to uniform moistening of grain surfaces,
- intensive relative movements of individual solid particles to each other to obtain a maximum number of contact points and surfaces in order to form as many capillaries as possible,
- movements for producing a slight pressure in order to reduce the number of cavities between solid particles and to form porous conglomerates,
- rolling movement in order to form balls from the agglomerates which are partly still irregular.

8.2.1 Ball Formation and Operation of the Principal Pelletizing Units

Pelletizing units should have all constructional features so as to allow a mechanical transformation of the process parameters for ball formation. The grain mix to be pelletized with about 80%–0.045 mm, of different grain shape and surface is moved in such a way that the most effective bonds required for good ball formation can arise. This movement is achieved by using suitable apparatus and special tools, e.g. in so-called positive mixers. However, the most natural and the simplest movement is the *freely rolling movement* for which favourable conditions for ball formation are given by nature. The rolling movement is also the basis for the most frequently employed pelletizing units. It arises when the angle of repose of an ore pile is so steep that the gravity of particles overcomes the frictional resistance of its environment. When a loose ore mass is dumped on a plain support, a pyramide with a specific angle of repose is formed which results from the frictional resistance of the pile. Dry grains form a flat angle of repose while irregularly shaped and wet grains with a major friction form a steeper one. In the position of rest, the pile forms the static angle of repose. When the friction is overcome at a steeper slope, the pile surface undergoes a rolling movement until the static angle of repose is again reached and the pile is once more in a position of rest. The rolling movement can be maintained if it is possible to keep the grains moving so that the angle of repose is below the dynamic one. This can be achieved if the grains are placed on an adequately inclined support moving in opposite direction to gravity of the mass i.e. moving diagonally upwards.

In this way, the support continuously moves material upwards due to the frictional resistance between support and ore. When the angle of the inclined support becomes steeper, the grains are compelled to reverse and roll downwards over the ore surface. On rolling down, the wet grains tend to pick up other particles and start to form balls. If this downward movement can continue in the presence of new, fresh particles, the diameter of agglomerates increases and green pellets of desired size are finally formed. Under these conditions, a combination of balls of different diameter down to the original fines particle size develops. During the downward rolling movement a certain sorting of the mix occurs according to the different frictional resistance. The largest balls gather on the surface of the ore charge and the fines with the highest frictional resistance accumulate on the support. The balls already formed roll down earlier whereas the very fine particles are compelled to reverse. If the support is plain like the bottom of a balling disc a corresponding device is necessary to reverse the material flow. However, if the support is curved like the inner wall of a drum, the material automatically reverses at a certain wall slope. According to their weight and gravity, the downward rolling balls give rise to slight hits to the surrounding pellets. As a result, the balls are consolidated or weak balls may break. The condition of such a rolling ore mass with a wide size range is diagrammatically shown in Fig. 101. If the support is moved in the opposite direction to gravity, it lifts a mixture of grains of different diameter at a specific slope, due to its lifting power and frictional

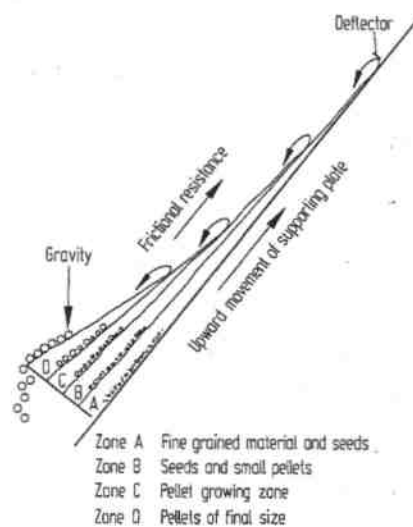


Fig. 101. Factors influencing rolling movement of particles (gravity, frictional resistance, upward conveyance, angle of supporting plate)

resistance, until gravity overcomes the frictional resistance. The rolling-down movement then begins selectively according to the different frictional resistance which automatically brings about classification. Owing to the classifying effect, zones of agglomerates with different diameters are clearly perceptible. According to the type and mode of operation of the balling unit, the finished balls automatically separate from the remaining mix as in the case of the balling disc.

If there is no sufficient sorting effect — as with the drum — the discharged pellet mass has to be separated by smooth screening behind the balling unit. The crushed oversize and undersize are recycled to the fresh feed. Nowadays, mostly drums and discs are used as balling equipment, the design and function of which is the subject of the following considerations.

8.2.2 Balling Drum

The balling drum was developed from the mixing drum used in sinter plants and adapted to its new function. During the first years of development, the drum was the sole balling unit. All pelletizing plants operated on an industrial scale in the USA and in Sweden were exclusively equipped with drums up to about 1956. Owing to the fact that their component parts have been known and proved for many years, as well as to their easy operational control under relevant operating conditions, they are nowadays also used frequently in pelletizing plants.

8.2.2.1 The Principal Drum Component Parts and the Balling Operation

8.2.2.1.1 The Main Component Parts. The drum consists of a slightly inclined cylinder open at both ends, occasionally with a low retention ring or cone at the feed end in order to prevent any backward flow of pellet feed. For the improvement of the adhesive strength and roughness, the metallic smooth inner wall is coated with a layer of moist fines and its thickness is controlled and limited by scrapers. These scrapers are stationary or rotating and arranged in parallel to the drum axis. In modern plants, so-called rotating spiral scrapers are used which not only limit the bed height but also impart a higher frictional resistance to the inner face.

In order to ensure a successful operation, the dimensions and functions of the principal drum component parts must be variable, such as:

- length and diameter of drum
- angle of inclination of drum axis to the horizontal
- number of revolutions.

Fig. 102 shows diagrammatically the essential balling drum component parts, their dimensions and operating characteristics as they are used for industrial plants with capacities of 90–130 tph green pellets for various ore types.

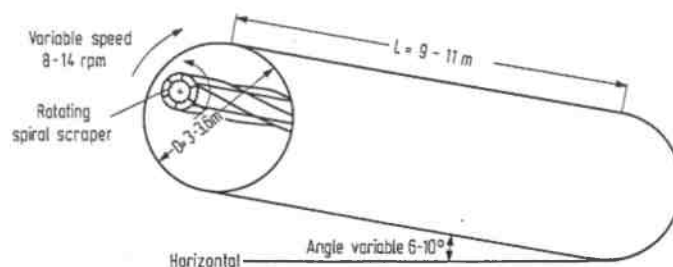


Fig. 102. Main dimensions and influencing features of a drum for green pellet production at a rate of 90–130 t/h

8.2.2.1.2 Operation of the Balling Drum. The prepared feed is charged to the upper end of the drum. If necessary, water is sprayed on determined areas for the achievement of optimum ball formation. The material rolls in flat spirals towards the discharge end. According to the length, slope, rotating speed and filling degree of drum, pellets with a certain size distribution are produced at a capacity dependent on the ore type used. Due to the mode of operation the drum has practically no sorting effect. The drum discharge has to be screened and the pellets of desired size are separated. Any produced oversize is, after crushing, combined with under-size and fresh feed material and jointly charged to the drum. Thus, there is an inevitable circulating load of recycled undersize whose quantity may vary between 100–400% of the fresh feed depending on the operating conditions. The small pellets contained in the undersize serve, during their repeated passage through the drum, as seeds for the formation of properly sized pellets. According to the circulating load involved, the raw material passes repeatedly through the drum before finished pellets are discharged. The separation of the utilizable fractions is normally achieved through a specially developed, smoothly vibrating screen in order to preserve the green ball quality and to avoid water from the capillaries being pressed to the surface. The screen capacity must be sufficient to compensate for major fluctuations. The normally used vibrating screen is nowadays increasingly replaced by a roller screen especially developed for green ball handling. Fig. 103 diagrammatically shows the green pellet and undersize circuit. The separation of pellets of proper size is achieved according to alternative I – with vibrating screen – and alternative II – with roller

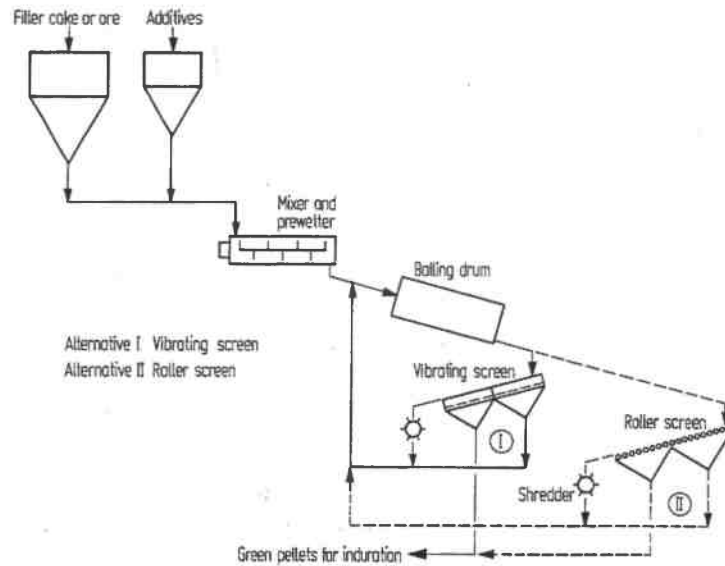


Fig. 103. Flow sheet of pelletizing drum operation

screen. The operation of the roller screen is smoother. The fluctuations of the circulating load influence the filling degree and properties of the drum and to some extent, the size range of the pellets. This is a disadvantage of the drum operation and is still the subject of special endeavours to reduce or even to avoid it ¹¹²). However, it is such an important influencing factor that it has to be considered for the evaluation of all other factors.

8.2.2.2 Influencing Factors for Green Ball Formation in a Drum

8.2.2.2.1 Drum Rotating Speed. A specific rotating speed of drum is necessary for green ball formation. A rotation which is either too slow or too fast has to be avoided, as is diagrammatically shown in Fig. 104. The behaviour of the charge is observed at three different speeds:

(a) The drum rotates too slowly. The charge does not roll but slides as a mass in swinging movements upwards and downwards on the wall. No pellets are formed.

(b) The drum rotates at such a speed that due to the frictional resistance prevailing on the wall, the charge is lifted until the material reaches and exceeds the dynamic angle. On the charge surface where the friction reaches its minimum, the particles begin to roll downwards while the first agglomerates emerge. At the same time the pellets are growing due to the layering of fines on the already existing nuclei from the

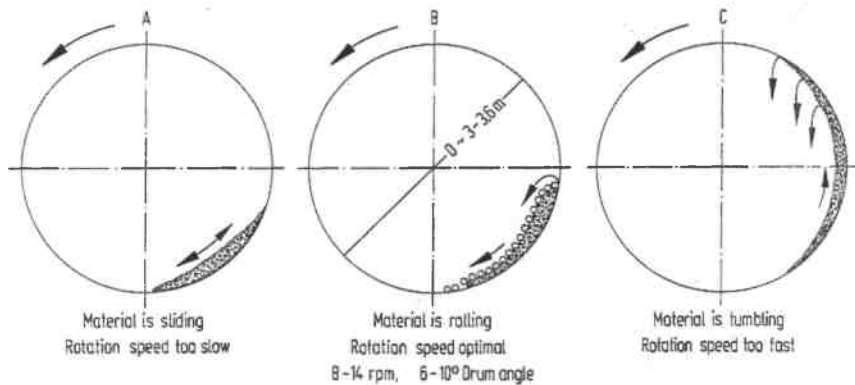


Fig. 104. Movement of pellet feed in a drum at various rotating speeds

rotating mass. At this optimum speed, the material mainly carries out a *rolling* movement while it is being turned over. This movement is designated as cascade movement.

(c) The drum rotates so fast that the charge is moved beyond the dynamic angle of repose and pressed against the wall. At the steeper angle, the mass dumps onto the lower layer, without rolling. Under these conditions no agglomerates can be formed. The basic criterion for all further considerations is the optimum speed of rotation. However, this speed is dependent on the frictional properties of the particles. It has to be ascertained by tests for each particular pellet feed. For this reason, many industrial drums can be operated at varying speed.

8.2.2.2.2 Length and Tilt Angle of Drum. Before the finished green ball is finally formed, the charge needs a certain formation period during which the necessary rolling distance is covered for which a certain drum length is required. Empirically, a multiplier of $2\frac{1}{2}$ –3 of drum diameter is required. Apart from the length, the tilt angle of the drum also plays an important role. It determines the passage time, Fig. 105, and the filling load at a given throughput. The limits are determined by two different drum speeds. The lower range corresponds to the passage time of the whole charge.

The upper period only refers to the feed rate which corresponds to the pellet production rates.

The amount of material to be recycled is dependent on the drum slope, curve I in Fig. 106, drum length, curve II, and screen openings for separating the green pellets of desired size, curve III. A great length decreases the quantity of recycled material and vice versa. The greater the screen openings, the higher the amount of undersize or circulating load.

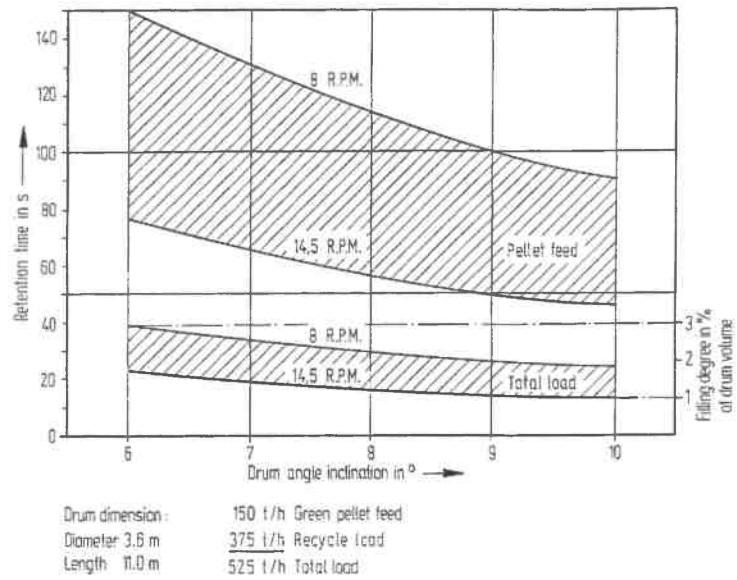


Fig. 105. Influence of drum slope and rotating speed on retention time of green pellet feed and total load

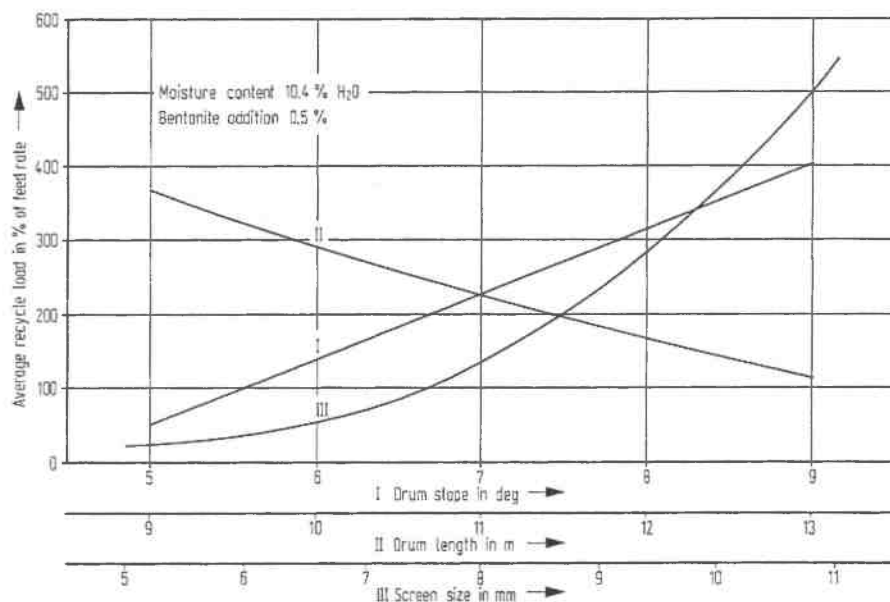


Fig. 106. Influencing factors of drum operation on circuit load

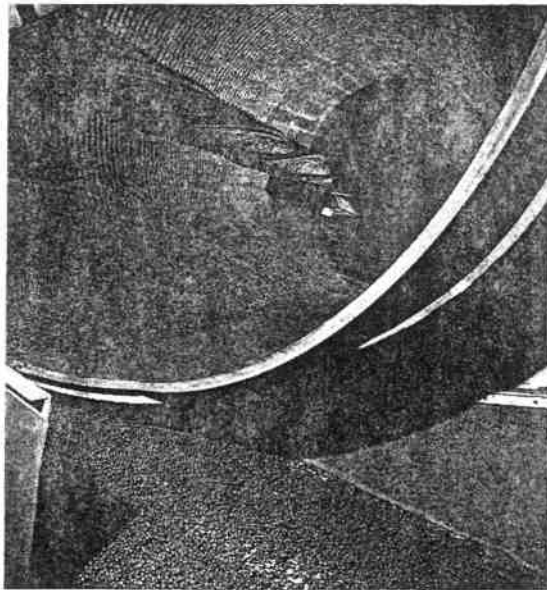


Fig. 107. Interior of a pelletizing drum equipped with rotating spiral scraper and loaded with a pellet charge

Fig. 107 shows the interior of a balling drum¹¹³), the rotating spiral scraper, the roughened wall and low filling degree. The surface area of the bed, which is available for the downward rolling movements is important for the ball formation.

8.2.2.3 Balling Drum Capacity

The capacity depends very much on the properties of the material to be pelletized. Mathematical calculations cannot yield exact data. Operational data from laboratory tests allow the definition of reliable dimensions and

Table 27. Dimensions, operating conditions and production rate of pelletizing drums

Drum diameter mm	Length mm	Green ball production tph
1800	6100	20
2745	9150	80
3050	9755	120
3660	9753	170

Slope 6° – 10°

Rotation speed 8 – 14/min depending on ore properties

time required for the production of green pellets of good quality. In order to ensure a flexible throughput of the drum in an industrial plant and to compensate for fluctuations, the tilt angle and rotating speed of drums can be varied. In principle, the capacity is dependent on similar criteria as for the disc. According to the information obtained from a drum supplier ¹³⁾, the following correlations shown in Table 27, exist.

These values may vary according to the ore type, properties and quantity of additives as well as to the desired pellet size. When optimum operational parameters are maintained, pellets of good quality are produced.

8.2.3 Balling Disc

The disc was already used for balling of cement raw meal and in the fertilizer industry before its application for iron ore pelletizing was investigated about 1949/50 ¹¹⁴⁾. When balling fine ores on a disc, this is done under the same physical conditions as in a balling drum. The rolling movement is initiated by the inclination of the plain disc bottom instead of the concave drum wall. Due to the design and operation of the disc a classification by the ball diameter already starts during ball formation. Today, even though at a much later date than the drum, a considerable portion of world pellet production is covered by the disc.

8.2.3.1 The Principal Component Parts and Disc Operation

8.2.3.1.1 The Main Component Parts. In a similar manner to the drum, the disc consists of the component parts necessary for ball formation. They are represented in Fig. 108. The concentrically rotating, inclined disc is

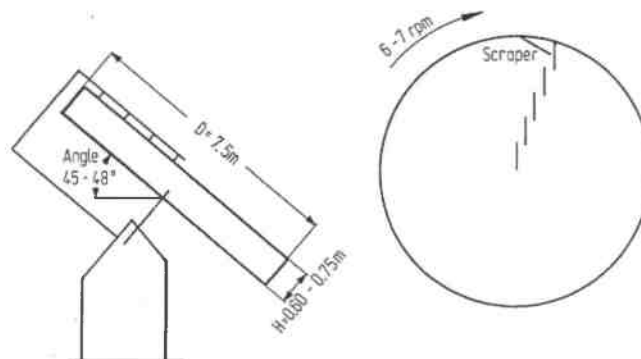


Fig. 108. Main dimensions and influencing features of a disc for green pellet production at a rate of 90–140 t/h

composed of a circular, plain bottom area. To ensure sufficient frictional resistance and a good lifting effect for the pellet feed, a moist ore bed of about 3–10 cm thickness is layered on the bottom and is controlled by scrapers. Different designs were developed such as stationary and oscillating scrapers or rotating spirals. The capacity of the disc is given by the side wall positioned at an angle of 90° to the bottom. The height of the rim is, to some extent, dependent on the disc diameter. The speed can be varied within certain limits depending on the pelletizing properties of raw material.

8.2.3.1.2 Operation of the Balling Disc. Attempts should be made to utilize a maximum part of the disc area for green ball formation. At the beginning of the development work, the portion of bottom area was as low as some 50% and could be raised to approx. 90% in the course of further development. Since during ball formation a classification occurs up to the discharge of pellets of the desired size, the quantity of the necessary pellet feed corresponds to the amount of pellets discharged. This results in a simple flowsheet for the material flow shown in Fig. 109. If, nevertheless, small amounts of undersize develop which mostly occurs during transportation, these can be separated by a roller screen and recycled.

To initiate the downward rolling movement, the disc is inclined at such an angle that the material layer charged exceeds the dynamic angle of repose. According to the lifting power of the rough disc bottom and the

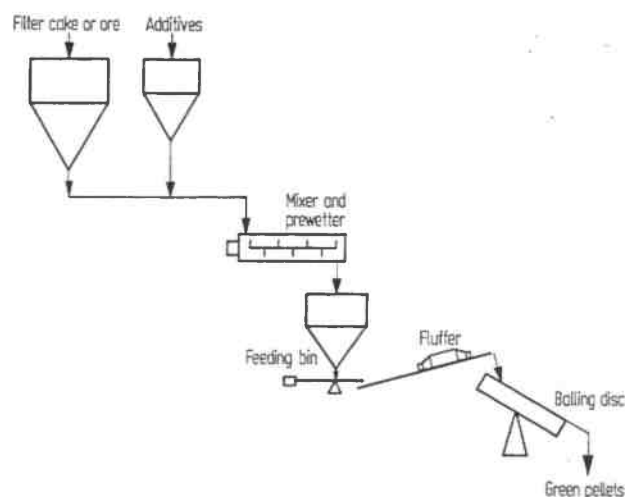


Fig. 109. Flow sheet of pelletizing disc operation

frictional resistance of the material, the finest particles are lifted up to the culmination point from where they are forced to roll down by deflectors. The pellets already produced reverse earlier and roll downwards over the surface of the charge while their diameter increases, Fig. 110. By an adequate arrangement of scrapers, the charge is so guided that during its downward-rolling a classification is promoted. The feed point of raw material should be there located where seeds are formed i.e. with a clock-

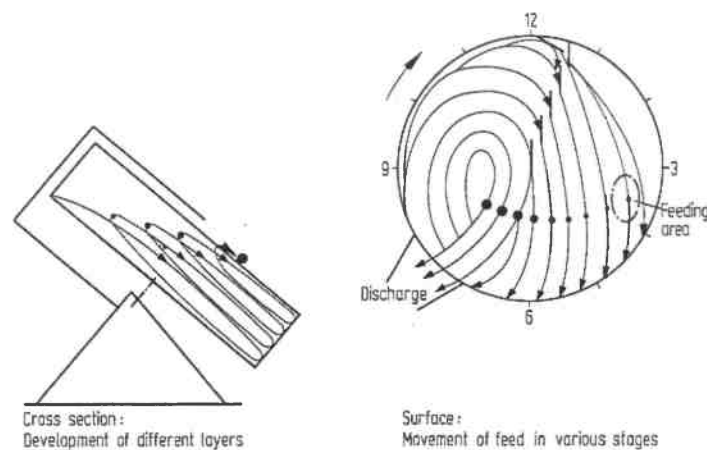


Fig. 110. Movement of pellet feed in the disc (formation of green pellets, size increase and discharge of finished pellets)

wise disc rotation approximately 3–4 hrs. This point can be varied for influencing the pellet diameter and according to the ore properties. If water is needed for ball formation, this can be added at points where the pellets are still nascent. Fig. 110 shows the material movements of the downward rolling charge, additionally guided by scrapers, as well as the raw material feed and discharge point of the finished pellets located at about 7–8.30 hrs. In a cross section the classification is perceptible in many layers according to the diameter of the individual agglomerates. The sector of a balling disc with the recognizable separating effect is shown in Fig. 111.

8.2.3.2 Influencing Factors of Green Ball Formation on a Disc

In case of drums the concave shape of the wall and the rotating speed are the two factors initiating and controlling the downward rolling movement. For a disc, the inclined plain bottom, the side wall, the deflector and scrapers have the function of initiating and maintaining the rolling

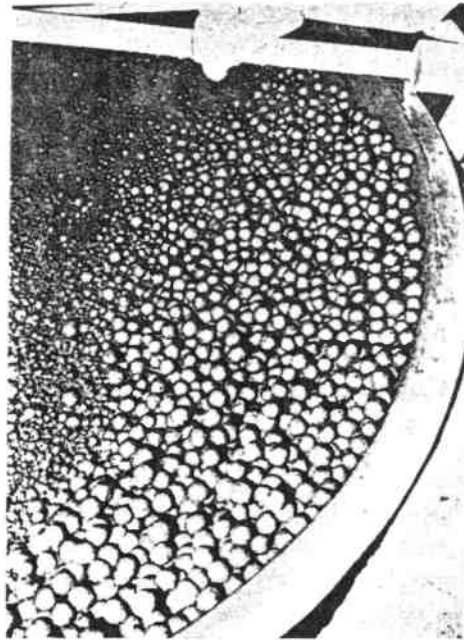


Fig. 111. Size classifying effect in a disc

movement. In this connection, it is important to provide a maximum rolling-down distance for the material to be pelletized by the inclination of the disc, its lifting power and the frictional resistance of the charge.

8.2.3.2.1 Disc Slope and Rim Height. The disc slope is determined by the dynamic angle of repose of specific material. To overcome this angle, the

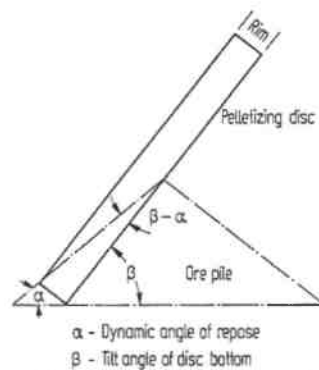


Fig. 112. Relation between disc slope, rim height and angle of repose of a fine-grained ore pile

disc slope must always be slightly steeper which is shown by Bhrany on the sketch in Fig. 112. If α is the dynamic angle of repose and ϵ the tilt angle of the disc bottom, the latter must always be greater than α . If it were smaller or equal, the material would be brought to a position of rest. At too steep an angle, the charge would no longer be lifted by friction. As in all previous cases, the frictional factor, dependent on the ore type used, plays a decisive role. The tilt angle to the horizontal line of discs for high production rates with a minimum diameter of 6 m varies between 45 and 48° according to the frictional coefficient of ore and the lifting coefficient. The rim height is also determined by the tilt angle. The filling volume is dependent on both factors.

8.2.3.2.2 Disc Rotating Speed. This is subject to the same conditions as for the drum. With insufficient speed, the charge remains in a relative position of rest. No rolling of material occurs. At an excessive speed, the material moves upwards without rolling down. Due to the centrifugal force, it is slung against the disc rim and no longer comes off so that no relative rolling movement is possible. This phenomenon occurs at the critical speed. According to experience the optimum speed must be below about 70% of this value. Primarily the fine-grained particles should be practically lifted up to the vertex and are then forced to roll downward. In this way, the length and the greatest part of the surface are utilized as rolling path. The speed of discs in industrial plants ranges from 6 to 7 rotations per minute at diameters of 6–7.5 m which means a circumferential speed of 140–160 m/min. In the case of large drums of 3.6 m diameter and at a speed of 10–14 rpm, the circumferential speed is also about 110–160 m/min.

8.2.3.2.3 Residence Time of Material in the Disc. The residence time required for ball formation is about the same in the drum for a given pellet size. The time varies linearly with the pellet diameter¹⁴).

Bhrany found the following relation between time and pellet size for the different ores:

Pellet size in mm	8	10	12
Residence Time	Ore A 120	150	200
in sec.	Ore B 70	90	100

see also Fig. 105, item 8.2.2.2.2 for drum operation.

This results from the disc filling degree which is determined by the diameter, rim height, tilt angle and desired pellet size.

Besides the bulk density which may vary between 2 and 2.2 t/m³, the moisture content of the charge plays a decisive part. If a pelletizable concentrate having the moisture content required for ball formation is

involved, the residence time of the charge can almost exclusively be utilized for ball formation. However, if water has to be added to the charge, the residence time extends and results in a corresponding larger capacity, as shown in Fig. 48, item 5.2.

8.2.3.2.4 Disc Diameter. In view of the simple design and mode of operation of the balling disc, it can easily be used for small pelletizing capacities. As indicated under item 4.4.3, a laboratory type balling disc has, for example, a diameter of 0.8–1 m and the commercial disc may have any diameter required. In big pelletizing plants built recently, discs of diameters between 6.5 and 7.5 m are in operation. The size of disc area has no influence on the pellet quality apart from the fact that the porosity decreases slightly with increasing diameter. However, the diameter and disc area are decisive for the quantity of pellets produced. All criteria for the formation of balls of good quality must be given in an optimum manner for each disc size, i.e. there is a certain correlation dependent on the ore-type used which should be determined by tests between speed, tilt angle, rim height, filling degree and residence time.

Consequently, there are direct relations between disc diameter, disc surface and throughput rate.

8.2.3.3 Balling Disc Capacity

Subject to optimum quality of green pellets, the throughput rate is determined by the filling degree of the disc, bulk density and residence time.

All factors for quality control can be ascertained previously in the laboratory where the capacity limit can be easily determined. It is exceeded when the pellet quality decreases. The throughput related to disc area in tph can then be converted to the dimensions of an industrial plant. In such a plant, values which are sometimes better than those found in the laboratory are reached. Table 12, item 4 shows a comparison of the values obtained in industrial plants with those in the laboratory. Except for minor variations in favour of the industrial plant, a good correlation is observed as is the case with green ball qualities. Mathematical models suggest that the capacity be determined through the balling disc diameter. However, it appears that the simplest way to convert the capacity is through the balling disc area.

Table 28 indicates the dependency of capacity on the dimensions of different balling discs in operation.

The raw material characteristics represent an important influencing factor for capacity variations. According to the ore type as well as composition and quantity of additives (see items 5.3.1.3–5.3.3.3) the capacity

Table 28. Dimensions, operating conditions and production rate of pelletizing discs

Disk dia- meter mm	Area m ²	Rim height mm	Tilt angle	Speed r.p.m.	Green pellet production	
					tph	tph/m ²
5000	20	550/600	45 – 48°	6.5/7.5	40 – 60	2 – 3
5500	23.5	550/600	45 – 48°	6.5/7.5	50 – 70	2.1 – 3
6000	28	550/600	45 – 48°	6/7	60 – 90	2.1 – 3.2
7000	38	600/700	45 – 48°	6/7	90 – 120	2.4 – 3.1
7500	44	600/800	45 – 48°	6/7	90 – 140	2.1 – 3.2

may fluctuate up to 30%. This calls for the performance of careful tests with each individual ore or mixture. Minor variations during operation can be compensated for by an adjustable disc slope, disc rim height and speed.

8.2.4 Comparison Between Balling Drum and Balling Disc ^{15 42)}

Balling drums and balling discs are the two units with which practically all big pelletizing plants throughout the world are equipped. Both units operate according to the same process principle. The green balls formed are almost of the same quality. Water consumption, granulometric properties and binder consumption do not influence either of the systems. The great difference is that in the case of the drum operation a relatively high circulating load of undersize is maintained by screening. This offers a certain material buffer to compensate for minor irregularities of feed rate. The drum is, to some extent, less sensitive to feed rate variations than the disc. LKAB carried out a complete comparison between drum and disc at its travelling grate plant with a capacity of 2.5 million tpy pellets at Malmberget ⁴²⁾. The mode of operation of a drum with a diameter of 3.6 m and a length of 9.5 m was compared with that of a balling disc of 7.5 m dia. The results of these tests can be summarized as follows:

- The flexibility of the drum to material fluctuations is to some extent better than that of the disc.
- The product quality is equal for both systems.
- The pellets leaving the balling drum are screened and the undersize is recirculated.
- The pellets leaving the balling disc are screened if it is desired to maintain a very close size range for direct reduction. For blast furnaces screening is not necessary.

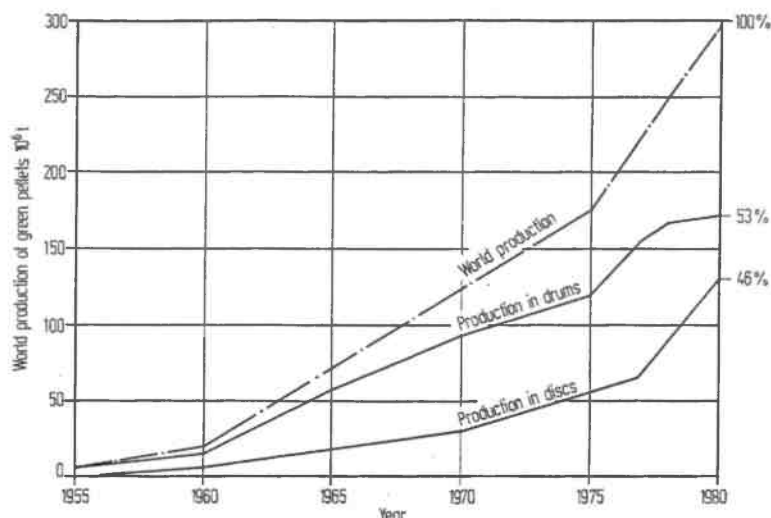


Fig. 113. Development of green pellet production in drums and discs

Process technological and qualitative differences apparently do not exist for either system. The question regarding different costs arises. The comparison made by LKAB yielded an economic advantage in favour of the disc operation. For the production of blast furnace pellets where no screening is necessary, the costs are by 4–8% lower as compared with drum operation. In this connection, a pellet size range of 85–92% between 9–15 mm and less than 3% under 5 mm are expected when a disc is used.

Fig. 113 shows the development of pellet production in drums and discs. The use of discs increases compared with that of drums.

8.2.5 Comparison of Vibrating and Roller Screens

Within the scope of the comparative tests performed with drums and discs LKAB also investigated the green ball screening with vibrating and roller screens, see flowsheet of Fig. 103. A vibrating screen of 2.1 m width and 4.3 m length with different screen decks was compared with a roller screen of 2.5 m width having 49 rollers of 10.2 cm diameter with different gaps between the individual rolls. The purpose of this comparison was to find out how distinct was the separation of under- and oversize from the desired product size between 10 and 12.5 mm. In this connection, it was ascertained that the efficiency of the roller screen under equal conditions was higher by about 25% than that of the vibrating screen. Consequently, roller screens were installed in an existing plant. Furthermore, it was

assumed that pellets of a better surface quality could be obtained by using roller screens. In addition, the operation of these roller screens proved to be smoother with lower vibrations observed in the building structure.

8.2.6 Other Balling Systems

For both systems, discs and drums, alternative constructions were developed e.g. the stepwise balling disc called “flying saucer” or a drum with inner retention cones. In each case, the undisturbed, free, rolling movement required for good ball formation was purposely interrupted which finally proved to be a disadvantage. Nowadays, such systems are no longer used. Only the free drum space and the free disc area ensure optimum rolling effect for the formation of perfect green balls.

8.2.6.1 Balling Cone ⁽¹⁶⁾

In some pelletizing plants of Bethlehem Steel balling cones were used on an industrial scale. Fig. 114 diagrammatically shows the most important component parts. The mode of operation is halfway between that of drum and disc. The rolling principle of green ball formation is identical. Separation of undersize is unnecessary because a classification takes place inside the balling cone and only pellets of the greatest diameter are discharged. Cone angle, diameter and slope referred to the horizontal are variable. Nowadays balling cones are no longer used.

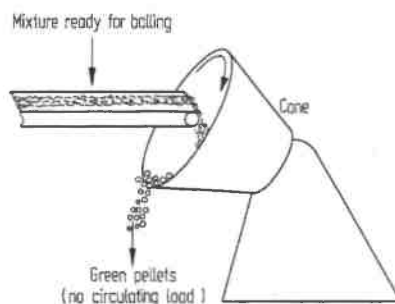


Fig. 114. Green pellet formation in a cone

8.2.6.2 Mix Granulator ⁽¹⁷⁾

This apparatus operates intermittently. Mixing devices installed in a concentrically rotating circular vessel carry out partly eccentric circular movements and thus force the particles to be mixed and granulated into contact with each other by a sliding effect under a slight pressure. In the

presence of water, capillary forces may thus develop which bring about the formation of agglomerates. This apparatus successfully used in many industries has not proved suitable for the iron ore pelletizing technology due to its low capacity compared with the high throughput required in big pelletizing plants.

8.2.6.3 Vibrating Trough ¹⁴⁾

Attempts have always been made to apply other movement principles apart from rolling to ball formation. Most of these attempts are more or less of theoretical value. Nevertheless, they are briefly described below. Curved troughs are vibrated with the frequency and vibration amplitude as well as the curvature being variable. The material is fed at one point and passes into the zone of the vibrating bottom. On this occasion, the direction of the trajectory parabola opposes gravitation so that a downward movement is obtained as resultant. A screening device arranged at the end of each pelletizing trough discharges the undersize into the next trough and the finished pellets are delivered laterally. Apart from the vibrating rolling movements, slight impact forces tend to improve the pellet strength.

8.2.6.4 Eccentrically Moving Unit ²¹⁾

Such an apparatus was considered for ball formation. Raw material and water were charged into an *eccentrically moving bowl* and, due to horizontal rotation, ball formation started. As a result of the centrifugal force, the bulkier pellets leave the bowl and drop into the *vertical downward tapering pipe* which performs the same eccentric, circular movements as the bowl. The pellets roll spirally downwards along the wall.

In this way, it was possible to produce green balls of high strength with a low water content. The apparatus was too complicated and was never used on an industrial scale.

8.3 Handling and Feeding Devices

The transport of green balls from the balling to the indurating units makes, from a mechanical viewpoint, the highest demands on their strength, drop resistance and tumbling behaviour. Therefore, the principal function of the handling equipment is to transport the pellets to the subsequent process stage without causing any damage. It is worthwhile to look for adequately designed handling and feeding devices which enable careful handling of the soft green balls. It should be noted that the

methods for testing the green ball strength were especially developed for testing the pellet properties at the transfer points (drop test) and during their sliding over chutes or during their downward movement in the shaft furnace (abrasion test). Normally, green balls are carried on conveyor belts to the indurating reactors. The design of the reversing station of these conveyor belts determines the height of pellet drop which may be up to one meter. Despite the deficiency of these designs which was early recognized it took a long time until better devices were developed.

8.3.1 Roller Conveyor

The roller conveyor was especially developed for green ball handling problems in pelletizing plant No. 1 of the International Nickel Co. at Copper Cliff, Canada and was proved on an industrial scale (1958). The technical innovation and adequate design resulted in patents being issued throughout the world¹¹⁾. The functioning principle is based on the rotation of individually driven rolls which, as a combined system, transport the green balls at a specific angle of inclination from a higher point downwards. Each of the individual green balls rolls downwards with its rotating direction being opposite that of the rollers, as is diagrammatically shown in Fig. 115. The roller diameter and the distance between the rolls are in a certain relationship to the ball diameter. The pellet rotating in the gap between two rolls is forced out by the following ones and moves over the roll apex to the next gap. At the same time, the balls are laterally pushed off from their straight-line move-

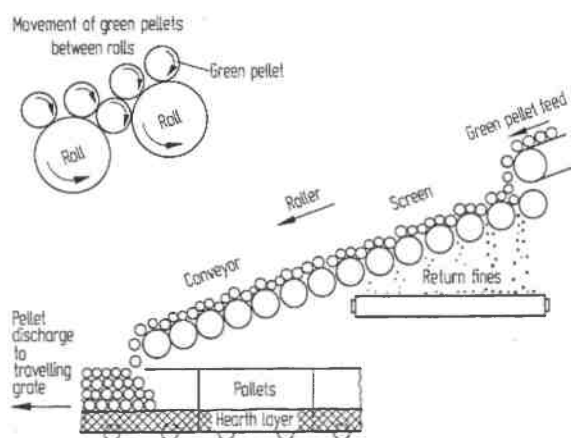


Fig. 115. Functioning of roller conveyor and roller screen

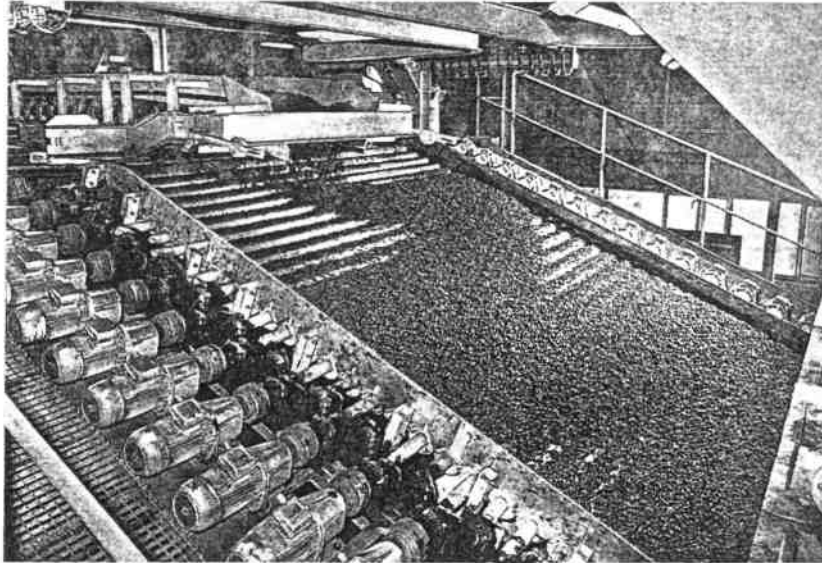


Fig. 116. Industrial size roller conveyor in operation

ment and are thus distributed over the full width of the conveyor feeding the indurating machine. Nowadays, the roller conveyor is used in travelling grate plants and is also increasingly applied to other firing systems. Fig. 116 shows a photograph of a roller conveyor on an industrial scale.

8.3.2 Roller Screen

The roller screen was derived from the roller conveyor with the gap widths between individual rolls having been adapted to the undersize particles to be separated. Thus, part of the roller conveyor operates as a screen, before the green balls are fed to the indurating machine, see Figs. 115 and 116. In this way, fines and ball fragments can be separated from the feed and recirculated. The roller conveyor has the additional advantage that the balls receive a very smooth, uniform surface by their continuous rolling movement.

8.3.3 Rolling Belt Conveyor ¹¹⁹⁾

Another interesting alternative has already been tested in Inco's Copper Cliff Pelletizing plant, namely the rolling belt conveyor. A belt conveyor

with a relatively steep angle of inclination referred to the horizontal moves upwards in opposite direction to the downward movement of green balls. The accelerated speed of ball movement can be slowed down by swinging rubber aprons. Fines and pellet fragments which do not roll are discharged upwards over the head pulley of belt conveyor and recycled. The rolling belt conveyor was also experimentally used as a balling unit. However, the pertinent development work was not continued.

9 Heat Treatment Systems

The last step in pellet production, thermal treatment, consisting of drying, heating and cooling is carried out in several systems which already have been successfully employed for similar operations. Provided that the green pellet quality is sufficient, the various heating systems must be adapted to the new task. This means, modifications have to be made, if necessary. Three important burning systems are presently used. Their principal features are outlined in general before they are described in greater detail.

(a) *Shaft Furnace.* Due to its high thermal efficiency and its relatively simple operational requirements, it was used as the first unit both in the USA and in Sweden for indurating pellets from magnetite concentrates. As long as magnetite was the main raw material, the shaft furnace was of great importance.

The green balls are charged on top of the furnace opening. They move by gravity downwards through all thermal zones towards the discharge end. The pellets are in continuous movement and exposed to friction and increasing pressure.

Control and influence of individual thermal steps from outside are practically impossible. The process gases flow at varying temperatures through the pellet bed, absorbing heat in the cooling zone and emitting heat in the burning and preheating zone.

(b) *Travelling Grate – Rotary Kiln Combination.* Following successful use with the burning of cement raw meal, the combination of travelling *grate-rotary kiln-cooler* was also adapted to the firing of iron ore pellets. This process has become known throughout the world under the name “Grate-Kiln-Process” and is suitable for nearly all pelletizable ores.

In the grate-kiln system three specific process units for different thermal conditions are connected with each other. – The travelling grate is used for drying, preheating and oxidation of magnetite. The green balls are in a relative position of rest. Hot waste gases from the rotary kiln or additionally from the cooler pass through the green ball layers in different

directions and zones while the green balls are dried and preheated. – In the rotary kiln, provided with refractory lining the preheated pellets are indurated mainly by radiation heat to the required temperature. During the transfer from the preheating grate to the rotary kiln, special care has to be taken in order to bring the pellets in sound condition into the rotary kiln to avoid breakage. Reaction of oxide dust with the hot lining and formation of accretions or rings must be avoided. After dropping from the travelling grate over a chute into the rotary kiln the pellets move in the form of flat spirals towards the discharge end. – Subsequently, the hot pellets pass into the third unit, the cooler, where they are cooled with air. The heated cooling air flows chiefly into the rotary kiln and partly over the travelling grate. With the possibility of having three different process units, the heat supply can be proportioned according to the ore type to be treated. The use of the travelling grate with its various functions is imperative for a successful operation of the rotary kiln. For thermal, operational and quality reasons, the rotary kiln alone would not be sufficient.

(c) *Travelling Grate.* Since the turn of the century, the travelling grate had been used for the sintering of fine-grained iron ores and was adapted round about 1948–50 to pellet firing after adequate modifications had been made. Today travelling grates are successfully in operation for practically all ore types throughout the world.

The individual thermal zones of the travelling grate can be rather easily separated into horizontal reaction areas and adapted to the relevant requirements by using process gas of controlled flow rates and temperatures. After the green balls have been charged to the grate, they remain in a relative position of rest until they are discharged. The last grate area serves to cool the hot pellets with fresh air. The recovered heat is recirculated to the system.

9.1 Shaft Furnace

Compared with other firing systems, the shaft furnace has some advantages, such as:

- simple construction, a small number of moving parts, refractory lining of total furnace with bricks of optimum ceramic quality differing in various zones
- intensive heat exchange between gases and solids due to countercurrent flow.

A disadvantage of the shaft furnace is the little chance of influencing individual process stages and thus causing a lower flexibility. To avoid

corrective action and to ensure trouble-free operation, some important conditions have to be fulfilled:

- (a) Green balls of best quality are required. In particular, bentonite is one of the principal binders for shaft furnace pellets.
- (b) Uniform distribution of pellet charge over the cross sectional area.
- (c) Careful introduction of process gases without overheating the furnace walls and marginal parts of the pellet charge.
- (d) Uniformly proportioned supply of burning gases and cooling air as well as intensive mixing in the thermally relevant firing and preheating zone.

Each impairment of the uniform permeability of the feed causes an irregular gas flow and thus an irregular heat supply which inevitably results in a differing pellet quality.

9.1.1 Shaft Furnace Types

In the course of development, various proved constructions were employed. A quite early important modification to the furnace design was the change from the circular to the rectangular shape of the furnace cross section which is generally used nowadays. The green ball feeding device was repeatedly modified. The shape, size and arrangement of burner gas inlet openings into the furnace space was also changed and especially the cooling method so that shaft furnaces with coolers of different design are used. Two of the best-known types are diagrammatically shown in Figs. 117/118.

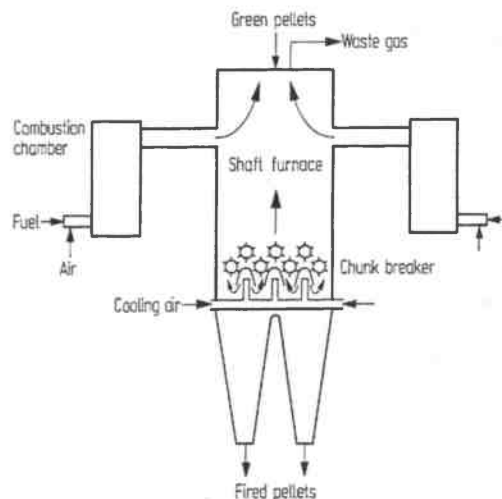


Fig. 117. Long shaft furnace with internal cooling

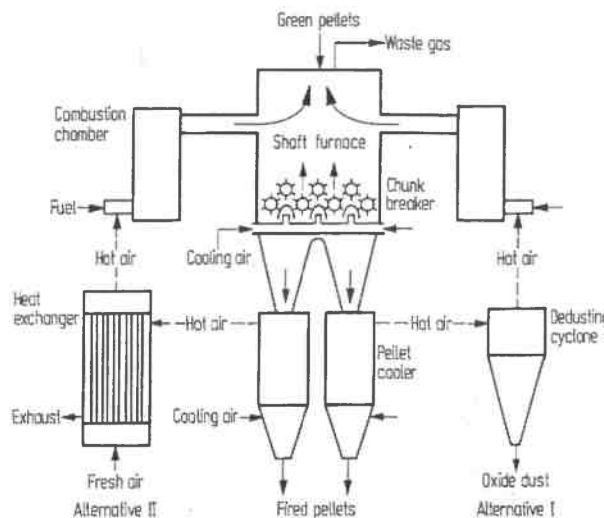


Fig. 118. Medium shaft furnace type with alternative external coolers

In the case of the first furnace type, Fig. 117, the cooling is largely accomplished in the same space as the firing. The cooling zone is relatively long so that this furnace is designated as a long shaft-type furnace. Such a cooling air flow rate is injected as is needed for optimum heat exchange. The chambers for combustion of the fuel supplied are provided with fresh air.

As far as the second furnace type, Fig. 118, is concerned, the major part of cooling is carried out outside the shaft in separate cooling chambers. Two alternatives are possible for recovering the sensible pellet heat. According to alternative I, the hot cooling air is dedusted and, depending on the pertinent requirements, introduced directly into the combustion chambers. As regards alternative II, the heat exchange is achieved by using a recuperative system in which the cool, fresh air is indirectly heated and conveyed to the combustion chambers.

At the present time, the long-type furnace, Fig. 117, is mainly given preference for comparatively high throughputs. The following comments thus refer to this furnace type.

9.1.2 Process Stages

9.1.2.1 Charging of Green Balls to the Furnace

One of the most important prerequisites to a regular furnace operation is a good gas permeability of the charge. To ensure this, the green balls

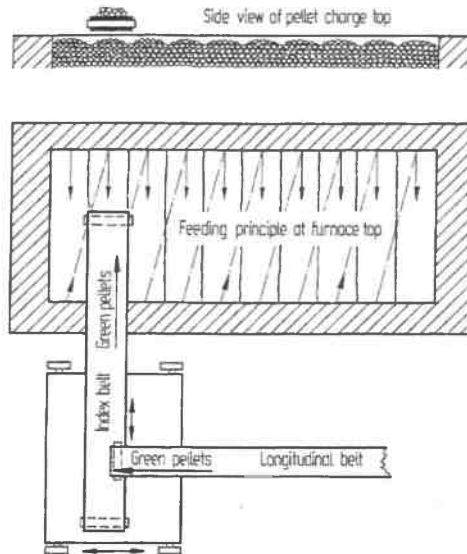


Fig. 119. Shaft furnace green pellet feeding device

have to be loosely and evenly fed onto the charge surface. In the course of development, a special feeding system was developed with which the pellet surface is evenly shaped by formation of regular rills and valleys the difference between peak of rills and base of valleys being about 15 cm. This system is shown diagrammatically in Fig. 119. The pellets are fed in thin layers by means of reversible belt conveyors with programmed moving rhythm with the rill shape being perpendicular to the longitudinal axis of the furnace port. The feed level is about 0.3 m below the furnace lip. From here, the green balls slide at a speed of 3–4 cm per minute down into the furnace. The process gases leave the furnace in the opposite direction through the pellet bed at a temperature of about 120–150 °C. To maintain the different temperature ranges inside the furnace, it is important that the surface of the pellet charge is kept always at the same level.

9.1.2.2 Drying, Preheating and Firing

At a depth of 120–150 mm below the bed surface and after 4–6 minutes residence time, the pellets are largely dry and preheated before the oxidation of magnetite begins. Once the charge has moved downwards by about 500 mm the optimum firing temperature of approximately 1350 °C is reached. The amount of heat available inside the furnace con-

sists of the following components if magnetite concentrate without additional fuels is to be treated:

- (a) The sensible heat of hot pellet recovered from the cooling zone is transferred with cooling air into the upper zones where it is mixed with burner gases.
- (b) During conversion of magnetite to hematite, the oxidation heat, almost 50% of total requirements, is released and produces an additional temperature rise.
- (c) The remaining heat originates from hot combustion gases being produced by combustion of oil or gas with air in the outside combustion chambers and forced through corresponding inlet openings at a temperature of about 1280 °C into the descending pellet charge ¹²¹).

To achieve a high thermal effect, the cooling air flow is to be so controlled that an optimum firing temperature of about 1300–1350 °C is obtained in conjunction with the oxidation heat as mixing temperature prevailing above the burner gas inlet level ¹²¹). Approx. 35–40% of the total process air volume is supplied to the combustion chamber. The remaining process air volume is introduced as cooling air.

A uniform temperature distribution over the entire furnace section is an important prerequisite to good pellet quality. The gas distribution is dependent on the pertinent feed porosity representing a specific resistance to flow and thus limiting the gas flow rate, see also items 13.2 and 13.4. According to operational values found the ratio of process air to pellet charge is 1:1 by weight. A higher gas velocity at an adequate pressure may result in eruptions in the charge or in a fluidization of the pellet surface. Due to the resistance of the charge to the gas flow, the penetration depth of burner gases from the furnace walls to the charge centre is limited and therefore also the calories available locally. For this

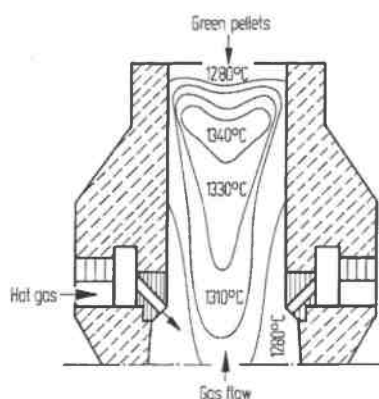


Fig. 120. Temperature isotherms in the upper stove of the shaft furnace

reason, magnetite concentrate is exclusively treated. If hematite pellets had to be processed, the lack of heat would have to be compensated from outside and this would cause overheating at the furnace walls and in pellets near the wall.

The lateral gas flow problems are an important reason for limiting the width of furnace section to a maximum of about 2.5 m. To enable sufficient mixing of different process gases arriving simultaneously at approximately the burner level, the necessary height of the furnace shaft from the burner level up to the pellet charge surface is about 2.5–3 m. As the different gas flows unite isotherms are formed over the upper stove section which are diagrammatically shown in Fig. 120¹²²).

9.1.2.3 Cooling of Pellets

The major part of the shaft furnace volume serves for cooling the hot pellets. The cooling air is injected into the lower furnace part where the section is interrupted by a series of swinging rolls (chunk breakers). These rolls, equipped with breaking teeth support the whole pellet charge and keep it loose. Any agglomerates which may have been formed by overheating, are broken in order not to choke the discharge devices. The cooling air is blown into the loosened bed approximately at this level at such a pressure and flow rate that it flows evenly upwards through the entire charge and carefully cools the pellets. The cooling air flow rate is adjustable, thus controlling the pellet discharge temperature.

9.1.2.4 Heat Consumption

During the first years that shaft furnaces were used, insufficient experience was available to profit by the possibilities offered by this heat exchange system. In 1958, the heat consumption was about 1.1 million kJ and is today approximately 500,000 kJ/t pellets in industrial furnaces. Only pellets of magnetite concentrate are fired successfully. Numerous attempts have been made to increase the hematite portion and to compensate for the lack of oxidation heat by the addition of finely ground coal¹²³). But no considerable success has yet been achieved where the pellet quality is primarily concerned. So far an approximate hematite portion of up to 15% in the magnetite concentrate is tolerable.

9.1.3 Furnace Dimensions, Capacity and Market Position

In recent years, the biggest shaft furnaces with a design capacity of approximately 500,000 t pellets per year were built on the basis of magnetite concentrates in different countries throughout the world. The correspond-

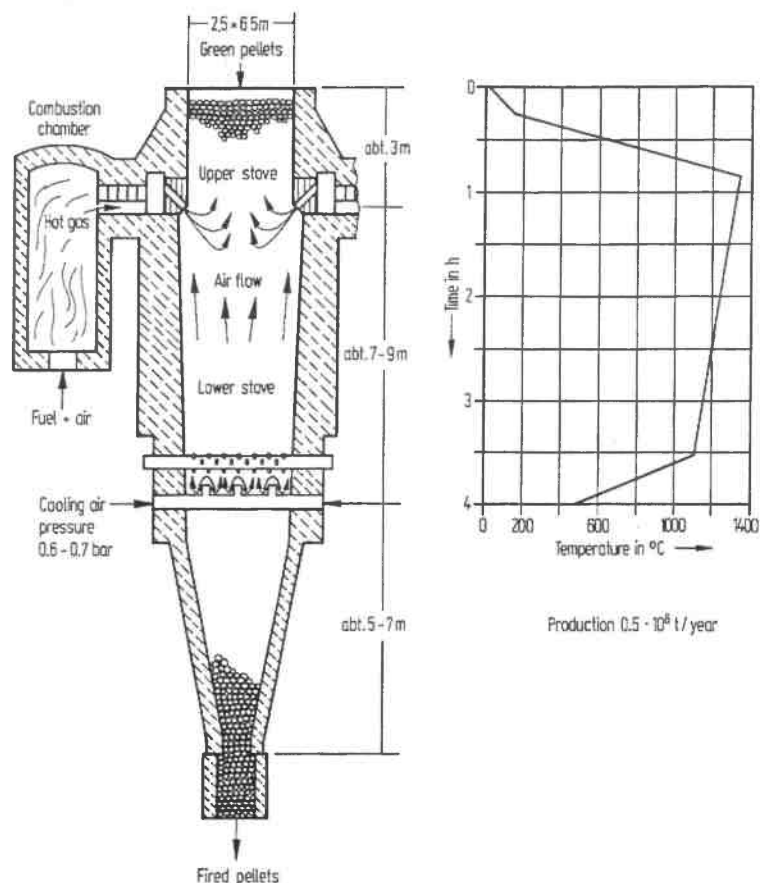


Fig. 121. Main dimensions, gas flow and temperature profile of shaft furnace

ing furnaces had roughly the same dimensions and equipment as shown in Fig. 121 (24). The various zones, the residence time of pellets in these zones and the principal temperatures are also described. The furnace has a rectangular sectional area of about 2.5×6.5 m, i.e. about 16 m^2 . The furnace width is limited due to the penetration depth of heating gases into the pellet charge. The length is mainly dependent on the design of the lateral combustion chambers. The shaft space is vertically divided into two zones, called upper and lower stove. The upper stove begins at the burner level and has a height of about 2.5–3 m. In this section, all heating stages are carried out. At a descending speed of charge of 3–4 cm per minute, the pellets remain for about one hour in this zone. Underneath this burner level, where no external heat supply occurs, the cooling zone

in the lower stove begins where a rest of the magnetite may also oxidize. The lower stove ends at about the level of the air admission inlets and chunk breakers. It has a height of 7–9 m. Consequently, the process-efficient total height of shaft furnace is approximately 11–12 m. The residence time is about 4–6 hours and depends on the relevant gas permeability of the charge.

The annual capacity of such a shaft furnace is approx. 500,000 t pellets. Some of these furnaces are operating e.g. at the

Erie Mining Co.	in Minnesota, USA	1 furnace
Griffith Mine	in Ontario, Canada	3 furnaces
LKAB	in Northern Sweden	1 furnace
Sierra Grande	in Argentina	4 furnaces

In the course of years, the initial great importance of the shaft furnace has decreased more and more. About 25 million tons of the magnetite concentrates treated in pelletizing plants in 1978 are still indurated in shaft furnaces which corresponds to about 9–10% of world production.

Reasons for the decreasing importance of the shaft furnace use are:

- limited throughput
- almost exclusive use of magnetite
- comparatively high fuel consumption
- somewhat inferior quality compared to other systems.

However, even if the quality of shaft furnace pellets was slightly lower than that obtained in other firing systems, it is sufficient to meet the requirements in blast furnace and direct reduction plants.

9.2 The Grate-Kiln Combination ¹²⁵⁾

The main development work for conversion of the successful cement burning process to the thermal treatment of green balls produced from iron ore was first performed by Allis Chalmers in Milwaukee, Illinois, USA.

Initial considerations to develop a new cement burning process with a low heat consumption led at the time to a great success. Endothermic reactions on the travelling grate and the burning of cement clinker at high temperatures in the rotary kiln were the best prerequisites to the application of this technology to the firing of iron ore pellets. Due to the experience gained in the course of construction of many cement plants, the machinery and equipment were of such a sound functional design that no substantial modifications were required for green ball heat treatment. The three main process units, namely travelling grate – rotary kiln – cooler, and their individual functions are discussed on the basis of Fig. 122 ¹²⁶⁾.

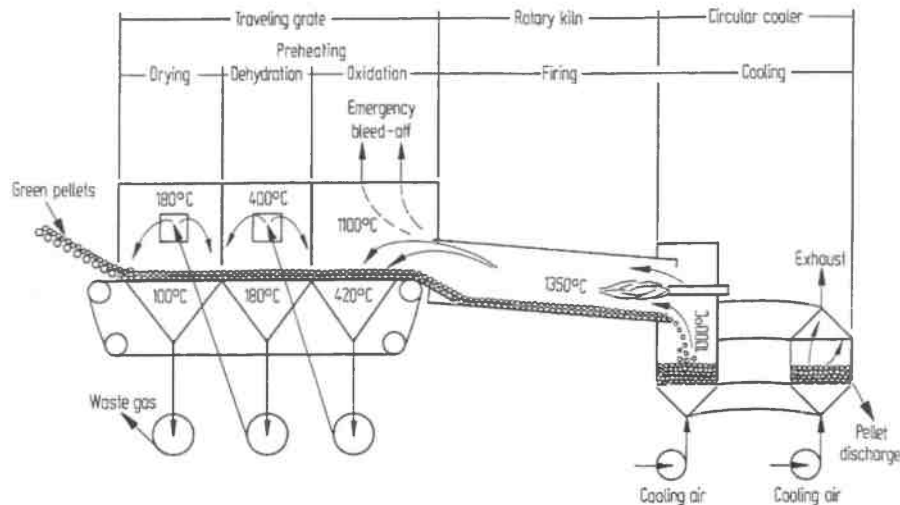


Fig. 122. Functioning of grate-kiln process

9.2.1 The Travelling Grate and its Functions

The travelling grate consists of 3 main parts: the movable grate, the stationary windboxes below, and stationary hood above. The grate consists of an endless chain of grate plates which are connected with the windboxes in a gas-tight manner. The process gases are passed through adequately dimensioned fans. The windboxes, as well as the drying and preheating hood are divided into individual process zones.

On the grate, the following thermal stages successively proceed: down-draught or up-draught drying, preheating, dehydration and oxidation of magnetite. The green balls are charged directly onto the grate plates without hearth layer at a bed height of about 20 cm. Nowadays, in many plants this is achieved through a roller screen and roller conveyor. Due to the relatively low bed height and careful feeding, a good gas permeability is maintained in the charge. The pellets travel into the first drying zone in which both down- and up-draught may be applied. The drying gas flows through the bed at a temperature of approximately 180–210 °C and leaves it at about 100 °C. In the second zone, the gas temperature is already so high that a dissociation of hydrates may start. The necessary energy is supplied at about 400 °C from the preheating zone which already serves for preheating, dissociation of carbonates or magnetite oxidation. It is supplied by the waste gases from the rotary kiln. At the end of the grate, the pellet bed reaches about 1100 °C. The first crystal compounds begin to form primarily due to magnetite oxidation. In the

case of other ores, e.g. hematite or limonite, the necessary heat energy can be made available by additional heating which, however, then gives rise to an extended residence time. The prefired pellets leave the grate over a chute and tumble into the rotary kiln.

This transfer point is a critical imperfection of this system. There is the risk that weak pellets are abraded or broken at this point. Provision is made for collection of the undesirable material and for its separation from the material flow before it enters the kiln. This serves to avoid reactions between the hematite containing dust and the refractory lining of the kiln wall. If such dust nevertheless enters the kiln, this results in accretions and ring formation which cause great disturbances of the entire system. This difficulty can be largely avoided by improving the pellet strength through a higher preheating temperature on the travelling grate.

In this way, the travelling grate already takes over part of the functions of the rotary kiln.

By adjusting the fan capacity and process gas temperature, the travelling grate has a considerable flexibility which may have a compensating effect particularly in the case of ores with different properties. Also by changing the individual zone split and, above all, by extending the preheating period, it is possible to provide optimum conditions for the rotary kiln operation. The kiln waste gases enter the preheating hood at about 1100 °C and leave it at about 100 °C after they have repeatedly passed through the pellet charge, indicating a good heat exchange. The most important function of the travelling grate is to supply the rotary kiln with preheated pellets of a sufficient resistance to breakage and abrasion. The rotary kiln alone, without preceding travelling grate, would more correspond to a nodulizing kiln.

Therefore, the entire system only works successfully as a grate-kiln combination.

9.2.2 The Rotary Kiln and its Functions

In the rotary kiln, the pellets are brought from their relative position of rest on the travelling grate into a rolling movement. They roll spirally in a very thin layer towards the discharge end. The pellets are uniformly heated by radiation heat of the hot kiln wall and hot gases thus leaving the kiln as indurated pellets. To ensure that the pellets reach a temperature of approximately 1320–1340 °C, the furnace wall temperature is higher, which particularly intensifies the risk of accretions. The kiln is heated by fuel and hot air from the cooler in a central burner. Fuel can be supplied as oil, gas or, to a certain extent, pulverized coal insofar as quantity and melting properties of the coal ash permit this. To obtain a

large heating surface at optimum residence time, the kiln diameter is relatively great compared to the kiln length.

9.2.3 The Cooler

The cooler is designed as an annular cooler with lateral walls and grates which serve as the bottom. The pellets leave the rotary kiln at about 1300 °C and are charged as a layer of 75–80 cm depth onto the cooler. The cooling air is forced through the bed into two zones. When heating pellets from magnetite concentrates, it may be that the residence time and preheating temperature on the travelling grate are insufficient for a complete magnetite oxidation. Since the rotary kiln is not very suitable for further oxidation, the final oxidation must then be carried out in the cooler¹¹⁾, which may sometimes lead to an initial slight temperature rise in the first cooling zone. The hottest part of cooling air goes directly into the kiln. The cooling air of lower temperature can be blown into the drying zone of travelling grate. The efficient recuperation of the sensible heat from the indurated pellets is very important for a good heat recovery. Many efforts are successfully made for decreasing the heat input¹²⁾.

The cooling air and waste gas fans control the main process gas stream. Fans which have been installed between the preheating and drying zone regulate partial gas streams. A grizzly is arranged between rotary kiln outlet and cooler inlet in order to remove any major undesirable lumps from the system.

9.2.4 Heat Consumption

It should be borne in mind that the grate-kiln process was at the time chiefly developed for saving heat energy for cement burning by using the optimum heat transfer methods. In the rotary kiln, the heat transfer is achieved by radiation and on the grate by convection. This advantage also applies to iron ore pelletizing. The following heat consumption figures are available from industrial plants over a long operating period:

For pellets produced from magnetite:

about 300–250,000 kJ/t pellet.

For pellets produced from a mixture consisting of 30% magnetite,
70% hematite-limonite,

8% dolomite:

approximately 1,200,000 kJ/t pellet.

For pellets produced from hematite:

about 850,000–1,000,000 kJ/pellet.

In this connection, it should be noted that the recuperation of sensible heat from the hot pellet bed has reached a high stage of perfection. However, in competing firing systems the heat consumption does not greatly differ.

9.2.5 Current State and Market Position of the Allis Chalmers Grate-Kiln Process

The three process-specific units are adapted to a specific ore or ore mix in such a way that residence time and heat supply permit optimum results to be achieved with regard to power consumption, thermal efficiency and pellet quality. The possibility of changing the dimensions of the various apparatus during the design stage results in great flexibility where the use of different ores is concerned. Thus, grate kiln plants for ore types of the greatest variety, e.g. magnetite and hematite concentrates as well as natural ore fines and mixtures^{12a)} are nowadays operated all over the world. It is also possible to produce pellets of different basicity. The specific capacity of the three thermal units is determined by the properties of different ore types, see Fig. 123. The specific capacities referred to the travelling grate area (Curve I), the rotary kiln throughput with regard to kiln volume (Curve II) and the cooling capacity (Curve III) were compared.

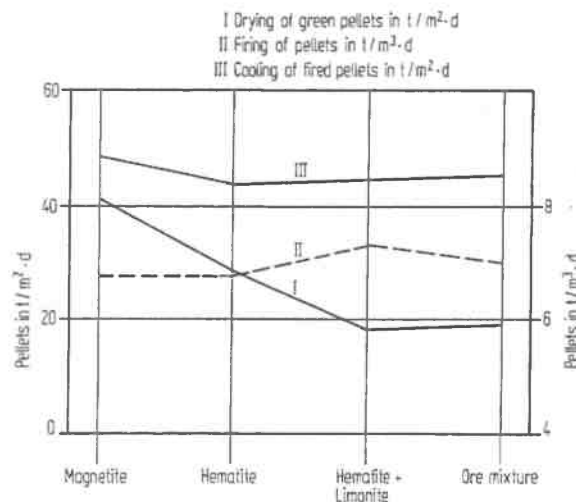


Fig. 123. Influence of ore types on drying, induration and cooling rate in grate-kiln operation

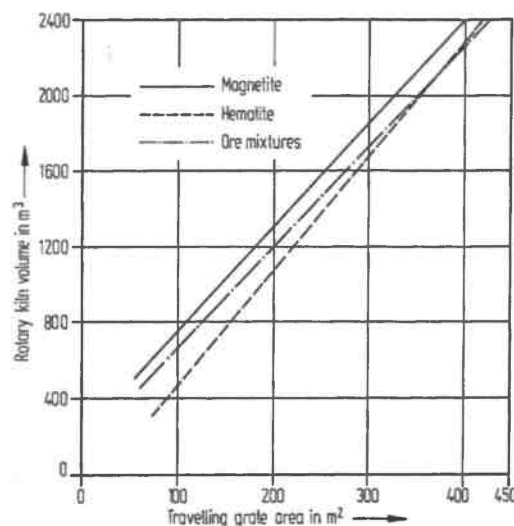


Fig. 124. Relation between kiln volume and grate area for various ore types

There are differences in the travelling grate section. The capacity achieved with magnetite pellets is higher by 25% than with hematite and higher by 50% than with limonite-containing hematite pellets or an ore mix. When the preheated pellets have reached a certain strength and temperature and are oxidized upon leaving the grate, there are hardly any differences for their residence time in the rotary kiln. For cooling, only the pellet temperature and the specific calorific value are of importance unless the pellets show great fluctuations in their bulk density.

From the time the first industrial plant with a capacity of about 350,000 tpy pellets was built at the Humboldt Mine in 1960 with a grate area of about 62 m² and a kiln volume of about 350 m³, a period of only two years elapsed before plants with a capacity of 1 million tpy were erected. The dimensions of the various units were increased according to the rising demands so that nowadays plants with a capacity of 4 million tpy in one single line are already in operation. The grate area is increased up to 400 m² and the kiln volumes up to about 2,200 m³.

The relationship between grate area and kiln volume is more or less linear but with minor differences caused by various ore types, as is apparent from Fig. 124. The grate area for magnetite pellets is smaller than that for hematite pellets at equal kiln volumes while that for ore mixtures depends on the constituents. The application range of this process can be demonstrated by the quantity of pellets worldwide produced from different raw materials up to 1978:

– magnetite ores	
approximately 60 million tpy	=38% *)
– hematite ores	
approximately 19.5 million tpy	=31% *)
– magnetite-hematite mix	
approximately 11.3 million tpy	=24% *)
– hematite-limonite mix	
approximately 6.2 million tpy	=22% *)

*) % of the corresponding world production from this ore type.

Up to 1978 about 97 million tons of pellets were produced in grate-kiln plants. This corresponds to approximately 33% of the total world production, see Fig. 133. The real production rates are often higher but cannot be easily determined since many individual plants are sometimes operated at overload. This latter statement also applies to other hardening systems.

9.2.6 Other Grate-Kiln Processes

The designation “grate-kiln process” for iron ore pelletizing is connected with the name Allis Chalmers although the original burning system was first developed in Germany in the thirties under the name “Lepol Process” (LEllep-POLysius). As licensor of the Lepol process, Polysius also decided in favour of ore pelletizing even though at a later date than Allis Chalmers. The combination of travelling grate-rotary kiln-cooler is generally the same as for the grate-kiln process. Up to now, it was to a lesser extent, applied to iron ores than to other raw materials, e.g. nickel, chrome or vanadium ores, in-plant fines and phosphates ¹²⁸).

9.3 Travelling Grate Systems

The travelling grate is one of the oldest and most frequently used units for the production of agglomerates from fine-grained ores. Its flexibility allows a wide application range in the various fields of agglomeration e.g.:

- Raw materials: iron ores, non-ferrous metal sulphides or oxides, fly ash, cement raw meal, clay
- Fuels: coke breeze, anthracite, sulphide sulphur, oil, gas and composite fuels
- Process variants: down-draught, up-draught gas flow or a combination of both systems

- Reactions: endothermic reactions in which heat energy is consumed or exothermic reactions in which heat energy is released.

Its main application range is the agglomeration of fine-grained iron ores to be treated in the blast furnace. About 70% of the raw materials used for the present pig iron production originate from iron ore sinter and 30% from pellets and lump ore.

It is not surprising that the travelling grate was also tested and successfully employed for pellet induration. The travelling grate construction was taken over from the sinter strand and consists of three main parts:

- the central part is movable and consists of pallets, composed of a frame and a supporting structure into which grate bars are inserted. The pallets are connected by means of sliding seal bars with the windboxes in a gas-tight manner,
- the bottom part is composed of the stationary windboxes connected with the gas mains and the moving grate,
- the upper part comprises the heat energy and air supply systems in a stationary hood above the grate.

The system serves to convey the necessary drying, heating or cooling gases through the pellet bed.

Important process facilities are the fans with which the process gases are moved through the charge. At one end the green balls are charged and the indurated pellets leave the grate at the opposite end. The entire thermal treatment is achieved during one passage of pallets. The residence time of pellets on the grate is between 30 and 40 minutes depending on the ore type treated, see Fig. 84.

9.3.1 Application of Travelling Grates to Thermal Treatment of Pellets

Due to the great challenge of travelling grate applications development work was started simultaneously and independently at various places in the world. Different ores and various heating technologies were investigated. Three prototypes were, in parallel, developed and installed on an industrial scale, which are outlined below:

(a) *The travelling grate plant of Cleveland-Cliffs, Iron Co.* This plant was started up at Ishpeming, Michigan in October 1956. Flotation concentrates from specular hematite ores were treated. The whole operation, except for the ignition, was carried out in up-draft gas flow. Solid fuel, mostly anthracite or coke breeze at a rate of about 4–5% was charged in layers onto the surface of green pellets. The final product obtained consisted of pellets and a certain amount of pellet sinter.

(b) *The travelling grate plant of Reserve Mining Co. at Silver Bay, Minnesota* was started up in October 1955. The ore basis was magnetite concentrates. The fuel supply consists of anthracite (12–15%) and oil (85–90%). At the beginning the entire process was carried out in down-draught except for up-draught drying and, later on, up-draught cooling was applied.

(c) *The travelling grate plant of International Nickel Co. of Canada Ltd. at Copper Cliff, Ontario* was started up in February 1956. In this plant, artificial magnetite was treated. The only extraneous fuel source was *oil*, and, later on, natural gas. No coal was added. In this plant new equipment, especially developed and designed for pellet formation and induration and further new process variants were applied.

9.3.2 General Features

Some features of the travelling grate are favourable for the thermal treatment of green balls.

- (a) The relatively low depth of 20–40 cm of the green ball layer avoids excessive pressure and allows a uniform gas permeability.
- (b) Any irregularities in the gas flow and permeability of the bed only influence a small part of the layer. They are quickly eliminated by the horizontal movement of the grate.
- (c) The arrangement of windboxes and the possibility of sealing them against the moving pallets allows an adequate delimitation of individual zones of different temperatures, gas flow rate and gas flow direction.
- (d) Gases of different temperature and atmosphere can be introduced into the burner hood above the charge.
- (e) The possibilities of using different fuel types and consequently burner designs permit a great flexibility in the choice of fuel types.
- (f) Due to the variation range of process parameters, optimum firing conditions can be provided for a wide variety of ore types at a good pellet quality.
- (g) Extensive recuperation of sensible heat of the fired pellets results in a relatively low heat consumption.
- (h) The construction of big units allows the production of correspondingly large pellet quantities in one single line.

However, these features do not apply equally to the various travelling grate processes, which are separately described below.

9.3.3 Up-draught Induration Process for Specular Hematite

Due to the fact that a flotation concentrate is not suitable for normal down-draught sintering, pelletizing in an experimental shaft furnace was tested with a negative result. Subsequently, the *up-draught pelletizing process* was jointly developed by the Cleveland Cliffs Iron Company, Ishpeming, Michigan and the Mines Experiment Station of the University of Minnesota in Minneapolis^{12(f)}. The individual green balls which are fed onto a travelling grate of 1.8 m width and 50 m length are coated with the necessary solid fuel for the heat treatment.

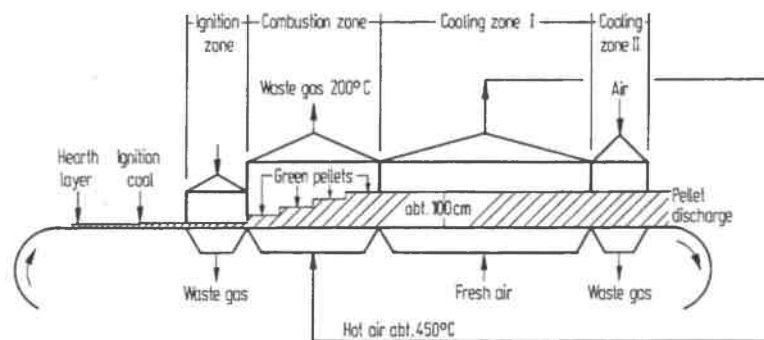


Fig. 125. Up-draught induration on travelling grate

Fig. 125 shows the process flowsheet. The grate bars are first covered with a layer of fired pellets onto which a thin layer of ignition coal is placed. The coal is ignited with an ignition furnace so that the pellet layer is heated in down-draught flow. The first green balls containing solid fuel are layered on the surface of the red hot pellets at a depth of about 20 cm. By reversing the air flow direction to up-draught this first pellet layer is dried, preheated and the coal therein contained is ignited. By further air injection, the flame front is forced to travel upwards. When it reaches the surface, a further layer of green balls is fed and the air continued to be forced through the bed. This procedure is repeated up to a pellet bed height of 80 cm. In the last grate section, the cooling takes place. From this zone, part of the sensitive heat of the pellets is recuperated and blown under the grate as hot air of approx. 450 °C.

The discharged product is screened and the oversize is crushed. After fine grinding the undersize is recycled and combined with the concentrate for balling. The final product is a variable mixture of pellets and pellet sinter. An advantage of this process is that the pallet parts and grate bars never come in contact with red-hot material or hot gases.

On the other hand, its disadvantage is that the volume and pressure of the up-draft air flow is limited in order to avoid any fluidization of the charge. At that time the product quality did not fully correspond to the customer's expectations. The design capacity was approx. 2000 t agglomerate/day. After a few years of operation the plant was shut down.

9.3.4 Travelling Grate Process According to Arthur G. Mc Kee and Company

This induration process was for the first time applied on an industrial scale by the Reserve Mining Co., Messrs. Arthur G. Mc Kee and Allis Chalmers at Silver Bay, Minnesota, after it had been jointly developed and tested in the laboratory of the Mines Experiment Station of the University of Minnesota¹³⁶). A pilot plant with a capacity of 1000 t/day was first built at Babbitt, Minnesota.

This process was virtually based on the down-draught principle of a normal sinter machine. The first six machines had a suction area of $1.8\text{ m} \times 51\text{ m} = 91\text{ m}^2$. A belt conveyor and a vibration screen arranged directly above the grate served as a green ball feeding device. Initially, a certain amount of coal was powdered onto the magnetite green pellet surface. In this case the following heat sources had to be so harmonised, that an optimum thermal effect at a specific moment was ensured:

- coal on the surface of pellets
- oxidation of magnetite inside the pellets
- oil converted to hot gas
- cooling of heat recuperated from hot pellets.

This harmonisation could not be easily achieved and the heat input required for ensuring a good pellet quality was thus relatively high, viz. altogether about 1.5 million kJ per t pellets and was composed of:

oil firing:	29%
coal consumption:	59%
oxidation heat:	12%
	100%

This process was also very similar to the firing technology applied during down-draught sintering and only differed by a larger oil-fired hood instead of the normal ignition furnace. The side walls and grate bars of the pallets were not protected by hearth and sidewall layer against overheating. This overheating of the metallic parts initially caused the greatest difficulties even if specific alloys were used. To avoid any excessive thermal stress, magnetite ores have hitherto been used for *this*

travelling grate system only because the induration of magnetite pellets can be carried out at lower temperatures than hematite pellets. Fig. 126 is a typical process flowsheet indicating the zones of different thermal treatment. In order to optimally control the individual process stages, the area above the 28 windboxes is divided into separate reaction zones:

- | | |
|---|---|
| (a) Up-draught drying zone | = 7 windboxes = 25% of the suction |
| (b) Down-draught drying and preheating zone | = 4 windboxes = 14% of the suction |
| (c) Ignition zone | = 2 windboxes = 7% of the suction |
| (d) Firing and heat exchange zone | = 9 windboxes = 32% of the suction |
| (e) Up-draught cooling zone I | = 3 windboxes = 11% of the suction |
| (f) Down-draught cooling zone II | = 3 windboxes = 11% of the suction |
| | <u>28 windboxes = 100% of the suction</u> |

Numerous attempts were made to improve the operating parameters for which purpose pellet producers and plant constructors had to cooperate closely (33).

- The green ball feeding can be improved by roller conveyors and roller screens so that a higher porosity of the pellet bed is to be expected.
- The down-draught cooling was converted to up-draught cooling.
- The fuel supply was limited to oil or gas. Coal was no longer used. In this way, it was possible to achieve a better pellet quality and to lower the fuel consumption drastically, which is now approximately 700,000 kJ tons per ton pellets.

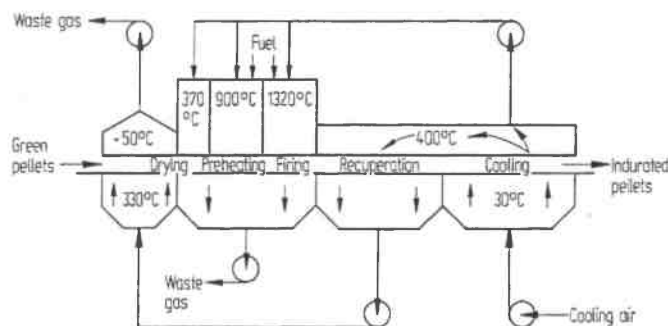


Fig. 126. Principle of the McKee travelling grate induration system

- The suction area was enlarged from $1.8 \text{ m} \times 51 \text{ m} = 91 \text{ m}^2$ to $2.4 \text{ m} \times 73 \text{ m} = 175 \text{ m}^2$ which allowed a higher production rate. The zone division was also changed:

up-draught drying	5 windboxes
down-draught firing	8 windboxes
down-draught cooling	8 windboxes
up-draught cooling	<u>7 windboxes</u>
	28 windboxes

According to this system, Arthur G. Mc Kee and the licensees built plants on the basis of magnetite concentrate with a total annual capacity of approx. 12.5 million t pellets.

Plants operated according to a similar system with a total annual capacity of about 24 million tons of pellets were erected in the Soviet Union which corresponds to a total annual capacity of approx. 37 million tpy pellets and about 13% of the world production, see Fig. 133.

9.3.5 Lurgi-Dravo Travelling Grate Process

The development of this process variant is based on the considerations leading to the third development phase, the pelletizing of almost all ore types, see item 1.2.3. This all-round pelletizing process was presented at the AIME meeting held in New Orleans in 1957 and is characterized as follows^{18/132}): “A pelletizing plant in Germany, however, must be able to process ores of different origin, having quite different characteristics. This requirement was of great importance for the development of the Lurgi process. For the production of green pellets, a machine would, therefore, have to be capable of dealing with all kinds of raw materials, and hardening must be done in a furnace, the temperature of which is adjustable to the different temperatures of the ores”.

The first publication appeared in 1956⁹⁵) after several years of intensive development work which had been started in 1948/49 and yielded promising results. Owing to the political situation at that time, communication with foreign experts was very difficult in contrast to the close contacts of American engineers and metallurgists with their Swedish counterparts. As a result, all knowledge on the state of sinter technology in Germany and all elaborated new process parameters were repeatedly compared with and weighed against each other.

9.3.5.1 Important Process Features

The most important function of this process was to pelletize all ore types as efficiently as in sinter plants. Fundamental considerations

referred both to process parameters and process specific apparatus e.g.:

- (a) Technology of green ball formation from different ores on the balling disc,
- (b) Use of binders,
- (c) Gentle handling of green balls,
- (d) Protection of metallic parts against overheating,
- (e) Thermal technology, type and quantity of fuels,
- (f) Extensive recuperation of sensible heat from the hot pellet charge.

According to this programme, the work was first carried out in laboratories and, later on, in a continuously operating pilot plant. The following results were obtained:

- (a) After extensive orienting tests in 1948/49, the *disc* was found to be a very suitable balling unit and already used in 1953 on an industrial scale for the pelletizing of flotation pyrite cinders¹⁰⁵). In this case, it was ascertained that a maximum free bottom area is important for green ball formation in contrast to the construction of the flying saucers.
- (b) The development of gentle handling facilities for green balls with low drop heights in order to be able to forego bentonite addition.
- (c) The side wall layer and hearth layer were introduced for the protection of metallic parts of pallet side walls and grate bar supporting structure against overheating.
- (d) From the beginning, one *single* additional heat source was principally aimed at in order to control more exactly the heat supply.
- (e) To achieve an extensive recuperation of sensible heat from hot pellets, cooling air was blown in proportioned quantities through the hot pellet bed whereupon pallets and hearth layer were first cooled. The initial cooling air, slightly preheated, passes through the hot pellet bed whereby the pellet quality is preserved.
- (f) Drying was initially accomplished in down-draught only but, later on, was carried out in up-draught too.

The burners and fan constructions are special fabrications of the relevant suppliers.

9.3.5.2 Application of the Process on an Industrial Scale

Since, at the time when the process had reached a certain development level (1953), there was no real demand for a pelletizing plant in Germany, negotiations were conducted with potential foreign customers. At that time, the International Nickel Co. at Copper Cliff, Ontario, Canada had the intention to recover the nickel components from nickel bearing pyrrhotite whereby highly reactive, fine-grained artificial magnetite was obtained as by-product. Inco accepted the proposals submitted by Lurgi. In 1954, the first plant was ordered which was started up in 1956. The

designed daily capacity of this plant was approximately 1200 t pellets^{18/132}). The travelling grate had a suction area of 120 m², a width of 2.5 m and length of 48 m. The plant was initially heated exclusively with oil and, later on, with natural gas only. In this first plant, new constructions and process-technological developments were used. After solving some initial difficulties, Inco started up a second plant of the same system with an annual capacity of 600,000 t pellets in 1963.

Once it had been possible to pelletize one of the raw materials most difficult to treat, artificial magnetite, numerous further plants were erected on the basis of ores of different chemical composition and morphology¹³³).

9.3.5.2.1 Charging of Green Balls to Indurating Grate and the Mode of Operation. The green balls pass via an oscillating belt conveyor over a roller screen and conveyor onto the indurating machine. Fine particles and pellet fragments are separated by screening and recycled. Before the green balls are fed onto the grate bars, the latter are covered with a 10 cm thick hearth layer consisting of fired pellets for protection against overheating. The same material is also introduced between the side walls and green ball charge through chutes and guide plates. Fig. 127 shows the scheme of the feeding station of the travelling grate. A cross section of the green pellet bed within the quasi refractory capsule, composed of material already fired in the form of side wall and hearth layer is represented in Fig. 128. This also shows the thermal insulating effect of the hearth layer and contains information on the temperature distribution over the entire pellet bed height, hearth layer, grate bars and in the windbox on the boundary between the end of the firing and beginning of the cooling zones. (The temperatures are measured according to the scheme represented in Fig. 39, item 4.) In the entire pellet bed (measuring points T_1 – T_3), the temperature is, at this stage, 1300–1340 °C according to the

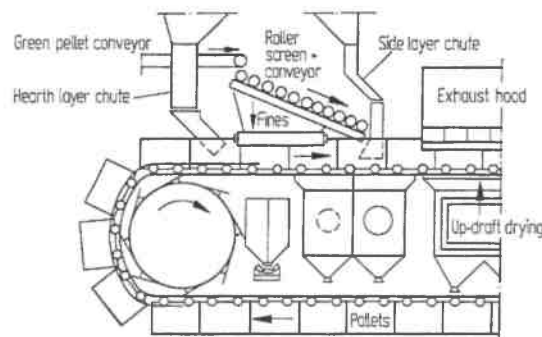


Fig. 127. Green pellet, side and hearth layer feeding device of Lurgi-Dravo travelling grate system

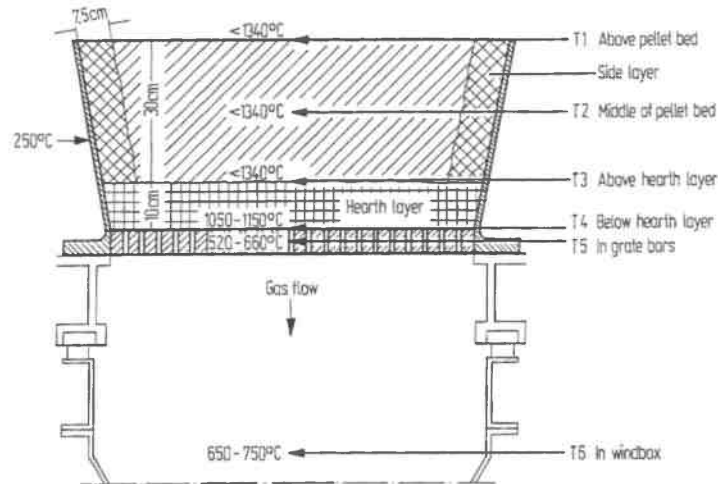


Fig. 128. Thermal insulating effect of hearth and side layer

ore type and additives used. On the hearth layer surface, the temperature required for firing prevails whereas it is lower by about 200 °C on the underside of the hearth layer (measuring point T_4) and above the grate bars. Thus, it can be clearly seen that the hearth layer has an insulating effect and also that temperatures of 1340 °C can still be applied which, for instance, is essential for induration of hematite pellets. A similar insulating effect applies to the side wall layer. The grate bar temperatures are about 520–650 °C (measuring point T_5), while the waste gas temperature in the windbox may rise to a temperature of 650–750 °C (measuring point T_6). When the cooling air is introduced, the metallic parts and hearth layer first cool down before the cooling air reaches the pellet bed.

9.3.5.2.2 Firing Pattern and Heat Consumption. The ore type, nature and quantity of additives, loss on ignition and moisture content determine the firing pattern required, as is shown in Fig. 84, item 5. From this pattern and the periods needed for the various thermal stages, there results the division of the individual zones in the firing hood and windboxes. Fig. 129 represents the heating cycle and the reference temperatures for the various zones. The periods and percentages given for the entire thermal treatment in Table 29 correspond with the cycles for various ore types in Fig. 84.

The periods required for the individual thermal stages vary according to the feed characteristics and thus the total induration time. Fluctuations between 33 minutes for magnetite and 41 minutes for limonite-hematite-

Table 29. Thermal treatment zones according to the pelletizing process

Thermal treatment	Time in minutes*	%
Up-draught drying	4 – 7	12 – 17
Down-draught drying	2 – 5	6 – 12
Preheating	7 – 9	17 – 22
Dehydration		
Calcination		
Oxidation		
Firing	7 – 11	17 – 28
After-firing	3 – 5	8 – 12
Cooling	12 – 14	30 – 35
Total period	33.5 – 41.0	

* According to the ore characteristics

containing raw materials may occur. This is also an indicator of the indurating machine capacity to be expected. A particular feature of this system is shown in Fig. 129, namely the direct recuperation of hot air from the cooling zone without hot gas fans. The arrangement of the process gas mains and the method of recycling the sensitive heat give rise to very low heat consumption. The designed and real heat consumption of many big pelletizing plants planned and operating on typical ores are shown in Table 30.

9.3.5.2.3 Capacity, Flexibility and Market Situation. The capacities given in tons of product per m² grate area and day are also indicated in Table 30. In conjunction with the diagrams of Fig. 84 and 129 it shows the

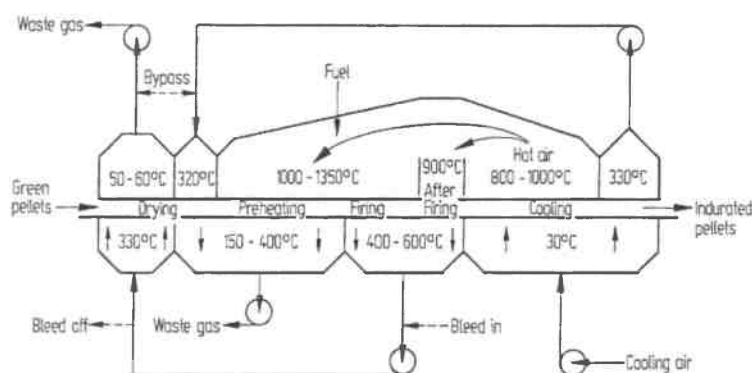


Fig. 129. Principle of Lurgi-Dravo travelling grate induration system

great flexibility of the process. As a result many plants are constructed worldwide on the basis of quite different raw materials. Both acid and basic pellets of different basicity have been produced. As is apparent from the following Table 31, referring to 1978, the Lurgi-Dravo travelling grate process reaches about 44% and other grate processes attain about 13% of the world production, see Fig. 133. These capacities only relate to design values. The effective production rates are probably higher. The process equipment also shows a great flexibility. Due to the demand for higher

Table 30. Productivity and fuel consumption of pelletizing plants according to the Lurgi-Dravo method for various ore types

Types of ores	Pellet production t/m ² · day		Fuel consumption KJ/pellets		Comments
	design	operation	design	operation	
100% Magnetite	26 – 30	32	460/550 000	325 000	Sweden
100% Hematite	22 – 24	23	ca. 1 · 10 ⁶	850 000	Brazil
50 : 50 Magnetite Hematite	24 – 26	27.5	700/800 000	700 000	Netherland
Limonite Hematite	16 – 18	18.5	1.2 – 1.5 · 10 ⁶	1.25 · 10 ⁶	Australia

Table 31. World production of pellets in travelling grate systems in 1979

Ore types	Portion of world production		
	10 ⁶ t/year	% ^a	% ^b
Magnetite	34	22	—
Hematite	42	68	—
Magnetite-Hematite	33	70	—
Hematite-Limonite	21	75	—
Lurgi-Dravo	130	—	44
Other travelling grates	37	—	13
Total	167	—	57
World production	293		

^a % of the world production from this ore type on LURGI-DRAVO grates

^b % of the total world production

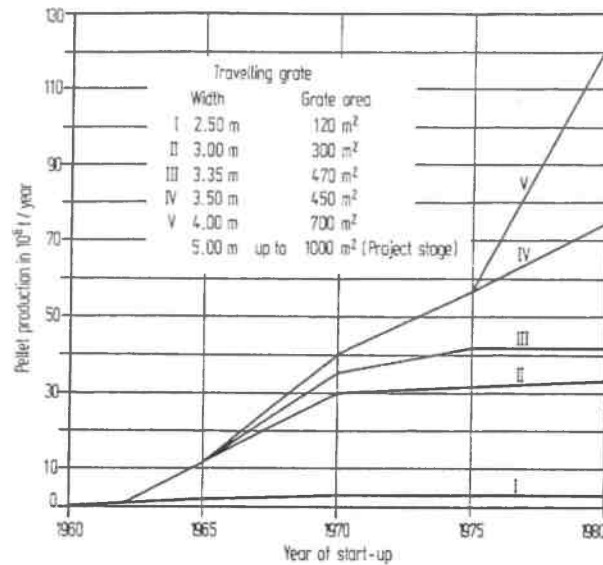


Fig. 130. Development of Lurgi-Dravo travelling grates

capacities of the individual units, it was not difficult to increase the pallet dimensions and travelling grate length. The change of pallet dimensions and suction area since 1960 as well as the pellet quantities produced on various machine types are described in Fig. 130.

According to the demands made over the years (abscissa), the production rates are shown in the different curves in conjunction with pallet widths and suction areas. Complete constructional drawings are available for a 5 m wide machine, corresponding to a suction area of 1000 m² or a production capacity of about 9 million tpy pellets per unit at a specific capacity of 27 t/m²/day. However, the question arises whether it is worthwhile or advisable to build and operate such units.

9.4 Other Heat Treatment Systems

The challenge to engineers and metallurgists in connection with the development of the pelletizing process was so great that numerous attempts were made to develop and design a pellet-specific process without reference to systems already existing. High expenses were incurred and much work was done for this purpose. However, in the course

of years, the three well-known processes were developed to such a degree of perfection that pellets of high quality can be produced.

Nevertheless, the endeavours to develop new ideas should not be neglected.

9.4.1 Circular Indurating Furnace

Circular sinter machines have already been used since the turn of the century primarily for sinter-roasting of sulphide ores in many non-ferrous metal smelters. The simple seal between movable and stationary machine parts was one of their advantages considering the conveyance of SO_2 -containing roaster gases. Subsequently, the circular machine was also used successfully for sintering of iron ores and pyrite cinders. Because of its relatively simple operation, it was also utilized for the production of light-weight aggregates. Some such plants are still in operation in Europe. Due to the low capacity of about 1000 tpd sinter per unit the interest to use this type of machine decreased rapidly.

It is to the credit of Arthur G. Mc Kee & Company to have tested and developed the circular machine type for pellet induration¹³⁴⁾.

Since 1970, a pilot plant has been in operation; in 1974 an industrial plant with a grate area of approx. 160 m², an effective suction area of 120 m² and a capacity of 0.6 million tpy pellets was built and started up in Mexico. The thermal treatment is similar to that of the straight-line travelling grate. The gas and cooling air flow is down-draught which may give rise to a special risk of overheating for the metallic constructional parts. The grate bars are protected by hearth layer and the green pellet bed height is about 20 cm so that a better gas permeability is reached and thus fans with a lower capacity are admissible. The side walls are insulated by refractory lining. The fired pellets are removed from the grate by a scraping device which is installed at a sufficient distance between grate bar and hearth layer (depth: approx. 5 cm), to leave the hearth layer in its position. McKee estimates a heat consumption of about 500,000 kJ per ton pellets produced from magnetite concentrate and a heat consumption of approx. 900,000 kJ for pellets produced from hematite ores. Up to now, only the plant in Mexico is in operation.

9.4.2 "Heat Fast" Process¹³⁵⁾

As was often in the past equipment suppliers, pellet-producers and pellet-consumers jointly attempted to develop a pellet-specific process in order to produce in such a plant alternatively oxidized or reduced pellets.

It was intended to employ specific equipment for the various thermal stages such as:

- (a) Drying on a belt dryer at a temperature of approx. 300 °C.
- (b) Transfer of dry pellets to an annular hearth furnace for pellet pre-heating up to a temperature of about 600 °C in a layer with a depth corresponding to the diameter of one single pellet.
- (c) Induration and cooling in a shaft furnace, similar to the functions in a normal shaft furnace.

The preliminary tests led to the construction of an industrial plant with a design capacity of 1.2 million tpy pellets. For several reasons, this plant was shut down and dismantled. The alternative process, prereduction, was only tested on a pilot plant scale.

9.4.3 “Annular Furnace” of Huntington-Heberlein ⁽³⁴⁾

This system was based on a circular hearth furnace. The green balls are placed at a bed height of about 80 cm on the grate. Hot gases are sucked through the bed. The furnace has lateral, gas-tight walls. The pellet charge is heated with a concurrent gas flow. The waste gas is sucked off upwards shortly before the discharge point of the furnace. The hot pellets drop into a cooling shaft from which the hot cooling air passes into the system. An industrial plant has not yet been built.

9.5 Comparison of Important Pelletizing Systems

Since the start of the first industrial plants at the Erie and Reserve Mining Co. in 1955/56, various firing processes were competing with each other. Some processes developed during this period were not successful. After a short time they disappeared from the market. Some systems which, above all during the years directly after 1955, played a great part are no longer important since the raw material properties changed in the meantime and they could not be adapted to these varied conditions. Further systems which later on, from about 1960 onwards, were introduced on the world market meanwhile hold a leading position, e.g. the grate-kiln and the Lurgi-Dravo-travelling grate process. Some reasons for this development are given below:

- (a) Flexibility to different ore types
- (b) High capacity in one single unit
- (c) Uniformly high quality, irrespective of ore type, quantity and composition of additives

- (d) Low capital and operating costs
- (e) High plant availability.

Above all, the demands on the flexibility of processes were particularly acute at the time when, besides magnetite concentrates, ores containing hematite or ore mixtures of different composition had to be pelletized.

9.5.1 Change of Ore Basis

During the early years up to about 1960, magnetite concentrates were exclusively used. From this date onward, hematite ores or concentrates as well as magnetite-hematite mixtures were also treated. These three ore variants are still the principal raw materials for pellet production. Fig. 131 shows the change of ore types from the beginning of industrial production up to 1978.

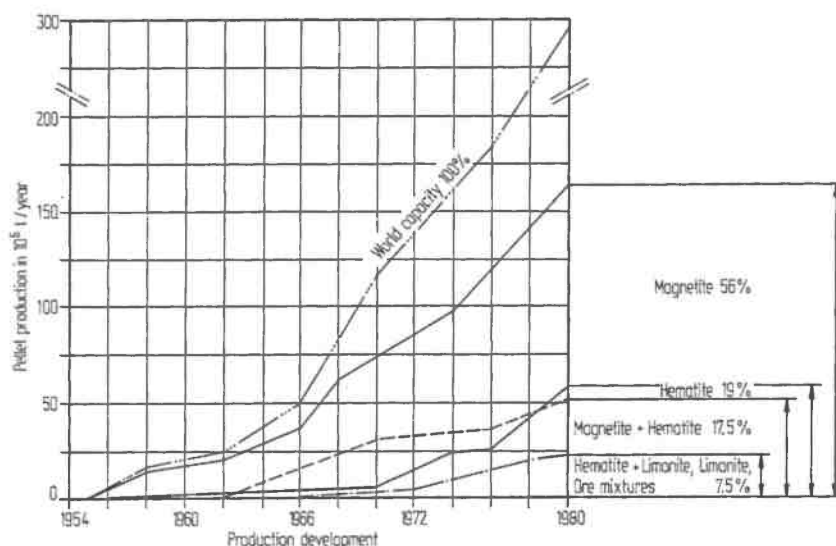


Fig. 131. Proportions of various ore types for pellet feed

9.5.2 Production Figures per Unit of Various Indurating Systems

With the increasing competition on the worldwide ore market, the pellet producers were compelled to keep the capital and operating costs as low as possible which was partly achieved by using bigger units. From the capacity of the firing units according to the different firing systems, the choice of a suitable system resulted almost automatically for high produc-

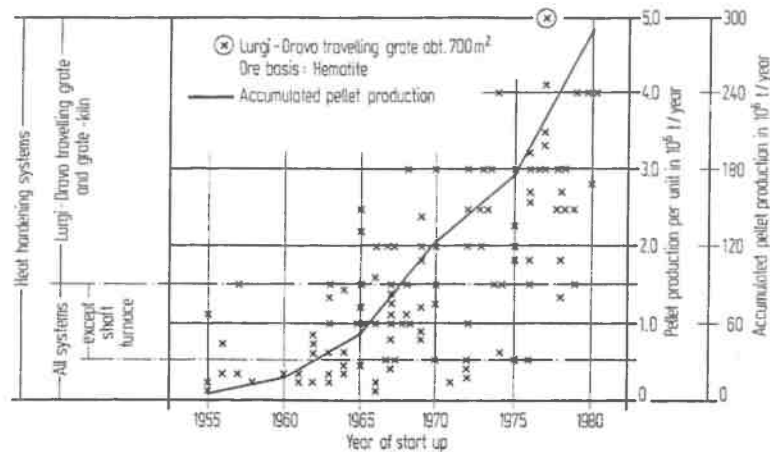


Fig. 132. Production rates per unit of various heat treatment systems

tion rates, as shown in Fig. 132. The production figures per unit are plotted against years. The capacity values reach up to 5 million tons pellets per year for the biggest, and down to less than 0.5 million tons for the smallest units. The major amount of smaller plants was built before 1965. From 1960 onwards, the capacities already attained up to about 2 million tons of pellets and, from 1965, the capacities continuously increased. From about 1975, the first units with a capacity of 4 or 5 million tons pellets were erected. For capacities of up to 0.5 million tons pellets, shaft furnaces and travelling grates were predominantly used whereas for capacities exceeding 0.5 million tons pellets all travelling grate processes and the grate-kiln process are applicable. Production rates of above 2 million tons pellets per year in one single unit were only attained in Lurgi-Dravo travelling grate or grate-kiln plants. For the present, only these two systems are suitable for units with high capacities.

9.5.3 Proportion of Various Firing Systems in the World Pellet Production

The advantages of greater flexibility regarding the availability of materials and the rising capacities per unit had sooner or later to lead to different market positions of the various competing processes. The respective development is shown in Fig. 133 relating to the time and the installed total capacity. The evaluation of the individual curves leads to some interesting conclusions.

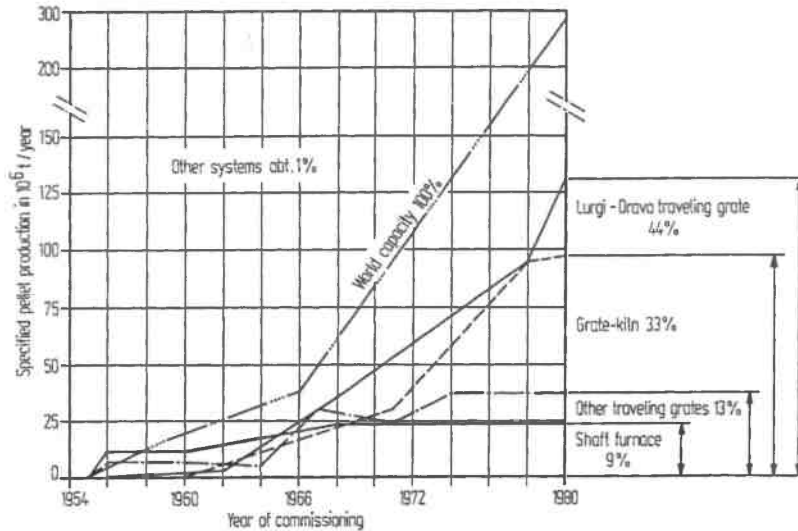


Fig. 133. Shares of various heat treatment systems in world production

The shaft furnace process, one of the first and at that time most important firing processes, has only changed its position slightly in years. The travelling grate process of Arthur G. Mc Kee was meanwhile modified, but its importance did not improve. Although the grate-kiln and Lurgi-Dravo travelling grate processes were developed at a later date, their proportion in the world market has increased rapidly.

The use of travelling grates generally found the widest application range because even the grate-kiln process without preceding travelling grate could not be operated successfully.

9.5.4 Cost Comparison

It is not the purpose of this book to make a cost comparison in support of a decision regarding the choice of one or other indurating system. The numbers of plants hitherto operated according to the various processes may generally serve as a criterion. It may also be assumed that the decision in favour of one or the other induration system has been taken after consideration of all cost factors with a good pellet quality being imperative. The capital investment depends on many specific conditions for each particular plant which must not be directly related to the chosen firing system.

10 Plant Layout and Process Control

10.1 Plant Layout

The choice of the most important apparatus for the performance of the various process stages, the arrangement of individual plant items relative to each other as well as the total layout are dependent on various factors, the most important of which are discussed below:

- (a) Plant Site: Nowadays, pelletizing plants are built at the following locations: the mine, the port, the iron and steel plant.
- (b) Raw Material Basis: Ore types, chemical and physical properties, as well as their preparation stage determine the selection of the various apparatus to be used.
- (c) Pelletizing and Induration Units of different design also influence the arrangement of individual plant items relative to each other.

Fig. 134 is a general schema based on the travelling grate process for depicting the material flow in a pelletizing plant. This scheme is, in a varied form, also valid for other induration systems. For the purpose of this scheme, it is assumed that all raw material constituents have already been prepared for green ball formation.

The first part covers the raw material bins and handling facilities, whereas the second part shows the mixing and prewetting equipment as well as the green ball formation system. In the third part, the induration system is represented which consists either of a shaft furnace, grate-kiln combination or travelling grate. This scheme may also serve as a guide for process control.

10.2 Process Control ¹³³⁾

In order to have at any time a good surveillance of the pelletizing process, the plants are equipped with the necessary measuring and control systems. The instruments are combined in a central control room where all data is collected.

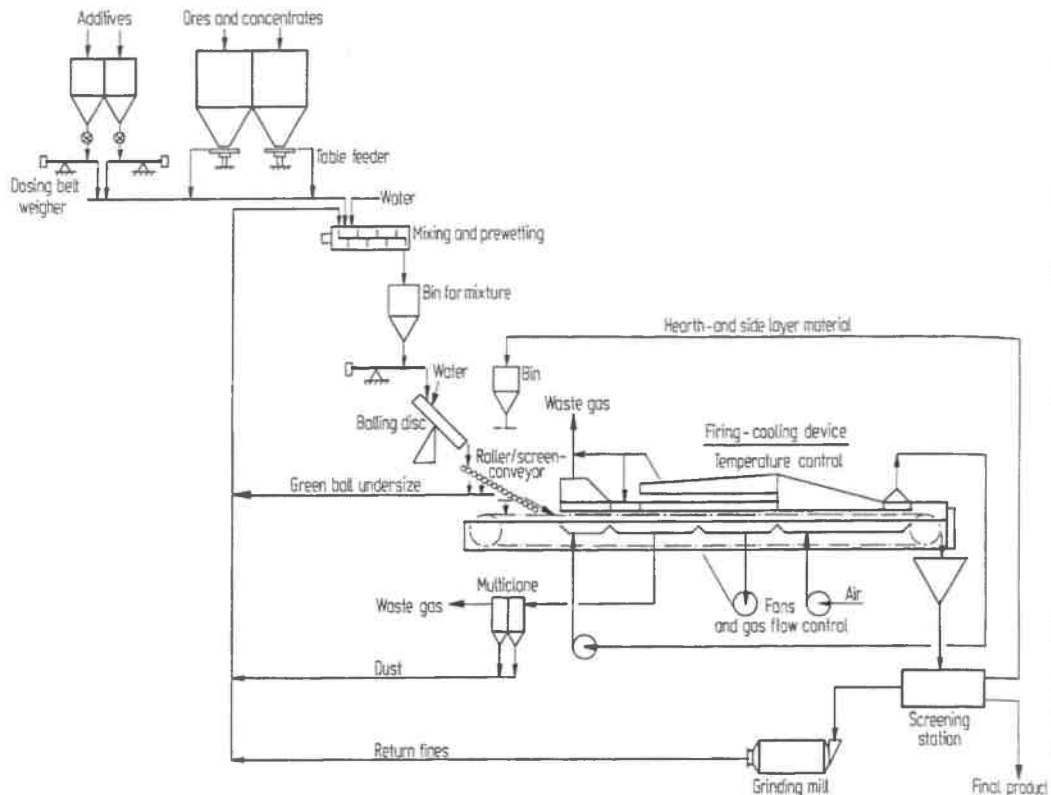


Fig. 134. Typical flow sheet of a pelletizing plant travelling grate system

(a) These controls refer to the process cycle with a view to achieving an optimal pellet quality by

- distribution and proportioning of material masses
- preparation of a homogeneous mix
- forming of green balls
- induration and cooling of pellets.

(b) The measuring equipment also has the function of technical operational control to provide

- low energy consumption
- high and steady productivity
- high availability of the plant.

Nowadays, such control facilities form an integral part of each modern pelletizing plant and are adapted to the demand of various firing systems. By way of example, the principal control functions in a travelling grate

plant are explained below with the individual plant sections having been combined in the form of three sections similarly to those shown in Fig. 134.

10.2.1 Distribution and Proportioning of Material Flows

In the first section the material streams are distributed over the individual bins through travelling belt conveyors and plough scrapers arranged above the bins. These bins are supported by load cells allowing continuous control of their filling degree. After a specified filling weight has been attained, the belt conveyors are switched over to the next bin according to a predetermined programme.

10.2.2 Proportioning of Solid Components and Water

Raw material is extracted from the various raw material bins and proportioned by weigh feeders. The admissible variation is not greater than ± 0.5 percent by weight. The necessary water amount is also measured and in some plants controlled proportionately to the solids quantity with part of the water being already added at the premixer. In many plants, the amount of water is still controlled by hand.

10.2.3 Formation and Transport of Green Pellets

In principle, the pelletizing unit is operated by hand after the individual components have previously passed a mixer. The total quantities of green balls formed originate, in most cases, from several pelletizing units. They are collected on a belt conveyor and carried to the indurating machine. The amount of green balls supplied is recorded by means of a belt weigher and corrected according to the quantity of screened undersize. This belt weigher is an important control unit, is connected to the pellet indurating machine and controls its velocity.

10.2.4 Green Pellet Charging

The grate velocity control is important in order to keep the pellet bed height constant. In this connection, the additional amounts of hearth layer and side wall layer are taken into account. A correction to compensate for the varied green ball bulk density and time lag caused by the distance between green ball belt weigher and pellet feeding point onto the grate is also ensured.

10.2.5 Thermal Treatment of Green Balls

The procedure of pellet induration is controlled by process gases flowing at the rates predetermined according to the heating pattern and at a corresponding temperature through the pellet bed. An indication of a sufficient supply with the necessary heat energy results from the temperatures prevailing in the wind boxes.

In a similar way as for down-draught sintering, burn-through points can be used as guide values. For specific process stages, they correspond to defined temperatures. When the temperatures predetermined in the heating programme are exceeded, or lower temperatures prevail, the process gas flow rate is changed. This is achieved by controlling the capacity of the main fan located behind the wind boxes of the firing zone.

In the case of other process gas fans also, the necessary gas flow is forced through the bed by means of by-pass connections as well as through particular inlets and outlets. In this way, the gas pressure in the burner hood is controlled through the cooling air fan, since the hot cooling air from the cooling hood is introduced through a direct duct into the burner hood. The up-draught drying and waste gas fans control the gas flows in the front part of the indurating machine. Thus, the process gas fan capacities, varied according to the temperatures measured, virtually control the thermal procedure of pellet induration.

10.3 Development and Trends of Further Control Variants

The very fast and successful development of digital systems primarily in control and computer technology led to an extensive use of these systems in pelletizing plants. Their application range extends from simple data collection, fault recording, coefficient calculation and fault analysing through "on-line controls" to the conversion from one operating scheme to another. The use of digital controllers for controlled systems with an extreme time behaviour as well as for control circuits with several mathematical interactions, e.g. for controlling the indurating machine speed, proved particularly successful. Also master control functions concerning material handling or mix compositions on the basis of chemical analyses can be solved more simply and reliably with a digital system than by adopting the conventional methods.

As new automation systems, including modern measuring methods, undergo current, systematic investigations and testing and as new mathematical process models are developed, it can be expected that in the near future, the measuring and control systems of pelletizing processes will be greatly influenced.

11 Pellets in the Blast Furnace Burden

Since it is possible to produce pellets of good quality from a great variety of raw materials, as explained in detail in chapters 5 and 6, it would still be advisable to set out the ways in which the blast furnace operators accept this new agglomerate in practice. As long as pellets were only produced from fine-grained magnetite concentrates difficult to sinter, they were considered as a supplement to sinter. Their use was first geographically limited to a few regions. However, when pellets from fine-grained ores were available on the world market, pellets really started to compete with lump ore and sinter. In countries with high portions of imported ores, such as Japan or Western Europe, a highly developed sinter technology already exists according to which the blast furnace can be supplied with burdens of good quality. Furthermore, the sinter quality was continuously improved. A statement on the advantages or disadvantages of using pellets for the blast furnace burden can only be made by a comparison with the quality of all blast furnace constituents and under controlled operating conditions. Some initially recognised advantages, such as the spherical shape or the high iron content of pellets, are nowadays no longer considered as superior. Furthermore, the other iron oxide constituents, such as sinter or lump ores and even coke, are available in a defined size range after crushing and distinct classification. Today, the iron content of a well prepared sinter burden is quite comparable with the analysis of many varieties of pellets. However, before pellets influenced the positive development of the total blast furnace technology, many attempts were necessary to render the pellets suitable for the blast furnace operation. At first, the mechanical pellet properties had to be developed so that they met the requirements of handling and stresses in the blast furnace operation.

11.1 Influence of Mechanical Properties

When the first major quantities of pellets were available for blast furnace tests, the expected success was not fully realised. On the contrary,

a high fines portion and above-average quantities of flue dust in the blast furnace compelled the pelletizing plant operators to improve the mechanical strength of the pellets. The partly dramatic development and the results obtained were described by W. E. Marshall ⁴⁷⁾, as is shown in Fig. 85, item 6. This work was, so to say, performed in a closed combine, because the first pelletizing plants and blast furnaces were owned by the same companies and their special demands were of overriding importance.

With great interest, a large-scale test run on 150,000 t of pellets in a blast furnace of Mannesmannwerke in Duisburg, West Germany in 1962/63 and the experience thus gained was recorded ²⁹⁾. From the favourable results of these tests, and tests in Japan, pellets were considered, also outside the United States, as being an equivalent blast furnace constituent alongside sinter and lump ore. In the meantime, the issue of guiding principles for the evaluation of the mechanical pellet quality had begun. Nowadays, such standards are internationally acknowledged and described in chapter 4.

After the methods of improving the mechanical strength of Mesabi Range pellets had become known, major problems were no longer encountered in the respective blast furnace operations. The Mesabi pellets contain by nature, high proportions of acid gangue with a basicity of about 0.2, at which no pellet degradation or pellet swelling is observed during reduction. As a result of this development phase, it was clearly recognised that only pellets of a perfect mechanical strength high in acid gangue can withstand any premature degradation. The relevant conditions are described in chapter 5 and 6.

For other pellet types with a high iron and low gangue content, great difficulties arose, so that the dependence of the metallurgical properties on the chemical composition also had to be thoroughly investigated.

11.2 Influence of Chemical Composition

It was first recognised in Sweden that a high mechanical strength of high-grade iron ore pellets alone is insufficient to withstand the stresses during reduction ^{7/81)}. This was confirmed by a blast furnace test carried out with Swedish pellets, low in gangue, by the Thyssenhütte ⁸⁰⁾, in West Germany. In particular, the unsatisfactory results when the first Marcona pellets were treated in Japan ⁸²⁾ initiated a broad discussion on the causes of degradation of these pellet types, although their mechanical strength was perfect. Many efforts were made to investigate and explain this phenomenon without a satisfactory explanation having been found up

to now. On the other hand, measures for decreasing or even preventing pellet degradation or pellet swelling during reduction are meanwhile known.

Only after it was possible to forecast both the mechanical and, to a high degree, the metallurgical properties by controlled action, could pellets qualitatively compete with the other blast furnace constituents namely sinter or lump ore.

11.3 Methods of Pellet Charging to the Blast Furnace

Like all blast furnace constituents, the pellets are normally screened before they are charged into the blast furnace and the undersize is recirculated to the pellet cycle or sinter plant. In order to ensure full utilization of their uniform and high permeability, they are charged in separate layers, alternating with the other components. Special attention was paid to this during the blast furnace test run by Mannesmann. Nowadays, the charging of constituents in layers having the same gas permeability is a generally acknowledged charging technology. Pellets with good mechanical properties and a low tendency to degradation during reduction can be produced by using any pelletizing process whatsoever. Further possibilities of ensuring a more economic pellet production and of adapting the blast furnace technology even more efficiently to the use of larger pellet portions are being studied.

11.4 Comparison of Pellets and Sinter

Experts still hold different opinions concerning the advantages and disadvantages of the use of pellets in the blast furnace. Partly, because sufficient experience with the use of pellets is not available, and sometimes, primarily during boom periods, pellets of lower quality enter the market. It is difficult to make a generally valid statement either way, since often too many very different local operating conditions may influence the result to a higher degree than the quality of one or the other pellet type. However, a comparison nevertheless appears interesting.

By way of example, trials carried out in the blast furnace plant at Hoogovens, IJmuiden B. V., in the Netherlands are referred to¹³⁷). As is known, Hoogovens have to import all the ores required for pig ore production. To achieve an optimum agglomeration situation, they operate both a pelletizing and a sinter plant, each with an annual capacity of

3·10⁶ tons. For the test carried out over a prolonged period, acid and basic pellets having a basicity of 0.15, 0.90 and 1.35, as well as overbasic sinter having a basicity of 2.0 were prepared and charged at different mixing proportions to the blast furnace. The programme included the tests shown in Table 32.

Table 32. Test programme for comparing influence of pellets with sinter in blast furnace burden ¹³⁰⁾

Pellets in %	Basicity	Sinter in %	Basicity	Number of trial weeks	Hearth diameter of in m
95	1.35	5	2.0	3	5.9
70	0.90	30	2.0	6	13.0
50	0.15	50	2.0	Normal practice	

Information available from the blast furnace operations e.g. from Japan, North America and Western Europe were incorporated into the evaluation of the trials carried out by Hoogovens. These results altogether cover a wide range of varying mixtures from 95% fluxed and overfluxed sinter up to 95% acid and fluxed pellets in the blast furnace burden. A comparison was made for the fuel consumption and the furnace productivity. The results obtained were recently confirmed by information given at the JJSJ conference in Sidney, October 1979 ³⁷⁾.

(a) *The fuel consumption* is calculated as an average standardized rate (coke + 1.16 × fuel) in kg coke per ton of hot metal. The following values were obtained for the above mentioned areas:

- (A) Japanese blast furnaces operated with 75–95% self-fluxing sinter, balance sized lump ore and pellets
=530 kg fuel/THM (ton hot metal)
- (B) Japanese blast furnaces operated with 46% self-fluxing sinter, 45% self-fluxing pellets, balance sized lump ore
=514 kg fuel/THM
- (C) North American furnaces operated with 75%–95% acid pellets and limestone
=542 kg fuel/THM
- (D) European furnaces operated with 75–95% self-fluxing sinter
=532 kg fuel/THM
- (E) trials at Ijmuiden including standard operation 45% acid pellets and 45% overfluxed sinter
=528 kg fuel/THM

There are practically no differences between (A) and (D) at roughly the same blast furnace charge, the figures of (A), (D) and (E) are almost equal with 45% acid pellets in the blast furnace burden, (C). The highest heat consumption is obtained when using acid pellets, and the lowest is achieved at equal portions of self-fluxing pellets and overbasic sinter, (B). Except for (C), the differences are not very great. From this, it can be seen that at a good preparation of sinter and pellets, the coke consumption is similar to that resulting from the use of a high portion of self-fluxing sinter. As a result, it is demonstrated that pellets are just as suitable for the blast furnace as sinter.

(b) *The resistance to gas flow* in the blast furnace charge is the lowest at a pellet portion of 95%. However, no remarkable differences in the furnace charge against a well prepared sinter feed were found. Also in this case there is no negative influence of pellets on the blast furnace burden, provided that the individual components show a good behaviour during reduction ³⁷⁾.

(c) *Production costs.* To achieve these favourable values regarding coke consumption, adequate preparation of agglomerates is required, which may be reflected in corresponding production costs ¹³⁸⁾. These costs are about 10–12% higher for basic pellets than for acid pellets. The production costs for basic sinter are roughly between these two values, so it is cheaper to introduce the necessary basic constituents through a sinter product. Thus, the standard mix in the Ijmuiden plant is composed of approximately 50% acid pellets and 50% overfluxed sinter.

11.5 Pellet Proportion in the Blast Furnace Burden

For different reasons, the pellet utilisation in various countries has developed in very different ways and in dependence on the existing sinter plants there, e.g. in Japan or Western Europe, as can be seen from Table 33 ¹³⁹⁾. In this table a trend of the blast furnace burden up to 1985 is shown for some countries with major steel production. Except for the United States where pellets are predominant, in all other countries the higher portion of agglomerates consists of sinter, approx. 70%. In the long run a slight change can be expected by raising the pellet portion at the expense of lump ores. Their amount will decrease from about 25% to 18% while the pellet consumption will rise from 17% to about 26%.

In the United States the situation will be different. The pellet portion will increase up to 70% and the balance will consist of sinter and lump ore.

Table 33. Composition of blast furnace burden in 1976 and future trends ¹³⁹⁾

	1976 in %			1985 in %		
	Pellets	Sinter	Lump ore	Pellets	Sinter	Lump ore
1. Japan	approx. 11	72	abt. 17	13	70	12
2. USSR	approx. 15–18	78	abt. 6	20	75	5
3. Fed. Rep. of Germany	approx. 7	74	abt. 18	23	65	12
4. Great Britain	approx. –	79	abt. 21	25	65	10
5. USA	approx. 56	30	abt. 13	73	16	11
6. Western Countries	approx. 22	58	abt. 20	30	53	17
7. Eastern Block	approx. 5	68	abt. 27	21	59	20
8. World (total)	approx. 17	59	abt. 24	26	56	18

Another forecast up to the year 2000 ¹⁴⁾ roughly shows the following tendency: the sinter portion will move up to around 70% and the pellet portion to about 25%, which corresponds to double the present portion, whereas the lump ore portion will further diminish. This is an indication of the intention to predetermine the blast furnace burden properties as far as possible. The tendency to cover the *increasing rate* of pig iron and steel in the future mainly by pellets is caused by various factors unfavourable for the construction of new sinter plants, such as high capital investment, dependency on coke breeze as heat energy and above all greater ecological problems in sinter plants. The severe prescriptions regarding air and water pollution control in urban centres, where most blast furnaces and sinter plants are located, almost impede the construction of new sinter plants. According to the information obtained from a competent sinter and pelletizing plant constructor, the capital costs of such plants with a complete environmental protection system, including SO₂ absorption, are, at an annual capacity of 3×10^6 tons, approximately 10–12% higher for sinter plants than for pelletizing plants.

12 The Utilization of Pellets in Direct Reduction Plants

The high iron content of pellets, their spherical shape, limited size range and practically no fines were the typical properties of agglomerates which gave a fresh impetus to the development of direct reduction, primarily on the basis of gas, in the shaft furnace. The first positive experience was already made in 1950 in Wiberg plants in Sweden^{7/8}). When Hojalato y Lamina (HyL) converted their retort process developed in Mexico in 1957 from lump ore to pellets in 1970, the operational results improved the capacity by about 30% and the fuel consumption by about 15%¹⁴⁾).

The Midrex process was developed and commercially introduced exclusively on the basis of pellets. However, due to the high gas permeability of the pellet charge, attempts were made to replace a part of the expensive pellets by carefully selected, cheaper lump ores, which have a lower bed porosity. The percentage of lump ores in the charge is dependant on the change of gas permeability of the entire mixture, which is influencing the shaft furnace productivity, as shown in Fig. 11. Another influencing factor is the behaviour of the natural ores during reduction, as far as swelling and degradation is concerned, whereby the gas permeability can be varied.

The basic conditions for the pellet behaviour during direct reduction are the same as for the blast furnace. However, additional demands are

Table 34. Pellet consumption in direct reduction plant with gaseous reductants

Plants 1978	In operation	Under construction	Sum
Process*	Pellet consumption in 10 ⁶ t/year (approx.)		
Midrex	4.9	7.3	12.2
HyL	4.9	4.9	9.8
Purofer	0.9	—	0.9
Armco	0.3	—	0.3
Sum	11.0	12.2	23.2

* In the above processes it is also possible to use, to some extent, classified lump ores

existing as described under items 4.7 and 4.7.1.3. Above all, the pellets shall not prematurely soften, stick together and thus form lumps. Furthermore, the sponge iron pellets shall have a sufficient cold crushing strength and resistance to abrasion in order to withstand transport from the reduction plant to the steel plant without damage. The pellet quantity in the most important gas reduction plants, which in 1978 were already in operation or under construction, is shown in Table 34.

In reduction processes carried out with solid reductants in rotary kilns, pellets and lump ores can be utilized with less stringent restrictions provided that the lump ores used are generally suitable for direct reduction. Although the pig iron curve proceeds flatly, Fig. 10, the pellet production curve rises further. On one hand, this is due to the increasing pellet proportion in pig iron production and on the other, to the raised steel production by the application of the direct reduction processes. The latter allow an enlargement of the steel capacity in small increments and a closer plant location to the consumers' market whereby the capital investment is lowered accordingly.

13 Some Theoretical Considerations

List of Frequently used Symbols

Symbol	Meaning	Unit and Remarks
	Green Pellet Formation 13.1–13.1.4.3	
ψ	Liquid filling degree of existing voids, pores	up to 1
h	Liquid column height	m
ρ	Liquid density	$\text{kg} \cdot \text{m}^{-3}$
g	Acceleration of gravity	$\text{m} \cdot \text{s}^{-2}$
γ	Surface tension of water	$\text{mN} \cdot \text{m}^{-1}$
R	Concave radius of curvative of liquid surface	m
r	Radius of capillaries	m
ε	Pore, void volume	
S	Specific surface of concentrate	$\text{m}^2 \cdot \text{kg}^{-1}$
ρ_w	Real volume density of concentrate	$\text{kg} \cdot \text{m}^{-3}$
H	Adhesive force at contact points	N
d	Diameter of spherical particles	m
σ	Tensile stress of green pellets by bridge bonding	$\text{N} \cdot \text{m}^{-2}$
d_h	Representative particle size	m
P_k	Tensile strength of green pellets by capillary bonding	$\text{N} \cdot \text{m}^{-2}$
m	Mass of a pellet	kg
a	Acceleration of speed for lifting the center of gravity (R) over the diameter (d) of an ore particle for the total height of R + d	$\text{m} \cdot \text{s}^{-2}$
F	Cross section of particle	$F = c \cdot d_1^2 \text{ (m}^2\text{)}$
v	Moving velocity of a pellet	$\text{m} \cdot \text{s}^{-1}$
R	Radius of a Pellet	m

Symbol	Meaning	Unit and Remarks
b	Ratio of sizes $\frac{R}{d}$	
d	Diameter of particle	m
	Balling Equipment 13.1.4	
$n_{(crit)}$	Rotating speed per minute	r.p.m.
42.3	Factor expressing angular velocity and rotating speed	
D	Disc, drum diameter	m
H	Wall, rim height	m
β	Tilt angle of disc bottom	degree
α	Dynamic angle of repose of ore pile	degree
Heat Transfer, 13.2.1 – 13.2.5.2		
H	Thickness of a layer	m
ε	Pores, void volume	
ψ	Flow resistance coefficient	$f \cdot Re_{ch}$
w	Speed of gas flow	$m \cdot s^{-1}$
φ	Shape factor	φ for uniform balls = 1
	$\frac{\text{pellet surface}}{\text{particle surface}}$	φ for pellets = 0.90–0.98
		φ for ore particles 0.6–0.9
ρ_P	Apparent density of pellets	$kg \cdot m^{-3}$
ρ_{CH}	Bulk density of charge	$kg \cdot m^{-3}$
ρ_G	Bulk density of gas	$kg \cdot m^{-3}$
Re_P	Reynold's number (pellet)	$\frac{w \cdot d}{\nu}$
ν	Kinematic viscosity	$m^2 \cdot s^{-1}$
Re_{CH}	Reynold's number (charge)	$Re_{CH} = \frac{w \cdot d \cdot \varphi}{\nu \cdot (1 - \varepsilon)}$
V	Volume	m^3
P	Gas pressure	bar
ΔP	Gas flow resistance	bar
ζ	Resistance factor of a body or a grate	bar
N_U	Nusselt number	$N_U = \frac{\alpha \cdot d}{\lambda}$
λ	Thermal conductivity	$W \cdot m^{-1} \cdot K^{-1}$
α	Heat transmission coefficient	$W \cdot m^{-2} \cdot K^{-1}$
ε	Void volume of uniform pellets	

Symbol	Meaning	Unit and Remarks
ε_m	Void volume of mixture	
V	Volume of pellet charge	m^3
$V_1 \dots V_n$	Fraction of volume of pellet charge	m^3
q	Heat flow density	$W \cdot m^{-2}$
E_G	Heat emission coefficient of a gas	
E_W	Heat emission coefficient of a solid (Brick Lining)	
E_P	Heat emission coefficient E of material surface	e.g. pellet charge
E'	Equivalent emission factor for gas-solid radiation	
T_P	Temperature of pellet charge	$^{\circ}C$ (K)
T_W	Temperature of radiating wall	$^{\circ}C$ (K)
S_R	Thickness of a radiating gas layer	m
C_S	Radiation factor of black body	$5,77 \cdot W \cdot m^{-2} \cdot K^{-4}$
F_P	Area of charge surface	m^2
F_W	Area of radiating wall	m^2
Green Pellet Drying 13.3 – 13.3.2		
$M_{(w, d)}$	Mass (pellet) w = wet, d = dry	kg
$\dot{M}$	Mass variation related to time	$kg \cdot s^{-1}$ $\dot{M} = \frac{dM}{dt}$
t	Time	h, s
$\dot{m}$	Density of mass flow	$kg \cdot m^{-2} \cdot s^{-1}$
R	Gas constant	$J \cdot kg^{-1} \cdot K^{-1}$
P	Partial gas pressure	bar
X	Moisture in solids	$kg \cdot kg^{-1}$
β	Mass transfer coefficient	$m \cdot h^{-1}; m \cdot s^{-1}$
φ	Relative moisture of drying gas	

For a better comprehension of the process parameters, and for supplementing results of experiments and experience, some theoretical considerations are set forth below.

To begin with, the basic features for pellet formation are discussed, followed by considerations dealing with the thermal treatment of green pellets, with particular attention being given to drying.

Some of the data, equations and diagrams are of more general character and are merely valid for particular applications. They may rather serve as a guide for better understanding of the influence of some factors and should be read in close connection with the respective chapters concerned.

13.1 Green Ball Formation

Under item 2.1 bonding mechanisms are described which become active during the formation of green balls from fine-grained iron ores, particularly in conjunction with water, as shown in Figs. 12, 13, 14. On the basis of test results and measurements carried out in laboratories and industrial plants, the significance of influencing factors is explained under items 5.1 and 5.2. For supporting this knowledge, some mathematical considerations have been made and already repeatedly discussed in the literature²³⁻²⁶). Some of these investigations are based on defined spheres, such as glass or metal balls, which differ remarkably from the shape of finely ground ores. Part of the mathematical derivations are thus applicable to green ball formation by way of comparison only. Three factors are decisive for the formation of green balls and their mechanical strength:

- the bonding forces between grain surface and water,
- the granulometric properties, such as size distribution of particles, specific surface, properties of particle surface and wettability,
- mechanical compression and impact forces which become active during rolling of solids particles with water in drums or discs.

13.1.1 Bonds Between Water and Fine-Grained Particles

In general, pre-wetted ore particles are charged to a pelletizing unit. The green balls are formed, if necessary, by further water addition the voids between the individual ore-grains gradually filling.

During this operation, different bonding mechanisms become successively active. The liquid filling degree serves as a criterion for the water amount contained in existing voids between the individual grains.

This degree indicates the portion of voids filled with water referred to the total void volume.

13.1.1.1 Bonding by Liquid Bridges

In the case of a low water addition, liquid bridges form at favourable coordination points of individual ore particles at a liquid filling degree μ of less than 0.2, as diagrammatically illustrated in Fig. 12 B. This first phase of bonds is designated as the *bridge bonding phase*¹⁴²⁾. However, this kind of bonding is not sufficient for green pellet formation. With further water addition individual capillaries fill with water, Fig. 12 C and form conglomerates held together by capillary forces. The strength developing in the various stages of water filling is described in Fig. 135¹⁴⁴⁾ which also indicates the influence of oversaturation with water.

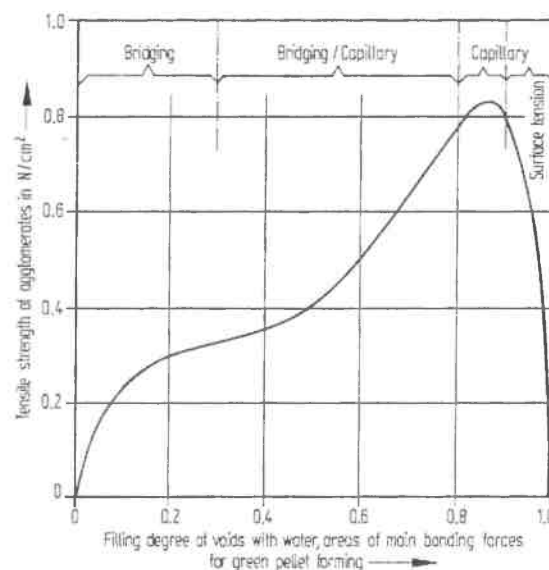


Fig. 135. Influence of water filling degree of capillaries on tensile strength during green ball formation, raw material: limestone, $\mu = 0.41$

13.1.1.2 Bonding Forces in Transition Range

As long as the voids are only partly filled with water, capillary tensile forces and bridge bonds are jointly active. This ball formation stage is designated as the *transition stage*. The liquid filling degree φ has increased to about 0.4⁽⁴²⁾. However, the joint bonding forces are not yet sufficient to ensure the necessary strength of pellets. The gradual void filling continues, as shown in Fig. 12 D.

13.1.1.3 Bonding Forces in the Capillary Range

The optimum strength is to be expected when the voids between the individual ore particles have nearly filled with water and the liquid surface of the water-filled capillaries on the pellet surface shows concave menisci. The capillary tension thus arising is, according to Tigerschiöld, the main cause of the green pellet strength. The liquid filling degree has now attained a value φ ranging from 0.8 to 0.9 of the total voids. The bridge bond practically no longer exists. Only under certain conditions, it may remain active on the pellet surface according to the size of particles involved. As per calculations, the optimum bonding power by bridging only reaches a value of about 35% of the fully efficient capillary bonding forces²³⁾.

These have meanwhile moved to the pellet surface as is illustrated in Figs. 12 E and 13.

The tension built up in the capillaries corresponds to the liquid column level in the various voids. It is dependent on the void radius and on the properties of the ore grain surface. The capillary underpressure P_k results from the following factors:

$$P_k = h \cdot \rho \cdot g \quad \text{or} \quad P_k = \frac{2 \cdot \gamma}{R}$$

The radius of curvature R depends on the capillary radius r and on the contact angle between meniscus and capillary wall. At a complete wetting of capillaries, radius of curvature R becomes equal to capillary radius r . In this case, the tension can be expressed as follows:

$$P_k = \frac{2 \cdot \gamma}{r}$$

This calculation applies to agglomerates for which a liquid filling degree of 0.8–0.9 has been attained in the voids.

The capillary underpressure P_k can be represented as

$$P_k = \frac{\gamma}{m}$$

where $m = \frac{r}{2}$

In this equation, m is designated as the hydraulic pore radius. It results from the ratio of the pore volume to the surface of the pores filled with water. In a conglomerate of finely ground ores with a statistical size distribution, the average hydraulic radius is responsible for the value of capillary tension. On this basis, Tigerschiöld and Ilmoni established the following relationship:

$$m = \frac{\varepsilon}{S \cdot \varrho_w \cdot (1 - \varepsilon)}$$

If this term is introduced into the formula

$$P_k = \frac{\gamma}{m}$$

the following equation for the capillary tension is developed:

$$P_k = \gamma \cdot S \cdot \varrho_w \cdot \frac{1 - \varepsilon}{\varepsilon} \quad (1)$$

According to this equation, the green pellet strength is primarily *proportional* to the pores and capillaries of *the fine grains*. The equation only shows the trend. Experimental values differ from the calculated figures. The liquid filling degree of 0.8–0.9 is optimal. If more water is added, value $\mu = 1$ is reached and exceeded.

13.1.1.4 Oversaturation with Water

If this is the case, the concave voids on the surface are overfilled with water. The surface is coated with a water skin and more corresponds to a solids – containing water droplet. The capillary bonding forces no longer exist. Only the surface tension of the water is active, Fig. 12 F. The surface which previously appeared dry and rough becomes now bright and the pellet slightly more plastic but more resistant to dropping. If the water addition is further continued, the pellet may even be converted to sludge.

The dependence of the compression strength on the liquid filling degree and the decrease of the resistance at oversaturation are shown in Fig. 135.

The strength is here expressed as tensile strength in Newton units.

13.1.2 Influence of Granulometric Properties on Green Pellet Strength

The second important factor for green ball formation is the nature of particles from which the pellets are made. Rumpf¹⁴³⁾ calculated the tensile strength from balls consisting of particles of *equal diameter* and found the simplified relationship

$$\sigma_z \approx 2 \cdot \frac{H}{d^2}$$

In this formula, H is the adhesive force at contact points and d is the diameter of the spherical particle. During grinding of ores, a mixture of particles with a wide size range and a steady size distribution is obtained, in which the portion of fines – 0.045 mm diameter should be about 85%. For the determination of the strength of green pellets derived from particles of different *diameters*, a representative particle size d_h has to be established. If the range of particle size is not too widely spread, the particle size d_h can be determined from the calculated or measured specific surface.

If this is not the case, the value d_h has, according to a model consideration by Rumpf, to be graphically defined by the fact that the partial surface $\int_{d_h}^{d_{max}} dO$ formed by all major grains can just be coated by grains of smaller size. Their sum of digits is $\frac{1}{4} \int_{d_{min}}^{d_h} dO$

The conditional equation for d_h is then:

$$\frac{1}{4} \int_{d_{min}}^{d_h} dO = \int_{d_h}^{d_{max}} dO \quad (2)$$

13.1.3 Influence of Rolling Forces During Movement of Green Pellets

Movement forces are considered as the third factor influencing green ball formation. During rolling, fine-grained ore particles are pressed into the surface of already existing large agglomerates. This is achieved by the pressure which, due to an acceleration impact, is exerted by the pellet rolling over a particle. The intensity of this impact P is expressed by the following equation ¹⁴⁴):

$$P = m \cdot a = \frac{4 \pi}{3 g} \cdot \gamma \cdot R^2 \cdot v^2 \left(1 + \frac{1}{b} \right)$$

The ore particle is pressed at a specific force into the surface of a rolling pellet. The corresponding pressure K at the contact point between particles and pellets is as follows:

$$K = \frac{P}{F} = \frac{4 \pi}{3 g} \cdot \gamma \cdot v^2 \cdot \frac{b_1^2}{c} \cdot \left(1 + \frac{1}{b} \right)$$

In this equation, c is dependent on the shape and position of particle on the pellet surface. If the particle has the cross section $F = c \cdot d_1$ and a cubic shape, c is equal to one, d_1 and b equal to d and b . The formula can be changed; K is then calculated as follows:

$$K = \frac{4 \pi}{3 g} \cdot \gamma \cdot v^2 \cdot \frac{R}{d} \cdot \left(1 + \frac{R}{d} \right) \quad (3)$$

This formula implies that pressure K rises proportionally to the ratio $\frac{R}{d}$, as well as to the square of motion velocity v of the pellets. During rolling, the pellets are compacted by the accelerative force and they receive their spherical shape which is schematically shown in Figs. 14 A and C. The decisive factors for the formation of green balls of good mechanical quality are:

- optimum water addition, equation (1), to produce capillary forces
- sufficient particle size range, equation (2)
- impact and pressure during rolling, equation (3).

Two types of apparatus, the balling disc and the balling drum, are chiefly used for ball formation. As already mentioned, the theoretical considerations are in practice not very important. All the necessary operating data have to be found out by tests.

13.1.4 Design and Operation of Balling Disc and Balling Drum

As already described under item 8.2, dimensioning, adjustment and operation of pelletizing units are largely based on empirical values. Mathematical ideas are employed to a certain extent only. Nevertheless, some mathematical relationships can be used for the construction and operation of the two most important balling units namely discs and drums.

13.1.4.1 Design and Dimensions of Balling Discs

The main *dimensions* of a disc required for ascertaining a given production rate are the disc diameter and height of the wall, the rim. Many investigators have found the relationship between diameter D and wall height H as:

$$\frac{H}{D} = \text{const.}^{44b)}$$

According to Pietsch and Bomble⁴⁵⁾, this constant is about 0.2; this means

$$H = 0.2 \cdot D$$

According to Klatt⁴⁶⁾ the constant of 0.2 is only valid up to a disc diameter of 4 meters, then the constant is decreasing. When evaluating the figures from Table 27²⁸⁾ for large discs of 5–7.5 m diameter, the values are no longer constant, they vary between 0.12 and 0.08.

13.1.4.2 Rotating Speed and Disc Slope

To produce green pellets of good quality, the fine-grained material must be brought into rolling movement. For this purpose an optimum rotating

speed of the disc or drum is necessary to harmonise the static, dynamic and centrifugal forces. The so-called *critical speed*, at which the gravity is just compensated by centrifugal forces acting on the agglomerates is of great importance. When the critical speed is exceeded, the granules are slung against the disc wall due to higher centrifugal forces and no longer become detached from the wall. Therefore, the critical speed n_{crit} is decisive for good balling and described in the formula developed by several investigators ^{44/145/146}).

$$n_{\text{crit}} = \frac{42.3}{\sqrt{D}} \cdot \sqrt{\sin \beta} \quad (4)$$

Furthermore, for a given material, the dynamic angle of repose (see Fig. 112) and the frictional resistance have to be considered. To ensure a good operation, the optimum speed is about 60–75% of the critical rotating speed.

According to Klatt ¹⁴⁷) the formula

$$n = \frac{22.5}{\sqrt{D}} \quad (5)$$

can be used as a thumb rule to estimate the optimum speed. However, for large discs in operation the optimum speed is, as indicated in Table 28, lower and reaches 6–7 r.p.m. at disc diameters of 6–7.5 m. The optimum speed does not only allow good balling but also ensures a maximum utilization of disc area.

13.1.4.3 Balling Drum and its Design Data

In the literature, only a few mathematical indications on the dimensions, operating method as well as capacity and quality to be expected, are known. They are essentially based on data from the construction of ball mills. The major part of the information relies on empirical values being described under item 8.2.2.

(a) The *slope* of the drum axis does not serve for controlling the ball formation and green pellet quality. It is mainly influencing the mass throughput, respectively the retention time.

(b) The drum *length* and *diameter* in combination with the retention time or rotating speed respectively are responsible for a good balling and green pellet quality.

(c) The *rotating speed* is limited by the critical speed, Fig. 104 and calculated according to the formula

$$n_{\text{crit}} = \frac{30}{\pi} \cdot \sqrt{\frac{2g}{D}}$$

After conversion of $n_{\text{crit}} = \frac{42.3}{\sqrt{D}}$ for a drum with 3.6 m diameter, the rotating speed is 70% of the critical speed i.e. about 15 r.p.m. which is somewhat higher than the values shown in Table 27 and Fig. 105.

(d) The frictional resistance varying according to the ore properties is a further leading factor controlling the rotating speed.

13.2 Thermal Treatment of Green Pellets

The formation of green pellets of good quality is followed by the most important steps:

Drying, heating and cooling. There are various ways of transferring the necessary energy from the heat source to the pellet charge. According to different firing methods adopted two main heat transfer procedures are applied:

In the *shaft furnace* and on *travelling grates* the heat is supplied at more than 90% by *convection* when hot gases are passing through the pellet charge. In the *rotary kiln*, the major portion of the heat energy is transferred by *radiation*.

Preheating and firing always start with dry pellets. Therefore, drying must be finished beforehand. The necessary heat supply is accomplished only by convection whereby an additional factor, the water evaporation, has to be considered. Since this is a different procedure compared to normal heat transfer the corresponding steps for drying are discussed separately under item 13.3. Besides convection and radiation, there are other heat transfer possibilities. They all are discussed in connection with the induration systems nowadays mainly used.

13.2.1 Heat Transfer in a Pellet Charge on the Travelling Grate or in the Shaft Furnace

Fig. 136 represents a simplified section through a pellet bed on a pallet of a travelling grate. The indicated figures refer to the various possibilities of introducing heat into the bed. These transfer mechanisms can be described as follows:

- 1) Hot gas flowing through the bed gives off heat by *convection*; its temperature drops from the inlet temperature prevailing at the top to the outlet temperature prevailing underneath the grate bars.
- 2) If the gas in the hood contains notable portions of CO_2 , H_2O and SO_2 and if the distance between the brick lining of the hood and the pellet

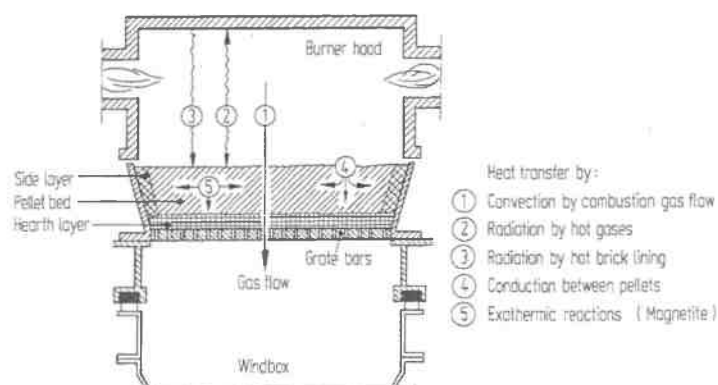


Fig. 136. Heat transfer to a pellet layer in position of rest

bed surface is sufficiently great, a heat supply by gas *radiation* additionally takes place. However, radiation only influences the top pellet layer temperature.

- 3) If the bricklining of the hood has a higher temperature than the pellet bed surface underneath, heat is transferred to the pellet bed by *radiation*. This again only applies to the top pellet layer. A part of the wall radiation (3) is absorbed by gas radiation (2) and thus cannot pass onto the pellet bed.
- 4) Inside the bed, heat is transferred by conduction inside the individual pellet and from pellet to pellet through points of direct contact. This kind of heat transfer would also take place if no gas flow (1) existed. The heat conduction factor (4) also contains a certain portion of radiation as for (2) and (3), but this radiation only becomes active at pellet temperatures exceeding 800 °C.
- 5) An “internal heat supply” by exothermic reaction occurs for magnetite ores when the magnetite oxidizes to hematite. This heat supply may roughly cover half of the total heat consumption and is to be introduced additionally when hematite containing ores are treated.

13.2.2 Heat Transfer of Green Pellets by Convection and Gas Flow

13.2.2.1 Gas Flow

For the heat transfer by convection, the gas flow through a pellet bed is of particular importance. The gas flow is depending on the gas permeability or bed resistance and highly influenced by the physical consistency of the pellets. Some considerations are advisable concerning the gas flow

based on physical rules¹⁴⁷⁾. The simplest way of thermal treatment is the single phase gas flow through an unmoved pellet bed. On the basis of presently available data¹⁴⁾, the nearly spherical shape of pellets and the relatively narrow size range of 9–15 mm pellet diameter, a predetermination of the resistance to gas flow in a bed is possible. If the resistance values are known, the basis for calculating the fan capacity is given, although the final dimensions of the fan are additionally dependent on other factors.

13.2.2.1.1 Resistance of a Charge of Uniform Pellet Size to Gas Flow. The resistance to gas flow ΔP_{CH} follows linearly the height of a pellet charge and is dependent on the following equation:

$$\Delta P_{CH} = H \cdot \psi \frac{1 - \varepsilon}{\varepsilon^3} \cdot \frac{\rho_{G'} \cdot w^2}{d \cdot \varphi} \quad (6)$$

The void volume ε can be calculated from the specific density of pellets ρ_P , charge ρ_{CH} and gas $\rho_{G'}$ in conformity with the following equation:

$$\varepsilon = \frac{\rho_P - \rho_{CH}}{\rho_P - \rho_{G'}} \approx 1 - \frac{\rho_{CH}}{\rho_P} \text{ for } (\rho_P \gg \rho_{G'})$$

The portion of void volume can vary between 0.40–0.49 for a pellet bed. It is of great importance for the resistance to gas flow.

The flow resistance coefficient ψ of the bed, which is in close relation to the Reynolds' number, is composed of a laminar and turbulent part¹⁴⁹⁾

$$\psi = \psi_{\text{lamin}} + \psi_{\text{turb}}$$

The relation with the Reynolds' number is as follows:

$$\psi = f \cdot Re_{CH}$$

$$\psi = \frac{160}{Re_{CH}} + \frac{3.1}{Re_{CH}^{0.1}}$$

(laminar) (turbulent)

Before the flow condition in a bed can be evaluated, it is necessary to know the Reynolds' number. For beds, it is expressed as follows:

$$Re_{CH} = \frac{w \cdot d \cdot \varphi}{\nu \cdot (1 - \varepsilon_m)}$$

13.2.2.1.2 Resistance of Pellet Charge of Different Pellet Size to Gas Flow.

If the pellet diameter greatly varies, additional factors have to be considered. First, the bulk densities ρ_{iCH} and the parts of volume are to be determined from the screen analysis¹⁴⁾.

From this, an average pellet diameter d_m is calculated according to the equation

$$d_m = \frac{1}{\sum_{i=1}^n \frac{V_i}{V \cdot d_i}} \quad (7)$$

V_i proportional volume

V total volume

Subsequently, the average void volume factors of charges composed of grains of different diameters ε_m and of the smallest fraction ε_k are to be determined. From this results an empirical correction factor $\frac{\varepsilon_k^{0.75}}{\varepsilon_m}$ which is to be introduced into the resistance equation.

The resistance to flow of charges composed of pellets of different diameters results from the following equation:

$$\Delta P_{mCH} = H \cdot \psi \cdot \frac{1 - \varepsilon_m}{\varepsilon_m^3} \cdot \frac{Q_G \cdot w^2}{d_m \cdot \phi_m} \cdot \left(\frac{\varepsilon_k}{\varepsilon_m} \right)^{0.75} \quad (8)$$

The data for designing the process fans can be calculated by means of equations (7) and (8) for charges of uniform and different pellet size. These considerations only refer to the pellet bed. Other factors may influence additionally the resistance to flow of the whole firing system including duct work and dedusting facilities. In order to be able to cope with extreme conditions due to poor pellet quality, a corresponding capacity reserve is required for the process fans.

13.2.2.1.3 Resistance of Pellet Charge and Travelling Grate to Gas Flow.

Apart from the pellet bed, another resistance arises on the travelling grate due to the restriction of the space between the grate bars ΔP_{GR} .

The following relationship exists:

$$\Delta P_{GR} = \zeta \cdot \frac{Q_G \cdot w^2}{2} \quad (9)$$

The resistance to flow of the pellet bed and grate can be calculated according to the equation:

$$\Delta P = \Delta P_{CH} + \Delta P_{GR} \quad (10)$$

Fig. 137 shows diagrammatically the resistance to flow of a charge of uniform pellets with a diameter of 10–12 mm having a height of 40 cm and of small pellets and particles of 3–8 mm diameter including the grate resistance as found in pot pelletizing tests.

The grate resistance is only perceptible in a bed of approximately 5 cm height. From this bed height onward, both curves are linear with the bed height. In the case of pellets of different diameters, the resistance to flow is substantially higher. That is why the pellet fractions of 3–8 mm diameter

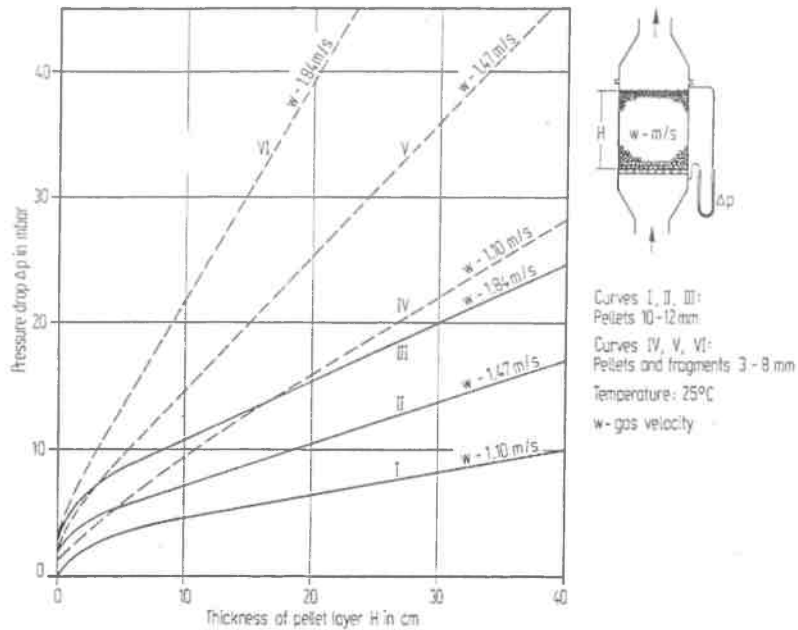


Fig. 137. Influence of bed height on pressure drop of gas flow at a different gas flow velocity and pellet size

serve as an insulating layer between pallet side walls and the porous pellet feed in Lurgi-Dravo travelling grates.

A good gas permeability and an efficient gas flow through a pellet bed are achieved if the pellet diameter is within a close range.

13.2.2.2 Heat Transfer by Convection

The main heat transfer through a pellet charge is realized by convection. The following data on heat transfer by convection are available. The convective heat transfer to a pellet bed through which gas is flowing is represented in a manner generally valid by the non-dimensional Nusselt number:

$$Nu = \alpha_{CH} \cdot \frac{d}{\lambda} \cdot \frac{\varepsilon}{1 - \varepsilon} \quad (11)$$

where α_{CH} is the convective heat transmission coefficient referred to the pellet bed surface ($W \cdot m^{-2} \cdot K^{-1}$).

The dependence of the convective heat transmission coefficient on flow conditions, characterized by the Reynolds' number of the pellet bed of

uniform size can be represented according to Jeschar¹⁵⁰) as follows:

$$N_U = 2 \cdot \frac{\varepsilon}{1 - \varepsilon} + Re_{CH}^{0.5} + 0.005 Re_{CH} \quad (12)$$

In the case of charges composed of pellets of different diameters, the Reynolds' number and average pellet diameter have to be calculated accordingly, as expressed in the following equation:

$$N_U = 2 \cdot \frac{\varepsilon_m}{1 - \varepsilon_m} \cdot f \left(\frac{V_n}{V}, \frac{d_1}{d_n} \right) + Re_{CH}^{0.5} + 0.005 Re_{CH} \quad (13)$$

which refers to ideal and smooth balls. In general, pellets show notable deviations from the ideal spherical shape, which for pellet charges amount to about 40–60% of the theoretical value.

The equations 11, 12 and 13 are typical for conditions in the shaft furnace and on the travelling grate. Fig. 138 shows the coefficient of heat transmission α as a function of the temperatures for both gas velocities. The gas velocity is referred to 273 K, 1 bar and to the voids inside the charge. As is apparent from the temperature dependence, heating and cooling processes in high pellet beds can be calculated more exactly if the total bed height is divided into a certain number of smaller layers. On the other hand, an average coefficient of heat transmission may be assumed. The convective heat transmission in the rotary kiln mainly refers to the area of the charge over which the gases flow. Therefore, the α value can be neglected. The convective heat transfer in the rotary kiln charge is

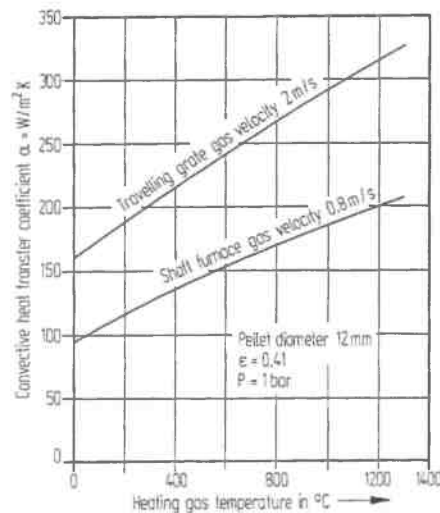


Fig. 138. Convective heat transfer by gas flow through a pellet bed

smaller by one order of magnitude than the heat transfer on the travelling grate and in the shaft furnace.

13.2.2.2.1 Heat Transfer to the Pellet Charge on the Travelling Grate. As concerns the pellet sectional area shown in Fig. 136 the heat transfer rules are comparatively simple, whereas they become more complicated if the pellets on the travelling grate are taken into consideration. In travelling direction the waste gas outlet temperature follows, with some delays, the hot gas inlet temperature at the same location. Due to this “cross-flow effect”, the calculation of temperature gradient in the pellet bed becomes complicated. In this case, heat balances of small differential layers of the total bed and the travelling time are established as in a similar way shown for the drying progress in Fig. 144. To compensate for this delay, an after-firing section is incorporated in the firing cycle, see Fig. 84. This figure shows the temperature gradient in conjunction with the individual process stages and for different ore types on the basis of the results of computer calculations. These calculations tally with measurements made in laboratories and industrial plants.

13.2.2.2.2 Heat Transfer to the Pellet Charge in the Shaft Furnace. One advantage is the good heat economy. Compared to materials usually treated in shaft furnaces, pellets represent a uniform and porous bed. The pellets are moving downwards by gravity. Friction between pellets and brickwork and between individual pellets may have some detrimental effect on the pellet quality so that the residence time, temperature profile and gas distribution may be impaired. The uniform gas flow through the bed sectional area, which is important for the heat transfer, is better ensured in the travelling grate, where the pellets are transported under controlled conditions. Fig. 122 shows diagrammatically a pelletizing shaft furnace and the temperature profile. The heat transfer mechanisms (1), (4) and (5) described in Fig. 136 are also valid for the shaft furnace charge. Since, inside the furnace no big cavities exist, the heat transfer from gas to pellets is almost completely accomplished by *convection* (1). The same applies to the heat emission from the hot pellets by cooling air in the lower stove.

13.2.3 Heat Transfer to the Pellet Charge in the Rotary Kiln

The partial steps of heat transfer from the heat sources to the pellet bed in the rotary kiln are illustrated in Fig. 139 and marked by numbers corresponding to the various heat transfer mechanisms. They show some substantial differences compared to the travelling grate technology. When

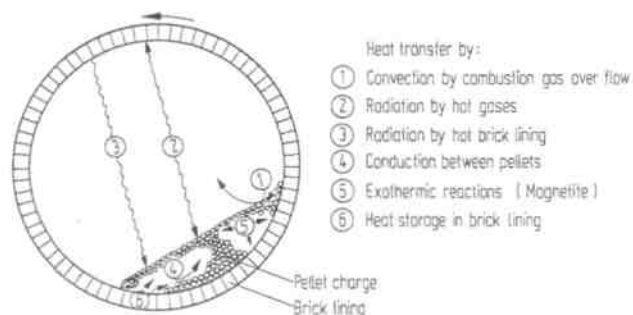


Fig. 139. Heat transfer to a pellet layer moving in a rotary kiln

the pellets roll down on the bed and inner kiln shell, approximately 90% of the necessary heat energy is supplied to them by gas radiation (2) and brickwork radiation (3). For a short time the pellets reach temperatures, which are only slightly below the gas temperature of the free furnace volume. However, this temperature rise only refers to a low bed height of 3–4 pellet diameters. Due to the kiln rotation, the surfaces of the highly heated pellets are pulled into the charge at the lower end of the pellet bed. They give off some of their surplus heat to cooler adjacent pellets. Due to the lifting effect of the bricklining cooler pellets pass over to the charge surface, where they are further heated by radiation.

In the case of the rotary kiln, an additional mechanism (6) is added contributing heat energy by the continuously varying contact between charge and brickwork. Owing to the heating of brickwork above the pellet bed, a small amount of heat, the storage heat, is absorbed and partially given off to the cooler pellet charge if the brickwork moves under the latter. However, this effect is not important due to heat loss by radiation to the environment. The magnetite oxidation (5) does not make any notable contribution as a heat source since practically no current of air is flowing through the pellet charge and the oxidation thus only proceeds slowly. The total heat transfer in the rotary kiln is complicated and still the subject of investigations. The components (1), (2), and (3) are calculable to some degree. As the heat transfer by convection is insignificant, the considerations concerning heat conduction by radiation are more important.

13.2.4 Heat Transfer by Radiation

The heat transfer by radiation can be initiated by radiant gas molecules and a radiant solid, such as the inner surface of the brick lining in the rotary kiln above the charge.

13.2.4.1 Gas Radiation

The calculation of this heat transfer method was primarily promoted by Hottel and his colleagues¹⁵¹). An extensive survey of the state of knowledge in this field is given by R. Jeschar¹⁴⁹). Polyatomic gases, such as CO₂, H₂O, CH₄, SO₂ radiate and absorb in certain regions of wavelength according to how the frequency of vibrations of atoms in a molecular compound tallies with the frequency of the electromagnetic radiation. The calculation is complicated if the regions of wavelength for individual gas constituents intersect and if red-hot solid particles are contained in the gas flow, which is called “solids radiation”¹⁵²). The example given below refers to radiant gases. Radiation heat can be transferred to the pellet surface (P) $q_{G \rightarrow P}$ or to the furnace wall (W) $q_{G \rightarrow W}$. The approximation method developed by God¹⁵³) is adopted for numerical evaluation. With reference to Fig. 139 and analogously to Fig. 136 – firing space above the pellet bed – the formula for the radiation heat transferred *from gas to pellet bed* surface is the following:

$$q_1 = q_{G \rightarrow P} = C_S \cdot E' \cdot \left[E_G(T_G) \cdot \left(\frac{T_G}{100} \right)^4 - E_{G'}(T_P) \cdot \left(\frac{T_P}{100} \right)^4 \right] \quad (14)$$

C_S is the radiation value of the black body. The emission factor E_G is to be individually calculated for each gas constituent, such as CO₂ and H₂O, and to be added; including correction factor ΔE

$$E_G = E_{CO_2} + E_{H_2O} - \Delta E \quad (15)$$

Each addend is a function of gas layer thickness S , temperature T and partial pressure P_{CO_2} and P_{H_2O} . In the burner hood located above the travelling grate, distance H between the inner hood surface and the pellet surface may be assumed for S . For the rotary kiln, an “equivalent” gas layer thickness S_F is used, which, according to Schack¹⁵⁴) is $S_F = 0.9 \cdot D$ of the furnace diameter. Under the radiation conditions during pellet induration, the emission value can, according to Hottel¹⁵¹), be assumed as 0.95.

According to the equations 14 and 15, heat is also given off by gas radiation to the wall above the pellet bed $q_2 = q_{G \rightarrow W}$ with the surface temperature T_1 having to be replaced by the wall temperature T_A in equation (14). This component can be neglected within the scope of the above considerations.

13.2.4.2 Kiln Lining Radiation

The heat reflected by the brickwork as solids radiation $q_{W \rightarrow P}$ to the pellet bed surface is also of importance and calculated according to the

following equation:

$$q_3 = q_{W \rightarrow P} = \frac{C_{S'}}{\frac{1}{E_P} + \frac{F_P}{F_W} \left(\frac{1}{E_W} - 1 \right)} \cdot \left[\left(\frac{T_W}{100} \right)^4 - \left(\frac{T_P}{100} \right)^4 \right] \quad (16)$$

Between the vault and the pellet bed, part of $q_{W \rightarrow P}$ is absorbed by gas and therefore does not pass onto the pellet surface. This is the heat radiation, which, according to equation 14, the gas would emit itself if it had the wall temperature T_N .

Consequently, the brickwork radiation (3) is the difference between two heat flows:

$$q_4 = q_3 - q_2$$

The total heat amount transferred to the pellet bed by gas radiation (2) and brickwork radiation (3) is then:

$$q = q_1 + q_4 \quad (17)$$

According to calculations the major portion of heat is transferred via solids radiation and not via gas radiation. Compared to the travelling grate and shaft furnace the heat conduction by radiation is about three times as high in the rotary kiln whereas the convective heat transfer is predominant in the shaft furnace and on the travelling grate, Table 35.

13.2.5 Heat Conduction

As shown in Figs. 136 and 138 there is yet another possibility of heat transfer by direct heat conduction. It can be effective in two ways: By conducting the heat from the pellet surface to the core and by direct contact from pellet to pellet at different temperatures by points of contact.

13.2.5.1 Heat Conduction Inside the Pellet

The heat conduction inside an individual pellet is important because it influences the necessary minimum firing time $T_{\min}$. This is the time needed to transfer the heat, required for proper induration from the pellet surface to the pellet core. In the case of the various heat transfer methods described above it is supposed that the pellets are already dry and no other thermal influences become active. The pellet is heated in a surrounding gas medium of a specific temperature. This temperature is not constant, but varies with different velocities according to process application in shaft furnaces, rotary kilns or travelling grate plants. For pellet heating at a temporally varying ambient temperature, equations, whose evaluation is very complicated, were developed¹⁵⁵⁾. Starting from a constant ambient temperature, it is possible to ascertain by an approximation¹⁴⁸⁾ a theo-

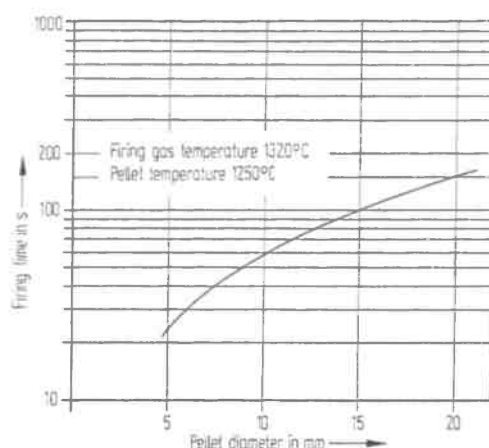


Fig. 140. Minimum firing time required for heat transfer into single pellets of different size

retical minimum firing time for different pellet diameters limited to a mean calorific value, as is diagrammatically demonstrated in Fig. 140.

13.2.5.2 Heat Conduction by Points of Contact

Heat conduction by points of contact is only possible if adjacent pellets are of different temperatures. Since on the travelling grate the individual pellets have a relatively restful relationship to each other, the individual pellets situated at the same level are supplied with the same amount of heat so that between adjacent pellets the necessary temperature drop does not really exist, but only for pellets in two layers one above the other. In the shaft furnace and rotary kiln, the pellets are moving and the points of contact change continuously. In the rotary kiln, a temperature balance can be achieved by the mixing of hot pellets with colder ones during the rolling movement. However, it is more important that the rolling movement causes cooler pellets on the bed surface to be constantly further heated by gas and brickwork radiation.

13.3 Green Ball Drying

To satisfy the relevant thermal requirements it is necessary to coordinate the heat supply and the temperature of the heating gas. This is of particular importance during green ball drying, because an additional factor is to be considered, namely the water evaporation.

Under items 2.2.1 and 5.4.1, important factors for successful drying were experimentally investigated and described. In the light of the preceding considerations, the knowledge of heat transfer specifically for drying is of great interest. In this connection, drying only means the expulsion of the water required for green ball formation, which is contained in the grain surface and in the capillaries between the individual grains.

In the three well-known firing processes, the drying is exclusively carried out with hot gases flowing through the pellet charge. Therefore, the following considerations are limited to *heat supply by convection* of a ball charge at a preponderantly turbulent flow of heating gases.

The drying process starts simultaneously on an individual pellet and in the pellet charge. For better understanding it is considered separately.

13.3.1 Drying of an Individual Pellet

The drying process of a moist porous body corresponding to an individual pellet is diagrammatically shown in Fig. 141. Hot gas of temperature T_D flows towards the moist pellet, which has an initial mass of M_W and the heat of the gas causes part of the water to evaporate from the pellet surface. The drying process results from the change in weight of the drying pellet. Drying is terminated when the weight M_D of the pellet no longer shows any change. The pellet moisture X can then be ascertained according to the following equation:

$$X = \frac{M_W - M_D}{M_D} \cdot 100 \text{ in \%} \quad (18)$$

which corresponds to the difference between wet and dry mass divided by dry mass. In practical operation, the moisture content is often related to the wet mass, as is described under item 2.2.1.1. The drying proceeds from

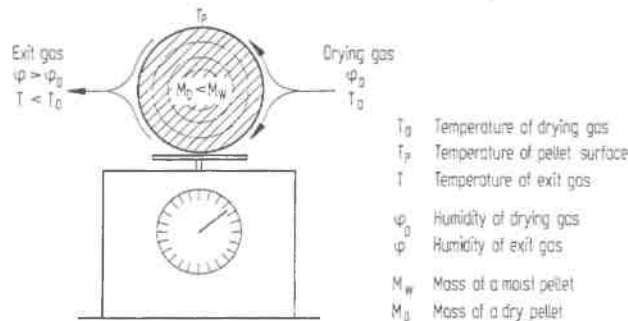


Fig. 141. Influence of hot gas flow on drying of a green pellet

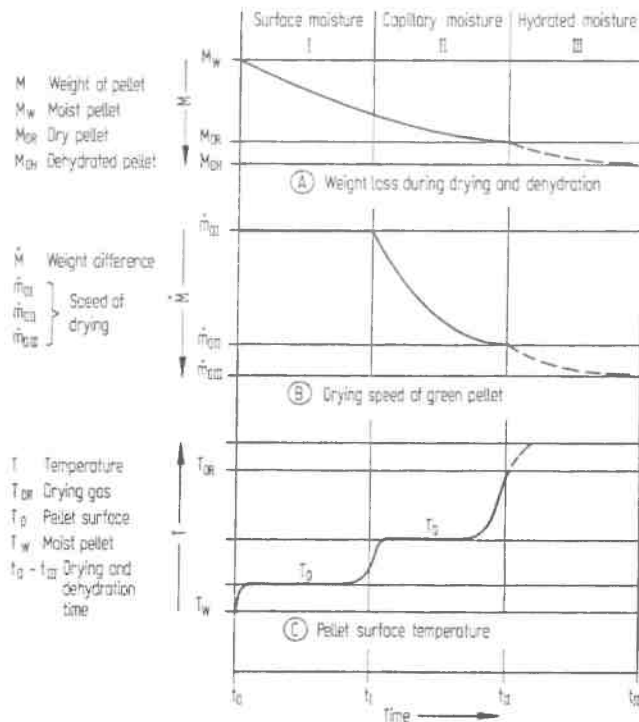


Fig. 142. Drying progress of a moist pellet

the surface in concentric “skins”, shown as dotted rings in Fig. 141, through various stages into the pellet core, as is also shown in Fig. 15.

The time-related drying procedure $X(t)$ is proportional to weight decrease $M(t)$ as can be seen from Fig. 142 A. The greatest weight reduction takes place in phase I, see Fig. 16. As a result, phase I also has the highest drying velocity m_{DI} (Fig. 142 B). It is represented by the following equation:

$$\dot{m}_{DI} = \frac{M_D \cdot \beta}{R_D \cdot T} (P_{DPE} - P_{DS}) \quad (19)$$

If the steam pressure on the pellet surface P_E is approximately equated with the saturated steam pressure P_s at a surface temperature T_s , evaporation values of up to 40 kg/m²h can be calculated for the individual pellet. A comparable amount would be 100–150 kg/m²h for a sinter mix.

In phase II, the water has already been evaporated from the surface. The drying front shifts towards the pellet core. The steam arising must cover a longer diffusion distance S through the capillaries which are

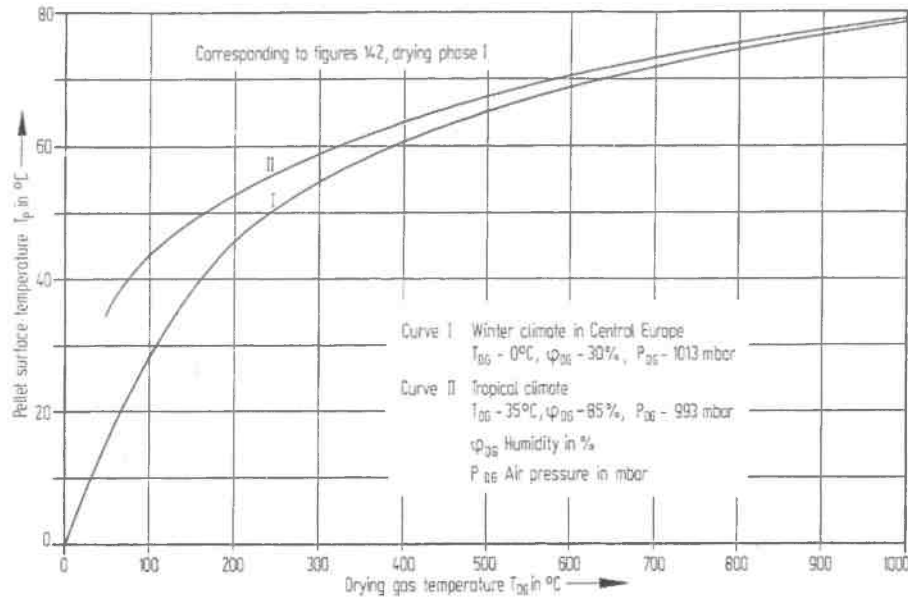


Fig. 143. Relation between drying gas and pellet surface temperature

already dry. Consequently, the drying velocity slows down accordingly, m_{DII} . It drops to zero when the water in the capillaries also evaporates and a constant weight M_{DIF} is reached Fig. 142 B. If combined water is still present, phase III, weight variations have to be detected by using sensitive thermo-scales.

The drying procedure during the individual phases also results in a change in the pellet surface temperature, which corresponds to the drying gas temperature, Fig. 142 C.

For evaporation of water from hydrates, higher temperatures are necessary, phase III.

During drying, the specific surface temperature of pellets is obtained for each relevant drying gas temperature. These temperatures are shown in Fig. 143 for two different climatic zones according to calculations by O. Krischer¹⁵⁶⁾.

13.3.2 Drying of a Pellet Charge

When the drying takes place by a hot gas flow through a pellet charge, the fundamental rules¹⁵⁷⁾ do not change compared to the drying of a single pellet. However, the mathematical correlations become more complicated, since the condition of hot drying gases changes according to time

and place when they enter the pellet charge. The drying procedure in three superimposed pellet layers is shown in Fig. 144 A–E for consecutive drying steps under equal conditions of drying gases. The drying proceeds in three phases I–II but has already been terminated after phase II when it is assumed that only adhering water would exist.

In the initial stage A, before drying starts, the entire layer is uniformly moist, temperature and moisture content are unchanged, T_A , X_A . In step B, the drying has commenced. The drying gas with the temperature T_{DR} and a moisture content φ_{DR} flows upwards through the pellet bed. The moisture content from the bottom layer has partly been expelled and the moisture content is smaller than X_A . The drying air is oversaturated with steam and the excess steam condenses on the second, the cooler pellet layer, whereby its moisture content becomes higher than it initially was. The surface temperature is increased from T_A to T_P by condensation heat. The third and the following layers are unchanged under given conditions. The exhaust gas is nearly saturated.

The drying process continues in step C. Now the bottom layer is already dry, the central layer is partially dried and the top layer is overwetted. The exhaust gas is still nearly saturated. The pellet temperature is about the same as in step B.

At a further drying gas supply, the bed becomes completely dry, D to E. The surface temperature of the pellets and the drying gas temperature as well as the humidity of the exhaust and drying gas have balanced out. In an unmoved bed with many pellet layers through which hot drying gases

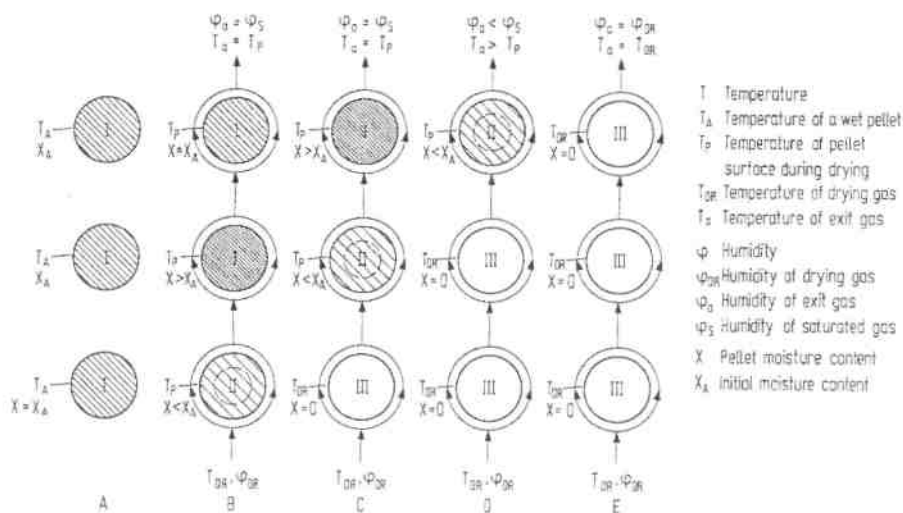


Fig. 144. Water content variation in a green pellet layer during drying

are flowing, evaporation velocity, drying time and temperature gradient can be calculated on the basis of similar conditions.

The space-time development of the drying process in a green ball layer can be simulated in a step-wise calculating procedure. On the basis of a computer simulation¹⁵⁾, such a result is diagrammatically illustrated in Fig. 145. The pellet charge of 30 cm thickness is divided into 30 partial layers y , each 1 cm thick. The heat balance for each partial layer was established:

“Cooling of hot drying air = heating of pellets + water evaporation”.

The drying situation was ascertained after 1–4–7 minutes from the moment of drying gas inflow in one direction as “updraught drying”.

The following curves give information concerning the various drying times and the respective bed heights:

(a) the situation after *one minute* of drying:

(α) The temperature in the pellet bed just above the hearth layer rapidly drops from about 175 °C to about 40 °C at a bed height of 10 cm from bottom and remains unchanged for the rest of the charge.

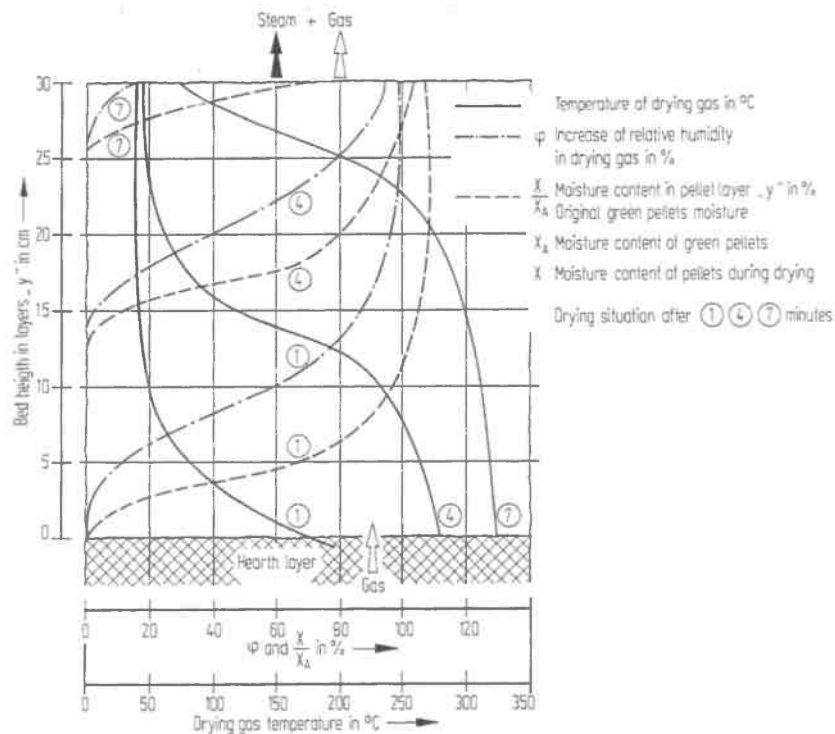


Fig. 145. Influence of time on the drying process of a green pellet bed

- (f) The average moisture content in the lower part of the bed is less than the moisture content of the green pellets but from a level of above 10 cm of bed height the moisture content is higher than that of green pellets.
- (g) The humidity of the drying gas is increasing and the gas is saturated at about 20 cm of bed height.
- (b) The situation after *four minutes* of drying:
 - (α) A greater part of the pellet bed already has a higher temperature. But at the top of the bed the temperature of 40 °C is still prevailing as before.
 - (β) The pellet bed is already dry for the first 12 cm from charge bottom. From this level the moisture content increases and exceeds the normal value just below the top level of the pellet bed.
 - (γ) On the bed surface the drying gas contains about 95% humidity.
- (c) The situation after *seven minutes* drying is as follows:
 - (α) The temperature in the bed rises and reaches about 75 °C on the bed surface.
 - (β) The pellet bed is almost dry over a height of about 25 cm.
 - (γ) The humidity of the escaping gas is not higher than that of the incoming drying gas.

The computed values explained above in Fig. 145 show a good conformity with the corresponding measured values shown in Figs. 17, 18 and 144.

Since the rules of the proper drying procedures are known, it is possible to make available dry pellets of good quality for further thermal treatment.

Final Remarks

For fine-grained iron ore particles, pelletizing is an efficient alternative to down-draught sintering. Despite the generally acknowledged favoured pellet properties, the initially great expectations concerning the improvement of the blast furnace operation were worldwide not equally realized although the metallurgical behaviour of pellets is, in general, better than that of many lump ores and practically equivalent to that of sinter. Fig. 146 ⁴⁾ explains the different behaviour of lump ores, sinter and pellets of various basicity during reduction.

The uniform spherical shape of the pellets caused some difficulties by segregation from the other components of the blast furnace burden when major quantities were used. This problem was overcome by the applica-

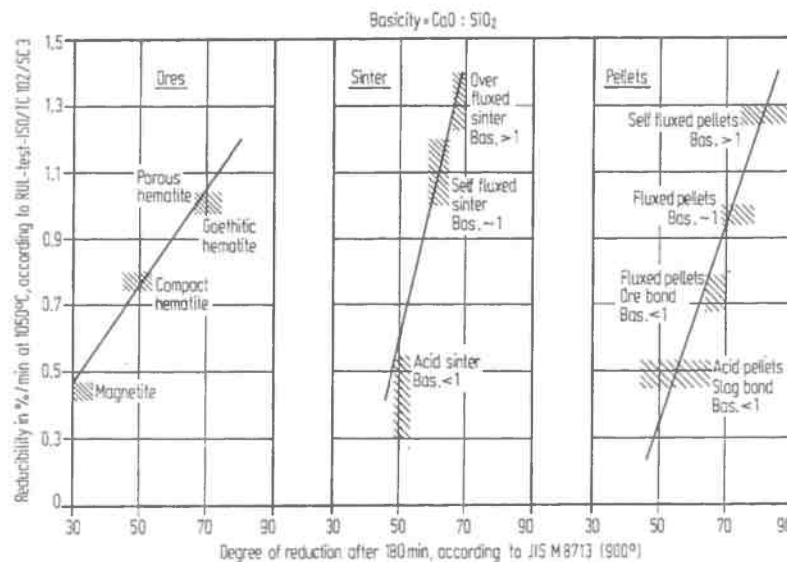


Fig. 146. Reducibility of different ores, sinter and pellet types – correlation between two different testing methods

tion of a more suitable charging technique in which material of similar size and shape is charged in corresponding layers.

Another alternative was to crush pellets of large size into pieces and to charge these pieces into the blast furnace¹³⁵). By comparing the behaviour of this material with sinter and uncrushed pellets of smaller size, some benefits were found. Therefore a shape other than the spherical shape could be imaginable.

The use of pellets is, no doubt, of decisive importance for the introduction and progress of the direct reduction processes. In this connection a remarkable contribution is made to the successful development of the steel plants with lower capacity (Mini-steel plants) in which steel is directly produced, bypassing the blast furnace. This development is only at the beginning and will be of increasing importance for many countries in the future. Since pelletizing is closely connected with these new steel technologies, it will participate in the future growth accordingly.

The advantage of the lower heat consumption for pellet firing as compared with sintering decreases in view of the fast increasing fuel oil prices. Attempts to partly replace the fuel oil by coal should be continued^{67/68}).

The ever increasing costs for agglomeration lead to considerations for direct processing of fine-grained iron ore particles into steel without agglomeration. Efforts in this direction should be intensified even if a notable success appears hardly realisable for the present.

References

Chapter 1. Definition and Development of Pelletizing Process

1. Bennet, R. L.; Lopez, R. D.: Agglomeration of iron ore concentrates. Chem. Eng. Progr. Sympos. Ser. (1963) 40–51
2. Cappel, F.; Wendeborn, H.: Sintern von Eisenerzen. Düsseldorf: Stahleisen-Bücher, Bd. 19, Stahleisen 1973
3. Andersson, A. G.: Swedish patent No. 35124, Class 29 : a 1912
4. Brackelsberg, C. A.: Die Herstellung von Agglomeratkugeln. Sonderdruck aus Tech. Mitt. H. 15 (1916) 1–8
5. Hüttemann, P.: Diskussionsbeitrag Stahl und Eisen 72 (1952) 1577–1579
6. Haley, K. M.; Apuli, W. E.: Pelletizing on a horizontal grate machine. Agglomeration (ed. W. A. Knepper) New York: Interscience 1962 pp. 931–964
7. Tigerschiöld, M.: Aspects on pelletizing of iron ore concentrates JISI May 1954. Special meeting in Sweden, pp. 13–24
8. Stalhed, J.: Die Herstellung von Eisenschwamm nach dem Wiberg-Verfahren. Stahl und Eisen 72 (1952) 459–466
9. Firth, C. V.: Agglomeration of fine iron ores. Proc. AIME, Blast Furn. Coke Oven Raw Mater. 4, 46 (1944) 44–69
10. Bennet, R. L.; Hagen, R. E.; Mielke, M. V.: Nodulizing iron ores and concentrates at extaca. Min. Eng. 6 (1954) 32–38
11. Ramsey, R. H.: Teamwork on taconites. Eng. Min. J. 156 (1955) 72–93
12. Wendeborn, H.: Neuere Entwicklungen der Bandsinteranlagen. Stahl und Eisen 71 (1951) 1212–1218
13. Wenzel, W.; Gudenau, H. W.; Moeljono, I.: Filtrieren und Sintern von Feinerzschlämmen. Stahl und Eisen 93 (1973) 49–55
14. Meyer, K.: Stand der Entwicklung der Pelletierung von Eisenerzen, Stahl und Eisen 82 (1962) 147–154
15. Brandes, G.; Rausch, H.: Mixing and Conditioning of Sinterplant feed. Proc. AIME, Blast Furn. Coke Oven Raw Mater. 18 (1959) 233–249
16. Violetta, D. C.: Updraft pelletizing of specular hematite concentrates. J. Metals 10 (1958) 118–121
Hamilton, F. L.; Mean, H. F.: Production and properties of experimental pellet-sinter. Proc. AIME, Blast Furn. Coke Oven Raw Mater. (1955) 1–8
17. Rausch, H.; Meyer, K.: Einfluß der Mischfeuerung auf die Betriebsergebnisse von Sinteranlagen. Stahl und Eisen 78, 9 (1958) 600–606
Rausch, H.; Cappel, F.: Comparison between conventional hot air and mixed fired sinter. Agglomeration (ed. W. A. Knepper). New York: Interscience 1962, pp. 455–480
18. Meyer, K.; Rausch, H.: The Lurgi pelletizing process. J. Metals 10 (1958) 129–133

19. Dailey, W. H.: Blast furnace performance pellets – vs – sinter. Meeting of Association of Iron & Steel Engineers Pittsburgh Feb. 1962
Kaas, W.; Gerstenberg, B.: Ermittlung der Kaltdruckfestigkeit an Hochofen Pellets nach unterschiedlichen Prüfverfahren. Stahl und Eisen 99 (1979) 513–517
20. Petersen, U.; Kahlhöfer, H.; Send, A.: Betriebsversuche zur Leistungssteigerung des Hochofens durch Einsatz von Pellets. Stahl und Eisen 83 (1963) 1397–1407
21. Meyer, K.: Entwicklung der Pelletierung von Eisenerzen und Herstellung von Mischerzpellets. Stahl und Eisen 83 (1963) 1337–1344
22. Koen, W.: Two years of pelletizing at hoogovens. Metals Society London 1972, pp. 12–16

Chapter 2. Fundamentals of Pelletizing

23. Rumpf, H.: The strength of granules and agglomerates. Agglomeration (ed. W. A. Knepper). New York: Interscience 1962, pp. 379–418
24. Tigerschiöld, M.; Ilmoni, P.: Fundamental factors influencing the strength of green and burned Pellets made from fine magnetite-ore concentrates. Proc. Blast Furn., Coke Oven Raw Mater., Session on Ore and Agglomeration 9 (1950) 18–45
25. Sastry, K. V. S.; Fuerstenau, D. W.: Mechanism of agglomerate growth in green pelletizing. Powder Technol. 7 (1973) 97–105
26. Linkson, P. B.; Glastonbury, J. R.; Duffy, G. J.: The mechanism of granular growth in wet pelletizing. Trans. Inst. Chem. Eng. 51 (1973) 251–259
Bhrany, U. N.; Johnson, R. T.; Myron, T. L.; Pelczarski, E. A.: Dynamics of pelletization. Agglomeration (ed. W. A. Knepper). New York: Interscience 1962, pp. 229–259
Newitt, D. M.; Conway-Jones, J. M.: A contribution to the theory and practice of granulation. Trans. Inst. Chem. Eng. 36 (1958) 422–442
Schubert, H.: Tensile strength and capillary pressure of moist agglomerates. Agglomeration 77, AIME New York 1977, Chapt. 9, pp. 144–155
27. Krischer, O.; Jaeschke, L.: Trocknungsverlauf in durchströmten Haufwerken. Chem. Ing. Techn. 33 (1961) 592–598
Krischer, O.; Kast, W.: Die wissenschaftlichen Grundlagen der Trocknungstechnik, Vol. 1, 3rd. ed. Berlin, Heidelberg, New York: Springer 1978, pp. 258–263.
28. Information from the Laboratories and Engineering Department of Lurgi Chemie und Hüttentechnik Frankfurt/Main, FRG
29. Pietsch, W.: Die Festigkeit von Granulaten mit Salzbrückenbindung und ihre Beeinflussung durch das Trocknungsverhalten. Doctorthesis. Aufbereitungstech. (1967) 297–307
30. Vitiyugin, V. M.; Leonteva, T. G.; Trofimov, V. A.: Thermal stability of iron ore pellets during drying. Steel USSR (1971) 587–589
31. Westenberger, H.: Über Phasenbestand, Kornbindung und Gefüge gebrannter Eisenerzpellets. Diplom Ingenieur Thesis. Johann Gutenberg-Universität Mainz 1967
32. Urich, D. M.; Tsu, Ming Han: A progress report on the effect of grind, temperature and pellet size upon the quality of specular hematite pellets. Agglomeration (ed. W. A. Knepper). New York: Interscience, pp. 669–719
33. Yefimenko, G. G. et al.: Thermal dissociation of hematite during oxidizing firing of iron fluxed briquettes. Steel USSR (1977) 307–308

Report on teamwork of Studiengesellschaft für Eisenerzaufbereitung Ottfresen and Lurgi Chemie und Hüttentechnik, Frankfurt/Main, FRG

34. Eisermann, E.: Ein Beitrag zur Deutung des Reduktions- und Schwellverhaltens von Hämatitpellets aus Magnetitkonzentrat. Doctorthesis TU Berlin 1969. Stahl und Eisen 90 (1970) 676–682

Chapter 3. Raw Materials and Their Preparation for Pelletizing

35. Kortmann, H.; Mai, A.: Untersuchungen über die Eignung verschiedener Bentonite für den Einsatz bei der Eisenerzpelletierung. Aufbereitungstechn. (1970) 251–256
36. Lefond, J.: Industrial Minerals and Rocks AIME New York, 4th ed.
37. Meiler, H.: Untersuchungen zur magnetisierenden Röstung und Magnetscheidung fein verwachsener Eisenerze. Aufbereitungstechn. (1964) 413–420

Chapter 4. The Pelletizing Laboratory and its Tasks

38. Taggart: Handbook of mineral dressing 1948
39. Burghardt, O.: Die Vorbereitung von Mahlprodukten zur Durchführung von Oberflächenbestimmungen. Rittinger Symp. Leoben 1973, pp. 60–69. Ed.: Bergmännischer Verband Österreichs.
40. Jornados Minero Metallurgica Bilbao June 1975, pp. 295–314
41. Bond, Frd. C.: The third theory of continuation. Min. Eng. (1952) 484–494
42. Lofgren, O.; Nilson, C. G.; Ödman, R.: Operational experiences of balling circuits with drums, discs and roller screens. Agglomeration 77, AIME, pp. 425–436
43. Rumpf, H.: Grundlagen und Methoden des Granulierens. Chem. Ing. Tech. (1958) 144–158
44. Bhrany, U. N.: Entwurf und Betrieb von Pelletiertellern. Aufbereitungstechn. (1977) 641–647. Trans. India Inst. Metals 29 (1976) 118–126
45. Sommer, K.; Hermann, W.: Auslegung von Granulierteller und Granuliertrommel. Chem. Ing. Tech. 50 (1978) 518–524
46. Bunge, F.; Wakeman, J.: Pelletizing Butler, Groveland and Carol Lake concentrates. Minnesota Section of AIME Meeting 1962, p. 52
47. Marshal, W. E.: Taconite pellets in the blast furnace J. Metals (1961) 308–313
48. Kortmann, H. A.; Burghardt, O. P.: Test methods for evaluating iron ores, pellets and sinter. Agglomeration 77, Vol. 1, pp. 219–242
49. Linder, R.: Program controlled reduction for blast furnace burden. JISI 1958, pp. 233–243
49. Kaneko, D.; Kimura, Y.; Onoda, M.; Tujita, I.: Reduction propertion raw materials for direct reduction shaft furnace. Central Res. Lab. Kobe Steel Ltd. Kobe Japan 1977, pp. 1–19

Chapter 5. Process Influencing Factors

50. v. Struve, G.: Grundlegende Betrachtungen über das Pelletieren von Eisenerzen. Chem. Ing. Tech. (1964) 1019–1027
51. D'Rozario, H. L.; Vodic, P. A.; Young, P. A.: A preliminary examination of iron ore pellets produced from relatively coarse particles size distribution. The Institution of Engineers, Australia. Paper Nr. 2505, presented at the Chemical Engineering Conf. Adelaide Aug. 1968
- Davison, J.; Thompson, R. E.; Welch, W. P.: Pelletizing of relatively coarse iron ores. JISI May (1966) 443–451

- 52/28. Neuer, B.: Der Einfluß von Zuschlägen auf die Grün- und Trockenfestigkeit während des Aufheizens in oxidierender und reduzierender Atmosphäre. Studienarbeit, TU Berlin
- 53/28. Maidorn, Chr.: Untersuchungen über die Zusammenhänge zwischen Qualität von Eisenerzpellets und dem Aufmahlungsgrad des Ausgangsmaterials, sowie dem Zusatz von Bindemitteln. Thesis for degree of Diplom Ingenieur Bergakademie Clausthal, FRG, 1962
- 54/28. Ebrahimzadeh, Mohammed-Reza: Untersuchungen über das Pelletieren von Eisenerzen mit einem im Vergleich zur heute üblichen Praxis groben Kornaufbau unter Verwendung von Bindemitteln. Thesis for degree of Diplom Ingenieur Bergakademie Clausthal, FRG, 1964
- 55/28. Walden, K.: Der Einfluß von basischen Zuschlägen auf die metallurgischen Qualitätsmerkmale von Eisenerzpellets. Thesis for degree of Diplom Ingenieur TU Berlin, 1961
56. Björkvall, B.; Ilmoni, P. A.: Production and use of fluxed pellets. *Journées internationales de sidérurgie*, 1975. Société française de la métallurgie, pp. 1–24
- Hasenack, N. A.; Vogel, R. B.; Homminga, F.: The manufacture of basic pellets and their behaviour in the blast furnace. AIME Iron making conference, St. Louis, 1976, pp. 144–163
- Malysheva, T. Ya.; Chernyshev, A. M.: Comparative study of the mechanism of the formation of fluxed and unfluxed pellets. *Stal* 5 (1974) 392–394
- Tayama, A.; Shimomura, Ya.; Fujita, K.; Takemura, T.: Production of self-fluxing pellets at Hirohata works of Nippon Steel Corp. *Trans. ISIJ* 18 (1978) 52–60
- Bentell, L.; Mathison, G.: Oxidation and slag-forming process in dolomite-fluxed pellets based on magnetite concentrates. *J. Metallurgie* 7 (1978) 231–236
57. Sengfelder, G.: Pelletisieren von Doggererzen und Feinspat. *Stahl und Eisen* 70 (1950) 765–767; *Stahl und Eisen* 72 (1952) 1577–1579
- v. Struve, G.: Zur Frage der Pelletisierung von Eisenerzen und anderen eisenhaltigen Rohstoffen. *Freiberger Forschungshefte*, B 25 (1958) 38–52
58. van Latenstein, A.; van Langen, J. M.: Mischerzpelletierung in Ijmuiden. *Stahl und Eisen* 92 (1972) 101–106
59. Bragard, A.; Matthieu, L.: Erfahrungen mit der Pelletierung selbstgängiger Erzmischungen. *Stahl und Eisen* 92 (1972) 106–112
60. N. N.: Outline of pelletizing plant. Kakogawa works, Kobe Steel, Ltd. Company report May 1978, pp. 1–11
61. Gudenau, H. W.; Wenzel, W.: Das Pelletieren von Eisenerzen mit vorgebranntem Gut. *Stahl und Eisen* 87 (1967) 933–938
62. Meyer, K.: Die Herstellung und Eigenschaften gangartarmer Eisenerzpellets unter Zusatz von Eisenschwamm. Thesis for degree of Doctor Ingenieur TH Aachen, FRG, 1968
- Schenck, H.; Wenzel, W.; Meyer, K.: *Stahl und Eisen* 90 (1970) 683–689
63. Mueller, B.; v. Struve, G.: Design of pelletizing plants for blast furnaces and direct reduction processes incorporating inplant fines. *Agglomeration* 77, Vol. 1, pp. 25–45
64. N. N.: Humates Candidates for pelletizing iron ores. *Nalco Chemical Corp. Eng. Min. J.* (1968) 117–118
65. De Vaney, F. D.: U. S. Patent 2596 132
66. Aubrey, W. M.; Ketter, R. P.: Use of solid fuel in the pelletizing shaft furnace. SME Fall meeting, Las Vegas, 1967

67. Hütter, B.: Die Herstellung gebrannter Eisenerzpellets aus Grünpellets mit geringer Brennstoffbeimischung. Thesis for Degree of Doctor Ingenieur, Rhein. Westf. TH Aachen, FRG 1977
68. Nigro, J. E.; Zahl, R. K.: Preliminary experiments in pellet induration using a coal-fired cyclone combustor. *Skellings Mining Rev.* 65 (1976) 1–14
 Broj, K.: Use of solid fuels for pelletizing. Paper from Lurgi-Chemie und Hüt-
 tenttechnik GmbH Frankfurt/Main, 1978 Nov., pp. 1–17
 De Klaver, M. A. A.; Kestner, D. W.: Empleo de Combustibles Solidos en el
 Proceso de Peletización de Ferrominerales en Parilla Recta, *Siderurgia Latino
 Americana*. Nr. 237, Enero 1980, pp. 47–54
69. Ball, D. F.; Dartnell, J.; Davison, J.; Grieve, A.; Wild, R.: The drying of green
 balls, Chapt. 30. *Agglomeration of Iron Ores*. New York: American Elsevier
 Publ. Comp. Inc., 1973
70. Izgiz, S.; Wenzel, W.; Gudenau, H. W.: Der Einfluß morphologischer Größen
 auf die Pelletiereigenschaften von Eisenerzen im Grünzustand. Thesis for
 degree of Doctor Ingenieur, Rhein. Westf. TH Aachen, FRG
71. Pape, P. O.; Frans, R. D.; Geiger, G. H.: Magnetite oxidation kinetics and
 thermal profiles in a magnetite pellet plant cooler. *Ironmaking Steelmaking*
 (1976) 138–144
72. Joseph, T. L.: Pelletizing of iron ore concentrates, Part II: Blast Furn. *Steel
 Plant* (1955) 745–752
 Zetterstrom, J. D.: Oxidation of magnetite concentrates. U. S. bureau of
 mines, Rep. on Investig. 4728, 1950
 Strathmore, J. D.; Cooke, Stowasser, W.: The Effect of heat treatment and
 certain additives on the strength of fired magnetite pellets. *Min. Eng. Trans.
 AIME* (1952) 1223–1229
73. Callender, W.: Heat fastening of artificial magnetite pellets. *Agglomeration*
 (ed. W. A. Knepper), New York: Interscience 1962, pp. 641–667
74. Bowen, N. L.; Schairer, I. F.; Posnjak, E.: The system CaO-FeO-SiO_2 . *Am. J.
 Sci.* 26 (1933) 193–281
75. Hedvall, J. A.; Sjöman, P. S.: Über die Bedeutung kristallographischer Um-
 wandlungen der Kieselsäure für ihre Reaktionsfähigkeit im festen Zustand. *Z.
 Elektrochem.* 37 (1931) 130–142
76. Hass, K. P.; Bitsianes, G.; Joseph, T. L.: Calcium ferrites in relation to
 sintering of iron ores. *Blast Furn. Coke Oven Raw Mater. Conf.*, 1960, pp.
 429–453
77. Philipps, B.; Muan, A.: Phase equilibria in the system CaO-iron oxide in air
 and at atmosphere. *J. Am. Ceram. Soc.* 41 (1958) 445–454
78. Bowen, N. L.; Schairer, J. F.; Posnjak, E.: The system $\text{Ca}_2\text{SiO}_4\text{--Fe}_2\text{SiO}_4$.
Am. J. Sci. 25 (1933) 273–297
79. Yefimenko, G. G.; Knyazhanskii, E. N.; Grigor'ev, E. N.; Mishchenko, V. S.:
 Thermal dissociation of hematite during oxidizing firing of iron ore fluxed
 briquettes. *Steel USSR* (1977) 307–308

Chapter 6. Behaviour of Indurated Pellets During Reduction

80. Heynert, G.; Zischkale, W.; Willems, I.: Austausch von Sinter gegen Pellets
 bei voll vorbereitetem Möller. *Stahl und Eisen* 82 (1962) 1641–1647
81. Edström, I. O.: The mechanism of reduction of iron oxides *JISI*, 179 (1953)
 289–304
82. Kodama, K. et al.: Yawata Technical Report – Tokyo 1965, pp. 5899–5909
 Hasegara, T. et al.: *Tetsu To Hagane Oversees* 5 (1965) 223–242
 Ishimitsu, A.: *Tetsu To Hagane Oversees* 5 (1965) 223–242
 Kanbara, K. et al.: *Tetsu To Hagane* 51 (1965) 586–590

- Kodama, K. et al.: Tetsu To Hagane 51 (1965) 590–593 Tetsu To Hagane 50 (1964) 327–330
83. Chang, M. C.; Vlnaty, I.; Kestner, D. W.: North American pellet-swelling during reduction 26. Iron Making Conference Dec. 1967. Palmer House, Chicago
 84. von Bogdandy, L.; Engell, H. I.: The reduction of iron ores. Düsseldorf: Verlag Stahleisen und Berlin, Heidelberg, New York: Springer 1971, p. 47
 85. Mc Kewan, W. M.: Trans. Metall. AIME 212 (1958) 791–793
 86. Schuschunow, V. A.; Blagina, M. M.: Gelehrte Abhandlungen der N. I. Lobatschowski Staatsuniversität, Gorki, N 32. 1958, pp. 9–12
 87. Wahlster, M.: Tech. Mitt. Krupp 19 (1961) 1–16
 88. Riecke, E.; Bohnenkamp, K.; Engell, H. I.: Über die Reduktion von Wüstite mit Wasserstoff-Wasserdampf und Kohlenmonoxid-Kohlendioxidgemischen: Arch. Eisenhüttenwes. 38 (1967) 249–255
 89. Fuwa, T.; Ban-Ya, S.: Swelling of iron ore pellets during reduction. Trans. Iron Steel Inst. Jpn. 9 (1969) 137–147
 90. Pothenkandath, M.: Über das Reduktionsschwellen von Eisen. Doktor Ing. Diss. Rhein. Westf. TH Aachen, FRG 1971
 91. Ottow, M.: Ursachen der Zerstörung von Hämatitpellets aus sehr reinem Magnetitkonzentrat während der Reduktion und Versuche zur Qualitätsverbesserung. Doktor Ing. Diss. TU Berlin 1966
 92. Mehl, R. F.; Mc Chandless: Oxide films on iron. Trans. AIME (1937) 531–559
 Ramdohr, P.: Die Erzminerale und ihre Verwachsungen. Berlin: Akademie Verlag 1955.
 93. Bleifuss, R. L.: The swelling of pellets during reduction. Univ. of Minnesota. Progress Rep. No. 19 (1979) 24–47
 94. Kortmann, H.: Untersuchungen zum Schwellverhalten bei der Reduktion von Eisenerzpellets mit unterschiedlicher Gangart. Doktor-Ing. Diss. Technische Universität Clausthal, FRG 1972
 95. Burghardt, O.; Kortmann, H.; Grover, B.: Einfluß der mineralischen Zusammensetzung auf die Güte von Eisenerzpellets. Stahl und Eisen 90 (1979) 660–666
 Grebe, K.; de Haas, H.; Keddeinis, H.: Schwellverhalten gebrannter Eisenerzpellets mit unterschiedlicher Gangartmenge und Gangartzusammensetzung. Stahl und Eisen 93 (1973) 472–479
 96. Frazer, F. W.; Westenberger, H.; Boss, K. H.; Thumm, W.: The relationship between basicity and swelling on reduction of iron ore pellets. Int. J. Miner. Process. 2 (1975) 353–365
 97. Hillnhuetter, F. W.; Kister, H.; Koch, K.: Der Einfluß von Calcium- und Magnesiumoxid auf den Niedrigtemperaturzerfall von Eisenerzintern. Stahl und Eisen 96 (1976) 987–993
 98. vom Ende, H.; Grebe, K.; Thomalla, S.; Hoffmann, E.: Alkalien als Ursache von Schwell- und Zerfallvorgängen bei der Reduktion von Eisenerzpellets. Stahl und Eisen (1970) 667–676
 Möhlmann, H. H.: Unterzeichnungen zum Schwellverhalten bei der Reduktion von Hämatitproben mit Na_2O_2 -, K_2O -, CaO -, MgO - sowie SiO_2 -Zuschlägen. Dr.-Ing. Diss. TU Clausthal, FRG, 1975
 99. Thaning, G.: Reduction strength of superfluxed pellets made from rich magnetite concentrates. Ironmaking Steelmaking (1976) 57–63
 Björkvall, B.; Ilmoni, P. A.: Production and use of fluxed pellets. Journ. Int. de Siderurgie, Paris, 1975

100. Cappel, F.; v. Struve, G.: Technische und wirtschaftliche Betrachtungen über die Herstellung basischer Pellets. *Stahl und Eisen* 89 (1969) 49–56

Chapter 7. Special Processes for Pellet Production

101. Goksel, M. A.: Cold bond pelletizing for steel production processes. *Met. Mater.* (1978) 19–26
Goksel, M. A.: Application of the MTU cold bond agglomeration process for production of metallized pellets. *Skilling Mining Rev.* (1979) 4–8
Bergmann, M.: Herstellung und Festigkeitsprüfung kaltgebundener Fe_3O_4 - und Fe_2O_3 -Pellets mit ausreichender Festigkeit für den Einsatz bei der Hoch-ofenmöllerung. Diplom-Arbeit Rhein. Westf. TH Aachen, FRG, 1978
102. Linder, R.; Thulin, D.: Grangcold Pelletierung von Eisenerzkonzentraten. *Aufbereitungstechn.* (1973) 799–802
Linder, R.: Grangcold pelletizing – state of the art AIME, Duluth Mining Symp., Januar 1971
Svensson, K. I. V.: Swedish patent No. 226 608, Class 18a: 1/24 Granges. *Ore News, Marketing Dept.* June 1975
Granges Ore News. Published by Granges Mines, Marketing Dept., Grängesberg, Sweden 1975
103. Nippon Steel News, Feb. 1979: Cold bonded pellet plant achieves high performance. Feb. 1979, Nr. 106
104. Hässler, B.; Kihlstedt, P. G.: Grundlagen zur Gestaltung des „Cobo“-Prozesses als Agglomeriermethode für Mineralkonzentrate. *Aufbereitungstechn.* (1973) 811–817
105. Meyer, K.: Entwicklung der Eisenerzpelletisierung. *Stahl und Eisen* (1956) 588–591
106. Lippert, K. K.; Pietsch, H. B.; Roeder, A.; Walden, H. W.: Recovery of non-ferrous metal impurities from iron ore pellets by chlorination (CV or LDK Process). *Trans./Sect. C of the Inst. of Mining and Metallurgy* 78 (1964) C97–C108
107. Okubo, Y.: Kowa Seiko pelletizing chlorination process – integral utilisation of iron pyrites. *J. Met.* 20 (1968) 63–67
108. Tikkanen, M.: Extraction of vanadium containing magnetite iron ore concentrates. *Dechema Monographie* Vol. 56, pp. 260. Direct information by Rautaruukki Oy, Finnland, Aug. 1978
109. Bings, H.; Thome, R.: Gewinnung von Vanadiumpentoxid aus Titanomagnetit. *Erzmetall* 31 (1978) 387–394
110. Pietsch, H.: Combined thermal and extractive treatment of ores in the LDK shaft furnace. 38th Int. Congr. of Industrial Chemistry Istanbul, Sept. 1969

Chapter 8. Balling Equipment

- 111/28. Direct Information by LKAB Sweden and Hoogovens, Ijmuiden, Holland
Krendelev, V. L.; Mironnikowa, V. V.: Optim. consumption of bentonite in pellet production. *Metallurgy i gornoruden Prom.* Vol. 16, 1975, Nr. 1, Henry Brucher Nr. 9553/1975
Jacobs, W.; Brennecke, K.; Hert, P.: Blending and homogenising of crude ore and pellet feed at the bong mine, Liberia. *Erzmetall* 32 (1979) 316–320
112. Cross, M.: Mathematical model of balling drum circuit of a pelletizing plant. *Ironmaking Steelmaking* (1977) 159–169
Wellstaed, P. E.; Cross, M.; Munro, N.; Ibrahim, D.: On the design and assessment of control schemes for balling drum circuits used in pelletizing. *Int. J. Mineral Process.* 5 (1978) 45–67

113. Prospekt of Sala Maschinenfabriken, Prospekt 705 T Information from Sala Sweden
114. Meyer, K.: Überblick über neuere Granulierungsverfahren und ihre Anwendungsmöglichkeiten in der Zementindustrie. Zement-Kalk-Gips (1952) No. 6
- 115/42. Ranish, R. L.: Balling drums versus balling disc, an economic evaluation. Inst. of Briquetting and Agglomeration. Biennial Conf., Aug. 12th, 1975
116. British Patent F. D. De Vaney 825 114, 1956/57
117. Ries, H. B.: Verfahrenstechnische Möglichkeiten der Granulierung von Kalk und kalkhaltigen Düngemitteln. Aufbereitungstech. (1977) 633–639
118. Patent: Verfahren und Vorrichtung zur Förderung von Grünpellets, (Rollenförderer). D.B.P. Nr. 1063 811, Jan. 1st 1961, U.S.P. Nr. 2988 781 and other countries. Inventor: K. Meyer
119. Patent: Vorrichtung zur Herstellung von Granalien. D.B.P. 1009 096, Jan. 31st 1957. Inventor: K. Meyer

Chapter 9. Firing Equipment

120. English, A.; Frans, R. D.: Developments in pelletizing Vol. 1, Agglomeration 77, pp. 3–23, Atlanta
Traice, F. B., Lappin, R. L.: Survey of modern pelletizing technique, ICI Publication No. 152, 1972. Iron and Steel Inst. 1973, Publication 152, pp. 17–31 and 971–978
De Vaney, F. D.: Pelletizing in shaft furnaces. J. Met. (1958) 125–128
121. Ilmoni, P. et al.: Comparison between the three Pelletizing Processes used by LKAB. Congr. for Mineral Processing, Prague, 1970
122. Morawski, F. P.: Pelletizing methods at Erie Mining Company Minnesota, Sect. AIME Meeting 1963, pp. 15–21
123. Aubrey, W. M.; Ketter, R. P.: Use of a solid fuel in the pelletizing shaft furnace. SME Fall Meeting, Rocky Mountain Minerals Conf. Las Vegas, 1967
124. Eberts, B. R.: Pelletizing at the Griffith Mine. Can. Min. Metall. CIM Bull. (1970) 1285–1288
125. Koski, R. A.; Nora, D. D.: Pelletizing of various ore types in grate-kiln systems. Society of Mining Eng. of AIME. Paper 69–B–358, Salt Lake City, Sept. 1969
Stowasser, W. F.: The grate and kiln process for burning pelletized magnetite concentrates. Pamphlet by Allis Chalmers Mfg. Co.
126. Koski, R. A.: Pelletizing of various iron ore concentrates and natural ores as practised by the Cleveland Cliffs Iron Company. Agglomeration 77, Vol. 1, pp. 46–73
Pape, P. O.; Frans, R. D.; Geiger, G. H.: Magnetite oxidation kinetics and thermal profiles in a magnetite plant pellet cooler. Ironmaking Steelmaking (1976) 138–145
127. Cnare, R. F.; Glenn, M. H.: The recup system – a new method of heat recuperation in the grate-kiln system. Ironmaking Proc., St. Louis, 1976, Vol. 35, pp. 164–177
128. Boehm, P. W.: Der Einsatz des Lepol-Verfahrens bei der Pelletierung von Erzen. Aufbereitungstech. (1975) 626–630
129. Ban, T. E.; Erck, L. I.: Laboratory Procedures for determining the pelletizing characteristics of iron ore concentrates. AIME Trans. 196 (1953) 803–811
Marquette starts second jasper plant. Eng. Min. J. (1957) 76–79
Violetta, D. C.: Updraft pelletizing of specular hematite concentrates. J. Met. (1958) 118–121

130. English, A.; Morgan, T. F.: Dowlraft taconite pellet hardening plant. J. Met. (1958) 122–124
131. Haley, K. M.: Reserve mining company pelletizing practice annual meeting of the Canadian Institute of Mining and Metallurgy, Toronto 1960
Scott, I.: Improvements and updating at reserve mining comp. iron ore pellet plant. Skilling's Mining Rev. (1978) 18–20
Ilmoni, P. et al.: Comparison between the three Pelletizing Processes used by LKAB. Congr. for Mineral Processing, Prague, 1970
- 132/18. Queneau, P.; Bracken, E. H.; Kelly, D.: High grade iron ore at Copper Cliff, Ontario. J. Met. (1958) pp. 527–532
133. Information given by Lurgi, Dravo and various pellet plant operators.
134. Sephton, S.; Sandish, R.; Mackley, O.: Pelletizing in the round. S. M. E. Fall Meeting Oct. 1973
N. N.: Circular grate, new tool for pelletizing iron ores. Eng. Min. J. (1970) 102–106
135. Smith, L. W.; Beggs, D.; Rinker, F. G.: New process for oxide pellet production on the Mesabi range. Soc. Min. Eng. (1966) 47–52
136. Huntington, Heberlein & Co.: A new approach to pellet hardlining. Paper 1964 January (company paper)

Chapter 10. Plant Construction and Process Control ²¹⁾

Chapter 11/12. Pellets in the Blast Furnace. Pellets for the Direct Reduction

137. Flierman, G. A., Homminga, F.: A comparison of B. F. operating results obtained with sinter of pellet burden. Agglomeration 77, Vol. 2, pp. 817–829
Dixon, J. M.: Report on JISI's meeting in Australia 1979. The Internat. Metals and Metalworking Magazine, 1980, pp. 12MP7–9
Engel, K.; Grebe, K.; de Haas, H.; Kleppe, W.; Winzer, G.: Hochofenverhalten verschiedener Möllerstoffe. Stahl und Eisen (1979) 891–897
138. Koen, W.; Flierman, G. A.; Maes, I.: Blast furnace trials with acid pellets, fluxed pellets and fluxed sinter. Chicago 1978, AIME Trans. Ironmaking Proc. V37, pp. 273–28
139. Rumberger, M.; Wettig, E.: Rohstoff Eisenerz: Weltmarktentwicklung und Versorgungssicherheit. Forschungsinstitut der Friedrich-Ebert-Stiftung Dokumentationsstelle, Godesberger Allee 149, 5300 Bonn, FRG (not published)
Hoppe, R. W., Thomas, R. A.: Taconite progress report. Eng. Min. J. 180 (1979) 64–143
Technological Forecasting Study: Iron and Steel Industry, April 1977. Hamersley Iron PTY. Ltd., Melbourne
Winzer, G.; Reichenstein, E.: Technologie der Eisen- und Stahlerzeugung in den Jahren 1975–2005. Stahl und Eisen 98 (1978) 1119–1126
Le Cerf, B. H.: Pellet/sinter results differ worldwide. Iron Age (Nov. 1979)
141. Lawrence jun, R.: The HyL direct reduction process. Past–present–future. Seminar Direct-Reduction of Iron Ores, Bucharest, Roum., Sept. 1972

Chapter 13. Theoretical Considerations

142. Batel, W.: Menge und Verhalten der Zwischenraumflüssigkeit in körnigen Stoffen. Chem. Ing. Tech. 33 (1961) 541–547
Schubert, H.: Grundlagen des Granulierens. Chem. Ing. Tech. (1979) 266–277
Schubert, H.: Tensile strength and capillary pressure of moist agglomerates. Agglomeration 77, Vol. 1, pp. 144–156
Rumpf, H.: Particle adhesion. Agglomeration 77, Vol. 1, pp. 97–130

- 142/44. Sommer, K.; Herrmann, W.: Auslegung von Granulierteller und Granuliertrommel. Chem. Ing. Tech. (1979) 266–277
143. Rumpf, H.: Grundlagen und Methoden des Granulierens. Chem. Ing. Tech. (1958) 144–158
Rumpf, H.; Ebert, K. F.: Darstellung von Kornverteilung und Berechnung der spezifischen Oberfläche. Chem. Ing. Tech. (1964) 523–537 (Special print)
144. Tarjan, G.: Der Einfluß von Bewegungskräften auf die Granulation. Aufbereitungstech. 1 (1966) 28–32
145. Pietsch, W.: Die Beeinflussungsmöglichkeiten des Granulierbetriebes und ihre Auswirkungen auf die Granulateigenschaften. Aufbereitungstech. (1966) 177–191
Papadakis, M.; Bombled, J. P.: La granulation des matieres premieres de cimenterie. Rev. Mater. Constr. Trav. Publics. (1961) 289–299
146. Klatt, H.: Die betriebliche Einstellung von Granuliertellern. Zement-Kalk-Gips 11 (1958) 144–154
147. Molerus, O.: Neue Druckverlustgleichung für die Schüttungsdurchströmung im laminaren und im Übergangsbereich. VDI-GVC Fachsitzung „Mehrphasenströmung“, Düsseldorf 1976
Marincic, L.; Gerstenberg, B.: Untersuchungen über die Struktur und den Druckverlust von Kugel- und Möllerschüttungen unterschiedlicher Kornbandbreiten. Stahl und Eisen 98 (1978) 1353–1359
148. Jeschar, R.: Druckverlust und Mehrkornschüttungen aus Kugeln. Arch. Eisenhüttenwes. 35 (1964) 91–108
VDI-Wärmeatlas, 2nd ed. 1974, pp. LE1–LE2
149. Brauer, H.: Die Eigenschaften der Zweiphasenströmung bei der Rektifikation in Füllkörpersäulen. Dechema Monographien Vol. 37, pp. 7–78
150. Jeschar, R.: Analogie zwischen Wärme und Stoffübergang in Schüttungen aus Kugeln. Arch. Eisenhüttenwes. (1964) 955–961
Heiligenstaedt, W.: Wärmetechnische Rechnungen für Industrieöfen. Düsseldorf: Stahleisen 1966
151. Hottel, H. C.; Sarofim, A. F.: Radiative transfer. New York: Mc. Graw-Hill 1967
152. Lichtenberger, H.: Flammenstrahlung und Wärmeabbau in Feuerräumen. Techn. Mitt. 3 (1972) 110–115
153. God, Ch.: Berechnung der Strahlungswärmeübertragung von Verbrennungsgasen. Radex Rundsch. 4 (1974) 250–273
154. Schack, A.: Der industrielle Wärmeübergang, 7th ed.
155. Carslaw, H. P.; Jaeger, J. C.: Conduction of heat in solids, 2nd ed. Oxford, pp. 230–254
156. Krischer, O.; Jaeschke, L.: Trocknungsverlauf in durchströmten Haufwerken. Chem. Ing. Tech. 33 (1961) 592–598
157. Kroell, K.: Trockner und Trocknungsverfahren, 2nd ed. Berlin, Heidelberg, New York: Springer 1959, pp. 238–253
158. Computer Centre of Lurgi, FRG

Final Remarks

159. Onoda, M.; Takenada, Y.; Kawaguchi, F.; Fujita, J.: Physical and metallurgical properties of crushed pellets. Trans. ISIJ, 18 (1978) 611–617

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