Studies in the Sintering Permeability and Pellet Strength of Australian Hematite Ores

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SINTERING of fine iron ores is achieved by causing a combustion zone to move progressively through a suitably prepared porous bed of the ore in which is incorporated a small quantity of a fuel such as finely crushed coke. The agglomeration of the ore particles takes place by their complete fusion and/or the formation of a partial slag bond between them. In general the faster the combustion zone passes through the bed the faster will be the sintering rate.

It has been shown that the passage of the combustion zone through a sinter bed is essentially a function of the rate at which air can be drawn through the bed (Davies and Mitchell, 1957), so that a sound understanding of the sources of resistance within the bed is all important.

Much work has been done in the preparation of sinter feed to determine factors controlling the permeability prior to ignition. The basis for such an approach is that the permeability will certainly not increase on ignition. Permeability actually decreases immediately on ignition and remains at a lower level until towards the completion of sintering (Davies and Mitchell, Bogan and Urane, 1957). Again, for a given mix, an increase in sintering rate can be shown to follow an increase in preignition permeability (Grice and Davies, 1955). This concept may be used as an important control when the sinter mix is standardised (Voice et al, 1955), but it is to be noted that a high preignition permeability does not necessarily mean a high sintering rate. The permeability to gas flow must be maintained "after drying, as well as in the state of softening and at the beginning of melting" (Wendeborn, 1955). It is this permeability of the bed *after* ignition which is all important.

The basic knowledge required for faster sintering is a knowledge of factors affecting bed permeability during sintering i.e. the sources of resistance to gas flow within the bed.

An improved gas permeability of the ore in the pasty and molten state within the sintering zone accounted for a twofold increase in sintering rate when 5% calcined lime was added to a siliceous ore (Wendeborn, 1955). The improved sintering rates obtained by addition of lime to Sierra Leone concentrates were found (Gledhill et al, 1955) to be due principally to the reduction in air required to complete sintering and, to a minor extent, to improved permeability. Again, from studies with pressure probes inserted in the bed, it was concluded that the wet unsintered charge ahead of the drying front is the controlling factor in faster sintering (Grice and Davies, 1955 ; Davies and Mitchell, 1957). Whilst these workers have tried different ores and techniques, no real comparison has been made between the major zones within the bed with respect to resistance to gas flow, viz. the wet zone, dry zone, actual combustion zone and the sintered zones respectively.

Studies of the sintering process are being carried out at the Central Research Laboratories of The Broken Hill Proprietary Company Limited in association with the use of high grade, fine hematite ores in Australian steel plants.

During preliminary trials on the "balling" of hematite ores, and the same ores plus additives, very significant differences were noted in the dry ball strength which were not apparent in the green state.

The following work was carried out to establish the major sources of resistance in sinter beds containing high grade hematite ores and attempts were made to relate the information obtained to the "balling" characteristics of different ore mixes.

Ores from two sources, designated Yampi and Whyalla, were used in these studies. Yampi ore is a fine grained hematite ore containing a kaolinitic gangue with a little free quartz and is obtained from the Cockatoo Island deposits of Yampi Sound, Western Australia. Whyalla ore is a lump manganiferous hematite obtained from the Iron Monarch deposits of South Australia. Typical chemical and sizing analyses of the $-\frac{1}{4}$ in. fractions used in sintering are given in Tables I(*a*) and I(*b*).

While this work was done for a specific purpose it throws light on the mechanism of sintering of high grade hematites and is felt to be of significance in the general study of sintering.

Experimental procedure for permeability studies

The sources of resistance in sinter beds were determined by measuring suctions at a number of levels within the beds. The greater the pressure drop between pressure probes the greater will be the resistance of the bed to flow of gases between these points.

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TABLE I

Chemical Composition and Size Analysis

(*a*) Chemical Composition of Ores and Additives

	% Fe	Mn	SiO_2	Al_2O_3	TiO_2	P	S	CaO	MgO	% H_2O + 110°C
Yampi Ore	61·1	0·01	5·6	4·05	0·27	0·01	0·02	0·01	0·01	2·15
Iron Monarch Ore	59·7	1·86	4·4	3·40	0·37	0·06	0·05	—	—	—
Flue Dust	45·9	1·33	6·6	4·10	0·40	—	—	3·4	Total carbon 19·4%	

Coke: 23% Ash, 75% F.C.
Water Glass: 1·54 S.G. 23% Na_2O
Bentonite: Wyoming—(Montmorillonite Type)

(*b*) Sieve Analyses of Sinter Ingredients

Cumulative % B. S. S.	−22	−30	−44	−60	−72	−100	−150	−200
Yampi Ore	88·3	86·5	84·1	80·3	77·8	69·2	56·8	33·9
Iron Monarch Ore	33·2	28·2	33·9	20·0	18·4	14·8	12·0	8·0
Flue Dust	96·4	91·2	82·2	79·5	62·9	43·9	31·0	16·3
Coke	41·5	30·0	22·2	16·2	14·1	9·7	7·2	—

Sinter Returns: 100%−¼in.

By carrying out pressure surveys before, during and after sintering, and after removal of sinter cake, a comprehensive picture can be obtained of where major resistance to flow occurs during sintering.

To carry out this pressure survey a pot was designed consisting of four sections, each section containing a mica observation port and pressure point (Fig. 1A). The mica ports allow the passage of the drying and flame fronts to be observed, so enabling the sintering to be stopped at the desired level. A wire mesh grid supported the charge in each section.

The procedure adopted to obtain a general picture of the variation in resistance or suction between

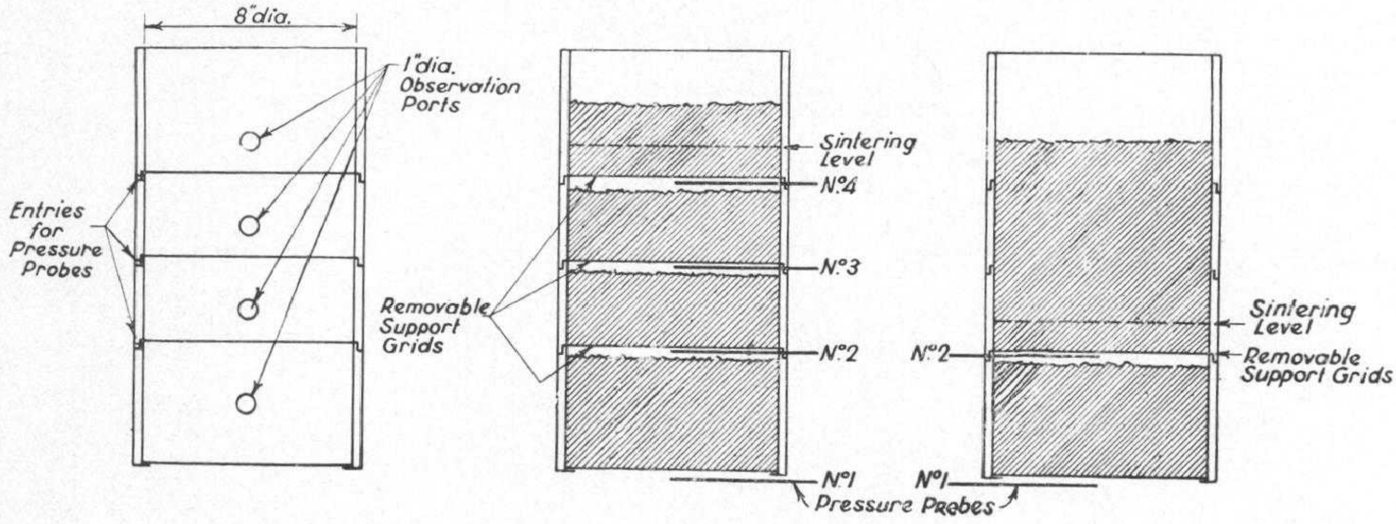


Fig. 1.

(A) Section of Pot.
(B) Distribution of charge and pressure probes when sintering to top port.
(C) Distribution of charge and pressure probes when sintering to lower port.

various levels in a twelve-inch sinter bed was to charge the sections of the pot as uniformly as possible by hand, and sinter each mix to:

(*a*) the top port (1½″ sintered approximately)

(*b*) the second lowest port (6½″ sintered approximately).

Suctions at the different levels within the bed were measured prior to ignition, during sintering, after cessation of sintering (and cooling) and after removal of the sinter cake whilst a suction of 30″ W.G. was maintained below the bed. Figs. 1B and 1C show the distribution of the charge and the position of pressure probes when charges are to be sintered to different levels.

The particular positioning of pressure probes gives the actual suction existing at these points and eliminates complications introduced by placing probes within the mix. The choice of sintering level aims at ensuring that the sintered and unsintered dry charge lies above and the unsintered wet charge lies below the upper pressure probe.

Suctions at the different levels, prior to ignition, during sintering and after cooling for four different mixes were determined. The basic mix consisted of 40 per cent ore or ore plus additives, 52 per cent of—¼″ return sinter and 8 per cent of—1/8″ coke.

The ore or ore plus additive component for the respective mixes were Yampi ore Yampi plus 3 per cent bentonite and Yampi plus 3·7 per cent slaked lime. Details of composition and sieve analyses for the components are given in Table I. Moisture in all cases was controlled between 5 and 5·5 per cent of the total mix, care being taken not to overwet the mix.

Discussion of results

The change in suctions at different levels followed the same general pattern for all mixes. Immediately on ignition gas flows through the sinter beds decreased whilst suctions at the different levels in the bed below the sintering zone increased and soon became relatively stable (±¼″ S.W.G.): these suctions are those used in determining the change in pressure ($\triangle$p) between the different pressure pobes during sintering. After cessation of sintering and cooling, suctions decreased below those existing during sintering whilst after removal of the sinter cake the greatest change in pressure or highest resistance to gas flow occurred within the region of the dry unsintered material.

The largest change in suctions occurred when sintering the Yampi ore mix and the smallest when sintering the Yampi ore plus bentonite mixes. These limiting cases have been chosen to illustrate the results obtained.

During the sintering of the different mixes to either the upper or lower levels, the greatest rate of change of $\triangle$p with depth (i.e. lowest permeability) occurred for all mixes over a region encompassing the freshly sintered material, the combustion or sintering zone and the drying zone. The addition of Wyoming bentonite to Yampi ore mix decreased the $\triangle$p, i.e., increased premeability, over this region (Figs. 2A and 2B). Since the resistance to air flow of the sinter proper is low compared with that of the granular mix, the region of major resistance to air flow must occur in the combustion or sintering zone and the drying zone.

After cooling, the rate of change of $\triangle$p with depth was again greatest over the above region for all mixes except that containing bentonite sintered to the lower port (Fig. 2B). Here the effects of high temperatures on gases and slags have been removed and the region of highest resistance to gas flow may

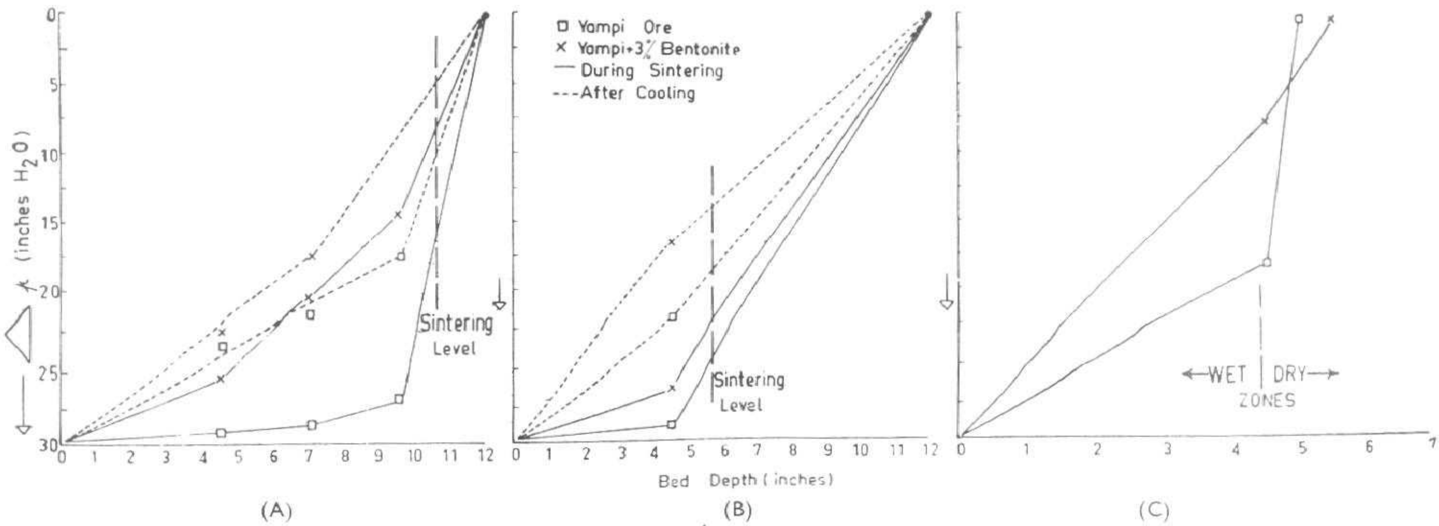


Fig. 2. Showing $\triangle$p Vs - depth of bed.

(A) During sintering to top port and after cooling.

(B) During sintering to lower port and after cooling.

(C) After sintering to lower port and removing sinter cake.

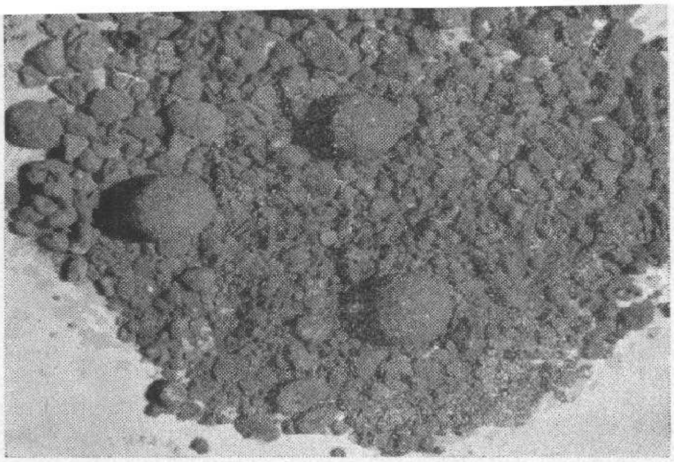
be described as containing the original combustion or sintering zone and the drying zone. For the bentonite mix it could be said that the temperature effect is the major factor in decreasing the permeability of this region to below that of the wet lower layers during sintering. The effect of temperature on suctions within the bed will be dependent both on the flow of the gas and the temperature of the gas within the combustion zone. It is to be expected that with lower combustion zone temperatures, as in self-fluxing limestone bearing mixes, this effect on bed resistance will be lower.

On removal of the sinter cake it was found that the advance of the flame front was not uniform across the bed and, despite the use of observation ports, sintering could not be halted at exactly the same point for each mix. Bed depths plotted in Fig. 2C show the most advanced position of sintered material, i.e., the minimum depth of dry feed above the pressure probe. In all cases the highest rate of change of $\triangle p$ with depth occurs over the dry zone just ahead of the true sintering zone. The pressure differential across this zone is sufficient to suggest that the greatest resistance to flow during the sintering of Yampi ores, without additions or excessive moisture, occurs in the dry (or perhaps better "rapidly drying") zone immediately ahead of the flame front. The rate of change of $\triangle p$ with depth is not so marked for the mix containing bentonite indicating that the addition of bentonite is most effective in reducing the resistance of this rapidly drying zone.

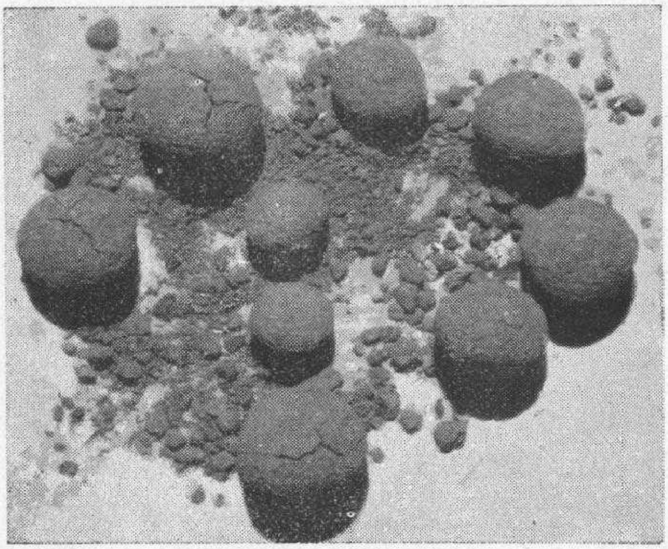
A hypothesis suggested by these conclusions is that on drying and heating, prior to being consumed by the sintering zone, the bond between ore particles and between ore particles and sinter returns, etc. is lost or decreased, freeing fines to clog the bed. This bond is of different strength for different mixes and accounts for the differing sintering characteristics. Any addition which will increase or maintain this bond during heating will reduce the amount of fines freed to clog the bed, and so decrease the resistance of the "rapidly drying zone", thus maintaining good permeability during sintering and so result in faster sintering.

To test this hypothesis qualitatively, a number of balls made from ore, ore plus lime and ore plus bentonite were placed in gauze holders below the sinter pot and exposed to the exhaust gases. The balls thus received a drying treatment approaching that of actual sintering. Fig. 3 shows the results obtained. The balls made from Yampi ore collapsed to a much greater degree than those containing lime and bentonite. Of the last two, cracking was more obvious with the lime bearing mix. In the case of Yampi mixes without additives the collapse of the pellets would enable ore particles to be sucked into the fine air passages in the rapidly drying mix.

To obtain a clearer picture of the breakdown into fines a small (2") diameter pot was designed which could be split to allow examination of the charge



(A) Balls of Yampi ore.



(B) Balls of Yampi ore plus 3·7% $Ca(CH)_2$.

(C) Balls of Yampi ore plus 2·0% bentonite.

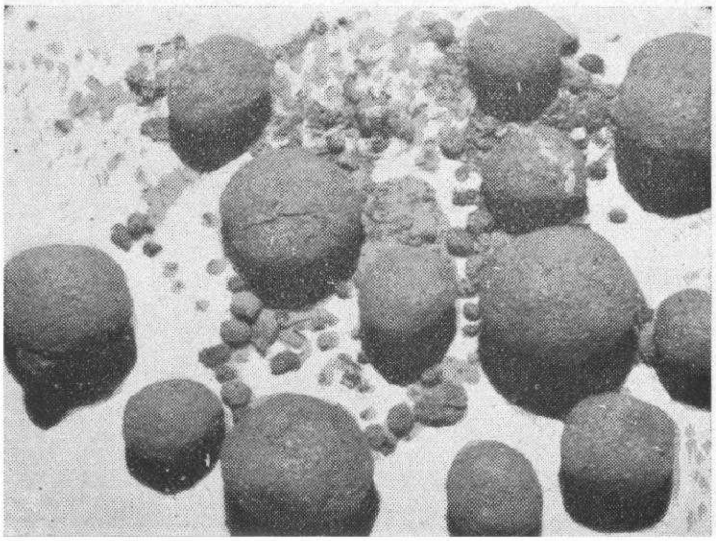
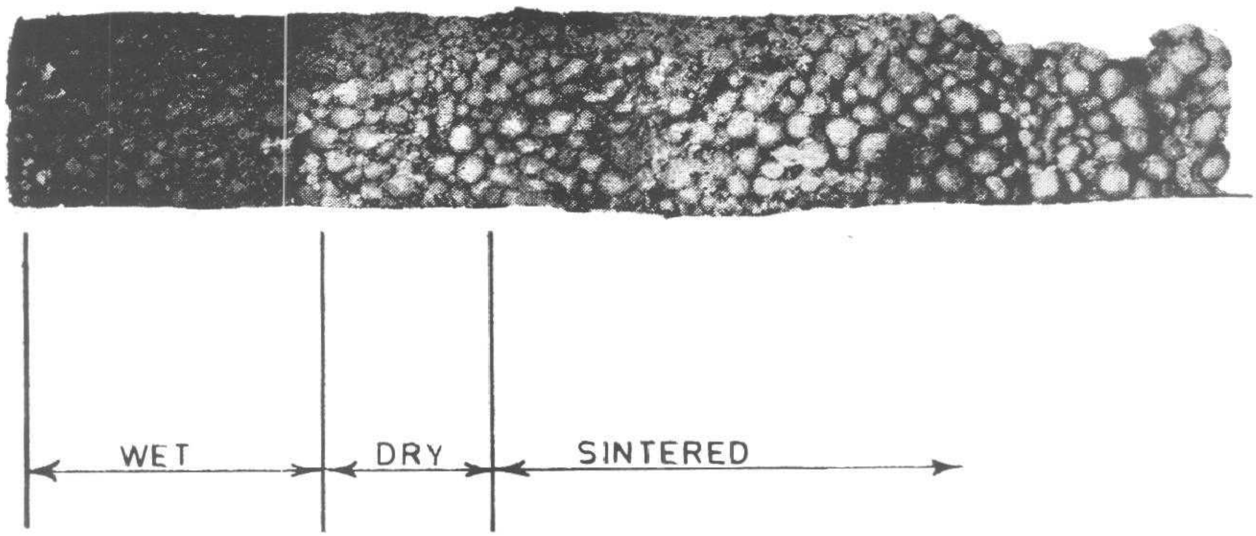


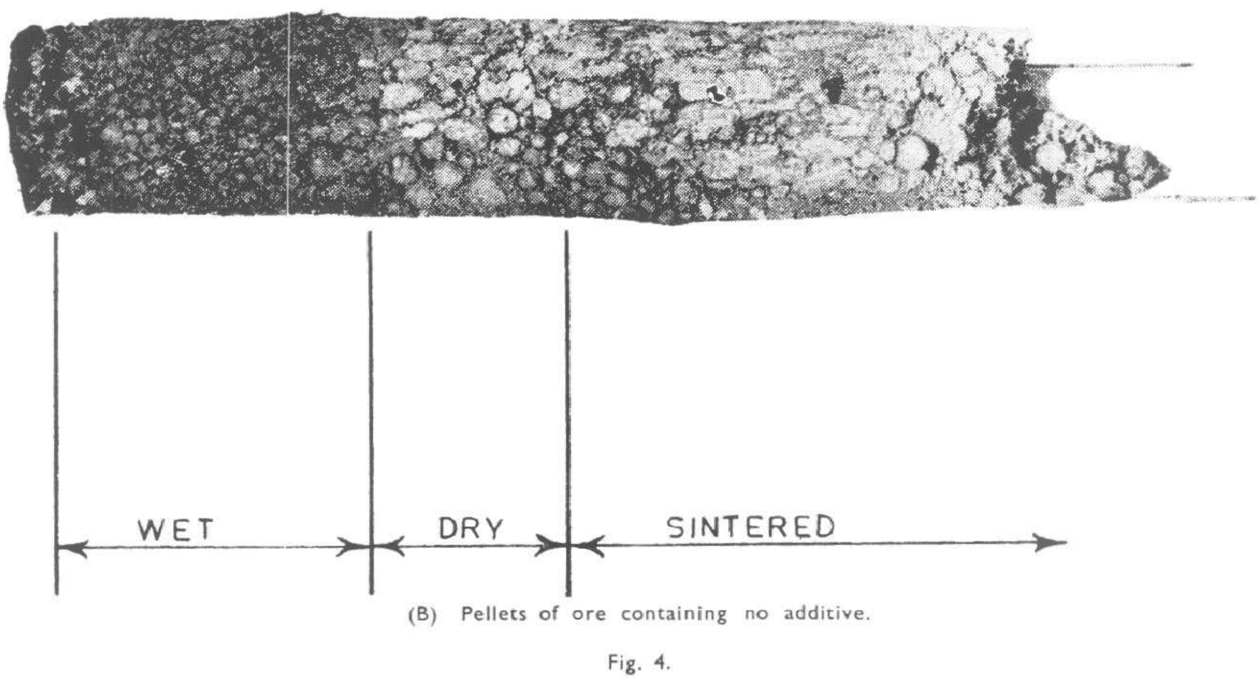
Fig. 3. Effect of exposure to hot exhaust gases.

after partial sintering. Fig. 4 shows the result obtained after partially sintering $\frac{1}{4}''$ diameter pellets of Yampi ore containing a 2 per cent bentonite addition and pellets containing no additions. Sintering in both cases was poor. However, the main purpose of the tests was to show the effect of the advancing flame front on the charge and in the case of pellets containing bentonite, little breakdown is evident whilst for the case of pellets containing no additions extensive breakdown and clogging of bed is evident in the dry and sintered zones. The poor sintering of the latter charge is fortuitous in that it clearly shows fines above the flame front. With complete sintering these would have been absorbed into the sinter.

The most important points illustrated by these tests are the breakdown of the pellets into fines and the fact that the fines are not necessarily sucked right through the bed by the gas stream (Fig. 4). This gives an explanation of why the flame front



(A) Pellets of ore containing 2% bentonite.



(B) Pellets of ore containing no additive.

Fig. 4.
Appearance of the sinter bed after partial sintering.

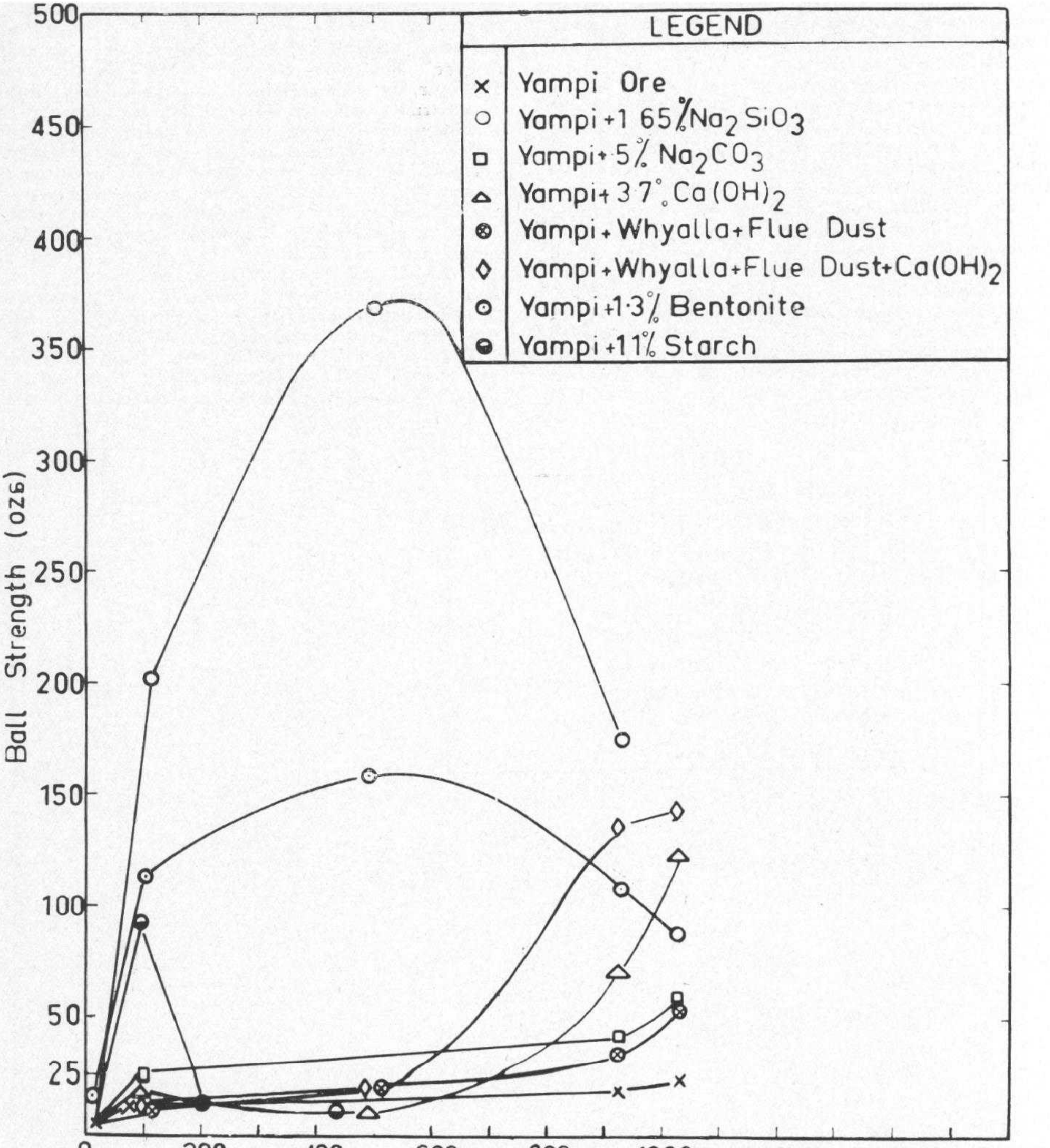


Fig. 5.
Effect of temperature on the strength of balls containing various additives.

speed remains relatively constant, after an initial decrease during ignition, until towards the end of sintering. The initial breakdown, plus temperature effects, slow down the gas velocity to such an extent that the fines are not necessarily carried down by the gas stream but remain *in situ* until "incorporated" in the sinter itself. Such an explanation cannot be given for the moisture hypothesis (Davies and Mitchell, 1957) (Grice and Davies, 1955). Here one would expect the flame front speed to decrease gradually until the effect of moisture condensing in the lower layer reached a limiting point.

To summarise, a method has been developed which allows comparison of various zones in sinter beds as sources of resistance. By its use an hypothesis has been suggested and qualitatively tested which states that the limiting factor in the faster sintering of fine Yampi ore, not excessively wetted, is the ability of the ore particles to bond to each other and to returns and the stability of this bond on heating prior to sintering.

Balling characteristics of different ore mixes

During preliminary experiments into the pelletising or balling characteristics of fine ores it was found that the dry compressive strengths of balls differed significantly with different Australian hematite ores. If compressive strength is a measure of the bond which exists between the ore particles and between ore particles and sinter returns (prior to being consumed by the flame front) then it would appear that the behaviour of ores in the dry zone during sintering could be predicted by a suitable strength test on the individual dried balls.

Further, since the coherence between ore particles and particles and returns seems to bear on the source of resistance to gas flow in a sinter bed, a relation could exist between ball strength and sintering rates.

To explore this possibility a series of experiments was carried out to determine the ball strengths and sintering rates for different ore mixes.

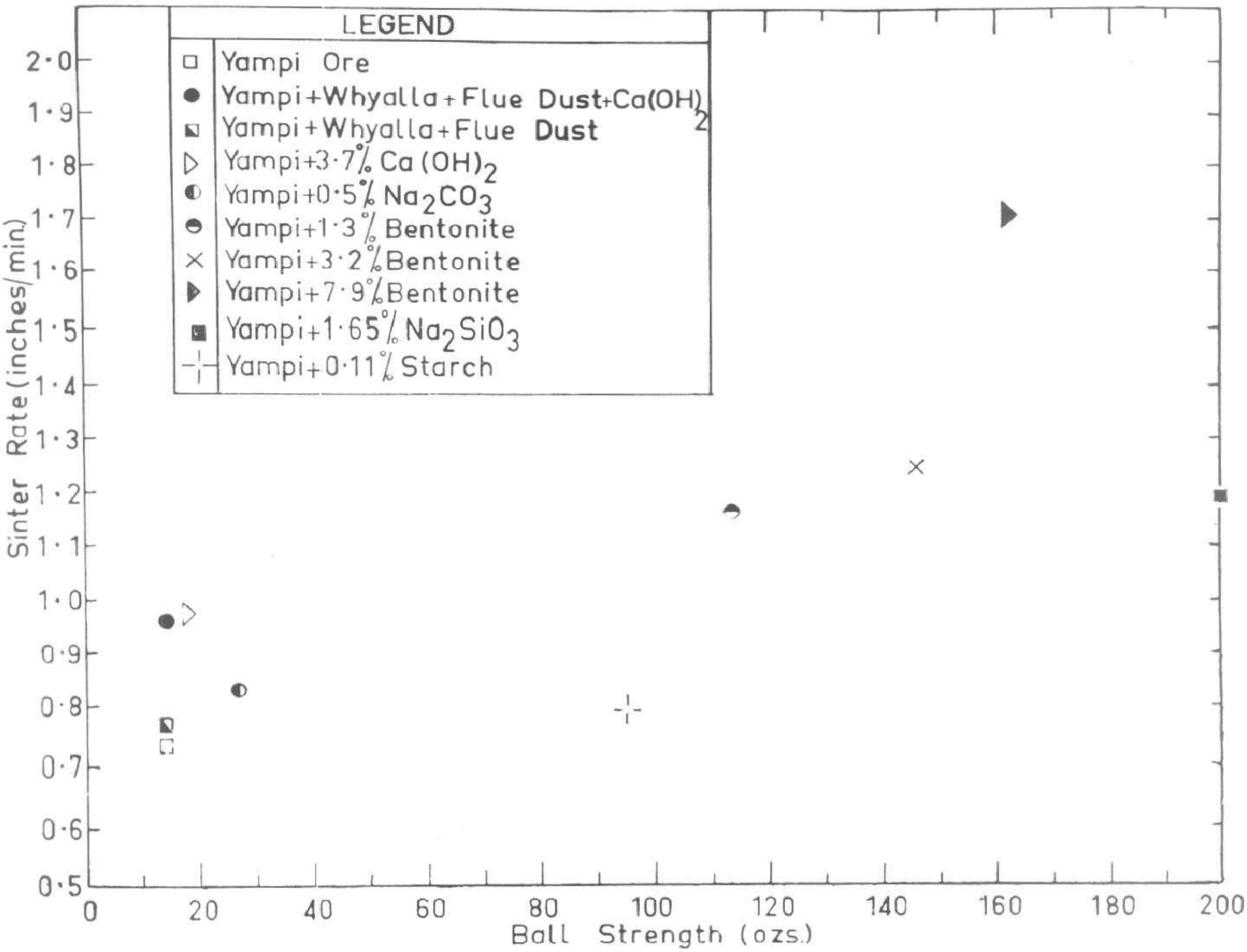


Fig. 6.

Ball strength (dried in air) plotted against sintering rate.

Experimental procedure for balling studies

Balling was carried out by alternatively feeding the ore mix and water (as a fine spray) into an 8″ diameter drum rotating at 44/48 rpm. The compressive strengths were measured by means of a B.C.I.R.A. type sand tester.

Slightly different techniques were necessary to produce the required balls from different mixes. Lime bearing mixes tended to form into very large balls whilst those containing the high percentages of bentonite were irregular in shape and adhered to the sides of the drum. In all cases the fineness of the spray and the amount of water added were important in producing the desired balls. In addition, all over large lumps were removed from the ore by passing through a No. 9 mesh screen.

Balls were produced from Yampi ore, and ore plus one or more of the following additives: 13 per cent Whyalla ore, 5 per cent flue dust, bentonite, starch, line, sodium carbonate and sodium silicate. Ball strengths were determined for ten to twenty balls varying from 0·36″ to 0·39″ in diameter.

To obtain a broad picture of what may happen to their strength during sintering, balls were tested after drying in air at 110°C after drying in carbon dioxide at approximately 110°C and after drying in air and holding at 500°C, 940°C and 1,040°C for twenty minutes. Results obtained are graphed in Fig. 5.

Certain additives increased sintering rates (in inches per minute) by as much as 134 per cent (Fig. 6).

In the percentages tried water glass and bentonite were by far the most effective in increasing sintering rates. Here it must be noted that moisture content was controlled and need not be the optimum amount for a particular mix.

Plots of sintering rates against ball strengths, after drying at 110°C in air are given in Fig. 6. It appears that in general the higher the ball strength, the faster the sintering rate. The effect of temperature on ball strengths (Fig. 5) provides a possible explanation of the apparently anomalous result obtained for the mix containing starch; this mixture loses its bond strength around 200°C.

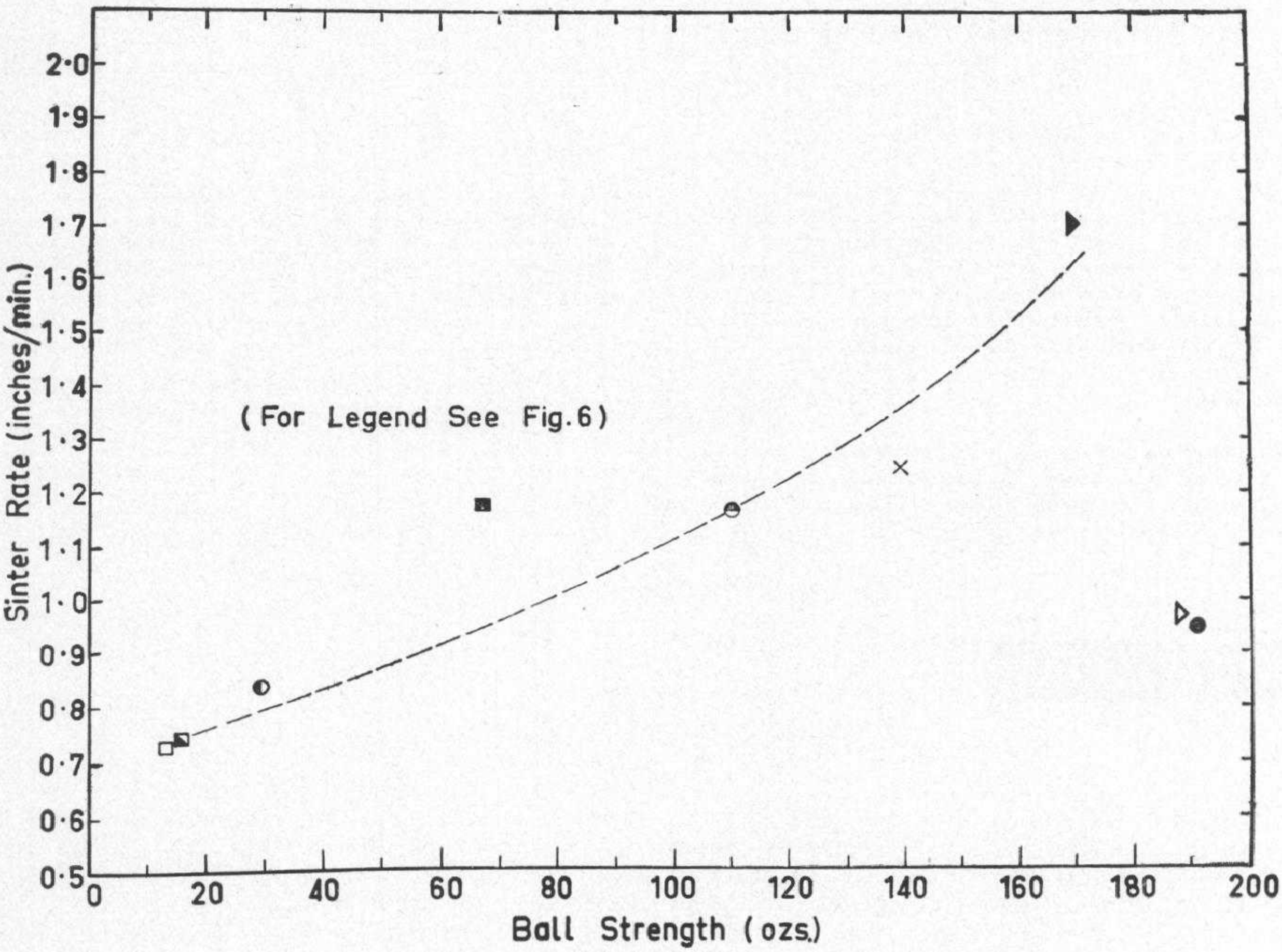


Fig. 7.
Showing ball strength (dried in CO_2) plotted against sintering rate.

Dry strengths under an atmosphere of CO_2 (which is normally present in waste gases during sintering) may provide an explanation of the action of lime and sodium silicate during sintering. When dried under a 100 per cent CO_2 atmosphere the ball strength of lime bearing mixes is much higher and of mixes containing sodium silicate much lower than if dried in air. It would appear that lime picks up CO_2 and consolidates the outer layers by the formation of the carbonate on drying, as in mortar, whilst for the water glass, a weaker bond results.

Plots of ball strength dried at 110°C under a 100 per cent CO_2 atmosphere against sintering rates in inches per minute are shown in Fig. 7. Here balls containing sodium silicate have a lower strength than those containing $Ca(OH)_2$; this is the reverse to that when dried in air (Fig. 6). With an atmosphere more closely approximating that of sintering waste gases it would be reasonable to expect that the increase in strength of lime bearing balls and the decrease in strength of silicate bearing balls would not be so great and a reasonably good relationship could be obtained between ball strengths and sintering rates.

The hypothesis suggested by the pressure survey work "that on drying and heating prior to being consumed by the flame front the bond between ore particles and returns, etc. is lost or decreased and frees fines to clog the bed", is not explained by dry compressive strengths alone.

In all cases strengths increased on drying (Fig 5). Why fines should be freed from the dry material and not from the wet is probably due to the elimination of surface tension forces. However, it is possible that some other factor may be involved, such as lack of resistance of the bond to thermal shock by the advancing flame or heat front.

Conclusions

A method has been evolved which allows comparison of various zones in the sinter bed as sources of resistance. The application of this method has shown the rapidly drying zone in front of the sintering zone to offer the major resistance to gas flow during the sintering of Yampi ore not containing additives of excessive moisture. The permeability of this zone is a limiting factor in the sintering rate.

It is suggested that the dry bond strength between sinter feed particles determines the degree by which fines are liberated to clog the bed, it being necessary that this bond be stable when exposed to hot exhaust gases during sintering.

Addition of slaked lime, water glass and Wyoming bentonite increases the sintering rates of Yampi ore by marked degrees and it is claimed that the increase is primarily due to an increased bond between feed particles in the rapidly drying zone preceding the sintering zone.

Attempts to relate sintering rates with ball strengths show considerable promise. It is expected that with a thorough testing technique more representative of conditions within the sinter bed a stronger relationship will be shown.

Acknowledgements

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DISCUSSIONS

Mr. T. Krishnappa, Mysore Iron and Steel Works: I was much interested by Mr. Callender's paper studying the zones of major resistance to gas flow during the sintering of fine high grade Australian hematite ore. I would further like to know if any experiments have been conducted to replace the returned fines with mill scale and whether the same can be done to reduce the resistance in the zone ahead of flame. Was any attempt made to study the effect of moisture in reducing the resistance in the zone ahead of flame?

Mr. A. E. Rogers, The Broken Hill Pty. Co., Australia: We have so far carried out no experiments using mill scale but it may be very well worthwhile trying it on the sinter bed. Quite a few experiments were made on moisture content with relation to permeability and the results now published are those which gave us optimum moisture content. We found that decreasing moisture leads to greater dust collection through the windboxes and with increased moisture we have got to increase coke in order to dry it out, so that basically, the moisture content referred to in the paper represents the best operating conditions for our particular ores. You will realise of course that the control of moisture in a sinter plant is of prime importance and cannot be overlooked without affecting the whole process. We have two sinter machines in operation, one at Port Kembla and one at Newcastle, and it has been our experience that a lack of strict control on moisture causes deleterious effects on the sintering process.

Mr. G. V. S. Iyer, N. M. L.: We have been interested in our laboratory on the problems of sintering and I am glad to hear that some interesting studies were made at the B.H.P. Laboratories on the determination of permeability and its effect on sintering.

It has been stated by the author that the use of reagents like sodium silicate and bentonite, helps in decreasing the sintering time. This may be probably due to the excessive fines contained in Yampi ores. The sieve analysis indicates that about 34 per cent is finer than 200 mesh and about 57 per cent finer than 150 mesh. Without these reagents fines will clog the pores and decrease permeability. Addition of the reagents mentioned above does of course automatically ball up the fine material and give the required permeability and the process might be very efficient in sintering fine ores such as Yampi ores. On the other hand, the iron ore we tested here for the Bhilai Steel Plant for its sintering characteristics contained say little of 150 mesh material (about 2 to 3 per cent). I wonder if the addition of such reagents will be of much help in such cases because there is not much of fines to clog the pores and decrease permeability of the bed during sintering. I would be interested to know if this excess of fines has led to any work on the up-draught sintering in which case the fines may not clog so much as in the case of down-draught sintering. This practice is particularly suited to and applied in sulphide ore sintering.

Mr. A. E. Rogers: A number of aspects have been covered by the speaker and regarding the question of fines he has raised, I may say that in our particular process we coat a return fine particle by means of a layer of Yampi or other ores and the conclusion we came to was that as we increased the percentage of return fines, so we, in fact, reduced the thickness of the layer of fine ore on the return fines particle and, therefore, as far as we are concerned, it seems quite clear that if we attempt to ball or pelletise in what can be termed our mixing drums, then in fact it does tend to lead to a decrease in output and not to an increase. This we thought was quite a significant point. We, however, had certain ideas on additives, and whether we could in fact pelletise as compared with the coating of return fines which is the basis of our process now and that was why we tried various additions for pelletising purpose. There is no difficulty in pelletising our ores ; we can make the pellets as large as we need but when we do this we cannot sinter them, because, as was shown in the graphs, they break up under temperature conditions, and that, we feel, is the basis of this high percentage of return fines which we propose to use. Using various additives we got the best results from bentonite and sodium silicate, etc., as was mentioned in the paper, but the cost of bentonite is such that it is impossible to use it and other materials did not show the same promise with respect to increasing the percentage of fines.

Referring to the up-draught sintering machine, there are many in operation as you know, mainly on non-ferrous products. Maintenance is very high on a ferrous sintering machine and it seems more economical to build a down-draught machine taking into account this maintenance question. Also the amount of dust being collected in the windboxes is considerable and our investigations at the time clearly indicated that the down-draught machine was most suited for our purpose.

Mr. W. Callender (Author): The limiting factors in determining the sintering rate of an ore are the physical and chemical properties of the ore and this will remain so if the possibility of altering these properties is not considered. The general approach to sintering is that, given an ore, plant and/or practice is designed to obtain an optimum sinter mix, i.e. one which will give the fastest sintering rates consistent with some quality criterion. This involves varying the proportion of returns, fuel, moisture, etc. and the methods of mixing and preparing these components until what is considered the optimum mix is obtained. All these factors play important parts in the efficiency of the sintering operation. However, to my mind it is not axiomatic that a plant which has found these optimum operating conditions has reached the limits of its production rate. It is shown in the report that relatively small additions of bentonite, etc., increase sintering rates remarkably and if additional production is required without the installation of new plant an investigation along the lines of the roport would be well worthwhile. Any such additive however would have to be considered in the light of costs and subsequent behaviour in the blast furnace.