

April 5, 1966

R. J. LINNEY

3,244,507

METHOD OF INDURATING ORE PARTICLES

Filed June 10, 1964

6 Sheets-Sheet 1

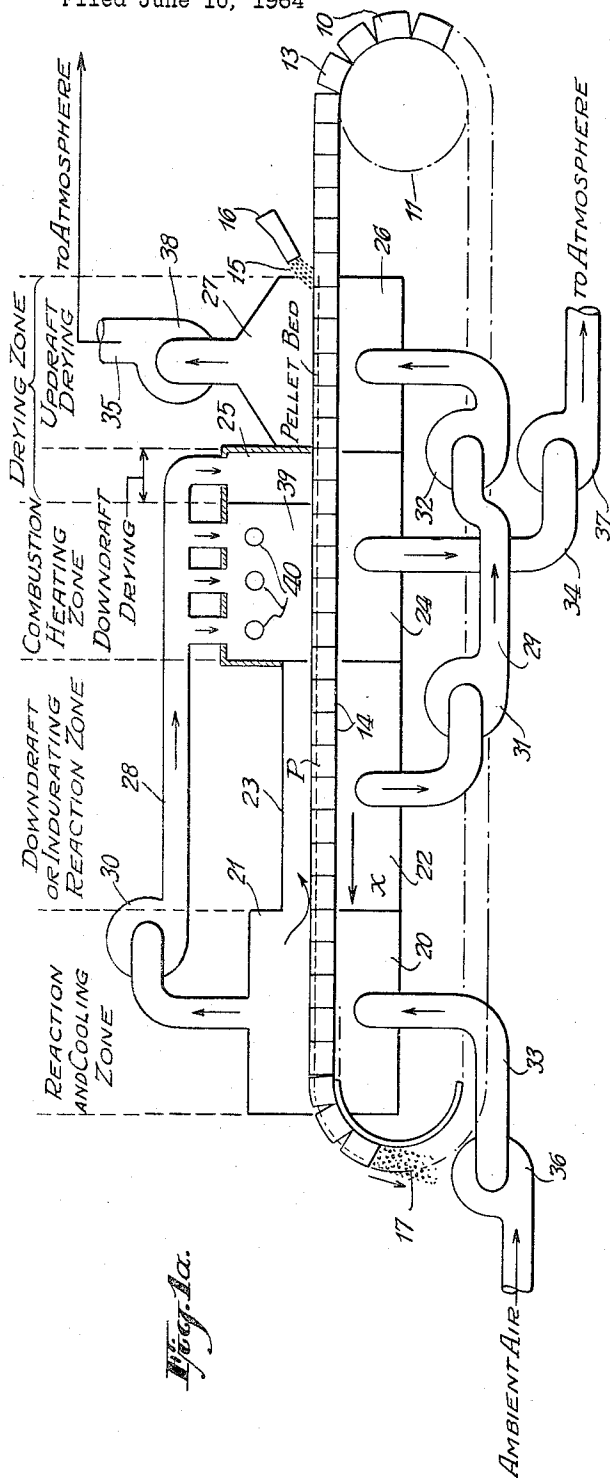


Fig. 1a.

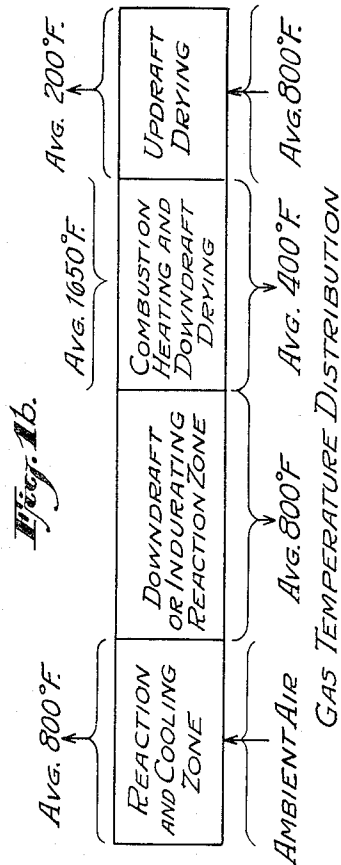


Fig. 1b.

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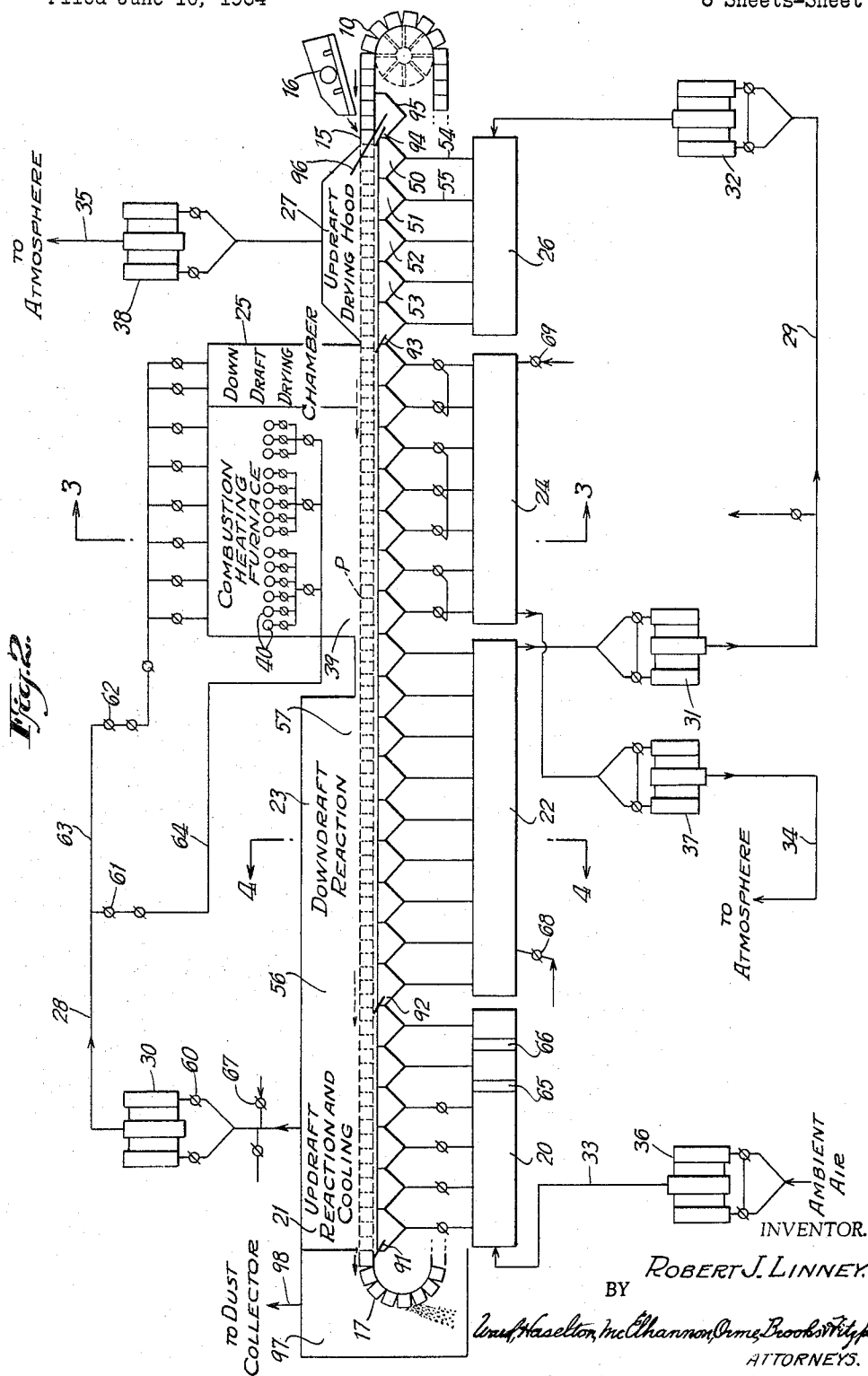
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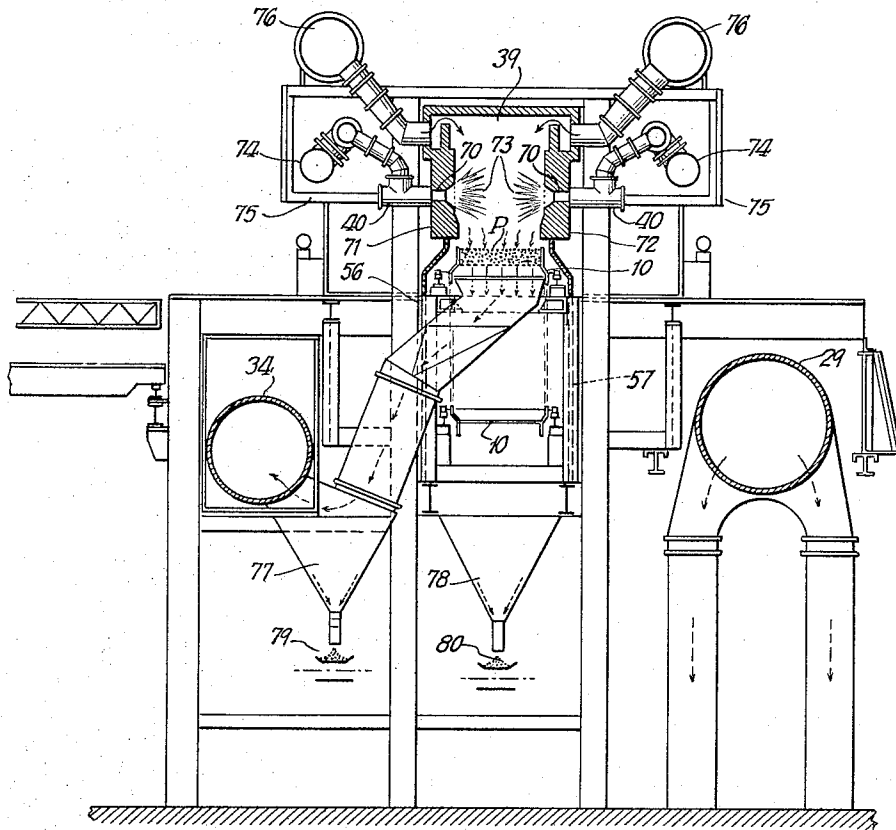
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Fig. 3.



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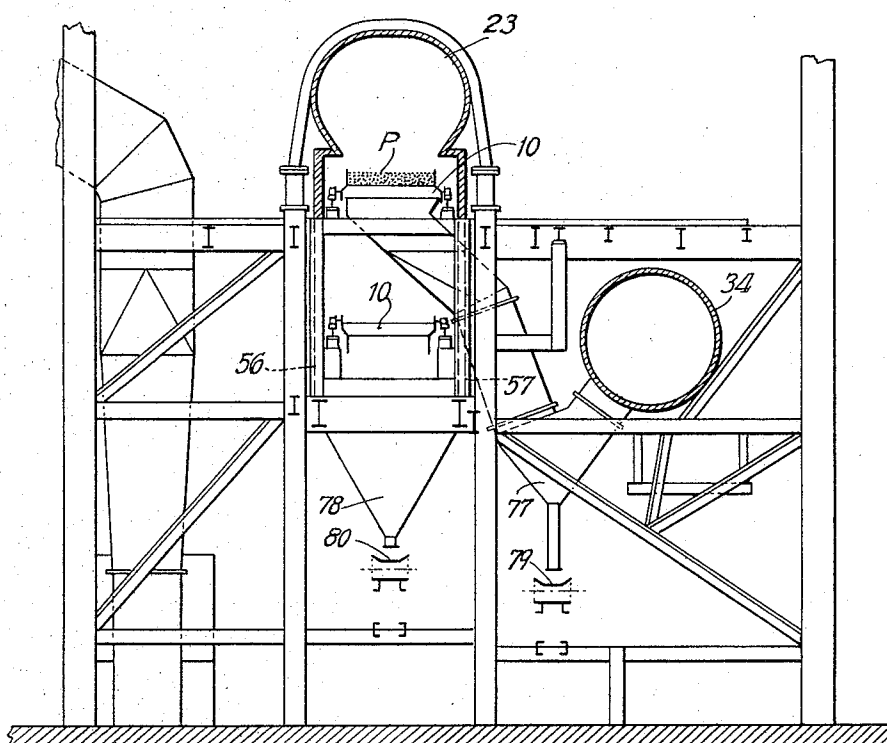
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Fig. 4.



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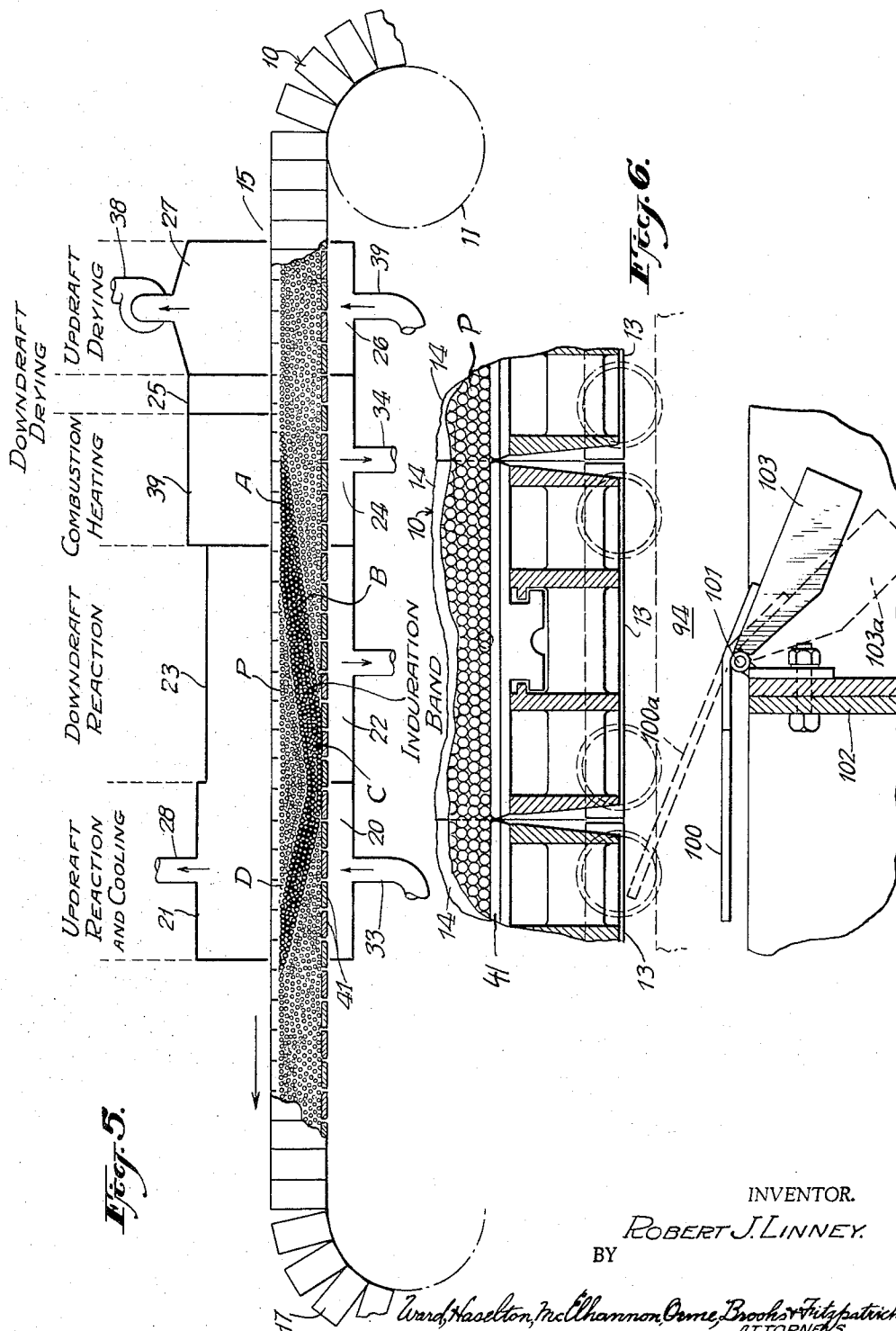
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Fig. 7.

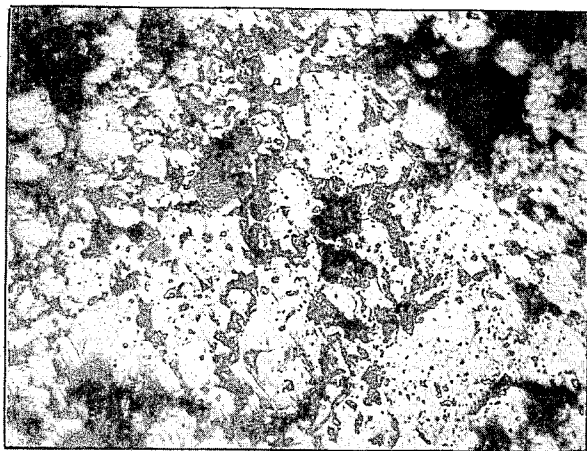
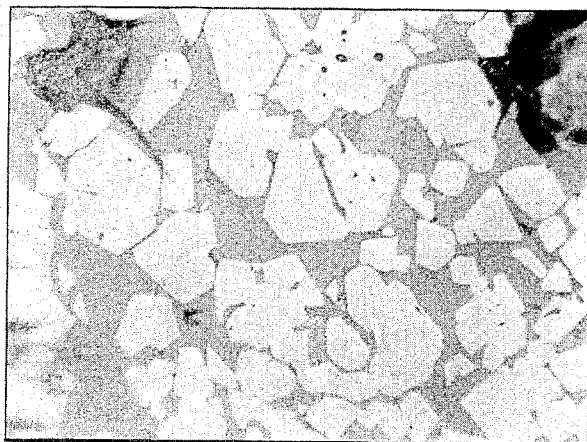


Fig. 8.



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3,244,507

METHOD OF INDURATING ORE PARTICLES
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Filed June 10, 1964, Ser. No. 374,119

9 Claims. (Cl. 75—3)

This application is a continuation-in-part of my copending application Serial No. 154,308, filed November 22, 1961 (now abandoned), and also of my copending application Serial No. 849,811, filed October 30, 1959 (now abandoned), and which is in turn a continuation-in-part of my application Serial No. 682,826, filed September 9, 1957 (now abandoned).

This invention pertains to methods and apparatus for agglomerating finely comminuted ores and ore concentrates into pelletized form and for indurating the pellets by heat treatment for imparting thereto high hardness, strength, and resistance to fragmentation in handling or shipping.

As a convenient example, the present invention is exemplified with respect to pelletizing concentrates of taconite ores. However, it is not limited thereto but is applicable to the agglomeration of all types of finely comminuted ores and ore concentrates into pelletized form.

The invention finds particular application in the agglomeration and indurated pelletization of oxidic iron ores and concentrates and, more especially to pulverulent concentrates of the taconite ores, containing the magnetic oxide, Fe_3O_4 , which undergoes during the indurating heat treatment of the invention, an exothermic oxidation to the non-magnetic or hematitic oxide, Fe_2O_3 , with resultant recrystallization and grain growth between discrete particles within each pellet which firmly bonds them together into an integrated pelletized structure of extremely high strength, hardness and correspondingly high resistance to fragmentation when subjected to the pressures and shock impacts incurred during loading, shipping, unloading or otherwise conveying or handling.

The taconites, being low grade iron ores, cannot economically be reduced as such in the blast furnace and hence must be beneficiated by crushing, grinding and magnetic separation techniques until a finely comminuted concentrate of for example 60–65% iron content is obtained. This powdery product is, however, unsuitable for treatment in blast furnaces, open hearth furnaces and the like, and hence must be agglomerated into aggregates or lumps of suitable size and of sufficient strength for such applications. Various procedures to this end have heretofore been proposed such as briquetting, sintering, pelletizing, etc. Briquetting techniques are, however, expensive as to equipment and power requirements, and the briquetted product is at best quite frangible. Also certain ore and concentrate fines cannot be effectively briquetted without the use of binders in character and amount objectionable in subsequent reduction. Sintering is objectionable on various grounds, such as excessive fuel consumption in processing and excessive bulk of the product.

Pelletization as heretofore proposed or practiced has likewise proved objectionable in various respects. Shaft kilns have been employed for this purpose, but owing to the excessive depth and volume of the pellet bed, are difficult to control as to uniformity of feeding and temperature of heating of the pellets, with resultant formation of sintered pellet aggregates, obstructive of gas flow and productive of overburned aggregates. Also the green pellets entering the kilns tend to be crushed and slurried by the pressures encountered and moisture condensation from the kiln gases.

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Travelling grate processes for pellet induration have likewise been proposed but none prior to my invention has proved commercially successful insofar as I am aware, this by reason of defects inherent therein. It has heretofore been proposed to indurate a bed of "green" pellets fed through an ignition zone on a travelling grate conveyor, by direct flame impingement upon the pellet bed and penetration thereof by flames from fuel-fired burners disposed above the bed. I have found this to be highly objectionable, for one reason because direct flame impingement on the bed causes the top layer of pellets to be fused together into a mass which is objectionable for this reason, and also for the further reason that this fused mass has poor porosity and thus retards the flow of gas through the bed and thereby likewise prevents proper induration of the pellets at the lower bed levels.

As applied particularly to induration of pellets agglomerated from taconite ore concentrates, direct flame impingement on the pellet bed is further objectionable for reasons as follows. My investigations have established that the strongest and finest quality iron ore pellets derived from taconite concentrates, are produced when the temperature and oxidation conditions are such that the magnetite grains are oxidized to hematite and sufficient grain growth occurs after this oxidation and recrystallization to form an almost complete network of interconnecting hematite grains, as illustrated in the accompanying drawings as discussed below. The total strength of the pellet is related to the bridging of the hematite particles as the result of the recrystallization and grain growth process. This ideal pellet structure is obtained by controlling the actual temperature of pellet induration at about 2300 to 2350° F. and below 2400° F.

In contrast to this, the temperature of oxidizing flames from combustion of normal commercial fuels, i.e., gas, oils or pulverized coals, is about 2700 to 3000° F. Direct impingement of such a flame on a bed of pellets heats some of the pellets to so high a temperature that oxidation of the magnetite to hematite does not occur and the slag formation is so extensive that the grains of magnetite are embedded in a brittle slag matrix, also illustrated in the accompanying drawings as discussed below. The so-treated pellets by reason of their resultant brittleness are easily fragmented, and thus quite inferior to pellets indurated free from flame impingement.

Now in accordance with an important aspect of my invention, I provide a travelling grate process for progressively hardening a bed of moist green pellets of ore or ore concentrate fines, by subjecting the same after drying to a hardening heat treatment during no stage of which are the pellets subjected to direct flame impingement from fuel burners or other heating sources. In my process the pellets are hardened by forced flow of hot gases through the bed at a temperature such as to heat the pellets to temperature within the range of about 2300–2400° F. and below that productive of fusion or sintering.

A further basic objection to travelling grate type pelletizing systems as heretofore proposed, resides in the thermally inefficient manner in which they are arranged and operated with resultant excessively high fuel consumption. In such systems oxygen burned fuel, such as oil or gas, is burned throughout the length of zone required for preheating the pellet bed to indurating temperature and for maintaining the bed temperature thereat until induration or hardening of the pellets is completed, whereupon the hot pellet bed is immediately cooled to low temperature by a forced draft of air at atmospheric temperature. Although the combustion gases after passing through the bed in the induration zone are at a temperature of about 1000° F., they are nevertheless

immediately discharged to atmosphere as waste gases. This is due to the inept arrangement of compartments wherein waste gases and gases carrying sensible heat are exhausted into a common chamber, necessitating their discharge to atmosphere. Such operation is therefore exceedingly wasteful of fuel, since only a small fraction of the chemical heat values of the fuel is usefully employed in hardening the pellets.

In accordance with a further important aspect of my invention, I largely eliminate this defect by employing the heat from oxygen burned fuel only over a relatively short traverse of the pellet bed, just sufficient to preheat a two to three inch band of the bed to indurating temperature to initiate the hardening action therein, following which the bed is fed through a downdraft reaction zone wherein the induration band is caused to progress down through the bed by air preheated to about 800° F. as derived from a subsequent updraft reaction and cooling zone through which the pellet bed is fed and wherein induration is completed and the bed is cooled by a forced draft of ambient air which is thus preheated in passing through the hot pellet bed. In the induration of pellets composed of taconite ore concentrates the recuperative induration heating obtained in this way is of course supplemented by the exothermic heat resulting from oxidation of magnetite present in the ore particles to hematite as above explained.

I find that as a result of the heat conservation thus obtained in my process, that the fuel energy consumption is only about 450,000-500,000 B.t.u. per gross ton of pellets processed as compared to about 700,000-750,000 B.t.u. per gross ton of pellets processed in accordance with the prior art proposals above discussed. The saving on fuel consumption is accordingly about 33 percent with my process.

I have also found that as a result of first passing the pellets through a downdraft reaction zone and thence through an updraft zone there is, in effect, a double induration of the pellets and substantial improvements in pellet quality as compared to pellets processed in accordance with prior art proposals above discussed. For example, in tests of the product from my process as measured against the product from prior art proposals, I found that my product had: (a) a 3.6% higher porosity which resulted in a 6.8% faster deoxidation rate and a subsequent increase in production in a blast furnace; (b) an increase of 14.2% in crushing strength and 10.5% less -28-mesh fines after a standard tumbler test which indicates that my product is delivered to the blast furnace with a greater percentage of whole pellets and a lesser percentage of fine material, thereby allowing greater amounts of air, with less pressure drop, to flow through the charge in a blast furnace and hence increasing production; (c) a decrease of 48% in residual ferrous iron due to a more complete oxidation of the magnetite to hematite as a result of the secondary induration in the updraft reaction and cooling zone wherein the primary induration band which has progressed down to the grate in the downdraft reaction zone is caused to reverse direction by the updraft of ambient air in the updraft reaction and cooling zone and thus migrate up through the pellet bed before the sensible heat contained therein is given up to heat the air used for recuperation. This secondary induration also provides for additional grain growth, thereby increasing pellet strength.

In my process I find that only about one-half of the preheated air from the updraft reaction and cooling zone is required for primary induration of the pellets in the downdraft reaction zone, the balance being available and utilized for supplying preheated air to the combustion heating zone and also to a downdraft drying zone through which the pellet bed is fed for drying the moisture-laden, green pellets prior to heating to indurating temperature.

Having thus generally described the basic features of my invention, reference will now be had for a more de-

tailed description of these and other features to the accompanying drawings, wherein:

FIG. 1a is a simplified, diagrammatic showing in longitudinal elevation of a preferred apparatus for practicing my invention and which also illustrates my novel process as to operational sequences.

FIG. 1b is a temperature profile of gas temperatures at successive stages of the FIG. 1a sequence of operations.

FIG. 2 is a more or less diagrammatic showing in longitudinal side elevation of a preferred form of apparatus for practicing the invention commercially. FIG. 3 is a transverse sectional elevation as taken substantially at 3-3 of FIG. 2. FIG. 4 is a transverse sectional elevation as taken substantially at 4-4 of FIG. 2.

FIG. 5 is a diagrammatic showing in longitudinal side elevation of the indurating band commencing in the downdraft combustion heating zone, thence down through the pellet bed in the downdraft reaction zone and the reversal of direction up through the pellet bed in the updraft reaction and cooling zone, thus illustrating my novel double induration as to operational sequence.

FIG. 6 is a side elevation of a counterweighted air seal for isolating and maintaining positive and negative pressures between updraft and downdraft zones as practiced in my invention.

FIGS. 7 and 8 are photomicrographic showings of the pellet structure after induration of pellets of taconite ore concentrates as indurated in accordance with the invention versus induration in accordance with the prior art proposals above discussed.

Referring to FIG. 1a, there is shown a gas-permeable, travelling grate, endless conveyor 10, fed about sprocket 11, which is driven for moving the grate in the direction of the arrow X. The grate is made of articulated links 13, provided with oppositely disposed sidewalls, which during horizontal travel of the grate, form continuous sidewalls, as at 14, for retention of the pellet bed, indicated at P. Moist green pellets are continuously deposited in a uniform layer onto the grate at the feed end, as at 15, from a vibrating feed screen 16, the indurated pellets being discharged from the delivery end of the grate, as at 17. The grate during its upper path of horizontal travel, is completely hooded and compartmentalized, as at 20-27, inc. Certain of the compartments are interconnected by conduits, as at 28, 29, provided with blowers, as at 30, 31, 32; while other compartments are provided with inlet or outlet conduits, as at 33, 34, 35, also provided with blowers, as at 36, 37, 38, for purposes explained below. A combustion heating chamber or furnace 39, is provided with fuel-fed sidewall burners 40, as discussed below.

In the operation of the pellet indurating process of my invention as illustrated in FIG. 1a, the bed P of the moist, green pellets as laid down at 15 at the feed end of the travelling grate 10, is fed thence successively through the various treating zones indicated by the legends at the top of the drawing and comprising, updraft drying, downdraft drying, combustion heating, downdraft reaction and updraft reaction and cooling zones.

The only source of fuel-fired heat supplied to the system is by way of the fuel-fired burners 40 mounted in the sidewalls of the hooded chamber 39 comprising a combustion chamber or combustion zone. The hot gases from these burners are caused to flow in downdraft through the pellet bed and grate by the suction blower 37 in conduit 34 which connects to chamber 24 beneath the furnace chamber 39. Since these gases are deficient in oxygen due to combustion of fuel in the burners 40, they are discharged as waste gases to atmosphere via conduit 34 depleted of their sensible heat.

These hot gases in passing through the pellet bed from chamber 39 to 24, heat up the top two or three inches of the bed of pellets to indurating temperature in the manner illustrated at A, FIG. 5. As the bed of pellets

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is conveyed thence across the downdraft reaction zone 22, 23, this band of induration which started on top of the bed progresses down through the bed as shown at B, FIG. 5, until the two to four inch band reaches the grate 41, as at C, just before the pellets are conveyed into the updraft reaction and cooling zone 21, 20.

The recuperation is initiated in chamber 20 wherein the hot pellets are subjected to an updraft of cool, ambient air forced into the lower cooling chamber 20 via conduit 33 and forced draft blower 36, FIG. 1a. This updraft of cool air impinges first on the conveyor grate bars, as at 41, FIG. 5, thus to cool the same to prevent warpage and distortion, and the heat from which is caused to flow up through the pellet bed along with cool air, as at D, FIG. 5, thereby reversing the direction of the indurating band causing it to migrate up through the bed and at the same time cooling the bed beneath the indurating band and also heating the air flowing into upper chamber 21. As shown by the gas temperature diagram of FIG. 1b, the thus heated air enters chamber 21 at a temperature of about 800° F., while meantime completing induration and cooling the grate bars and pellet bed down to temperature of about 200° F. for discharge.

The upper reaction and cooling chamber 21 opens into the upper downdraft reaction chamber 23, as indicated by the arrow, and a portion, preferably about one-half of the 800° F. air flowing into chamber 21, is caused to flow into the upper downdraft reaction zone chamber 23 and thence in downdraft through the pellet bed in the downdraft reaction zone by virtue of the suction blower 31 in conduit 29, FIG. 1a, connected to the lower chamber 22 of the downdraft reaction zone.

The thus preheated air from chamber 21 in passing in downdraft through the pellet bed completes primary induration of the pellets initiated in the combustion heating zone. As shown by FIG. 1b, the downdraft air after passing through the pellet in the downdraft reaction zone and after tempering in the manifold 22, has a temperature of about 800° F. It is fed via conduit 29 and blower 31, thence through a second blower 32 into the lower drying zone chamber 26, and thence in updraft through the travelling grate and pellet bed into the upper drying zone chamber 27, from whence moisture-laden, it is discharged to atmosphere via conduit 35 containing the suction blower 38, at temperature of about 200° F., as shown by reference to FIG. 1b.

The hot dry air entering the lower drying zone chamber 26 at about 800° F., in passing in updraft through the pellet bed, is thus most effective in drying the pellets in the lower portion of the bed thereby to "green" harden and strengthen the same, and it also provides a supporting column of uprising air to prevent crushing by the upper layer of pellets. Also in this way such moisture condensation as occurs on the cold pellets will do so only on the upper layer of pellets having minimum load thereon, thereby to prevent injury by crushing.

My investigations have shown that if the hot air is first passed in downdraft through the cold, entering bed of pellets, that although the pellets in the upper layer of the bed will be dried and "green" hardened, those in the lower layer will slurry and crush due to moisture condensation thereon from the now moisture-laden, heated air, which in passing through the upper pellet layer has picked up considerable moisture, and that the wet slurried pellets in the lower part of the bed will crush due to being subjected to the pressure of the downdraft column of air and the weight of the pellet bed.

Reverting to the discharge end 17 of the grate, as above stated, only about one-half of the heated air flowing into the upper updraft reaction and cooling zone chamber 21, is caused to flow into the upper downdraft reaction zone chamber 23. The remainder is drawn off from chamber 21 over conduit 23 through the suction blower 30, and conveyed thence to the downdraft drying and combustion heating zone chambers 25 and 39. The portion enter-

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ing the downdraft drying zone chamber 25, passes in downdraft through the pellet bed to further dry and "green" harden the pellets by removing residual moisture therefrom, with particular reference to the residual moisture contained in the upper pellet layer. The portion entering the combustion heating zone chamber 39, serves to provide preheated air to the burners 40 and also to the combustion heating zone chamber 39, and thus reduces to that extent the amount of thermal energy to be supplied by fuel consumed by the burners for heating the upper part of the pellet bed up to the indurating temperature of about 2300-2400° F.

As above stated and as described more in detail below with reference to FIG. 3, the burners 40 are so mounted, flame adjusted and positioned above the pellet bed, that there occurs no direct impingement of flame from the burners on the pellet bed. Only hot gases heated by the burners contact the bed being drawn therethrough as explained by the suction blower 37 in conduit 34 connected to the lower combustion zone chamber 24. The temperature of these gases is so adjusted as to heat the upper layer of the pellet bed to indurating temperature of about 2300-2400° F. and thus to initiate the indurating reaction as the bed passes into the downdraft reaction zone, wherein the primary induration reaction is completed in the manner above explained. That is to say, as the pellet bed traverses the downdraft reaction zone, a wave of heat at indurating temperature is caused to pass downwardly through the bed due to the forced flow downdraft of preheated air from chamber 21 passing through the bed while the exothermic reaction of the magnetite to hematite oxidation occurring therein aids in holding the pelletizing temperature at optimum.

As shown by FIG. 1b the gases from the lower chamber 24 of the combustion heating zone exit to atmosphere at only about 400° F. This is in marked contrast to the prior art systems above discussed wherein these gases exit at about 1000° F. This marked difference in temperature of exit waste gases in my process versus the prior art, results from the heat conservation obtained by recuperation in my process. This recuperation takes dry air at about 800° F. containing an oxygen level of 100% of ambient from chamber 21 as preheated by updraft reaction and cooling of the hot indurated pellets and employs the heat values thereof for primary induration of pellets in the downdraft reaction zone and thence for updraft drying in the updraft drying zone, the air from which is exhausted to atmosphere at the low temperature of about 200° F. In addition, blower 30 transports part of the 800° F. air from the updraft reaction and cooling chamber 21 to the combustion heating chamber 39, to the burners 40, and to the downdraft drying zone 25, these gases passing thence through the pellet bed to atmosphere at 400° F. The prior art is devoid of any such teaching or suggestion insofar as I am aware.

Referring now to the commercial embodiment of my invention as shown in FIGS. 2-6, inc., equivalent elements have been similarly designated as in FIG. 1a from which the identity of equivalent components will be apparent. However, there are some structural modifications in the FIGS. 2-6, inc., embodiment which will become apparent by comparison with the simplified showing of FIG. 1a. Thus, referring to FIGS. 2-6, inc., a series of funnel-like wind boxes, as at 50, 51, are disposed seriatim substantially the length of the traveling grate 10, and are positioned with the flared openings just beneath the grate, as at 52, 53. A series of manifolds 20, 22, 24, 26, corresponding in function to the like numbered lower chambers of FIG. 1a, are disposed seriatim below the wind boxes as shown, and from each wind box a conduit extends downwardly to the manifold positioned beneath the same. Thus, conduits 54, 55, extend from wind boxes 50, 51, down to manifold 26, positioned beneath them, and so on for the remaining wind boxes. The manifolds, accordingly function to segregate the

wind boxes into groups corresponding to the lower like numbered lower drying, combustion heating, downdraft reaction and updraft reaction and cooling compartments of FIG. 1a.

Above grate 10, are disposed compartmentalized hoods 27, 25, 39, 23 and 21, corresponding to the like numbered upper hood compartments or chambers of FIG. 1a, for providing the upper drying, combustion heating, downdraft reaction and updraft reaction and cooling compartments. Likewise, in FIGS. 2-6, inc., the motor driven blowers and conduits containing them are arranged and connected the same as the like numbered components of FIG. 1a and for performing the same functions, respectively. Referring to FIGS. 3 and 4, oppositely disposed side panels 56 and 57, extend down from the upper hoods to hoppers 73, in order to enclose the grate 10 substantially throughout its length, thereby making the entire enclosure a pressure balancing plenum chamber similar to that described in U.S. Patent 3,088,723. This tunnel-like housing encloses the grate from the upper hoods 21, 23, 39, 25 and 27 to below the return strand of the grate by walls 56 and 57 as shown in FIGS. 3 and 4. The entire tunnel-like structure is under a slight negative pressure and acts as a vacuum cleaner to contain essentially all of the air-borne dust in the system. The tunnel also acts as a pressure equalizing plenum chamber to contain the small surges of positive or negative pressure in the air flow system of the machine rather than allowing them to dissipate to atmosphere.

In addition to the above described dust collection system, dust collecting means are provided both at the feed end and discharge end of grate 10. Referring to FIG. 2, at the feed end, wind box 95 is connected to updraft drying chamber 27 by conduit 96. Wind box 95 is under slight negative pressure, being exhausted by blower 38, and picks up air-borne dust from the slight blow-by through air seal 94, FIGS. 2 and 6.

Referring to FIG. 6, the air seal mechanism shown generally at 94, comprises an air sealing plate member 100, pivotally mounted as at 101, to a supporting structure 102 of the wind box assembly, the air sealing plate member having integral therewith a counterweight 103, of sufficient magnitude to maintain the sealing plate and counterweight assembly in the position shown by the dotted lines 100a, 103a, whereby the outer edge of the sealing plate rides along the underside of the pellets or articulated links 13 of the travelling grate conveyor 10, thus to minimize blow-by of air between the sealing plate and the grate.

Reverting to FIG. 2, the discharge end of grate 10 is enclosed by dust collecting hood 97, whereby dust is exhausted to dust collectors, not shown, via conduit 98 and is eventually returned to the system. The blow-by in the terminal wind box is controlled to a minimum by air seal 91 similar to that shown in FIG. 6. Two additional and similar air seals 92 and 93, FIG. 2, effectively prevent the short-circuiting of air between the pressurized wind box on one side of the seal and the suction wind box on the other side of the seal.

As further shown in FIG. 2, damper controls are provided in the various conduits, as at 60, 61, 62, for controlling the flow of air therethrough. There are also tempering air dampers, as at 67, 68 and 69, to permit ambient air to be drawn into the respective ducts or chambers to control the temperature of the gases passing through blowers for their protection against excessive temperatures. Conduit 28 is branched as at 63, 64, for directing desired fractions of the hot updraft air from chamber 21 into the combustion heating and downdraft drying chambers 39, 25, on the one hand, and as preheated air supply to the fuel burners 40, on the other. The lower manifold 20 in the updraft reaction and cooling zone is provided with removable sections, as at 65, 66, for increasing or decreasing the effective length of

this manifold, and thereby correspondingly varying the effective length of the updraft reaction and cooling zone.

Referring to FIG. 3 the burners 40 are fitted as above stated into ports, as at 70, extending through sidewalls, as at 71, 72, of the combustion furnace chamber 39. By reason of this mounting the burners direct their flames horizontally into the combustion heating chamber 39 at a level well above the pellet bed P of the travelling grate 10, in the manner illustrated at 73. Thus, there occurs no direct impingement of the flames 73 from the burners 40 onto the pellet bed P. The flames are additionally adjusted to assure this by controlling the rates of air and fuel supply to the burners over the air lines, as at 74, and fuel lines, as at 75. The air supplied to the air lines 74 is preheated air supplied over conduits 28 and 64, FIG. 2. The air fed into the combustion heating chamber through the inlet conduits 76 is the preheated air supplied thereto over conduits 28 and 63, FIG. 2.

The preferred pellet size is about $1\frac{1}{32}$ to $\frac{3}{4}$ inch. The screen 16 which feeds the green pellet agglomerates into the feed end of the travelling grate is of a mesh to retain pellets of $\frac{1}{4}$ inch but to reject smaller sizes. The grate bars of the travelling grate are likewise spaced to retain pellets of about $\frac{1}{8}$ inch and over but to pass smaller sizes. Referring to FIGS. 3 and 4, pellets fragmented during feed over the travelling grate or those that fall through openings caused by broken grate bars, fall into hoppers, as at 77, 78, at the base of the wind box conduits, and are removed on travelling belts, as at 79, 80.

As was pointed out above, taconite ore pellets as indurated at about 2300-2400° F. in the absence of direct flame impingement on the pellet bed produce the strongest and finest quality iron pellets when the temperature and oxidation conditions are such that the magnetite grains are oxidized to hematite and sufficient grain growth occurs after this oxidation and recrystallization to form an almost complete network of interconnecting hematite grains. The microstructure of pellets as thus produced in accordance with the present invention is shown in FIG. 7 of the drawings. As there shown the microstructure consists of a well bridged network of hematite grains comprising the white areas. It will be noted that the slag content comprising the gray areas is generally confined to coalesced patches within the individual grains or as longer isolated particles. The voids are shown in black.

It was further pointed out in contrast to this desired, indurated microstructure, that if the pellets are indurated by direct flame impingement on the pellet bed, this heats at least the surface layer of pellets to so high a temperature that oxidation of the magnetite to hematite does not occur, as a result of which the slag formation is so extensive that the grains of magnetite are embedded in a brittle slag matrix. The microstructure obtained in this way is illustrated in FIG. 8 of the drawings. In this view the magnetite grains are shown in gray, with a complete slag network, shown in darker gray, surrounding the magnetite grains, the interstices or voids being again shown in black.

What is claimed is:

1. The method of hardening and strengthening moist, green pellets of ore-bearing particles, which comprises: continuously depositing said pellets in a substantially uniform bed on a gas-permeable, travelling grate conveyor and feeding successively through drying, combustion heating, indurating reaction and cooling and reaction zones, generating heated gases in said combustion heating zone and passing through said bed thereat to heat said pellets, passing cool air through said bed in said cooling and reaction zone to cool said bed and heat said air, passing a substantial portion of said heated air through said bed in said indurating reaction zone and thence through said bed in said drying zone, passing a substantial portion of the heated air from said cooling and reaction zone to said combustion heating zone to supple-

ment the heat of the gases passed through said bed thereat, and adjusting the temperature and the rate of flow of the heated gases passed through said bed in said combustion heating zone and the rates of flow of said gases passed through said bed in said cooling and reaction, indurating reaction and drying zones, to dry said pellets in said drying zone, to initiate induration of said pellets in said combustion heating zone, to continue the induration of said pellets in said indurating reaction zone and to complete induration of said pellets and cool said pellets in said cooling and reaction zone.

2. The method of hardening and strengthening moist, green pellets of ore-bearing particles, which comprises: continuously depositing said pellets in a substantially uniform bed on a gas-permeable, travelling grate conveyor and feeding successively through drying, combustion heating, downdraft reaction, and updraft reaction and cooling zones, generating heated gases in said combustion heating zone and passing in downdraft through said bed thereat to heat said pellets, passing cool air in updraft through said bed in said updraft reaction and cooling zone to cool said grate and bed and heat said air, passing a substantial portion of said heated air in downdraft through said bed in said downdraft reaction zone and thence in updraft through said bed in said drying zone, passing a substantial portion of the heated air from said updraft reaction and cooling zone to said combustion heating zone to supplement the heat of the gases passed through said bed thereat, and adjusting the temperature and the rate of flow of the heated gases passed through said bed in said combustion heating zone and the rates of flow of said gases passed through said bed in said updraft reaction and cooling zone, and said downdraft reaction and updraft drying zones, to dry said pellets in said drying zone, to initiate hardening of said pellets in said combustion heating zone, to continue the hardening of said pellets in said downdraft reaction zone and to complete hardening of said pellets and cool said pellets in said updraft reaction and cooling zone.

3. The method of hardening and strengthening moist, green pellets of ore-bearing particles, which comprises: continuously depositing said pellets in a substantially uniform bed on a gas-permeable, travelling grate conveyor and feeding successively through drying, combustion heating, downdraft reaction and updraft reaction and cooling zones, generating heated gases in said combustion heating zone and passing in downdraft through said bed thereat to heat said pellets, passing cool air in updraft through said bed in said updraft reaction and cooling zone to cool said grate and bed and heat said air, passing a substantial portion of said heated air in downdraft through said bed in said downdraft reaction zone and thence in updraft through an entrance portion of said bed in said drying zone, passing a substantial portion of the heated air from said updraft reaction and cooling zone in downdraft through a terminal portion of said drying zone, and another substantial portion to said combustion heating zone to supplement the heat of the gases passed through said bed thereat, and adjusting the temperature and the rate of flow of the heated gases passed through said bed in said combustion heating zone and the rates of flow of said gases passed through said bed in said updraft reaction and cooling zone, and said downdraft reaction and drying zones, to dry said pellets in said drying zone, to initiate hardening of said pellets in said combustion heating zone, to continue the hardening of said pellets in said downdraft reaction zone and to complete hardening of said pellets and to cool said pellets in said updraft reaction and cooling zone.

4. The method of hardening and strengthening moist, green pellets of ore-bearing particles, which comprises: continuously depositing said pellets in a substantially uniform bed on a gas-permeable, travelling grate conveyor and feeding successively through drying, combus-

tion heating, indurating reaction and cooling and reaction zones, generating heated gases by burning fuel in said combustion heating zone and passing said heated gases through said bed thereat to heat said pellets without flame impingement from said burning fuel on said bed, passing cool air through said bed in said cooling and reaction zone to cool said bed and heat said air, passing a substantial portion of said heated air through said bed in said indurating reaction zone and thence through said bed in said drying zone, passing a substantial portion of the heated air from said cooling and reaction zone to said combustion heating zone to supplement the heat of the gases passed through said bed thereat, and adjusting the temperature and the rate of flow of the heated gases passed through said bed in said combustion heating zone and the rates of flow of said gases passed through said bed in said cooling and reaction, indurating reaction and drying zones, to dry said pellets in said drying zone, to initiate hardening of said pellets in said combustion heating zone, to continue the hardening of said pellets in said indurating reaction zone without fusion or sintering of said pellets, and to complete induration of said pellets and to cool said pellets in said cooling and reaction zone.

5. The method of hardening and strengthening moist, green pellets of magnetite-containing particles, which comprises: continuously depositing said pellets in a substantially uniform bed on a gas-permeable, travelling grate conveyor and feeding successively through drying, combustion heating, indurating reaction and cooling and reaction zones, generating heated oxidizing gases in said combustion heating zone and passing through said bed thereat to heat said pellets, passing cool air through said bed in said cooling and reaction zone to cool said bed and heat said air, passing a substantial portion of said heated air through said bed in said indurating reaction zone and thence through said bed in said drying zone, passing a substantial portion of the heated air from said cooling and reaction zone to said combustion heating zone to supplement the heat of the gases passed through said bed thereat, and adjusting the temperature and the rate of flow of the heated gases passed through said bed in said combustion heating zone and the rates of flow of said gases passed through said bed in said cooling and reaction, indurating reaction and drying zones, to dry said pellets in said drying zone, to initiate hardening of said pellets in said combustion heating zone and to complete the hardening thereof in said indurating reaction and said cooling and reaction zones by exothermic oxidation of said magnetite particles to hematite and by integrating recrystallization and grain growth, and also to cool said pellets in said cooling and reaction zone.

6. The method of hardening and strengthening moist, green pellets of magnetite-containing particles, which comprises: continuously depositing said pellets in a substantially uniform bed on a gas-permeable, travelling grate conveyor and feeding successively through drying, combustion heating, indurating reaction and cooling and reaction zones, generating heated oxidizing gases by burning fuel in said combustion heating zone and passing said heated gases through said bed thereat to heat said pellets but without flame impingement from said burning fuel on said bed, passing cool air through said bed in said cooling and reaction zone to cool said bed and heat said air, passing a substantial portion of said heated air through said bed in said indurating reaction zone and thence through said bed in said drying zone, passing a substantial portion of the heated air from said cooling and reaction zone to said combustion heating zone to supplement the heat of the gases passed through said bed thereat, and adjusting the temperature and the rate of flow of the heated gases passed through said bed in said combustion heating zone and the rates of flow of said gases passed through said bed in said cooling and reaction, indurating reaction and drying zones, to dry said pellets in said drying zone, to

initiate hardening of said pellets in said combustion heating zone and to complete the hardening of said pellets in said indurating reaction and said cooling and reaction zones by exothermic oxidation of said magnetite particles to hematite and by integrating recrystallization and grain growth, and also to cool said pellets in said cooling and reaction zone.

7. The method of hardening and strengthening moist, green pellets containing hematite particles and particles of a solid carbonaceous fuel, which method comprises: continuously depositing said pellets in a substantially uniform bed on a gas-permeable, travelling grate conveyor and feeding successively through drying, combustion heating, indurating reaction and cooling and reaction zones, generating heated gases in said combustion heating zone and passing through said bed thereat to heat said pellets, passing cool air through said bed in said cooling and reaction zone to cool said bed and heat said air, passing a substantial portion of said heated air through said bed in said indurating reaction zone and thence through said bed in said drying zone, passing a substantial portion of the heated air from said cooling and reaction zone to said combustion heating zone to supplement the heat of the gases passed through said bed thereat, and adjusting the temperature and the rate of flow of the heated gases passed through said bed in said combustion heating zone and the rates of flow of said gases passed through said bed in said cooling and reaction, indurating reaction and drying zones, to dry said pellets in said drying zone, to initiate hardening of said pellets in said combustion heating zone, and to complete the hardening of said pellets in said indurating reaction and said cooling and reaction zones and to also cool said pellets in said cooling and reaction zones.

8. The method of hardening and strengthening moist, green pellets of ore-bearing particles, which comprises: continuously depositing said pellets in a substantially uniform bed on a gas-permeable, travelling grate conveyor and feeding successively through drying, combustion heating, downdraft reaction, and updraft reaction and cooling zones, generating heated gases in said combustion heating zone and passing in downdraft through said bed thereat to heat said pellets in an upper band of said bed to indurating temperature, passing cool air in updraft through said bed in said updraft reaction and cooling zone to cool said grate and bed and heat said air, and passing a substantial portion of said heated air in downdraft through said bed in said downdraft reaction

zone, thereby to propagate said indurating temperature band downwardly through said pellet bed in said downdraft reaction zone and thence upwardly through said bed in said updraft cooling and reaction zone, passing the gases fed through said downdraft reaction zone in updraft through said bed in said drying zone, and passing a substantial portion of the heated air from said updraft reaction and cooling zone to said combustion heating zone to supplement the heat of the gases passed through said bed thereat.

9. The method of hardening and strengthening moist, green pellets of ore-bearing particles, which comprises: continuously depositing said pellets in a substantially uniform bed on a gas-permeable, travelling grate conveyor and feeding successively through drying, combustion heating, downdraft reaction and updraft reaction and cooling zones, generating heated gases in said combustion heating zone and passing in downdraft through said bed thereat to heat said pellets in an upper band thereof to indurating temperature, passing cool air in updraft through said bed in said updraft reaction and cooling zone to cool said grate and bed and heat said air and passing a substantial portion of said heated air in downdraft through said bed in said downdraft reaction zone thereby to propagate said indurating temperature band downwardly through said bed in said downdraft reaction zone and thence upwardly through said bed in said updraft cooling and reaction zone, passing the gases fed through said downdraft reaction zone in updraft through an entrance portion of said bed in said drying zone, passing a substantial portion of the heated air from said updraft reaction and cooling zone in downdraft through a terminal portion of said drying zone, and another substantial portion to said combustion heating zone to supplement the heat of the gases passed through said bed thereat.

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