June 12, 1956 R. PERRIN 2,750,286

PRODUCTION OF IRON-NICKEL ALLOYS FROM LOW GRADE ORES

Filed June 9, 1953 3 Sheets-Sheet 1

Fig. 1

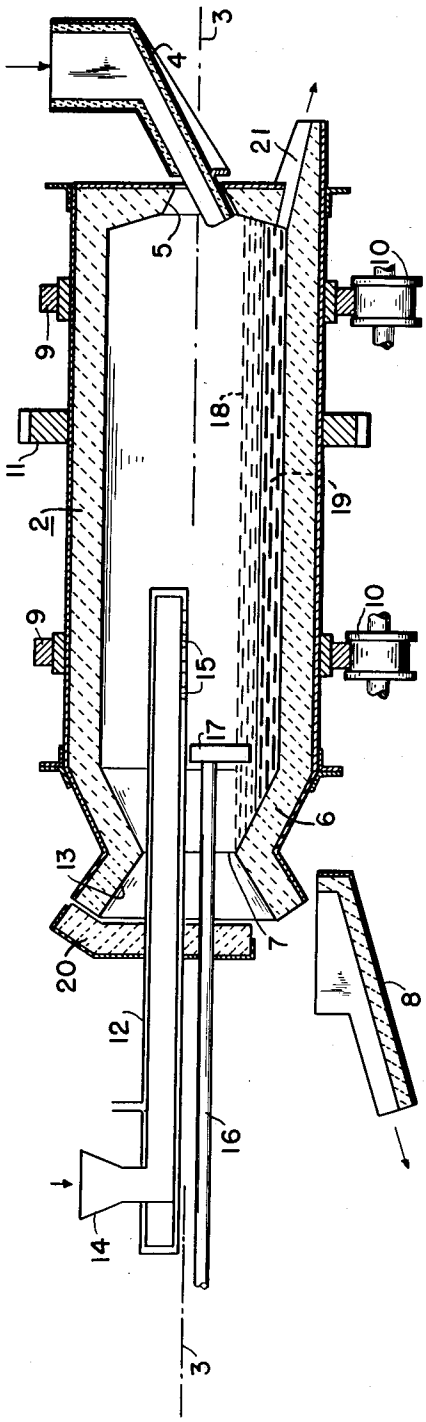
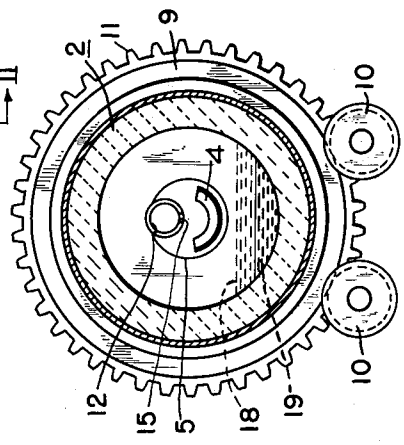


Fig. 2



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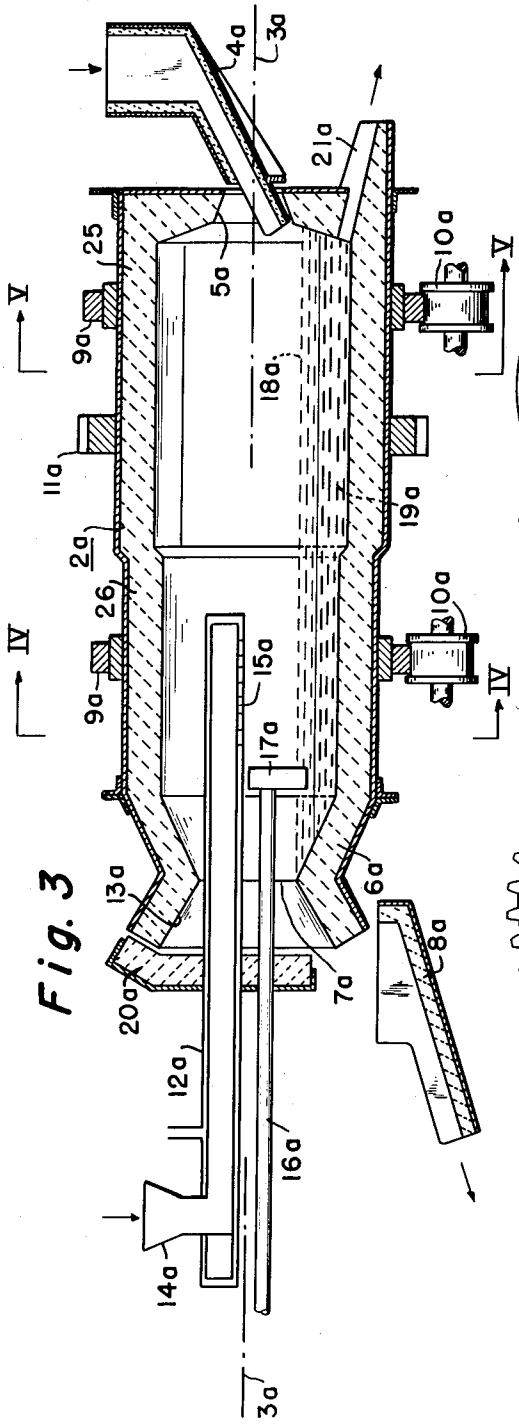


Fig. 3

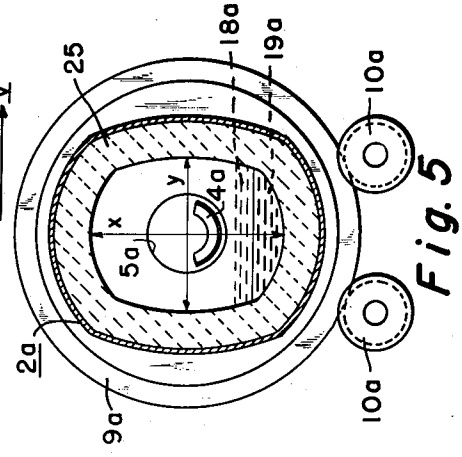


Fig. 5

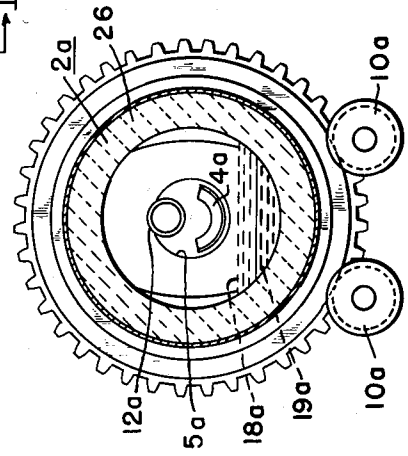


Fig. 4

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PRODUCTION OF IRON-NICKEL ALLOYS FROM LOW GRADE ORES

Filed June 9, 1953 3 Sheets-Sheet 3

Fig. 6

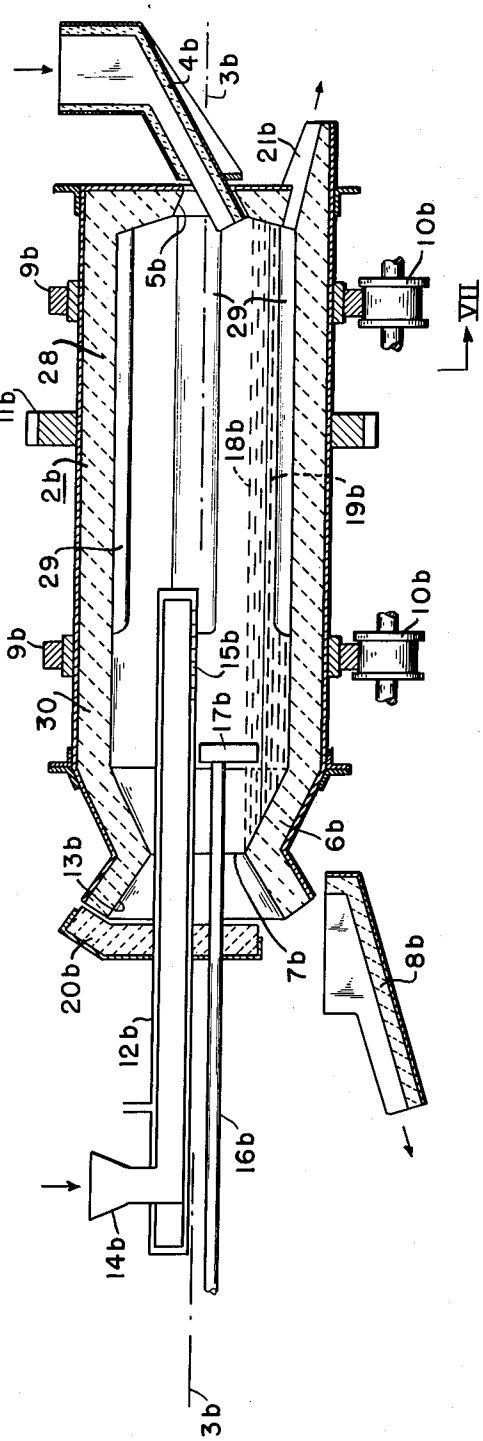
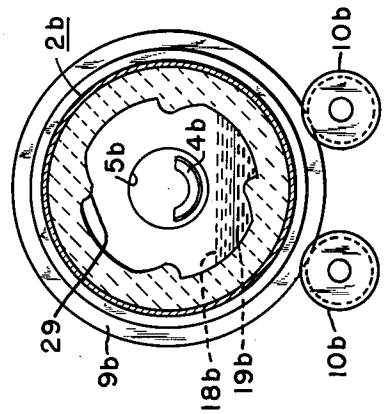


Fig. 7



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United States Patent Office 2,750,286 Patented June 12, 1956

2,750,286

PRODUCTION OF IRON-NICKEL ALLOYS FROM LOW GRADE ORES

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Application June 9, 1953, Serial No. 360,580

Claims priority, application France June 21, 1952

12 Claims. (Cl. 75—133.5)

This invention relates to a process and apparatus for extracting nickel from low grade nickel ores containing an oxidic compound of nickel. The present application is a continuation-in-part of my application Serial No. 300,355 filed July 22, 1952.

There are in the world important deposits of such low grade nickel ores. Chemical or metallurgical methods are now known for treating them to extract the nickel therefrom, but such methods are very costly.

An object of the present invention is to provide a process and apparatus for recovering nickel from such ores in an economical manner and in such a way as to produce ferro-nickel of high nickel content of the order of 25 to 60% nickel for instance, the nickel content usually being between about 25 and 40%. Such ferro-nickel alloys may be used as substitutes for pure nickel in almost every instance where nickel is employed in steel making processes.

The process can be carried out in a continuous or a discontinuous manner, the former being the preferred practice.

In the accompanying drawings which illustrate several forms of apparatus suitable for carrying out the process in a continuous manner,

Figure 1 is a longitudinal section through a rotatable vessel and associated parts;

Figure 2 is a transverse section taken on the line II—II of Figure 1;

Figure 3 is a view similar to Figure 1, but illustrating a modified form of rotatable vessel;

Figure 4 is a transverse section taken on the line IV—IV of Figure 3;

Figure 5 is a transverse section taken on the line V—V of Figure 3;

Figure 6 is a view similar to Figure 1, but illustrating another embodiment of the rotatable vessel; and

Figure 7 is a transverse section taken on the line VII—VII of Figure 6.

Applicant's Patent 2,100,265 granted November 23, 1937, discloses a discontinuous process for introducing nickel into a steel bath by violently intermixing such bath with a slag containing nickel oxide. A particularly convenient operating method consists in violently pouring the molten steel into a ladle containing the slag. The reaction is practically instantaneous. Such process is quite suitable if only small amounts of nickel are to be introduced into steel from slags containing relatively large proportions of nickel oxide. However, it is not suitable for introducing large amounts of nickel into steel from low grade nickel ores containing small proportions of nickel oxide.

According to the example given in the patent, a charge of 15,000 kgs. of molten steel is poured into a ladle containing 1,750 kgs. of molten slag containing oxide of the alloying metal. Using these proportions but substituting an ore containing 10% of nickel oxide for the slag, it is possible to introduce about 0.9% of nickel into the steel. If the ore contains 5% of nickel oxide, the amount of nickel introduced into the steel is about 0.4% and if the ore contains 1.5% of nickel oxide, the amount of nickel introduced into the steel is about 0.14%. It will be seen that according to the method of the patent, only a relatively small amount of nickel can be introduced into the steel if a low grade nickel ore is employed.

An object of the present invention, on the contrary, is to start with a low grade nickel ore containing not over about 10% nickel oxide, usually not over about 6% of nickel oxide, and often containing only about 1.5% nickel oxide, and to extract from this ore almost the whole nickel content and to recover it in the form of a high grade alloy containing a substantial amount of nickel, usually from 25 to 40% of nickel, which can be used for introducing nickel in steel making or other metallurgical processes.

As stated above, if the proportions of steel and slag disclosed in the example of Patent 2,100,265 are used in the treatment of a low grade nickel ore containing 1.5% nickel oxide, the process results in introducing into the steel only about 0.14% of nickel. Such alloy because of its low nickel content is entirely unsuitable for steel making purposes, particularly for the manufacture of nickel-chromium stainless steels, which require large amounts of nickel. On the other hand, if it is desired to produce from this ore a high grade nickel alloy suitable for steel making and containing, say, 25% of nickel by the single violent intermixing of the molten ore and molten steel as taught in this patent, the weight of steel used must be very small in comparison with the weight of the ore, for instance about 50 kgs. of steel for one ton of ore, which is a ratio of ore to steel of about 20:1. (Throughout this specification, the term "ton" means a metric ton of 1,000 kilograms.) In such case, the volume of the ore compared to that of the metal is considerable and it is impossible, even though both phases be violently intermixed, to obtain equilibrium between the metal and all parts of the ore. Consequently, the yield of nickel is very low. This treatment is therefore economically prohibitive when using low grade ores.

I have found that a high grade molten ferro-nickel containing 25% or more by weight of nickel, and even upwards of 40% by weight, can be used successfully for effecting substantially complete reduction of nickel oxide in a molten, low grade nickel ore in which the nickel content is much lower than in the ferro-nickel. I have found further that by repeated or continuous use of a molten ferrous metal in the treatment of successive quantities of the molten ore, each portion of ore treated thereby can be substantially completely denickelized, and at the same time, the nickel content of the ferrous metal can be progressively increased to a value much above that of the ore itself, and even to a value substantially above 25% by weight.

Based on these findings, the process of the present invention for extracting nickel from low grade oxidic nickel ores comprises forming a molten bath of said ore and vigorously intermixing the molten ore with a quantity of a molten ferrous metal sufficient to insure a complete reaction between ore and metal, thereby to reduce nickel oxide from the ore and introduce it into the ferrous metal. In accordance with the invention, the denickelized ore is separated from the molten ferrous metal, and the molten ferrous metal is itself repeatedly intermixed with successive charges of the molten ore. The molten ferrous metal, at least in the later of said repeated intermixings, is a ferro-nickel containing a substantially higher percentage of nickel than is contained in the ore itself. Indeed, the ferro-nickel will eventually contain at least 25% by weight of nickel and may contain as much as 40% or more by weight up to a maximum of about 60% by weight. (If the nickel content of the ferro-nickel ex-

ceeds about 60% by weight, the conditions of equilibrium between ore and metal become less and less effective for accomplishing a substantially complete denickelizing of the low grade oxidic nickel ores.) The quantity of ferrous metal or ferro-nickel used in the treatment of each quantity of molten nickel ore will always contain a substantially greater weight of iron than the weight of nickel in the ore, in order to insure substantially complete reduction of the nickel oxide. As regards the quantity of ferrous metal to be employed for a given amount of slag, it is preferable to employ an amount of ferrous metal or ferro-nickel which is not less than about ⅓ of the weight of molten ore and most advantageously the ratio of the weight of the ferrous metal or ferro-nickel to the weight of molten ore treated thereby is in the range from ½ to 2. For many ores, the weight of the ore should be approximately equal to the weight of the metal by which it is treated.

If the ore is very low in nickel oxide, it is advisable to use a relatively small amount of ore, these conditions being necessary to produce a complete reaction between the metal and the ore when both phases are thoroughly intermixed together, and thereby to insure the best exhaustion of the ore.

The degree of exhaustion of the ore is all the more important from an economical point, the smaller the amount of nickel oxide in the ore. For example, if 0.30% nickel oxide is retained in the exhausted ore, this has a much greater relative importance in the final cost of the ferro-nickel obtained, if one starts with an ore containing, say, 1.2% of nickel oxide, than if one starts with an ore containing, say, 4% of nickel oxide. In the first case, the exhaustion will be about 75%; in the second, about 92%. Preliminary tests will in any case help determine the optimum amount of ore to be used with a given weight of metal.

Various ways in which the process can be carried out in a discontinuous manner will now be described.

Discontinuous Processes

In carrying out the process, the molten ore and molten steel or other ferrous metal are violently intermixed. The iron of the bath reduces the nickel oxide of the ore to nickel which enters the bath. In some cases, a small amount of a strong reducing agent such as ferro-silicon or ferro-aluminum is introduced into the metal bath prior to or during mixing. Whether or not a reducing agent is introduced into the metal bath, the denickelized ore is separated from the metal bath after the intermixing and the metal bath is repeatedly intermixed with successive further charges of molten low grade nickel ore under the conditions as described, including removing the denickelized ore between mixings. The operation is repeated as many times as necessary until the required nickel content of the bath has been reached, after which the metal bath is removed partially or totally.

Owing to the low nickel content of the ore, a considerable number of pourings or other forms of violent intermixings are required in order to secure, from pure iron, a ferro-alloy having a high enough nickel content to make it suitable for steel making purposes. These repeated pourings cool the metal, and in order to overcome this, the ore may be heated to a temperature not only sufficient to melt it but to provide sufficient heat to compensate for the heat lost during the repeated pourings. Similarly, the ferrous metal bath can be heated to an excess temperature in order to compensate for heat losses during the pouring operations or both the metal bath and the ore can be heated to provide the excess heat required in order to carry out the operation. Another way of providing additional heat to compensate for heat losses during the repeated pourings is to add a strong exothermic reducing agent to the metal bath.

The ore can be melted for instance in a reverberatory furnace, in a rotating furnace, or in an electric furnace, but in any event, it must be brought to a temperature to make it fluid.

The successive intermixings of molten metal and molten ore can be made by violently pouring the molten metal into a bath of molten ore contained in a ladle or other receiver. It can be made by simultaneously pouring both the molten metal and the molten ore into the same receiver. In either case, if the respective amounts of ore and metal have been properly chosen, as above indicated, there is a dispersion of the metal into substantially all of the ore which causes the two materials to approach substantial equilibrium by the end of the pouring operation.

In one embodiment of the invention, a steel bath containing no nickel or only a small amount of nickel is violently intermixed with molten low grade nickel ore. The denickelized ore is removed from the metal bath and the bath is treated repeatedly with successive charges of fresh low grade nickel ore, each treatment involving a violent intermixing of the two materials. In carrying out these repeated intermixings of molten ore and molten metal, there may be added to the molten metal prior to each intermixing or prior to at least some of the intermixings, an exothermic reducing agent which may be silicon, aluminum or carbon or alloys thereof, in amount sufficient to maintain the bath at the desired temperature during the various intermixings. At each intermixing, nickel oxide of the ore is reduced to nickel, which enters the bath, thereby enriching it. After the content of nickel in the ferrous metal bath has reached the desired point, the bath is allowed to solidify or else it is used in the liquid state, as for example by adding it to a suitable steel bath for making 18–8 stainless steel.

In another embodiment of the process, I may start with an iron-nickel alloy already containing a large nickel content, for instance of the order of 35%. This molten alloy is first violently intermixed with molten low grade nickel ore. During this first intermixing, the nickel oxide of the ore is reduced to nickel and enters the alloy bath, thereby enriching it slightly. The exhausted nickel ore is then removed from the alloy bath. The intermixing operation is repeated again, using the same alloy bath with a further charge of molten nickel ore. A weight of alloy bath corresponding substantially to the surplus metal introduced into the bath from the ore is drawn off from the bath, thus obtaining a high grade nickel alloy. The previous operation is repeated with the remainder of the alloy bath, intermixing it with a new charge of molten ore and drawing off the exhausted ore, and this cycle, including the drawing off of a portion of the alloy bath, is repeated indefinitely. However, one must take care not to let the nickel content of the alloy rise to too high a value, say over 60% nickel, since, if this occurs, the reduction of the nickel oxide in the ore by the alloy bath, will not result in adequate exhaustion of the ore. In order to prevent the nickel content of the bath from reaching too high a value, iron is introduced into the bath. Iron can be introduced into the bath in either one of the following two ways or by a combination of both. According to one way, a direct addition of iron is made to the bath. Another way is to utilize an ore containing iron oxide, or by adding iron oxide to a nickel oxide ore. A reducing agent, for example silicon or aluminum or their alloys, is added to the metal bath. During intermixing of the molten ore and molten metal, the reducing agent reduces iron oxide in the ore to iron which enters the metal bath. The reducing agent is employed in such amount as to reduce at least some of the iron oxide of the ore. In this manner, iron resulting from reduction of iron oxide in the ore enters the bath and prevents the nickel content of the bath from reaching too high a value. One may, particularly, add to the metallic bath an amount of reducing agent such that the iron and nickel which will be reduced from the ore, are in the same ratio as the iron and nickel

in the metallic bath. Under these conditions, the metallic bath does not change its composition as the successive intermixings are carried out, but its weight increases each time.

In the case where iron or iron oxide in solid form is added to the metal bath, extra heat must be supplied in order to heat and melt these introduced elements. This extra heating may be accomplished by suitable reheating of the metal bath and/or the ore, and/or by an appropriate addition of the reducing agent. The reducing agent in this case must be of such character and used in such amount that the heat liberated by its reaction with the oxides will be great enough to heat and melt the metal or oxide added and to compensate for the heat losses occurring during the operation of the process. Ferro-silicon is particularly suitable for use as a reducing agent because it is not only a strong reducing agent but also provides iron.

The intermixing of the molten ferrous metal and the molten nickel ore can be accomplished by a pouring operation involving the use of a ladle, or it can be accomplished by the use of a rotating or oscillating furnace. If a rotating or oscillating furnace is employed, a ferrous metal bath may be obtained by reducing slag rich in iron oxide and nickel oxide with a strong reducing agent such as silicon or silico-aluminum. After the slag has been drawn off, a low grade nickel ore in molten state is added to the ferrous metal bath and the mixture is violently intermixed by rotating or oscillating the furnace in such a manner as to produce a penetration of the metal into the slag. Thereafter, the exhausted ore is removed from the furnace, and the ferrous metal bath is treated again with a further quantity of low grade nickel ore. These steps are repeated indefinitely until the desired amount of ferro-nickel has been withdrawn from the furnace. Thus it is possible to carry out all of the operations with only one furnace. The process can be started and continued without the need for any electric power, this being particularly useful where electric power is expensive or unavailable.

It will be noted that in one embodiment of the process, the starting metallic bath is substantially pure iron, whereas in another embodiment, the metallic bath used at the start of the operation contains a large nickel content. These two procedures can be combined. Thus, for instance, one can start with a metallic bath of substantially pure iron, enrich it in nickel content by successive intermixings with further quantities of nickel ore and withdrawal of the exhausted ore until a bath containing, say, 40% nickel is obtained. Thereafter, one-half of the metal bath is withdrawn, an amount of pure iron equal in weight to that withdrawn from the bath is added to the remaining portion of the bath, thereby giving a bath containing 20% of nickel. This bath is then enriched by treating it with successive charges of molten low grade nickel ore and removing the exhausted ore after each treatment until the bath contains a nickel content of 40%. These steps may be repeated indefinitely.

The following examples further illustrate my process.

Example 1

The ore treated was a New Caledonian ore containing:

	Percent
NiO	5
FeO	25
SiO_2	40
MgO	Balance

One ton of the molten ore was poured into a ladle and then two tons of molten ferro-nickel containing 35% nickel were violently poured into the molten ore in the ladle. The reaction between ore and metal was almost instantaneous and was practically complete; the NiO content of the ore fell to 0.20%. The resulting iron-nickel alloy amounted to about two tons and contained 36.5% nickel.

The exhausted molten ore was removed from the iron-nickel alloy bath and then 25 kgs. of ferro-silicon containing 75% silicon were added to the metal bath. This slightly lowered the nickel content of the bath. The bath was then intermixed with a new one ton charge of the ore. The bath of iron-nickel alloy then amounted to 2,075 kgs. and contained about 36.8% nickel. 75 kgs. of this alloy were withdrawn from the bath and the operation was repeated on the remaining metal with an addition of ferro-silicon. This resulted in a little more than two tons of metal. The surplus metal was removed and the operation was carried on for a further period. After about 10 operations, ten tons of ore had been denickelized in this manner and about 700 kgs. of a 37% nickel alloy had been drawn off.

Example 2

In this example, a Cuban ore containing a very low content of nickel oxide was used. The ore contained:

	Percent
NiO	1.5
FeO	35
SiO_2	35
MgO	Balance

Two tons of the molten ore were poured into a ladle and then two tons of a 25% Ni ferro-nickel to which had been added 25 kgs. of a 75% Si ferro-silicon were violently poured into the ore in the ladle. The NiO content of the ore dropped to 0.15% and about 2,070 kgs. of an alloy containing about 25% nickel were obtained.

The denickelized ore was withdrawn from the bath and the bath, after a further like addition of ferro-silicon, was violently intermixed with a further quantity of the ore. After the two intermixings, the bath amounted to 2,140 kgs. of iron-nickel alloy containing about 25% nickel. 140 kgs. of the bath were withdrawn and the operation was resumed with the remaining two tons of metal for treating a further molten charge of the ore. This operation may be carried on indefinitely.

In accordance with another embodiment of the invention, molten ore and molten ferrous metal, for example iron or ferro-nickel, are placed in a receiver and the mixture of the two materials is blown by a current of gas so as to create a strong intermixing between the ferrous metal and the ore. In carrying out this blowing operation, a Bessemer converter may be employed, preferably a bottom blow converter.

The gas employed may be neutral or reducing. Contrary to all expectations, I have found also that air is equally suitable in spite of its oxidizing character toward the metal. Where air is used as the gas, part of the iron of the bath and part of the reducing elements which may be added to the iron bath are oxidized by the air, but this does not prevent the remaining iron or reducing agents from reducing nickel oxide in the ore to very low values. This is particularly true where the duration of the blowing is short. In practice, a few seconds of violent blowing are sufficient. Where silicate ores are treated, the lining of the converter preferably is acid.

During blowing with air or other oxidizing gas, a small amount of iron is oxidized, thus providing additional heat and lowering somewhat the iron content of the bath. This additional heat helps to compensate for the heat losses occurring during the operation. However, it is advisable to introduce into the metallic bath a small amount of a strong exothermic element which is more easily oxidized than iron. This element may be, for example, carbon, manganese, silicon or silicon alloy. These are oxidized by the action of the air together with the action of the ore which is mixed with the metallic bath. In order to protect the acid lining of the blowing apparatus against attack by the bath, particularly where silicate

ores are being used, it is advisable to introduce into the metallic bath, before blowing, a small amount of silicon or silicon alloy. The amount of this reducing agent is proportioned so that, during the blowing operation, silicate of iron is formed. If manganese has been added to the bath, the amount of silicon or silicon alloy should be sufficient also to form manganese silicate. The reactivity of these silicates with acid linings is very slight.

Where intermixing of the metal bath and molten ore is accomplished by blowing a gas through the mixture, the proportion of ore to metal bath can be considerably increased, as compared to an intermixing performed by a pouring operation. Thus in intermixing by pouring, it is desirable, although not absolutely essential, that the weight of the ore be not substantially greater than the weight of the metal bath. However, where the intermixing is obtained by blowing a gas through the mixture, the weight of the ore can easily amount to 2 or more times the weight of the metal. This greatly reduces the number of intermixings, required for exhausting the same amount of ore of its nickel content. The proportions of ore and metal will vary somewhat according to the strength of the blowing and the nature of the apparatus which is used. Other conditions being equal, the stronger the blowing, the greater may be the amount of ore.

Air blowing makes it possible, once a particular nickel content has been obtained in the alloy, to further increase this nickel content by blowing the alloy with air, but this time not employing any ore. In this way, a substantial proportion of iron may be oxidized and passes into the slag formed during the operation without prohibitive concomitant nickel losses.

The following is an example of an embodiment of the invention in which a bath of molten ore and ferrous metal are blown with air.

Example 3

The ore treated was a low nickel Cuban ore containing:

	Per cent
NiO	1.5
FeO	35
SiO_2	35
MgO	Balance

Two tons of the molten ore and one ton of molten iron were loaded into a bottom blow acid lined converter while the converter was on its side. 7 kgs. of ferro-silicon containing 75% silicon were added to the mixture in the converter, the converter was raised, and about 10 cubic meters of air were blown in 10 seconds. The converter was lowered, and the metal was allowed to separate from the molten ore. The molten ore, after separation from the metal, contained 0.17% NiO. The remaining metal contained about 2% nickel.

7 kgs. of ferro-silicon containing 75% silicon were added to the metal in the converter and the metal was used to treat a new two ton charge of ore in the manner described. These operations were repeated many times. After 15 operations, the metal bath weighed 950 kgs. and contained about 30% of nickel.

In another embodiment of the invention, the molten iron or molten ferro-nickel contains a small amount of carbon, and the intermixing of the metal with the molten ore is obtained by pouring the molten metal into the molten ore, or by the simultaneous pouring of both the molten metal and the molten ore into a ladle or other receiver. The action of the carbon on the ore creates a strong bubbling which aids in mixing the two materials. The carbon reacts with the iron and nickel oxides contained in the molten ore, liberating carbon monoxide which causes bubbling of the mixture. The pouring must not be so violent as to cause the mixture to overflow from the ladle. If the pouring is made rather slowly, the carbon monoxide released causes rather strong bubbling of the liquid bath without overflow from the ladle and provides a protracted contact time between the metal globules and the molten ore, thus promoting an almost total exhaustion of the nickel oxide in the ore. The mass of metal used in one operation for treating a given quantity of ore may be lower than where intermixing is accomplished by pouring without bubbling.

The amount of carbon introduced or contained in the metal bath may be small, say 0.2 to 0.5%. Some carbon can be added between successive intermixings, if the bath becomes too poor in carbon so that bubbling no longer is strong enough.

Other reducing elements can also be added, such as aluminum or silicon or their alloys, in order to increase the exothermicity of the reducing reaction. However, the bubbling may be decreased or delayed due to the stronger reducing action of the aluminum or silicon on the nickel and iron oxide in the ore.

The metal bath which is used for treating successive charges of molten ore may be either iron containing carbon or ferro-nickel containing carbon. The latter can be obtained by reduction of nickel ore or slag with carbon or by any other means.

The following is an example of this embodiment of the invention.

Example 4

The ore treated contained:

	Per cent
Nio	5.7
FeO	25
SiO_2	40
MgO	Balance

Two tons of this molten ore were tapped into a ladle. Carbon in the amount of 0.3% and silicon in the amount of 0.15% were added to a two ton bath of ferro-nickel containing 32% nickel, and this bath was then cautiously poured into the molten ore in the ladle. The pouring lasted about 5 minutes and caused a strong bubbling of the mixture. The ore and the metal were allowed to separate and the exhausted ore was removed from the metal. The ore contained only 0.15% NiO. The metal contained 36.30% nickel. The silicon and carbon were practically wholly oxidized.

These operations were repeated many times, using the same metal bath and two ton charges of new ore, and adding to the metal bath before each pouring 0.2% carbon and 0.15% silicon. After five pourings, ten tons of ore had been exhausted of its nickel content. The weight of the metal had increased slightly, and its nickel content was 52%.

The discontinuous processes above described secure excellent exhaustion of the ore, but they require many handlings of the ore and metal, particularly where the nickel content of the ore is low and many intermixings are required to provide ferro-nickel of desired nickel content. A continuous process will now be described in which the operations can be effectively carried out with a minimum of labor and maintenance of the equipment employed.

CONTINUOUS PROCESS

Referring more particularly to the accompanying drawings and for the present to Figures 1 and 2, there is provided an elongated cylindrical vessel **2** lined with refractory material and open at each end. The vessel extends in a substantially horizontal plane and is rotatable about its longitudinal axis **3**. A chute **4** extends into an opening **5** at one end of the rotatable vessel for supplying to the vessel molten ore which has been melted in a separate furnace. The other end of the vessel has a sloping neck portion **6** forming a dam **7** over which the exhausted ore passes and discharges into a chute **8**. In passing through the rotatable vessel **2**, the molten ore flows over and in contact with a bath of molten metal introduced into the vessel prior to the introduction of

the molten ore through the chute 4. During the passage of the molten ore through the vessel 2, the latter is rotated so as to secure intimate mixing of the molten ore and molten metal bath. The vessel is provided with tires or wheels 9 which rest on rollers 10. The vessel also is provided with a gear wheel 11 which is driven by any suitable means (not shown) in order to rotate the vessel.

An externally water-cooled tube 12 extends through an opening 13 in the end of the vessel opposite the molten ore supply chute 4 for supplying reducing agent, as for example silicon, ferro-silicon or aluminum to the molten ore in the vessel. The reducing agent is fed into a hopper 14 communicating with the tube 12 and is conveyed by a screw (not shown) located in the tube to the inner end of the tube where it falls through openings 15 onto the molten ore in the vessel. An internally water-cooled tube 16 also extends into the vessel through the opening 13 and carries a baffle 17 which dips into the molten ore 18 which is on top of the molten metal bath 19 and prevents the reducing agent from flowing out of the vessel. The opening 13 is closed by a refractory piece 20. Ferro-nickel produced in the reduction process is withdrawn from the vessel 2 through a tap hole 21. By way of example but not limitation, the rotatable vessel 2 may have a length of about 7½ meters and an internal diameter of 2½ meters.

In the embodiment illustrated in Figures 3–5, parts corresponding to those shown in Figures 1 and 2 are designated by the same reference numerals with the letter *a* suffixed. This embodiment is similar to that shown in Figures 1 and 2 except that the vessel 2*a*, instead of being cylindrical throughout its length, has a non-cylindrical cross-section at the portion 25 which is adjacent the end of the vessel through which the molten ore is supplied. The remaining portion 26 of the vessel is cylindrical in cross-section. The non-cylindrical section 25 provides more effective intermixing of the molten ore and molten metal than does the cylindrical section 26. Thus in this embodiment, the molten ore and molten metal are vigorously intermixed while in the portion 25, after which the molten ore and molten metal flow into the portion 26 where no more intermixing occurs and there is an opportunity for metal globules in the molten ore to settle from the ore into the metal bath 19*a*.

By way of example but not limitation, the cylindrical portion 26 of the vessel 2*a* may have a length of 3½ meters and the non-cylindrical portion 25 a length of 4½ meters. The major axis X of the non-cylindrical portion 25 may be 2.7 meters long, and the minor axis Y 2.2 meters long.

In the embodiment illustrated in Figures 6 and 7, parts corresponding to those shown in Figures 1 and 2 are designated by the same reference numerals with the letter *b* suffixed. In this embodiment, the rotatable vessel 2*b* is cylindrical throughout its working portion, but is provided in the portion 28 adjacent the charging opening 5*b* with longitudinally extending inwardly projecting ribs 29. The remaining portion 30 is cylindrical. Thus, as in the embodiment shown in Figures 3–5, vigorous intermixing of the molten ore and molten metal is obtained while the ore is in the portion 28, but when the ore passes into the portion 30, any metal globules entrapped in the molten ore have an opportunity to settle into and be incorporated into the molten metal bath.

Due to the increased intermixing obtained in the portions 25 and 28 of the rotatable vessels shown in Figures 3–7, as compared with the embodiment shown in Figures 1 and 2, a larger quantity of ore can be treated in a given size vessel or the size of the vessel can be reduced while treating the same quantity of ore where increased agitation is provided.

The apparatus described above does not include heating means, which considerably simplifies its structure. Such heat as is required to maintain the molten charge within the apparatus at the desired temperature may be supplied by the addition of reducing agents (such as ferro-silicon or aluminum) which react exothermically with iron oxide and nickel oxide present in the ore.

As the apparatus rotates, its interior wall surface is wetted by a layer of the molten ore, and this layer solidifies as it is carried upwardly and out of contact with the molten ore charge. Such solidified layer forms a constantly renewed protective lining for the apparatus. When continued rotation of the apparatus carries the solidified layer again beneath the surface of the molten charge, it remelts, but at least partially it does so only after being carried to beneath the surface of the molten metal layer. Thereby globules of ore are released below the metal surface and rise upwardly through the metal, with the result that the intimacy and extent of reactive contact between molten ore and molten ferrous metal are increased.

The quantity of ore present at all times in the apparatus must not be too high compared with the quantity of ferrous metal present at the same time, otherwise it is not possible to obtain an effective intermixing of both phases and consequently a complete exhaustion of the nickel from the ore. However, the stronger the intermixing and the longer the passage of the ore through the apparatus, the more the amount of ore present at any time can be increased. But the quantity of metal will always have to be much greater than the quantity of nickel contained in the ore present in the apparatus at a given time. Thus, for instance, if the vessel contained one ton of molten ore containing 3% NiO and the iron in the metal bath amounted to only about 25 kgs., it would be practically impossible to secure substantially complete exhaustion of the nickel content of the ore in its passage through the vessel.

Several variants are possible in carrying out the continuous process irrespective of the particular form of rotatable vessel which is employed. These variants correspond substantially to those described in connection with the discontinuous processes. As a first variant, one may start with a molten charge of pure iron or iron containing a low nickel content, and gradually build up the nickel content of the metal bath by substantially continuously passing molten ore through the rotating vessel in contact with the metal bath. When the ferro-nickel has acquired the desired nickel content, it may be removed from the vessel and a new charge of pure iron or iron containing a low nickel content may be placed in the vessel and the process repeated.

As a second variant, the vessel may be charged with a ferro-nickel having the desired nickel content and molten ore may then be flowed over it continuously while rotating the vessel and supplying reducing agent, for example, ferro-silicon, which is capable of reducing iron oxide and nickel oxide contained in the ore. Preferably the reducing agent is used in an amount so proportioned that the quantity of metallic iron introduced into the molten ferro-nickel by reaction of the reducing agent with the iron oxide of the ore is in substantially the same proportion to the amount of metallic nickel introduced into the molten ferro-nickel by reduction of the nickel oxide of the ore as is the proportion of iron to nickel in the ferro-nickel. Thus, the nickel content of the ferro-nickel remains substantially constant throughout the process but its weight increases. Ferro-nickel is withdrawn from the vessel from time to time or continuously.

Of course, any combination of the two above described variants may be employed.

In carrying out the invention, the rate at which the molten ore is delivered to the surface of the metal bath in the rotatable vessel is limited to the rate at which the nickel content of the ore can be substantially completely reduced and can be incorporated in the metal bath in a single passage through the vessel. One can use in the apparatus all known methods for increasing the intermixing between ore and metal, for example blowing of

gas, production of CO by addition of carbon to the metallic bath, etc.

The following examples illustrate various ways in which the process can be carried out in a continuous manner.

Example 5

The ore which was treated had the following composition:

	Percent
NiO	4.20
FeO	25.4
SiO_2	41.3
MgO	24.5
Al_2O_3	3.4

In carrying out this example, the apparatus shown in Figures 1 and 2 was employed. Ten tons of molten steel were charged into the vessel **2**, and then molten ore previously melted in a separate reverberatory furnace was introduced into the vessel **2** through the chute **4** until the ore reached approximately the level of the dam **7**. The vessel was revolved at a speed of 4 revolutions per minute and after a short time, fresh molten ore was poured into the vessel through the chute **4** substantially continuously at a rate of 20 tons per hour while the vessel was rotating. Every ten minutes, 8.5 kgs. of ferro-silicon containing 75% silicon were introduced into the vessel through the tube **12**. The added ferro-silicon melted and dissolved in the metal bath **19**. The molten ore flowed through the furnace and over the dam **7** and into the chute **8**. The ore was substantially completely exhausted of its nickel content in a single passage through the vessel, its NiO content at the exit end of the vessel being of the order of 0.15%. After the process had been continued for 8 hours, the metal bath had become a ferro-nickel containing 50.3% nickel. The operation was stopped, the ferro-nickel withdrawn through the tap hole **21**, a new charge of molten steel was introduced into the vessel, and a new operation was begun.

Example 6

The ore treated had the following composition:

	Per cent
NiO	1.89
FeO	13.50
SiO_2	46
$MgO+Al_2O_3$	Balance

The process was carried out in apparatus of the type shown in Figures 3–5.

Ten tons of molten ferro-nickel containing about 50% nickel were charged into the vessel **2***a* and then molten ore was supplied through chute **4***a* until it reached a level of about 20 centimeters below the top of dam **7***a*. The vessel was then rotated at a speed of about 4 revolutions per minute, and molten ore was then introduced continuously into the vessel at the rate of 30 tons per hour while 25 kgs. of ferro-silicon containing 75% silicon were introduced into the vessel every 5 minutes. The depleted molten ore discharged over the dam **7***a* contained 0.10% NiO. After working for a period of about 12 hours, the operation was stopped. The metallic bath had approximately doubled in weight and contained about 50.3% nickel. It is seen that in carrying out this step of the process, the ferro-silicon was used in such amount that the iron and nickel reduced from the ore were in approximately the same proportions as the iron and nickel in the ferro-nickel bath so that the composition of the ferro-nickel bath remained substantially constant, but its weight increased. Ten tons of the ferro-nickel were then removed from the vessel and another operation was begun using the 10 tons of ferro-nickel remaining in the vessel and repeating the operation as described.

Example 7

The same ore as given in Example 1 was treated but the treatment was carried out in apparatus of the type shown in Figures 3–5.

Ten tons of molten ore were poured into the vessel **2***a*, and the vessel was rotated. During the first half-hour, 800 kgs. of ferro-silicon containing 75% silicon were introduced. At the end of this first half-hour period, there had been produced 2300 kgs. of a metallic bath containing 14% nickel, the rest being mainly iron.

The vessel was then charged with fresh molten ore up to a level of about 20 centimeters below the top of the dam **7***a* while the vessel was rotating and then while the vessel continued to rotate, molten ore was introduced continuously together with 80 kgs. of ferro-silicon (75% Si) per ton of ore. After the molten ore had reached the top of the dam, it overflowed from the vessel. During a period of 1½ hours, 35 tons of molten ore were treated so as to substantially completely exhaust the ore of its nickel content. In this period, the bath increased in weight to about 10 tons but its nickel content remained substantially at 14% because the proportion of iron and nickel reduced from the ore was approximately the same as that in the metal bath.

After the weight of the metallic bath had reached about 10 tons, the amount of ferro-silicon introduced into the vessel was decreased to 3 kgs. per ton of ore while the ore was passed through the rotating vessel at the rate of 30 tons per hour. The bath grew progressively richer in nickel, without greatly changing its weight, so that after 4 hours, its nickel content had been increased to about 50%.

The operation was then continued by supplying ore to the vessel at the rate of 30 tons per hour, but the amount of ferro-silicon containing 75% silicon was increased to 22 kgs. per ton of ore. After this step had been continued for 5½ hours, the weight of the bath had increased to about 20 tons but its nickel content remained at about 50% because during this step, both iron and nickel were reduced from the ore, and in approximately the proportions of these elements in the metal bath.

Rotation of the vessel was then stopped, and ten tons of the metal were withdrawn. The operation was then resumed using the 10 tons of metal remaining in the vessel and employing the same working conditions, i. e., a flow of 30 tons of ore per hour through the vessel while adding 22 kgs. of ferro-silicon per ton of ore. This operation was continued until the metal bath weighed about 20 tons, after which half of it was withdrawn and the process continued in a like manner.

The invention is not limited to the preferred embodiments, but may be otherwise embodied or practiced within the scope of the following claims.

I claim:

1. A process for extracting nickel from low grade nickel ores containing an oxidic compound of nickel, which comprises violently intermixing molten low grade nickel ore with a bath of ferro-nickel containing at least 25% by weight of nickel to reduce nickel oxide from the ore and introduce it into the metal of the bath, removing the denickelized ore from the bath, also withdrawing a portion of the ferro-nickel from the bath, adding a reducing agent to the remainder of the metal bath, then intermixing the remainder of the metal bath with a further quantity of molten low grade nickel ore, and repeating the above described sequence of operations.

2. A process for extracting nickel from a low grade nickel ore containing iron and nickel in the form of oxidic compounds, which comprises forming a molten bath of said ore, vigorously intermixing with said molten bath a quantity of molten ferro-nickel containing a reducing agent for ferrous oxide and nickel oxide, the amount of reducing agent being such as to reduce iron and nickel from the ore in about the same proportion as the propor-

tion of iron to nickel in the ferro-nickel, whereby the weight of ferro-nickel is increased while maintaining its percentage content of nickel substantially undiminished, withdrawing a portion of the ferro-nickel, and utilizing the remainder of the ferro-nickel for the treatment of a further quantity of molten ore.

3. A process for extracting nickel from low grade nickel ores containing oxidic compounds of nickel and iron, which comprises violently intermixing the molten ore with molten ferro-nickel containing at least 25% by weight of nickel and also containing a reducing agent for iron oxide, said reducing agent being in amount sufficient to reduce iron oxide in the ore and introduce it into the ferro-nickel bath, whereby the concentration of nickel in the metal bath is limited, and repeatedly intermixing the ferro-nickel bath with successive charges of said molten ore, said ferro-nickel bath having quantities of said reducing agent added to it prior to at least some of the successive intermixings.

4. A process for extracting nickel from low grade nickel ores containing an oxidic compound of nickel, which comprises intermixing ferro-nickel containing carbon and at least 25% by weight of nickel and a bath of molten low grade nickel ore containing oxidic compounds of nickel and iron by a pouring operation, whereby vigorous evolution of carbon monoxide ensues and effects thorough intermixing of the molten ferro-nickel with the molten ore, and whereby the nickel content of the ore is substantially completely reduced to metallic nickel and is incorporated in the ferro-nickel bath, removing the denickelized ore from the ferro-nickel bath, and repeatedly adding carbon to the ferro-nickel bath and intermixing it with successive charges of the molten low grade nickel ore.

5. A process for recovering nickel from a low grade ore containing nickel in the form of an oxidic compound which comprises continuously flowing such ore in the molten condition over the surface of a bath of molten ferrous metal, subjecting the molten ore and the molten metal bath to an intermixing action, maintaining the molten ore in contact with the molten bath for a sufficient period of time for the nickel of the ore to be substantially completely reduced by the iron of the bath and to become incorporated in the bath, substantially continuously withdrawing the molten ore residue after it has become substantially completely depleted of nickel, and withdrawing molten ferrous metal containing nickel in a substantially higher concentration than the ore from said bath.

6. A process for recovering nickel from a low grade nickel ore containing oxidic compounds of iron and nickel which comprises continuously flowing such ore in the molten condition over the surface of a bath of molten ferro-nickel, subjecting the molten ore and the molten metal while in contact with each other to a stirring action, treating the molten ore while in contact with the molten ferro-nickel with a reducing agent for iron oxide in an amount so proportioned to the nickel content of the ore that the quantity of metallic iron introduced into the molten ferro-nickel by reaction of said reducing agent with the iron oxide of the ore is in substantially the same proportion to the amount of metallic nickel introduced into the molten ferro-nickel by reduction of the nickel oxide of the ore as is the proportion of iron to nickel in the ferro-nickel, maintaining the molten ore in contact with the molten ferro-nickel until the ore has been substantially completely depleted of nickel, substantially continuously withdrawing the depleted ore residue, and withdrawing molten ferro-nickel from said bath at such a rate as to maintain the total volume of said bath approximately constant.

7. A process for recovering nickel from a low grade ore containing nickel in the form of an oxidic compound which comprises introducing a bath of molten metallic iron into a rotary vessel, melting said ore and delivering a substantially continuous flow of the molten ore on to the surface of said bath, promoting an intermixing between the molten iron and the molten ore by substantially continuously rotating said vessel about a substantially horizontal axis, maintaining the molten ore in contact with the molten metallic bath until the nickel content of the ore has been substantially completely reduced by reaction with the molten iron, substantially continuously withdrawing molten ore residue depleted of nickel from said vessel, and withdrawing metal from said bath when the nickel content thereof has been built up sufficiently to form a ferro-nickel of desired grade.

8. A process for recovering nickel from a low grade ore containing nickel in the form of an oxidic compound which comprises introducing a bath of molten metallic ferro-nickel into a rotary vessel, melting said ore and delivering a substantially continuous flow thereof on to the surface of said bath, stirring the molten ore into effective reactive contact with the iron of said bath by substantially continuously rotating said vessel about a substantially horizontal axis, maintaining the molten ore in contact with the molten metallic ferro-nickel for a sufficient period of time for the nickel content of the ore to be substantially completely reduced by reaction with the iron of the ferro-nickel and to become incorporated in the ferro-nickel, incorporating fresh metallic iron in the ferro-nickel in the same proportion to the amount of nickel incorporated therein by reduction from the ore as the initial proportion of iron to nickel in the ferro-nickel, whereby the composition of the ferro-nickel is maintained substantially constant, substantially continuously withdrawing molten ore residue depleted of nickel from over said bath, and withdrawing ferro-nickel from said bath as required to maintain the volume thereof in the vessel approximately constant.

9. A process for recovering nickel from a low grade ore containing nickel in the form of an oxidic compound which comprises introducing a molten metallic bath comprising iron into a rotary vessel, melting said ore and substantially continuously delivering a flow of the molten ore on to the surface of said bath, stirring the molten metallic bath and the molten ore into effective reactive contact by substantially continuously rotating said vessel about a horizontal axis, limiting the rate at which molten ore is delivered to the surface of the bath to the rate at which the nickel content of the ore can be substantially completely reduced by reaction with the iron of the bath and can be incorporated in the bath, substantially continuously withdrawing the spent ore melt after it has been substantially completely depleted of nickel from the surface of said bath at a point remote from where it is delivered on to the bath and at substantially the same rate as it is delivered thereto, and recovering the nickel reduced from the ore in the form of metallic ferro-nickel withdrawn from said bath.

10. A process for recovering nickel from a low grade nickel ore containing oxidic compounds of iron and nickel which comprises introducing a bath of molten metallic ferro-nickel into a rotary vessel, melting said ore and substantially continuously delivering a flow of the molten ore on to the surface of said bath, stirring the molten ore into effective reactive contact with the ferro-nickel by substantially continuously rotating said vessel about a substantially horizontal axis, limiting the rate at which molten ore is delivered to the surface of the bath to the rate at which the nickel content of the ore can be substantially completely reduced by reaction with the metallic bath and can be incorporated in the bath, adding to the bath while in contact with the molten ore a reducing agent for iron oxide in an amount so proportioned to the nickel content of the ore that the quantity of metallic iron introduced into the molten ferro-nickel by reaction of said reducing agent with the iron oxide of the ore is in substantially the same proportion to the amount of metallic nickel introduced into the molten ferro-nickel by reduction of the nickel oxide of

the ore as is the proportion of iron to nickel in the ferro-nickel, substantially continuously withdrawing the ore melt after it has been substantially completely depleted of nickel from the surface of the bath of ferro-nickel at a point remote from where it is delivered on to the bath and at substantially the same rate as it is delivered thereto, and recovering the nickel and iron reduced from the ore in the form of ferro-nickel by withdrawal thereof from said bath.

11. In a process for the recovery of nickel from a low grade ore containing nickel in the form of an oxidic compound, the steps which comprise substantially continuously delivering a molten stream of the ore to the surface of a molten metallic bath comprising iron and substantially continuously withdrawing the ore melt depleted in nickel from the surface of said metallic bath, subjecting the molten ore and the molten metallic bath to an intermixing action at a region remote from the point of withdrawal of the depleted ore melt, thereby to insure effective reactive contact between the molten ore and the molten metallic bath, and maintaining the molten ore and molten metallic bath relatively quiescent in the region adjacent the point of withdrawal of the depleted ore melt, thereby to enable substantially unhindered settling of metallic particles from the ore melt immediately prior to withdrawal of said melt.

12. A process for recovering nickel from a low grade ore containing nickel in the form of an oxidic compound, which comprises introducing a molten metallic bath comprising iron into a rotary vessel, melting said ore and substantially continuously delivering a flow of the molten ore on to the surface of said bath, flowing the molten

ore in contact with the surface of said bath successively through a first zone and then through a second zone, limiting the rate at which molten ore is delivered to the surface of the bath to the rate at which the nickel content of the ore can be substantially completely reduced by reaction with the iron of the bath and can be incorporated in the bath in passing through said zones, stirring the molten metallic bath and the molten ore into effective reactive contact while in the first zone by substantially continuously rotating said vessel, decreasing the amount of stirring of the molten ore during its passage through the second zone to cause effective settling of metal globules from the ore into the metallic bath, substantially continuously withdrawing the spent ore melt after it has been substantially completely depleted of nickel from the surface of said bath after it has passed through the second zone, and recovering the nickel reduced from the ore in the form of metallic ferro-nickel withdrawn from said bath.

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