April 2, 1968 J. H. CARPENTER 3,375,925

MAGNETIC SEPARATOR

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FIG. 1

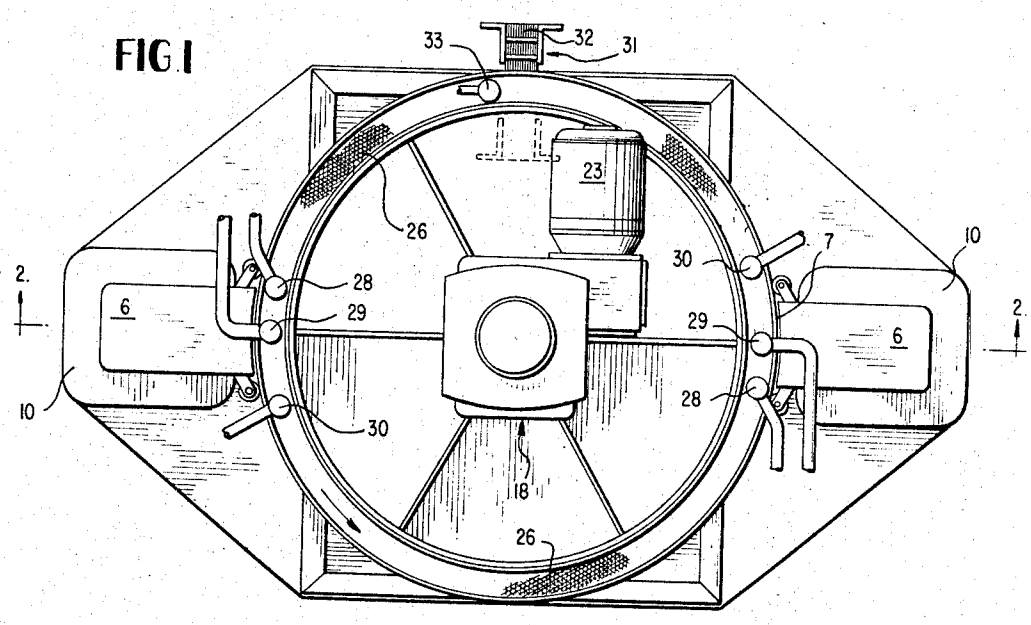
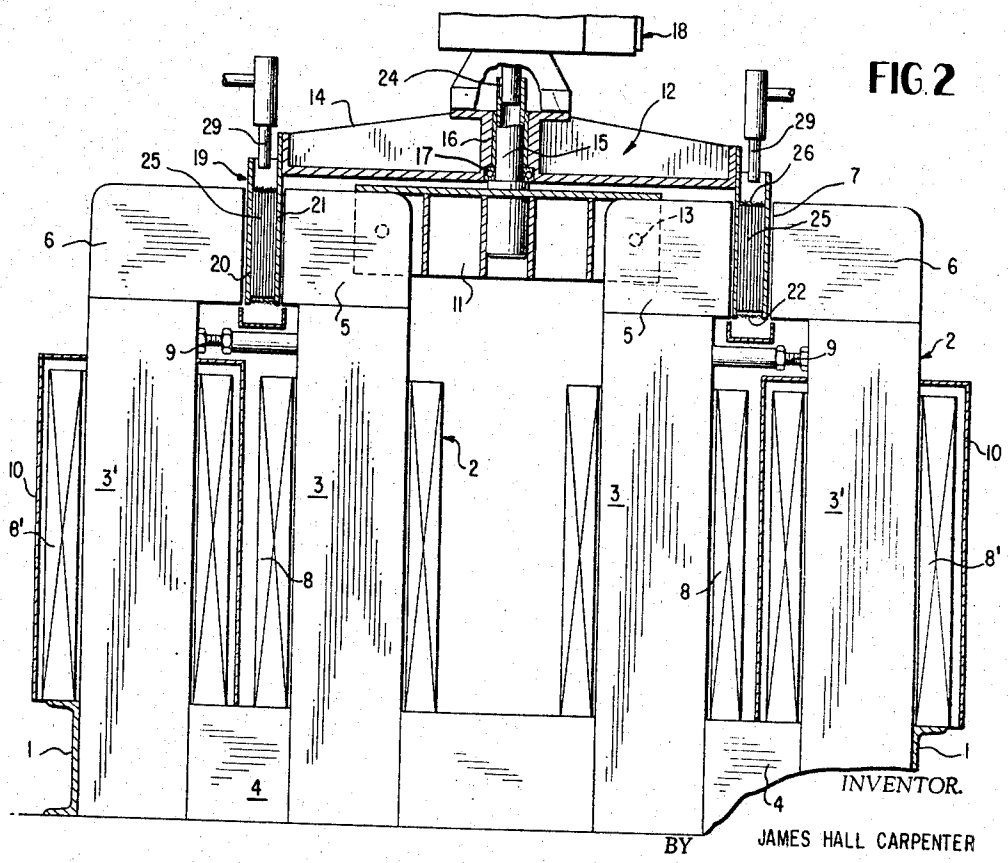


FIG. 2



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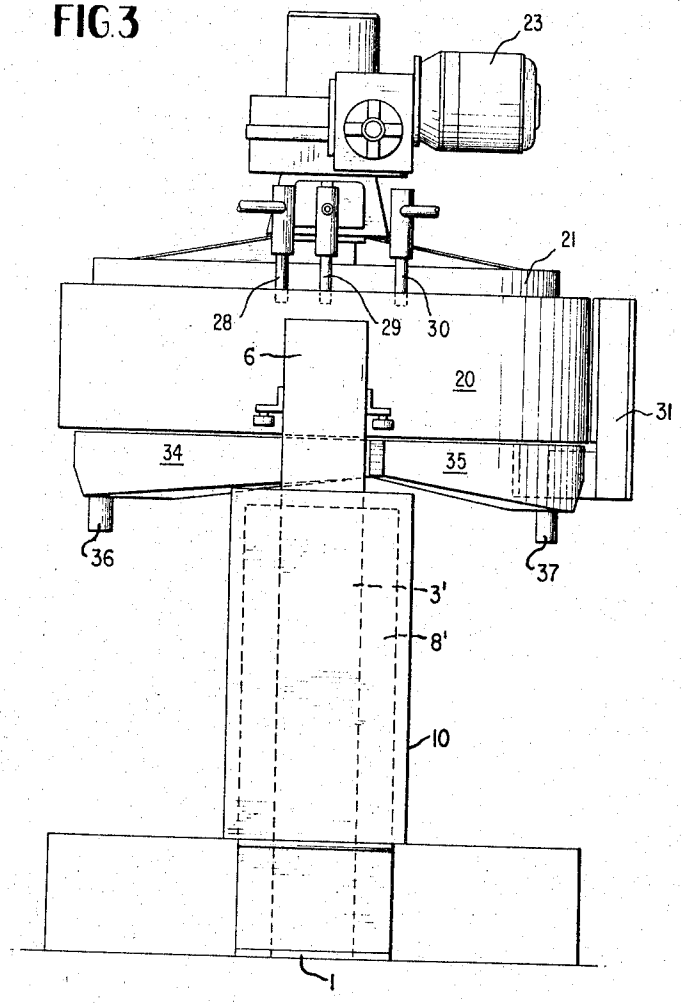
BY Jones, Birch, Swindler & McKie
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MAGNETIC SEPARATOR

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FIG. 3



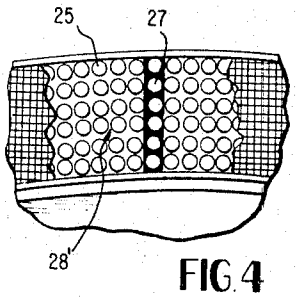


FIG. 4



FIG. 5

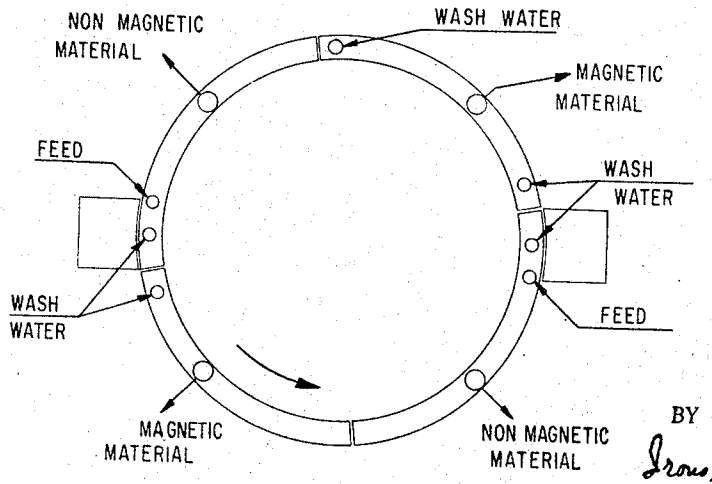


FIG. 6

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MAGNETIC SEPARATOR

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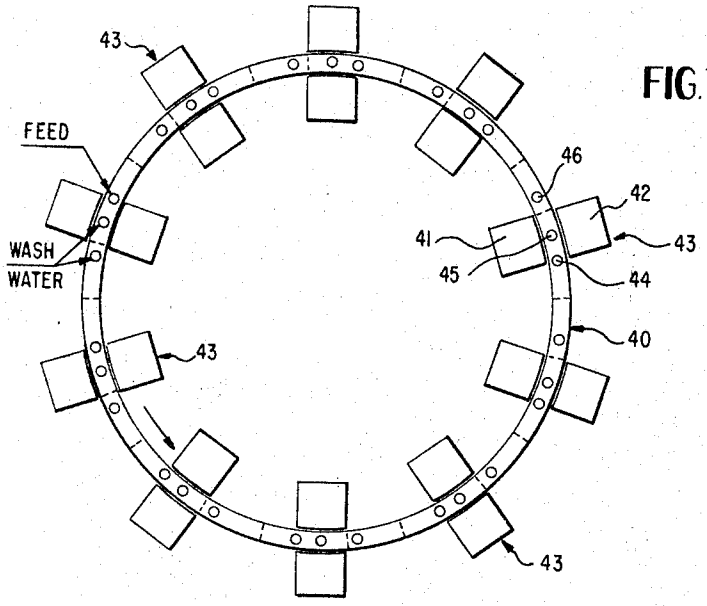
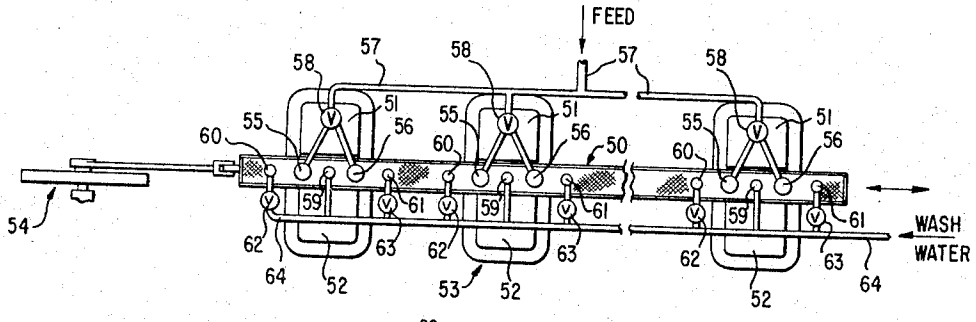


FIG. 7

FIG. 8



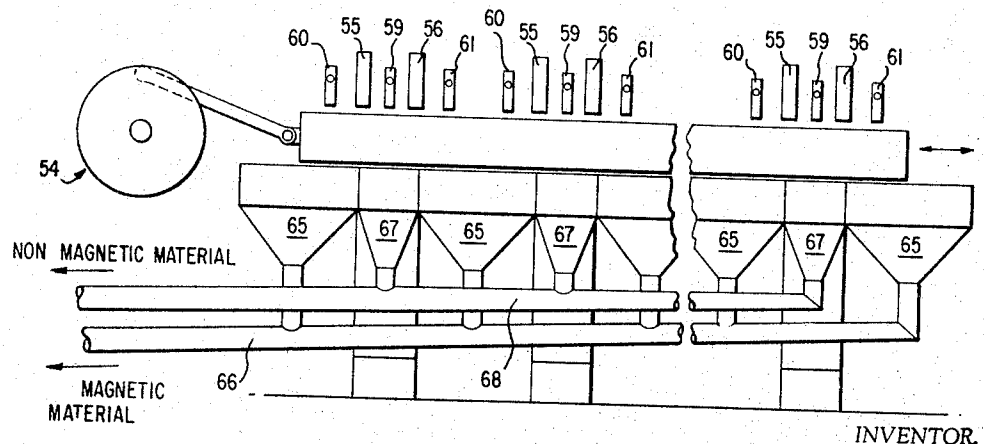


FIG. 9

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MAGNETIC SEPARATOR

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FIG. 10.

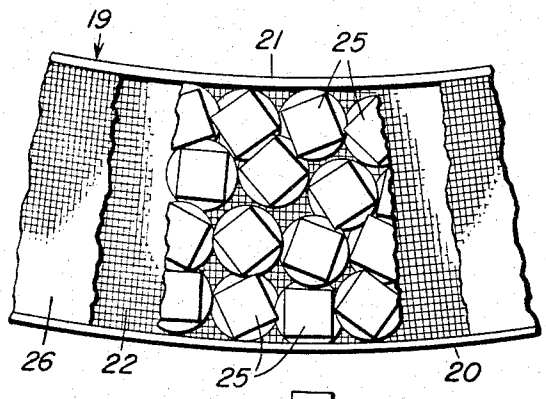
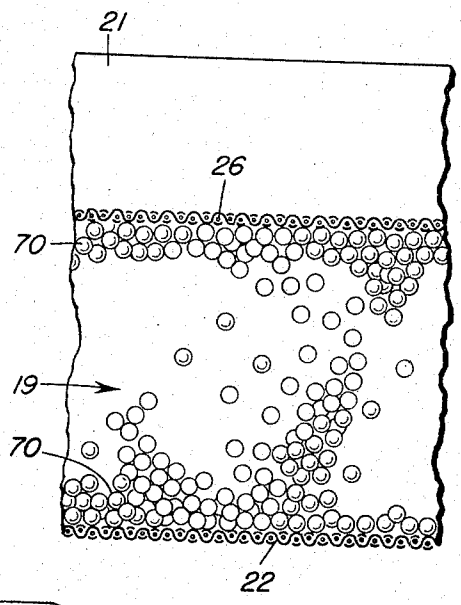


FIG. 11.



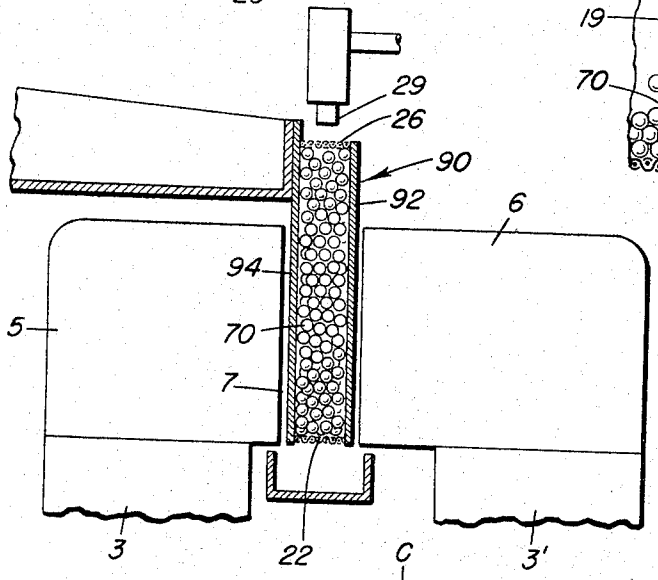
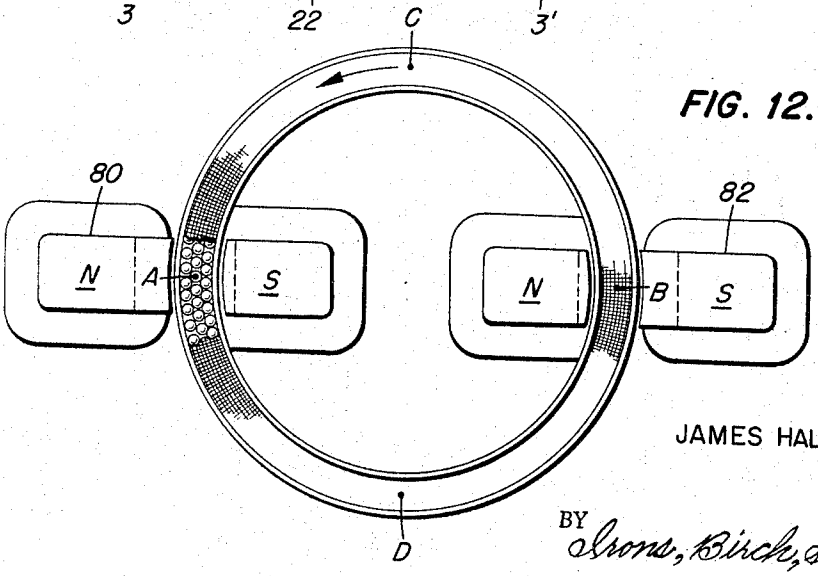


FIG. 13.

FIG. 12.



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United States Patent Office 3,375,925 Patented Apr. 2, 1968

3,375,925

MAGNETIC SEPARATOR

James Hall Carpenter, Jacksonville, Fla., assignor to Carpco Research & Engineering, Inc., Jacksonville, Fla., a corporation of Florida

Continuation-in-part of application Ser. No. 335,069, Jan. 2, 1964. This application Oct. 18, 1966, Ser. No. 587,494

24 Claims. (Cl. 209—214)

ABSTRACT OF THE DISCLOSURE

A method and an apparatus for separating materials of differing magnetic susceptibility utilizing a plurality of loose, unattached, individually movable bodies, at least some of which are composed of a highly permeable material, wherein the bodies are successively passed into, through and out of an effective magnetic field.

The present application is a continuation-in-part of copending application Ser. No. 335,069, filed Jan. 2, 1964, now abandoned.

This invention relates to magnetic separators for separating materials of differing magnetic susceptibility, and, more particularly, to magnetic separators adapted to separate materials of nonmagnetic susceptibility or materials of relatively low magnetic susceptibility from materials of relatively high magnetic susceptibility.

Magnetic separators long have been known in the art and have been particularly efficacious in the separation of materials of high magnetic susceptibility from materials of nonmagnetic susceptibility. Although the greatest success and commercial use of magnetic separators previously have been accomplished utilizing dry separation processes, some success in the separation of highly magnetically susceptible materials under wet conditions has been achieved. Despite strenuous efforts over a long period of time, however, there has not been developed heretofore a commercially satisfactory magnetic separator for the magnetic beneficiation of weakly magnetically or nonmagnetically susceptible materials, such as weakly magnetically susceptible molybdenum and tungsten ores or nonmagnetically susceptible titanium ores, under wet conditions.

The more successful magnetic separators developed and employed in the art usually have comprised an axially rotatable drum having disposed interiorly thereof a plurality of fixed magnets. The magnets normally are placed in close proximity to a selected portion of the interior surface area of the drum so that when magnetically susceptible particle-carrying material is fed against the external peripheral portion of the drum overlying the fixed magnets, the magnetically susceptible particles will adhere to the surface of the drum, and can thereafter be carried to a discharge position. The nonmagnetically susceptible material, unaffected by the magnetic field, normally is permitted to fall under the influence of gravity for separate collection. When such equipment is employed for wet separating processes, a slurry or pulp of the material to be separated either is fed against the external periphery of the drum in the same manner as dry material or, where more dilute slurries, pulps or suspensions of materials are employed as the feed, the rotating drum often is submerged in the liquid.

As indicated, processes employing such equipment have been quite successful with dry material and moderately successful with wet material where strongly magnetically susceptible particles were being separated from nonmagnetically susceptible particles. Under wet conditions, however, any relative movement between the particle-carrying fluid and the magnetically actuated surface employed to effect the separation, such as the movement resulting from the presence of eddy currents, has tended to wash weakly magnetically susceptible particles away from the surface after contact has been attained. Reduction of the rotational speed of the drum to avoid eddy currents has reduced the efficiency of the separation so that such processes have been found to be economically infeasible.

The extended efforts to solve the problem of separating weakly magnetically and nonmagnetically susceptible materials, particularly under wet conditions, are exemplified by Jones' Patents 2,834,470 and 3,021,007. However, these and other efforts have failed to provide the art with the practical commercial separator desired.

It is, therefore, the primary object of the present invention to provide a magnetic separator which effectively separates weakly magnetically susceptible materials from nonmagnetically susceptible or faintly magnetically susceptible materials under both dry and wet conditions.

A further object of the invention is to provide a magnetic separator which will effectively separate weakly magnetically susceptible materials from gangue materials in yields which are economically attractive.

Another object of the invention is to provide a magnetic separator which will effectively separate economically attractive yields of a desired nonmagnetically susceptible material from feed mixtures containing highly magnetically susceptible and weakly magnetically susceptible materials.

An additional object of the invention is to provide a magnetic separator which is economical to construct, has few moving parts and is readily serviceable.

Yet another object of the invention is to provide a magnetic separator which does not require meticulous sizing of feed materials and which tends to be essentially self-cleaning.

A further object of the invention is to provide a magnetic separator in which high field strengths of over 22,000 gauss can be obtained with a relatively minor power input, in the order of 2,000 watts, in a commercial machine capable of separating over 4,000 pounds of material per hour.

Another object of the invention is to provide a magnetic separator which does not require high pressure fluids for effecting the removal of magnetically susceptible materials from the apparatus and which is economical in washing fluid requirements.

A further object of the invention is to provide a magnetic separator which, when employed in the separation of weakly magnetically susceptible materials, demonstrates resistance to becoming clogged or choked with ferromagnetic impurities which may be present in the feed materials.

Another object of the invention is to provide a magnetic separator which, when utilized for the separation of desired nonmagnetically susceptible materials, substantially obviates entrapment of the nonmagnetically susceptible materials by the highly magnetically susceptible materials which may be present in the feed.

Yet a further object of the invention is to provide a method for separating nonmagnetically susceptible materials or materials of relatively low magnetic susceptibility from materials of relatively high magnetic susceptibility, which method is practical economically.

Additional objects of the invention will become apparent upon consideration of the general and detailed descriptions which follow.

Generally described, the apparatus of the present invention is a device for separating materials of differing magnetic susceptibility comprising: at least one magnet

means having oppositely disposed field poles of opposite polarity for producing an effective magnetic field therebetween; a plurality of loose, unattached induced pole pieces movable relative to the field poles, said induced pole pieces being individually movable relative to each other; means for moving the induced pole pieces and the field poles relative to each other so that the induced pole pieces pass into, through and out of the effective magnetic field, and means for introducing the material to be separated into the effective magnetic field and therein into proximity with the induced pole pieces as the pieces pass through said field.

Generally described, the method of the present invention is a process for separating materials of nonmagnetic susceptibility or materials of relatively low magnetic susceptibility from materials of relatively high magnetic susceptibility which comprises: passing a mixture of the materials to be separated into a continuous magnetic field and therein into proximity with a plurality of individually movable bodies at least some of which are composed of a highly permeable material; removing the feed material of nonmagnetic susceptibility or lower magnetic suspectibility from proximity with the individually movable bodies and from the feed material of higher magnetic susceptibility while the feed materials and the individually movable bodies are within the continuous magnetic field; separately collecting the material of nonmagnetic susceptibility or material of lower magnetic susceptibility; removing the feed material of higher magnetic susceptibility and the individually movable bodies from the continuous magnetic field; removing the feed material of higher magnetic susceptibility from proximity with the individually movable bodies; and separately collecting the feed material of higher magnetic susceptibility.

In accordance with the present invention, an induced pole piece is a piece of highly permeable material which will become magnetized by magnetic induction when the pole piece is disposed within a magnetic field. Such a pole piece may be characterized by a number of sharp edges, corners or surfaces which will become highly inductively magnetized and will cause the flux lines of a magnetic field in which the piece is disposed to converge, to provide optimum points for attracting magnetically susceptible material. In the alternative, an induced pole piece may be characterized by a smooth, continuous, contour-of-revolution configuration, having a surface which will become highly inductively magnetized at specific regions causing the flux lines of a magnetic field in which the piece is disposed to converge, and thus also provide optimum points for attracting magnetically susceptible material. Induced pole pieces operable in the present invention include, without limitation, helical rods resembling drill bits, cubes, spheres, deformed metallic screen, expanded metal and the like.

As used in the specification and claims, the phrase effective magnetic field defines a spatial region within which the strength of the magnetic field produced by a magnet means is of sufficient magnitude to cause an induced pole piece disposed therein to become inductively magnetized to such a degree that any substantial amount of magnetically susceptible material present in the feed material will be attracted by such induced pole piece.

The magnet means operable in the apparatus and method of the invention, for producing effective magnetic fields, may comprise either electromagnets or permanent magnets. Because of their greater strength, electromagnets are preferred. The magnet cores, magnet field poles and induced pole pieces may be fabricated from any highly permeable material. Preferably these members are fabricated from low carbon steel or an alloy of iron and cobalt. In particular, the induced pole pieces preferably are fabricated from a magnetically soft material to minimize any tendency of the induced pole pieces to become permanently magnetized.

In accordance with a preferred embodiment of the invention, a plurality of loose, unattached, individually movable induced pole pieces are carried by an annular container rotatably mounted to pass between the field poles of one or more magnet means. Alternately, the induced pole pieces may be disposed within a container which is mounted to pass between the field poles of one or more magnet means in a substantially straight line or in an arcuate path. Whether the induced pole pieces are passed between the field poles of the magnet means in a curvilinear or straight line, such passage through the effective magnetic field or fields produced by the magnet means may be reciprocal. In other words, the pole pieces may be passed through the effective magnetic field or fields in one direction and then the direction of passage may be reversed to cause the induced pole pieces to pass through the effective magnetic field or fields in the opposite direction.

The loose, unattached induced pole pieces are packed into a container and are retained therein by a foraminous member forming the container bottom. Another foraminous member forms the container top; however, the induced pole pieces are not fixedly secured to the side walls or to the top or bottom members of the container and thus are permitted to move about relative to each other therewithin. As the induced pole pieces are passed between the field poles of a magnet means and through the effective magnetic field produced thereby, the induced pole pieces will move about with respect to each other within the confines of the container. The magnitudes of the displacement and force of such movement have been found to be dependent upon the strength of the magnetic field through which the pieces are passed. Although all of the factors which cause this movement to occur may not be known presently, it is believed to be the result of the interaction of the magnetic field with the macroscopic magnetic properties of the individual induced pole pieces. Such properties derive from the individual orientation of the metallic crystalline structure of each of the induced pole pieces, and the orientation of the individual magnetic fields which emanate from the pieces upon the inductive magnetization thereof. Experience has shown that movement of the induced pole pieces relative to each other will occur each time the pieces are passed through an effective magnetic field.

The movement of the induced pole pieces produces several extremely beneficial results which particularly contribute to the advantageous operation of the magnetic separator of the present invention. Individual induced pole piece movement tends to produce a self-cleaning action. Thus, the natural propensity for sedimentary materials or gangue to accumulate on the surfaces of the induced pole pieces which might tend to clog or impair the flow of material through the magnetic separator is reduced.

More importantly, measurements have shown that the strength of an effective magnetic field will be maximized when the induced pole pieces move about and orient themselves under the influence of the flux patterns of the field. This phenomenon is one of the resultants attributable to the factors previously mentioned which are believed to cause the induced pole pieces to shift and move about within the container. It has been observed that as the induced pole pieces pass into an effective magnetic field and the various magnetic parameters interact to cause the pieces to shift and move about within the container, the strength of the magnetic field will attain a maximum value and the flux lines will converge at certain points on the surface of each induced pole piece. This convergence occurs principally at the sharp edges of induced pole pieces having a plurality of surface discontinuities, such as helical rods and cubes. Flux line convergence also occurs at specific regions on the surfaces of smoothly configured induced pole pieces, such as spheres. These surface points of flux line convergence provide optimum points for attracting magnetically susceptible particles present in the feed materials.

In the operation of the embodiments of the invention specifically described or other embodiments which will occur to those skilled in the art, the separation of materials of differing magnetic susceptibility is accomplished substantially as follows. The material to be separated is introduced into the effective magnetic field produced between the field poles of a magnet means and therein into proximity with the induced pole pieces as the pieces pass through the field. Conveniently, the feed material is introduced into the top of the container in which the pole pieces are disposed as the container enters the gap between the field poles of the magnet means. The passage of the feed material downwardly through the interstices between the induced pole pieces will be affected by a plurality of independently variable parameters, including the strength of the magnetic field, the size, shape and composition of the induced pole pieces, the rate at which the feed material is introduced into the container, the speed at which the container is passed through the magnetic field and the size of the openings through the foraminous members of the container. As will be apparent, the physical phenomena associated with these numerous parameters will subject the feed material to a plurality of complex hydrodynamic and magnetic forces. Passage of the nonmagnetically susceptible material through the container will be affected by all of the hydrodynamic forces; whereas, passage of the magnetically susceptible material will be affected by all of the forces, both of a hydrodynamic and magnetic character. The conglomerate effect of the hydrodynamic forces on the nonmagnetically susceptible particulate material results in the continuous movement of substantially all of this material with respect to the induced pole pieces during the entirety of the passage thereof through the container. Similarly, the conglomerate effect of the hydrodynamic and magnetic forces on the magnetically susceptible particulate material results in the continuous movement of a greater or lesser portion of this material with respect to the induced pole pieces during the entirety of the passage thereof through the container. This continual motion mode of passage, experienced by substantially all of the nonmagnetically susceptible material, may be functionally characterized as to this material as a magnetically uninfluenced, continuously dynamic passage. The greater or lesser portion of the magnetically susceptible material which is subjected to the continual motion mode of passage will not be retained statically on the surface of any one of the induced pole pieces, although the individual induced magnetic fields emanating therefrom obviously will affect the direction and velocity of such material as it passes between the pieces. This mode of passage with respect to the magnetically susceptible material may be functionally characterized as a magnetically influenced, continuously dynamic passage. The principal difference between the characteristics of the passage through the container of the nonmagnetically susceptible material and the magnetically susceptible material under conditions wherein each of the materials is subjected to forces causing continuous motion thereof with respect to the induced pole pieces resides in the dissimilar average vertical velocity of each of the materials through the container, due primarily to the retarding or deterrent effect of the magnetic activity on the passage of the magnetically susceptible material. Another portion of the magnetically susceptible material, which does not undergo magnetically influenced, continuously dynamic passage through the container, will be attracted to and statically retained intermittently on the surfaces of the individual inductively magnetized induced pole pieces, principally in the regions of flux line convergence thereon. Each of the particles passing in this mode will be statically retained on the surface of each of a plurality of induced pole pieces for a perceptible interval of time, each particle of the material thus passing downwardly with intermittent, as distinguished from continuous, motion with respect to the pole pieces. This mode of passage

of the magnetically susceptible material may be functionally characterized as magnetically influenced, intermittently dynamic. It will be evident that the average vertical velocity of the portion of the magnetically susceptible material which passes through the container in this mode will be less than that portion of such material which passes in the magnetically influenced, continuously dynamic mode due to the intermittent static retention of the material particles. A further portion of the magnetically susceptible material will pass through the container in a third passage mode that is distinct from both the magnetically influenced, continuously dynamic and intermittently dynamic modes. The third passage mode of the magnetically susceptible material is characterized by the static retention of individual material particles on the surface of a single induced pole piece for the interval of time during which the pole piece remains inductively magnetized by an effective magnetic field. After a particular induced pole piece passes without the effective magnetic field, the particles statically retained thereon will be released and will pass downwardly through the container under the influence of the hydrodynamic forces acting therewithin. This mode of passage may be functionally characterized as magnetically influenced, intermittently static. The average vertical velocity of the portion of the magnetically susceptible material which passes downwardly through the container in this mode will be less than the average vertical velocity of the material which passes in either of the magnetically influenced, continuously dynamic or intermittently dynamic modes due to the relatively long period during which the material particles are statically detained.

From the foregoing description, it will be apparent that the characteristics of the separation process may be controlled by appropriately varying one or more of the previously mentioned parameters which affect the passage of materials through the container. Such parameters may be controlled so that a desired proportion of the magnetically susceptible material will pass through the container in either of the magnetically influenced, continuously dynamic, intermittently dynamic or intermittently static modes. The nonmagnetically susceptible material, which passes through the container in the magnetically uninfluenced, continuously dynamic mode, largely will pass through the foraminous bottom of the container before the container passes out of the effective magnetic field; this material, being unaffected by the magnetic activity, experiences the greatest downward average vertical velocity. The magnetically susceptible material largely will be deterred in the container, passing therethrough in either of the magnetically influenced, continuously dynamic, intermittently dynamic or intermittently static modes, until the container and the induced pole pieces have passed out of the magnetic field. The effect of the magnetic activity on such material being to lower the average vertical velocity thereof as it passes through the container. After the induced pole pieces have passed out of the magnetic field, the pieces will become substantially inactive magnetically, and the magnetically susceptible material being no longer subjected to the deterrent influence of magnetic activity will pass through the foraminous bottom of the container. Preferably, the removal of the nonmagnetically susceptible material, which occurs within the effective magnetic field, will be accelerated by a fluid wash which may be introduced into the top of the container as the container is between the field poles of the magnet means. Similarly, the removal of the magnetically susceptible material, which occurs without the effective magnetic field, preferably will be accelerated by a fluid wash also which may be introduced into the top of the container after the container has passed from between the field poles of the magnet means. These fluid washes need not be highly pressurized since the individual movement of the induced pole pieces which occurs each time the pieces pass into an effective magnetic field results in a similarly reoccur-

ring variance of the size of the interstices between the individual pieces and facilitates the passage of the particulate material therebetween and through the container. Collection means such as launders are positioned appropriately below the container for receiving the separated nonmagnetically susceptible and magnetically susceptible fractions of the feed material upon the independent exit of the fractions through the foraminous container bottom.

The flushing fluid employed for the fluid washes may be liquid or gaseous, or a suitable mixture or liquid and gas. Water and/or air constitute the preferred flushing fluids.

With respect to the hydraulic action of the various feed and flushing fluids, it has been found that the efficiency of the separation process may be further enhanced by coating the surfaces of the induced pole pieces with a film of a nonwettable hydrophobic substance such as polytetrafluoroethylene, available commercially as Teflon, a trademark of E. I. du Pont de Nemours & Co., Inc., and modified polyvinylchloride resins, available commercially as Tygon, a trademark of U.S. Stoneware Co. By rendering the surfaces of the induced pole pieces nonwettable, the entrapment of small particles on the surfaces of the induced pole pieces by the feed and flushing fluids due to fluid adhesion is minimized. In addition, the nonwettable induced pole piece surface coating substantially reduces corrosion of the pieces to thus maximize the useful operating life of the pieces. The nonwettable substance, however, does not affect the magnetic properties of the pieces.

In accordance with one embodiment of the invention, the induced pole pieces, after the magnetically susceptible material has been removed from the proximity thereof and collected, are passed through a degaussing unit in order to remove any residual magnetism in the induced pole pieces and to facilitate the removal of any magnetically susceptible materials which have not been removed from the container by the fluid wash following exit of the induced pole pieces from the effective magnetic field. Such degaussing equipment may be chosen from any degaussing equipment known in the art and preferably will comprise coils disposed on opposite sides of the container in which the induced pole pieces are disposed which will be powered by an alternating current of sufficient strength to effect any degaussing necessary.

Alternatively, in magnetic separators employing a plurality of magnet means, a degaussing effect may be achieved by reversing the polarity of each successive magnet means. With such an arrangement, an area of polarity reversal between each successive magnet means will occur which is substantially free of any magnetic activity. Any magnetically susceptible materials which previously have not been removed from the container may be removed quite easily in such an area, either under the influence of gravity or with the assistance of a fluid wash. By reversing the polarity of each successive magnet means in a plural magnet means separator, the requirement for a degaussing unit may be obviated, further reducing the cost of the apparatus.

The magnetic separator of the present invention is a device of flexible usage; one embodiment thereof having particular utility for separating a desired nonmagnetically susceptible material from a feed having highly magnetically susceptible, weakly magnetically susceptible and the desired nonmagnetically susceptible materials intermingled therein. A problem that has often precluded the commercial feasibility of such a separation is the entrapment of small particles of the nonmagnetically susceptible material by the highly magnetically susceptible material, thus preventing the separate recovery of the valuable nonmagnetically susceptible material. This problem is largely alleviated by one embodiment of the present invention. In this embodiment, the container which retains the loose, unattached, individually movable induced pole pieces is provided with higher side walls. Between the upper portions of the side walls a plurality of the induced pole pieces are positioned in such a manner as to be held continuously above the gap between the field poles of a magnet means through which the container is passed. The induced pole pieces positioned above the gap are not subjected to the intense magnetic field produced therein and thus are inductively magnetized to a lesser extent than the induced pole pieces which pass through the gap.

In the operation of this embodiment, as the container and induced pole pieces pass into an effective magnetic field and the feed materials are introduced into the top of the container, the highly magnetically susceptible material in the feed will be deterred by the slightly magnetized induced pole pieces, such material passing through the interstices between the pieces in the magnetically influenced, continuously dynamic, intermittently dynamic and intermittently static modes. The weakly magnetically susceptible and nonmagnetically susceptible materials will pass through the upper portion of the container and past the slightly magnetized induced pole pieces in essentially the magnetically uninfluenced, continuously dynamic mode, these materials thus experiencing a greater downward vertical velocity through this portion of the container than the highly magnetically susceptible material. The weakly magnetically susceptible and nonmagnetically susceptible materials will then pass into proximity with the highly magnetized induced pole pieces within the gap between the field poles. At this point, the major portion of the weakly magnetically susceptible materials will be deterred by the highly magnetized induced pole pieces, passing therebetween in the magnetically influenced, continuously dynamic, intermittently dynamic and intermittently static modes; the average vertical velocity of this material thus being reduced with respect to the average vertical velocity of the nonmagnetically susceptible material. The nonmagnetically susceptible material which is unaffected by the magnetic activity, passes downwardly between the highly magnetized induced pole pieces in the magnetically uninfluenced, continuously dynamic mode and thereafter through the foraminous container bottom and into a launder or other collecting means positioned below the container.

As in the previously described separation process, the nonmagnetically susceptible material is removed from the container while the container is within the effective magnetic field, and the magnetically susceptible materials, both of a high and weak magnetic susceptibility, are removed from the container without the effective magnetic field. Also as in the previously described operation, this separation process may be regulated by controlling the numerous parameters which affect the passage of materials through the container. The significance of this process resides in the marked reduction of entrapment of the nonmagnetically susceptible material by the highly magnetically susceptible material which is realized as a result of the initial deterrence of the latter material by the slightly magnetized induced pole pieces.

In some mineral separation process, it has been found that if greater than .04% of a valuable nonmagnetically susceptible material is entrapped and lost with the magnetically susceptible materials, the separation process is not economically feasible. By utilizing a separator of the present invention having raised container side walls which position a portion of the induced pole pieces above the gap between the field poles, the separation of a desired nonmagnetically susceptible material can be accomplished in an economically attractive manner.

The container in which the induced pole pieces are disposed may be modified in another manner. The side walls of the container may be extended downwardly, terminating at a point below the gap between the field poles of a magnet means so that a plurality of the induced pole pieces will be positioned continuously below the gap as the container passes therethrough. In this embodiment,

the lower portion of the container may be filled or partially filled with nonmagnetically susceptible bodies or a mixture of such bodies and the highly permeable induced pole pieces. The nonmagnetically susceptible bodies may have a configuration that is either similar to or dissimilar from the induced pole pieces. Also, the size of such bodies may be substantially the same as or different from that of the induced pole pieces. The selection of nonmagnetically susceptible bodies of a particular composition, shape and size, is made on the basis of the effect of such bodies on the hydrodynamic forces which are imposed on the materials passing through the container. By placing nonmagnetically susceptible bodies of an appropriate composition, shape and size in the lower portion of a container which extends below the gap between the field poles, the hydrodynamic forces imposed on the feed materials may be regulated and the average downward vertical velocity of the materials through the container may be controlled. Regulation of the hydrodynamic forces affects the passage of all of the materials through the container to a greater or lesser extent; specifically all of the materials which pass through the container in each of the magnetically uninfluenced, continuously dynamic; magnetically influenced, continuously dynamic; magnetically influenced, intermittently dynamic and magnetically influenced, intermittently static modes.

Having generally described the present invention and various of the modifications and embodiments thereof, more detailed illustrations are provided with reference to the following drawings in which:

FIG. 1 is a plan view of a two-magnet, rotary separator in accordance with the invention;

FIG. 2 is a sectional elevational view of the two-magnet, rotary separator of FIG. 1, taken on line 2—2 of FIG. 1;

FIG. 3 is a side view of the two-magnet, rotary separator of FIG. 1 showing the drive motor in position and the operating parts suitably encased;

FIG. 4 is a fragmentary plan view showing a plurality of induced pole pieces disposed within a rotatable annular container;

FIG. 5 is an elevational view of a helically configured induced pole piece;

FIG. 6 is a diagrammatic plan view of the rotary separator shown in FIGS. 1–3 further showing the sequence of introduction of the feed and fluid washes and the removal of the separated materials in accordance with the invention;

FIG. 7 is a schematic plan view of a ten-magnet, rotary separator in accordance with the invention;

FIG. 8 is a plan view of a three-magnet, in-line separator in accordance with the invention;

FIG. 9 is a side view of the three-magnet, in-line separator shown in FIG. 8;

FIG. 10 is an enlarged fragmentary plan view showing a plurality of helically configured induced pole pieces disposed within an annular container;

FIG. 11 is a vertical sectional elevational view showing a plurality of spherically configured induced pole pieces disposed within an annular container;

FIG. 12 is a diagrammatic plane view of a two-magnet rotary separator showing the polarity arrangement of the magnet means in one embodiment of the invention; and

FIG. 13 is an enlarged fragmentary sectional view of a portion of the magnetic separator of the invention according to one modification thereof; all in accordance with various embodiments of the prevent invention.

Referring particularly to FIGS. 1–3, there is shown therein a nonmagnetic support frame **1** which supports two magnet means, electromagnet assemblies **2**. Each magnet assembly **2** comprises a pair of magnet cores **3**, **3'** bolted to an insert **4** adjacent support frame **1**. Field poles **5** and **6** are secured to the top ends of magnet cores **3**, **3'**, respectively, and define therebetween an operating gap **7**. Core windings **8**, **8'** are wound around cores **3**, **3'**; sixty-six thousand ampere turns being required to produce a field having a strength of about 22,800 gauss. The joints between cores **3**, **3'**, insert **4** and field poles **5** and **6** are ground to a smooth finish to provide a maximum flux path. All edges of the complete magnet assemblies **2** are rounded to prevent leakage of stray flux. Field poles **5** and **6** are tapered toward operating gap **7** therebetween, to provide the highest saturated flux possible in the area between the poles. Poles **5** and **6** also may be movably mounted so that the poles may be positioned to obtain the closest possible tolerances in gap **7**. A jack screw **9** made of a nonmagnetically susceptible material of high strength, such as stainless steel, is employed to keep field poles **5** and **6** from buckling together. Fiber glass shields **10** surround the outside coils of windings **8'** to protect the coils against mechanical abuse. Shields **10** are spaced out from the coils and preferably are painted black inside and out to provide maximum cooling.

A center structural support member **11** supports a drive mechanism **12**. Preferably support member **11** is constructed of a nonmagnetically susceptible material such as a Series 300 stainless steel. Support member **11** is secured to field poles **5** by supporting bolts **13**. A nonmagnetically susceptible head member **14**, preferably an aluminum casting, is rotatably mounted on a stationary stub shaft **15** by means of a sleeve bearing **16** and a thrust bearing **17**. A motor drive mechanism **18** is mounted on and bolted to supporting head member **14** for rotatably driving the head member. Affixed to head member **14** and rotatable therewith is a hollow annular container **19** formed by concentric annular rings **20** and **21**. Annular container **19** is interiorly supported by supporting members, subsequently described.

Motor drive mechanism **18** preferably comprises a gear-head motor **23** provided with conventional slip rings (not shown) for connecting the motor to an external source of electrical power. The torque generated by motor **23** reacts against a stationary hollow shaft **24** affixed to shaft **15**, and the motor rotates with support member **14**. Alternatively, the motor drive mechanism may comprise a stationary mounted motor drivingly connected to head member **14** by a ring gear, the ring gear being affixed to the head member and being engaged by a pinion gear rotatably driven by the motor.

Annular container **19** retains therein a plurality of loose, unattached helical induced pole pieces **25**. Helical induced pole pieces **25** are preferably fabricated from a magnetically soft, low carbon steel and are positioned vertically within container **19**. The induced pole pieces are retained within container **19** by an annular foraminous screen **22** forming the container bottom. Another annular foraminous screen **26** forms the top of container **19**. Interior supporting members **27**, which are formed by silver soldering together a plurality of helical induced pole pieces **25**, are soldered to annular rings **20** and **21**. Supporting members **27** divide annular container **19** into a plurality of compartments **28'**, and provide internal support for annular rings **20** and **21**, to thus ensure the structural rigidity of container **19**.

As best seen in FIG. 10, helical induced pole pieces **25** are retained within compartments **28'** by screen **22** at the bottom of container **19**. Movement of the induced pole pieces also is limited by the container side walls, annular rings **20** and **21**, and the container top, annular foraminous screen **26**, but the pieces are not secured fixedly to any portion of the container. Induced pole pieces **25** thus are free to shift and move about individually relative to each other within the confines of container **19**. As the container and induced pole pieces are successively passed between field poles **5** and **6**, the pole pieces will move about within the container due to the interaction of the magnetic fields generated between field poles **5** and **6** and the individual macroscopic magnetic properties of the induced pole pieces, as previously described.

Alternativey, instead of the helical induced pole pieces

25 shown in FIGS. 5 and 10, a plurality of loose, unattached spherical induced pole pieces 70 may be placed into container 19. Spherical induced pole pieces 70 will shift and move about with respect to each other within container 19 in a manner similar to the magnetically induced movement of helical induced pole pieces 25, as pieces 70 pass through the effective magnetic fields produced between field poles 5 and 6.

The induced pole pieces, whether of helical, spherical or of other configuration, will orient themselves within container 19 in such a manner as to maximize the field strength of the effective magnetic fields between field poles 5 and 6. The presence of the pole pieces in the effective magnetic fields also results in convergence of the flux lines at specific points or regions on the surfaces of the pieces. It is to be understood that these desirable resultants occur to a greater or lesser extent with induced pole pieces of vairous shapes, and that the particular description of helically shaped and spherically shaped induced pole pieces is not intended to be limiting, but as exemplary of various of the many induced pole pieces configurations which may be utilized.

Feed nozzles 28, from which the feed material is directed, are disposed above container 19 adjacent one end of gaps 7 between field poles 5 and 6, as best seen in FIGS. 1 and 3. Nozzles 29 for introducing washing fluid are disposed above container 19 in substantially the center of gaps 7 between field poles 5 and 6. Nozzles 30 for washing fluid are disposed above container 19 adjacent field poles 5 and 6 at the opposite end of gaps 7 from feed nozzles 28.

A degaussing unit 31, comprising a magnetic yoke 32 powered by alternating current, is situated at one position along the circular path traversed by container 19 for neutralizing any residual magnetic activity within the container, A nozzle 33 for washing fluid is disposed over container 19 at a point adjacent degaussing unit 31; the washing fluid assisting the removal of any residual magnetic material released from the container incident to the demagnetizing influence of unit 31.

Launders 34 and 35 are disposed beneath container 19 for receiving, respectively, the nonmagnetically susceptible and magnetically susceptible materials separated. As will be apparent from FIG. 6, the construction of the two-magnet separator shown in FIGS. 1–3 includes two diametrically opposed nonmagnetically susceptible material collection launders 34 and two diametrically opposed magnetically susceptible material collection launders 35. Launders 34 are equipped with outlets 36, while launders 35 are equipped with outlets 37.

The operation of the magnetic separator described above in conjunction with FIGS. 1–3 will now be characterized. Initially, motor 23 is started, causing container 19 to rotate about the axis of shaft 15. Induced pole pieces 25, retained within container 19, thus are successively moved between field poles 5 and 6 of magnet assemblies 2 which are disposed at opposite sides of the separator. Power is supplied to magnet assemblies 2 for generating an effective magnetic field between field poles 5 and 6 of each of the electromagnets. As the loose, unattached induced pole pieces successively enter the effective magnetic fields generated between field poles 5 and 6, the pieces shift and move about with respect to each other within container 19 assuming positions which produce an optimum magnetic configuration as previously described. A slurry of the material to be separated is introduced through feed delivery nozzles 28. Fluid wash is introduced through nozzles 29, 30, and 33. The nonmagnetically susceptible material, unaffected by the magnetic fields, falls through screen 26, the interstices between induced pole pieces 25 and screen 22 in the magnetically uninfluenced, continuously dynamic mode of passage. The magnetically susceptible material passes downwardly through container 19 in the magnetically influenced, continuously dynamic, intermittently dynamic and intermittently static modes. Removal of the nonmagnetically susceptible material from container 19 occurs within the effective magnetic fields produced in gaps 7 and is assisted by the fluid washes from nozzles 29. As induced pole pieces 25 leave operating gaps 7 the pole pieces pass without the effective magnetic fields, and the magnetically susceptible particles are there removed from container 19 with the assistance of fluid washes from nozzles 30. Any material having a tendency to adhere to the surfaces of induced pole pieces 25, which might tend to clog or impair the flow of feed through container 19, largely will be removed from the pole pieces incident to the scraping and rubbing of the pieces against each other which results upon the individual movement of the pieces as they successively enter operating gaps 7. The nonmagnetically susceptible material removed in the magnetic fields is collected in launders 34 and removed through outlets 36. The magnetically susceptible material is collected in launders 35 and removed through outlets 37. As container 19 rotates, induced pole pieces 25 pass through the alternating field of degaussing unit 31. Any residual magnetically susceptible materials remaining in container 19 are released at this point and are removed therefrom with the assistance of the fluid wash from nozzle 33, such materials being collected in one of the launders 35.

The separator shown in FIGS. 1–3, constructed to the dimensions and utilizing the power shown in the table below, was employed to separate molybdenum ore containing 0.05% by weight of molybdenum oxide. The capacity of the separator was found to be in excess of 4,000 pounds per hour; the yield was 93.7% of the recoverable molybdenum.

Cross-sectional dimensions of magnet cores	10.0 in. x 10.0 in. sq.
Cross-sectional dimensions of field poles	6.0 in. x 8.0 in.
Width of gap between field poles	2.5 in.
Average number of helical induced pole pieces	3,000.
Number of ampere turns of each magnet assembly	66,000.
Strength of each field	22,800 gauss.
Power required to energize magnet assemblies	4,000 watts.
Power required to drive motor	400 watts.

In one modification, magnet cores 3, 3' and field poles 5 and 6 are arranged in a manner which obviates the necessity for incorporating a separate degaussing unit. In this modification, the magnet assemblies are positioned with the polarity of each successive magnet assembly arranged oppositely to the polarity of the preceding magnet assembly. This construction is shown diagrammatically in FIG. 12, wherein the polarities of magnet assemblies 80 and 82 are shown by the letters N and S, representing the North and South magnetic poles, respectively. The N–S poles of magnet assembly 82 are reversed with respect to the N–S polarity of magnet assembly 80. The effective magnetic fields generated by magnet assemblies 80 and 82 will achieve maximum magnitude in the regions designated as points A and B, respectively. However, due to the reversed polarity of magnet assemblies 80 and 82, the magnetic field strength in the regions designated as points C and D will be of substantially zero magnitude. Any residual magnetically susceptible materials remaining in the container are removed therefrom as the container passes through the regions of points C and D. If desired, a fluid wash may be introduced into the top of the container adjacent points C and D to assist in the removal of any such materials.

In FIG. 7, a ten-magnet, rotary separator is shown. Except for the increased number of magnet means, the separator of FIG. 7 is constructed and functions in the

same manner as the separator described in conjunction with FIGS. 1–3.

Specifically, an annular container **40** is rotatably mounted to pass between field poles **41** and **42** of ten magnets **43**. Container **40** is filled with loose, unattached induced pole pieces, such as helical induced pole pieces **25** or spherical induced pole pieces **70**, made of a highly permeable soft magnetic material. Feed material such as a slurry of molybdenum ore is introduced through feed nozzles **44**. The nonmagnetically susceptible material passes through container **40** in the magnetically uninfluenced, continuously dynamic mode with the assistance of fluid washes provided by wash nozzles **45**. As container **40** is rotated, the magnetically susceptible material, which passes through container **40** in the magnetically influenced, continuously dynamic, intermittently dynamic and intermittently static modes, is moved out of the effective magnetic fields produced by magnets **43** and removed from the container with the assistance of fluid washes provided by wash nozzles **46**. The separated materials are suitably collected in launders (not shown). A degaussing unit (not shown) may be employed as in the separator of FIGS. 1–3, or preferably the polarity of each magnet **43** is reversed with respect to the polarity of the adjacent magnets, in the manner described in conjunction with FIG. 12.

An in-line separator is shown in FIGS. 8 and 9 having a foraminous-bottomed box **50** reciprocally mounted to pass between the field poles **51** and **52** of a plurality of electromagnets **53**. Reciprocal motion is imparted to box **50** by an eccentric drive assembly **54**. A plurality of loose, unattached induced pole pieces, such as helical rods, cubes or spheres of a highly permeable soft magnetic material, are retained within box **50**.

Feed nozzles **55** and **56** are located above box **50** adjacent the opposite outer edges of field poles **51** and **52**. The feed material is directed alternately to nozzles **55** and **56** through a feed line **57** and two-way valves **58**.

Fluid wash nozzles **59** are disposed above box **50** at a point intermediate feed nozzles **55** and **56**. Additional fluid wash nozzles **60** are disposed above box **50** outside the gaps between field poles **51** and **52**, and are spaced from feed nozzles **55**. A further group of fluid wash nozzles **61** are disposed above box **50** outside the gaps between field poles **51** and **52**, and are spaced from feed nozzles **56**. Wash nozzles **60** and **61** are connected through valves **62** and **63**, respectively, to a fluid wash delivery line **64**.

Launders **65**, for collection of the magnetically susceptible material separated, are disposed below box **50** and beneath wash nozzles **60** and **61**. Launders **65** empty into a header **66** from which the magnetically susceptible material is withdrawn from the separator. Launders **67**, for collection of the nonmagnetically susceptible material separated, are disposed below box **50** and beneath wash nozzles **59**. Launders **67** empty into a header **68** from which the nonmagnetically susceptible material is withdrawn from the separator.

The separator shown in FIGS. 8 and 9 operates in the following manner. Initially, drive mechanism **54** is actuated which, for example, moves box **50** to the right. Feed material is introduced into the top of box **50** through valves **58** and feed nozzles **55**, valves **58** preventing delivery of feed material to feed nozzles **56**. As the feed material moves into the effective magnetic fields between field poles **51** and **52**, and therein into proximity with the induced pole pieces retained in box **50** the nonmagnetically susceptible material passes through box **50** in the magnetically uninfluenced, continuously dynamic mode while the magnetically susceptible material passes through box **50** in the magnetically influenced, continuously dynamic, intermittently dynamic and intermittently static modes. The nonmagnetically susceptible material is removed from box **50** with the assistance of fluid washes from nozzles **59** and is received in launders **67** for removal from the separator through header **68**. As box **50** approaches the limit of travel, valves **58** shut off the flow of feed material through feed nozzles **55** while valves **63** are actuated to introduce fluid washes to the top of box **50** through wash nozzles **61**. Magnetically susceptible material, now outside the effective magnetic fields of field poles **51** and **52**, is removed from box **50** into launders **65** with the assistance of fluid washes from nozzles **61** and is removed from the separator through header **66**.

At this point, the direction of travel of box **50** is reversed. Valves **58** are now actuated to direct the flow of feed material through feed nozzles **56**. Valves **63** are actuated to shut off the flow of wash fluid through nozzles **61**, and valves **62** are actuated to initiate the flow of wash fluid through nozzles **60**.

The process above described is now repeated as box **50** travels to the left between field poles **51** and **52**. Nonmagnetically susceptible material is removed from box **50** within the magnetic fields produced between field poles **51** and **52** with the assistance of fluid washes introduced through nozzles **59**. Magnetically susceptible material is removed from box **50** without the effective magnetic fields with the assistance of fluid washes from nozzles **60**. Nonmagnetically susceptible and magnetically susceptible materials again are collected in launders **67** and **65**, respectively, and removed from the separator as before.

Accordingly, it will be seen that the in-line separator shown in FIGS. 8 and 9 operates continuously, the separation process necessitating only the actuation of a few valves to effect the flow of feed material and fluid washes through the proper nozzles as the direction of travel of box **50** changes.

In either a rotary or an in-line separator, it is possible to employ a single magnet means or as many magnet means as may be desirable or practical in a particular operation. Also, as mentioned previously, it is usually desirable to coat the induced pole pieces with a nonwettable substance to minimize liquid adhesion entrapment of small particles on the surfaces of the pieces, and to extend the operating life of the pieces.

The magnetic separator construction shown in FIG. 13 is an embodiment which is particularly adapted for separating a desired nonmagnetically susceptible material from a feed comprising a mixture of highly magnetically susceptible, weakly magnetically susceptible and the desired nonmagnetically susceptible materials. An example of such a feed is a natural mixture of highly magnetically susceptible magnetite, relatively weakly magnetically susceptible ilmenite, and rutile. In this mixture, the rutile, a natural ore of titanium, is a material of particular economic significance and is of an extremely low magnetic susceptibility.

The separator construction shown in FIG. 13 is similar in many respects to the magnetic separators previously described in conjunction with FIGS. 1–3 and FIGS. 8 and 9. Elements which have been described previously, therefore, are identified in FIG. 13 by like reference numerals. This embodiment includes a container **90** having opposed side walls **92** and **94** which extend above gap **7** between magnet field poles **5** and **6**. Side walls **92** and **94** may be configured as concentric annular rings similar to annular rings **20** and **21** for use in a rotary separator, or may be linearly configured as components of a rectangular container, such as box **50**, for use in an in-line separator. As is shown in FIG. 13, side walls **92** and **94** extend an appreciable distance above gap **7**. Foraminous screen **22** extends between the lower ends of side walls **92** and **94** and defines the bottom of container **90**. A plurality of induced pole pieces, such as spherical induced pole pieces **70**, are placed into container **90** on top of foraminous screen **22**. A portion of the induced pole pieces will be positioned at all times above gap **7** in the upper portion of container **90**. The remainder of the induced pole pieces, which are positioned in the lower portion of container **90**, will be carried by the container through gap **7**. Foraminous screen **26** extends between the upper portions

of side walls **92** and **94** to further confine the induced pole pieces within container **90**.

The operation of this embodiment is similar in many respects to the operation of the rotary separator shown in FIGS. 1–3, and the in-line separator shown in FIGS. 8 and 9, both of which have been described previously. However, there are some differences between the separation process performed by the separator shown in FIG. 13 and that effected by the magnetic separators previously described due to the extended height of container **90**.

In particular, the induced pole pieces retained in the upper portion of container **90** will not be subjected to the intense magnetic field in gap **7** and will not become as highly magnetized as the induced pole pieces which are retained in the lower portion of container **90**, and which do pass directly between field poles **5** and **6**. Since the induced pole pieces positioned in the upper portion of container **90** are magnetized, only weakly, the weakly magnetically susceptible material in the feed will pass through the interstices between these pole pieces in essentially the magnetically uninfluenced, continuously dynamic mode, similar to the mode of passage of the nonmagnetically susceptible material between the pole pieces which are both highly and weakly magnetized. The highly magnetically susceptible material in the feed, such as magnetite, however, will be deterred in the upper portion of container **90** by the weakly magnetized induced pole pieces, passing therethrough in the magnetically influenced, continuously dynamic, intermittently dynamic and intermittently static modes. The nonmagnetically susceptible and weakly magnetically susceptible materials will pass down through container **90** and into proximity with the highly magnetized induced pole pieces positioned in the lower portion thereof. These materials will there be separated in the manner described previously in connection with the operation of the separator shown in FIGS. 1–3; the weakly magnetically susceptible material passing downwardly in the magnetically influenced, continuously dynamic, intermittently dynamic and intermittently static modes with a lower average vertical velocity than the nonmagnetically susceptible material which experiences the magnetically uninfluenced, continuously dynamic mode of passage.

By first separating the highly magnetically susceptible material in a zone of weak magnetic activity, entrapment of the nonmagnetically susceptible and weakly magnetically susceptible materials by the material of high magnetic susceptibility will be minimized significantly. As the weakly magnetically susceptible material is deterred in the lower portion of container **90**, the nonmagnetically susceptible material passes through foraminous screen **22** at the bottom of the container, substantially uncontaminated by any of the magnetically susceptible materials. The valuable nonmagnetically susceptible material thus is separated from the feed and separatedly collected as the induced pole pieces pass through the effective magnetic field produced between poles **5** and **6**. The highly magnetically susceptible and weakly magnetically susceptible materials are removed from container **90** after induced pole pieces **70** have passed without the effective magnetic field; the deterrent effect of the magnetic forces on the passage of such materials having terminated at this point due to the absence of magnetic activity. The removal of the nonmagnetically susceptible as well as the magnetically susceptible materials may be facilitated by introducing fluid washes into the container in a manner similar to that described above in conjunction with the rotary magnetic separator shown in FIGS. 1–3 and the in-line separator shown in FIGS. 8 and 9.

The magnetic separator construction shown in FIG. 13 permits the separation of valuable nonmagnetically susceptible material in a single apparatus without the occurrence of significant losses of such material. The feed need not be separately treated first in a scalping machine, for removing the highly magnetically susceptible material prior to the separation of the nonmagnetically susceptible material from the weakly magnetically susceptible material, as has been the common practice heretofore. All of the necessary separating functions are accomplished in a single apparatus, and in a manner which minimizes entrapment of the valuable nonmagnetically susceptible material by the highly magnetically susceptible material. As will be evident, this construction provides an economically attractive method for separating valuable nonmagnetically susceptible materials.

In addition, the embodiment of the magnetic separator shown in FIG. 13 has been found to give excellent results in the separation of a desired weakly magnetically susceptible material from a nonmagnetically susceptible waste material. The operation of the apparatus for effecting this separation process is identical to the operational methods described previously in conjunction with the rotary separator shown in FIGS. 1–3 and the in-line separator shown in FIGS. 8 and 9. Due to the increased number of induced pole pieces, specifically the pieces carried in the upper portion of container 90, the magnetic and hydrodynamic forces may be more accurately controlled, thus allowing increased accuracy to be achieved in the regulation of the average vertical velocities of the materials through the container.

A separator constructed and operated in accordance with the parameters shown in the following table was utilized to separate ilmenite, a weakly magnetically susceptible ore of titanium, from a slurry containing a solid materials mixture comprising 75% silica and 25% ilmenite by weight. The magnetically susceptible fraction recovered contained 98.9% ilmenite which consisted of 85.1% of the total ilmenite present in the feed.

Cross-sectional dimension of magnet cores	5.0 in. diameter.
Cross-sectional dimensions of field poles	3.0 in. x 4.0 in.
Width of gap between field poles	2.5 in.
Average number of spherical induced pole pieces	300.
Height of container	8 in.
Strength of each field	20,000 gauss.

From the foregoing description and example, it will be apparent that the magnetic separator construction shown in FIG. 13 may be used to separate a desired nonmagnetically susceptible material from a mixture containing admixed therewith both highly magnetically and weakly magnetically susceptible materials, or conversely to separate a desired weakly magnetically susceptible material from a mixture containing both weakly magnetically and nonmagnetically susceptible materials. The adaptability of the separator to these diverse separation processes is indicative of its wide range of usefulness in the ore benefication art.

A further embodiment of the invention provides another means for accurately controlling the hydrodynamic forces imposed on the particulate materials which pass through the container. This embodiment employs an induced pole piece container having side walls that extend downwardly below the gap between the field poles. This structure is similar to that shown in FIG. 13 except that the container extends below instead of above the gap. The lower portion of such a container may be filled with highly permeable soft magnetic induced pole pieces or preferably with nonmagnetically susceptible bodies, composed, for example, of a ceramic or plastic material, or of a nonmagnetically susceptible metal such as an alloy of aluminum. Alternatively, the lower portion of the container may be filled with a mixture of induced pole pieces and nonmagnetically susceptible bodies. The bodies may be of the same shape and size as the induced pole pieces or of a different size and/or shape as required for obtaining the desired hydrodynamic forces.

The marked increase in efficiency which may be achieved in some separation processes by utilizing a container with side walls which extend below the operating gap of a magnet means is evidenced by the following example. An induced pole piece container was extended four inches below the gap between the field poles of an electromagnet and this portion of the container was filled with the same ⅜ inch diameter spherical induced pole pieces as were used for filling the upper portion of the container. A feed comprising a slurry of weakly magnetically susceptible iron ore admixed with nonmagnetically susceptible particulate materials was passed through the container, resulting in the separation of 74% by weight of the recoverable iron from the other particulate materials present in the feed. The test was performed again employing the same feed slurry and the same apparatus except that the bottom four inch portion of the container was filled with spherical ceramic beads having a diameter of three millimeters. The relatively small, nonmagnetically susceptible beads reduced the flow rate of the feed slurry through the container from 0.993 liter/second to 0.311 liter/second with the resulting separation of 90% by weight of the recoverable iron present in the feed. It will be seen from this example that by appropriately regulating the parameters which affect the hydrodynamic forces generated within the container, the efficiency of the separation process may be increased significantly for some materials.

Also, for the separation of particular materials it may be advantageous to intermix nonmagnetically susceptible bodies, such as the ceramic beads mentioned in the previous example, with the induced pole pieces throughout the entire height of the container. This arrangement will reduce the flux line concentration which results upon passage of the pole pieces through an effective magnetic field to thus decrease the magnetic forces imposed on the materials passing through the container while maintaining the desired hydrodynamic forces throughout the separating zone. A container having disposed therein a mixture of induced pole pieces and nonmagnetically susceptible bodies may be employed in any of the previously described separator embodiments, including those shown in FIGS. 1–3, FIGS. 8 and 9, and FIG. 13, as well as in separator having a container which extends below the gap between the field poles of a magnet means.

The separators of the invention are economical to construct and operate and are readily serviced. Due to the small number of moving parts, the separators of the invention have proven essentially trouble-free in extended operation.

Since modifications in the equipment and methods herein disclosed will be apparent to those skilled in the art, it is intended that the invention be limited solely by the scope of the appended claims.

What is claimed is:

1. An apparatus for separating granular materials of differing magnetic susceptibility comprising:
- at least one magnet means having oppositely disposed field poles of opposite polarity for producing an effective magnetic field therebetween;
- a pluarlity of loose, unattached induced pole pieces, said induced pole pieces being individually means for carrying and retaining the induced pole pieces, movable relative to each other;
- means for moving the induced pole pieces and the field poles relative to each other so that the induced pole pieces pass into, through and out of the effective magnetic field;
- means for introducing the material to be separated into the effective magnetic field and therein into proximity with the induced pole pieces as the pieces pass through the field; and
- means for flushing material from proximity with the induced pole pieces after the pieces have passed out of the effective magnetic field.

2. An apparatus for separating granular materials of differing magnetic susceptibility as recited in claim 1 wherein said induced pole pieces are helically configured.

3. An apparatus for separating granular materials of differing magnetic susceptibility as recited in claim 1 wherein said induced pole pieces are spherically configured.

4. An apparatus for separating granular materials of differing magnetic susceptibility as recited in claim 1 wherein said induced pole pieces are coated with a nonwettable substance.

5. An apparatus for separating granular materials of differing magnetic susceptibility as recited in claim 1 wherein a plurality of loose, unattached nonmagnetically susceptible bodies are intermixed with said induced pole pieces.

6. An apparatus for separating granular materials of differing magnetic susceptibility as recited in claim 1 further comprising a degaussing means positioned without the effective magnetic field and adjacent the induced pole pieces for ensuring the demagnetization of the pole pieces and any of the materials to be separated remaining in proximity therewith.

7. An apparatus for separating granular materials of differing magnetic susceptibility comprising:
- at least one magnet means having oppositely disposed field poles defining a gap therebetween, said field poles being of opposite polarity for producing an effective magnetic field therebetween;
- a movable container disposed within the gap, said container having a foraminous bottom;
- a plurality of loose, unattached induced pole pieces disposed within the container and retained therein by the foraminous bottom, said pole pieces being individually movable relative to each other;
- means for moving the container and the induced pole pieces disposed therein relative to the field poles so that the induced pole pieces successively pass into, through and out of the effective magnetic field;
- means for introducing the material to be separated into the effective magnetic field and therein into proximity with the induced pole pieces disposed within the container as the pole pieces pass through the field; and
- means for flushing material from the container and from proximity with the induced pole pieces disposed therein after the pieces have passed out of the effective magnetic field.

8. An apparatus for separating granular materials of differing magnetic susceptibility as recited in claim 7 wherein said means for moving the container and the induced pole pieces retained therein relative to the field poles comprises means for reciprocating the container.

9. An apparatus for separating granular materials of differing magnetic susceptibility as recited in claim 7 wherein said container comprises an annular member rotatably mounted to pass through the gap defined between the field poles of the magnet means.

10. An apparatus for separating granular materials of differing magnetic susceptibility as recited in claim 7 wherein a plurality of loose, unattached nonmagnetically susceptible bodies are intermixed with said induced pole pieces within the container.

11. An apparatus for separating granular materials of differing magnetic susceptibility as recited in claim 7 wherein said container has side walls which extend above the gap defined between the field poles of the magnet means, said side walls defining therebetween a portion of the container which remains above the gap at all times, and wherein at least some of said plurality of induced pole pieces disposed within the container are positioned in the portion thereof which remains above the gap.

12. An apparatus for separating granular materials of differing magnetic susceptibility as recited in claim 11

wherein a plurality of loose, unattached nonmagnetically susceptible bodies are intermixed with said induced pole pieces within the container including the portion thereof which remains above the gap at all times.

13. An apparatus for separating granular materials of differing magnetic susceptibility as recited in claim 7 wherein said container has side walls which extend below the gap defined between the field poles of the magnet means, said sidewalls defining therebetween a portion of the container which remains below the gap at all times, and wherein at least some of said plurality of induced pole pieces disposed within the container are positioned in the portion thereof which remains below the gap.

14. An apparatus for separating granular materials of differing magnetic susceptibility as recited in claim 13 wherein a plurality of loose, unattached nonmagnetically susceptible bodies are intermixed with said induced pole pieces within the container including the portion thereof which remains below the gap at all times.

15. An apparatus for separating granular materials of differing magnetic susceptibility as recited in claim 13 wherein the portion of said container which remains below the gap at all times is filled with a plurality of loose, unattached nonmagnetically susceptible bodies.

16. An apparatus for separating granular materials of differing magnetic susceptibility comprising;

a plurality of magnet means, each of said plurality of magnet means producing an effective magnetic field between opositely disposed field poles of opposite polarity intergral therewith, the field poles of each of the magnet means defining a gap therebetween;

a container mounted to pass through the gap between the field poles of each of the magnet means, said container having a foraminous bottom;

a plurality of loose, unattached induced pole pieces disposed within the container and retained therein by the formainous bottom whereby granular material may pass through the interstices between the pole pieces and through the foraminous bottom;

means for moving the container and the induced pole pieces disposed therein relative to the field poles so that the induced pole pieces successively pass into, through and out of the effective magnetic fields;

means for introducing the material to be separated into the effective magnetic fields and therein into proximity with the induced pole pieces disposed within the container as the pole pieces pass through the fields; and

means for flushing material from the container and from the proximity with the induced pole pieces diposed therein after the pieces have passed out of the effective magnetic fields.

17. An apparatus for separating granular materials of differing magnetic susceptibility as recited in claim 16 wherein the polarity of each of the magnet means is opposite to the polarity of the adjacent magnet means.

18. An apparatus for separating granular materials of differing magnetic susceptibility comprising:

a plurality of magnet means, each of said plurality of magnet means producing an effective magnetic field between oppositely disposed field poles of opposite polarity integral therewith, the field poles of each of the magnet means defining a gap therebetween;

a container mounted to pass through the gap between the field poles of each of the magnet means, said container having a foraminous bottom;

a plurality of loose, unattached induced pole pieces disposed within the container and retained therein by the formainous bottom whereby granular material may pass through the interstices between the pole pieces and through the foraminous bottom;

means for moving the container and the induced pole pieces disposed therein relative to the field poles so that the induced pole pieces successively pass into, through and out of the effective magnetic fields;

means for introducing granular material into the container and into proximity with the induced pole pieces disposed therein as the container passes through the effective magnetic fields;

a first delivery means for introducing flushing fluid into the contaner as the container passes through the effective magnetic fields;

a second delivery means for introducing flushing fluid into the container after the container has passed without the effective magnetic fields;

a first collecting means for receiving granular material removed from the container within the effective magnetic fields; and

a second collecting means for receiving granular material removed from the container without the effective magnetic fields.

19. An apparatus for separating granular materials of differing magnetic susceptibility as recited in claim 18 wherein the polarity of each of the magnet means is opposite to the polarity of the adjacent magnet means.

20. A method for separating granular materials of relatively low magnetic susceptibility from materials of relatively high magnetic susceptibility which comprises:

passing a mixture of the materials to be separated into an effective magnetic field and therein into proximity with a plurality of loose unattached individually movable bodies, at least some of which are composed of a highly magnetically permeable material and all of which are confined within a means for carrying and retaining said bodies;

thereafter passing the mixture of materials to be separated into proximity with a plurality of loose unattached individually movable, nonmagnetically susceptible bodies, all of which are confined within said carrying and retaining means;

removing the material of lower magnetic susceptibility from the proximity with all of the individually movable bodies and from the material of higher magnetic susceptibility while both materials and the highly magnetically permeable bodies are within the effective magnetic field;

separately collecting the material of lower magnetic susceptibility;

removing the material of higher magnetic susceptibility and the highly magnetically permeable bodies from the effective magnetic field;

removing the material of higher magnetic susceptibility from proximity with all of the individually movable bodies; and

separately collecting the material of higher magnetic susceptibility.

21. A method for separating nonmagnetically susceptible materials from granular materials of relatively weak and relatively high magnetic susceptibility which comprises:

passing a mixture of the material to be separated into a relatively weak magnetic field and therein into proximity with a plurality of loose unattached individually movable bodies, at least some of which are composed of a highly magnetically permeable material and all of which are confined within a means for carrying and retaining said bodies, for separating the material of higher magnetic susceptibility from the nonmagnetically susceptible material and the material of weaker magnetic susceptibility;

thereafter passing the nonmagnetically susceptible material and the material of weaker magnetic susceptibility into a relatively strong magnetic field and therein into proximity with a plurality of individually movable bodies, at least some of which are composed of a highly magnetically permeable material and all of which are confined within said carrying and retaining means, for separating the material of

weaker magnetic susceptibility from the nonmagnetically susceptible material;

removing the nonmagnetically susceptible material from proximity with all of the individually movable bodies and from the materials of weaker and higher magnetic susceptibility while all of the materials and all of the bodies are within the relatively weak and relatively strong magnetic fields;

separately collecting the nonmagnetically susceptible material;

removing the materials of weaker and higher magnetic susceptibility and all of the individually movable bodies from the relatively weak and relatively strong magnetic fields;

removing the materials of weaker and higher magnetic susceptibility from proximity with all of the individually movable bodies; and

separately collecting the materials of weaker and higher magnetic susceptibility.

22. An apparatus for separating materials of differing magnetic susceptibility comprising:

at least one magnet means having oppositely disposed field poles of opposite polarity for producing an effective magnetic field therebetween;

a plurality of loose, unattached induced pole pieces, said pole pieces being individually movable relative to each other;

means for carrying and retaining the induced pole pieces;

means for moving the induced pole pieces and the field poles relative to each other so that the induced pole pieces pass into, through and out of the effective magnetic field;

means for introducing the material to be separated into the effective magnetic field and therein into proximity with the induced pole pieces as the pieces pass through the field; and

means for flushing material from proximity with the induced pole pieces after the pieces have passed out of the effective magnetic field.

23. An apparatus for separating granular materials of differing magnetic susceptibility comprising:

at least one magnet means having oppositely disposed field poles defining a gap therebetween, said field poles being of opposite polarity for producing an effective magnetic field therebetween;

a movable container disposed within the gap, said container having a foraminous bottom;

a plurality of loose unattached individually movable induced pole pieces disposed within the container and retained therein by the foraminous bottom;

means for moving the container and the induced pole pieces disposed therein relative to the field poles so that the induced pole pieces successively pass into, through and out of the effective magnetic field;

means for introducing the material to be separated into the effective magnetic field and therein into proximity with the induced pole pieces as the pieces pass through the field; and

means for flushing material from proximity with the induced pole pieces after the pieces have passed out of the effective magnetic field.

24. A method for separating granular materials of relatively low magnetic susceptibility from materials of relatively high magnetic susceptibility which comprises:

moving a plurality of loose-unattached individually movable bodies, at least some of which are composed of a highly magnetically permeable material and all of which are confined within a means for carrying and retaining said bodies, into, through and out of an effective magnetic field;

passing a mixture of the materials to be separated into the effective magnetic field and therein into proximity with the individually movable bodies while the bodies are moving through the field so that the material of higher magnetic susceptibility will be attracted toward the highly magnetically permeable individually movable bodies;

removing the material of lower magnetic susceptibility from proximity with the individually movable bodies and from the material of higher magnetic susceptibility while both materials and the individually movable bodies are within the effective magnetic field;

separately collecting the material of lower magnetic susceptibility;

removing the material of higher magnetic susceptibility from proximity with the individually movable bodies after the bodies have moved out of the effective magnetic field; and

separately collecting the material of higher magnetic susceptibility.

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