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(54) Title: METHOD FOR PROCESSING ILMENITE-CONTAINING MINERAL MATERIALS WITH HIGH CLAY CONTENT, AND RELATED PRODUCTS

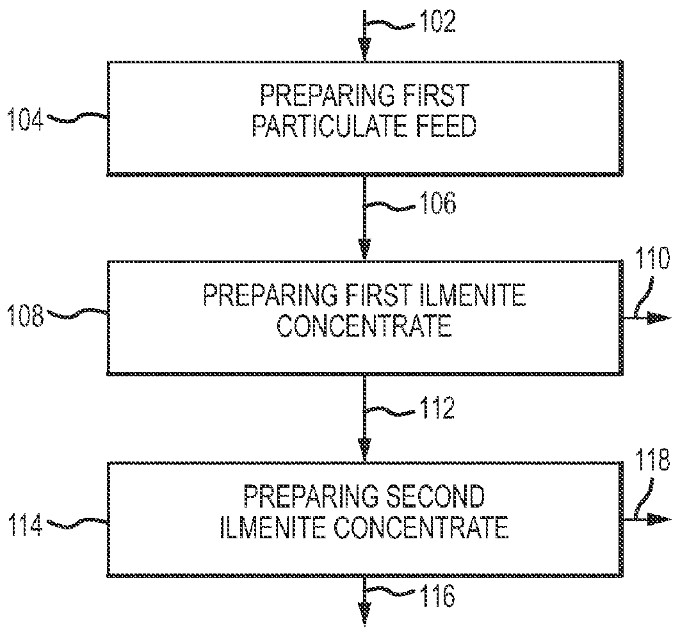

FIG.1

(57) Abstract: A method to process ilmenite-containing mineral material with high clay content includes processing involving settling velocity separation to prepare a first ilmenite concentrate followed by processing involving magnetic separation to prepare a second ilmenite concentrate. Settling velocity separation may include differential settling separation primarily for removal of clay and silica fines followed by elutriation for removal of coarse silica and additional fines. Also provided are high quality ilmenite concentrate products and slag products including low concentrations of problematic contaminant materials.

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METHOD FOR PROCESSING ILMENITE-CONTAINING MINERAL MATERIALS WITH HIGH CLAY CONTENT, AND RELATED PRODUCTS

CROSS-REFERENCE TO RELATED APPLICATIONS

This application claims the benefit of U.S. Provisional Patent Application No. 61/393,798 filed October 15, 2010 and U.S. Provisional Patent Application No. 61/510,375 filed July 21, 2011, the contents of each of which is incorporated by reference herein as if each and every portion thereof were set for in full herein.

FIELD OF THE INVENTION

The invention relates to processing ilmenite-containing mineral materials with high clay content, for example to prepare ilmenite concentrates containing titanium that may be further processed to make purified titanium dioxide products, such as for use as pigments and opacifiers. The invention also relates to related products, such as ilmenite concentrate products and titanium dioxide slag products.

BACKGROUND OF THE INVENTION

Titanium dioxide (TiO_2), also known as titania, is a high volume commodity material with a number of commercial uses. Large quantities of TiO_2 are used as pigments and opacifiers in a variety of products, including for example in paints, coatings, plastics, rubber, textiles, paper, ceramics, cosmetics, food and pharmaceuticals. Raw materials for preparing TiO_2 products are from ores rich in titanium-containing minerals, with rutile and ilmenite being two minerals that are of particular commercial importance. Rutile is a form of pure TiO_2. Ilmenite is an iron-titanium oxide mineral, generally of formula $FeTiO_3$, although the ilmenite may at times also contain quantities of other metals in addition to iron.

Current production of these titanium-containing minerals is by mining of sedimentary sand deposits rich in heavy minerals, often including rutile, ilmenite and zircon. The mineral sands may be dry-mined or wet-mined (e.g., dredged). Processing may include gravity separation (e.g., in spiral concentrators) to separate heavy-mineral sand particles (e.g., rutile, ilmenite, zircon) from other sand particles (e.g., silica). Processing may also involve desliming, such as in a centrifuge, to remove clay fines. In addition to the titanium-containing minerals, other heavy minerals (e.g., zircon) may also be concentrated in heavy-mineral concentrate. Electrostatic and magnetic properties may be used to separate different heavy minerals. For example, ilmenite has magnetic properties and is often recovered by magnetic separation from non-magnetic minerals (e.g., rutile and zircon). Further ilmenite processing may include smelting to separate the titanium and iron components of the mineral and to concentrate titanium in slag. The slag may then be processed through a traditional chloride process for production of titanium dioxide pigment or opacifier products.

Mining of heavy-mineral sand deposits has traditionally focused on deposits with low clay content. During mining, areas may be encountered that have significantly higher clay contents. Some attempts have been made to try to recover heavy minerals from those higher clay-content areas, but with only limited success. Often, areas with high clay content may be simply not processed for heavy-mineral recovery. This represents an underused resource in existing minable deposits that overall have generally low clay content except for the high clay-content areas. Also, the lack of processing options for heavy-mineral sand deposits that may overall have generally high clay content significantly limits available minable resources.

SUMMARY OF THE INVENTION

A first aspect of the invention is provided by a method of processing an initial feed of mined particulate mineral material comprising ilmenite and magnetite, and with high clay content in that the clay is present in the mineral material at a larger weight percentage than either the ilmenite or the magnetite. The method involves processing a first particulate feed to prepare a first ilmenite concentrate and then processing a second particulate feed containing at least a portion of the first ilmenite concentrate to prepare a second ilmenite concentrate. Preparing the first ilmenite concentrate comprises settling velocity separation from the first particulate feed a majority of the clay of the initial feed of the mineral material and recovering from the settling velocity separation the first ilmenite concentrate. The settling velocity separation is based on particle settling velocity in aqueous media. Preparing the second ilmenite concentrate comprises magnetically separating from the second particulate feed a majority of ilmenite contained in the second particulate feed.

The method of the first aspect permits the exploitation of nonconventional titanium resources that contain a high concentration of ilmenite, but that contain clay content that is too high for conventional heavy-mineral sand processing. Some examples of mineral material that may be processed using the method of the invention include areas of high clay content that may be encountered during mining of conventional heavy-mineral deposits with low clay content, as well as nonconventional deposits previously unexploitable due to a high clay content generally. This latter possibility is particularly important, because the application of the method to these nonconventional deposits permits processing mineral deposits having properties, other than the high clay content, permitting preparation of new and beneficial ilmenite concentrates and other products, for example, that beneficially contain very low quantities of one or more of the following: calcium, magnesium, manganese, chromium, uranium and thorium.

A number of feature refinements and additional features are applicable to the first aspect of the invention. These feature refinements and additional features may be used individually or in any combination. As such, each of the following features may be, but are not required to be, used with any other feature or combination of the first aspect.

The initial feed may be the mineral material as mined, also referred to as "run of mine" material. The initial feed of mineral material may include ilmenite in an amount of at least 7 weight percent, or at least 10 weight percent, or at least 13 weight percent, or at least 14 weight percent, or even at least 15 weight percent or more. The initial feed may include ilmenite in an amount of up to 22 weight percent, or up to 20 weight percent, or up to 18 weight percent. TiO_2 content in the initial feed of mineral material may be mostly or entirely provided by the ilmenite. When all or substantially all of the TiO_2 is provided by the ilmenite, then the ilmenite content will be approximately 1.9 times the TiO_2 content. The initial feed of mineral material may include TiO_2 in an amount of at least 3.5 weight percent, at least 6 weight percent, at least 7 weight percent, at least 7.5 weight percent, or even at least 8 weight percent or more. The initial feed of the mineral material may include TiO_2 in an amount up to 13 weight percent, up to 11 weight percent, up to 10 weight percent or up to 9 weight percent. At least 90 percent, at least 95 percent or at least 98 percent or more of the TiO_2 in the initial feed of the mineral material, and also in the first particulate feed, may be contained within ilmenite. The initial feed of the mineral material may include the magnetite in an amount of at least 2 weight percent, at least 5 weight percent or at least 7 weight percent or more. The initial feed of the mineral material may include the clay in an amount of at least 35 weight percent, at least 40 weight percent, at least 45 weight percent, at least 50 weight percent or at least 55 weight percent or more. The initial feed of the mineral material may often comprise the clay in an amount of up to 75 weight percent or up to 80 weight percent. The clay may be, include or have a majority composition of kaolin clay. The clay may be, include or have a majority component of kaolinite.

The ilmenite may be present in the initial feed in particles having a weight average particle size of at least 50 microns, at least 100 microns or at least 120 microns, but often not larger than 28 mesh (0.595 mm). The clay may be present in the initial feed in particles having a weight average particle size of no larger than 6 microns, no larger than 5 microns or no larger than 3 microns.

The initial feed of the mineral material may comprise one or more components in addition to the ilmenite, magnetite and clay. The initial feed in the mineral material may comprise silica, which may be in the form of coarse silica, in an amount up to 3 weight percent or up to 12 weight percent or more. When present, the silica may often be present in an amount of at least 0.5 weight percent. The initial feed of the mineral material may include calcium in an amount of up to 0.25 weight percent, up to 0.1 weight percent or up to 0.05 weight percent. When present, the calcium may often be in an amount of at least 0.005 weight percent, at least 0.01 weight percent or at least 0.03 weight percent. The initial feed of the mineral material may include manganese in an amount up to 0.25 weight percent or up to 0.1 weight percent. When present, the manganese may often be in an amount of at least 0.1 weight percent. The mineral material may include thorium and/or uranium in a combined amount of up to 100 parts per million by weight, up to 60 parts per million by weight, up to 40 parts per million by weight, up to 30 parts per million by weight. When present, the thorium and/or uranium may often be in a combined amount of at least 1 part per million by weight. With respect to components such as calcium, magnesium, manganese, thorium and uranium, the listed amounts refer to the amount contributed by those elements, even though those components will typically not be present in elemental form but will be contained within one or more minerals, for example one or more oxide or carbonate minerals. By a "combined amount", it is meant the total amount both of the thorium and uranium components when both are present or the amount of the one that is present when only one of them is present.

One preferred resource for the initial feed of the mineral material is from ilmenite-rich laterite deposits located in southern Paraguay and neighboring areas of Argentina and Brazil. The initial feed may be sourced from surface lateritic soils and lower laterite zones found in the Alto Parana laterite plateau in eastern Paraguay. A representative section may include a surface laterite soil 0.10-0.30 meters thick with about 20% organic material and a large concentration of iron oxides, mainly magnetite and hematite. TiO_2 content, predominantly in the form of ilmenite, may vary from 4 to 11 weight percent. The surface laterite soil may be underlain by a zone 5-10 meters thick of reddish brown laterite made up predominantly of kaolin clay with hematite, magnetite, ilmenite and silica. This zone may range from 3 to11 weight percent TiO_2 but in some zones may average 8 weight percent or more. Iron nodules 1 to 3 cm in diameter may be commonly found at the base of this main laterite horizon. These laterite resources may contain from 50-75 percent clay, predominantly kaolinite, and tend to have only very low concentration of a number of problematic components such as calcium, magnesium, manganese, chromium, uranium and thorium.

The method may include processing directed to preparing the first particulate feed for preparing the first ilmenite concentrate. The first particulate feed may be prepared as or to include the initial feed, e.g., run of mine material. Preparing the first particulate feed may include processing initial feed of the mineral material to better prepare the first particulate feed for beneficial processing by settling velocity separation. Preparing the first particulate feed may include removing one or more of the following from the initial feed: large particles (e.g., +28 mesh), plant material that may be mixed with the mineral material (e.g., from surface mining operations), or trash from mining operations or from storage or handling of the mined mineral material. For example, preparatory processing of the initial feed to remove plant material or other trash may include use of one or more of a trommel, a static screen, a vibrating screen and a log washer. In one implementation initial processing may include log washing prior to trommel or screen processing. Size separation of particularly large particles may, for example involve screening out a larger particle-size fraction of the mineral material. In one implementation, a 28 mesh screen may be used to screen out a +28 mesh fraction. In another implementation, such size separation may be preceded by one or more other operation, for example log washing, trommel processing and/or screen processing.

Preparing the first particulate feed may include blunging at least a portion of the mineral material from the initial feed to assist disaggregation of clay aggregates and dispersion of individual clay particles. Clays may have strong tendencies to aggregate and blunging may be an important preparatory operation to prepare the first particulate feed with characteristics conducive to preparation of high quality ilmenite concentrate without an excessive loss of ilmenite. Blunging is a known operation in clay processing and involves high-shear mixing of the clay in a liquid medium, such as an aqueous liquid, to promote the disaggregation of clay particles and dispersion of disaggregated, individual clay particles. Prior to or during blunging, clay dispersant may be added to assist dispersion of the clay particles in the liquid medium. By clay dispersant, it is meant a reagent that promotes dispersion of the clay particles and/or stabilizes a dispersion of clay particles to inhibit aggregation. Examples of some clay dispersants include sodium hexametaphosphate and polyacrylates. One example a polyacrylate dispersant is Colloid 211 from Kemira, which includes a sodium polyacrylate polymer. The blunging may be performed in a single stage or in multiple stages in series. In one implementation, the blunging may include at least a first blunging stage and a second blunging stage, and optionally with intermediate size separation of particles between the first and second blunging stages. The first blunging stage may help to liberate from clay aggregates larger particles not optimal for further processing. With the interstage size separation of larger particles, the second blunging stage may better disaggregate and disperse clay particles, without interference from the presence of those larger particles. The interstage size separation may be a size separation as previously described. In one implementation the interstage size separation may involve screening at 28 mesh. Clay dispersant may be added prior to or during either or both of the first blunging stage and the second blunging stage, and/ or other blunging stages if present.

During preparation of the first particulate feed from initial run of mine feed, some mineral material may be removed (e.g., large particles separated during interstage screening between blunging stages). However, the amount of mineral material may not be large, such as less than 5 weight percent or an even smaller amount of the mineral material of the initial feed of the mineral material. The first particulate feed may have a composition, in terms of the contents of the components ilmenite, TiO_2, magnetite and clay, and of possible other components such as one or more of calcium, magnesium, manganese, thorium and uranium generally in the same amounts as described previously for those components in respect to the initial feed.

The preparing the first ilmenite concentrate involves processing the first particulate feed and comprises settling velocity separation from the first particulate feed of a majority of the clay of the initial feed of the mineral material. Settling velocity separation is based on differences between settling velocities of different particles in a fluid medium. Primary variables affecting particle settling velocity include particle size and density and the nature of the fluid medium. The fluid medium for use in settling velocity separation according to the invention is preferably an aqueous liquid. Because ilmenite has a high specific gravity, (e.g., 4.5 to 5) and may be present in large quantities in particles having a size on the order of tens of microns or larger, whereas the clay particles may have much lower specific gravity (e.g., less than 2.7) and significantly smaller particle size (e.g., less than 5 microns), the clay particles will generally tend to settle more slowly than larger particles that are rich in ilmenite. The slower-settling clay particles may, therefore, be preferentially removed from a higher elevation within a process vessel (e.g., a settling tank) and particles enriched in ilmenite may be removed from a lower elevation within the process vessel. The settling velocity separation may involve hindered settling to the extent that particle concentrations in the liquid medium are high enough during processing to introduce significant interactions between particles during the settling velocity separation operation. Particle settling velocities may approach unhindered terminal velocities when hindered settling effects are largely absent.

The settling velocity separation may include any process operation that is based on differences in settling velocities between different particles. The settling velocity separation may include a differential settling separation. As used herein, "differential settling separation" refers to processing to settle coarse/heavy mineral particles through a dispersed pulp of fine particles in a process vessel (e.g., a tank), such as dispersed particles of clay and silica fines. By "fines" or "fine particles" it is meant generally particles of a size smaller than 10 microns. Dispersion of the clay may be aided by clay dispersant reagent. During differential settling, larger ilmenite particles may tend to preferentially settle due to both a larger particle size and higher density than the dispersed fines. Coarse silica particles may tend to preferentially settle primarily due to a larger particle size than the dispersed fines. During differential settling separation, a majority of the clay from feed to the differential settling separation may be recovered in overflow and a majority of ilmenite from the feed to the differential settling separation may be recovered in the underflow. A majority of coarse silica from the feed to differential settling separation may be recovered in the underflow. Underflow of differential settling separation may be concentrated in, and overflow of differential settling separation may be depleted in, ilmenite and possibly also coarse in silica relative to feed to the differential settling separation. A majority of clay from feed to differential settling separation may be recovered in overflow. Overflow of differential settling separation may be concentrated in, and underflow of differential settling separation may be depleted in, clay relative to feed to the differential settling separation. An upward flow of the liquid medium may be maintained in the process vessel during the differential settling separation to assist effective separation. To promote a good separation of clay and silica fines from coarse/heavy mineral particles, an upward flow may be sufficiently high to carry the dispersed fines, but not sufficiently high to carry a large quantity of coarse particles. By coarse particles (e.g., coarse silica) it is meant generally particles larger than 25 microns in size. Solids content in the liquid medium during differential settling separation may be in a range of from 6 to 25 percent solids by weight. Feed to a differential settling separation process tank may be at an elevation above an elevation of underflow removal and may be at, above or below an elevation of overflow removal. Residence time in a differential settling process tank may be at least 0.5 hour, and may be less than 2 hours. Differential settling may be at a pH of at least pH 6, and may be at a pH of up to pH 9. Differential settling separation may be performed in a thickener, which may be a high rate thickener such as available from WesTech Engineering, Inc., and which may be modified to provide for upward flow within the thickener tank.

The settling velocity separation may include elutriation processing. During elutriation, there is an upward flow of the liquid medium in a process vessel (e.g., a tank), that is sufficiently large to overcome the settling velocity of certain coarse particle constituents in feed to be separated from other particles during the elutriation processing. The elutriation may have an upward flow that is sufficient to overcome the settling velocity of at least some coarse silica particles, and preferably a majority of coarse silica, for separation of coarse silica particles from heavy mineral (e.g., ilmenite-containing) particles, and especially from coarse heavy mineral particles. During elutriation processing, faster-settling particles may be removed from the process vessel at a lower elevation of the process vessel and slower-settling particles may be removed from a higher elevation of the process vessel. The elevation of the process vessel from which the slower-settling particles are removed may be above the level at which feed of mineral material to be separated is introduced into the process vessel, and the elevation of the process vessel from which the faster-settling particles are removed may be below the elevation at which such feed is introduced into the process vessel. Solids content in the liquid medium during elutriation may often be in a range of from 2 to 25 percent solids by weight. During elutriation, a majority of the clay from feed to the elutriation may be recovered in overflow and a majority of ilmenite from the feed to the elutriation may be recovered in underflow. A majority of coarse silica from feed to elutriation may be recovered in the overflow. Underflow of elutriation may be concentrated in, and overflow of elutriation may be depleted in, ilmenite relative to feed to the elutriation. A majority of clay, and also a majority of coarse silica, from feed to elutriation may be recovered in overflow. Overflow of elutriation may be concentrated in, and underflow of elutriation may be depleted in, clay and also preferably in coarse silica relative to feed to the elutriation. Residence time in elutriation process tank may be at least 0.5 hours, and may be less than 2 hours. Elutriation may be at a pH of at least pH 6, and may be at a pH of up to pH 9.

In one implementation, settling velocity separation includes maintaining an upward flow of fluid in a process tank (e.g., a differential settling process tank or an elutriation process tank) between elevations where overflow and underflow are removed from the tank. In one variation when a main target component for removal in overflow is dispersed fines (e.g., differential settling to remove dispersed clay and/or silica fines), the velocity of the upward flow may be no larger than 10 centimeters per minute, no larger than 8 centimeters per minute or no longer than 6 centimeters per minute, and may often be at least 2 centimeters per minute, at least 3 centimeters per minute or at least 4 centimeters per minute. In another variation when a main target component for removal in overflow is coarse silica (e.g., elutriation processing to remove coarse silica), the velocity of the upward flow may be at least 3 centimeters per minute, at least 4 centimeters per minute or at least 5 centimeters per minute and may often be no larger than 10 centimeters per minute or no larger than 15 centimeters per minute. Maintaining an upward flow may include introducing upward flowing streams, or jets, of liquid (e.g., process water) into a process tank (e.g., differential settling process tank or elutriation process tank) at an elevation that is lower than an elevation of mineral material feed to the tank. Such upward flowing streams may be introduced into the tank adjacent the bottom (e.g., in upwardly flowing streams introduced via fluid ports through the bottom wall of the tank).

In one implementation, the settling velocity separation may include at least two different differential settling velocity separation steps implementing different settling velocity separation operations. The different settling velocity separation operations may include a differential settling separation and an elutriation. During a first settling velocity separation step, a first portion of the clay may be removed, followed by a second settling velocity separation step to remove a second portion of the clay. Feed to the second settling velocity separation step may include all or a portion of a larger-particle-size fraction of mineral material recovered with underflow from the first settling velocity separation step. In one preferred implementation, the settling velocity separation includes a first settling velocity separation step including differential settling separation and a second settling velocity separation step including elutriation. In one variation, a majority of clay from the first particulate feed is recovered in overflow from the first settling separation step and a majority of ilmenite of the first particulate feed is recovered in underflow from the first settling separation. In one variation, a majority of coarse silica from mineral material feed to the second settling velocity separation is recovered in overflow from the second settling velocity separation and a majority of ilmenite from the mineral material feed to the second settling velocity separation is recovered in underflow from the second velocity separation. In one variation, the first settling velocity separation is by differential settling separation and the second settling velocity is by elutriation. The solids density during the differential settling separation may be larger than the solids density during the elutriation. In one variation, attrition scrubbing may be performed between a first settling velocity separation step and a second settling velocity separation step, for example to further promote disaggregation and dispersion of particulates prior to the second settling velocity separation step.

The settling velocity separation may be performed in one or more liquid-containment process vessels (e.g., tanks). Upwardly flowing liquid may be introduced into the liquid medium in the vessel. The liquid medium in the vessel may be agitated and upwardly flowing liquid introduced into the liquid medium may be introduced at an elevation below the agitator. In one implementation of elutriation, a high-velocity, high-shear upward flow path may develop between a rotating agitator and a wall of the process vessel.

During the settling velocity separation, a majority of the clay is removed from the first particulate feed. The settling velocity separation may comprise removing at least 85 weight percent, or at least 90 weight percent or even at least 95 weight percent of the clay from the first particulate feed.

Any settling velocity separation operation within the settling velocity separation may be performed in one or in multiple stages in series. In a preferred implementation, each settling velocity separation step is performed in a single stage operation. In one implementation, the settling velocity separation includes a first step comprising a single stage of differential settling separation followed by a second step comprising a single stage of elutriation. Each stage may include multiple process vessels in parallel. Any settling velocity separation processing may proceed in a single process train or in multiple parallel process trains.

In one implementation, the settling velocity separation may include a first settling velocity separation step and a second settling velocity separation step, and with a size separation intermediate between the first settling velocity separation step and the second settling velocity separation step. A larger particle-size fraction from the size separation may be processed separately from the second particulate feed during the preparation of the second ilmenite concentrate. The size separation may be accomplished by a screen of an appropriate mesh size. In one implementation a 65 mesh screen may be used for the size separation. The screen may be a vibrating screen.

Preparing the second ilmenite concentrate may include magnetic separation of magnetic ilmenite-containing and/or magnetite-containing particles from the mineral material being processed, and may include separating the magnetic particles from clay and silica, including from coarse silica particles. The magnetic separation may comprise a low-intensity magnetic separation to recover a first portion of magnetic particles followed by high-intensity magnetic separation performed on a least portion of reject material from the low-intensity magnetic separation to recover a second portion of the magnetic particles. Either or both of the high-intensity magnetic separation and the low-intensity magnetic separation may be performed in multiple stages in series and may comprise a single process train or multiple parallel process trains. When the settling velocity separation includes size separation between a first settling velocity separation step and a second settling velocity separation step, the larger particle-size fraction not subjected to the second settling velocity separation step may be separately processed by magnetic separation processing apart from processing of the second particulate feed. In one variation, attrition scrubbing may be performed before the low-intensity magnetic separation, for example to further disaggregate and disperse particulates to promote effective processing during the magnetic separation operation.

The second ilmenite concentrate may comprise all or a portion of magnetic ilmenite-containing and/or magnetite-containing particles recovered by magnetic separation. The second ilmenite concentration is enriched in ilmenite relative to each of the initial feed, the first particulate feed and the second particulate feed. By the second ilmenite concentrate being “enriched” in a component it is meant that the second ilmenite concentrate has a higher content, or concentration, of that component relative to each of the initial feed, the first particulate feed or second particulate feed, as the case may be. The second ilmenite concentrate may be depleted in clay, and may be depleted in silica (including preferably depleted in coarse silica), relative to the initial feed, the first particulate feed and the second particulate feed. By the second ilmenite concentrate being “depleted” in a component, it is meant that the content, or concentration, of that component in the second ilmenite concentrate is lower than in the initial feed, first particulate feed or second particulate feed, as the case may be. The second ilmenite concentrate may also be enriched in magnetite relative to one or more of the initial feed, the first particulate feed and the second particulate feed.

The second ilmenite concentrate may include ilmenite in an amount of at least 57 weight percent, at least 60 weight percent, at least 65 weight percent, or at least 67 weight percent. The second ilmenite concentrate may include TiO_2 (including the TiO_2 content of the ilmenite) in an amount of at least 30 weight percent, at least 33 weight percent or even at least 35 weight percent. The second ilmenite concentrate may include the clay in an amount of not greater than 5 weight percent, not greater than 4 weight percent, not greater than 3 weight percent or not greater than 2 weight percent. The clay may be present in the second ilmenite concentrate in an amount of at least 0.2 weight percent, or at least 0.5 weight percent or at least 1 weight percent. The second ilmenite concentrate may include magnetite in an amount of at least 10 weight percent, at least 15 weight percent or at least 20 weight percent. The second ilmenite concentrate may include ilmenite and magnetite in a combined amount of at least 80 weight percent or at least 90 weight percent. The second ilmenite concentrate may comprise iron oxides (e.g., magnetite, hematite, etc.), other than contained in the ilmenite, in an amount of at least 15 weight percent, at least 20 weight percent or at least 25 weight percent. The second ilmenite concentrate may include silica in an amount up to 5 weight percent, up to 3 weight percent or up to 2 weight percent. When present, the silica may often be in an amount of at least 0.4 weight percent. The second ilmenite concentrate may include calcium in an amount of up to 0.08 weight percent, up to 0.06 weight percent, up to 0.03 weight percent or up to 0.02 weight percent. When present, the calcium may often be in an amount of at least .01 weight percent. The second ilmenite concentrate may include magnesium in an amount of up to 1.0 weight percent, up to 0.8 weight percent or up to 0.7 weight percent. When present, the magnesium may often be in an amount of at least 0.1 weight percent. The second ilmenite concentrate may include manganese in an amount of up to 0.8 weight percent or up to 0.6 weight percent. When present, the manganese may be in an amount of at least 0.1 weight percent or at least 0.2 weight percent. The second ilmenite concentrate may include thorium and/or uranium in a combined amount of up to 100 parts per million by weight, up to 60 parts per million by weight, up to 40 parts per million by weight or up to 30 parts per million by weight. When present, the thorium and/or uranium may often be in a combined amount of at least 1 part per million by weight or at least 5 parts per million by weight. The second ilmenite concentrate may include chromium in an amount of up to 0.05 weight percent or up to 0.03 weight percent. When present, the chromium may be present in an amount of at least 0.001 weight percent or at least 0.005 weight percent. Again, with respect to components such as calcium, magnesium, manganese, chromium, thorium and uranium, the listed amounts refer to the amount contributed by those elements, even though those materials will typically not be present in elemental form but will be contained within one or more minerals. The second ilmenite concentrate may have a weight average particle size of larger than 50 microns, or larger than 100 microns, or larger than 120 microns. The second ilmenite concentrate may be an ilmenite concentrate product of the second aspect of the invention discussed below.

The recovery of ilmenite in the second ilmenite concentrate may be at least 64 percent at least 68 percent, at least 70 percent, at least 72 percent, at least 74 percent or at least 76 percent or more relative to ilmenite in the initial feed or relative to ilmenite in the first particulate feed. Weight recovery in the second ilmenite concentrate may be no greater than 25 weight percent, or no greater than 20 weight percent, or no greater than 18 weight percent, or even no greater than 15 weight percent or less of the weight of the initial feed or of the weight of the first particulate feed.

The method of the first aspect of the invention may include recovery of a clay tail product of mineral material recovered during settling velocity separation and/or magnetic separation. The clay tail product may be more concentrated in clay, and may also be more concentrated in silica and may be more concentrated in coarse silica, than one or both of the initial feed and the first particulate feed. The clay tail product may include clay in an amount of at least 75 weight percent, at least 80 weight percent, at least 85 weight percent or at least 90 weight percent. The clay tail product may have a weight average particle size of smaller than 25 microns, smaller than 15 microns or smaller than 10 microns. Processing may include clarification of water, including flocculating clay suspended in resulting process liquid. A flocculent reagent may be used to assist flocculation, with an anionic flocculent reagent being more preferred for some implementations. Flocculation may involve pH adjustment. In one preferred implementation, flocculation of at least a portion of the process stream is at an acidic pH, such as in a range of pH 4 to pH 6, or even at about pH 5.

The method of the first aspect of the invention may comprise smelting at least a portion of the second ilmenite concentrate to produce a slag containing titanium dioxide, for example by electric arc smelting. This slag may be a slag product according to the third aspect of the invention discussed below.

The method of the first aspect of the invention may comprise making bricks comprising at least a portion of clay separated from the mineral material during the settling velocity separation.

A second aspect of the invention is provided by a particulate ilmenite concentrate product prepared from mined ilmenite-containing mineral material. The concentrate product comprises, relative to the total weight of the concentrate product on a dry basis: ilmenite, in an amount of at least 57 weight percent; iron oxides (e.g., magnetite, hematite, etc.), other than contained in the ilmenite in an amount of at least 15 weight percent; clay, in an amount of not greater than 5 weight percent; calcium, in an amount of not greater than 0.5 weight percent; and one or both of thorium and uranium, in a combined amount of not greater than 70 parts per million by weight. The concentrate product advantageously includes a combination of a large amount of ilmenite and iron oxides beneficial for smelting operations, and very low calcium content and uranium and/or thorium content that are undesirable for smelting operations. With respect to thorium and uranium, those components may also present low level radioactivity hazards during transportation, storage and handling, and a low content of those materials in the concentrate product of the second aspect of the invention is a significant advantage.

A number of feature refinements and additional features are applicable to the second aspect of the invention. These feature refinements and additional features may be used individually or in any combination. As such, each of the following features may be, but are not required to be, used with any other feature or combination of the first aspect.

The concentrate product may include any one or more of the features, including concentrations of components, described with the second ilmenite concentrate of the method of the first aspect of the invention. The concentrate product may be such a second ilmenite concentrate described with the method of the first aspect of the invention.

The concentrate product may be in any convenient form. The concentrate product may be in a wet form slurred with a liquid medium, such as an aqueous liquid. The concentrate product may be in dry form.

A third aspect of the invention is provided by a titanium-containing slag product. The slag product comprises, relative to the total weight of the slag product: titanium dioxide in an amount of at least 85 weight percent, or at least 87 weight percent, or even at least 90 weight percent or more; calcium oxides (e.g., CaO), in an amount of not greater than 0.03 weight percent, or not greater than 0.05 weight percent or not greater than 0.08 weight percent; one or both of thorium oxides and uranium oxides (e.g., ThO_2, U_3O_8), in a combined amount of not greater than 100 parts per million by weight, or not greater than 60 parts per million by weight or not greater than 40 parts per million by weight.

A number of feature refinements and additional features are applicable to the third aspect of the invention. These feature refinement and additional features may be used individually or in any combination. As such, each of the following features may be, but are not required to be, used with any other features or combination of the third aspect.

The slag product may comprises magnesium oxides (e.g., MgO) in an amount of not greater than 1 weight percent, or not greater than 0.8 weight percent, or not greater than 0.7 weight percent.

The slag product may comprise manganese oxides (e.g., MnO) in an amount of not greater than 1 weight percent, or not greater than 0.7 weight percent, or not greater than 0.5 weight percent.

The slag product may comprise chromium oxides (e.g., Cr_20_3) in an amount of not greater than 0.05 weight percent, or not greater than 0.03 weight percent.

The amount of the titanium dioxide in the slag product may be in a range having a lower limit of any of the weight percentages identified above for titanium dioxide in the slag product and an upper limit of 95 weight percent or 98 weight percent.

The slag product may comprise an amount of the calcium oxides that is in a range having an upper limit of any of the weight percentages for calcium oxides identified above for calcium oxides in the slag product and having a lower limit of 0.005 weight percent or 0.01 weight percent.

The slag product may comprise a combined amount of the thorium oxides and uranium oxides in a range having an upper limit of any of the combined amounts identified above in parts per million by weight for thorium oxides and uranium oxides in the slag product and a lower limit of 1 part per million by or 10 parts per million by weight.

The slag product may comprise magnesium oxides in an amount with a range having an upper limit of any of the weight percentages identified above for the magnesium oxides in the slag product and a lower limit of 0.01 weight percent. The slag product may comprise the manganese oxides in an amount in a range having an upper limit of any of the weight percentages identified above for the manganese oxides in the slag product and a lower limit of 0.1 weight percent. A fourth aspect of the invention is provided by a method for preparing a titanium-containing slag product, comprising smelting the ilmenite concentrate product of the second aspect of the invention and recovering titanium-containing slag from the smelting. The titanium-containing slag may be a titanium-containing slag product according to the third aspect of the invention.

A fifth aspect of the invention is provided by a method for preparing a titanium dioxide pigment product. The method comprises chloride treatment of a titanium-containing slag product, wherein the slag product is according to the third aspect of the invention.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 is a process diagram of an embodiment of a method of the invention.

Figure 2 is a process diagram of an embodiment of a method of the invention.

Figure 3 is a process diagram of an embodiment of a method of the invention.

Figure 4 is a process diagram of an embodiment of a method the invention.

Figure 5 is a process diagram of an embodiment of a method of the invention.

Figure 6 is a process diagram of an embodiment of a method of the invention.

Figure 7 is a schematic of an embodiment of a process tank for differential settling separation.

Figure 8 is a top view of a rake shown in the process tank of Figure 7.

Figure 9 is a schematic of one embodiment of a process tank for elutriation processing.

Figure 10 is a process diagram of an embodiment of a method of the invention.

Figure 11 is a process diagram of one more particular implementation of the more general embodiment shown in Figure 10.

Figure 12 is a process diagram of one particular implementation for tails processing, which may be used in combination with the processing shown in Figure 11.

Figure 13 illustrates one design for blugner vessel for use in a blunging operation of a method of the invention.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

Reference is made to Figures 1-6 concerning some embodiments of the method of the first aspect of the invention. Common reference numerals are used in different ones of Figures 1-6 to represent common features.

Figure 1 shows a generalized process block diagram relating to the method of the first aspect of the invention. As shown in Figure 1, an initial feed 102 of particulate, ilmenite-containing mineral material is subjected to a process sequence 104 for preparing first particulate feed. Resulting first particulate feed 106 is subjected to a process sequence 108 for preparing first ilmenite concentrate. During the process sequence 108, clay 110 is removed from the first particulate feed to prepare first ilmenite concentrate that is enriched in ilmenite relative to the first particulate feed 106 and in relation to the initial feed 102. During the process sequence 104, the separated clay 110 (which may be in one or multiple process streams) includes a majority of clay originally in the initial feed 102. A second particulate feed 112, which contains at least a portion of the first ilmenite concentrate (and may be comprised entirely of the first ilmenite concentrate), is subjected to a process sequence 114 for preparing second ilmenite concentrate. During the process sequence 114, additional clay 118 is removed from the second particulate feed and a second ilmenite concentrate 116 is prepared. During the process sequence 108, the separated clay 118 (which may be in one or multiple process streams) may include a majority of the clay from the second particulate feed. As used herein, the term "at least a portion of" a substance or composition means all of that substance or composition or a part of the substance or composition that is less than all of the substance or composition.

Figure 2 shows a process block diagram of one possible more particular implementation alternative of a method of the first aspect of the invention as generally represented in Figure 1. As shown in Figure 2, the initial feed 102 is processed through the process sequence 104, which includes blunging 130 at least a portion of the initial feed 102. The blunging 130 may be performed in the presence of a clay dispersant added before or during the blunging 130. The first particulate feed 106 is subjected to the process sequence 108, which includes subjecting at least a portion of the first particulate feed 106 to settling velocity separation 132. During the settling velocity separation 132 a majority of the clay from the initial feed 102 (e.g., the clay 110) is separated in one or more overflow streams from process vessels of the settling velocity separation 132, and the first ilmenite concentrate is recovered from one or more underflow streams from such process vessels. The second particulate feed 112 is processed through the process sequence 114, which includes magnetic separation 134 of a majority of the ilmenite from the second particulate feed 112. During the magnetic separation 134, magnetic particles (e.g., containing ilmenite) are magnetically separated from non-magnetic particles (e.g., clay particles and silica particles). The magnetic particles separated during the magnetic separation 134 may include magnetic materials besides ilmenite. For example, some or all of the separated magnetic particles may contain magnetite. The second ilmenite concentrate is enriched in ilmenite relative to the second particulate fed 102.

Figure 3 shows a process block diagram of one possible more particular implementation alternative of the implementation shown in Figure 2. As shown in Figure 3, the initial feed 102 is subjected to the process sequence 104, including the blunging 130. The blunging 130 includes a first blunging stage 140 and a second blunging stage 142, and with intermediate size separation 144 between the first blunging stage 140 and the second blunging stage 142. Either one or both of the first blunging stage 140 and the second blunging stage 142 may be performed with the mineral material being processed in the presence of clay dispersant. Such clay dispersant may be added before or during the first blunging stage 140 and/or before or during the second blunging stage 142. During the size separation 144, a larger-particle-size fraction is removed from the mineral material, for example by screening. The size separation 144 may, for example, may be a separation at 28 mesh, for example using a 28 mesh screen. The larger-particle-size fraction that is removed is not subjected to the second blunging stage 142.

Also as shown in Figure 3, the first particulate feed 106 is subjected to the process sequence 108, including the settling velocity separation 132. The settling velocity separation 132 includes a first settling velocity separation step 146 followed by a second settling velocity separation step 148. The first velocity separation step 146 and second velocity separation step 148 represent different unit operations, with each including implementation of a different separation operation based generally on particle settling velocity in aqueous liquid medium. For example, the first settling velocity separation could involve differential settling separation and the second settling velocity separation could involve elutriation. Each of the first settling velocity separation step 146 and the second settling velocity separation step 148 may include only a single stage or may include multiple stages in series.

Also as shown in Figure 3, the second particulate feed 112, which comprises at least a portion of first ilmenite concentrate prepared during the process sequence 108, is subjected to the process sequence 114, including the magnetic separation 134. As shown in Figure 3, the magnetic separation 134 includes low-intensity magnetic separation 150 followed by high-intensity magnetic separation 152. The low-intensity magnetic separation 150 removes magnetic particles, such as magnetic ilmenite-containing and/or magnetite-containing particles, from the second particulate feed 112. The high-intensity magnetic separation 152 removes additional magnetic particles from at least a portion of reject material from the low-intensity magnetic separation 150 (i.e., material not magnetically removed during the low-intensity magnetic separation 150). Additional magnetic particles removed during the high-intensity magnetic separation 152 may, for example, contain ilmenite and/or magnetite. The second ilmenite concentrate 116 may include all or some of the magnetic particles removed during both the low-intensity magnetic separation 150 and the high-intensity magnetic separation 152, or during either one of them. The low-intensity magnetic separation 150 involves subjecting material to a lower-intensity magnetic field (e.g., as accomplished with a permanent magnet) and the high-intensity magnetic separation 152 involves subjecting material to a higher-intensity magnetic field (e.g., 0.2 to 1 Tesla).

Figure 4 shows a process block diagram of one possible more particular implementation alternative of the implementation shown in Figure 3. As shown in Figure 4, the process sequence 104 is the same as shown in and described with respect to Figure 3. The settling velocity separation 132 of the process sequence 108 includes intermediate size separation 160 between the first settling velocity separation step 146 and the second settling velocity separation step 148. Oversize particulate material 162 from the size separation 160 includes a larger-particle-size fraction separated from the mineral material being processed in the process sequence 108. The size separation 160 may be accomplished, for example, using a screen with appropriate mesh size. The screen may, for example, be a 65 mesh screen for separating out a +65 mesh fraction. The screen may be a vibrating screen. The magnetic separation 134 includes a separate parallel magnetic separation sequence including low-intensity magnetic separation 166 and the high-intensity magnetic separation 168, similar to the low-intensity magnetic separation 150 and the high-intensity magnetic separation 152, except processing a feed of the oversize particulate material 162. In the low-intensity magnetic separation 166, magnetic particles, such as for example magnetic ilmenite-containing and/or magnetite-containing particles, are magnetically removed from the oversize particulate material 162. At least a portion of the reject material from the low-intensity magnetic separation 166 is processed in the high-intensity magnetic separation 168 to magnetically remove additional magnetic particles, such as additional magnetic ilmenite-containing and/or magnetite-containing particles. The second ilmenite concentrate 116 may include all or a portion of the magnetic particles removed in all of any of the low-intensity magnetic separation 150, the high-intensity separation 152, the low-intensity magnetic separation 166 and the high-intensity magnetic separation 168. The embodiment of the magnetic separation 134 shown in Figure 4 may advantageously permit more optimized design and implementation of the second settling velocity separation step 148 and more optimized design of magnetic separation 134 to more effectively handle the larger-particle-size material of the oversize particulate material 162 and the smaller-particle-size material of the second particulate feed 112.

Figure 5 shows a process diagram of one possible more particular implementation alternative of the implementation shown in and described with respect to Figure 4. As shown in Figure 5, the initial feed 102 is subjected to the process sequence 104, which includes the blunging 130 with the first blunging stage 140, the second blunging stage 142 and the size separation 144, generally as shown in and described with respect to Figures 3 and 4. The process sequence 104 includes a log washing 170 step prior to the blunging 130. The first particulate feed 106 is subjected to the process sequence 108, including the settling velocity separation 132 with the first settling velocity separation step 146, the second settling velocity separation step 148 and the size separation 160, as generally shown in and described with reference to Figures 3 and 4.

In Figure 5, the first settling velocity separation step 146 includes differential settling separation with two differential settling separation stages 172, 174 and with a scrub operation 176 (e.g., attrition scrubbing) intermediate between the first differential settling separation stage 172 and the second differential settling separation stage 174. The first differential settling separation stage 172 is arranged as a rougher stage and the second differential settling separation stage 174 is arranged as a cleaner stage. The intermediate scrub 176 prepares underflow 178 from the first differential settling separation stage 172 for feed to the second differential settling separation stage 174. Underflow 180 from the second differential settling separation stage 174 is fed to the size separation 160. Overflow 110a from the first differential settling separation stage 172 is rich in separated clay and is directed to tails thickening 182 and centrifuge processing 184 to prepare dewatered clay tails 186. Overflow 188 from the second differential settling separation stage 174 is returned to the blunging 130 for further processing. Undersize particulate material 190 from the size separation 160 is fed to the second settling velocity separation step 148. The second settling velocity separation step 148 includes settling velocity separation by elutriation. The second settling velocity separation step 148 includes a first elutriation stage 192 followed by a second elutriation stage 194. Overflow 110b, rich in separated clay from the second differential settling separation step 148, is sent to the tails thickening 182 and centrifuge 184 for preparation of the clay tails 186. Underflow 196 from the first elutriation stage 192 is fed to the second elutriation 194. Overflow 195 from the second elutriation stage 194 is returned to the first elutriation stage 192 for further processing through the first elutriation stage 192. The first ilmenite concentrate is recovered in underflow from the second elutriation stage 194 and is used to prepare the second particulate feed 112 that is fed to the process sequence 114.

In Figure 5, the process sequence 114 is generally the same as shown in and described with respect to Figure 4, including the magnetic separation 134 with separate parallel magnetic separation processing for the second particulate feed 112 and the oversize particulate material 162. The recovered magnetically-separated material is combined to prepare the second ilmenite concentrate 116. The separated clay 118 stream includes reject material from the magnetic separation 134, and the separated clay 118 stream is sent to the tails thickening 182 and centrifuge 184 for preparation of the dewatered clay tails 186. The second ilmenite concentrate 116 is processed through a filter 198 followed by drying 200 to prepare a dry ilmenite concentrate product 202. The dry ilmenite concentrate product 202 may be bagged or otherwise packaged or containerized for easy handling and transportation. Figure 5 also shows flows of process water from a process water feed 204 to various process operations and shows recycle water streams 206 and 208 from the tails thickening 182 and centrifuge 184, respectfully.

With continued reference to Figure 5, overflow 110a and 110b from the settling velocity separation 132 and separated clay 118 from the magnetic separation 134 are processed through the tails thickening 182 to clarify liquid for reuse in the recycle streams 206 and 208 and to prepare a thickened clay that is fed to the centrifuge for further dewatering, preferably to a water content of 50 weight percent or lower. The tails thickening 182 may be performed, for example, in a thickening tank providing sufficient time to significantly clarify the liquid and permit settling of the clay. The tails thickening 182 may include the addition of a clay flocculent reagent to promote flocculation and settling of clay and rapid clarification of the water. Examples of some possible clay flocculants include anionic flocculants, cationic flocculants and nonionic flocculants. The tails thickening may include a pH adjustment to promote flocculation of clay. In one variation, flocculation and settling of clay may be performed at a basic pH to produce high-clarity liquid. In this variation, the pH for the tails thickening may be at a pH of at least pH 7.5 or at least pH 8.0, and may be at a pH of up to pH 11, up to pH 10.5 or up to pH 10.0. In a preferred variation, flocculation and settling of clay is performed at an acidic pH, such as with the addition of sulfuric acid as a pH adjustment reagent. The pH may, for example be in a range of pH 4 to pH 6, with a pH of around 5 being preferred and particularly with use of an anionic clay flocculent reagent. Some or all of the dewatered clay tails 186 may be beneficially used to make bricks, either from the dewatered clay tails 186 as produced or after further processing and/or addition of additional components. Some or all of the dewatered clay tails 186 may be deposited into the mined terrain and returned to beneficial use, such as farming, following a period of natural dewatering to an appropriate water content.

Figure 6 shows a process diagram of another more particular implementation alternative of the implementation shown in and described with respect to Figure 3, including many of the features shown in and described with respect to Figure 5. As shown in Figure 6, the initial feed 102 is subjected to the process sequence 104, which includes the first blunging stage 140, the second blunging stage 142 and the site separation generally as shown in and described with respect to Figures 3 the log washing 170 step generally as shown in and described with respect to Figure 5. The first particulate feed 106 is subjected to the process sequence 108, which includes the settling velocity separation 132. With the first settling velocity separation step 146 and the second settling velocity separation step 148 generally as shown in and described with respect to Figure 3, and including some features shown in and described with respect to Figure 5. The first settling velocity separation step 146 includes a single-stage settling separation including the differential settling separation stage 172 and with the scrub operation 176 (e.g., attrition scrubbing). Overflow 110a from the differential settling separation stage 172 is rich in separated clay and is directed to tails thickening 182 and centrifuge processing 184 to prepare dewatered clay tails 186. The second settling velocity separation step 148 includes settling velocity separation by single-stage elutriation. The second settling velocity separation step 148 includes the elutriation stage 192, with the overflow 110b being sent to the tails thickening 182 and centrifuge 184 for preparation of the clay tails 186. The first ilmenite concentrate is recovered in underflow from the single elutriation stage 192 and is used to prepare the second particulate feed 112 that is fed to the process sequence 114. The process sequence 114 includes the magnetic separation 134 with the low-intensity magnetic separation 150 and the high intensity magnetic separation 152 generally as shown in and described with respect to Figure 3. Recovered magnetically-separated material is combined to prepare the second ilmenite concentrate 116. The separated clay 118 stream includes reject material from the magnetic separation 134, and the separated clay 118 stream is sent to the tails thickening 182 and centrifuge 184 for preparation of the dewatered clay tails 186. The second ilmenite concentrate 116 is processed through the filter 198 followed by the drying 200 to prepare the dry ilmenite concentrate product 202, generally as shown in and described with respect to Figure 5. The dry ilmenite concentrate product 202 may be bagged or otherwise packaged or containerized for easy handling and transportation. Figure 6 also shows flows of process water from the process water feed 204 to various process operations and the shows the recycle water streams 206 and 208 from the tails thickening 182 and centrifuge 184, respectfully, generally as shown in and described with respect to Figure 5.

The implementation shown in Figure 6 is advantageous in that it includes very simple and streamlined processing relative to the processing implementation of Figure 5. Important to implementing the implementation shown in Figure 6 is careful design for efficient operation of the single differential settling separation stage 172 and the single elutriation stage 192.

Reference is now made to Figures 7-9 concerning some example implementations for settling velocity separation processing.

Figure 7 shows generally features of a process tank 230, such as may be used for differential settling separation, for example in the differential settling separation stages 172, 174 of the first settling separation step 146 as shown in Figures 5 and 6. As shown in Figure 7, the process tank 230 includes an overflow trough 232, a rake 234 and a rotatable shaft 236 to drive rotation of the rake 234. During operation for differential settling separation, a feed 238 of mineral material to be processed (e.g., first particulate feed 106 of Figures 1-6) is introduced into an upper portion of the fluid containment volume of the process tank 230. The Overflow 240 spills over into the overflow trough 232 for collection. The overflow 240 is enriched in clay and depleted in ilmenite relative to the feed 238. Underflow 242 is collected from the bottom of the process tank 230. The underflow 242 is enriched in ilmenite and depleted in clay relative to the feed 238. The rake 234 is driven by drive shaft 236 to rotate along the bottom of the fluid containment volume of the process tank 230 to move particles concentrating at the bottom toward a central collection port (not shown) for collection as the underflow 242. A top view of the rake 234 is shown in Figure 8. As shown in Figure 8. As shown in Figure 8, the rake 134 includes four rake arms 244, each comprising multiple rake blades 246 that force movement of particulate material toward a central location when the rake 234 is rotated.

With reference again to Figure 7, during operation for differential settling separation, multiple upwardly-flowing streams, or jets, of liquid 248 (e.g., process water) are introduced into bottom of the fluid containment volume of the process tank 230 to help dislodge clay particles from ilmenite particles collecting at the bottom of the process tank 230 and to help carry clay particles upward for collection with the overflow 240. The upwardly flowing streams of liquid 248 may, for example, be introduced through fluid ports through the bottom of the process tank 230. A result is that during operation for differential settling separation, there is an upward flow of fluid through the fluid containment volume of the process tank 230 generally in a direction from an elevation of removal of the underflow 242 (the bottom of the process tank 230 in this implementation) toward the elevation of removal of the overflow 240 (the top of the process tank 230 in this implementation). This generally upward flow of fluid in the process tank 230 is represented by the arrows 249.

Figure 9 shows generally features of a process tank 250, such as may be used for elutriation, for example in the elutriation stages 192, 194 as shown in Figures 5 and 6. As shown in Figure 9, the process tank 250 includes an overflow trough 252, an agitator 254 and a rotatable shaft 256 to drive rotation of the agitator 254. During operation for elutriation, a feed 258 of mineral material to be processed (e.g., from underflow from prior a differential settling separation operation, such as one or more of the differential settling separation stages 172, 174 shown in Figures 5 and 6) is introduced at a mid elevation into of the fluid containment volume of the process tank 250. Overflow 260 spills over into the overflow trough 252 for collection. The feed 258 may include in particular ilmenite, coarse silica and clay particles to be separated. The overflow 260 is enriched in clay, and may also preferably enriched in coarse silica, and depleted in ilmenite relative to the feed 258. The underflow 262 is collected from the bottom of the process tank 250. The underflow 262 is enriched in ilmenite and depleted in clay, and also preferably is depleted in coarse silica, relative to the feed 258.

With continued reference to Figure 9, during operation for elutriation multiple upwardly-flowing streams, or jets, of liquid 268 (e.g., process water) are introduced into bottom of the fluid containment volume of the process tank 250 to help dislodge in clay and coarse silica particles from ilmenite particles collecting at the bottom of the process tank 250 and to help carry dislodged clay and coarse silica particles upward for collection with the overflow 260. The upwardly flowing streams of liquid 268 may, for example, be introduced through fluid ports through the bottom of the process tank 250. A result is that during settling separation operation, there is an upward flow of fluid through the fluid containment volume of the process tank 250 generally in a direction from an elevation of removal of the underflow 262 (the bottom of the process tank 250 in this implementation) toward the elevation of removal of the overflow 260 (the top of the process tank 250 in this implementation). This generally upward flow of fluid in the process tank 250 is represented by the arrows 269. As will be appreciated, the velocity of the upward flow 269 will generally be higher above than below the elevation of the process tank 250 where the feed 258 is introduced.

With continued reference to Figure 9, during operation of the process tank 250 for elutriation, the agitator 254 is rotated by the shaft to agitate the contents of process tank 250. The agitator includes a flat circular plate 270 and multiple blades 272. Rotation of the agitator 254 causes liquid to be expelled from the peripheral edge of the plate 270 generally toward the side wall of the tank. A high-shear zone of flow 274 develops in a high-velocity region between the peripheral edge of the agitator 254 and the side wall of the process tank 250. The upwardly flowing streams of liquid 268 are directed toward the rotating agitator and the development of the high-shear zone of flow 274 helps to make a clean separation especially between ilmenite particles and coarse silica particles. In one alternative for the process tank 250, a rake may be used at the bottom of the process tank 250 to rake particles concentrating at the bottom of the tank for collection through a central port, similar to the rake 234 shown in and described previously with respect to Figures 7 and 8.

Figure 10 shows a process diagram for another particular implementation alternative of the more general implementation shown in and described with respect to Figure 2. As shown in Fig. 10, the initial feed 102 is processed through the process sequence 104, which includes the blunging 130 of at least a portion of the initial feed 102. The resulting first particulate feed 106 is subjected to the process sequence 108, which includes subjecting at least a portion of the first particulate feed 106 to the settling velocity separation 132. The settling velocity separation 132 includes the first settling velocity separation step 146 and the second settling velocity separation step 148, for example as described with respect to Figure 3. Prior to introduction to the second settling velocity separation step 148, the treated material from the first settling velocity separation step 146 is subjected to scrubbing 280. During the scrubbing 280, mineral material being processed is treated to further disaggregate and dispose particles for more effective separation during the second settling velocity separation step 148. The scrubbing 280 may, for example, be an attrition scrubbing operation in which the mineral material being processed is subjected to high shear conditions to further disaggregate and disperse material prior to introduction to the second settling velocity separation step 148. Processed mineral material from the second settling velocity separation step 148 is then processed through scrubbing 282. The scrubbing 282 may be as described for the scrubbing 280, and preferably includes attrition scrubbing in which the processed mineral material is subjected to high shear environment to further disaggregate and disperse material to prepare the second particulate feed 112. After the process sequence 108, the second particulate feed 112 is subjected to the process sequence 114, including the magnetic separation 134. The magnetic separation 134 includes the low-intensity magnetic separation 150 and the high-intensity magnetic separation 152, for example as described with respect to Figure 3.

Reference is now made to Figure 11, showing one example of a more particular implementation of the more general process implementation shown in Figure 10. As shown in Fig. 11, the initial feed 102 of mineral material is first subjected to the process sequence 104. In the process sequence 104, the initial feed 102 is processed through a screen 300 to remove vegetation and oversize material to prepare a screened feed 302 that is introduced into a blunging vessel 304. The oversize material from the screen 300 is discarded as trash 306. In the blunging vessel 304, the material being processed is subjected to blunging e.g., high-shear attrition mixing. Also added to the blunging vessel 304 are recycle process water 308, clay dispersant reagent 310 and pH adjustment reagent 312, for example sodium hydroxide to raise the pH. Processed material from the blunging vessel 304 is transmitted via a hose pump 314 to a multi-stage screen 316 to prepare a large particle fraction 318, a middle particle fraction 320 and a small particle fraction 322. The large particle fraction 318 and middle particle fraction 320 may contain significant iron oxide (e.g., magnetite) and some ilmenite and may be further processed for iron oxide and ilmenite recovery as desired. The small particle fraction 322 is held and conditioned in three conditioning vessels 324, 326 and 328 arranged in series. In the conditioning vessels 324, 326 and 328 additional clay dispersant reagent 310 and pH adjustment reagent 312 are added. Also added to the first conditioning vessel 324 is additional recycled process water 308. In the conditioning vessels 324, 326 and 328 the material being processed is agitated and conditioned to assist in dispersing clay for effective processing. Material from the last conditioning vessel 328 is transmitted through a hose pump 330 to a single-stage screen 332 to remove an over-size particle fraction 334. An under-size particle fraction 336 is then subjected to the processing sequence 108.

In the processing sequence 108, the under-size particle fraction 336 is introduced via an agitated feed tank 338 into a hydrosizer vessel 340 for settling velocity separation. Overflow 342 enriched in clay is removed from the top of the hydrosizer vessel 340 and underflow 344 enriched in ilmenite is removed from the bottom of the hydrosizer vessel 340. The underflow 344 is transferred via a hose pump 346 to an attrition scrubbing vessel 348 where the material being processed is subjected to attrition scrubbing to further disaggregate and disperse particulates. The attrition scrubbing vessel 348 may be a two-stage vessel, as shown in Figure 11, with two chambers each fitted with a dual impeller attrition mixer 350. Each dual impeller attrition mixer 350 has two opposing impellers that force flow into the space between the impellers creating a high shear environment between the impellers conducive to disaggregating and dispersing particulates. For example, the top impeller forces fluid in a downward direction toward the bottom impeller and the bottom impeller forces fluid upward in a direction towards the top impeller. Processed material exiting the attrition scrubbing vessel 348 is transferred via a bowl pump 352 to an inlet to an elutriation vessel 354. Feed into the elutriation vessel 354 may be via an angled downspout 356 (e.g., inclined downward at an angle of about 45°) to introduce feed into a central portion of the elutriation vessel 354. Process water 308 is introduced into a bottom portion of the elutriation vessel 354. Overflow 358 enriched in silica and clay is removed from the top of the elutriation vessel 354 and an underflow 360 enriched in ilmenite is removed from the bottom of the elutriation vessel 354. The underflow 360 is transferred to an attrition scrubbing vessel 362 via a hose pump 364. The attrition scrubbing vessel 362 may be designed in a similar manner to the attrition scrubbing vessel 348 previously discussed. In the attrition scrubbing vessel 362, the material being processed is subjected to further attrition scrubbing to further disaggregate and disperse particulates. Material exiting the attrition scrubbing vessel 362 is transferred via a bowl pump 364 for processing through the process sequence 114.

In the process sequence 114, material from the scrubbing vessel 362 is fed to a series of three low-intensity magnetic separators 366, 368 and 370 arranged in series. Final magnetic concentrate 372 from low-intensity magnetic separation is transferred via a bowl pump 374 for collection as an ilmenite concentrate (second ilmenite concentrate) in a filter 376. Reject material 378, 380 and 382 from the low-intensity magnetic separators 366, 368 and 370 is transferred via a bowl pump 384 to a thickener vessel 386. Overflow 388 is removed from the top of the thickener vessel 386 and underflow 390 is removed from the bottom of the thickener vessel 386. The underflow 390 is transferred via a hose pump 392 as feed to a series of three high-intensity magnetic separators 394, 396 and 398. The underflow 390 may be diluted with fresh water 400 prior to introduction into the first high-intensity magnetic separator 394. A final magnetic concentrate 402 from the last high-intensity magnetic separator 398 is transferred via a bowl pump 404 for collection as ilmenite concentrate (second ilmenite concentrate) in a filter 406. Reject material 408, 410 and 412 from the high-intensity magnetic separators 394, 396 and 398 may be transferred via a bowl pump 414 as a combined reject stream 416 for tails processing.

As shown in Figure 11 recycle process water 308 may be added at various locations as needed to maintain appropriate slurry densities. It is preferred that fresh water 400 be used for water additions as needed for the magnetic separations.

Reference is now made to Figure 12, which shows a process diagram showing one example of particular implementation for tails processing that may be used, for example, in combination with the processing shown in Figure 11. As shown in Figure 12, overflow 342 from the hydrosizer vessel 340 (Figure 11) is fed to an overflow vessel 420. Material from the overflow vessel 420 is transferred via an air-operated pump 422 to a flocculation vessel 424. Flocculant reagent 425 is added to the flocculation vessel 424 to promote flocculation of clay particles. Material from the flocculation vessel 424 is transferred to a tailings thickener vessel 426. Underflow 428 from the tailings thickener vessel 426 is transferred via a hose pump 430 to a tailing storage pond (not shown). The underflow 428 is concentrated in flocculated clay settling in the tailings thickener vessel 426. Overflow 432 from the tailings thickener vessel 426 is transferred to a pH adjustment vessel 434 where pH is adjusted by addition of a pH adjustment reagent 436 to promote effective flocculation and setting of clay. If operating at an acidic pH, the pH may be lowered through addition of an acidic pH adjustment reagent 436 (e.g., sulfuric acid). If operating at a basic pH, a basic pH adjustment reagent 436 (e.g., sodium hydroxide) may be used. Material from the pH adjustment vessel tank 434 is transferred to a flocculation vessel 438, to which additional flocculant reagent 425 is added to further promote clay flocculation in the flocculation vessel 438. Also introduced into the flocculation vessel 438 for treatment in the flocculation vessel 438 is the overflow 388 from the top of the thickener vessel 386.

With continued reference to Figure 12, overflow 358 from the elutriation vessel 354 (Figure 11) is transferred to an overflow vessel 450. Material from the overflow vessel 450 is transferred via an air-operated pump 452 to a flocculation tank 454 to which is added flocculant reagent 425 to promote flocculation of clay particles in the flocculation vessel 454. Also added to the flocculation vessel 454 is the combined reject 416 from the bowl pump 414 (Figure 11). Material from the flocculation vessel 454 is transferred to a tailings thickener vessel 456. Underflow from the tailings thickener vessel 456 is transferred via a hose pump 458 to the tailings thickener vessel 424. Overflow from the tailings thickener vessel 456 is transferred to an overflow tank 460. Material from the flocculation vessel 438 is also transferred to the overflow tank 460. Additional flocculation reagent 425 is added to the overflow tank 460 and a treated stream 462 is withdrawn from the overflow vessel 460 for transfer to a recycle water pond (not shown).

A pilot plant is designed using the implementation shown in Figures 11 and 12 to process approximately 1.5 tonnes per day of a clay-rich run of mine feed containing about 7.5% titanium dioxide, mostly as ilmenite. With reference to Figures 11 and 12, the pilot plant is designed to operate as follows. The screen 300 is sized at 5 inches (127 millimeters) by 10 inches (254 millimeters) to remove vegetation and trash from the initial feed 102. The multi-stage screen 316 is such that the large particle fraction 318 is a plus 0.75 inch fraction (+9mm), the middle particle fraction is a 0.75 inch (19mm) by 0.5 inch (12.7mm) fraction and the small particle fraction is a minus 3/16 inch (-4.8mm) fraction. The clay dispersant reagent 310 is Colloid 211 (Kemira). The pH adjustment reagent 312 is sodium hydroxide to raise the pH in the conditioning vessels 324, 326 and 328. The pH of material exiting the final conditioning vessel 328 is at about pH 7.25. The single-stage screen 332 may be such that the over-size fraction 334 is a + 28 mesh fraction and the undersize fraction 336 is a - 28 mesh fraction. The hydrosizer vessel 340 is operated with an upward flow velocity of about 1.25 gallons per minute per square foot (about 6 centimeters per minute). The elutriation vessel 354 is operated with an upward flow velocity of about 1.25 gallons per minute per square foot (about 6 centimeters per minute). The pH adjustment reagent 436 is sulfuric acid. The pH in the pH adjustment tank 434 is at an acidic pH of about pH 5. The flocculant reagent 425 is Superlfloc A-110 (Kemira), an anionic flocculent reagent. Slurring densities (in percent solids) are designed for about 35 percent in the blunger vessel 304; about 12.5 percent in the conditioning vessels 324, 326 and 328 and the hydrosizer vessel 340; about 55 percent in underflow 344 from the hydrosizer vessel 340; about 10 percent in overflow 342 from the hydrosizer vessel 340; about 3 percent in the elutriation vessel 354; about 1-2 percent in overflow 358 from the elutriation vessel 354; about 60 percent in underflow 360 from the elutriation vessel 354; about 20 percent to the first low-intensity magnetic separators 366, 368 and 370; about 20 percent to the high-intensity magnetic separators 394, 396 and 398; about 11 percent in the tailings thickener vessel 426; and about 1-2 percent in the tailings thickener vessel 456. Additions of the clay dispersant reagent are about 2 kilograms per tonne total, with about half being added in the blunging vessel 304 and about half being added in the conditioning vessels 324, 326 and 328.

Reference is now made to Figure 13, illustrating one design for a blunger vessel, such as may be used for the blunger vessel 304 of the implementation in Figure 11. Figure 13 shows a blunger vessel 480 including a dual impeller agitator 482 with opposing impeller blades 484, 486. A partition barrier 488 is disposed within the vessel 480 to create a restricted space in the vessel 480 between the opposing impellers blades 484, 486. During operation, a feed 490 may be introduced into the blunger vessel 480 and processed material 492 may be removed as overflow. The shaft of the dual impeller agitator 482 is rotated causing rotation of the impeller blades 484 and 486. The impeller blades 484 and 486 direct circulation of fluid within the blunger vessel 480 as shown by the arrows within the blunger vessel 486, such that the impeller blades 484 and 486 force into the restricted space in the middle portion of the vessel 480, creating a high shear environment conducive to promoting disaggregation and dispersion of particulates.

The foregoing discussion of the invention has been presented for purposes of illustration and description. The foregoing is not intended to limit the invention to only the form or forms specifically disclosed herein. Consequently, variations and modifications commensurate with the above teachings, and the skill or knowledge of the relevant art, are within the scope of the present invention. The embodiments, implementations and variations described hereinabove are further intended to explain best modes known for practicing the invention and to enable others skilled in the art to utilize the invention in such, or other, embodiments, implementations or variations and with various modifications required by the particular applications or uses of the present invention. It is intended that the appended claims be construed to include alternative embodiments to the extent permitted by the prior art. Although the description of the invention has included description of one or more possible implementations and certain variations and modifications, other variations and modifications are within the scope of the invention, *e.g.*, as may be within the skill and knowledge of those in the art after understanding the present disclosure. It is intended to obtain rights which include alternative embodiments, implementations and variations to the extent permitted, including alternate, interchangeable and/or equivalent structures, functions, ranges or steps to those claimed, whether or not such alternate, interchangeable and/or equivalent structures, functions, ranges or steps are disclosed herein, and without intending to publicly dedicate any patentable subject matter. Furthermore, any feature described or claimed with respect to any disclosed embodiment, implementation or variation may be combined in any combination with one or more of any other features of any other embodiment, implementation or variation, to the extent that the features are necessarily not technically compatible, and all such combinations are within the scope of the present invention.

All process diagrams shown or described may be modified by the inclusion of one or more additional features, including additional process steps before or after processing shown or described or between any processing steps or stages shown or described. A “stage” as used herein means a stage in series of a process step or unit operation. Any processing shown or described may be performed in multiple parallel processing sequences. Any process flow or material shown or described may be in a single of multiple separate steams or portions.

The terms “comprise”, “include”, “have” and “contain”, and variations of those terms, as may be used in relation to the presence of a feature, are intended to indicate only that a particular feature is present, and are not intended to limit the presence of other features. The phrase “at least a portion” of a method means some or all of the material, and preferably a majority of the material.

What Is Claimed Is:

1. A method of processing an initial feed of mined particulate mineral material comprising ilmenite, magnetite and clay, and comprising the clay at a larger weight percentage than either the ilmenite or the magnetite, the method comprising:

preparing first particulate feed comprising at least a portion of the mineral material from the initial feed and comprising the clay at a larger weight percentage than either the ilmenite or the magnetite;

preparing first ilmenite concentrate from first particulate feed, comprising settling velocity separation of a majority of the clay of the initial feed of the mined mineral material based on particle settling velocity in aqueous liquid medium and recovering from the settling velocity separation the first ilmenite concentrate comprising faster settling particles and being enriched in the ilmenite relative to the first particulate feed of the mineral material; and

preparing second ilmenite concentrate from second particulate feed of the mineral material comprising at least a portion of the first ilmenite concentrate, the preparing second ilmenite concentrate comprising magnetically separating from the second particulate feed a majority of the ilmenite contained within the second particulate feed.

2. The method according to Claim 1, wherein:

the initial feed of the mineral material comprises from 7 weight percent to 25 weight percent of the ilmenite and at least 35 weight percent of the clay; and

the second ilmenite concentrate comprises the ilmenite in an amount of at least 57 weight percent and the clay in an amount of not more than 5 weight percent.

3. The method according to either one of Claim 1 or Claim 2, wherein:

the amount of the magnetite in the initial feed of the mineral material is at least 2 weight percent; and

the amount of the magnetite in the second ilmenite concentrate is at least 10 weight percent.

4. The method according to any one of Claims 1-3, wherein:

the initial feed of the mineral material comprises silica in amount of least 0.5 weight percent; and

the second ilmenite concentrate comprises the silica in an amount of no larger than 2 weight percent.

5. The method according to any one of Claims 1-4, wherein the second ilmenite concentrate comprises at least 70 percent of the ilmenite from the initial feed of the mineral

material.

6. The method according to any one of Claims 1-5, wherein the settling velocity separation comprises introducing upwardly flowing aqueous liquid into the liquid medium.

7. The method according to any one of Claims 1-6, wherein the settling velocity separation comprises a first settling velocity separation step to remove a first portion of the clay followed by second settling velocity separation step to remove a second portion of the clay.

8. The method according Claim 7, wherein at least one of the first settling velocity separation step and the second settling velocity separation step is comprised of multiple stages in series.

9. The method according to either one of Claim 7 or Claim 8, wherein the second settling velocity separation step comprises elutriation in an upwardly flowing volume of the liquid medium.

10. The method according to Claim 9, wherein the elutriation comprises:

agitating the liquid medium with a rotating agitator disposed within a liquid-containment vessel; and

feeding at least one upwardly flowing stream of the liquid medium into the liquid-containment vessel at an elevation lower than the rotating agitator;

wherein a high shear upward flow path develops between the rotating agitator and a wall of the vessel to aid separation of clay particles.

11. The method according to any one of Claims 7-10, wherein the first settling velocity separation step comprises:

recovering in overflow from the first settling velocity separation a majority of the clay of the first particulate feed; and

recovering in underflow from the first settling velocity separation a majority of the ilmenite of the first particulate feed.

12. The method according to any one of Claims 7-11, wherein the first settling velocity separation comprises:

feeding first settling velocity separation feed to a first separation tank, the first settling velocity separation feed comprising at least a portion of the first particulate feed slurried with aqueous liquid feed, the first settling velocity separation feed comprising clay particles dispersed in the aqueous liquid feed in the presence of a clay dispersant reagent to stabilize dispersion of the clay particles;

collecting first overflow from the first separation tank at a first overflow elevation, the first overflow comprising a first tail fraction of mineral material of the first settling velocity separation feed that is enriched in the clay relative to the first settling velocity separation feed; and

collecting first underflow from the first separation tank at a first underflow elevation that is lower than the first overflow elevation, the first underflow comprising a first concentrate fraction of mineral material from the first settling velocity separation feed that is enriched in ilmenite relative to the first settling velocity separation feed.

13. The method according to Claim 12, wherein the first settling velocity separation comprises during the collecting first overflow and the collecting first underflow:

maintaining first upward flow through at least a portion of the tank between the first underflow elevation and the first overflow.

14. The method according to Claim 13, wherein the first upward flow is at a velocity of no larger than 8 centimeters per minute.

15. The method according to either one of Claim 13 or Claim 14, wherein the velocity of the first upward flow is at least 2 centimeters per minute.

16. The method according to any one of Claims 12-15, wherein the feeding first settling velocity separation feed comprises introducing the first velocity separation feed into the first separation tank at a first feed elevation.

17. The method according to Claim 16, wherein the first feed elevation is between the first overflow elevation and the first underflow elevation.

18. The method according to either one of Claims 16 or 17, comprising introducing upwardly flowing first aqueous process liquid into the first separation tank at a first process liquid elevation that is lower than the first feed elevation.

19. The method according to Claim 18, wherein the first aqueous process liquid is introduced into the first separation tank adjacent a bottom of the first separation tank.

20. The method according to any one of Claims 12-19, wherein the collecting first underflow comprises raking particles toward an outlet for the underflow.

21. The method according to any one of Claims 12-20, wherein the first overflow fraction comprises at least 50 weight percent of the first settling velocity separation feed.

22. The method according to any one of Claims 12-21, wherein residence time in the first separation tank during the first settling velocity separating is from .5 to 2 hours.

23. The method according to any one of Claims 12-22, wherein the pH in the first

separation tank during the first settling velocity separation is at a pH in a range from pH 6 to pH 9.

24. The method according to any one of Claims 12-23, wherein the first separation tank is in one stage in a series of multiple stages of the first settling velocity separation.

25. The method according to any one of Claims 12-23, wherein the first settling velocity separation is performed in a single stage comprising the first separation tank.

26. The method according to any one of Claims 12-25, comprising clarifying the first overflow, the clarifying comprising:

adjusting the pH of the first overflow to pH 8 or higher; and

adding clay flocculent reagent to flocculate the clay in the first overflow.

27. The method according to any one of Claims 12-26, wherein the second settling velocity separation comprises:

feeding to a second separation tank a second settling velocity separation feed of mineral material comprising at least a portion of the first concentrate fraction of mineral material from the first settling velocity separation;

collecting second overflow from the second separation tank at a second overflow elevation, the second overflow comprising a second tail fraction of mineral material from the second settling velocity separation feed that is enriched in the clay relative to the second settling velocity separation feed;

collecting second underflow from the second separation tank at a second underflow elevation that is lower than the second overflow elevation, the second underflow comprising a second concentrate fraction of mineral material from the second settling velocity separation feed that is enriched in ilmenite relative to the second settling velocity separation feed.

28 The method according to Claim 27, wherein the second settling velocity separation comprises during the collecting second overflow and the collecting second underflow:

maintaining second upward flow through at least a portion of the tank between the second underflow elevation and the second overflow elevation, wherein the second upward flow is at a velocity that is greater than the velocity of the first upward flow.

29. The method according to Claim 28, wherein velocity of the second upward flow is at least 3 centimeters per minute.

30. The method according to either one of Claim 28 or Claim 29, wherein velocity of the second upward flow is no larger than 15 centimeters per minute.

31. The method according to any one of Claims 27-30, wherein the feeding second settling velocity separation feed comprises introducing the second velocity separation feed into the second separation tank at a second feed elevation.

32. The method according to Claim 31, wherein the second feed elevation is between the second overflow elevation and the second underflow elevation.

33. The method according to either one of Claim 31 or Claim 32, comprising introducing upwardly flowing second aqueous process liquid into the second separation tank at a second process liquid elevation that is lower than the second feed elevation.

34. The method according to Claim 33, wherein the second aqueous process liquid is introduced into the second separation tank adjacent a bottom of the second separation tank.

35. The method according to any one of Claims 27-34, wherein the collecting second underflow comprises raking particles toward an outlet for the underflow.

36. The method according to any one of Claims 27-35, wherein the second underflow fraction comprises at least 50 weight percent of the second settling velocity separation feed.

37. The method according to any one of Claims 27-36, wherein residence time in the second separation tank during the second settling velocity separating is from .5 to 2 hours.

38. The method according to any one of Claims 27-37, wherein the pH in the second separation tank during the second settling velocity separation is at a pH in a range from pH 6 to pH 9.

39. The method according to any one of Claims 27-38, wherein the second separation tank is in one stage in a series of multiple stages of the second settling velocity separation.

40. The method according to any one of Claims 27-38, wherein the second settling velocity separation is performed in a single stage comprising the second separation tank.

41. The method according to any one of Claims 27-40, comprising clarifying the second overflow, the clarifying comprising:

adjusting the pH of the second overflow to pH 8 or higher; and

adding clay flocculent reagent to flocculate the clay in the second overflow.

42. The method according to any one of Claims 27-41, wherein:

the first separation tank is in a first stage in a series of multiple stages of the first settling velocity separation; and the second settling velocity separation feed comprises a portion of the first concentrate fraction that has been further concentrated in ilmenite in at least a second stage in series of the first settling velocity separation.

43. The method according to any one of Claims 27-42, comprising attrition scrubbing at least a portion of the first concentrate fraction to prepare the second settling velocity feed.

44. The method according to any one of Claims 1-43, wherein the preparing the first particulate feed comprises blunging at least a portion of the mineral material of the initial feed in the presence of clay dispersant reagent.

45. The method according to Claim 44, wherein the preparing the first particulate feed comprises size separating from the mineral material a larger particle-size fraction that is not subjected to the settling velocity separation.

46. The method according to either one of Claim 44 or Claim 45, wherein:

the blunging comprises a first blunging stage and a second blunging stage; and the method comprises between the first blunging stage and the second blunging stage, size separating from the mineral material a larger particle-size fraction that is not subjected to the second blunging stage or the settling velocity separation.

47. The method according to any of Claims 1-46, wherein the settling velocity separation comprises separating at least 80 percent by weight of the clay of the first particulate feed

48. The method according to any of Claims 1-47, wherein the preparing a second ilmenite concentrate comprises magnetically separating magnetic ilmenite-containing and magnetite-containing particles from the second particulate feed of the mineral material.

49. The method according to Claim 48, wherein the magnetically separating comprises a low-intensity magnetic separation to recover a first portion of the magnetic ilmenite-containing and magnetite-containing particles and high-intensity magnetic separation performed on at least a portion of reject material from the low-intensity magnetic separation to recover a second portion of the magnetic ilmenite-containing and ilmenite-containing particles.

50. The method according to Claim 49, wherein the low-intensity magnetic separation comprises multiple stages in series.

51. The method according to Claim 49 or Claim 50, wherein the high-intensity magnetic separation comprises multiple stages in series.

52. The method according to any one of Claims 48-51, comprising attrition scrubbing at least a portion of the first ilmenite concentrate to prepare the second particulate feed of the mineral material.

53. The method according to Claim 1, wherein:

the preparing the first particulate feed comprises blunging at least a portion of the mineral material of the initial feed in the presence of a clay dispersant reagent, the blunging comprising a first blunging stage, a second blunging stage and size separation of a larger-particle size fraction of the mineral material between the first blunging stage and the second blunging stage;

the settling velocity separation comprises a first settling velocity separation step to remove a majority of the clay of the first particulate feed followed by second settling velocity separation step to elutriate coarse silica;

the first settling velocity separation comprising:

feeding first settling velocity separation feed to a first separation tank, the first settling velocity separation feed comprising at least a portion of the first particulate feed slurried with aqueous liquid feed, the first settling velocity separation feed comprising clay particles dispersed in the aqueous liquid feed in the presence of a clay dispersant reagent to stabilize dispersion of the clay particles;

collecting first overflow from the first separation tank at a first overflow elevation, the first overflow comprising a first tail fraction of mineral material of the first settling velocity separation feed that is enriched in the clay relative to the first settling velocity separation feed; and

collecting first underflow from the first separation tank at a first underflow elevation that is lower than the first overflow elevation, the first underflow comprising a first concentrate fraction of mineral material from the first settling velocity separation feed that is enriched in ilmenite relative to the first settling velocity separation feed;

the second settling velocity separation comprising:

feeding to a second separation tank a second settling velocity separation feed of mineral material comprising at least a portion of the first concentrate fraction of mineral material from the first settling velocity separation;

collecting second overflow from the second separation tank at a second overflow elevation, the second overflow comprising a second tail fraction of mineral material from the second settling velocity separation feed that is enriched in the clay relative to the second settling velocity separation feed;

collecting second underflow from the second separation tank at a second underflow elevation that is lower than the second overflow elevation, the second underflow comprising a second concentrate fraction of mineral material from the second settling velocity separation feed that is enriched in ilmenite relative to the second settling velocity separation feed; and

maintaining second upward flow through at least a portion of the second separation tank between the second underflow elevation and the second overflow elevation, during the collecting second overflow and the collecting second underflow; and

the preparing a second ilmenite concentrate comprises magnetically separating magnetic ilmenite-containing and magnetite-containing particles from the second particulate feed comprising at least a portion of the second concentrate fraction from the second settling velocity separation, the magnetically separating comprising a low-intensity magnetic separation step to recover a first portion of the magnetic ilmenite-containing and magnetite-containing particles and a high-intensity magnetic separation step performed on at least a portion of reject material from the low-intensity magnetic separation to recover a second portion of the magnetic ilmenite-containing and magnetite-containing particles.

54. The method according to Claim 53, wherein:

the initial feed of the mineral material comprises:

from 10 weight percent to 20 weight percent of the ilmenite;

at least 5 weight percent of the magnetite; and

at least 50 weight percent of the clay; and

the second ilmenite concentrate comprises:

at least 65 weight percent of the ilmenite;

from at least 10 weight percent of the magnetite;

not more than 5 weight percent of the clay; and

at least 70 percent of the ilmenite contained in the initial feed of the mineral material.

55. The method according to any one of Claims 1-54, comprising smelting at least

a portion of the second ilmenite concentrate to produce a slag containing TiO_2.

56. The method according to any one of Claims 1-55, comprising making bricks comprising at least a portion of the clay separated from the mineral material during the settling velocity separation.

57. A particulate ilmenite concentrate product prepared from mined ilmenite-containing mineral material comprising, relative to the weight of the concentrate product on a dry basis:

ilmenite, in an amount of at least 57 weight percent;

iron oxides, other than contained in the ilmenite, in an amount of at least 15 weight percent;

clay, in an amount of not greater than 5 weight percent;

calcium, in an amount of not greater than 0.08 weight percent; and

one or both of thorium and uranium in a combined amount of not greater than 100 parts per million by weight.

58. The ilmenite concentrate product according to Claim 57, comprising magnesium, in an amount of not greater than 1.0 weight percent.

59. The ilmenite concentrate product according to either one of Claim 57 or Claim 58, comprising manganese, in an amount of not greater than 0.8 weight percent.

60. The ilmenite concentrate product according to any one of Claims 57-59, comprising magnetite in an amount of least 10 weight percent.

61. The ilmenite concentrate product according to Claim 60, wherein the magnetite amount is at least 15 weight percent.

62. The ilmenite concentrate product according to any one of Claims 57-61, wherein the ilmenite amount is at least 65 weight percent.

63. The ilmenite concentrate product according to any one of Claims 67-62, wherein the clay amount is in a range of from 0.1 weight percent to 2 weight percent.

64. The ilmenite concentrate product according to Claim 57, wherein:

the ilmenite amount is at least 70 weight percent;

the clay amount is in a range of from 0.1 weight percent to 2 weight percent;

the calcium amount is in a range of from 0.005 weight percent to 0.08 weight percent;

the combined amount of thorium and uranium is in a range of from 1 to 50 parts per million by weight; and

the product comprises:

magnetite, in an amount of from at least 15 weight percent:

magnesium, in an amount of from 0.1 weight percent to 1.0 weight percent; and

manganese, in an amount of from 0.1 weight percent to 0.8 weight percent.

65. A titanium-containing slag product, comprising relative to the weight of the slag product:

TiO_2 in an amount of at least 85 weight percent;

calcium oxides in an amount of not greater than 0.08 weight percent; and

one or both of thorium oxides and uranium oxides in a combined amount of not greater than 100 parts per million by weight.

66. The titanium-containing slag product according to Claim 65, comprising magnesium oxides, in an amount of not greater than 1.0 weight percent.

67. The titanium-containing slag product according to either one of Claim 65 or Claim 66, comprising manganese oxides in an amount of not greater than 0.7 weight percent.

68. The titanium-containing slag product according to any one of Claims 65-67, wherein the amount of the TiO_2 is in a range from 87 weight percent to 98 weight percent.

69. The titanium-containing slag product according to Claim 65, wherein:

the amount of the TiO_2 is in a range of from 87 weight percent to 98 weight percent;

the amount of the calcium oxides is in a range of from 0.005 weight percent to 0.08 weight percent;

the combined amount of the thorium oxides and uranium oxides is in a range of from 1 to 50 parts per million by weight; and

the product comprises:

magnesium oxides, at an amount of from 0.01 weight percent to 1 weight percent; and

manganese oxides, at an amount of from 0.1 weight percent to 0.7 weight percent.

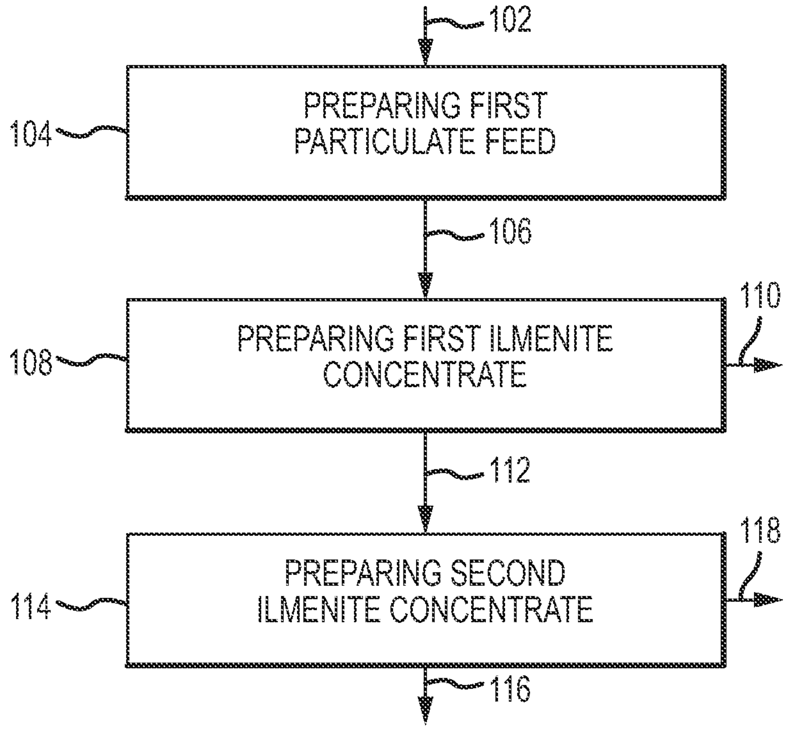
70. A method for preparing a titanium-containing slag product, comprising;

smelting an the ilmenite concentrate product of any of Claims 57-64;

recovering titanium-containing slag from the smelting.

71. A method for preparing a TiO2 pigment product, comprising:

chloride treatment of the titanium-containing slag product of any of Claims 65-69.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PREPARING FIRST PARTICULATE FEED
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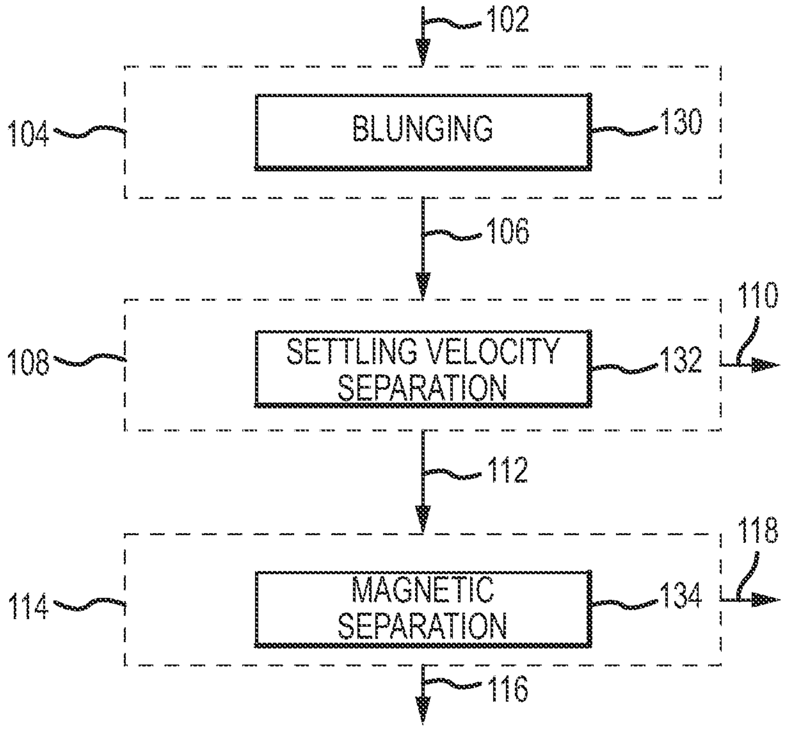
108
PREPARING FIRST ILMENITE CONCENTRATE
110
112
114
PREPARING SECOND ILMENITE CONCENTRATE
118
116

FIG.1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BLUNGING
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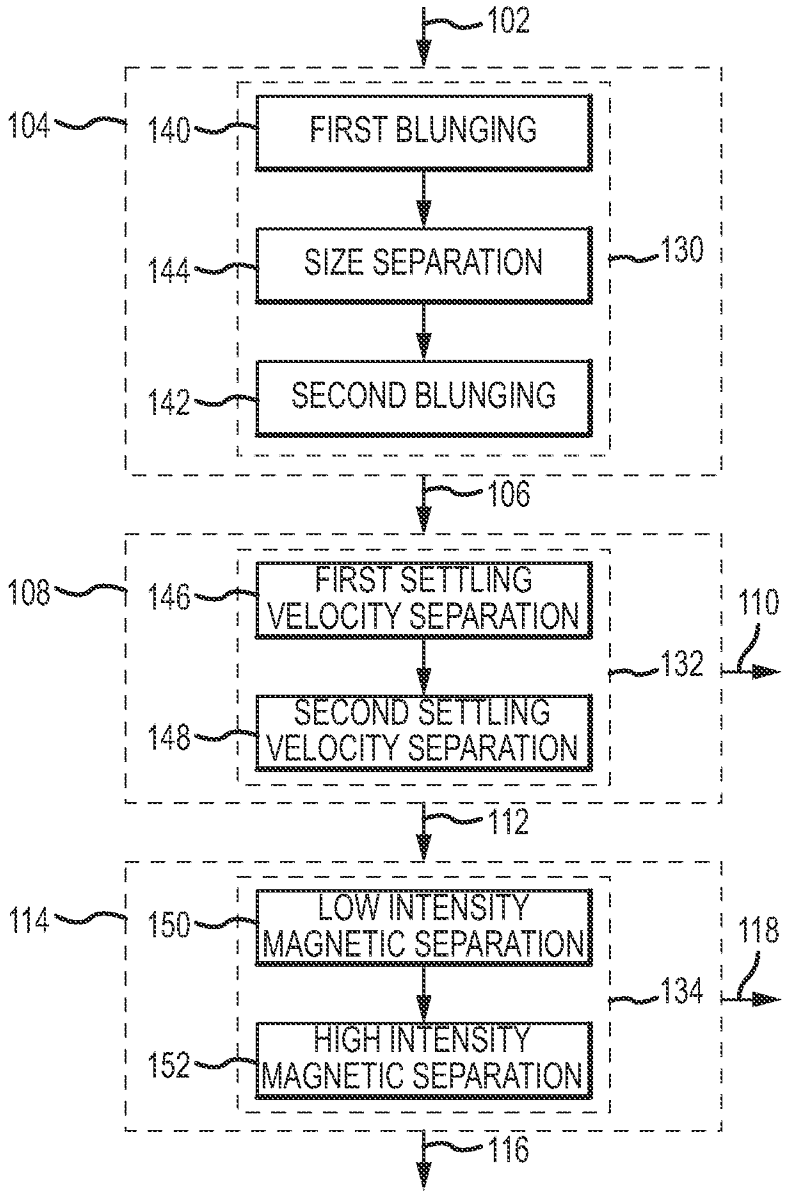
106
108
SETTLING VELOCITY SEPARATION
132
110
112
114
MAGNETIC SEPARATION
134
118
116

FIG.2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SIZE SEPARATION
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SECOND BLUNGING
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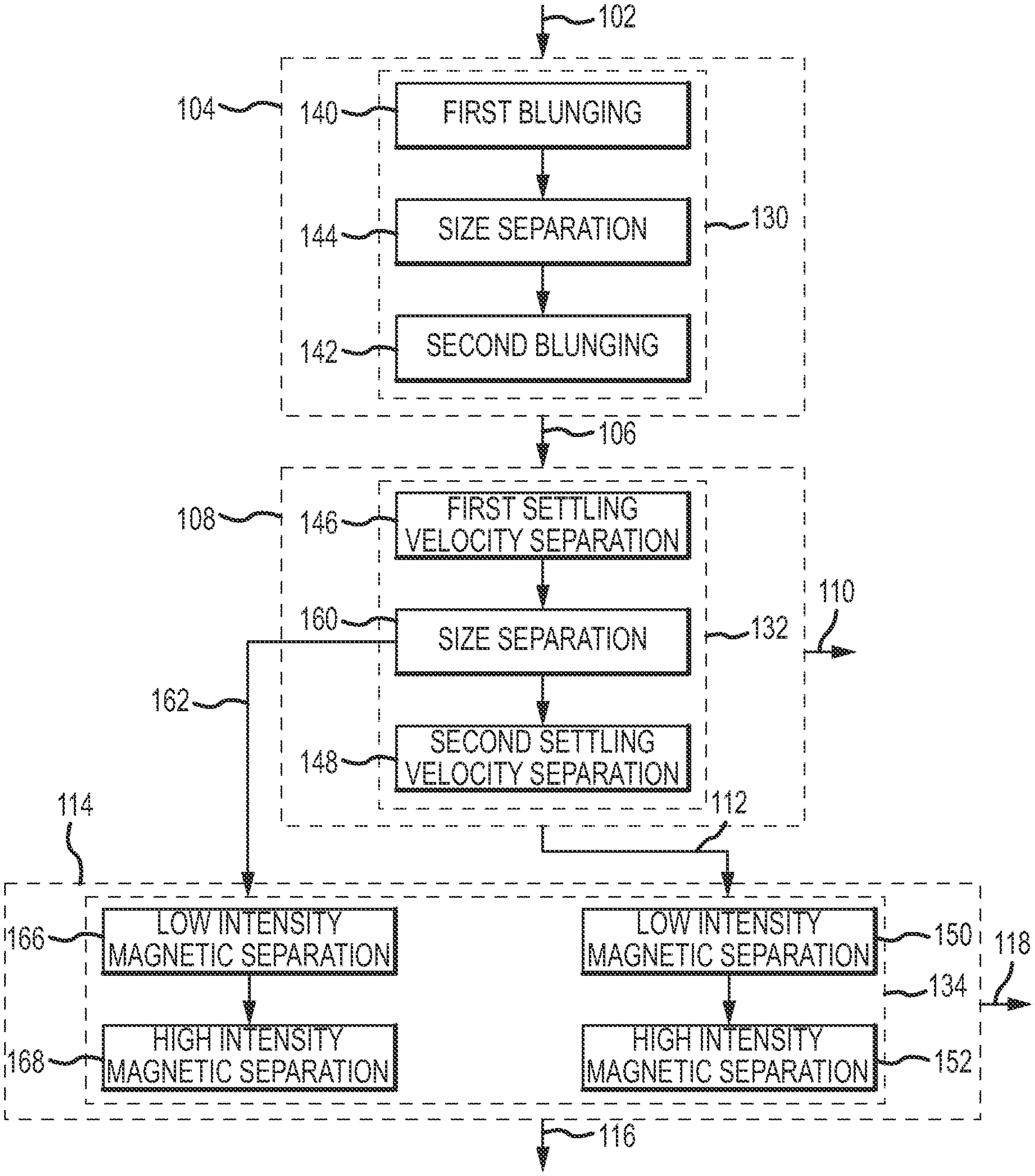
108
146
FIRST SETTLING VELOCITY SEPARATION
110
132
148
SECOND SETTLING VELOCITY SEPARATION
112
114
150
LOW INTENSITY MAGNETIC SEPARATION
118
134
152
HIGH INTENSITY MAGNETIC SEPARATION
116

FIG.3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104
140
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130
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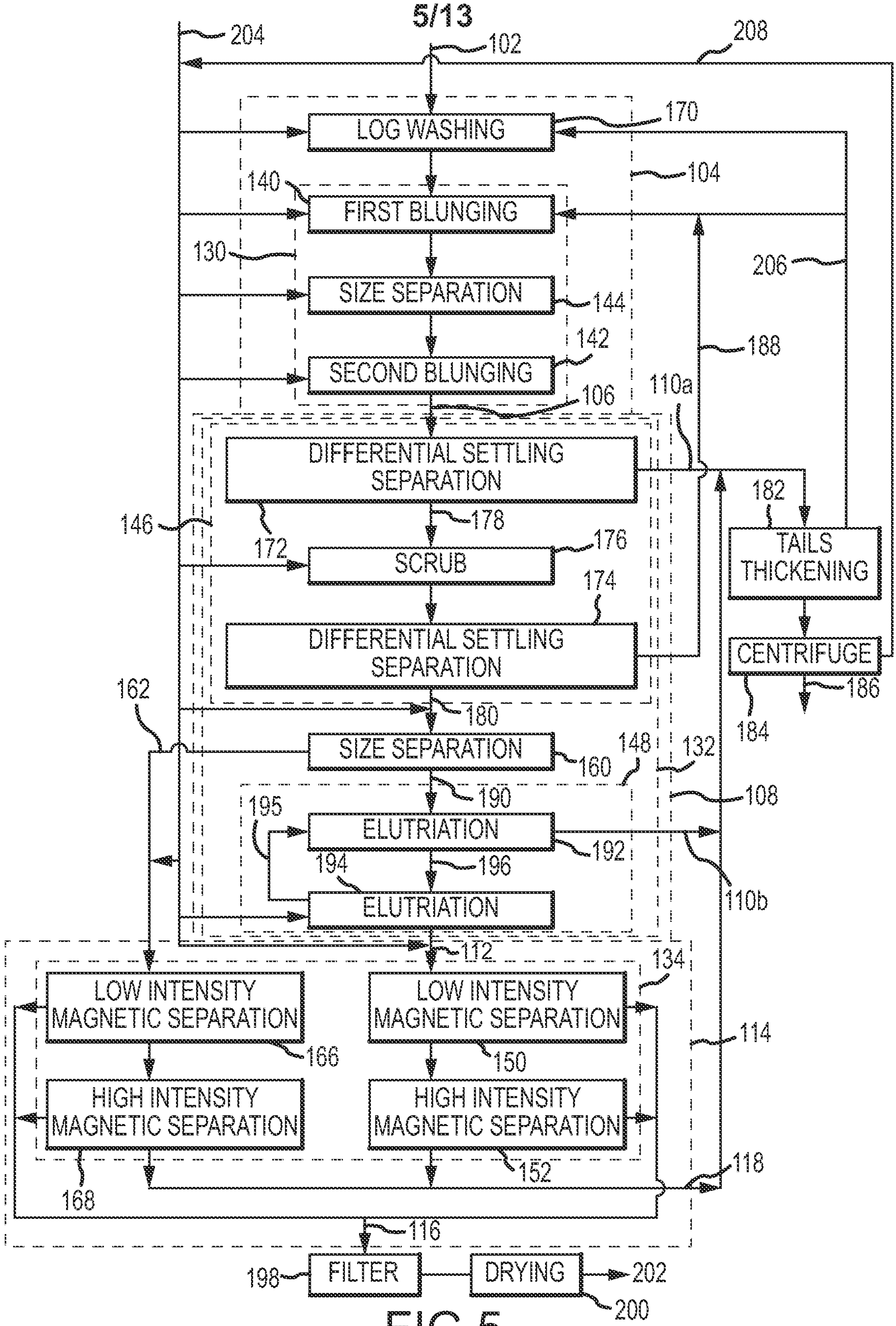
FIRST SETTLING VELOCITY SEPARATION
160
SIZE SEPARATION
132
110
162
148
SECOND SETTLING VELOCITY SEPARATION
114
112
166
LOW INTENSITY MAGNETIC SEPARATION
168
HIGH INTENSITY MAGNETIC SEPARATION
LOW INTENSITY MAGNETIC SEPARATION
150
118
134
HIGH INTENSITY MAGNETIC SEPARATION
152
116

FIG.4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102
208
LOG WASHING
170
104
140
FIRST BLUNGING
130
206
SIZE SEPARATION
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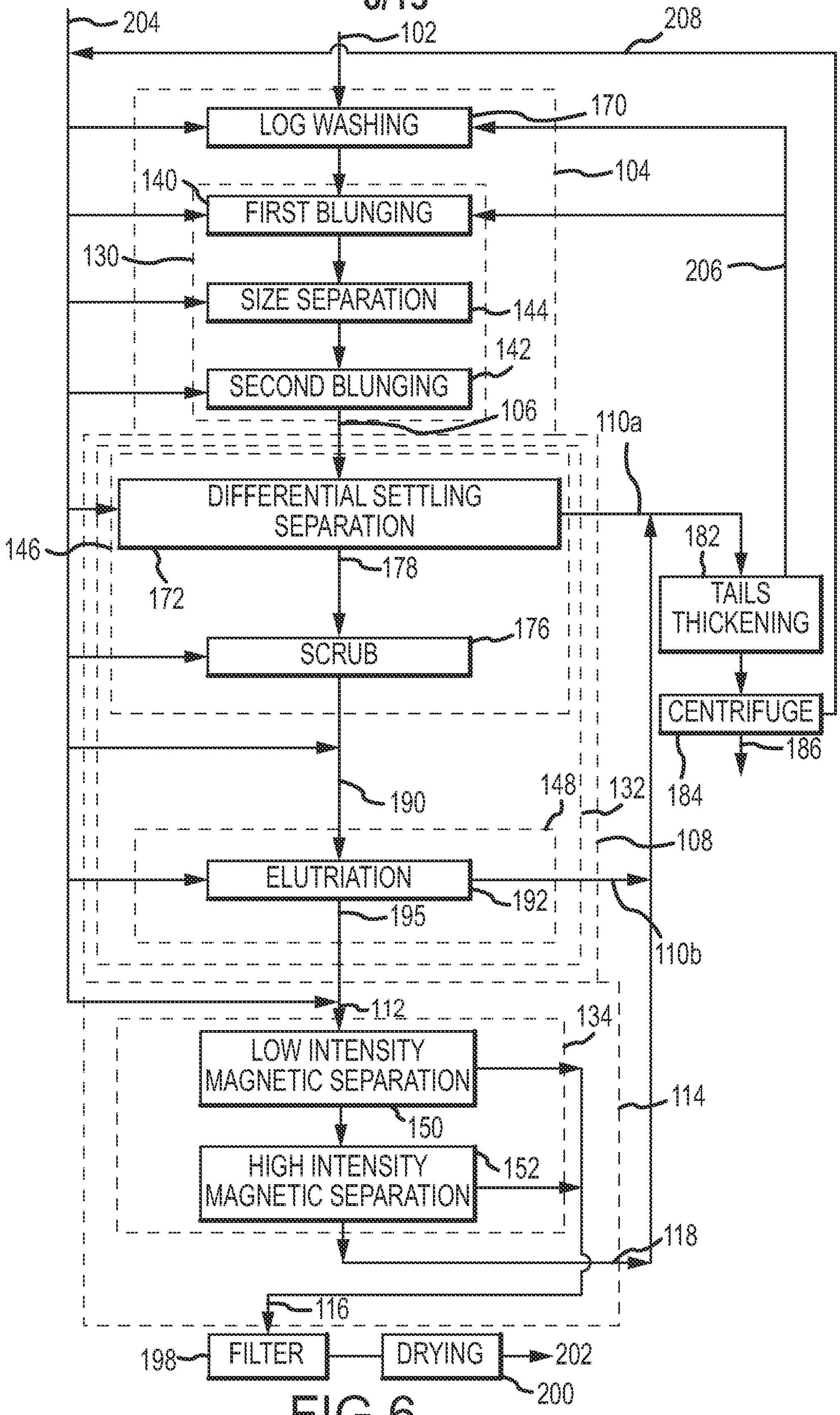
SECOND BLUNGING
188
106
110a
DIFFERENTIAL SETTLING SEPARATION
182
146
178
172
176
SCRUB
TAILS THICKENING
174
DIFFERENTIAL SETTLING SEPARATION
CENTRIFUGE
162
186
180
184
SIZE SEPARATION
148
132
160
190
108
195
ELUTRIATION
192
194
196
ELUTRIATION
110b
112
134
LOW INTENSITY MAGNETIC SEPARATION
LOW INTENSITY MAGNETIC SEPARATION
166
150
114
HIGH INTENSITY MAGNETIC SEPARATION
HIGH INTENSITY MAGNETIC SEPARATION
152
118
168
116
198
FILTER
DRYING
202
200

FIG.5



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208
LOG WASHING
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FIRST BLUNGING
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206
SIZE SEPARATION
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142
SECOND BLUNGING
106
110a
DIFFERENTIAL SETTLING SEPARATION
146
172
182
178
TAILS THICKENING
176
SCRUB
CENTRIFUGE
186
184
190
148
132
108
ELUTRIATION
192
195
110b
112
134
LOW INTENSITY MAGNETIC SEPARATION
150
114
HIGH INTENSITY MAGNETIC SEPARATION
152
118
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198
FILTER
DRYING
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FIG.6

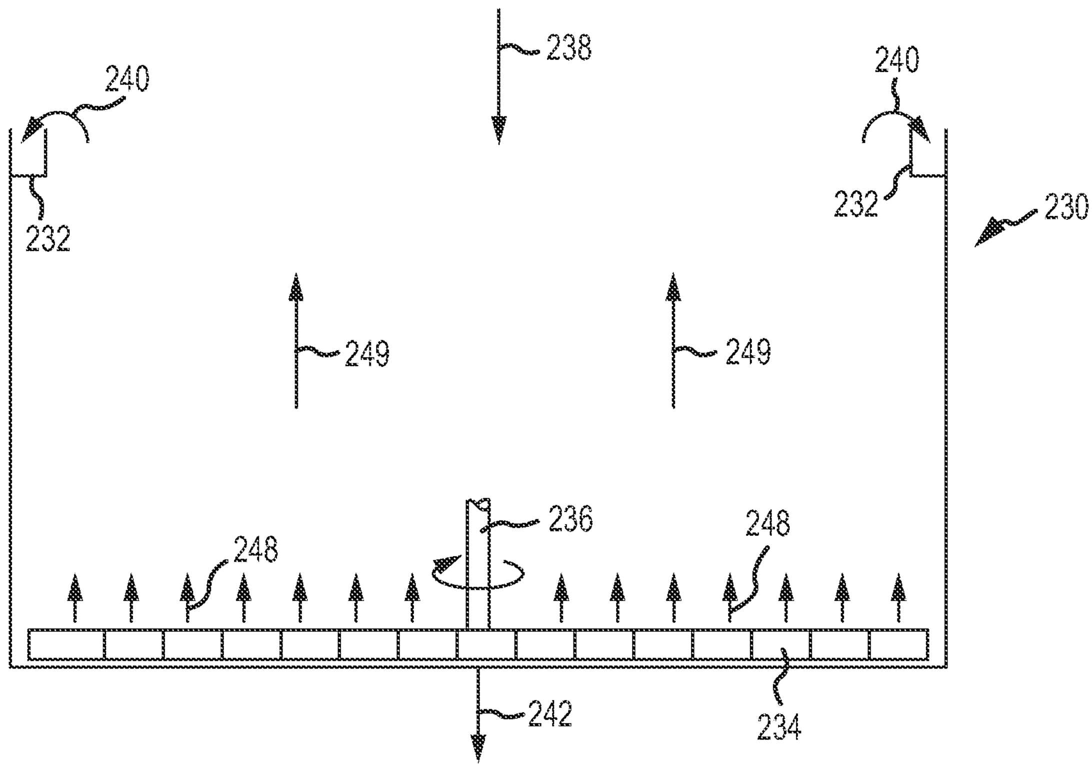

FIG.7

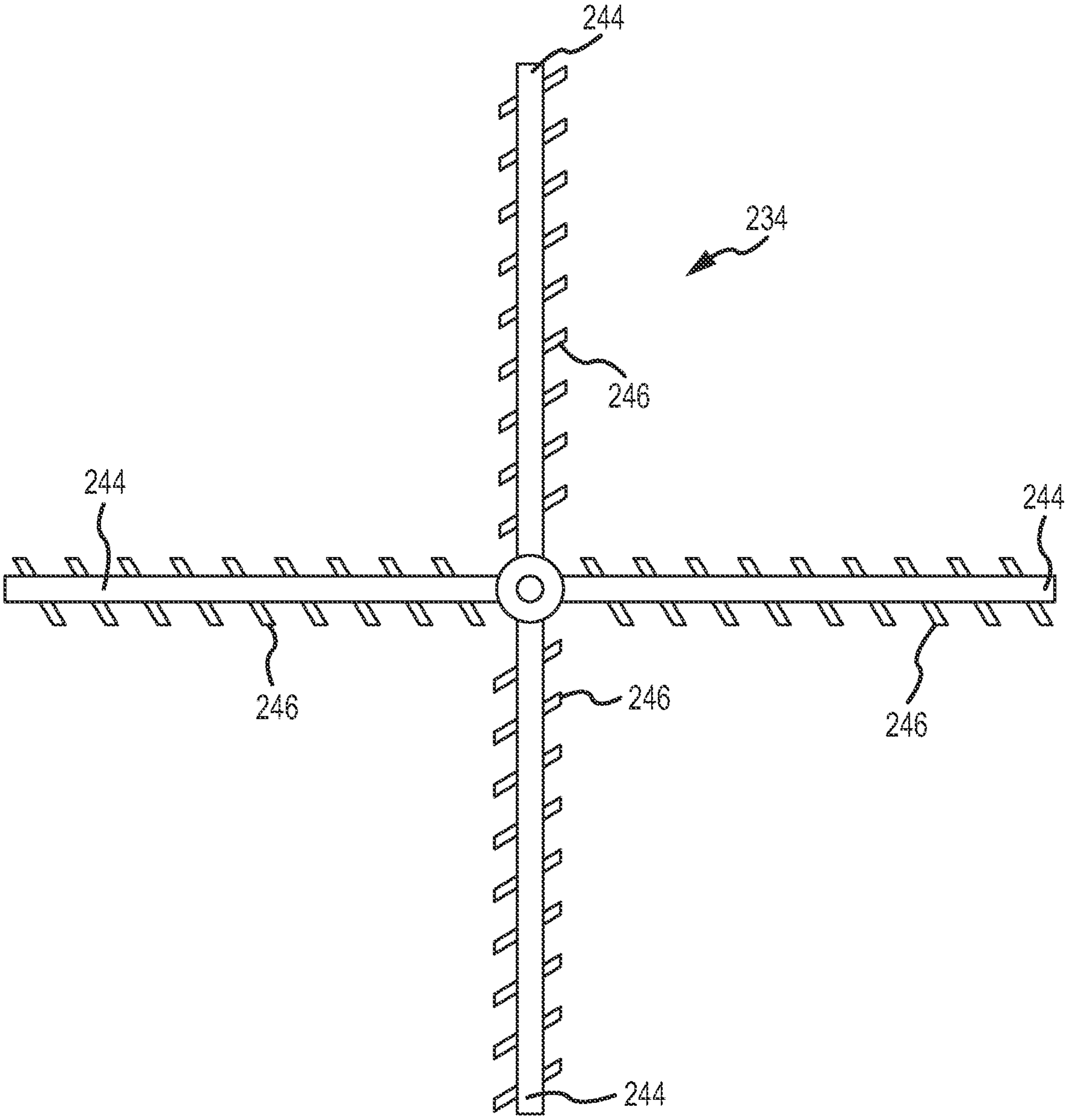

FIG.8

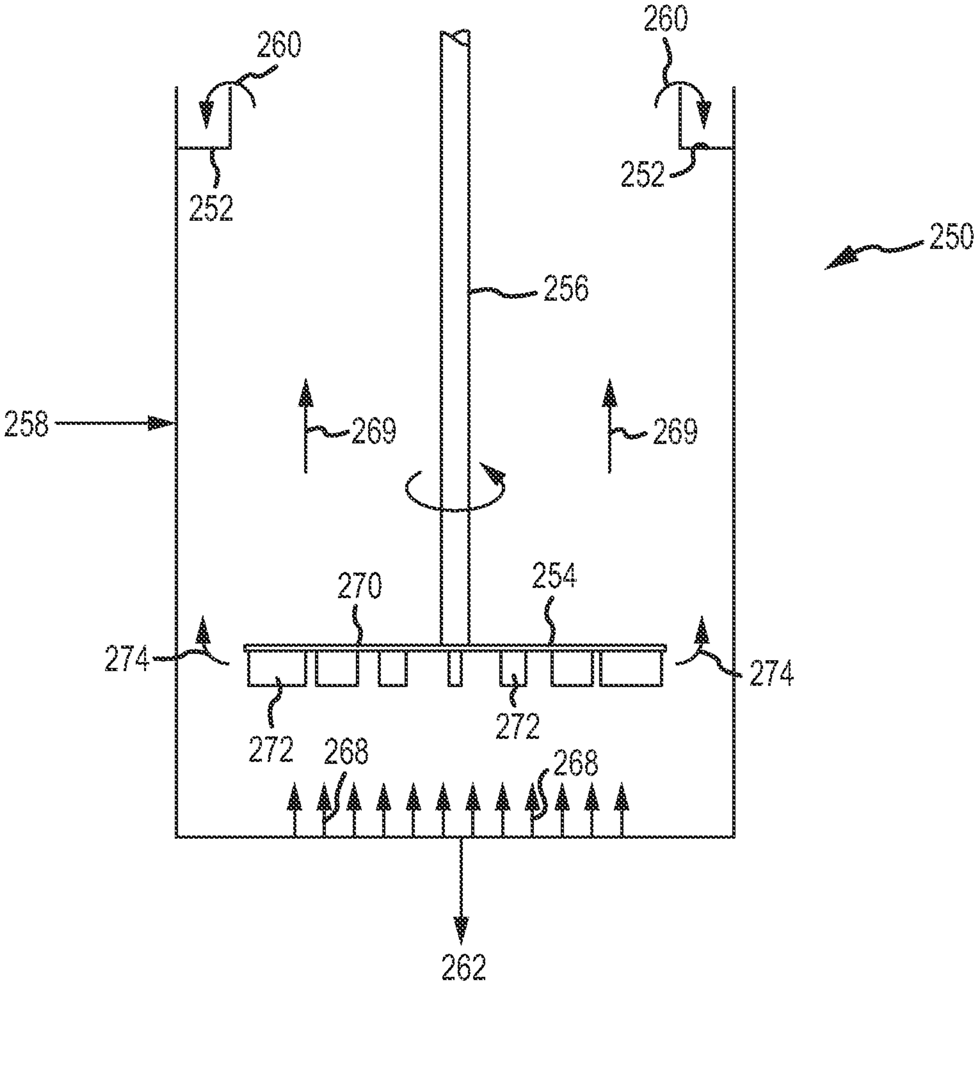
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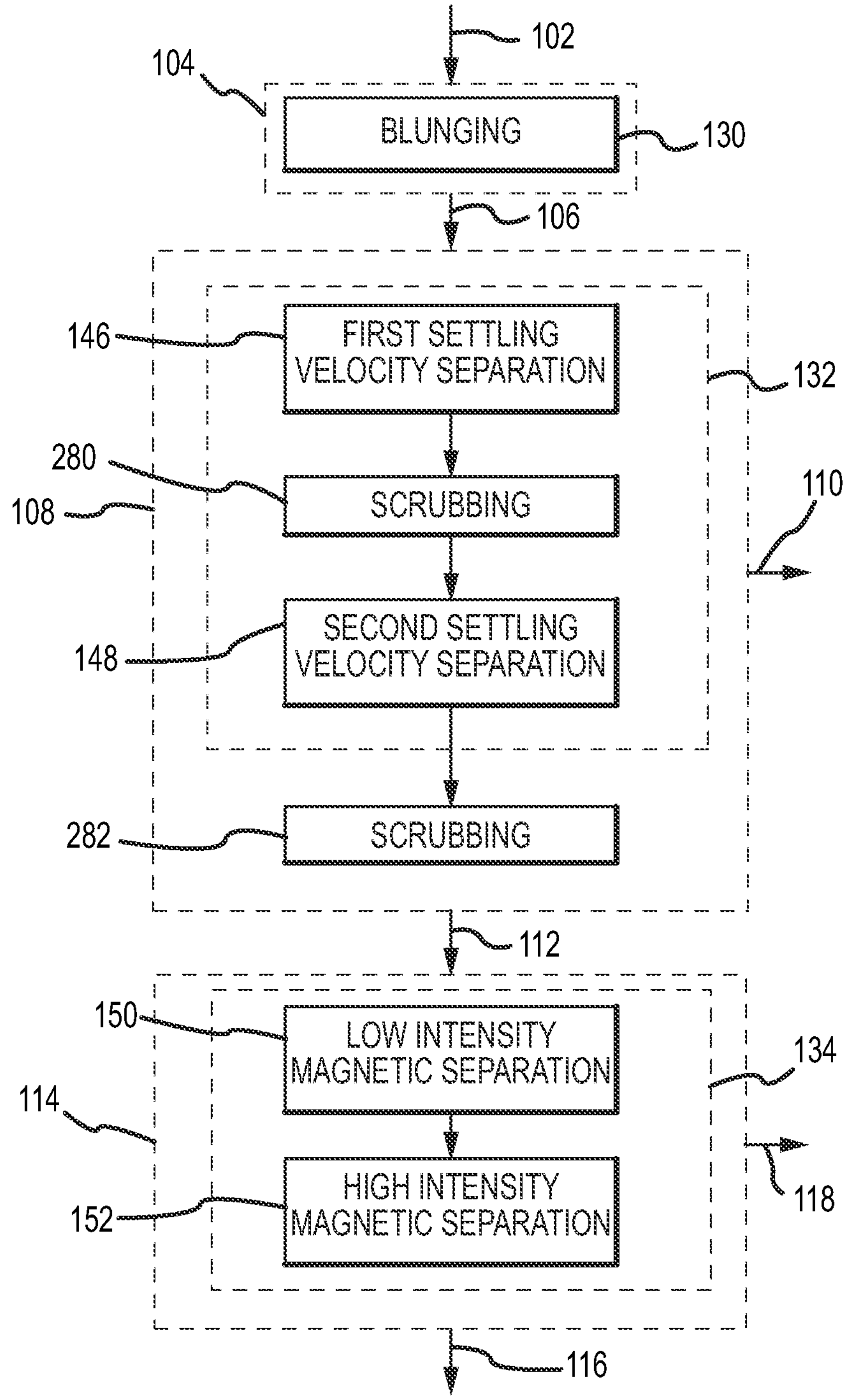
FIG.9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BLUNGING
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146
FIRST SETTLING
VELOCITY SEPARATION
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SCRUBBING
108
110
148
SECOND SETTLING
VELOCITY SEPARATION
282
SCRUBBING
112
150
LOW INTENSITY
MAGNETIC SEPARATION
134
114
118
152
HIGH INTENSITY
MAGNETIC SEPARATION
116

FIG.10

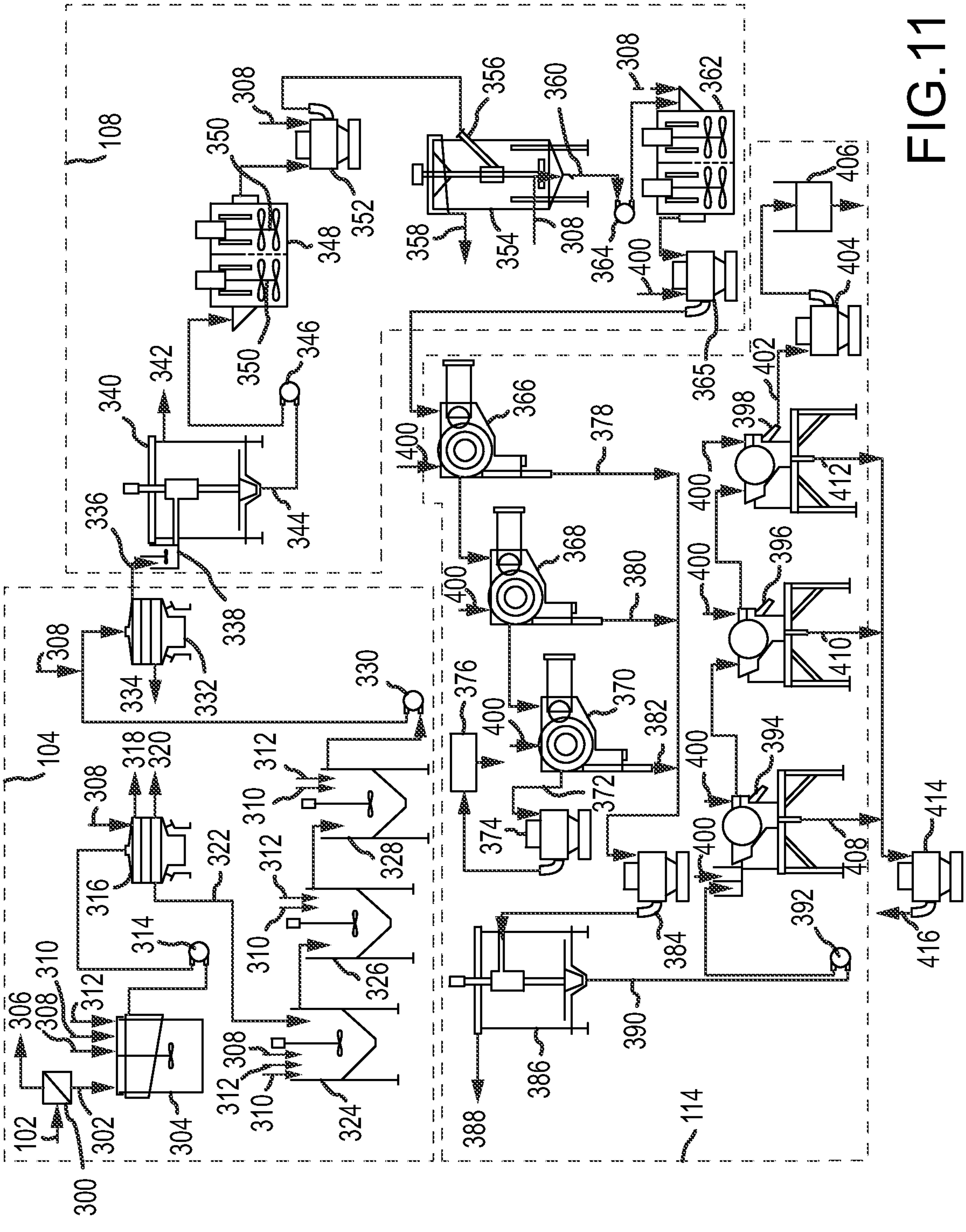
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FIG.11

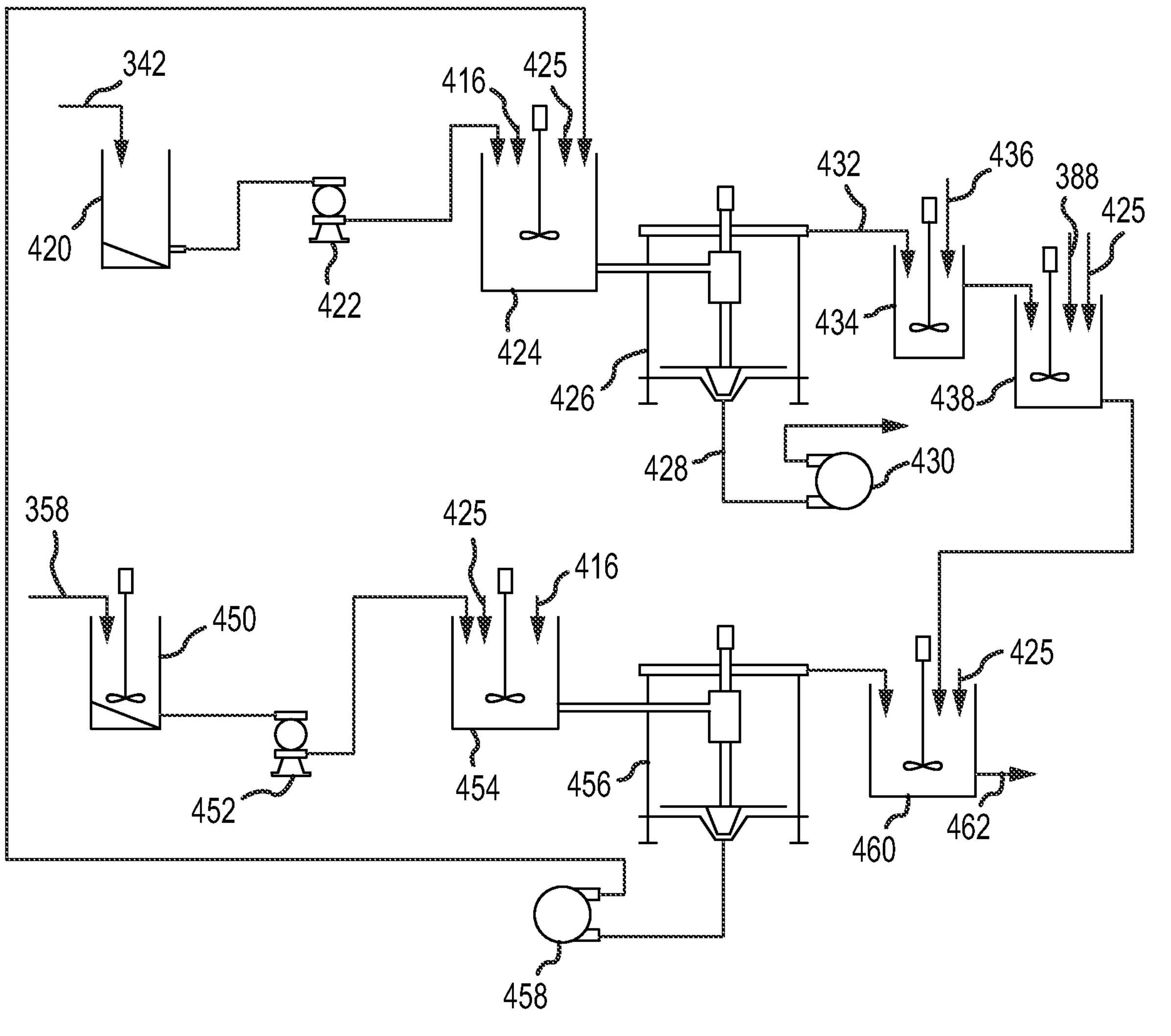
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FIG.12

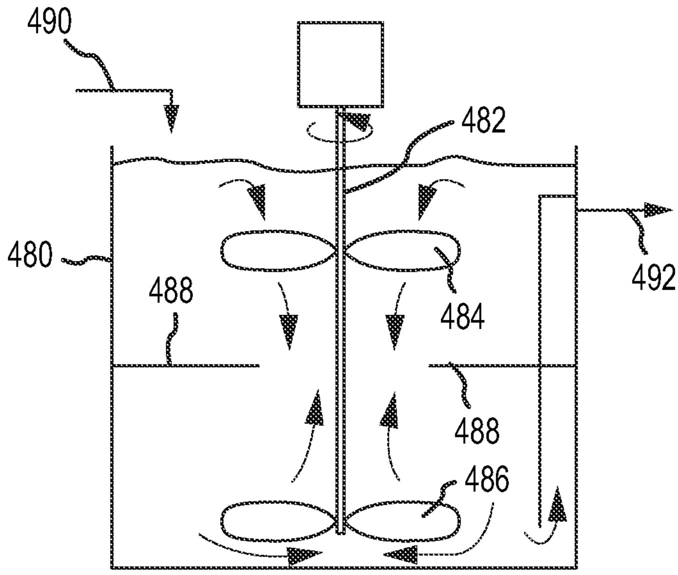

FIG.13