CHAPTER 6.3

Dense Medium Separation

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Dense (or heavy) medium separation (DMS) is used for upgrading minerals to meet market specifications (e.g., coal and iron ore) or as a preconcentration step to remove gangue minerals before further downstream treatment (e.g., diamonds and metalliferous ores such as lead, zinc, nickel, and copper). The transition of the float–sink principle from a laboratory heavy-liquids method to continuous industrial practice offers the prospect of very precise mineral separations based on density differences alone.

The process offers some advantages over other gravity processes. It has the ability to make sharp separations at any required density (D), with a high degree of efficiency even in the presence of large amounts of "near-density" particles. The density of separation can be closely controlled, within a relative density (RD) of 0.005, and can be maintained under normal conditions for indefinite periods. The separating density can, however, be changed fairly quickly to meet varying requirements. The process is relatively expensive compared to other gravity separation processes, mainly because of the ancillary equipment required to clean the medium and the cost of the medium itself.

DMS is applicable to any ore where a suitable degree of mineral liberation by comminution exists. The process is most widely applied when the density difference occurs at a coarse particle size, as separation efficiency decreases with particle size. Particles larger than 0.5 mm can be treated by DMS. However, treatment rates are much lower at the finer particle sizes. Separation can be effectively carried out where RDs of 0.1 exist. Again, particle size affects separation efficiency, finer particles having a lower efficiency of separation.

Various solids can be used to make up a heavy liquid. The media used most widely are suspensions of finely ground magnetite or ferrosilicon in water. These solids are particularly suitable because they are relatively dense (with RDs of 5.1 and 6.8, respectively), are physically stable and inert, and have magnetic properties that enable simple and efficient recovery of the solids by use of a magnetic separator.

DMSs are employed most extensively in the beneficiation of coal and in the extraction of diamonds. The most important use of DMS is in coal preparation, where a relatively simple separation removes the low-ash coal from the heavier high-ash discard and associated shales and sandstones. In addition, DMS is used in the upgrading of iron ore and preconcentration of lead-zinc ores (Munro et al. 1982).

HEAVY MEDIUM SUSPENSIONS

Below a concentration of about 15% by volume, finely ground particle suspensions in water behave essentially as simple Newtonian fluids. Above this concentration, however, the suspension becomes non-Newtonian and a certain minimum stress, or yield stress, has to be applied before shear will occur and the movement of a particle can commence. Therefore, small particles, or those close to the medium density, are unable to overcome the rigidity offered by the medium before movement can be achieved. This can be overcome to some extent either by increasing the shearing forces on the particles or by decreasing the apparent viscosity of the suspension. The shearing force may be increased by substituting centrifugal force for gravity. The viscous effect may be decreased by agitating the medium, which causes elements of liquid to be sheared relative to each other. In practice, the medium is never static, as motion is imparted to it by paddles, by air, and also by the sinking material itself.

To produce a stable suspension of sufficiently high density, it is essential to use fine particles of high specific gravity with some means of agitation to maintain a homogeneous medium. The fine solid particles of the medium must be hard, with no tendency to slime, as degradation increases the apparent viscosity. The medium must be easily removed from the mineral surfaces by washing, be amenable to recovery from the washings by magnetic separation, and be corrosion resistant. The heavy medium for coal is magnetite, while ferrosilicon is used for all other DMSs (e.g., diamonds, iron ore, and base metals).

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DENSE MEDIUM SEPARATION VESSELS

DMS vessels can be categorized into two broad categories. Static, open-bath vessels (e.g., drums) are used for separations at coarser particle sizes, while dynamic separators are generally employed for finer particle size ranges. Open-bath vessels make use of the natural settling velocity of particles in a dense medium slurry (at standard gravity), whereas dynamic vessels, namely centrifugal devices, make use of centrifugal forces to enhance the settling forces acting on the particles, thereby effectively increasing the settling velocity of the particles (and in turn increasing the capacity of the process). Cyclones are the most common centrifugal DMS devices in most industries. However, multistage separators are gaining traction outside of North America. The trend is moving toward gravity-fed separators where only the medium is pumped into the separation vessel via one of the inlets. Feeding by gravity ensures a consistent head pressure, while feeding by variable-speed pumping allows for variation and control of the pressure to the separating vessel. This reduces power and maintenance costs.

Gravitational units comprise some form of vessel into which the feed and medium are introduced and the floats (light particles) are removed by lifters, or merely by overflow. Removal of the sinks (heavy particles) is the most difficult part of separator design. The aim is to discharge the sinks particles without removing enough of the medium to cause disturbing downward currents in the vessel.

IMPLEMENTATION OF DENSE MEDIUM SEPARATION

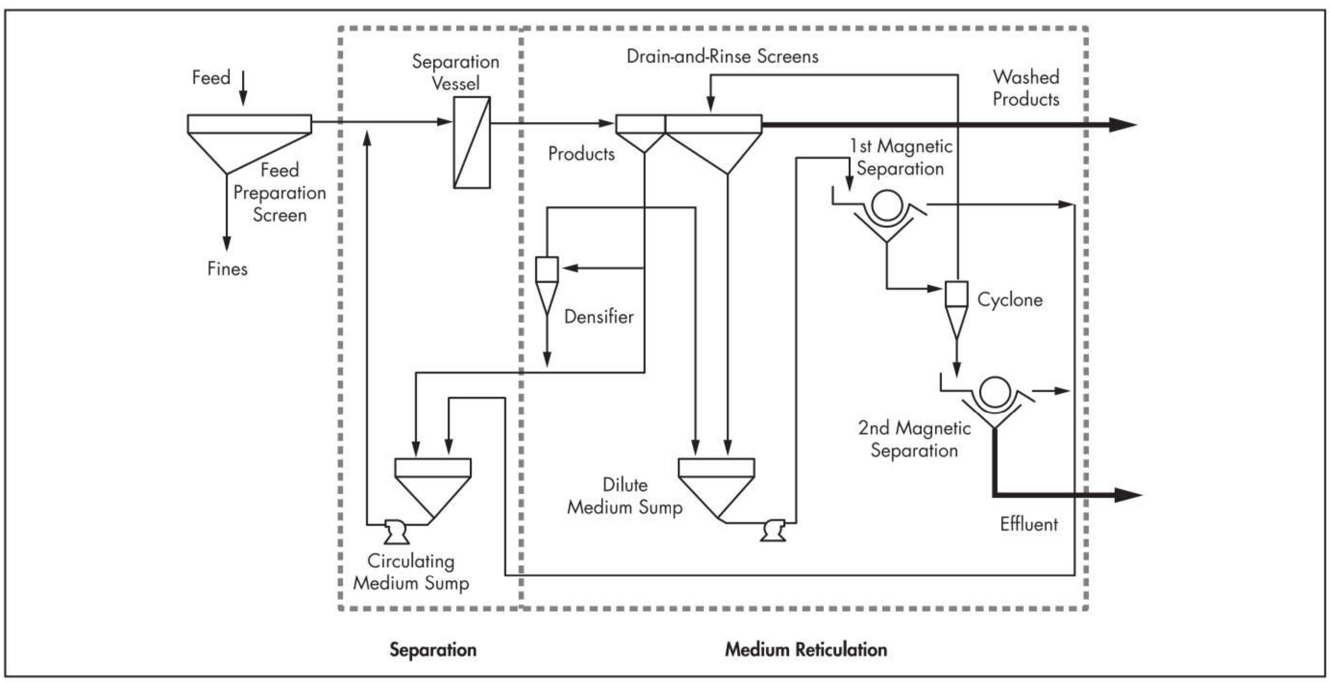
The operation of dense medium beneficiation circuits is fairly straightforward. A generic DMS circuit is shown in Figure 1. The medium, controlled to the density dictated by the separation desired, is mixed with feed ore prior to entering the separating vessel. The float and sink products, intimately mixed with medium, leave the bath and each proceeds to a separate medium recovery circuit. The system of recovery is identical in each case. The product is fed to a drain-and-rinse screen. Most of the medium is drained from the product at the head of the screen. This medium is undiluted, or is "at density," and can be recycled directly to the "correct medium" tank, ready for immediate reuse. After draining, the product is washed in two or more stages to remove any adhering medium; otherwise, such medium would be lost from the circuit. This washing is crucial, and inefficiencies at this stage lead to increases in the overall losses of medium and, hence, operating costs. The washings from the "dilute" medium are treated in a densifying circuit. This involves the extraction of the ferrosilicon from the medium entering the cyclone. This dilute medium is treated by low-intensity magnetic separators. The magnetic product is stored in the "over-dense" tank. This over-dense medium is then used for the making of more medium, on an intermittent basis, by the addition of appropriate quantities of water.

DENSE MEDIUM CIRCUITS

Although the separating vessel is the most important element of a DMS process, it is only one part of a relatively complex circuit. Other equipment is required to prepare the feed and to recover, clean, and recirculate the medium (Symonds and Malbon 2002). The feed to a dense medium circuit must be screened to remove fine ore. Slimes should be removed by washing to minimize any tendency of the slime content to create significant increases in medium viscosity.

Dense Medium Recovery

The medium recovery portion of a DMS plant consists of two circuits: the circulating medium and the dilute medium. The sinks and floats streams from the separation vessels each report to horizontal vibrating screens fitted with screen panel apertures finer than those of the feed preparation screen. The first portion of the screen is used to drain the dense medium.



Adapted from Napier-Munn et al. 2013

Figure 1 Dense medium process flow sheet

The screen undersize then reports to the circulating medium tank. The second portion of the screen is fitted with water sprays to rinse any remaining ferromagnetic particles from the solid particles in the two streams. The cleaned solids are discharged from the screens for further treatment or disposal.

Densification of Washed Medium

The undersize products from the washing screens, consisting of medium, wash water, and fine solid particles, are too dilute and contaminated to be returned directly as medium to the separating vessel. They are treated individually as shown in Figure 1 or together, by magnetic separation, to recover the magnetic ferrosilicon or magnetite from the nonmagnetic fines. Reclaimed, cleaned medium is thickened to the required density by small cyclones or a pipe densifier, and continuously returned to the DMS vessel. In some circuits, the densified medium passes through a demagnetizing coil to ensure that a non-flocculated, uniform suspension is returned to the separating vessel.

Magnetic Separation

Dilute medium is pumped to a magnetic separation stage, which is the primary step in media recovery. Wet, low-intensity, permanent magnetic drum separators are almost exclusively used for this role, and typically in two stages to maximize medium recovery and mitigate the impact of magnetic separator feed fluctuations. The primary drum collects the majority of the medium, while the secondary drum is used as a scavenger. Criteria to consider in the design and operation of a magnetic separation circuit include the volumetric flow rate of the dilute medium, the pulp density of the dilute medium, and the percentage of magnetics in the dilute medium. These factors influence the performance of the magnetic separators, and pulp levels and magnet positions in the separators must be controlled to enable an acceptable balance between maximum medium recovery and minimum dilution of the magnetic concentrate.

Demagnetizing Coil

A demagnetizing coil is often used in the densification circuit to demagnetize ferrosilicon following recovery through a magnetic separator. Ferrosilicon has a tendency to form magnetic flocs when subjected to a magnetic field, and this can lead to medium instability in the DMS operating circuit. The demagnetizing coil essentially prevents flocculation of the magnetic particles and allows thorough mixing of a stable ferrosilicon medium.

Control

Most large DMS plants include automatic control of the feed medium density. The density of the densifying medium is usually measured with a gamma attenuation gauge. The signal is used to adjust the amount of water added to the medium to return it to the correct density. Control of the medium density is a major factor in the operation of the DMS process. The medium density must be kept close to the target or set-point density to avoid displacement of "near-density material," which will affect the yields and product grades. The density should be controlled to a precision of two decimal points, or ±0.005.

Medium Rheology

Medium rheology is critical to efficient operation of dense medium systems (Napier-Munn 1990; Bosman 2014), although the effects of viscosity are difficult to quantify (Reeves 1990; Dunglison et al. 1999). Management of viscosity includes selecting the correct medium specifications, minimizing operating density, and minimizing the content of clays and other fine contamination (Napier-Munn and Scott 1990). If the quantity of fines in the circuit reaches a high proportion, it is usual to increase the volume of medium diverted to the cleaning circuit. Many circuits have such a provision, allowing medium from the draining screen to be diverted into the washing screen undersize sump.

Water Balance

Control of the medium density requires removal of water added to and retained in the circulating or correct medium circuit. The main source of water entering the system is from the ore feed, which has been wet screened and has retained water because of the medium solids adhering to the float and sink products. Other sources of water entering the circulating medium circuit include rinse screen water sprays and medium pump gland water. Thus, to be able to control the medium density, the system must remove water from the circulating medium circuit. The most effective mode of control is to remove more water than enters the circuit, and control is established by adding water. This is referred to as positive water addition. The medium density is controlled by the operation of the densification and medium recovery circuits. In lower operating density separations (e.g., coal operating at 1.4–1.8 RD), the dilute medium circuit magnetic separator is sufficient to remove water from the circulating medium and to enable density control. For higher-density mineral separations operating at RDs of 2.5 and higher, centrifugal densifiers are usually required to maintain good density control. Furthermore, densifiers will reject lower-density contaminant minerals from the circulating medium (e.g., silicates and clays). However, in higher-density mineral separations, such as sulfides, it is recommended that a circulating medium bleed to the dilute medium circuit be incorporated to remove fine high-density nonmagnetic particles that can build up in the circuit and affect the medium density and viscosity.

Medium Losses

Despite the recovery systems of ferrosilicon through the float and sink screens and magnetic separator circuits, these recovery systems are not 100% efficient. Losses due to medium attached to the float and sink particles and effluent losses via the magnetic separators are unavoidable. Generally, ferrosilicon consumption is typically in the range of 0.15 to 0.25 kg/t of DMS feed. Losses are made up by mixing fresh ferrosilicon into the correct medium circuit. Magnetite losses of around 0.5 to 1.0 kg/t of coal treated are common.

The actual quantity of medium lost will depend on the size and porosity of the feed ore, the characteristics of the medium solids, and plant design (Napier-Munn et al. 1995). Losses increase for fine or porous ores, fine media, and high operating densities.

Effluent water always contains some entrained medium—the more that can be recycled back to the plant, the better

(Dardis 1987). Careful attention should also be paid to the quality of the medium used. Williams and Kelsall (1992) demonstrated that certain ferrosilicon powders are more prone to mechanical degradation and corrosion than others.

Operating Costs

The major costs in DMS are power (for pumping) and medium consumption. Medium losses can account for 10%–35% of total costs.

APPLICATION OF HEAVY LIQUIDS

Heavy liquids are dense fluids or solutions used to separate minerals of different density through their buoyancy. Minerals with a density greater than the heavy liquid will sink, while materials with a density less than the heavy liquid will float on the liquid surface. The aim of heavy liquids in the mineral industry is to separate the minerals in an ore sample into a series of fractions according to density, establishing the relationship between the high- and low-density minerals. Australian Standard AS 4350.2 (1999) and American standard D4371 (ASTM 1999) are used for heavy liquid separation.

Heavy liquids are used widely in metallurgical laboratories for the appraisal of gravity separation techniques on ores. Heavy liquid testing may be performed to determine the feasibility of DMS on a particular ore, and to determine the economic separating density, or it may be used to assess the efficiency of an existing dense medium circuit by carrying out tests on the sink and float products.

Given the cost and toxicity of heavy liquids, the range of available materials has been reduced considerably compared to previous decades. The liquids are mainly high-density organic compounds or aqueous salt solutions. Commonly used heavy liquids include the following:

- Tetrabromoethane (TBE), having a density of 2.96, is commonly used. It may be diluted with white spirit or carbon tetrachloride (1.58 SG [specific gravity]) to give a range of densities lower than 2.96.
- Bromoform (density 2.89) may be mixed with carbon tetrachloride to give densities ranging from 1.58 to 2.89. It is an expensive chemical but evaporates much quicker than other reagents, so sample processing is faster, in particular when dealing with large sample volumes.
- Perchloroethene (density 1.6).
- White spirits (density 0.78) is used as a diluent for bromoform and TBE.
- Diiodomethane or methylene iodide (density 3.325).
- Clerici solution (thallium formate–thallium malonate solution) allows separation at densities up to 4.2 at 20°C or 5.0 at 90°C. Clerici liquids are extremely poisonous and must be handled with extreme care.
- Sodium polytungstate, or SPT (density 3.100). Aqueous solutions of sodium polytungstate have certain advantages over organic liquids, such as being virtually nonvolatile, nontoxic, and of lower viscosity, and densities of up to 3.1 can be easily achieved (Anon. 1984).
- Lithium polytungstate (density 2.92) is an inorganic heavy liquid.

Two of the most commonly used organic heavy liquids are bromoform and TBE. Of these, bromoform has the lower viscosity (1.8 cP) but is considered more hazardous to work with because it has a higher vapor pressure (5.9 mm Hg at 25°C). TBE has a higher viscosity (9 cP) and a lower vapor pressure (0.02 mm Hg at 25°C). Another organic heavy liquid, used when higher densities are required, is diiodomethane, which has a density of 3.31 g/mL, a vapor pressure of 1.2 mm Hg at 25°C, and a low viscosity of 2.6 cP.

The highly soluble inorganic salt sodium polytungstate, when dissolved in water, can be used to replace the toxic organic liquids traditionally used for gravity separation work. Sodium polytungstate is mainly used for mineral separation and for density gradient centrifugation. The inorganic salt is available in powder form and results in an aqueous, colorless, transparent neutral solution. It has no obnoxious smell and no corrosive properties, is not flammable, and is ecologically safe and simple to handle. Losses are minimal (<5%) during treatment, washing, and reconcentration.

For the separation of fine particles, sufficient time is required for the particles to settle properly in the heavy liquid, especially because the viscosity of the liquid increases as the density increases. Fine materials are often centrifuged to reduce the settling time, but this should be done with care, as there is a tendency for the floats to become entrained in the sinks fraction. Unsatisfactory results are often obtained with porous materials, such as magnesite ores, because of the entrainment of liquid in the pores, which changes the apparent density of the particles.

Heavy suspensions can achieve float–sink separations at densities higher than 3.0. Cargille liquids, which are heavy metal particles dispersed in organic liquids, can provide densities ranging up to 7.5 (Browning 1961). However, the use of these liquids is limited to the separation of mineral particles coarser than 0.6 mm, given the physical properties of the suspension. Rhodes et al. (1993) showed that high-density heavy suspensions can be made from finely divided ferrosilicon added to solutions of SPT. Eroglu and Stallknecht (2000) took the same approach but added lithium heteropolytungstate. Recently, Koroznikova et al. (2007) demonstrated that individual mineral sand minerals in the particle size range –250 +150 µm can be separated by a mixture of ultrafine tungsten carbide (3.3 µm) and a solution of lithium heteropolytungstates.

Magnetohydrostatics separation utilizing the supplementary "weighting force" produced in a solution of a paramagnetic salt or ferrofluid placed in a magnetic field gradient is another technique to separate minerals on the basis of density (Parsonage 1980; Walker 1985). The separation is applicable primarily to nonmagnetic minerals with a lower limiting particle size of about 50 µm (Parsonage 1980; Domenico et al. 1994).

DETERMINING THE SUITABILITY OF DENSE MEDIUM SEPARATION

Laboratory testing may be performed on ores to assess the suitability of DMS and to determine the appropriate separating density. Liquids covering a range of densities in incremental steps are prepared, and the representative sample of crushed ore is introduced into the liquid of highest density. The floats product is removed and washed, then placed in the liquid of the next lower density. The float product from this liquid is then transferred to the next lower-density liquid, and so on. The sinks product is finally drained, washed, and dried, and then weighed, together with the final floats product, to give the density distribution of the sample by mass.

The next step is to submit the individual float and sink fractions for chemical analysis. The results from this assessment, in conjunction with the masses obtained from the heavy liquid test, provide a mineral/metal distribution by mass. Similarly, a distribution with density in place of mass can be generated for the sample. For coal, the technique is referred to as a washability curve (ASTM International 1999). Inspection of the distribution will provide the desired density of separation for the appropriate recovery of mineral into either the float or sink product.

Near-Gravity Material

The amount of near-gravity material present is sometimes regarded as being the mass of material in the range of ±0.1 or ±0.05 kg of the separating density, and separations involving feeds with less than ~7% of ±0.1 near-gravity material are regarded by coal preparation engineers as being fairly easy to control. Such separations are often performed in Baum jigs, as these are cheaper than dense medium plants, which entail expensive media-cleaning facilities, and also do not require feed preparation (i.e., removal of the fine particles by screening). However, the density of separation in jigs is not as easy to control to close limits as it is in dense medium baths; and for near-gravity material much above 7%, DMS is preferred.

Efficiency of Dense Medium Separation

While laboratory heavy liquid separation testing is done under near-ideal conditions, the dynamic conditions of a continuous DMS process introduce natural inefficiencies, with higher-density particles misplaced into the floats stream and lower-density particles misplaced into the sinks stream. The degree of inefficiency increases relative to the proportion of particles in the feed whose density is near the density of the separation (i.e., near-density material). The efficiency of the separation process can be determined through the generation of a partition curve (coal), also known as a Tromp curve (metalliferous ores and diamonds).

Other factors also play a role in determining the efficiency of separation. Fine particles generally separate less efficiently than coarse ones, again because of their slower settling rates. The properties of the medium, the design and condition of the separating vessel, and the feed conditions, particularly feed rate, will all influence the separation.

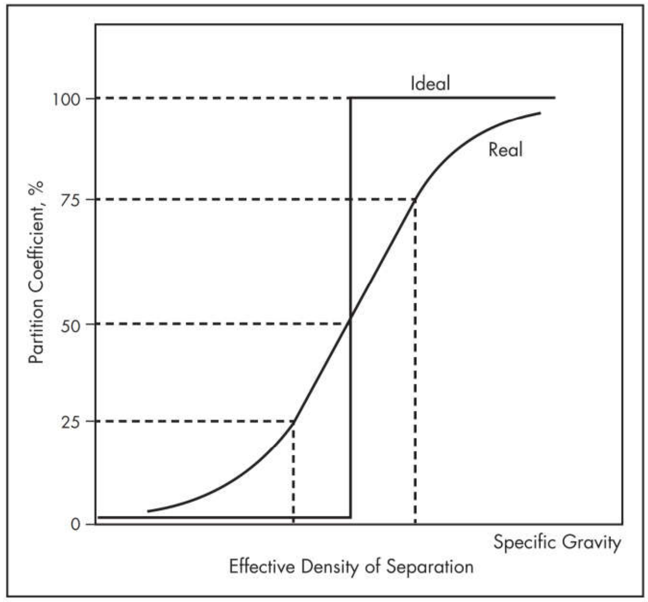
Partition Curve or Tromp Curve

The partition curve relates the partition coefficient or partition number—the percentage of the feed material of a particular specific gravity that reports to either the sinks product (generally used for minerals) or the floats product (generally used for coal)—to specific gravity. This is analogous to the classification efficiency curve, in which the partition coefficient is plotted against size rather than specific gravity.

The partition curve can be constructed after the separation of the sample has been completed by collecting representative samples from the floats and sinks streams during the separation and performing heavy liquid tests on each sample to assess the degree of misplaced material in each of the floats and sinks streams. The partition curve of the reconstituted feed can then be constructed.

Determining Efficiency Using a Tromp Curve

The efficiency of separation can be represented by the slope of a partition or Tromp curve, first introduced by K.F. Tromp (1937). It describes the separating efficiency for the separator, whatever the quality of the feed. The ideal partition curve reflects a perfect separation in which all particles having a density higher than the separating density report to sinks and those lighter report to floats (Figure 2). There is no misplaced material. The partition curve for a real separation shows that efficiency is highest for particles of density far from the operating density and decreases for particles approaching the operating density. The area between the two curves is called the "error area" and is a measure of the degree of misplacement of particles to the wrong product. Many partition curves give a reasonable straight-line relationship between distributions of 25% and 75%, and the slope of the line between these distributions is used to show the efficiency of the process (Terra 1938).



Source: Wills and Napier-Munn 2005

Figure 2 Partition or Tromp curve

The probable error of separation, or the Ecart probable (Ep), is defined as half the difference between the density where 75% is recovered to sinks and that at which 25% is recovered to sinks, that is, from Figure 2:

$$Ep = \frac{\rho_{75} - \rho_{25}}{2}$$

The density at which 50% of the particles report to sinks is shown as the effective density of separation, which may not be exactly the same as the medium density, particularly for centrifugal separators. The separating density is generally higher than the medium density. The lower the Ep, the nearer to vertical is the line between 25% and 75% and the more efficient is the separation. An ideal separation has a vertical line with an Ep = 0, whereas in practice, the Ep usually lies in the range of 0.01 to 0.10. The Ep is not commonly used as a method of assessing the efficiency of separation in units such as tables, spirals, cones, and so forth, due to the many operating variables (wash water, table slope, speed, etc.) that can affect the separation efficiency. It is, however, ideally suited to the relatively simple and reproducible DMS process (Jowett 1986). However, care should be taken in its application, as it does not reflect performance at the tails of the curve, which can be important.

Construction of Partition Curves for an Operating Plant

The partition curve for an operating dense medium vessel can be determined by sampling the sink and float products and performing heavy liquid tests to determine the amount of material in each density fraction. The range of liquid densities applied must cover the working density of the dense medium unit.

An alternative, rapid method of determining the partition curve of a separator is to utilize density tracers (Chironis 1987). Specially developed color-coded plastic tracers can be fed to the process, the partitioned products being collected and hand sorted by density (color). It is then a simple matter to construct the partition curve directly by noting the proportion of each density of tracer reporting to either the sink or the float product. Application of tracer methods has shown that considerable uncertainties can exist in experimentally determined Tromp curves unless an adequate number of tracers is used. Napier-Munn (1985) provides graphs that facilitate the selection of tracer sample size and the calculation of confidence limits.

Partition curves can be used to predict the products that would be obtained if the feed or separation gravity were changed. The curves are specific to the vessel for which they were established and are not affected by the type of material fed to it, provided the following are true:

- The feed particle size is the same—efficiency generally decreases with a decrease in size. Centrifugal separators are better than baths.
- The separating gravity is in approximately the same range—the higher the effective separating density, the greater the probable error, due to the increased medium viscosity. In fact, the Ep is directly proportional to the separating density, all other factors being the same (Gottfried 1978).
- The feed rate is the same.

The partition curve for a vessel can be used to determine the amount of misplaced material that will report to the products for any particular feed material.

Modeling of Tromp/Partition Curve

This method of evaluating the performance of a separator on a particular feed is tedious and is ideal for a spreadsheet, provided that the partition numbers for each density fraction are known. These can be represented by a suitable mathematical function (Tarjan 1974; Stratford and Napier-Munn 1986; Wood et al. 1987; Napier-Munn 1991; Scott and Napier-Munn 1992; Dunglison and Napier-Munn 1997). A large body of literature exists on the selection and application of such functions. Some are arbitrary, and others have some theoretical or heuristic justification. The key feature of the partition curve is its S-shaped character. In this it bears a passing resemblance to several probability distribution functions, and indeed the curve can be thought of as a statistical description of the DMS process, describing the probability with which a particle of given density (and other characteristics) reports to the sink product.

However, in practice, many real partition curves do not behave ideally. In particular, they are not asymptotic to 0% and 100% but exhibit evidence of short-circuit flow to one or both products. Stratford and Napier-Munn (1986) identified four attributes required of a suitable function to represent the partition curve:

1. It should have natural asymptotes, preferably described by separate parameters.
2. It should be capable of exhibiting asymmetry about the separating density; that is, the differentiated form of the function should be capable of describing skewed distributions.
3. It should be mathematically continuous.
4. Its parameters should be capable of estimation by accessible methods.

EQUIPMENT

Historical Development

The early DMS circuits employed a "static" bath-type separator. These machines treated feed particle sizes as coarse as 300 mm and as fine as +6 mm or +12 mm, depending on the application. The development of cyclone technology introduced the "dynamic" separators used to treat particles down to 0.5 mm. Recent large-cyclone developments allow the treating of particles with a top size as coarse as 100 mm.

The following selected chronology of the historical development of DMS is adapted from Burt and Mills (1984), Wills (1988), Leonard (1991), Hillman (2003), Holtham (2006), and Napier-Munn et al. (2013).

1858	Bessemer's patent covered the use of chlorides of iron, manganese, barium, and calcium as medium, but there was no serious industrial application until the 20th century.
1911	Du Pont developed the use of chlorinated hydrocarbons to achieve higher densities. The Chance process patent covered the use of a sand/water medium in a cone separator. This would probably be called a teetered-bed separator today.
1921	First Chance industrial process for cleaning anthracite.
1922	First experiments with magnetite medium for coal cleaning (Conklin process).
1930s	DMS plants for minerals using galena, in the United Kingdom and the United States.
1931	First general use of DMS plants.
1937	First use of FeSi in an ore concentrating plant in the United States, with medium recovery using cross-belt magnetic separators.
1938	Tromp process first to use magnetite medium commercially in Germany.
1940	First U.S. ferrosilicon patent. American Cyanamid Company introduced the DMS process for coal cleaning, including magnetic recovery of magnetite medium.
1942	Dense medium cyclone patented by Dutch State Mines, Holland.
1946	First use of dense medium cones in diamond processing.
1950s	Wemco (United States) developed bath (drum) using magnetite medium to treat –200/+6 mm feed and produce three products. Drewboy bath developed using magnetite medium. Teska (United States) implemented the bath method using magnetite medium.
1955	First use of dense medium cyclones in diamond processing.
1960s	Dyna Whirlpool developed in the United States for coal and later used for minerals. Vorsyl dynamic separators developed in the United Kingdom.

Table 1 Economies of scale in the coal industry for a 1,000-t/h plant

Equipment	1977	1987	1997	2007	2017
Number of modules	6	4	2	1	1
Number of deslime screens	6	4	2	1	1
Number and size of dense medium cyclones	12 × 500 mm	8 × 660 mm	2 × 1,200 mm	1 × 1,500 mm	1 × 1,500 mm
Number of drain-and-rinse screens	24	16	4	2	2
Total number of items in circuit	164	110	90	82	82
Capital expenditure, million $	26	23	20	18	18

Source: Osborne 2010

1970s Tri-Flo, a multistage separator similar to two Dyna Whirlpools bolted together in series.

1980 Larcodems, similar to the Dyna Whirlpool and developed by British Coal, as an efficient replacement for the Baum jig.

~1992 First use of cyclone diameters >1,000 mm in coal preparation (current maximum 1,500 mm).

~2005 First use of cyclone diameters >610 mm in mineral separations (current maximum 800 mm).

All the early dense medium processes were of the static bath type, in which the separation takes place under gravitational forces. Most of the development over the years was in the mechanical arrangement by which feed was introduced to the bath and the products removed. This led to many proprietary devices manufactured by different companies, including the Wemco cone, Wemco drum, Drewboy, Teska, Barvoy, and Norwalt bath trough-type separators, and many others (Osborne 1988; Wills and Napier-Munn 2005).The design innovations were developed principally in the United States and Europe (mostly in Germany and the United Kingdom).

Current Trends

The practice of treating coarse coal in static DMS vessels (Wemco and Teska drums) has changed over the last three decades to treating coarse material in large-diameter dense medium cyclones (DMCs). Finer coal (millimeter sized) has been processed in DMS cyclones for a long time. Spirals, water-only cyclones, and teetered-bed separators are used to process fine coal (+0.5–1 mm) while ultrafine coal is recovered by flotation. The trend toward using very large DMS cyclones over the last four decades is shown in Table 1.

The introduction of large-diameter DMCs into the coal industry and the belief that fine coal particles are not effectively beneficiated below the "breakaway" particle size led to a change in circuit design. Increasing the aperture of the desliming screens to 3 mm increased screen capacity and improved cyclone efficiency on the coarser product. The <3-mm particles are treated in teetered-bed separators and spirals (de Korte and Bosman 2006).

Static Gravitational Separators

Static gravitational units comprise some form of vessel into which the feed and medium are introduced, and the floats are removed by paddles or merely by overflow, and sinks by mechanical conveyors or lifters fixed to the inside of a rotating drum. The lifters empty into a sink launder when they pass the horizontal position. Removal of the sinks is the most difficult part of the design of these types of separators. The aim is to discharge the sinks particles without removing large quantities of medium that will cause disturbing downward currents in the vessel. Drum separators have very large sinks capacities. They are commonly used in the coal industry because of their simplicity, reliability, and relatively small maintenance needs. Drum, Wemco or Teska, and rectangular separators are still used in the minerals industry (Galvin and Iverson 2013) and available from engineering companies.

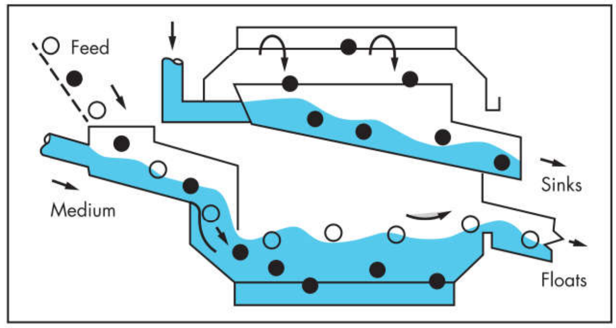
Wemco Dense Medium Drum

Wemco drum separators, patented in 1954 (Maust 1954), are built in several sizes, up to 4.3 m diameter by 6 m long, having a maximum capacity of 450 t/h, and able to treat feeds up to 300 mm in diameter (Wilkes 2006). Separation is accomplished by the continuous removal of the sink product through the action of lifters fixed to the inside of the rotating drum (Figure 3). The lifters collect solids into the sink launder when they pass the horizontal position. The float product overflows a weir and flows into the second compartment where the middlings and the true sinks are separated.

The Wemco drum consists of a steel shell equipped with two specially designed tire-and-collar assemblies (England et al. 2002). The shell is supported from and runs on four support roller assemblies. Removable and replaceable perforated-sinks lifter plates are attached to the inside of the shell. The drum shell is maintained in its operating position longitudinally on the support rollers by two thrust rollers that engage on both sides of one of the main tires as required. The support and thrust roller assemblies are located on a sub-frame that also carries the drive motor, V-belt drive, gearbox (and protective coupling where fitted), drive and idler sprocket assemblies, and drive chain. The drive chain engages with the drive sprockets bolted around the outside of the drum shell to provide a positive nonslipping drive to rotate the drum at the correct operating speed (Wilkes 2006).

The main internal components of the drum are the feed chute and feed box, sinks hopper, curtains, and media addition pipework. Media of the appropriate type and density are circulated through the Wemco drum. The media are normally introduced into the feed chute, behind one of the curtains, and into the sinks launder.

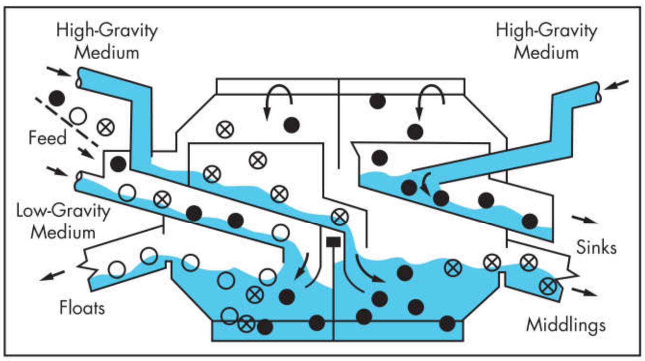
A twin-compartment (Figure 4), three-product Wemco drum is also available. In this design, two different media densities are used. The first compartment uses low-density medium and the second compartment uses high-density medium. In this way, three products can be made, namely, low-density floats, high-density floats (or middlings), and a final sinks.



Courtesy of FLSmidth

Courtesy of Wemco

Figure 3 Wemco dense medium drum



Courtesy of Wemco

Figure 4 Twin-compartment Wemco drum

This separator requires various treatments to the media addition points. Primary or low-density media are added to the feed chute and behind the primary curtain. Secondary or high-density media are added to the primary sinks launder (to introduce high-density media into the second compartment of the drum), behind the secondary curtain, and to the final secondary compartment sinks launder. The drained media from the screens are recirculated to the drum by a pump. For certain specific applications, it is possible to vary the twin-compartment drum design to treat two separate size fractions (one in each compartment) and to make a common sinks product.

The maximum size of coal that can be handled in the Wemco drum depends on the size of the inlet, outlet, and lifters. Material with a top size of 300–500 mm is not unusual if liberation of mineral matter from the coat is not a requirement. The Wemco drum can handle as much as 400 t/h feed, ~20–25 t/h/m^2 pool area, with very good separation efficiencies (Osborne 1988). High separation efficiency can be maintained through manipulation of the residence time in the vessel, either by supplying a large enough pool surface or by reducing the throughput of the raw coal. Ep values of 0.03 or better can be achieved (Osborne 1988).

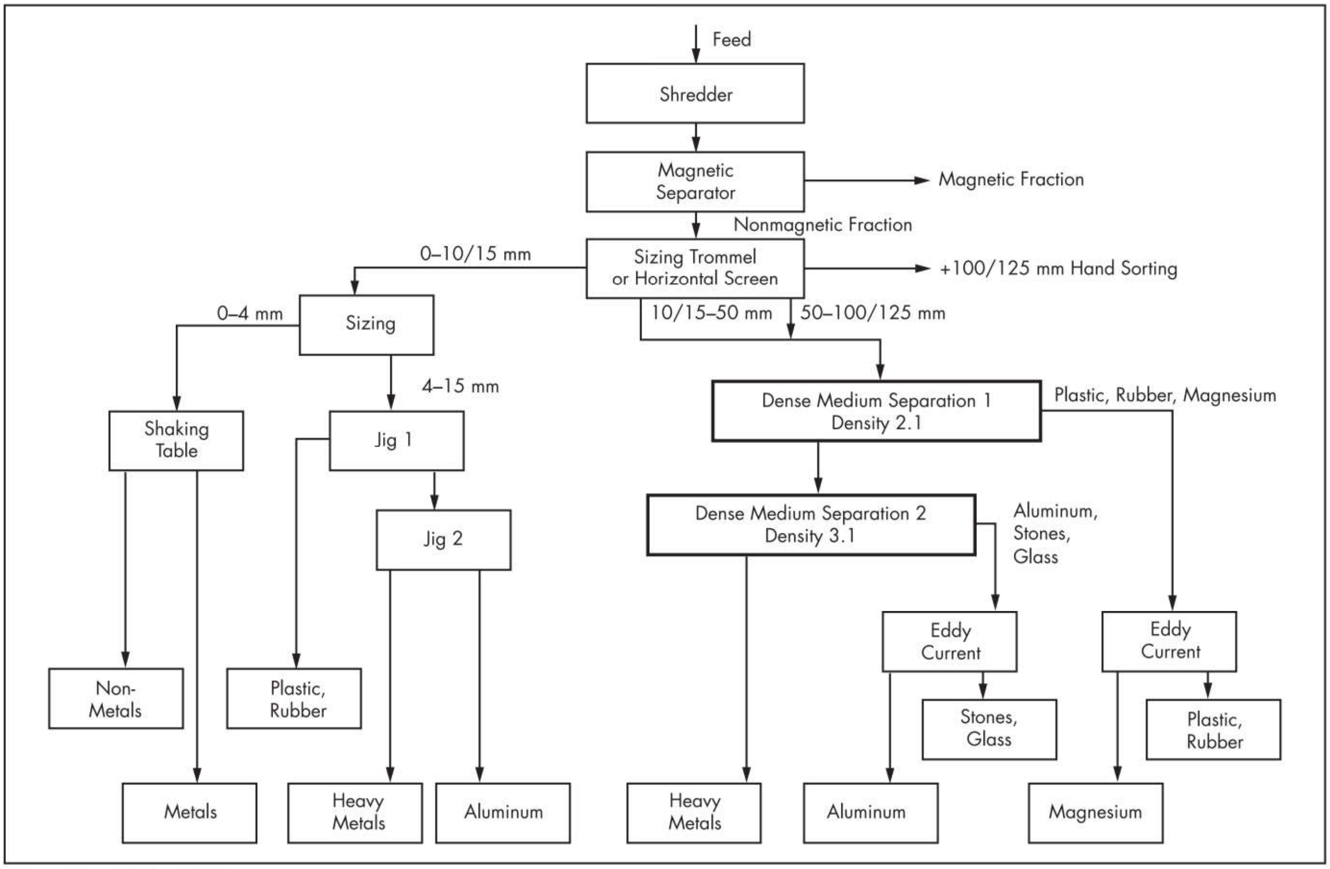
Wemco drums are available in sizes from laboratory scale, 460 mm in diameter × 690 mm long, to industrial units up to 5.4 m in diameter and 8.1 m long and having a two- or three-product separation format. Maximum capacity on a Wemco drum for coal is around 900 t/h. Modeling information of drum dense medium separators is provided by Baguley and Napier-Munn (1996) and Boseman (2014).

Metals recycling. In metals recycling, the top size is usually set by the metal shredder and is around 100–125 mm. The bottom size is nominally 10 mm, with the small material going to jigs because DMCs are susceptible to blockage when treating metal/plastic wires present in most scrap metal feeds. Metals recycling plant design has its own challenges. For example, consideration needs to be given to removing fibrous materials, if present, from the media to facilitate suitable downstream separations. The entire feed material should be thoroughly prewashed, followed by a separation stage with water (normally upward current) to remove light materials such as plastics, light rubber, and so on. Metal separation is often achieved in a DMS Wemco drum. Excessive wear and high medium losses are usually the major problems. Medium tends to be lost on the underside of flat metal pieces and in crevasses of crushed and mangled metal fragments.

Metals recycling plants are smaller-tonnage operations, and because of their complexity and the highly variable size range of materials, it is common to use fairly large Wemco drum separators. However, the drums are modified internally to obtain the best results with the types of material encountered. Typical feeds can be the nonferrous components of shredded cars and airplane engines, and so forth. The simplified flow sheet in Figure 5 shows the basic process.

Teska Drum Separator

The Teska drum separator shown in Figures 6 and 7 has a slowly rotating bucket wheel that is joined to the separating compartment by mechanical seals (England et al. 2002). The bucket wheel for sinks is partitioned into compartments by means of perforated plates that enable removal of the sinks. The floats flow toward a discharge paddle wheel. The sealing system mounted between the rotary bucket wheel and stationary inlet and outlet section of the separating compartment prevents the escape of slurry to the tires and drive mechanism. The bath width is similar to the inside diameter of the bucket wheel. The chute for sinks can be positioned at the right or left (i.e., either concurrent with or opposite to the direction of feeding). Adjustable nozzles arranged over the bucket-wheel



Adapted from Wilkes 2006

Figure 5 Simplified flow sheet for car scrap treatment

circumference induce a downward flow of dense medium and thus prevent undesirable density concentrations in the bath. At the same time, this feature avoids the formation of layers within the suspension of the bath. The discharge of dense medium is increased by the admission of additional working medium from above. A continuous flow is maintained via nozzles mounted over the complete bath width. One of the features of the Teska drum separator is optimal bath utilization relative to the separator's volume. To protect against wear, ceramic tiles are fitted to high-wear areas such as the inlet, the separating compartment, and the bucket wheel for sinks.

The Teska units can be supplied with bucket wheels up to 6.5 m in diameter, bucket widths of 1.5 m, and bath widths of 3.0 m. Feed particle sizes up to 1.2-m edge length can be processed. Treatment rates of 800 t/h on coal of +6 mm have been realized. Separation efficiency is controlled by residence time, or pool surface, and throughput.

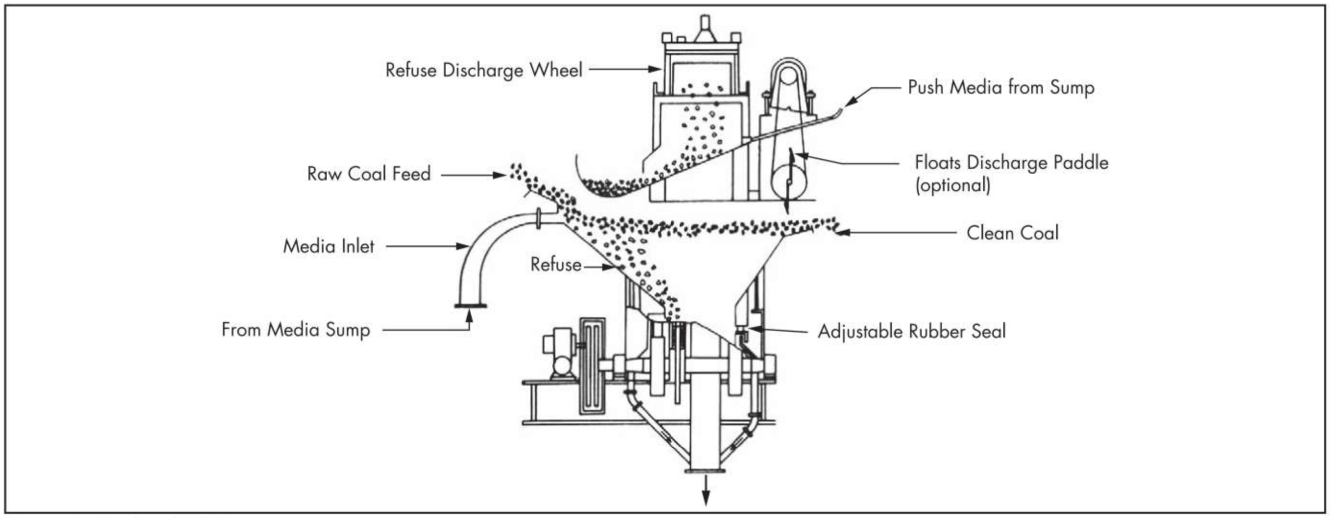
Rectangular Heavy Medium Separators

The rectangular heavy medium separator shown in Figure 8 is manufactured by several engineering companies, such as The Daniels Company, Peters Equipment, and FLSmidth, among others (Symonds 1986; see also Figure 6 in Chapter 12.6, "Coal Preparation"). The separator can be manufactured in 3- to 8-m lengths with capacities for coal up to 650 t/h. The feed enters the vessel from one side and is immersed into the vessel medium bath by means of a submergence baffle to prevent rafting of heavy sink material. Medium enters just below the feed and carries the coal into the separation zone. Heavy particles settle to the bottom of the vessel and are removed by a flight conveyor system. Any floatable particles trapped with falling heavy particles are released by upflowing medium from the purge hoppers. Light particles float to the surface and are carried across the bath to the overflow weir. The medium stream exiting the bath flows by gravity to screens and into the return media sump before being pumped back to the washer. Any medium adhering to coal particles is rinsed with water that flows to a media recovery system.

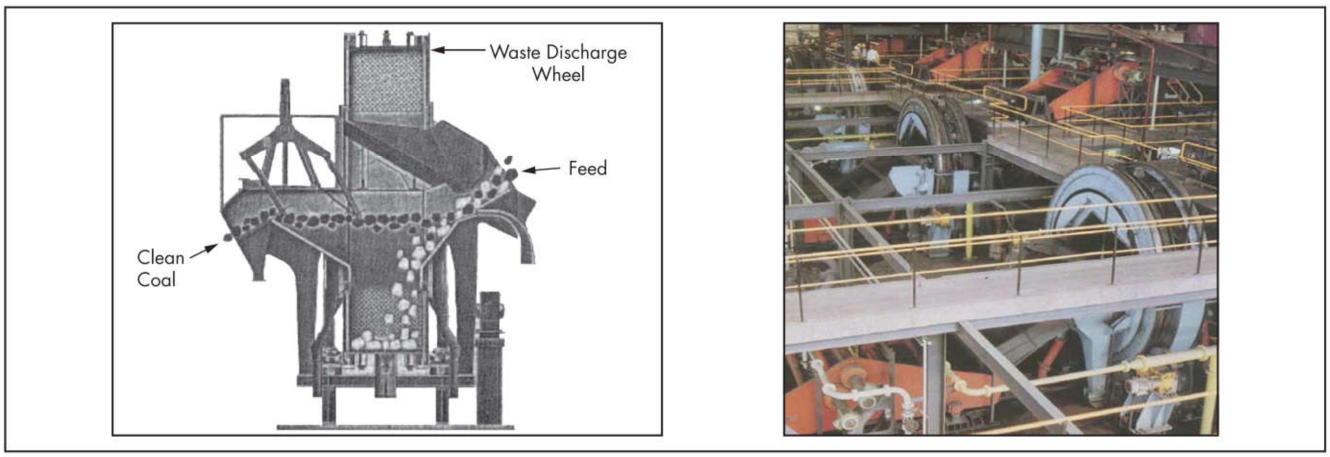
The medium in the separation zone is controlled to maintain the appropriate flow without excess velocities that will cause poor separation. Upcurrent from the purge system prevents stratification of the media into layers of different densities. The washer requires minimal monitoring and adjustment. The gentle bath agitation minimizes the creation of fines. The separator is capable of treating coal with particles ranging between 6 and 200 mm.

The length of the unit is based on the overflow weir width needed to effectively carry the coarse material into the product overflow stream. Width is based on the amount of reject needed to be removed by the drag flight conveyor (see estimated capacities in Table 2). A general rule is that the length should be based on 75 t/h of feed material for every meter of overflow weir. This rule is based on a separation gravity below 1.55 and for a 50% yield to the product stream.

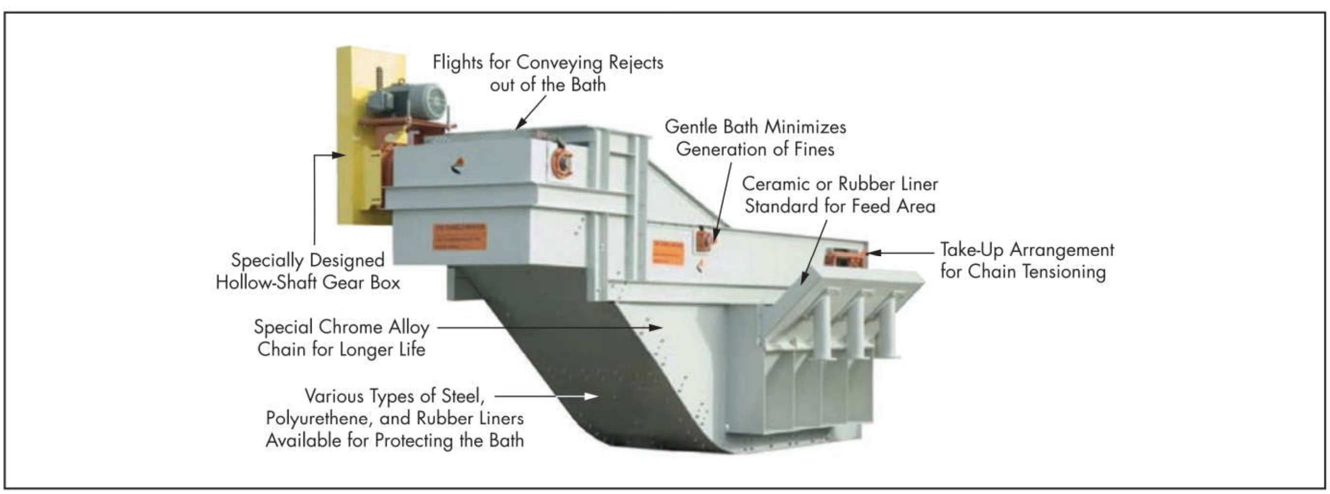
Prior to feeding coal to the vessel, the correct dense medium is pumped into the vessel through the feed washer



Source: England et al. 2002
Figure 6 Teska drum dense medium separator



Source: Humboldt Wedag India 2008
Figure 7 Teska drum separator



Courtesy of The Daniels Company
Figure 8 Rectangular heavy medium separator

Table 2 Flight conveyor sink capacities for rectangle dense medium separators

Height of Flights, mm	Approximate Sink Removal Rate, t/h — Width of Conveyor 1.21 m	1.37 m	1.52 m
203	260	300	330
229	300	330	336
254	330	336	363

Adapted from UAF 2018.
Note: Capacity values are based on a flight speed of 21 m/min. Conveyor capacity can be increased by either a change in speed or an increase in the number of flights, up to a critical value. The wear rates of the conveyor and vessel parts increase exponentially as the chain speed exceeds 23 m/min.

manifold and the purge hoppers. The vessel is filled until it is freely overflowing the weir. The proper inflow of medium is around 3.2 m^3/min for every meter of overflow weir length. Coal is fed to the vessel via the feed manifold. The depth of feed injected should be minimized to avoid any short-circuiting of light particles to the tailings stream. If refuse (gangue) particles adhere to coal particles, then the feeder plate needs further adjustment downward, where higher current flows are present. This plate is a high-wear item and should be checked periodically. Approximately 10% of the dense medium enters through the purge hoppers and provides a gentle up current that helps stabilize the medium. The purge hopper also serves as the drain when the unit is shut down.

The bypassing of low-density material in the separator may be attributed to

- Insufficient upward flow of medium,
- Plugged purge hoppers,
- Feed injection that is too deep,
- Unstable medium,
- Overloaded overflow weir, or
- False reading caused by laminated middlings.

Dense Medium Cyclone Systems

DMC separators are now widely used in the treatment of ores and coal. They provide a high centrifugal force and enable much finer separations than in gravitational (static) separators. Since the early 2000s, various design improvements have been made to DMCs to allow for ever-increasing throughput and sometimes better separation efficiency.

Pressure energy in the fluid (the mixture of medium and coal/ore particles) is converted into a centrifugal force in a rotational motion that causes the particles to separate from each other. The rotational motion is created by the tangential injection of the fluid into the vessel. At the entry point of the fluid, the vessel is cylindrical. Depending on the technology employed, the vessel can stay cylindrical in shape (Larcodems separator) or become conical (cyclones). The smaller the radius of the cylinder or cyclone, the higher the centrifugal forces on a particle. Hence, the centrifugal forces become larger than the gravitational forces acting on the particle. At relatively low tangential velocities in the cyclone, the gravitational forces are of no relevance to the separation. Indeed, a cyclone separator can work upside down without detrimental effects on separation efficiency.

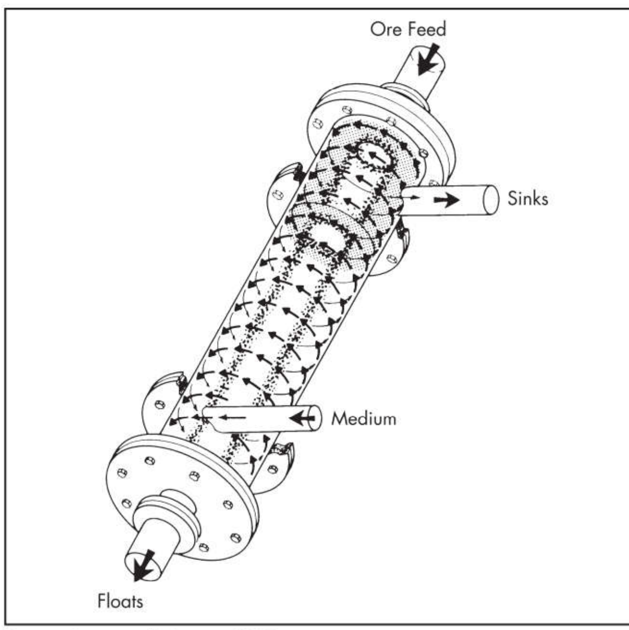
Dyna Whirlpool and Tri-Flo Separators

The Dyna Whirlpool shown in Figure 9 is a cylindrical vessel that employs centrifugal forces to enhance the separation process (Hacioglu and Turner 1985). The dense medium is not introduced together with solids, but separately. Wills and Lewis (1980) provide information on the applications of the Dyna Whirlpool in the minerals industry.

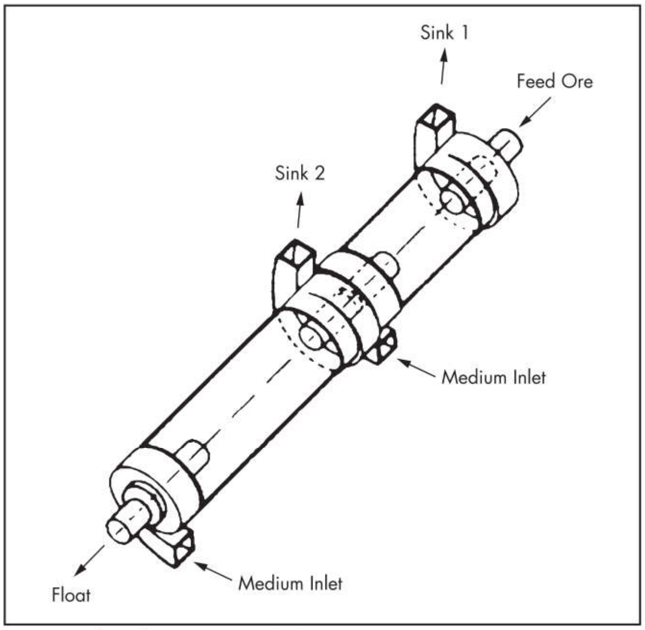
The Tri-Flo separator can be regarded as two Dyna Whirlpool separators joined in series (Figure 10). Tri-Flo separators have been installed in numerous coal, metalliferous, and nonmetallic ore treatment plants (Burton et al. 1991; Kitsikopoulos et al. 1991; Ferrara et al. 1994). Involuted medium inlets and sink outlets are used. This produces less turbulence than tangential inlets.

The Tri-Flo separator can also be operated with two mediums of differing densities to provide sink products of individual controllable densities. Two-stage treatment using a single-medium density produces a float and two sinks products with only slightly different separation densities. With metalliferous ores, the second sink product can be regarded as a scavenging stage for the dense minerals, thus increasing the recovery. This second product may be subjected to a comminution step to increase liberation, and, after desliming, returned for retreatment in the separator. Where the separator is used for washing coal, the second stage cleans the float to produce a higher-grade product. Two stages of separation also increase the sharpness of separation. The Tri-Flo separator is capable of handling large-size coal particles of up to 100 mm.

Burton et al. (1991) and Ferrara et al. (1994) provide numerous examples of operations and pilot programs utilizing the Tri-Flo separator. Applications include ores containing fluorspar, chromite, lithium, lead-zinc-copper, tin, nickel, and iron. Sepro Minerals Systems markets the Tri-Flo separator under the brand name Condor dense medium separator (Sepro 2018). Available sizes are shown in Table 3. Performance



Source: Stortz and Houston 1963
Figure 9 Dyna Whirlpool



Source: Wills and Napier-Munn 2005

Figure 10 Tri-Flo separator

details of a Tri-Flo separator are provided by Dehghan and Aghaei (2014).

Larcodems Dense Medium Separator

The Larcodems separator in Figure 11 is cylindrical and mounted at an angle of approximately 30° to horizontal (Shah 1992; Rudman 2000). The medium and feed material flows are countercurrent, similar to the Dyna Whirlpool. The extractor is off-center, which gives improved control. The medium split between discard/rejects and product outlet can be varied from 60/40 to 40/60 to suit the yields of product and discard without detrimental effects on separation efficiency (Rudman 2000). Furthermore, the separation efficiency is not materially affected when handling a feed with a large percentage of discard material. This is an issue with DMCs. Applications include destoning of a 100 mm × 12 mm steaming coal feed to a power station at a feed rate of ~450 t/h feed. The relative density of separation was 1.81–1.88 with an Ep of 0.0095–0.0105. The available equipment sizes are shown in Table 4. A mathematical model for the separator is described by Álvarez et al. (2017). Suppliers include Mineral Processing Technologies and Don Valley Engineering.

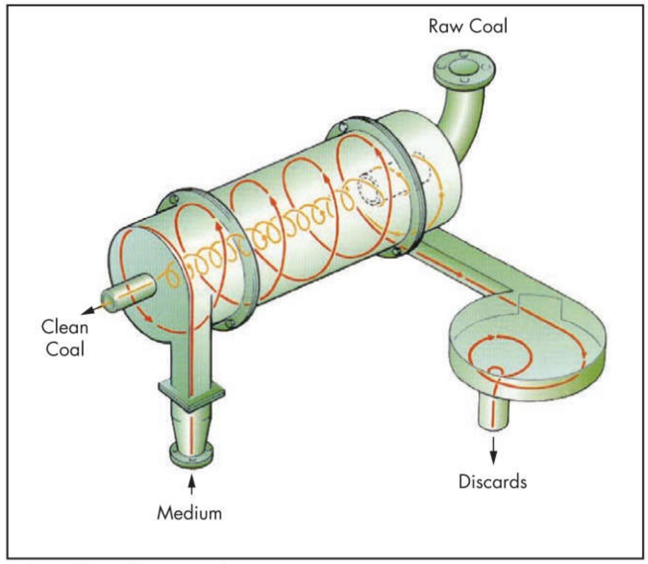
Three-Product Dense Medium Cyclones

The three-product DMC consists of a cylindrical dense medium vessel, with a conventional DMC attached to the rejects outlet of the primary unit. The YTMC-series cyclones from Haiwang Technology Group (2016) are widely applied in raw coal separation processes and for pre-desliming washing in China. The cyclones can be pump fed or gravity fed. Figure 12 shows schematics for both a pump-fed and gravity-fed DMS cyclone, and Figure 13 shows an actual installation in China. The three-product DMS cyclone for coal beneficiation is the preferred option for new coal preparation plants in China (Jacobs and de Korte 2013). Available cyclone sizes and throughputs are shown in Table 5.

Table 3 Condor dense medium separator

Separator Dimensions			
Diameter, mm	Length, mm (approximate)	Feed Capacity, t/h	Maximum Feed Size, mm
250	2,450	10–30	20–25
300	2,850	30–50	30–38
400	3,250	50–80	40–50
500	3,300	80–120	60–75
600	3,940	120–170	70–88
700	4,580	170–230	80–100

Adapted from Sepro Mineral Systems 2018



Adapted from Álvarez et al. 2017

Figure 11 Larcodems separator

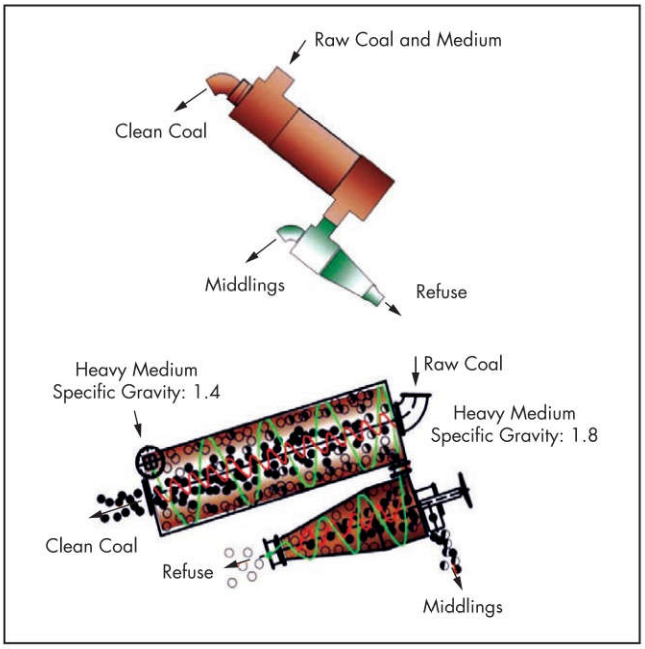
Table 4 Sizes and capacities of the Larcodems separator

Separator Diameter, mm	Medium Flow Rate, m^3/h	Solids Feed Rate, t/h	Maximum Feed Size, mm
850	500	200	75
1,000	700	250	85
1,200	850	350	100
1,350	1,250	450	120

Source: Rudman 2000

Pump-fed three-product DMCs. The largest size in this category has a primary cyclone with a diameter of 1,400 mm and secondary cyclone of 1,000 mm. The capacity is between 450 and 550 t/h, and it has an Ep of ≤0.03 in the primary cyclone and ≤0.05 in the second cyclone. The cyclone comes with an alumina ceramic lining.

Gravity-fed three-product DMCs. The largest size in this category has a primary cyclone with a diameter of 1,500 mm and secondary cyclone of 1,000 mm. The capacity is between 500 and 600 t/h, and it has an Ep of ≤0.03 in the primary cyclone and ≤0.05 in the second cyclone. The cyclone is supplied with an alumina ceramic lining.



Adapted from Jacobs and de Korte 2013
Figure 12 Pump- and gravity-fed three-product DSM cyclones

Source: Jacobs and de Korte 2013
Figure 13 Installation of three-product DMS cyclone in China

Dense Medium Cyclone

Developed in the Netherlands by De Staatsmijnen, the DSM cyclone is the basis of all later cyclone developments (Driessen et al. 1951). The principle of operation of a DMC is similar to that of a conventional hydrocyclone. For pump-fed DMS cyclones, the ore is suspended in a dense medium and is introduced tangentially to the cyclone under pressure. Particles denser than the slurry will move to the wall of the cyclone and travel down to the apex and through the cyclone underflow, while less-dense particles migrate to the vortex and ultimately to the cyclone overflow. A typical schematic of a DSM cyclone is shown in Figure 14.

Cyclone feed pressures are low compared to classification hydrocyclones. In DMS, the cyclone feed pressure is generally held within 9–14 times the cyclone diameter. This pressure is required to maintain the stability of the medium. Excessive feed pressure will impart high gravitational forces (g-forces) on the particles of both the ore and the medium and will cause separation by size of the medium.

DMC separators are widely used in the treatment of ores and coal. They provide a centrifugal force and low viscosity in the medium, enabling much finer separations to be achieved than in static separators. Feed to these devices is typically deslimed at around 0.5 mm to avoid contamination of the medium with slimes and to minimize medium consumption. A finer medium is required than with gravitational vessels, to avoid medium instability. In recent years, work has been carried out in many parts of the world to extend the range of particle sizes treated by dense medium centrifugal separators to much finer particles, particularly those operating in coal preparation plants.

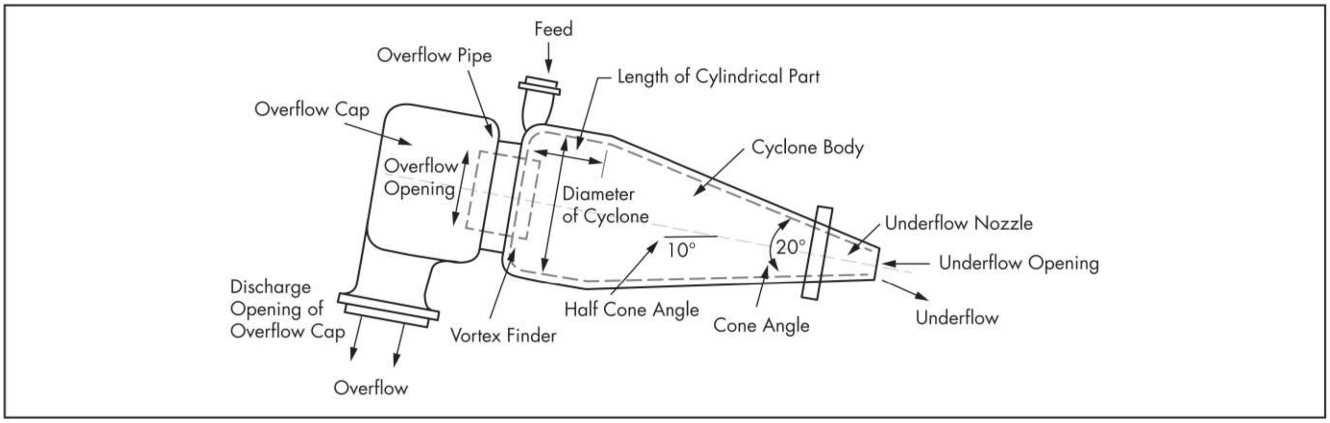
Cyclones are widely used for the beneficiation of coal. In general, the particle size of the raw coal ranges from ~50 mm to 0.5 mm. When the coal particle size becomes smaller, the separation becomes influenced by the medium stability and viscosity. Large-diameter cyclones (up to 1,500 mm in diameter) can treat particles as large as 100 mm and still have good efficiencies. The ore and medium are tangentially fed to the cyclone either by a pump or by gravity.

Gravity-fed DMCs are favored primarily because a static head can be maintained on the cyclone, which results in improved cyclone efficiencies. The effective cut point of the cyclone is higher than the density of the medium because of the centrifugal forces experienced. The various components

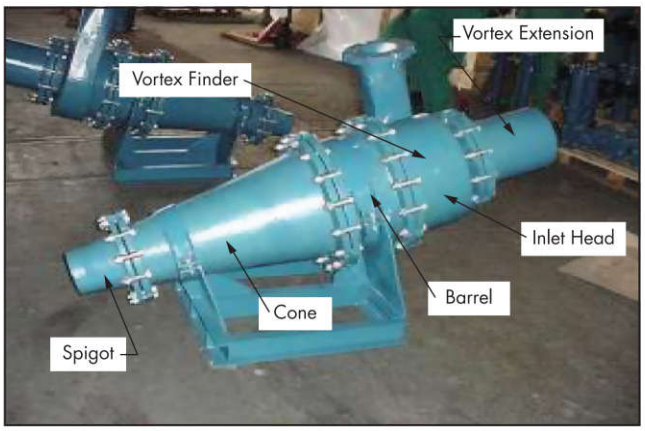
Table 5 Capacities of the pump-fed three-product heavy medium cyclones

Model YTMC	Diameter, mm		Feeding Size, mm	Inlet pressure, MPa	Capacity, t/h	Volume Capacity, m³/h
	1st Stage	2nd Stage				
500/350	500	350	≤20	0.06–0.10	40–60	200–300
600/400	600	400	≤30	0.08–0.12	50–80	300–400
710/500	710	500	≤35	0.09–0.14	70–120	400–550
780/550	780	550	≤40	0.10–0.15	100–160	550–650
850/600	850	600	≤45	0.13–0.16	120–180	650–750
900/650	900	650	≤50	0.15–0.18	140–200	750–950
1000/710	1,000	710	≤55	0.18–0.22	180–240	900–1,100
1100/780	1,100	780	≤60	0.20–0.24	220–300	1,100–1,400
1200/850	1,200	850	≤70	0.22–0.28	300–400	1,400–1,700
1300/920	1,300	920	≤80	0.26–0.32	350–450	1,600–1,900
1400/1000	1,400	1,000	≤90	0.30–0.40	450–550	1,900–2,300

Source: Haiwang Technology Group 2016



Source: Sanders 2007
Figure 14 Typical dense medium cyclone



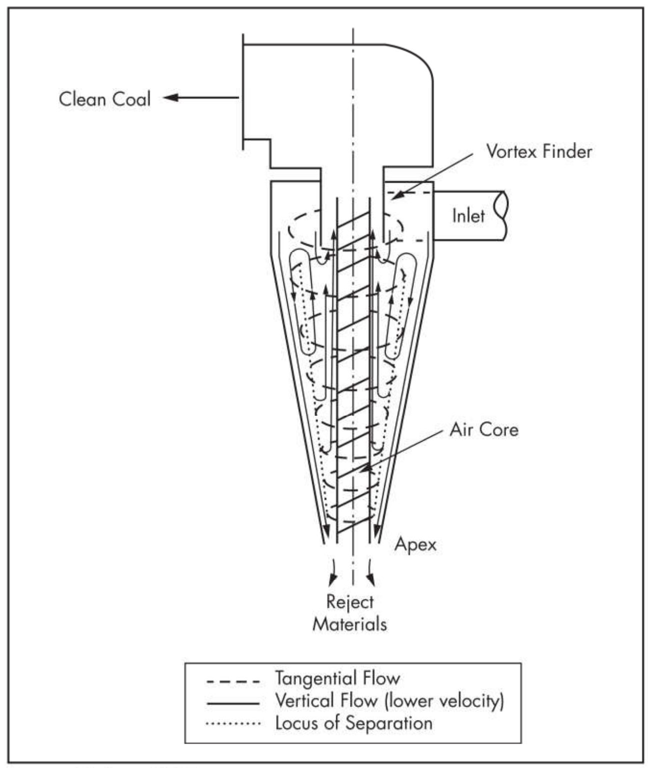
Source: Bornman 2014
Figure 15 Components of a dense medium cyclone

of a DMC are shown in Figure 15. The flow patterns in the cyclone are shown schematically in Figure 16.

Constraints on DMC selection. The first step in choosing the appropriate cyclone dimensions and medium for a DMS separation is to identify the constraints and their sources that are applicable to the equipment selection process to prepare a flow sheet. These are given in Table 6. For most DMC applications, only one constraint will apply. In some cases, two will apply, and the second one is normally the breakaway size constraint. It is considered, but rarely is it imposed as a constraint.

Cyclone geometry. The standard DMC has a fixed geometry (Bosman 2008), as shown in Table 7.

DMC operating efficiency. The performance of a DMC can, as with other DMSs, be represented by a partition curve. In the day-to-day operation of an industrial DMS plant, the performance of a DMS cyclone is checked on a regular basis with density tracers. The tracers, which are essentially cubes, are manufactured in various sizes and densities. For more frequent (daily) cyclone performance testing, standard tracers of a single and small size at the designated separating density are normally tested. The efficiency or recovery of the cyclone is determined as the percentage of tracers recovered in the sink product from the cyclone feed. On a less frequent but regular



Source: Clarkson 1987
Figure 16 Flow pattern in a dense medium cyclone

basis, density tracers of varying sizes and colors are added to the DMS cyclone circuit, sometimes at varying feed densities. This allows partition curves or Tromp curves to be plotted and the efficiency of separation to be established.

Regular inspection and cyclone maintenance is also an essential part of ensuring high operating efficiencies. Measurement of the cyclone(s) vortex finder and apex diameter will monitor wear and allow replacement of parts before cyclone operation is adversely affected. Pressure gauges/transducers are often installed at the DMC inlet to monitor pressure, which can give a more immediate indication of potential problems within the cyclone. Gravity-fed DMCs

Table 6 Dense medium cyclone constraints and sources of constraint

Item	Constraint	Source of Constraint
Ore	Particle size distribution	Liberation
	Mass recovery/yield	Ore mineralogy
Cyclone	Cyclone diameter	Capacity (maximum flow rate)
		Breakaway size (reduced efficiency)
	Inlet dimensions	Top size (prevents blocking)
	Vortex finder diameter	Floats capacity (maximum)
	Spigot diameter	Sinks capacity (maximum)
	Spigot/vortex finder ratio	Maximum 0.85 (reduced efficiency)
Operational	Operating head	Minimum 9D (performance)
	Feed medium/ore ratio	Efficiency
	Medium type	Stability/viscosity (efficiency)

Adapted from Bosman 2008

Table 7 Fixed ratios for dense medium cyclones

Parameter	Ratio of Cyclone Diameter
Dc (cyclone diameter)	1
Di (cyclone inlet)	0.2
Do (cyclone overflow)	0.43
Barrel (length)	1.6–2.5
Cone angle	20°
Du—Standard (spigot)	70% of Do
Du—Maximum (spigot)	80% of Do

Adapted from Bosman 2008

are favored primarily because a static head can be maintained on the cyclone, which results in improved cyclone efficiency.

Operating parameters. The following information is for a tangential inlet design with a square opening (Bosman 2008). Other designs can result in significant differences, especially with regard to cyclone capacity.

- **Feed size distribution.** The smaller the particle, the less centrifugal force exerted, resulting in an increase in the fine sinks reporting to the floats. The separation efficiency (Ep value) is usually measured at selected particle size ranges. The smallest particle range will have the lowest efficiency of separation. Smaller-diameter cyclones are employed for finer feed materials to reduce the breakaway size. For a given cyclone diameter, there is a particle size, termed the *breakaway size*, below which Ep deteriorates rapidly. As cyclone diameter increases, the breakaway size becomes larger (Meyers et al. 2014).
- **Vortex-finder-to-spigot ratio.** The spigot size determines the mass/yield recovery to the underflow or overflow (coal). The spigot diameter also affects the differentials; the higher the spigot-to-vortex-finder ratio, the lower the differentials. The spigot diameter should not exceed 85% of the vortex finder diameter. The smaller the spigot, the higher the cut-point density and the lower the spigot capacity. Larger spigots reduce the hang-up of coarse particles and the excessive wear that takes place when hang-up occurs.
- **Density shift as a function of particle size.** The density separation of ore particles is time dependent; larger particles separate faster than small particles. The separation of large particles will take place at a higher level within the cyclone and hence generate lower density. As the feed solids get smaller, the d50 cut point for that particular size of solids increases. This is referred to as the density shift.
- **Head pressure.** At a high feed inlet pressure, the slurry flow rate to the cyclone increases. The tangential velocity of the particles also increases, which intensifies the centrifugal force. This, in turn, improves the separation process, especially of fine particles, despite the shorter residence time. Unfortunately, a high feed inlet pressure amplifies the classification of the media, and the density differential of the media increases, which is measurable by determining the underflow and overflow densities, respectively, and calculating the density differential. A fluctuating head affects the medium-to-ore ratio, especially when the solids feed rate is left unchanged.

  Generally, a fluctuation of 10% in cyclone pressure will result in a fluctuation of 15% in the inlet velocity to the cyclone. The intent should always be to keep the cyclone pressure as constant as possible. Cyclone operation should not be at too high a pressure (>20D [cyclone diameter]), as the pressure-to-wear-rate ratio is an exponential function. The differential over the cyclone can be calculated to determine whether the operation is in the acceptable range.

  Recommended feed heads are as follows (Bornman 2014):
  - Coal, 9 × D
  - Diamonds, 12 – 15 × D
  - Other minerals, 12 – 20 × D

  It is generally accepted that below 7D, the cyclone air core becomes unstable and the cyclone performance is likely to deteriorate (Bornman 2014).

  The operating pressure of a DMC is normally expressed in meters of head as a function of the cyclone diameter. For example, a cyclone of 500-mm diameter operating at a head of 9D will have an operating head of 4.5 m (9 × 0.5).
- **Medium-to-ore ratio.** The medium-to-ore ratio is important to prevent overcrowding of the ore. Typical ratios are as follows (Bornman 2014):
  - 3:1 for washing coal, as this a relatively easy separation
  - 5–7:1 for diamond washing
  - 5:1 for other minerals

  Higher ratios seem to have very little effect in terms of improved efficiency and typically result in increased equipment size, higher operating costs, and increased medium losses (Bornman 2014).
- **Medium differentials in feed, underflow, and overflow.** A DMC performs a separation within a separation. All the solids in the cyclone are classified (separated by size); hence, the medium solids will separate to a certain degree. Therefore the feed, overflow, and underflow will have different medium densities. The following factors affect differentials (Bornman 2014):
  - Medium viscosity/stability
  - Feed head (pressure)
  - Cyclone diameter
  - Inlet design
  - Barrel section
  - Spigot size
  - Medium density

The differential is calculated as follows (Bornman 2014):

$$\frac{RD_{feed} - RD_{overflow}}{RD_{feed}} = 3\% - 12\%$$

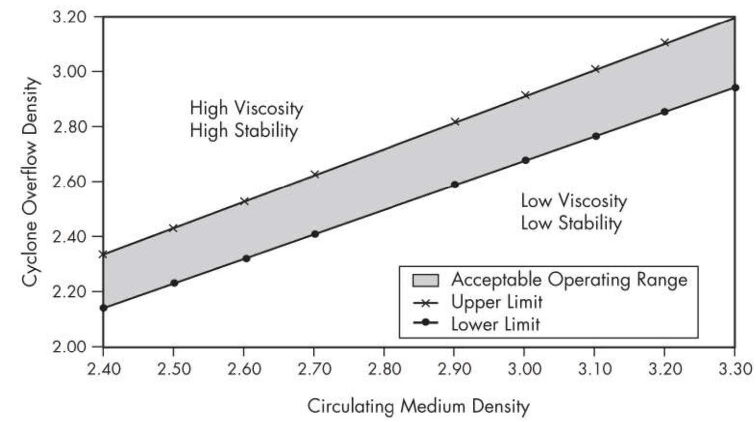
If the differentials are too large, hang-up of particles in the cyclone can occur. The amount of near-density material in the cyclone is usually the major factor leading to hang-ups. The acceptable medium densities during operation for diamonds are shown in Figure 17 (Bornman 2014).

- **Clays and slime.** *Slimes*, defined as <45-µm clay particles, cause viscosity problems in the medium, which will influence the separation of near-density particles. Therefore, slimes need to be removed (washing and desliming) ahead of treatment in the DMC.

Cyclone check and problem solving. Table 8 lists several observations and identifies possible problems for the observations as well as the recommended actions (Bosman 2014).

Multotec Dense Medium Cyclones

Multotec is one of the largest suppliers of DMS cyclones and provides a range of sizes having different capacities, as shown in Table 9. Multotec has developed several cyclones that have different inlet designs. The newest are the MAX range cyclones. The MAX DMS cyclones have a scrolled evolute inlet design with wear surfaces tiled in alumina.



Source: Bornman 2014

Figure 17 Acceptable medium properties

Table 8 Dense medium cyclone separation fault finding

Observation	Possible Problem	Action
Feed to the preparation screen is fluctuating	Inconsistent feed rate from ore preparation section.	Investigate problem and rectify.
Not enough water on screens	Water pressure too low, water valves not open, spray nozzles blocked.	Verify water pressure, ensure that water valves are open, unblock spray nozzles, and add sufficient water to remove clay. Minimize clay balls and cyclone blockages by ensuring that the spray nozzles on the spray bars are open; better to have too much water than too little.
Screen blockage, no proper draining	Type of material treated, contamination with vegetation, requires different type of screen panel, screen motion.	De-blind screen where required, maintain aperture size, verify correct panels for the application, ensure screen stroke is sufficient.
	Contamination of medium.	Have a weir bar between the drain-and-rinse screens to prevent medium carryover to the rinse section; use enough water on the rinse section to minimize adhering medium losses.
Coarse material in effluent and medium	Holes in screen panels.	Check condition of screen panels and rectify.
Fluctuating cyclone pressure	Mixing box level not constant; insufficient medium in circuit.	Ensure header tank level. Check for correct medium sump level, and add medium if required.
	Medium to mixing box is fluctuating.	Maintain level in mixing box; open medium flow to mixing box. Check for obstructions in medium flow to mixing box.
	Poor cyclone efficiency.	Low pumping efficiency. Check condition of medium pump, and make sure ore feed rate is constant. Operate as constant as possible.
	Accelerated wear.	Ensure that cyclone pressure is in the specified operating range.
Cyclone pressure increase	Blocked cyclone inlet (product disappears from screens).	Stop plant and unblock inlet, and check for source of oversize.
	Increase in medium density.	Check density and rectify; add water.
	Mixing box level too high.	Adjust level by restricting medium flow to box.

Adapted from Bornman 2014

Table 9 Dimensions and capacities of Multotec dense medium cyclones

Standard-Capacity Cyclone			High-Capacity Cyclone		
Cyclone Diameter, mm	Maximum Particle Size, mm	Coal Feed, t/h	Cyclone Diameter, mm	Maximum Particle Size, mm	Coal Feed, t/h
510	34	54	510	51	99
610	41	81	610	61	145
660	44	97	660	66	175
710	47	114	710	71	207
800	53	149	800	80	270
900	60	196	900	94	355
1,000	67	249	1,000	100	454
1,150	77	351	1,150	115	638
1,300	87	468	1,300	130	854
1,450	97	608	1,450	145	1,108

Source: Bornman 2014

Table 10 Operating information for Krebs heavy medium cyclones

Model	Maximum Feed Size, mm	Feed Capacity* (dry), t/h	Pulp Flow Rate, m³/h	Head Equivalent, m
D20LSB	19	77	238	4.6
D26B	38	136	434	6.1
CoalMAX26	38	145	464	6.1
D263B	38	150	469	6.0
D30B	51	205	643	7.0
D33T154	63	264	829	7.6
D33T214	63	286	892	7.6
D40B	76	418	1,308	9.2
D44B-A	76	432	1,348	10.1
D44B-U	76	527	1,653	10.1
D48B	89	659	2,066	11.0
D55B	102	895	2,792	12.6

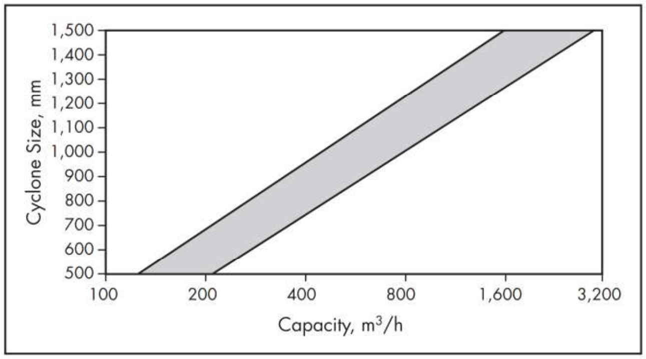
Source: FLSmidth-Krebs 2014
*Based on a 4:1 medium-to-coal ratio. Capacities represent maximums for units fitted with the largest inlet and vortex finder.

Krebs Dense Medium Separation Cyclones

Krebs heavy medium cyclones (HMCs) are designed specifically to clean coal. Krebs HMCs are usually operated in a near-horizontal orientation, allowing large apex sizes to be used for refuse/waste removal. The medium density primarily determines separating gravity. Pressure should be kept relatively low to reduce classification effects. The Krebs large-diameter cyclones allow the larger top size to be efficiently cleaned at higher feed rates. Cyclones of 760-mm diameter and larger utilize a proprietary ceramic "acceleration wedge" to modify capacity and g-forces. Inserting a smaller wedge will have an immediate effect on increasing capacity. Inserting a larger wedge will generate higher g-forces, which are required to clean fine coal more efficiently. The large cyclones can handle feeds with a particle top size of 100 mm. Capacities for the Krebs HMCs are shown in Table 10.

Minco Tech Dense Medium Cyclones

Minco Tech's design philosophy for their HMC separator is based on extensive research carried out by the Julius Kruttschnitt Mineral Research Centre in Queensland, Australia, during the 1990s. The research generated the JK cyclone simulation and modeling program. Further cyclone research was carried out by the Australian Coal Association Research Program. This work assisted with improving cyclone performance parameters, especially with cyclone feed inlet design. Minco Tech cyclones are modeled and designed with consideration given to the above-mentioned research and also supported by results from installations throughout the world. Available DMC units range in size from 50 to 1,500 mm with nominal feed rates of 10 to 1,000 t/h. Cyclones are available in various materials, from 27% chrome to pre-engineered high-alumina ceramic tiles. Wall thickness ranges from 25 to 38 mm. Cyclone capacities are shown in Figure 18 in terms of volumetric feed rates. Figure 19 shows a large-diameter Minco DMC (Minco Tech 2015).



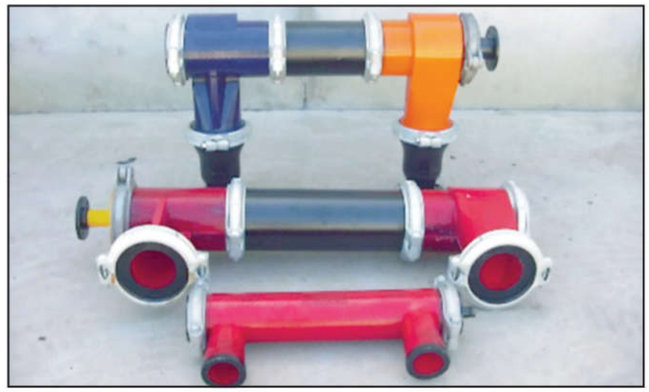
Courtesy of Minco Tech

Figure 18 Volumetric capacities of Minco dense medium cyclones

Haiwang DMS Cyclone

The two-product HMCs (FZJ series) marketed by Haiwang Technology Group are widely used in China for rougher and cleaner applications in primary and secondary coal separation plants. Cyclones range in size from 350 mm to 1,500 mm. The 1,500-mm-diameter cyclone has a capacity of 700–800 t/h and comes with an alumina ceramic lining (Haiwang Technology Group 2016).

Courtesy of Minco Tech
Figure 19 Minco large-diameter dense medium cyclone



Courtesy of Concord Engineering
Figure 20 Concord densifier

Densifier Circuits and Equipment

Most dense medium plants use "circulating medium" densification methods, where a part of the medium is fed by gravity or pump to the densifier. Some operations use "dilute medium" densification, where the feed to the densifier is rinse medium/water from the product screens. This stream is pump-fed to the densifier to reduce height. Densifier overflows from both methods are treated by magnetic separators to recover contained medium. To allow for medium cleaning, some of the medium bypasses the densifier and goes directly to the magnetic separators. Loading on the magnetic separators is higher with circulating medium densification than with dilute medium densification. This is not much of an issue with modern-day magnetic separators.

A comparison of the two methods shows that the pipe densifier rejects significantly fewer magnetics to the overflow than the cyclone densifier. This greatly reduces the dilute medium circuit magnetics loading and, in turn, the size of the wet drum magnetic separator required. Additional advantages of correct medium densification using a pipe densifier are reduced magnetics classification and reduced fine magnetics losses from the dilute medium circuit wet drum magnetic separator.

Both types of densifier will reject lower-density contaminant minerals from the circulating medium (e.g., silicates and clays). However, in high-density mineral separations, such as sulfides, it is recommended that a circulating-medium bleed to the dilute medium circuit be incorporated to remove fine high-density nonmagnetics that can build up in the circuit and affect the medium density and viscosity.

Densifiers have become increasingly important in dense medium circuits for the following reasons:

- The production of an over-dense stream into the correct medium tank significantly reduces the start-up time required to achieve density, from typically 30 minutes using magnetic separators alone to less than 10 minutes using a combination of magnetic separator and densifier.
- Improved density control through the introduction of an over-dense stream into the correct medium tank.
- Cleaning nonmagnetics that continuously build up in the media. Analysis has shown that where 80% of the magnetics are recovered to the cyclone underflow, 65% of the nonmagnetics report to the cyclone overflow.

The Concord densifier (Figure 20) manufactured by Multotec is widely used in the DMS industry. It works over a broad range of operating pressures, from 300 to 700 kPa. It can also cope with much greater volumetric feed flow rates.

Work by Davidson et al. (1987) found that major medium losses were adherence losses and losses in the water recovery circuit. Operating density and medium blend had a significant effect on the medium consumption. Viscosity was thought to be the problem. The viscosity problem was resolved by adding dilution water to the cyclone spigot discharge to reduce viscosity. The result was a reduction in medium consumption of around 25%.

Densifying cyclones are available in diameters of 100, 165, 250, and 350 mm and vary in materials of construction:

- Long-lasting and high-elasticity polyurethane
- Twenty-seven percent high-chrome cast iron for highly abrasive applications
- Ceramic lined for pulp distribution and abrasion resistance

DESIGN OF DENSE MEDIUM CIRCUITS

Details of DMS circuit design that include equipment sizing are provided by Symonds (Symonds 1986; Symonds and Malbon 2002). Information on sizing and performance of dense media is provided by Chaston and Napier-Munn (1974), Dardis (1987), King and Juckes (1988), Reeves and Platt (1988), Lee et al. (1995), Rylatt and Poplewell (1999), England et al. (2002), Holtham (2006), and Napier-Munn et al. (2009). The economics of DMS is detailed by Burton et al. (1991) and Schena et al. (1990).

CYCLONE WEAR PERFORMANCE

The most common materials used for DMS cyclones are high-chrome cast iron and alumina ceramic tiles bonded to a mild steel body. Other materials include tungsten carbide and stainless steel. Table 11 provides the relative life of a DMC.

MEDIUM TYPE AND SELECTION

The most important factor that must be taken into account when selecting a medium grade for a particular application is the operating density. This is determined by the separation desired, the characteristics of the feed ore, and the nature of the separation vessel being used. Once the operating density has been selected, the stability and viscosity will then determine

Table 11 Relative life and costs of dense medium cyclones*

Materials of Construction	Relative Life	Relative Cost	Relative Cost per Unit of Duty
High-chrome cast iron	1.0	1.0	1.0
Alumina tile lined	2.0	1.25	1.6
Sintered silicon carbide	3.0	3.7	0.82
Reaction-bonded silicon carbide	3.0	3.7	0.82
Nitride-bonded silicon carbide	3.2	3.7	0.86
Zirconium oxide	No data	No data	No data

Source: Bookless 2008
*Based on plant data. Does not include labor cost of replacement, loss of production, or cost of storing the replacements.

the appropriate ferrosilicon grade. The ideal medium is one with high stability and low viscosity. Any selection involves a compromise between these two mutually exclusive properties.

Ferrosilicon Medium

The following general guidelines for the medium are recommended:

- For very high operating densities (say, higher than 3.2 RD), only atomized grades can be used, as the milled grades are too viscous at the high solids concentrations required.
- Atomized grades may also be appropriate where corrosive conditions or highly porous ores (leading to high medium losses and thus operating costs) are suspected. Otherwise, milled grades are preferred because of their lower cost.
- Dynamic separators require finer grades than bath separators, because of the greater tendency for instability (large differentials) in dynamic separators. High-pressure dynamic vessels (large static heads or high pump-delivery pressures) require finer grades than low-pressure systems, to preserve stability.
- All things being equal, coarser particle grades are preferred to finer particle grades because, under most conditions, medium losses occur preferentially in the finer sizes. In addition, the coarser grades are often less expensive.

The wide-scale acceptance of heavy media separation is due to its simplicity and efficiency. Conventional heavy medium separation of ores having a specific gravity in the range from 2.5 to 4.0 utilizes a mixture of either milled or atomized ferrosilicon powder containing 14%–16% Si and water.

One of the most important parameters of the heavy medium process is the rheology of the medium. Because rheological behavior is extremely complex, the medium grade—and, more specifically, the size distribution of the ferrosilicon required for a specific application—is still sometimes chosen arbitrarily or on the basis of subjective experience.

Media Type and Specification

The information in this section is based on information regarding Samancor ferrosilicon products (Blair 1983). The three grades represented in Table 12 are products produced by Samancor and represent 90% of ferrosilicon used in diamond heavy medium processing.

Table 12 Samancor ferrosilicon products

Specification	Medium Product		
	100D	150D	270D
Medium type	Milled	Milled	Milled
% Passing 20 µm	25–35	40–50	52–62
% Passing 45 µm	61–69	73–81	85–93
% Passing 75 µm	90–95	94–98	97–100
Silicon, %	14–16	14–16	14–16
Carbon, % maximum	1.3	1.3	1.3
Iron, % minimum	80	80	80
Sulfur, % maximum	0.05	0.05	0.05
Phosphorus, % maximum	0.15	0.15	0.15
Rust index, % maximum	1.2	1.2	1.2
% Nonmagnetics (Davis tube), maximum	0.75	0.75	0.75
Density, specific gravity	6.7–7.1	6.7–7.1	6.7–7.1

Source: Blair 1983

Table 13 Typical size analysis for milled ferrosilicon 14%–16% Si

Particle Size, µm	Medium Product, %				
	48D	65D	100D	150D	270D
+212	1.5	0.4	0.2	0.1	0.0
–212 +150	7.2	1.5	0.6	0.3	0.1
–150 +105	16.1	5.8	2.7	1.2	0.3
–105 +75	22.3	12.7	7.4	4.1	1.7
–75 +45	20.8	27.9	23.9	16.9	10.0
–45 +20	22.5	37.2	29.6	29.0	49.9
–20	8.8	14.5	35.7	48.4	38.0
–45 (typical)	3.1	52	65	77	88
–45 (limits)	20–38	38–58	58–70	70–85	85+

Source: Blair 1983

Some of the more important properties essential to a metal or alloy powder that is to be used as a heavy medium are as follows:

- Resistance to abrasion
- Resistance to corrosion
- High specific gravity
- Magnetism, which allows easy magnetic recovery with subsequent easy demagnetization
- Economical operating costs

The typical size analyses of available milled ferrosilicon 14%–16% Si are shown in Table 13, and the size analysis for atomized ferrosilicon is provided in Table 14. The typical chemical and physical properties of milled and atomized ferrosilicon are shown in Table 15. The respective chemical and physical data with sizing analyses given for both the milled and atomized ferrosilicon grades represent typical average values obtained and are in no way meant to constitute final specifications.

Particle-to-Particle Homogeneity

The "in circuit" performance of 14%–16% Si ferrosilicon medium is directly related to its chemistry and physical metallurgy. Particle-to-particle homogeneity is important, particularly in relation to the required properties of the medium. The

Table 14 Typical size analysis for atomized ferrosilicon 14%–16% Si

	Medium Product, %				
	Special		Cyclone		
Particle Size, µm	Coarse	Fine	60	40	20
+212	2.5	1.7	0.0	0.0	—
–212 +150	6.7	5.3	0.1	0.0	—
–150 +105	13.0	10.6	0.3	0.1	—
–105 +75	18.2	16.2	3.2	1.2	—
–75 +45	21.9	21.6	21.6	14.8	—
–45 (typical)	38	45	75	84	—
–45 (limits)	35–40	40–50	65–80	80–85	90+

Source: Blair 1983

Table 15 Chemical and physical properties for milled and atomized ferrosilicon

	Medium	
Specifications	Milled	Atomized
Si, %	14.7	14.9
Fe, %	80.7	82.9
C, %	1.0	0.3
P, %	0.04	0.06
Rust index, %	0.5	—
Nonmagnetics, %	0.5	0.2
Density	6.78	6.85
Satmagan, %	57	73
Spherical particles, no.	—	69

Source: Blair 1983

presence of a dual-phase structure (silica-enriched dendritic structure), which is characteristic of ferrosilicon alloys containing 15%–25% Si, affects the performance of atomized ferrosilicon to a greater extent than milled ferrosilicon.

Particle Shape

The manufacturing processes for milled and atomized ferrosilicon result in a marked difference in both the shape and nature of the particles of ferrosilicon powder produced. This difference in the individual particle shape has marked effects on the rheological properties of the aqueous suspensions of the two types of ferrosilicon.

Rheological Properties

The rheological properties of heavy medium suspensions play an important part both in the heavy medium separation itself and in the handling of the medium with regard to pumping and storage. The rheological properties of the medium that are regarded as process determining are its viscosity and stability. The details of medium viscosity measurement are provided by Ferrara and Schena (1986), Reeves (1990), and Myburgh (2002).

Viscosity

Because heavy media suspensions are unstable, they do not follow the same laws of fluid mechanics as ordinary liquids and are referred to as non-Newtonian. The main feature of the atomized grades is their ability to produce high pulp densities combined with low viscosities. This is due to the greater friction of collision of the irregularly shaped milled particles, which requires a larger energy input to achieve a given deformation of suspension.

Stability

The *stability* of a suspension can be defined as the reciprocal of the settling rate, because the consistency or apparent viscosity of the separation medium is a direct function of the settling rate of the media (i.e., the higher the consistency, the lower the settling rate). The settling rate or stability is a very valuable parameter for characterizing the condition of the medium. However, as in the case of viscosity, the stability increases with both the fineness of the ferrosilicon and the pulp density. The viscosity-effect grades of milled ferrosilicon show greater stability than grades of atomized ferrosilicon of equivalent size.

Modification of Rheology

The rheological properties of ferrosilicon suspensions can be modified in the following ways:

- Adding polymeric compounds or other reagents (positive impact)
- Extraneous contamination by ore slimes of clays (negative impact)
- Demagnetization of the circulating medium (positive impact)
- pH modification
- Increasing the proportion of spherical particles (for atomized applications only)

Magnetic Properties

Ferrosilicon is inherently magnetic, being an iron alloy, which enables easy recovery and cleaning of the medium in circuit. The magnetic properties are measured by a Satmagan balance, which effectively measures the magnetic moment of a sample when saturated in a strong magnetic field.

Corrosion Resistance

Corrosion resistance is important for the following reasons:

- Corrosion leads to loss of ferrosilicon.
- The finely divided products of corrosion increase the viscosity of the medium and affect separating efficiency.
- Corrosion in situ when stored wet can result in start-up difficulties after long shutdowns.
- Corrosion of ferrosilicon adversely affects the density of the medium.

Stewart and Guerney (1997) provide information on the detection and prevention of ferrosilicon corrosion in dense medium plants.

Density of Separation

In general, for actual separations above ~3.0 for static baths and 3.2 for cyclones, the use of atomized ferrosilicon is necessary, because above a true pulp density of ~3.0, the viscosity of the milled material can increase rapidly to unmanageable proportions. At higher densities, the question is one of selecting a grade of atomized ferrosilicon that exhibits adequate stability in suspension of the required density. The finer grades are used at the lower end of this range.

Particle Size of Ore

A finer medium is required in dynamic separators than for static separators because of the tendency of the medium to thicken and create high differentials as a result of the centrifugal forces involved in dynamic separators. Finer, more stable medium is required for smaller cyclones. As with most gravity separations, the narrower the size range of the feed, the greater the efficiency of the separation for small particles.

Sharpness of Separation

The sharpness of the separation achieved is influenced by the grade of ferrosilicon used, being higher for the finer, more-stable ferrosilicon and particularly in the finer particle sizes of ore. The flexibility of cyclone operation is greater with finer medium, enabling specific gravity of media feed, pressure, and cone ratio to be adjusted to give variations in quality and quantity of the apex discharge.

Selection of Medium for Industrial Application

The appropriate selection of a ferrosilicon medium for application in DMS equipment is discussed by Collins et al. (1974) and Hunt et al. (1986).

Magnetite Medium

The most popular manufactured media used in coal preparation are a fine magnetite suspension in water (1.25–2.2 RD), ferrosilicon suspension (2.9–3.4 RD), or a mixture of the two (2.2–2.9 RD), depending on the selected separating density. The effective density of such a slurry can be controlled by adjusting the solid concentration of the suspension (King 2001; Galvin and Iverson 2013; Gupta and Yan 2006). Various grades of magnetite, which are determined by fineness, are produced for coal cleaning processes (Robertson and Williams 1991). The grade of magnetite is typically marketed based on the percentage of ultrafine particles smaller than 44 µm. The most common grade of magnetite used in coal preparation is grade B, which is normally more than 95% below 44 µm. The physical and rheological properties are of considerable importance in determining the effectiveness of magnetite as a medium. Since the RD of magnetite is relatively high (about 5.0), the generation of low-viscosity dense media over a wide range of densities, even in the presence of slimes contamination, is possible given the low degree of solids concentration. Furthermore, highly effective medium recovery and regeneration are achievable because of the magnetic characteristics of magnetite (Osborne 1988; Sanders 2007).

Physical properties used to specify the quality and suitability of a particular source of magnetite must be assessable by standard techniques. Several countries have been actively involved in establishing magnetite specifications for heavy medium applications (Mikhail and Osborne 1990; Osborne 1988).

The general specifications for magnetite based on the British coal mining industry are

- Particle size distribution at a maximum of 5% by weight larger than 45 µm and 30% by weight smaller than 10 µm;
- RD of 4.9–5.2; and
- Magnetite content not less than 95% by weight.

Industrial experience and practices in several coal-producing countries have been used to develop standard procedures to test magnetite for coal preparation purposes. The international standard ISO 8813 specifies the properties for testing moisture content, particle size distribution, magnetic content, and relative density. The following properties of magnetite are important for coal washing (Robertson and Williams 1991):

- Ratio of ferrous to total iron content
- Hardness and resistance to degradation
- Coercive force of 38 Oe (oersteds) or less
- Miscibility with water
- Susceptibility (emu/g) at 30 Oe should be 0.035 or greater and at 800 Oe should be 0.05 or greater
- Saturation moment (emu/g) of 0.80 or greater.
- Purity:
  - Magnetics, ≥96%
  - Total iron, ~6%
  - Ferrous iron, ~22%

Magnetite for DMS is available in different particle sizes: fine (95% <45 µm), medium (85% <45 µm), and coarse (75% <45 µm) (Idwala Industrial Holdings 2018).

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