CHAPTER 6.5

Electrostatic Separation

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Electrostatic separation is a generalized term describing processes that exploit differences in the electrical conductivity on the surfaces of various minerals. By nature, these are dry processes that rely on a free-flowing granular feed with particle size limits from approximately 40 µm to approximately 1 mm. There are principally three types of electrostatic separator in general industrial use: high-tension roll (HTR), electrostatic plate separator (EPS), and the tribostatic separator. The most commonly used separators are HTR and EPS units, which are extensively employed in the treatment of concentrates produced from mineral sand mining. These minerals are generally well liberated, which enables high product purity levels to be achieved. The effectiveness of separation of minerals using electrostatic and electrical technology depends on the degree of difference in the conductivity between the particles in the feed. As most minerals have some difference in conductivity, exploiting this feature could likely offer a means of separating them from each other. Moisture and surface contamination of the minerals are two of the factors that may reduce separation efficiency; these have to be considered by the process technology designers. Specialist reagents may also enhance conductivity and/or nonconductivity of targeted minerals for difficult feed types.

PRINCIPLES OF SEPARATION

High-Tension Roll Separation

HTR separation uses a rotating earth-grounded roll to carry feed particles under a thin electrode wire suspended above and parallel to the roll. The electrode typically carries between 20 and 30 kV, which causes partial ionization of the air between the wire and the roll. This allows movement of ions across the air gap and enables all the feed particles to accumulate a surface charge. This charge on the particles generates an attractive force against the surface of the earth-grounded roll, which is generally described as an *image force* (Figure 1). The image is effectively the result of the charged particle inducing an opposite charge in the surface of the roll such that there is attraction between the two opposing charges. This image force pulls the particles toward the rotating roll until they move past the wire electrode.

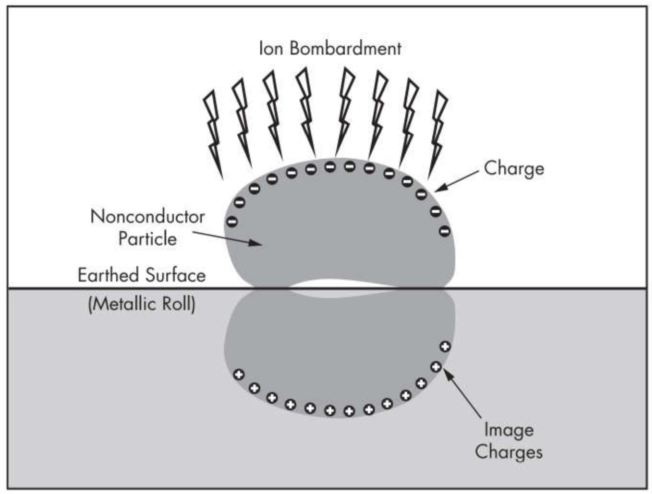

Figure 1 Image force and respective charge

As the particles are carried out of the charging zone beyond the wire electrode, the charge on the conducting particles will begin to discharge into the roll. When they have lost sufficient charge, the particles will follow a normal trajectory away from the roll, based on the speed imparted to them from the rotating roll. The most nonconductive particles will tend not to lose their charge and thus will be retained by the image force on the roll surface and be carried around to a brush that dislodges them from the roll surface. Mineral species exhibiting intermediate conductivity will discharge more quickly and fall from the roll at an earlier point into the middlings area. Hence, the different streams can be collected by the positioning of product splitters at appropriate locations beneath the roll (Figure 2).

Traditionally, the wire electrode has been supported by a metallic tube that can also act as a secondary nonionizing electrode, because the large diameter prevents ionizing of the air. When moved into a position sufficiently close to the roll, the nonionizing electrode provides a strong static field at the roll surface. This field induces the charge on a conductive

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particle to cause separation. The charge carriers of a polarity opposite to the electrode are attracted toward it. The charge at the side closest to the roll flows to the earth-grounded roller, leaving the particle with a net charge of opposite polarity to the electrode. This process also accelerates the loss of corona charge by the conductive particles. The process is called *conductive induction*, and it is also the charging mechanism used by EPS units.

The effect of the secondary metallic bar electrode is limited in that it can only influence a small area of the roll surface, and hence some separators have been designed with a metal plate electrode instead of the bar. The limitation of the metallic electrode is that it cannot be brought too close to the roll without risk of arcing between the two conductive materials. Recent developments in HTR separators have incorporated secondary electrodes made from nonconductive materials, which have allowed them to be positioned much closer to the roll surface (Figure 3). This enables a stronger electric field to be generated, which significantly enhances the efficiency of separation. The nonconductive plate is able to impart additional induction charging of conductor minerals such that they are actively attracted toward the plate while coarse-sized nonconductors are held on the roll for a longer time. Thus, the resulting general trajectories of the conductor and nonconductor streams are farther apart, and the proportion of minerals misreporting to middlings is reduced.

HTR machine parameters that are normally adjusted to optimize the separation are the roll speed, electrode voltage, and product splitter positioning. Some separations may benefit from adjustments to the positioning of the electrodes. Introducing the feed material to the roll at an elevated temperature is also important for efficient separation. Increased roll speed will tend to improve the purity of the nonconductor stream, but reduce its weight yield. This may also cause increased levels of nonconductors to report with the conductor stream. Hence, there will be an optimum roll speed for any particular separation. HTR separators incorporating nonconductive secondary electrodes are generally most efficient when operated at the maximum electrode voltage that does not cause arcing between the wire and the roll (Figure 4). At a given roll speed, which has been set to give the most appropriate weight split between conductors and nonconductor species, the conductor quality can be adjusted by the positioning of the conductor splitter. Processing a narrow feed-size distribution with this technology will also improve the separation efficiency.

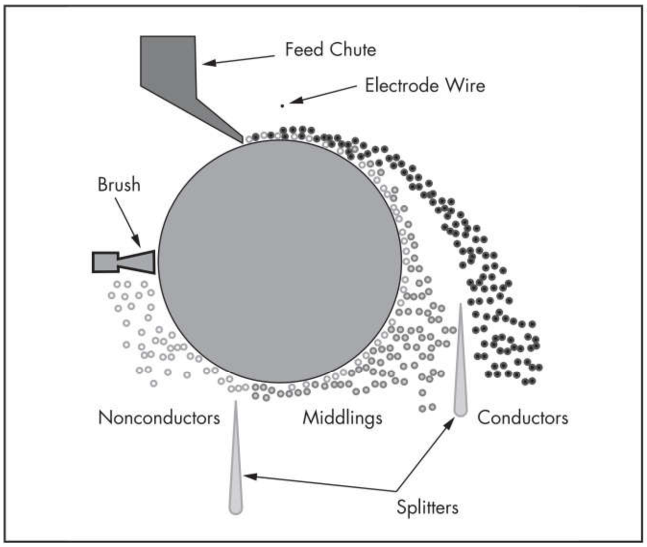


Figure 2 High-tension roll separator

Electrostatic Plate Separation

EPS allows feed particles to roll under gravity down an earth-grounded sheet metal plate. The particles pass under a nonionizing electrode in the form of an elliptical tube or plate, which is situated parallel to the length of the plate. The nonionizing electrode provides a strong static field at the plate surface. This field induces the charge on a conductive particle to separate. The charge carriers of polarity opposite to the electrode are attracted toward it. The charge at the side closest to the plate flows through the earth-grounded plate, leaving the particle with a net charge of opposite polarity to the electrode. The charging mechanism adopted is conductive induction.

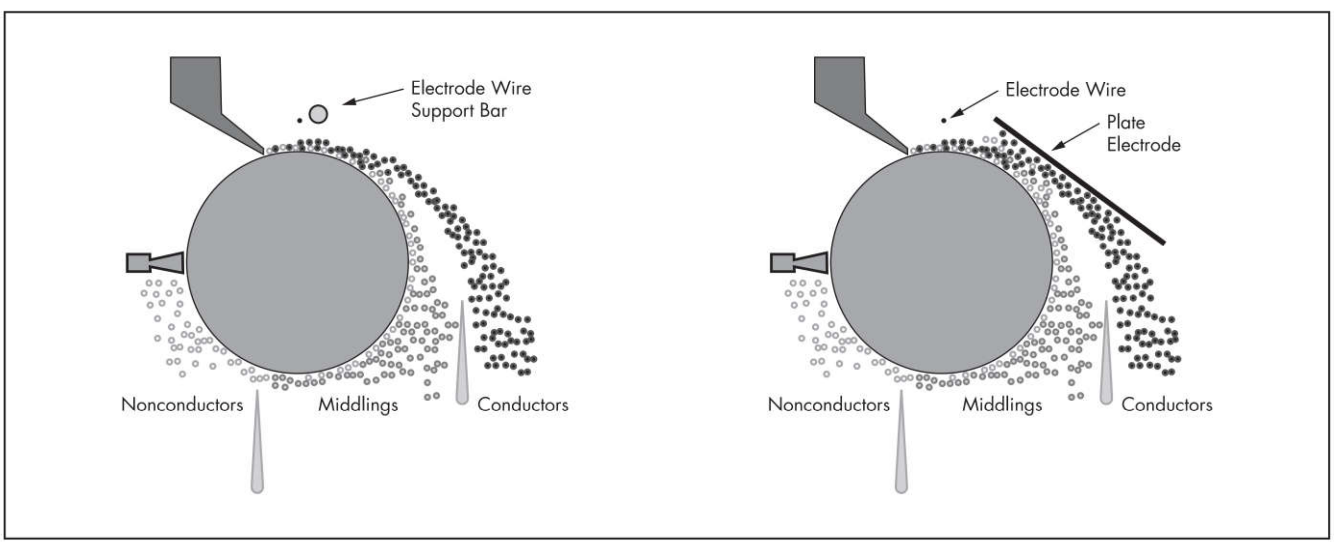


Figure 3 High-tension roll with bar- and plate-type secondary electrodes

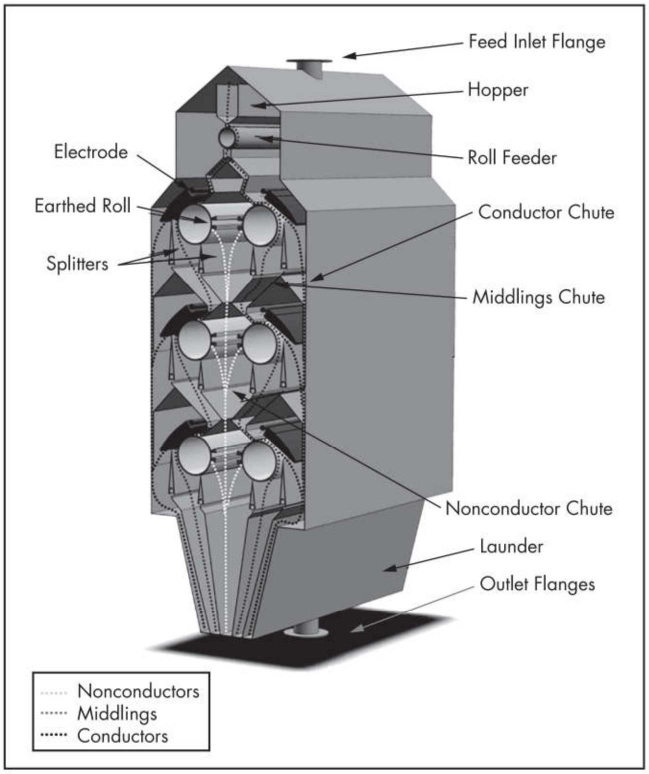


Figure 4 Front sectional view of a typical industrial multistage high-tension roll separator setup for middlings retreat

Conducting particles will easily collect charge from the plate and then be attracted up toward the oppositely charged electrode. This attraction, coupled with their momentum down the plate, will produce a trajectory that carries the particles over a suitably placed product splitter. Nonconducting particles will tend not to acquire charge from the plate and thus will be unaffected and continue on their natural trajectory. The charging mechanism is substantially weaker than that for the HTR separator and thus the separation forces are smaller. Consequently, the EPS unit is ideally suited to finer-sized conductor particles that are more easily deflected from their natural trajectory.

Two types of EPS units are *curved plate* and *screen plate* (Figure 5). The curved plate is the most commonly used and features an earth-grounded plate that is shaped to have an inflection point under the electrode, which assists the transfer of charge to the conductor particles. The screen plate has an earth-grounded plate with a simple concave curvature that directs the nonconducting particles to a coarse screen. The nonconductors fall through the screen while the conductors are lifted across it by the electrode and fall into a separate chute. Similar separations can be achieved with both types of EPS units; however, the curved plate type can be simpler to operate in a plant environment.

Tribostatic Separation

Tribostatic separation relies on the tendency for certain materials to exchange electrons during contact such that one component becomes negatively charged while the other becomes positively charged. The polarity of the charge retained is a function of the surface chemistry of the materials. The charging process depends on many factors, such as the contact velocity, temperature, and prevailing atmospheric conditions. A tribostatic separator will normally incorporate a means of charging the particles immediately ahead of the separation zone. This may simply consist of a cascade chute where the particles fall under gravity through a zigzag chute to provide opportunity for interparticle contact. Other charging mechanisms may include rotating tubes, brushes, or turbulent air currents.

The separation zone in a free-fall tribostatic unit consists of two vertically arranged electrodes of opposite polarity (Figure 6). The charged feed material is directed between the electrode plates where it falls under gravity. The particle trajectories are modified by the attraction toward the oppositely charged electrode, and thus the separated minerals can be collected at the bottom of the separation zone.

Triboelectrostatic Belt Separation

The triboelectrostatic belt separator uses triboelectric charging (Figure 7). Feed material is introduced into a narrow gap between two parallel planar electrodes. The action of a high-speed open-mesh belt moving between the electrodes causes interparticle collisions, resulting in triboelectrostatic charging of the particles. The different mineral particles are attracted toward the electrode plate of opposite charge. This causes them to engage with one side of the moving belt, which transports them to either end of the separator where they are captured in hoppers and chutes for product materials handling. The unique feature of this technology stems from the countercurrent flow of the separated particles making two distinct products.

This technology requires no additional chemicals, produces no emissions, and is suited for separation of particles with sizes from 1 to 500 µm. Throughput capability ranges from 1 to 50 t/h (metric tons per hour) per machine.

The ST Equipment and Technology triboelectrostatic belt separator (Figure 8) has demonstrated the capability to process fine particles from <0.001 to approximately 0.5 mm. These separators have been in operation since 1995, separating unburned carbon from fly ash minerals in coal-fired power plants in North America, Europe, and Asia to produce a concrete-grade pozzolan for use as a cement substitute (Bittner et al. 2013). Through pilot-plant testing, in-plant demonstration projects, and/or commercial operations, ST Equipment and Technology separators have demonstrated beneficiation of many minerals, including potash, barite, calcite, and talc (Bittner et al. 2014).

The primary interest in this technology has been its ability to process particles less than 0.1 mm; there are currently two sizes of the ST Equipment and Technology fine-particle triboelectrostatic belt separators available, with nominal capacities of 23 and 40 t/h.

The principles of operation of the ST Equipment and Technology separator are illustrated in Figures 9 and 10. The particles are charged by the triboelectric effect through particle-to-particle collisions in the air slide feed distributor and within the gap between the electrodes. The applied voltage on the electrodes is between ±4 and ±10 kV relative to ground, giving a total voltage difference of 8–20 kV. The belt, which is made of a nonconducting plastic, is a large mesh with approximately 60% open area. The particles can easily pass through the openings in the belt.

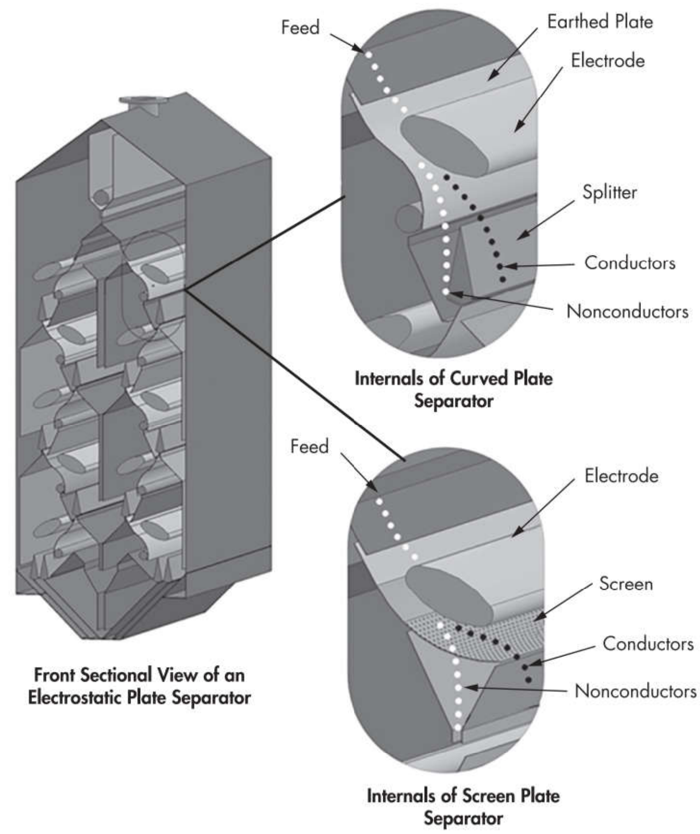


Figure 5 Curved plate and screen plate separators

The flow patterns and particle-to-particle contact within the electrode gap that are established by the moving belt are key to the effectiveness of the separator. On entry into the gap between the electrodes, the negatively charged particles are attracted by the electric field forces to the bottom positive electrode. The positively charged particles are attracted to the negatively charged top electrode. The speed of the continuous loop belt is variable from 4 to 20 m/s. The geometry of the belt cross-direction strands serves to sweep the particles off the electrodes, moving them toward the proper end of the separator and back into the high-shear zone between the oppositely moving sections of the belt. Because the particle number density is so high within the gap between the electrodes (approximately one-third the volume is occupied by particles) and the flow is vigorously agitated, there are many collisions between particles, and optimal charging occurs continuously throughout the separation zone. The countercurrent flow induced by the oppositely moving belt sections and the continual recharging and reseparation creates a countercurrent multistage separation within a single apparatus. This continuous charging and recharging of particles within the separator eliminates the need for any *charger* system prior to introducing material to the separator, thus removing a serious limitation on the capacity of electrostatic separation. The output of this separator is two streams, a concentrate and a residue, without a middlings stream. The efficiency of this separator is equivalent to approximately three stages of free-fall separation with middlings recycle.

The ST Equipment and Technology fine-particle triboelectrostatic belt separator has many process variables that enable optimization of the trade-off between product purity and recovery that is inherent in any beneficiation process. The coarse adjustment is the feed port through which the feed is introduced to the separation chamber. The port farthest from the discharge hopper of the desired product gives the best grade but at the expense of a lower recovery. A finer adjustment is the speed of the belt. The electrode gap, which is adjustable between 9 and 18 mm, and the applied voltage (±4 to ±10 kV) are also important variables. The polarity of the electrodes may be changed, which aids in the separation of some materials. Pretreatment of feed material by precise control of trace moisture content (as measured by feed relative humidity) is important to achieve optimum separation results. The addition of trace amounts of charge-modifying chemical agents can also aid in optimizing the process.

As stated earlier, the initial commercial application of the belt separator has been separation of unburned carbon from the glassy aluminosilicate particles in fly ash from coal-fired power plants. This technology is unique among electrostatic separators in its ability to separate fly ash, which typically has a mean particle size less than 0.02 mm. The fine-particle triboelectrostatic belt separator has also been proven to effectively separate magnesite from talc, halite from kieserite and sylvite, silicates from barite, and silicates from calcite. The mean particle size of all of these feed materials has ranged from 0.02 to 0.1 mm. Examples of separations for several materials

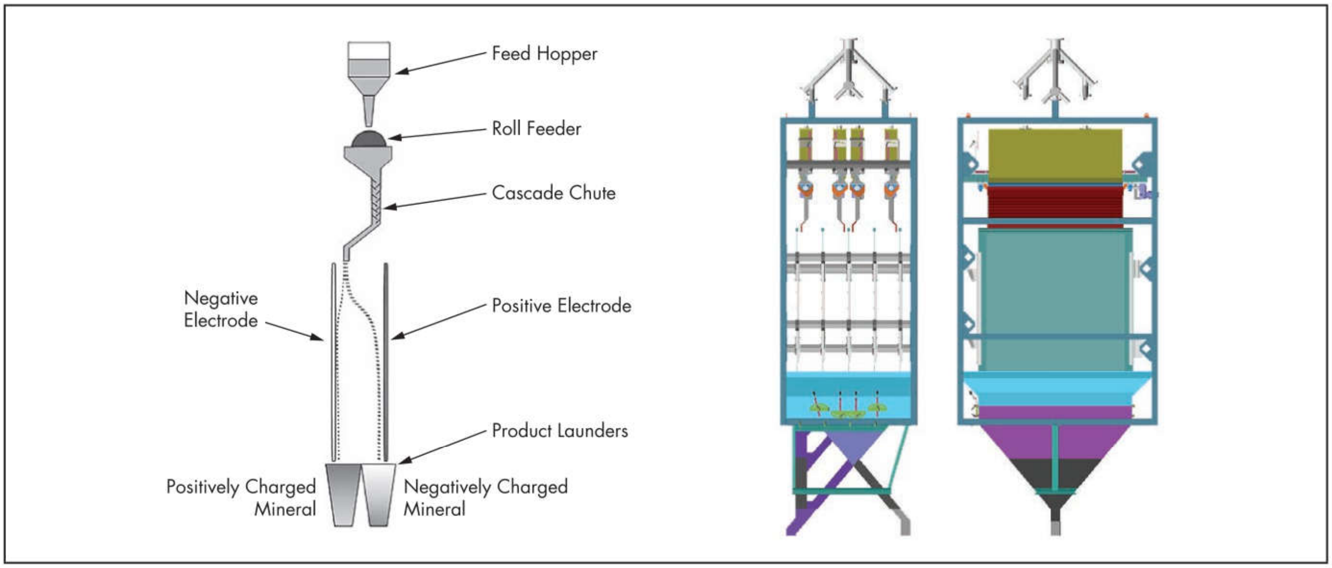
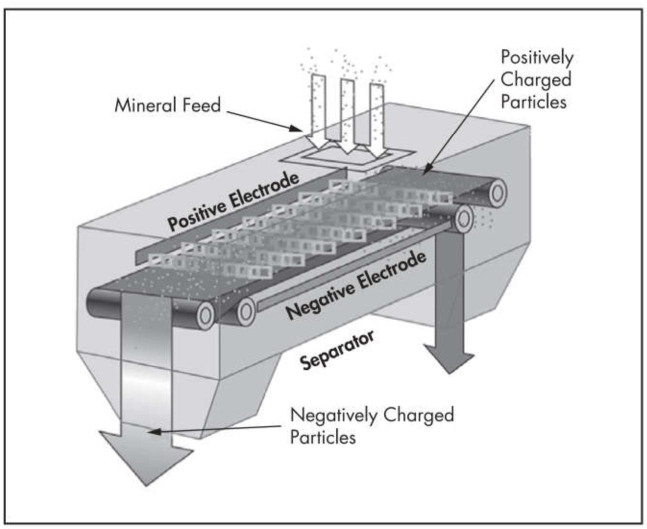
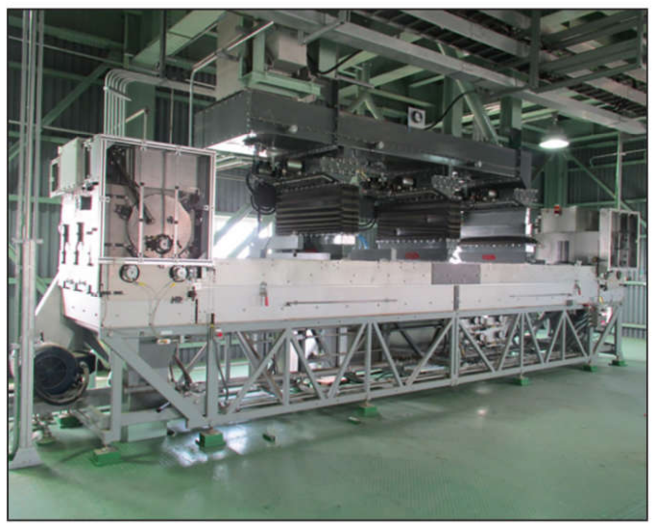


Figure 6 Cross section of a free-fall tribostatic separator



Courtesy of ST Equipment and Technology LLC

Figure 7 Operating principle of a triboelectrostatic belt separator



Courtesy of ST Equipment and Technology LLC

Figure 8 Industrial triboelectrostatic belt separator

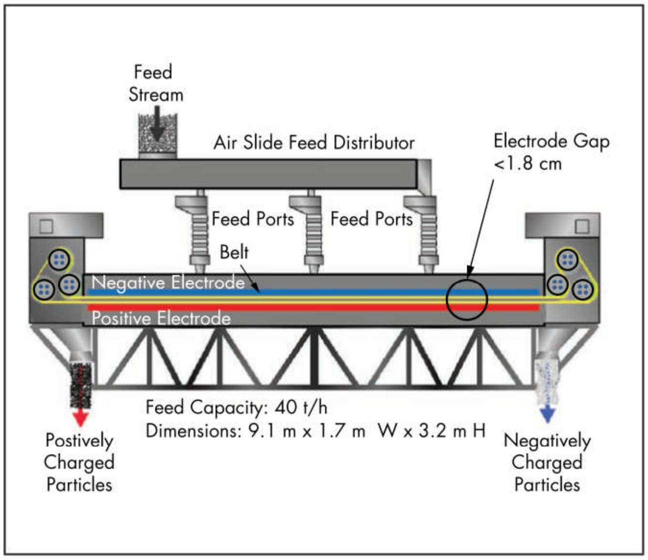
are included in Table 1. The operating costs (Table 2) for the fine-particle triboelectrostatic belt separator are low, typically ranging from US$0.75 to US$2/ton feed (2015 prices, which include fine-particle triboelectrostatic belt separator consumables and electricity, excluding operating labor).

APPLICATIONS OF THE SEPARATION PRINCIPLES

HTR separators and EPS units are commonly used together in a plant flow sheet as their individual separation characteristics are complimentary. HTR separators will tend to generate a middlings product, enriched in finer-sized conductors and coarser nonconductors. This type of feedstock may be better suited to separation using EPS units as they are particularly effective at removing the fine-sized conductors from a coarse nonconductor stream.

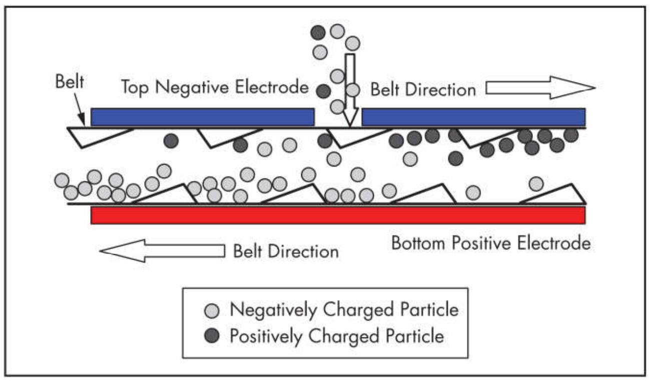
The most common application for HTR separators and EPS units is in the treatment of mineral concentrates derived from mineral sand mining. After a mineral sand ore has been concentrated through wet gravity processes, a mixed mineral concentrate is produced, which generally contains up to 90% heavy minerals (minerals with specific gravity above 3.0). This concentrate would normally require additional upgrading to remove the remaining quartz and ensure that the mineral surfaces are clean and free of slime. This cleaned concentrate is then dried and treated through the *dry mill*, which consists of various stages of separation with HTR and EPS equipment along with magnetic separation as required. Depending on the constituents of the ore, varying proportions of the following minerals can be produced as final concentrates:

- Ilmenite
- Leucoxene



Courtesy of ST Equipment and Technology LLC

Figure 9 Schematic of fine-particle triboelectrostatic belt separator



Courtesy of ST Equipment and Technology LLC

Figure 10 Electrode gap of fine-particle triboelectrostatic belt separator

- Rutile
- Zircon
- Garnet
- Sillimanite
- Monazite
- Xenotime

The conductor minerals in the preceding list are ilmenite, leucoxene, and rutile; all others are nonconductors. Hence, the final separation of the individual mineral species requires the use of magnetic separators and wet or dry gravity separators in conjunction with the electrostatic separators.

HTR separation is also commonly used in processing concentrates from alluvial tin mining where minerals such as cassiterite, ilmenite, and columbite are separated. It has also been applied to the rejection of nonconductive silicates from both iron ore and chromite concentrates. EPS units have also been used to reject weakly conductive contaminant grains from salt concentrates. Because most metal sulfides are more conductive than gangue minerals, there is also potential for dry separation of some sulfide ores.

Table 1 Separation examples

Separation	Feed	Product	Recovery
Calcium carbonate (silicates)	9.5% Acid insols	<1% A1	89% $CaCO_3$
Talc (magnesite)	58% Talc	95% Talc	77% Talc
		88% Talc	82% Talc
Kieserite + KCl – NaCl	11.5% K_2O	27.1% K_2O	90% K_2O
	12.2% Kieserite	31.8% Kieserite	94% Kieserite
	64.3% NaCl	14.3% NaCl	92% NaCl reject
Fly ash mineral (carbon)	6.3% Carbon	1.8% Carbon	88% Mineral
	11.2% Carbon	2.1% Carbon	84% Mineral
	19.3% Carbon	2.9% Carbon	78% Mineral

Courtesy of ST Equipment and Technology LLC

Table 2 Cost overview*

Overall Costs	Wet Beneficiation (flotation), %	Dry Beneficiation (fine-particle triboelectrostatic belt separator), %
Purchased major equipment	100	94.5
Total CAPEX	100	63.2
Annual OPEX	100	75.8
Unitary OPEX ($/ton conc.)	100	75.8
Total cost of ownership	100	70.0

Courtesy of ST Equipment and Technology LLC

*Capital expenditure (CAPEX) and operating expenditure (OPEX) of crushing are the same for both processes and are not included.

Free-fall tribostatic separation is used in the removal of quartz from lime sand or limestone and the removal of silica sand from feldspar. The tribostatic belt separator has proven application in the separation of the following mineral combinations:

- Potash–halite
- Talc–magnesite
- Limestone–quartz
- Brucite–quartz
- Iron oxide–silica
- Mica–feldspar–quartz
- Wollastonite–quartz
- Boron minerals and carbon–silica

Other potential applications being tested are

- Phosphate–calcite–silica,
- Barites–silicates,
- Zircon–rutile,
- Silver and gold slags,
- Beryl–quartz, and
- Fluorite–silica and fluorite–barite–calcite.

In theory, because particle charging depends on the triboelectric effect, any two minerals that are liberated from each other (conductor–conductor or nonconductor–conductor) can be separated by this method. Other potential applications include magnesite–quartz, feldspar–quartz, mineral sands, other potash mineral separations, and phosphate–calcite–silica separations.

FUNDAMENTALS OF EQUIPMENT SELECTION

Virtually every mineral suite will have its own peculiarities, and thus the quantity and arrangement of electrostatic separators required for beneficiation is likely to vary from site to site. While there are some general principles for machine selection that will give a first estimate of the quantity and type required, the only way to ensure the correct selection is through laboratory or pilot-scale testing.

The primary separation stages will generally employ HTR separators as these are able to treat material at a higher feed loading than EPS units. Indeed, the modern dual-electrode HTR separators are able to separate many mineral streams that once required EPS units. So the general principal in any test work program is to use HTR separators until it becomes apparent that they cannot perform a particular separation. Commonly, EPS units are used in the retreatment of difficult streams rejected from prior HTR separation stages.

EPS units are most efficient at separating finer-sized conductors from streams containing coarser-sized nonconductors. Such streams are commonly generated from the middlings product of HTR separators. Thus, microscopic inspection of the stream can give insight into when EPS units may be applicable. An EPS can sometimes differentiate between minerals exhibiting very similar conductivity where the HTR separator may be ineffective.

TYPICAL INDUSTRIAL APPLICATIONS

Various machine configurations exist to offer advanced techniques for electrostatic separation within a tribostatic panel. Some of the more common configurations are depicted in Table 3.

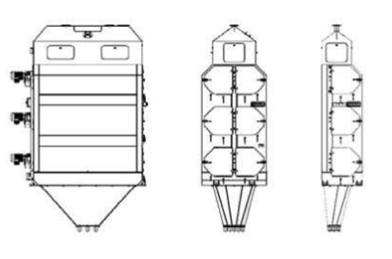
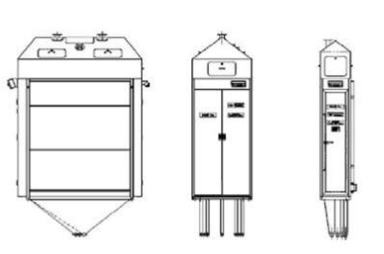
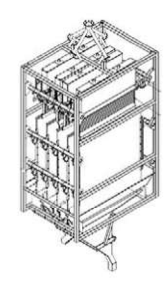
Particle Size Considerations

Most mineral separators operate more efficiently with a relatively narrow feed sizing. This is true of HTR separators in particular because the conditions ideally suited for separation of a fine particle are likely to require a higher roll speed than those for coarser particles of the same mineralogical composition. Thus, a mixed-size feed must adopt a compromise roll speed between the two ideals. That said, it is generally found that a ratio of 3:1 between the coarsest and finest particles allows a very reasonable separation to be achieved. Ratios higher than this can often still be handled adequately when the HTR separator is used in conjunction with the EPS unit or perhaps with screening of the final HTR products. For more difficult separations, reducing the size range to 2:1 can sometimes assist; however, this may be hard to justify in a plant situation unless the final product requires such narrow sizing.

Generally, the effectiveness of the HTR separation diminishes with separation of particles sized larger than 1 mm. This is caused by the difficulty of presenting the particles onto the rotating roll without having excessive bouncing of the particles. Also, the mass-to-surface-area ratio of large particles is increased such that there is insufficient charge accumulated to cause the particle to be retained on the roll surface in opposition to the centrifugal force and gravity.

An EPS unit can separate a wide particle size range, provided that the conductor minerals are preferentially at the fine

Table 3 Common equipment sizes

	High-Tension Roll	Electrostatic Plate Separator	Tribostatic Separator
Configurations	6 roll (2 × 3 configuration) 4 roll (2 × 2 configuration) 3 roll (1 × 3 configuration) Single-roll lab units Roll diameters: 6–16 in. (400 mm) Roll lengths: 300–2,000 mm	1 × 3 plates 2 × 3 plates 1 × 5 plates 2 × 5 plates 2 × 10 plates Single-plate lab unit	1 stage × 1 zone 1 stage × 2 zone 2 stage × 1 zone 2 stage × 2 zone
Mass range	250–2,500 kg	250–2,500 kg	350–1,500 kg
Size range	750–5,000 mm height 	700–5,000 mm height 	1,100–4,550 mm height 
Throughput (subject to test work)	300 kg/h–10 t/h	100 kg/h–5 t/h	5 kg batch–40 t/h
Services required			
Power	0.08–5.5 kW Heating of feed to be considered Dust collection to be considered	0.08–0.5 kW Heating of feed to be considered Dust collection to be considered	0.25–5 kW
High-tension power supply	7.5–15 mA	7.5–15 mA	7.5–25 mA

end of the size range. If there is no size differentiation between the conductor and nonconductor minerals, then the same 3:1 sizing ratio applies as per the HTR separator.

The particle size also has a significant bearing on the capacity of the HTR and EPS units. As the feedstock becomes finer, the feed rate generally needs to be reduced to maintain a similar level of separation efficiency. For example, separation of a mineral sand suite, with a mean size of 130 µm, may typically be performed at around 1.8 t/h/m. A reduction in the mean size to 90 µm may require the loading to be reduced to around 1.2 t/h/m, while reduction to 50 µm may require loadings below 0.6 t/h/m. It is generally found that electrostatic separation is ineffective on particles below 30 µm as the interparticle attractions tend to prevent particles acting independently.

High-Tension Roll Size

Over the years, commercial HTR separators have been manufactured with various roll diameters ranging from 150 mm to approximately 400 mm. In general, a larger roll diameter will give an increase in capacity for a given mineral feed type, particularly in the primary separation stages. However, the degree of increase in capacity is subject to the feed composition and mineral characteristics. In the final cleaning stages of a circuit, there may be smaller differences between roll sizes larger than 250 mm as the majority of the feed must report to one or other product.

The use of larger-diameter rolls allows more area for charging of the mineral being fed onto the roll and permits more flexibility in positioning of the corona wire. The larger diameter also allows a greater surface area of the roll to be influenced by the plate electrode, which can significantly assist separation efficiency. Also, there is a longer retention time for the nonconductor particles that are adhered to the roll, which allows weakly conductive particles more time to lose their charge and be released from the roll into the middlings product. The effect of roll size on performance for a two-component feedstock is shown in Figure 11.

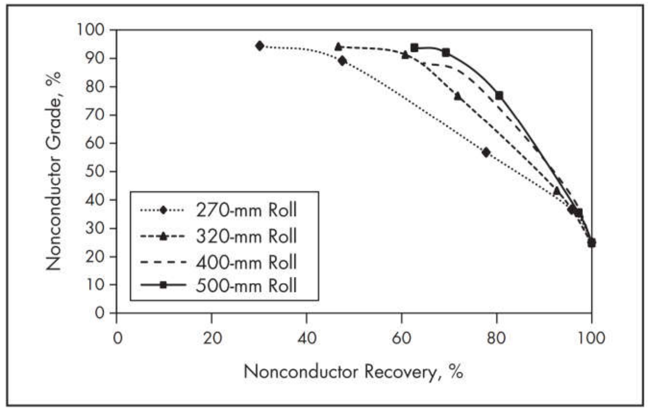


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Figure 11 Effect of high-tension roll diameter on separation of a two-component feedstock

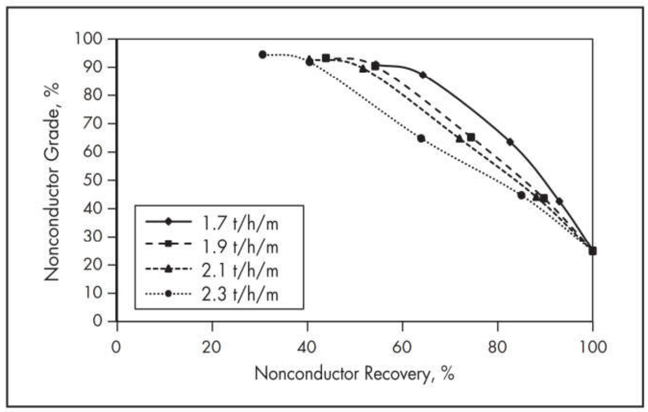

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Figure 12 Effect of feed loading on high-tension roll separation of a two-component feedstock

Feed Loading

To minimize the capital expense of a plant, the minimum number of separators is always sought. Hence, the unit feed loading to any stage of separation should be maximized within the constraints of the required grade and recovery targets. Increasing the feed loading on electrostatic separators will generally reduce the metallurgical efficiency of the separation, as shown in Figure 12.

With a complex feedstock containing many different mineral types, or where a very high product purity is required, it is expected that multiple stages of electrostatic separators will be required to achieve the final grade and recovery specifications. Thus, the primary HTR separation stage may employ a higher feed loading as the product streams generated will pass on to a second, and possibly third, cleaning stage, which would be able to remove the remaining contaminant minerals. For example, a feedstock with a mean particle size of around 130 µm may give an acceptable primary stage HTR separation at feed loadings between 1.7 and 1.9 t/h/m. To achieve the required product stream quality in the final stage of separation, the feed loading may need to be reduced to approximately 1.5 t/h/m. If the challenge is to make a sufficiently clean nonconductor product, a larger-diameter roll, which provides more time for the charge on the conductors to decay, should be considered. Larger roll diameters can also be used for coarser feeds.

The use of higher feed rates will tend to reduce the quality of both the conductor and nonconductor streams as more entrainment and interparticle collisions occur. This can be mitigated to some degree by allowing a middlings stream to be taken. Thus, some improvement in product grades can be made, as feed rates increase the proportion of material reporting to middlings is also likely to increase.

Middlings Handling

In many applications, it is appropriate to take a middlings stream from the HTR separator and direct it to its own re-treatment stage. A reasonable proportion of the minerals in this middlings stream will simply be present because of misreporting, and historically, such streams have often been returned to the feed of the separator. Nevertheless, such streams tend to contain an elevated level of coarse nonconductors and fine conductors along with minerals having an intermediate conductivity. Returning such streams to the same separator does not provide the ideal separation conditions for such minerals and consequently results in a buildup of a circulating load, which can at times grow to represent a very significant proportion of the total feed to the separator.

It is almost impossible to predict the ultimate size of this circulating load from laboratory testing. Also, small changes in the feed characteristics can significantly affect the magnitude of the circulating load, making control of the plant very difficult. Consequently, most modern electrostatic flow sheets are designed to minimize the need for recirculation of middlings streams. When such a middlings stream represents a very small mass flow that does not justify an additional separation stage, a decision must be made as to whether it should be recirculated or directed to a stockpile for subsequent batch treatment. It is not uncommon for a very minor middlings stream, or rejects from a final HTR cleaning stage, to grow up to five times its original mass flow when recirculated.

Number of Separation Stages

Achieving a high-purity final product that meets the required specification normally requires multiple HTR separation stages to overcome the statistical chance of contaminant entrainment and to reject any minerals that have very similar conductivity to the product species. In doing this, a significant proportion of the product mineral will be lost to the various reject streams. Thus, additional HTR stages will be required to recover this lost mineral and maintain suitable recovery levels for the plant as a whole.

Historically, plant HTR separation machines have been supplied with single, dual, or triple tiers of separation rolls. Much of the space required for an electrostatic separation plant is involved with feed distribution and product laundering. A more compact overall design can generally be achieved using separators having multiple tiers of separation rolls. The modern dual-electrode HTR separators are able to generate a significant proportion of relatively clean conductor and nonconductor streams from a single roll while allowing the remaining unseparated minerals to report to a middlings stream. Rather than direct this middlings stream to a different separator, it can be immediately treated on the second-tier roll of a multiple-tier separator. The proportion of material reporting to such a middlings stream is typically around 50% of the original feed. It can be argued that the second-tier roll is underloaded and that fewer separation rolls would be required with a dedicated middlings treatment stage. However, as most HTR separations require operation at elevated temperature, this immediate re-treatment has the advantage that no heat is lost from the stream prior to the second separation roll. Also, as discussed earlier, the middlings will contain an increased proportion of minerals that are more difficult to separate, and the reduced feed rate enables a significant improvement in the separation efficiency. Indeed, this is so much so that the quality of the conductor and nonconductor streams from the second-tier roll can generally match that of the first tier and can be immediately combined with them. Inclusion of a third-tier roll, again treating the second-tier middlings, requires a minimal increase in plant space and allows the maximum recovery of both conductor and nonconductor minerals to their respective product streams while generating a very low mass flow to middlings, typically representing only 5%–10% of the original feed.

For some mineral separations where a high-purity product is sought, there may be the requirement to use the second- and/or third-tier roll for re-treating either the prior roll conductors or nonconductors rather than the middlings. Ideally, the separator design should be able to permit this flexibility by standard adjustments to the splitter configuration.

Temperature Considerations

Electrostatic separation exploits the difference in the surface conductivity of various minerals. The effect of moisture on the mineral surface has a significant effect on the resultant conductivity. Commonly, the feed to electrostatic separators is freshly dried after prior concentration in wet processes. While the minerals need to be fully dry to be free flowing, it is also required that the surfaces be free from moisture that condenses from the atmosphere as the mineral grains cool down. Hence, most electrostatic separations need to be performed at elevated temperature to minimize such condensation. This effect is more significant in humid climates, and it may be necessary to adjust the separation temperature and other separation parameters to compensate for local changes in atmospheric conditions. The absolute measure of the atmospheric moisture content is via the dew point rather than humidity. It is common for operating plants to install instruments for measurement of dew point to permit proactive adjustment of the separator parameters.

Typically, most HTR separations are performed at temperatures higher than 60°C, with optimum separation for many conductor minerals requiring temperatures around 100°C. Temperature loss between stages of HTR separators can be 10°–15°C, depending on the mass flow. Smaller mass flow streams will tend to lose more heat and thus may require reheating prior to the next stage of separation. The EPS units are generally operated with the feed temperature higher than 50°C, otherwise atmospheric moisture will cause significant amounts of nonconductor minerals to report to the conductor stream. With some minerals, there can be a maximum temperature for an EPS separation because excess heat can result in particles tending to adhere to the earth-grounded plate, which prevents the free flow required for separation.

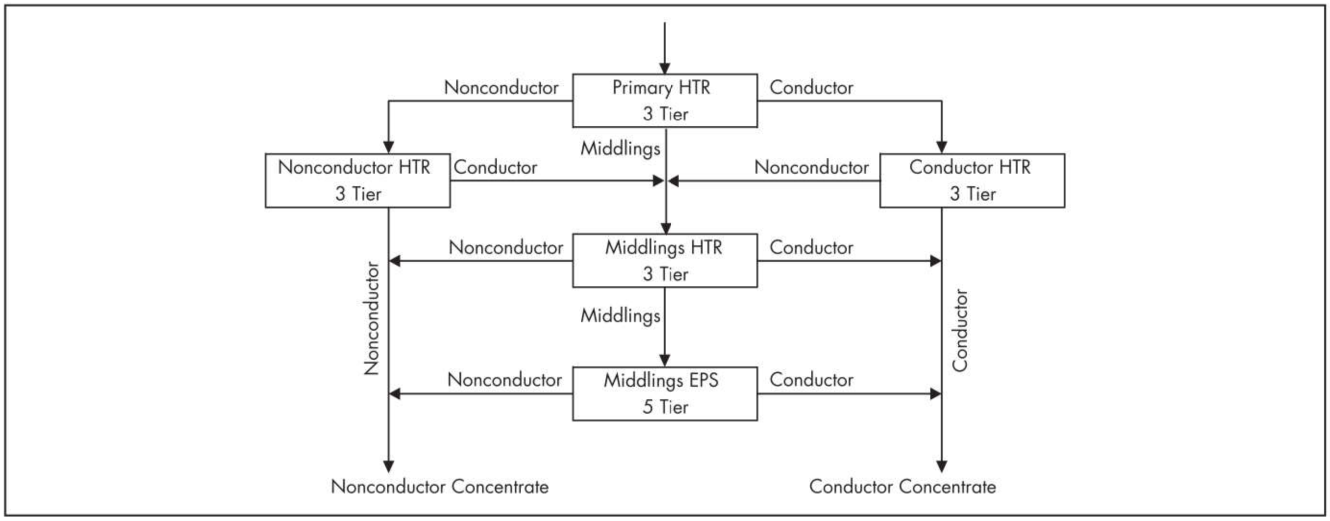
Surface Preparation of Minerals

Similar to the effect of moisture, any contaminants on the mineral surfaces can affect conductivity. Thus, it is a requirement for efficient electrostatic separation that the feedstock be suitably prepared prior to entering the separators. This may simply involve washing in clean water to remove loose slime or dirt contaminants. If the contaminants are bonded to the mineral surfaces, then some form of mechanical scrubbing or attritioning will be required followed by desliming and clean water washing. If the minerals have been extracted from a saline groundwater situation, then thorough washing will be required to remove all traces of salt.

Some clays or organic surface contaminants may require the use of acidic or caustic reagents to clean the mineral surfaces. It is equally important that all traces of these reagents be removed from the mineral surfaces before separation. Hence, even though the process itself is dry, it can require water (and sometimes reagents) for surface cleaning and energy for drying.

Laboratory Test Work

Effective design of a flow sheet to suit a specific mineral suite can only be achieved by testing a representative sample with pilot-scale laboratory separators. Each stage of separation may require different parameter settings to optimize the separation, and thus a suitable quantity of feedstock should be prepared. It is essential to provide sufficient material so that the smallest mass flow stream can be properly tested, as it is often the case that these small middlings streams contain the most difficult



Courtesy of Mineral Technologies Pty Ltd.

Figure 13 Common flow-sheet structure for multistage electrostatic separation

minerals to separate. Without proper consideration, unwanted minerals contained in these streams can adversely affect the final product quality and jeopardize plant performance.

The tests must be performed with a view to what would be the most likely separation conditions found in an operating plant with regard to feed temperature and feed loading. An allowance must also be made for the likely variation in plant conditions caused by changes in ore type, upstream operational difficulties, and ongoing maintenance. It is relatively easy to precisely set up a single laboratory separator; however, such precision is unlikely to be achieved in a plant with multiple stages of separation and several separators in each stage. Thus, the typical metallurgical efficiency in a plant is likely to be below that achieved in laboratory tests performed under well-controlled conditions.

The materials handling of the mineral through an electrostatic separation plant will tend to generate some amount of dust as the particles rub on each other. The presence of this dust in the atmosphere inside the separators can affect the ability to maintain the high voltage required for separation. This can result in repetitive arcing from the corona wire to the roll, which is detrimental to the separation and can damage the high-voltage rectifiers. Thus, it is necessary to operate at a reduced voltage in the plant to prevent this arcing. This must be considered when performing laboratory test work as significantly higher voltages can be maintained in a laboratory separator where there is no dust and heat buildup. Typically, a maximum corona wire voltage for laboratory testing would be 0.43 kV/mm; however, with highly conductive and friable feedstocks, this may reduce to 0.38 kV/mm.

Common Flow-Sheet Structure

Each particular feedstock will require its own flow-sheet peculiarities. A common structure for a mixed feedstock containing reasonable proportions of both conductor and nonconductor minerals is shown in Figure 13. Additional stages of separation may be warranted at either of the conductor HTR or nonconductor HTR stages. Also, re-treatment of the middlings HTR and EPS products may be required for more difficult separations. Each of the conductor and nonconductor concentrates would commonly be directed to further separation processes, such as magnetic or gravity, so that the individual minerals contained therein can be separated. Following these processes, there may be a requirement for further stages of electrostatic separation to achieve specifications for very high-purity products.

CASE STUDY: LABORATORY-SCALE TEST WORK PROGRAM

High-Tension Roll Separation

Typically, a bench-scale laboratory unit will be fitted with a roll of the same diameter as the industrial plant-size unit (270–400 mm) but with a much shorter roll length. The dry test sample is fed onto the roll by a mechanized roll feeder with a feed-path length of normally around 100 mm.

Critical Test Work Variables

The following parameters are the most commonly investigated operating variables that influence the quality of the separation.

1. **Feed rate.** The feed rate must be set and should be a direct ratio of the feed-path width in the test work compared with the plant-scale unit for representative results.
2. **Feed temperature.** Electrostatic separation is much more effective at elevated temperatures where the conductivity of minerals, such as rutile and ilmenite, is enhanced. Typically, the feed is heated to between 80°C and 110°C for separation. Even higher temperatures may produce a better result, but the cost of heating has economic limitations.
3. **Electrode position.** The test unit may have a single ionizing electrode (corona wire), as in the older style "conventional" high-tension separators, or two electrodes (ionizing and plate electrodes), as in most separators built since 2000. The distances between the electrodes and the roll surface will influence separation. These distances should be set to a standard setting or a setting based on knowledge of the test sample or plant experience.
4. **Electrode potential.** The distance between the roll and the corona wire determines the absolute voltage. This is altered by changing the applied voltage on the electrode. Usually, increasing voltage will produce a higher-grade

conductor stream by increasing the mass yield reporting to the nonconductor fraction because more particles are *held* on the separating roll. Optimum voltage is achieved when increasing the applied voltage does not improve the quality of the conductor stream.

5. **Roll speed.** The rotational speed of the separating roll is one of the main operating variables. Roll speed influences the trajectory of the conductor fractions that are centrifugally thrown from the roll and can also influence how tightly nonconductive particles are held onto the roll. Normally, the interplay of electrode potential and roll speed are used to establish the optimum separation.
6. **Splitters.** Three or four adjustable splitters are used to divide the separated minerals and divert the flows into collection trays. The splitters are adjusted to achieve the desired mass yields or product quality. Typically, the conductor/middlings splitter is adjusted most frequently in the test work. Various forms of chute work exist to retreat different streams.
7. **Electrode polarity.** The polarity of the ionizing electrode may be changed. This variable is not commonly changed but may occasionally be necessary. An example of where it may be used is to assist in the adherence of fine quartz to the separating roll.
8. **Atmospheric conditions.** Electrostatic separation is significantly influenced by environmental conditions and, in particular, the water vapor content (measured as relative humidity) of the air. While this may be difficult to control or optimize in a laboratory environment, ideally the conditions should be as similar as possible to the plant environment.

Setup Considerations

The following procedure is typically adopted as best practice when setting up an HTR machine.

1. **Electrical isolation.** Ensure that the separator is electrically isolated and that the unit is properly earth-grounded.
2. **Cleaning.** Safely remove the covers and cautiously clean out the machine using compressed air and brushes, including inside the feed roller, any hangout points inside the main body, the product collection trays, and the brush at the rear of the separation roll (which removes nonconductive minerals from the roll).
3. **Set electrode positions.** Set the electrode positions to the desired gap settings; normally, this is initially a standard position. A spacing template is a useful tool for this setting.
4. **Power and heat up.** Turn on the isolation switch. Start the feed bin heater and set to the desired feed temperature. Turn on the separation roll and heater to the starting rotation rate and let the machine heat up for at least 30 minutes.
5. **Feed-rate measurement.** Using a measured weight of a small sample of feed, adjust the feed roller speed to produce the desired initial feed rate by taking a timed sample of products and calculating the rate. Once the desired feed rate is set, the machine should be cleaned again.
6. **Heat test sample.** The test sample should be kept at the desired temperature in an oven if possible. The temperature is confirmed using a digital thermometer prior to separation. For reheating feed during the test work, it is normally faster to use electric hot plates with continual turning of the sample to achieve the desired temperature consistently through the whole sample.

Test Work Methodology

The following methodology is typically adopted when performing metallurgical test work with an HTR machine.

1. **Initial test.** Switch on the power to the HTR separator and select a standard kilovolt setting. Ensure that there is no arcing. If arcing occurs, then the positioning of the electrodes must be incorrect. Set the roll speed and splitters to standard positions and pass the heated test sample. View the trajectory of the conductors (a spotlight or torch may be required) and adjust the conductor splitter if necessary (modern facilities use high-speed cameras for this evaluation). If arcing occurs while the sample is processing, then the feed temperature or voltage setting may be too high or the electrodes incorrectly positioned too close to the roll. Collect and examine the separated fractions.
2. **Optimization.** Reheat the test sample to the desired temperature and repass, using adjustments of splitters and voltage to improve the separation until it cannot be improved further. If the separation is unsatisfactory at this point, roll speed and feed-rate adjustments may be necessary, especially if the sample is unusually coarse or fine, or contains composite particles reducing the separation quality.
   - Typically, the range of parameters should be maintained between 22 and 30 kV.
   - The feed rate should be an equivalent of 3–6 t/h for a standard-sized plant-scale separator.
   - The feed temperature should be 85°–110°C.
3. **Quality.** If the separation quality is still not acceptable, it may be necessary to adjust the electrode positions. This is the most difficult parameter to adjust, so it should be done after other parameters have been evaluated and the separation is still unsatisfactory. Always ensure that the separator is electrically isolated before adjusting electrodes or reaching into the separation space at any stage.

Tribostatic Separation

The tribostatic separation is generally used in the separation of a two-component feedstock where both minerals are nonconductors. Thus, HTR separators would not be considered for this duty. For some applications, the EPS unit can be operated as a tribostatic separator where there is sufficient contact charging of the particles as they travel down the earth-grounded plates and through the various feed chutes. The EPS unit has been used commercially for the removal of residual quartz from zircon and sillimanite concentrates: however, feedstocks containing larger amounts of quartz would normally be directed to other separation processes.

Tribostatic charging generally only permits relatively weak charges to be accumulated on the mineral surfaces, and thus the condition of the mineral surfaces is more critical than for HTR and EPS separation. For effective tribostatic separation, it is a common requirement that the temperature of the feed material be higher than 100°C and temperatures around 120°C are typical. This ensures that there is absolutely no moisture on the mineral surfaces.

The selection of tribostatic separation can only be made following laboratory test work confirming its effectiveness.

Some feedstocks permit a degree of upgrading by tribostatic means. This, however, may be insufficient to permit a viable plant process to be developed.

A GUIDE TO OPERATOR TROUBLESHOOTING

Metallurgical Issues

In the event of unsatisfactory metallurgical performance of the HTR separator, the following actions may assist.

High-Tension Roll Separation

Problem 1: The nonconductor product contains too many conductor minerals.

- Move the nonconductor splitter farther under the roll.
- Increase the separation roll speed.
- Reduce the feed rate.
- Reduce the feed temperature.
- Decrease the voltage to the electrodes.
- Reduce the plate electrode gap.

Problem 2: The conductor product contains too many nonconductor minerals.

- Move the conductor splitter farther out from the roll.
- Decrease the separation roll speed.
- Reduce the feed rate.
- Increase the feed temperature.
- Increase the voltage to the electrodes.
- Increase the plate electrode gap.
- Clean the corona electrode wire.

Electrostatic Plate Separation

In the event of unsatisfactory metallurgical performance of the EPS unit, the following actions may assist.

Problem 1: The nonconductor product contains too many conductor minerals.

- Move the splitters closer to the earth-grounded plate.
- Increase the voltage to the electrodes.
- Reduce the feed rate.
- Reduce the feed temperature.
- Reduce the plate electrode gap.
- Clean the surface of the earth-grounded plate.

Problem 2: The conductor product contains too many nonconductor minerals.

- Move the splitters farther out from the earth-grounded plate.
- Decrease the voltage to the electrodes.
- Reduce the feed rate.
- Increase the feed temperature.
- Increase the plate electrode gap.
- Check for blocked screens on screen plate separator.

Tribostatic Separation

In the event of unsatisfactory metallurgical performance of the free-fall tribostatic unit, the following actions may assist:

- Adjust the splitters toward the flow of the off-specification stream.
- Reduce the feed rate.
- Vary the feed temperature.
- Vary the voltage to the electrodes.
- Adjust the position of the feed presentation.
- Clean the surfaces of the plate electrodes.

In a plant environment, there are many factors that can influence the overall performance of the various separators. If the preceding adjustments to the individual separators do not resolve an issue with the overall separation quality, then the following other external factors may affect the performance of all types of electrostatic and tribostatic separators:

- Atmospheric moisture (dew point)
- Mineralogical composition of feedstock
- Sizing of minerals to be separated
- Cleanliness of mineral surfaces

Mechanical Issues

The following points relate to mechanical issues that may influence the metallurgical performance of the equipment and should be considered. All types of electrostatic separators may suffer from feed material misreporting within the internal transfer chutes. This may be the result of blockages causing overflows or holed chutes. Regular monitoring is advised to avoid such occurrences.

High-Tension Roll Separators

Issues with the separation roll include

- Heavy scouring or grooved surfaces from over-tensioned brushes;
- Coating, slimes, or organic buildup not removed by the brushes;
- Poor or nonexistent earth-grounding via the brushes or other device; and/or
- Worn bearings causing vibration that prevents particles from properly adhering to the roll.

Issues with the high-voltage supply include

- Loose or broken high-voltage leads,
- Varying voltages between individual separation module electrodes,
- Poor reticulation to the machine and internally,
- Earth-ground leakage in the cable run from the high-voltage source,
- Non-corresponding indicated and actual voltages, and/or
- Corona wire with incorrect gauge.

Electrostatic Plate Separators

EPS machines have few moving parts; however, attention to the condition of fixed components is still advised, such as

- Deformed earth-ground plates, perhaps from overzealous cleaning;
- Deformed electrodes, also from overzealous cleaning;
- Damaged electrodes that have permitted feed material ingress; and/or
- Non-corresponding indicated and actual voltages.

High-voltage supply challenges include

- Loose or broken high-voltage leads,
- Varying voltages between individual separation module electrodes,
- Earth-ground leakage in the cable run from the high-voltage source, and/or
- Poor reticulation to the machine and internally.

Tribostatic Separators

Free-fall tribostatic separators have fewer moving parts than an EPS unit, and because of the separation principle, wear of the vertically positioned electrodes is found to be the majority of mechanical issues. High-voltage reticulation issues are also possible, and performing checks as per the EPS machine is advised.

The tribostatic separator uses high voltages (up to 70 kV). These voltages are potentially lethal. Safe procedures must be followed by certified fitters at all times during the operation of this machine. Earth-grounding is critical and the machine must be securely earth-grounded with zero electrical impedance between the machine frame and the plant electrical earth-ground. The machine must be operated with all doors and access panels closed. The access doors are fitted with safety cut-out switches to stop the machine and cut both standard-voltage and high-voltage circuits.

Larger industrial machines can weigh up to 10,000 kg and more than 15,000 kg if fully sanded, so lifting consideration and sturdy support structures for fixing the machine are essential. It is also recommended to allow around 30 minutes after stopping the machine to discharge all of the residual static charge on the electrodes before maintenance.

Wear on the moving belts of the tribostatic belt separator is to be expected, and hence a regular inspection and replacement schedule is warranted.

TROUBLESHOOTING CASE STUDY

A long-established mineral sands producer had noticed a gradual decline in the throughput of its dry separation plant, together with a constant struggle to achieve grade and recovery targets despite installation of new equipment in some parts of the circuit.

Through consultation with separator specialists, the decision was made to perform a comprehensive mechanical audit of each machine and the associated maintenance work practices. The audit identified areas where key components, either individually or when combined with a group of components, were negatively impacting the overall performance of the separator. This, together with a gradual decline in operational maintenance, contributed to the gradual worsening in overall plant performance.

Using the data compiled by the separator specialists, a program of refurbishing or replacing the components in the key areas was undertaken. The most common components identified were worn or out-of-specification separation rollers, alternative supply separation roller brushes that did not fit correctly in the brush holders, and ineffective earth-grounding. Also, the high-voltage leads were, in many cases, very old with deteriorated insulation causing voltage leakage, resulting in inconsistent voltage at the various electrodes within a single machine. All high-voltage leads were subsequently replaced.

Consequently, it became clear to senior operational personnel that, without revising work practices, the ability to maintain the operational integrity of the machines would be short-lived. Procedures for the day-to-day operation were implemented, together with structured personnel training for both new and existing employees. Also, the approach to separator maintenance was changed from a “fix it when it breaks” culture to a more structured program of planned maintenance.

The initial audit and refurbishment program took approximately 12 months to complete. Over that time, the previously noted decline in plant performance slowly reversed, and, ultimately, the performance returned to expected levels. The benefits of improved plant performance were not the only positive outcome. While the component replacements initially required additional expenditure, the maintenance costs decreased over the following two-year period and then stabilized.

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