CHAPTER 4.5

Ore Washing

Richard Williams

To *wash* can be defined as "to remove [a substance] by or as by the action of water" (Dictionary.com 2018). In a mineral processing sense, this commonly refers to the removal of loosely attached particles, often fine clays, from the surface of more competent ore. In this definition, it is distinct from classification, which would be a subsequent processing step that separates the different sized fractions. Despite increasing concerns about the value and availability of water, ore washing remains a common and cost-effective means of beneficiation, as water usage is enhanced by the greater use of water recovery. Advantages that accrue from the scrubbing of ore can range from a reduction of gangue to process further, to improved product quality and higher throughput of downstream equipment. Although generally thought of as removing waste material, in highly weathered deposits, the inverse may apply and the valuable mineral may be contained in the fines. Examples occur in alumina (Husaini and Cahyono 2010), nickel laterites, uranium, and occasionally gold.

DESIGN PRINCIPLES

The overriding principle in ore washing is to provide sufficient energy and time to detach the fine clays but not sufficient to cause comminution of the intrinsic particles to smaller components. Care must also be exercised to provide appropriate energy and flow to maintain the fine particles in suspension and not allow them to agglomerate and grow as *clay balls*. Thus, defining a suitable ore washing process should consider the following:

- Energy input, kW·h/t
- Particle size distribution, mm
- Time
- Throughput

Equipment sizing for ore washing has been largely empirically based on scale-up of laboratory or pilot tests, subsequently benchmarked off operating installations. Miller (2004) created a mathematical model for sizing rotary drum scrubbers that calculated input power and residence times based on physical geometry; however, this still relied on test work to establish the range of acceptable criteria. The high degree of variability in clay mineralogy leads to a preference to do site-specific testing. Standards such as ASTM D4318 (2017), ASTM D4221 (2017), and ASTM D3744 (2003) exist to help define the *plasticity* and/or the *dispersive* characteristic of clay materials and *aggregate durability*, but to date, a measurable correlation between these and energy input has not be published.

TEST WORK

Test work is commonly carried out either in commercial testing laboratories (Figure 1) or by vendors. Equipment used can vary from scaled-down vendor equipment to adapted commercially available substitutes (concrete mixer) to equipment designed for alternative testing (ISO tumble drum [ISO 3271:1995]) to purpose-built pilot plants capable of taking the full size range. A major limitation with all but the last is the inability to process a representative sample size range, particularly for those duties with a feed size of up to 250 mm.

Most small-scale test work is done on a batch basis. This can create some interpretation issues. It is generally acknowledged that batch testing provides an indication of the required solids residence time; however, most equipment is operated in a continuous mode. Subject to the geometry and flow patterns within the equipment, the fluid phase will traverse at a different rate. Given such residence time, distributions of both the liquid and solid phases must be accounted for. Miller (2004) suggested 0.3–0.5 mm as a guideline for the coarse–fine (approximating solids–liquids) split; however, it was also acknowledged that this is application specific. Industry standards use a range of 2.0 to 2.5 to compare the solids residence time to an average. Common design specifications refer only to an average residence time; hence, evaluation of the equipment used for testing is critical for establishing design parameters. Discrete element modeling with computer simulation has been successfully used to approximate both residence time and power draw on a comparative scale when calibrated against known installation.

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Figure 1 Pilot- and laboratory-scale log washer

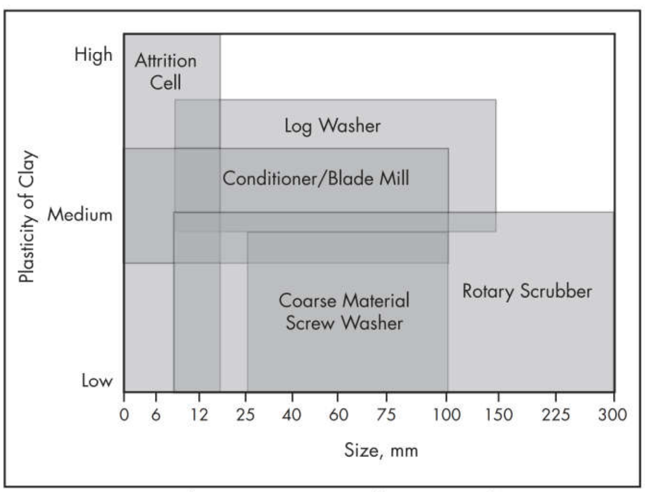

Figure 2 Ore-washing equipment selection guide

KEY EQUIPMENT DESCRIPTIONS

Once the energy requirement, particle size, residence time, and throughput are established, the matrix shown in Figure 2 can provide a guideline for equipment selection.

Attrition Cells

Attrition cells are high-energy devices used to liberate tough plastic deleterious material and remove it from competent material. They are also proven to liberate clays, reducing product turbidity, and to break apart loosely conglomerated clusters in frac sand plants. Manufacturers of high-quality silica sands use them to remove iron staining from the surfaces of sand grains.

These devices are primarily made up of a tank (cell) in which a vertical shaft drives a set of two to three diametrically opposed mixer blades. The cell itself can be round, square, hexagonal, or octagonal, but all are generally baffled to an extent to minimize swirling. Configurations of the blades and whether these are simple axial turbine or propeller in design is largely manufacturer dependent. As the blades rotate, material is forced against itself to cause particle-on-particle collisions, thus abrading the surfaces and liberating the coating material. Because of the intense mixing action, the particle residence time distribution in any one cell can be quite broad, with some particles leaving the cell quickly (bypass) and others remaining for longer. To help ameliorate the bypass, attrition cells are commonly supplied as multiple cells, with two to four cells per machine being most common. Often, alternating cells in series like this will reverse the pitch of the impeller blades to aid direction of the flow toward the outlet at either the top or bottom of the tank. Weirs at the final discharge lip allow the operator to adjust the height of the slurry within the tank and hence increase or decrease residence time.

Attrition cells are typically fed at high solids (60%–80% solids by mass). As such, upstream unit operations will commonly consist of dewatering cyclones or even dewatering screens. These present the material at a high density to achieve maximum particle-on-particle scrubbing action. The feed size is limited to ~6 mm for materials in the range of 2.7 specific gravity. Because the attritioning efficiency is greater at higher solids concentrations, one must be careful not to run the machine into an operating environment that causes plugging. Monitoring of the power input can assist in operating in a more desirable region with simple water addition on demand.

It is also important to understand any changes in the state of the slurry as the attritioning process takes effect. In instances where there is a presence of high clays, or clays that only become broken down and suspended after high shear, the slurry itself may take on an oatmeal-like consistency. The resulting effect is that the competent particles are well lubricated in the mass, and further attritioning is impeded. The solution to this is to use an interstage wash operation between sets of attrition cell units. These wash circuits remove the liberated clays and return the remaining competent particles to downstream attritioning. To help reduce water consumption by the wash stages, a countercurrent approach is often recommended, with the dirtiest discharges being washed with the dirtiest water (Figure 3).

Because of the high-shear environment, it is important to have suitable wear protection (rubber lining and/or hardened steels) to maximize life and minimize time and costs of replacement parts.

Attrition cells are used in the glass, heavy mineral, and frac sand industries to provide intensive scrubbing (Preston and Tatarzyn 2013), with an energy input of 5–10 kW·h/t. To accommodate the high energy, these are small units of 1–10 m^3 and commonly fitted with a direct-drive motor. Residence times may range from 0.5 to 5 minutes.

Coarse and Fine Material Screw Washers

Also known as *spiral classifiers* or *screw classifiers*, these machines are primarily built to wash and classify crushed stone, gravel, and other hard ore minerals, generally ranging from 0.075 to 100 mm. They effectively remove light loamy-type clays, dirt, crusher dust, and coatings that cannot be removed by wet screening alone. They can also be used to take out floating vegetation and soft aggregate, although not all vegetation and waterlogged sticks may be removed completely. Coarse material screw washers are not intended to remove the tough plastic clay that normally requires a more energy-intensive machine.

The sizing and selection of a coarse material screw washer is based on the type of material, desired capacity, and maximum feed size (Figure 4A). The more paddles that are used, the lower the capacity; however, the washing action is increased because paddles do not convey material up the washer box as fast as spiral flights. A coarse material screw washer can be furnished with up to 40 paddles per shaft. When using additional paddles, it is also necessary to lower the slope of the box and increase motor power. This will help convey material to the discharge end.

Subject to the duty, either volumetric and solids capacity limitations may lead to the use of twin-screw units. The larger pool area on the twin-screw unit (Figure 4B) will lower the rise rate, resulting in a finer classification, and the double screw will permit a higher solids loading.

In coarse material screw washers, paddles are used in conjunction with screw flights to provide scrubbing, scouring, and agitation. The turbulent washing action combined with rising current water introduced at the bottom of the box at the feed end results in separation of the lighter fraction from the sound aggregate. The lighter fraction (i.e., clay and floating vegetation) rises to the surface because of the water rising in the box and then overflows the weir located in the back of the box. The desired clean product is then scrubbed and conveyed by the paddles and flights to the discharge end of the box. A rinsing screen is recommended for use after the coarse material screw washer for material classification.

The screw shaft is composed of an extra-heavy steel pipe shaft with inner and outer renewable and reversible abrasion-resistant hard iron paddles bolted to the shaft in the feed area. These paddles are preceded and followed by heavy steel flights equipped with bolt-on abrasion-resistant liners. The screw shaft is flanged at both ends and bolted to stub shafts to facilitate normal maintenance.

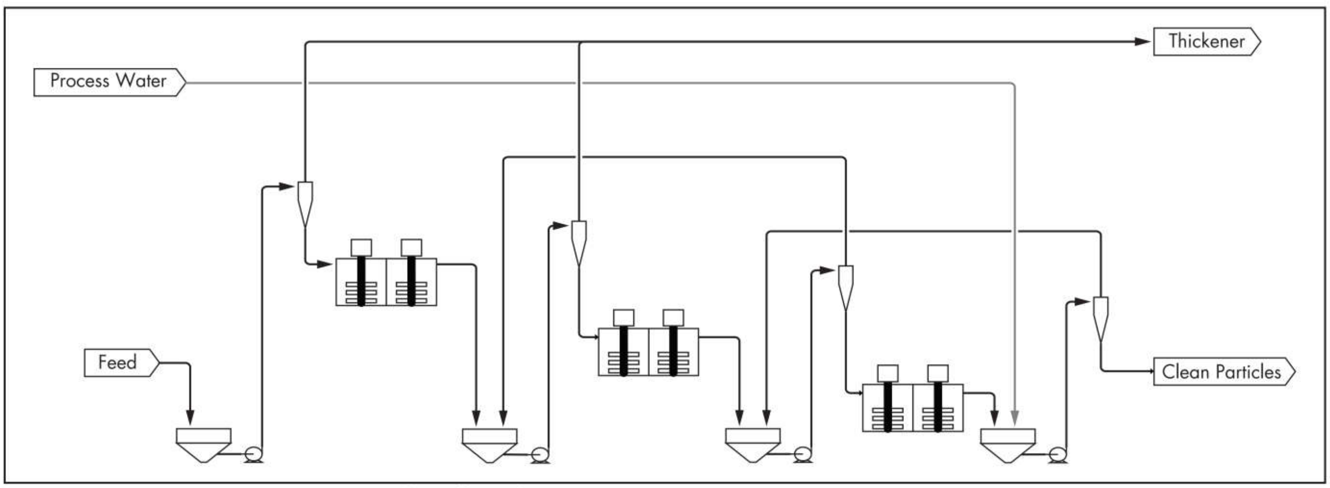

Figure 3 Interstage countercurrent-washing flow sheet

A. Coarse material single-screw washer

B. Fine material twin-screw washer

Figure 4 Screw washers

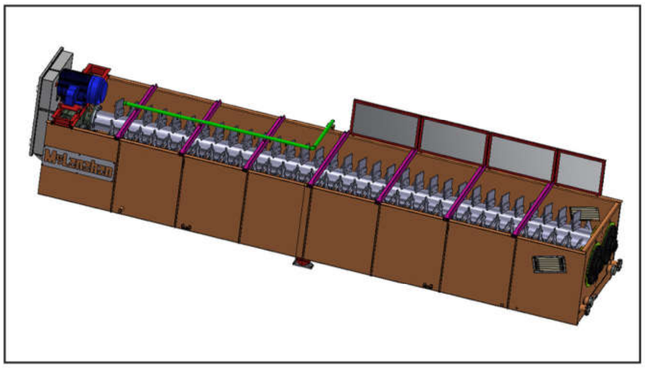

Figure 5 Log washer

Figure 6 Conditioner or blade mill

Log Washers

The twin-shafted log washer is so called as the original design utilized a wooden log as the shaft into which were driven fixed iron paddles. Log washers are used in a variety of material processing applications and are best known for their ability to remove tough, plastic clays from natural and crushed gravel, crushed stone, and ore feeds (Figure 5). Inputs of 2–5 kW·h/t would be typical. One limitation of log washers is that they must have a controlled top size. In general, most units can accept feed material with cubical-shaped particles up to 100 mm. Some larger-diameter units can accept a feed material up to 150 mm. When processing fines, it may be necessary to capture the overflow of the unit to save this fraction for further processing or close off the overflow opening so that material is carried the full length of the box for scouring of the fines.

When selecting a log washer for an application, the amount, type, and percentage of deleterious material (i.e., clay) to be removed should be considered. As the percentage of deleterious material to be removed increases, options exist to

- Vary the length of the wash box,
- Change the angle of the intermeshing paddles to either impart more power or accelerate the conveyance of material,
- Alter the angle of mounting,
- Alter the overflow weir height, or
- Vary water flow rates for rising current and rinsing.

Most log washers come standard with adjustable weirs at the overflow openings that permit the change in water depth, which in turn can affect the quality of the washed product. They are often equipped with a spray bar for rinsing the material prior to discharge.

Critical to the reliability of a log washer is the need for a robust design of the washer box, log shafts, gear box/drive train, and the submerged rear bearings. Depending on the rock or ore being washed, paddle life varies from one to several years between replacements. The submerged-bearing design varies among manufacturers. A separately lubricated seal design provides extended availability. The paddles are often provided with replaceable wear shoes.

Conditioners and Blade Mills

Conditioners, also referred to as blade mills, are designed to help producers begin liberating light, loamy clay or dirt from either coarse rock or sand before further processing. There are many applications where a conditioner can be used. As an example, when washing coarse rock, the conditioner can be placed ahead of a wash screen, resulting in cleaner rock or ore. When washing finer materials, such as sand, the unit can be placed ahead of a screen, sand-classifying tank, or fine material screw washer. Conditioners are able to accept either coarse or fine feed material.

Keep in mind that conditioners are designed to do just that, condition. They are not designed to remove tough, plastic clay or a high percentage of clay. Conditioners are usually selected for use with other processing equipment to improve the downstream washing and separation of material. Because of all the material and water exiting the unit, the discharge material cannot be fed onto a conveyor belt. Generally, the amount of water needed for a conditioner is an additional third of the weight of the material being processed.

Conditioners are very similar in appearance to coarse material screw washers, but function much differently (Figure 6). The major difference is that any material and water that enters the conditioner must exit through the discharge opening located at the bottom of the box opposite the feed end. There is no overflow in this type of unit. Using a combination of paddles and flights arranged in alternating format the entire length of the shaft, they begin to scour, abrade, and break down deleterious material. The shafts can have different configurations, but mainly the idea is to have alternating flights and paddles. Conditioners sit on a slope of 0–5 degrees and have higher capacities than same-size coarse material screw washers. This is caused by the lower machine operating slope. Again, a conditioner is used where the material needs to be worked or wetted before it enters a vibrating screen, fine material screw washer, or other wet processing.

Rotary Scrubbers

Rotary scrubbers are designed primarily for the removal of loam and light clays and soft, soluble waste materials from aggregates, stone, and ore. Scrubbers are not intended to replace log washers in applications where tough plastic clays are contaminating the material to be cleaned. When these tough clays are fed to a scrubber, the clay particles may have a tendency to pelletize through the tumbling action of the material. For example, golf-ball-size pieces of plastic clay may not break down and have been known to increase to the size of a tennis ball.

Scrubbers and coarse material screw washers are often selected to wash out similar contaminants from aggregate and

Figure 7 Chain-driven scrubber

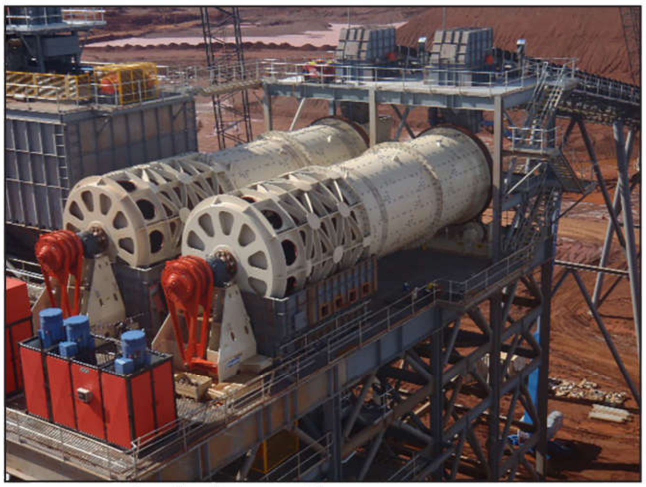

Figure 8 Hydraulic drive scrubber screen

various ores. The major difference is that scrubbers can accept larger feed sizes, whereas coarse material screw washers must have a controlled top size, and scrubbers have much higher throughput capacity. Because large-diameter scrubbers can handle feeds up to 250–300 mm, they are sometimes used as primary washers before any crushing or screening is done.

For long residence times and low energies, a smaller-diameter, longer machine is most effective, whereas for short residence times and high input energies, larger-diameter, shorter machines are more effective.

Capacities are normally determined by analyzing the type of feed material, percent and type of waste material to be removed, and available water; a screen analysis of the feed is also performed. The required retention time in a scrubber will vary for each application because of different types and varying amounts of wastes to be removed. Testing will help establish required guidelines.

Rotary scrubbers may range in diameter from 2.5 to 5.0 m and in length from 2.5 to 18 m, with aspect ratios (L/D) ranging from 1.8 to 3.0. Scrubbers can be sized to process up to 5,000 t/h of ore.

Figure 9 Scrubber internal view with solids pile at dynamic angle of repose

Improved washing can be accomplished by

- Adjusting the water rate to the scrubber,
- Modifying the lifter and liner design,
- Adjusting the discharge weir height (to alter residence time), and
- Altering the rotation speed to vary energy intensity.

The selection of an appropriate drive mechanism depends on the power and variability required. Small units may use a friction, chain, or rubber tire drive system (Figure 7). These styles are limited in power to 300–500 kW and ~3 m in diameter. Larger units may use an end drive stub-mounted hydraulic motor or girth gear with pinion. Power intensity required in most scrubbing duties ranges from 0.2 to 1.0 kW·h/t (Figure 8). Support systems offered include trunnion rollers with steel, rubber, or polyurethane tires or hydrostatic bearing pads similar to ball mills.

Rotary scrubbers work by having process water and solids introduced through the feed chute. As the cylinder rotates, the solid feed fraction is carried up the side of the drum by centrifugal force until its surface reaches the dynamic angle of repose—typically in the range of 35 to 45 degrees. The surface material then cascades and tumbles to the bottom of the solids pile before being carried back under the pile by the rotating drum (Figure 9). Lifter bars on the drum shell ensure that the solids pile cascades and tumbles rather than sliding down the wall. This action helps to break down the softer materials and liberates clays, dirt, loam, and other foreign materials into solution.

For special washing and screening applications, a combination scrubber screen may be used. These units combine the scrubbing characteristics of a rotary scrubber with the screening portion of rotary trommel screens all in one unit (Figure 10). The screen portion can be supplied with either a single- or double-shell design. Scrubber screens can be effective when handling hard-to-wash and hard-to-screen materials, such as oyster shells and phosphate matrix, and offer some benefits in plant layout options.

The maintenance required on rotary drum scrubbers will vary according to the size, hardness, throughput, and

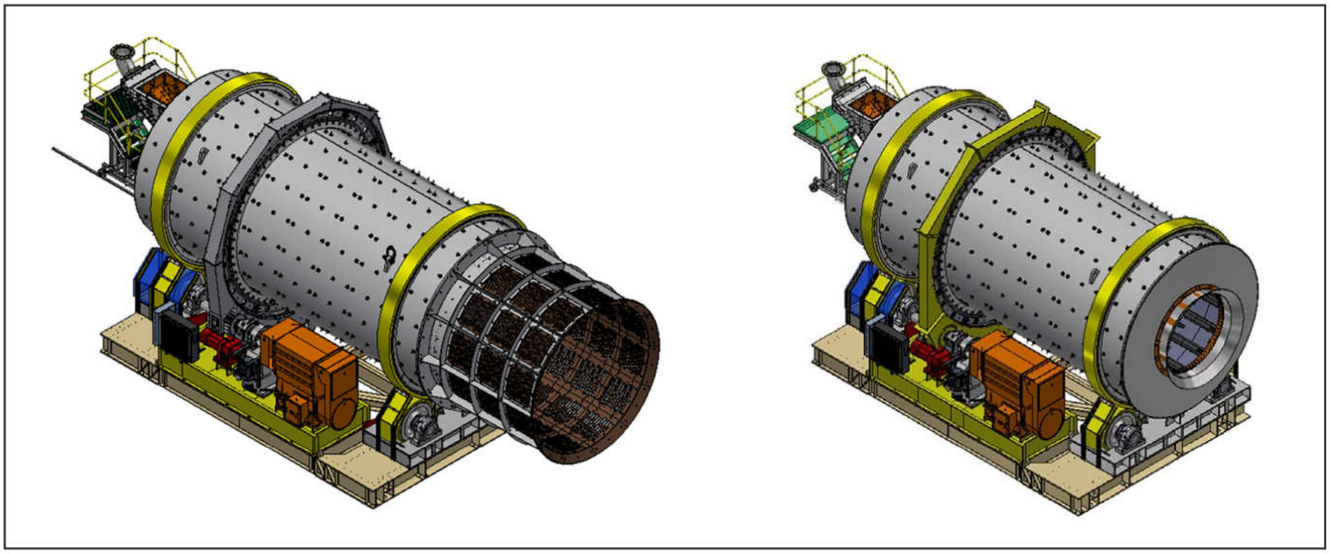

Figure 10 Scrubber with and without trommel screen

abrasivity of material being processed. Replaceable liners on the feed chute, shell, and end wall can be replaced at intervals of 12–36 months.

High-Intensity Washing

Some developments are being considered using high-intensity hydraulic washing drums (Slige 2016). These are suggested to use less water but similar overall power input and are largely adapted from chemical or municipal applications.

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