CHAPTER 7.1

Mechanical Flotation

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Machines used for most mineral flotation applications may be designated as either pneumatic or mechanical. Pneumatic machines rely on fluid flow to mix solids, liquid, and air. They include flotation columns, Jameson cells, and others, and are not discussed in this chapter. Mechanical machines use a rotary mechanism to provide mixing and, in some cases, aeration. Mechanical machines are often called *cells*.

Mechanical machines may be further categorized based on the location of the mechanism and the method of introducing air into the process. *Multi-chamber* machines, supplied by Eriez and Woodgrove, use individual chambers for mixing and froth separation. In *single-chamber* machines, made by FLSmidth, Metso, and Outotec, one chamber serves for mixing and phase separation. The single-chamber machines include self-aerating machines, in which air is induced into the pulp by the action of the mechanism, and externally aerated machines, in which air is delivered into the pulp by a separately powered blower. A compressor may also be used, but this is seldom done in practice. Self-aerating mechanisms locate the rotor or impeller near the top of the tank, while externally aerated mechanisms are near the bottom. Figure 1 illustrates this taxonomy in more detail.

Mechanical flotation machines have been designed in a wide variety of configurations. Mechanical machines are designed for use in almost all flotation applications, with variations in size, mechanism power, aeration rate, and cell operation specified so that each machine functions as desired in the circuit. Many of these machines have been previously described (Nelson et al. 2002). This chapter provides current information on machine design and sizes available; describes new machines and new features on machines described previously; and provides detailed information on design, installation, start-up, and operation of mechanical flotation machines of all makes.

Specially designed machines are used for flash flotation, in which large, liberated particles of value are recovered into a concentrate immediately after grinding. All flash flotation machines are externally aerated, with mechanisms located near the bottom of the tank.

AVAILABLE EQUIPMENT

All the information in this section was provided by representatives of the respective manufacturers, or taken from manufacturers' websites and printed literature. Machine descriptions and benefits are given as provided by each manufacturer, and readers are left to form their own opinions regarding the material presented. The respective manufacturers are presented in alphabetical order, with no implication as to which (if any) the authors believe to be superior. The machines described in detail in this chapter are those most commonly used in North and South America, Europe, Africa, and Australia. Bateman and Delkor, both now owned by Takraf Tenova, have also supplied machines in these markets. Suppliers in China and Russia also provide mechanical flotation machines, but they are similar or identical in design to those described here (see Glembotskii et al. 1972 for examples).

As noted by Sherrell and Yoon (2005), flotation may be thought of in four subprocesses: bubble–particle contact, particle attachment, particle detachment, and froth recovery. (Some authors consider the first two subprocesses as a single subprocess and thus identify only three subprocesses.) For many years, all of the commercially available froth flotation machines have been designed to accomplish all four subprocesses in the same vessel, as shown in the image in Figure 2.

Innovations in machine design continue. Manufacturers continue to refine the respective designs of their mechanisms. Machines introduced by Eriez and Woodgrove each use nonconventional designs to accomplish the four subprocesses just mentioned. Both machines are based on a perceived need to execute the subprocesses in separate vessels, as described by Zhou (1996).

Eriez Manufacturing

The concept behind the dual-chamber design is to use one vessel for collection and one vessel for froth recovery, with the conditions in each vessel optimized for its designated function. The collection vessel is optimized for high-energy turbulent contacting, and the separation vessel can be optimized for

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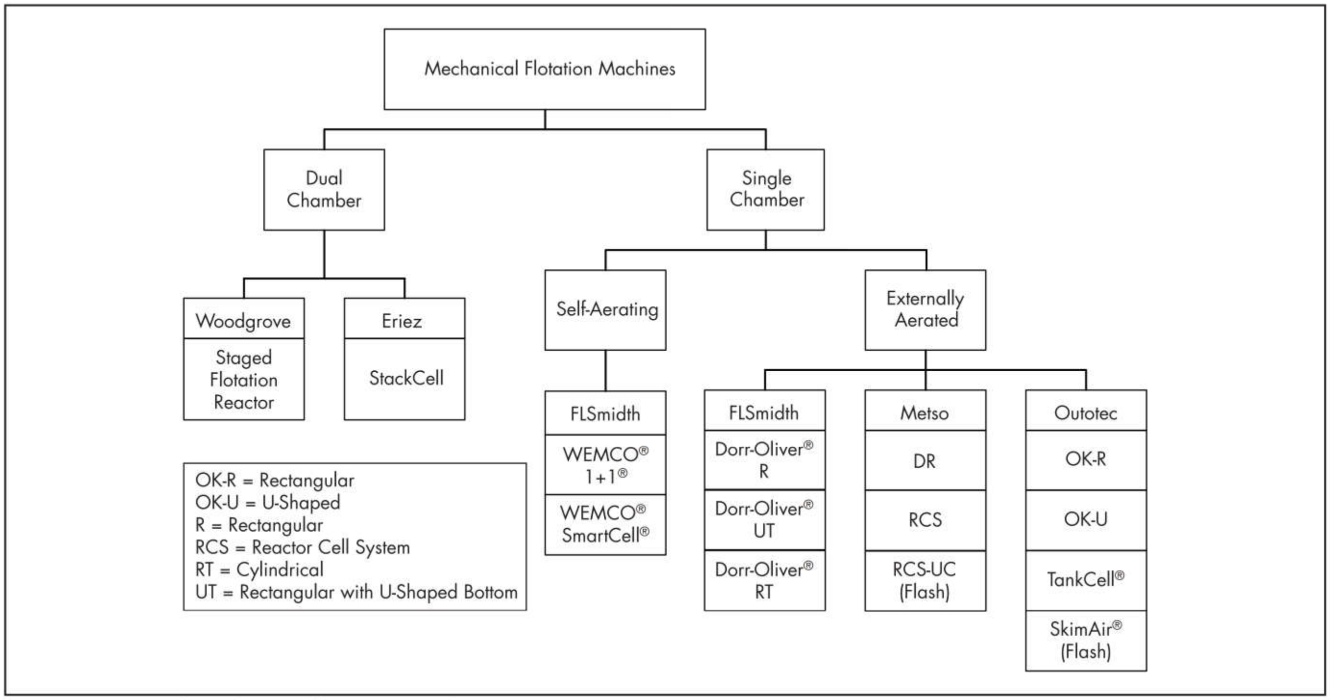

Figure 1 Types of mechanical flotation machines

gentle, nonturbulent bubble–particle separation from the pulp and froth recovery.

The Eriez StackCell® machine, shown in Figure 3, was developed to combine the metallurgical performance of a column with the footprint of a mechanical cell (Kohmuench et al. 2008).

Feed is introduced into an internal mixing and aeration canister. Intensely mixed, aerated slurry is discharged under pressure from the mixing canister into the larger cell, which operates under conditions designed to allow bubble–particle aggregates to rise into the froth and be recovered through an internal or external launder. The froth is washed by downflowing water to remove entrained hydrophilic particles. Because a rotor and stator are located inside the canister, mechanical energy is introduced into the system, as in a conventional cell. In comparison to conventional mechanical cells, the amount of mechanical energy introduced per volume into the canister is much higher, while the amount of mechanical energy introduced per volume into the overall system is much lower. This allows the StackCell machine to target and isolate the part of the system that benefits from mechanical energy.

In coal flotation, the StackCell machine is reported to deliver improved ash rejection and higher coal recovery. Its size and design also allows the installation of a bank of several cells in a vertical configuration. Such an installation increases retention time and minimizes the effects of short-circuiting, while the vertical configuration requires less floor space and decreases pumping costs by using gravity flow.

The StackCell machine has been applied in sulfide and gold flotation. Reportedly, equivalent metallurgical performance can be achieved compared to mechanical cells with a significant reduction in retention time or working volume of the flotation cell.

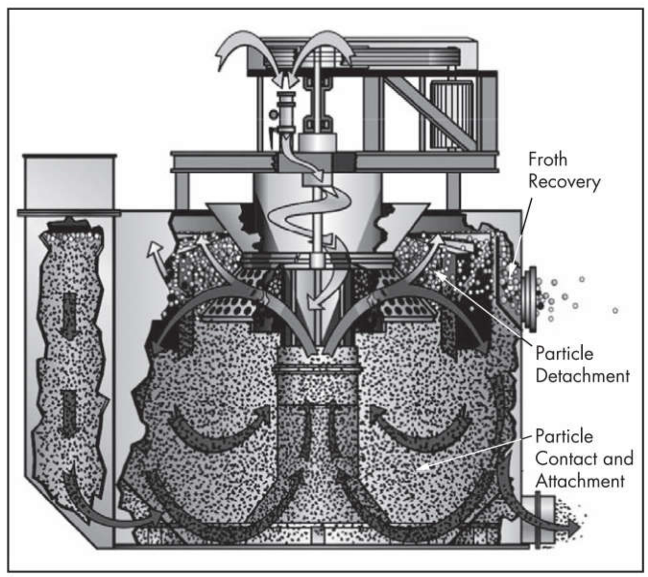

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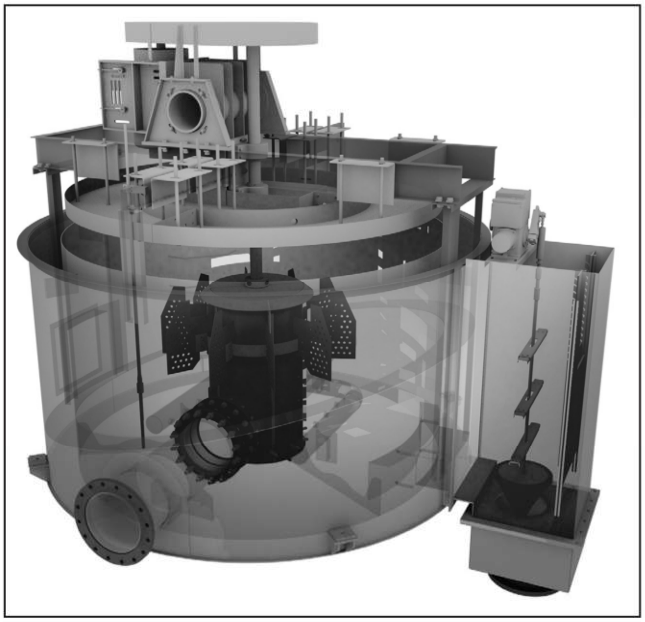
Figure 2 WEMCO® SmartCell® machine diagram, showing subprocessng areas

FLSmidth

FLSmidth supplies two types of flotation machines: WEMCO® and Dorr-Oliver®. The WEMCO® machine is self-aerating, while the Dorr-Oliver® machine is externally aerated. FLSmidth has delivered more than 53,000 flotation cells to operations worldwide.

The principles of operation for self-aerating and externally aerated machines are similar in concept, but the



Courtesy of Eriez
Figure 3 Eriez StackCell machine

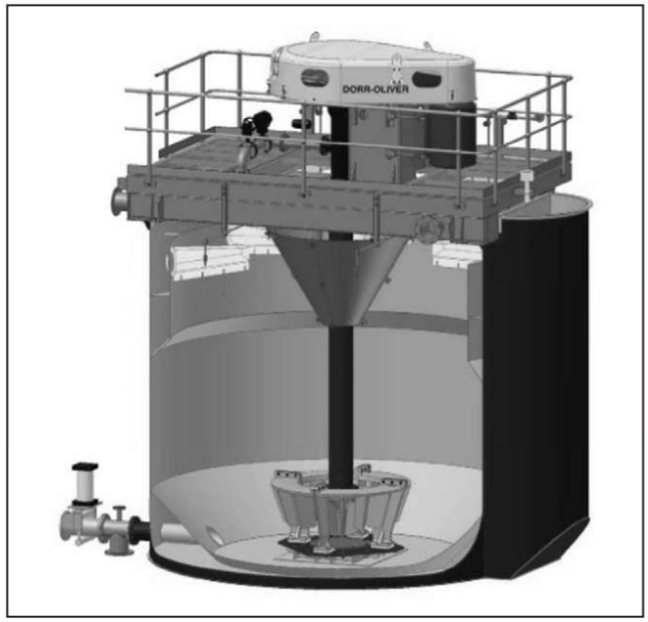


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Figure 4 FLSmidth Dorr-Oliver® machine

execution is different. The operating variables in the externally aerated machines are aeration rate, rotor speed, and froth depth. Aeration rate is controlled by adjusting valves in the air delivery line or by changing the blower speed. If this is varied independently of other variables, bubble size distribution in the cell will change. To a certain extent, aeration rate is independent of the site elevation and slurry density. However, the configuration of the blower and air delivery system may limit the ability to adjust the aeration rate. It is also important to realize that when the external aeration rate is changed, other parameters associated with aeration, such as superficial gas velocity, gas holdup, and bubble-surface-area flux, will also change.

Because WEMCO® machines are self-aerating, their flow is controlled differently than the flow in externally aerated machines, in which air is provided by blowers. The air intake for each WEMCO® machine can be fitted with manual or automatic control valves. Either of these may be used to decrease the airflow to the machine. The pumping of air and slurry by a WEMCO® machine is controlled by changing the position or speed of the rotor. In smaller machines, rotor position may be changed without removing the mechanism by raising or lowering the mechanism or changing the length of the draft tube. Rotor speed may be changed by changing belt position on a multi-sheave drive or through use of a variable-speed drive. Rotor position is described in terms of submergence and engagement. *Submergence* is the distance from the slurry surface to the top of the rotor blades; *engagement* is the depth to which the rotor engages the draft tube. Detailed description of these relationships can be found in Nelson and Lelinski (2000) and Nelson et al. (2002).

Figure 4 shows a typical Dorr-Oliver® machine. FLSmidth lists the advantages of these cells as follows: low power consumption, nonclogging, low-maintenance-design rotor, high air-dispersion capability, superior metallurgical performance, easier restarting mechanism, and low reagent costs.

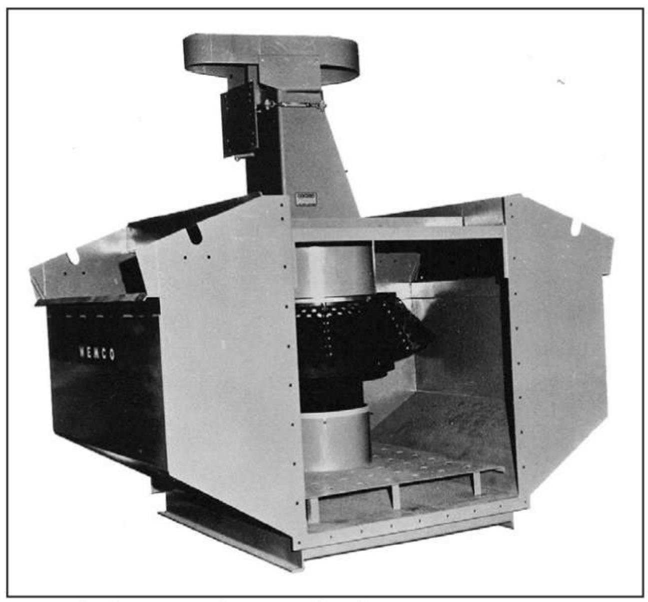

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Figure 5 FLSmidth WEMCO® 1+1® machine

The WEMCO® 1+1® machine is shown in Figure 5. FLSmidth literature states that the 1+1® provides the following advantages: higher recovery and grade with easier start-up, simpler operation, lower reagent consumption, longer mechanism life, and less required maintenance. The WEMCO® 1+1® cell uses a rotor-disperser design that delivers intense mixing and aeration. Ambient air is drawn into the cell and uniformly distributed throughout the pulp, providing optimum air-to-particle contact. In larger cells, a false bottom and draft tube channel slurry flow, ensuring high recirculation and eliminating sanding. The combination of efficient aeration and optimum solids suspension allow WEMCO® 1+1® cells to achieve high recovery and concentrate grade, with reduced reagent consumption.

The WEMCO® SmartCell® machine, shown in Figure 6, uses a redesigned 1+1® mechanism in a cylindrical tank. This cylindrical design improves mixing efficiency and air dispersion and also provides better surface stability, less pulp turbulence, lower capital costs, and reduced power consumption. It also features a hybrid draft tube and beveled tank bottom, which improve hydrodynamic mixing and coarse-particle recovery and increase solids suspension. Finally, the SmartCell® machine features radial launders and mixing baffles, which increase froth mobility, decrease froth residence time, increase recovery, and enhance froth stability.

FLSmidth has recently conducted extensive research into improving flotation efficiency in externally aerated machines by changing the design of the rotor and the stator. The rotor/stator (often called *the mechanism*) is responsible for solids suspension, gas dispersion, and bubble–particle attachment. Research on mechanism improvement started with laboratory testing of 200 different designs. The best designs were further tested in a 1.5-m^3 pilot cell using an industrial feed. This pilot work confirmed the results from the laboratory, and industrial prototypes were designed. The best three mechanism designs were then tested and compared at an industrial operation. After this extensive test work, the nextSTEP™ rotor and stator design was selected as FLSmidth's standard for flotation mechanisms. Figure 7 shows details of the nextSTEP mechanism.

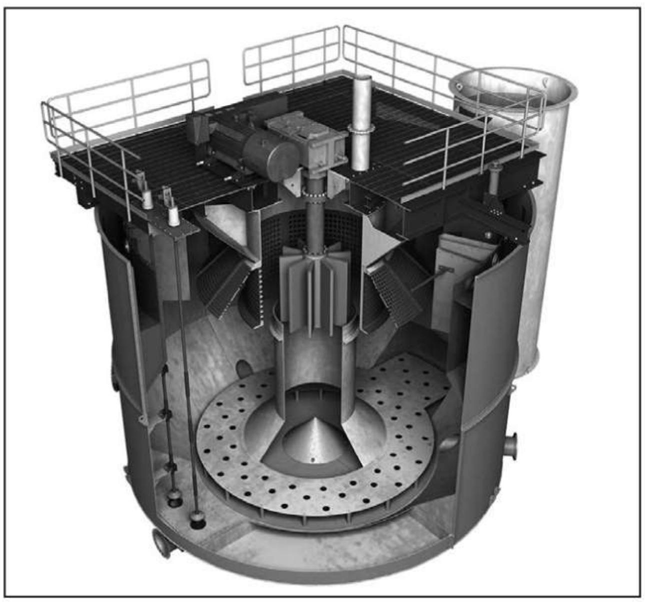

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Figure 6 WEMCO® SmartCell® machine

Hydrodynamic testing of the nextSTEP mechanism was conducted on slurry in a 660-m^3 SuperCell® machine. The influence of various operating variables on the absorbed specific power of the combined motor and blower was recorded, and statistical analysis was conducted to define the relationships among absorbed power, mechanism rotational speed (revolutions per minute), airflow, and solids suspension. These tests are described in detail by Lelinski et al. (2015). The key conclusions are as follows:

- The rpm–power relationship is very well defined and follows the generally accepted trend: the higher the rpm, the higher the absorbed power.
- The airflow–power relationship is different than that seen in smaller machines, where increased airflow *decreased* the absorbed power. In the 660-m^3 machine, this relationship was seen when just the motor power was considered, but when the blower power was included, the relationship was reversed in that increasing the airflow *increased* total absorbed power.
- With the nextSTEP mechanism installed, the specific power absorbed by the motor *decreased* to 0.2 kW/m^3.

Machines offered by FLSmidth are shown in Tables 1–3. Dorr-Oliver® machines are offered in three configurations: rectangular (R), rectangular with U-shaped bottom (UT), and cylindrical (RT).

Metso Group

Metso Group offers three types of externally aerated machines, the RCS™, the DR, and the RCS UC. The RCS UC is a flash flotation machine, and is discussed separately. The RCS machine is shown in Figure 8. The machine was designed to create the two classic zones within a flotation cell, an active lower zone for effective particle suspension and transportation and a relatively quiescent upper zone to minimize bubble–particle separation. A cylindrical tank was adopted to provide symmetrical hydraulic flow patterns with minimum upper-zone turbulence.

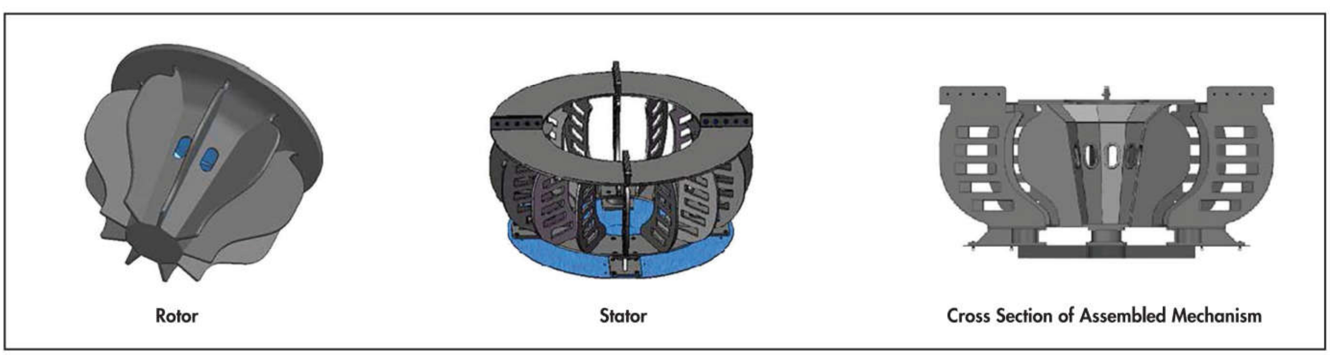

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Figure 7 FLSmidth nextSTEP mechanism

Table 1 Dorr-Oliver® machines

Cylindrical (RT) Tanks			Rectangular (R) and U-Bottom (UT) Tanks		
Model	Effective Cell Volume, m³	Motor, kW	Model	Effective Cell Volume, m³	Motor, kW
DO-1.5 RT (pilot)	1.5	7.5	DO-1 R	0.02	0.6
DO-5 RT	5	7.5	DO-10 R	0.24	1.1
DO-10 RT	10	14.9	DO-25 R	0.60	2.2
DO-20 RT	20	29.8	DO-50 R	1.2	3.7
DO-30 RT	30	37.3	DO-100 R	2.4	5.6
DO-40 RT	40	44.8	DO-300 UT	7.2	11.2
DO-50 RT	50	56	DO-600 UT	14.3	22.4
DO-70 RT	70	74.6	DO-1000 UT	23.8	29.8
DO-60 RT	60	74.6	DO-1350 UT	32.2	37.3
DO-100 RT	100	111.9	DO-1550 UT	36.9	44.8
DO-130 RT	130	149.2	DO-1550 UT	36.9	44.8
DO-160 RT	160	149.2			
DO-200 RT	200	186.5			
DO-330 RT	330	410			
DO-600 RT	600	500			
DO-660 RT	660	550			

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Table 2 WEMCO® 1+1® machines

Model	Effective Cell Volume, m³	Motor, kW
18	0.028	0.37
28	0.085	0.75
36	0.31	2.24
44	0.59	3.73
56	1.16	5.60
66	1.73	7.46
66D	2.83	11.2
84	4.25	11.2
120	8.50	18.7
144	14.16	22.4
164	28.32	44.8
190	42.48	74.6
225	84.96	149.2

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Features of the RCS machine include good particle–bubble contact, effective solids suspension during operation and resuspension after shutdown, effective air dispersion and distribution, flotation air provided by a separate air blower, manual or automatic control of aeration rate, V-belt drive standard up to 70-m^3 cell volume, and gearbox drive with extended output shaft bearings and drywell construction for cell volumes larger than 70 m^3.

The DR machine, shown in Figure 9, is based on the DR design developed by the former Denver Equipment Company. It features rectangular tanks, connected in the open, hog-trough configuration. It is especially suitable for small concentrators and for industrial minerals.

Table 3 WEMCO® SmartCell® machines

Model	Effective Cell Volume, m³	Motor, kW
1.5 (pilot)	1.5	7.5
5	5	30
10	10	37
20	20	50
30	30	75
40	40	90
50	90	90
60	60	150
70	70	150
100	100	150
130	130	185
160	160	185
200	200	250
250	250	315
300	300	373
350	350	373
600	600	800
660	660	875

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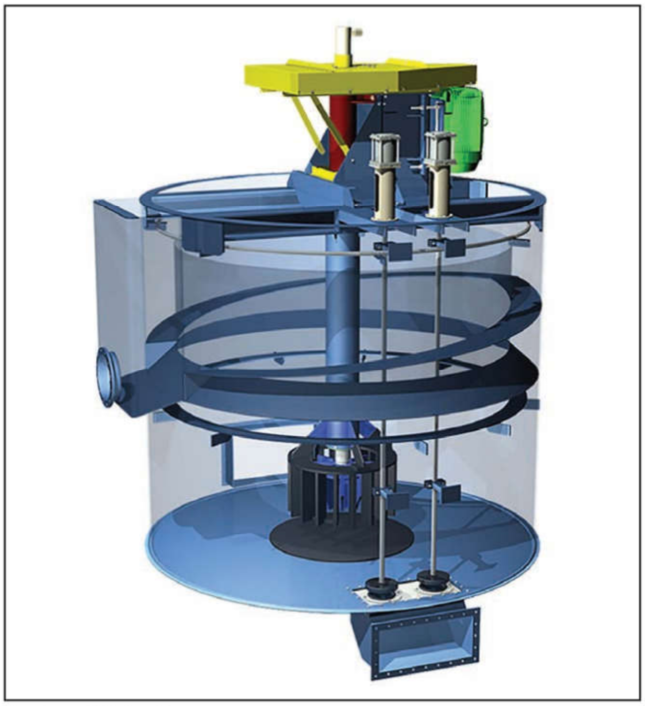
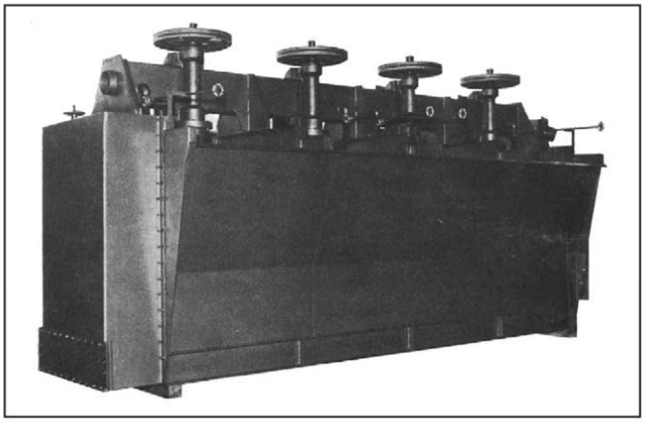


Courtesy of Metso Group
Figure 8 Metso RCS machine

Features of the DR machines include vertical circulation of pulp, achieved by combining a "recirculation well" with a reversible, top-feed impeller; external aeration; and minimized sanding, accomplished with the cell-to-cell design. Table 4 shows available models of the RCS and DR machines. Metso does not specify a motor size for each machine but selects the appropriate motor for each application.



Courtesy of Metso Group
Figure 9 Metso DR machines

Table 4 Current offerings of Metso RCS and DR machines

RCS Model	Effective Cell Volume, m^3	DR Model	Effective Cell Volume, m^3
RCS 0.8	0.8	DR 15	0.34
RCS 3	3	DR 18sp	0.71
RCS 5	5	DR 24	1.4
RCS 10	10	DR 100	2.8
RCS 15	15	DR 180	5.1
RCS 20	20	DR 300	8.5
RCS 30	30	DR 500	14.2
RCS 40	40		
RCS 50	50		
RCS 70	70		
RCS 100	100		
RCS 130	130		
RCS 160	160		
RCS 200	200		
RCS 300	300		
RCS 600	600–660		

Courtesy of Metso Group

Outotec

Outotec offers four types of machines, the OK-R, the OK-U, the TankCell®, and the SkimAir®. The SkimAir is a flash flotation machine and is discussed separately. All Outotec flotation cells are externally aerated. Outotec prioritizes maintaining maximum flexibility in terms of manipulating gas flow rate and number of bubbles. The first Outotec flotation cells were the U-shaped OK-16 and OK-38. The cylindrical cell, Outotec's TankCell, is now sold in sizes up to 630 m^3.

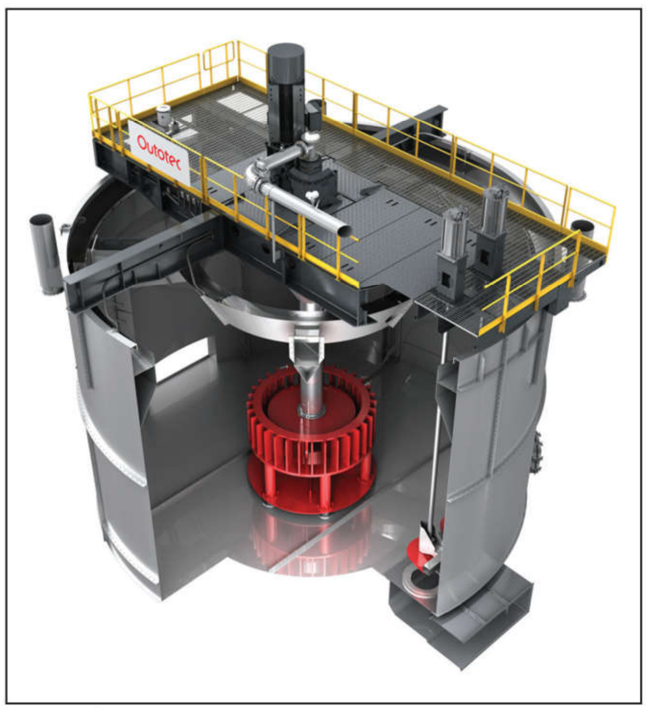
All Outotec cells are designed using hydrodynamic analysis and modeling with computational fluid dynamics (CFD). High-intensity microturbulence and macroscale laminar flow velocities must be correctly balanced to suit the particle sizes being floated.

The bottom part of the cell is considered the contact zone and is designed for suspending solids and placing air bubbles in contact with particles using turbulent conditions. Air is fed to the rotor through a hollow shaft. The flotation air is uniformly dispersed into the slurry through the slots of the rotor. Particles are collected by air bubbles forming aggregates in the contact zone, and particle–bubble aggregates rise by buoyancy toward the froth zone. The laminar flow field in the quiescent zone is dedicated for selectivity; it allows separation of valuable particles from unwanted particles. Particle–bubble aggregates form a froth phase, which acts as a cleaning zone, further rejecting unwanted solids and water, thereby upgrading the froth. The froth flows over the concentrate lip into the concentrate collection launder. Hydrophilic solid particles are carried out of the cell by the cell's flow fields through the valves at the bottom of the cell tank. Figure 10 shows a cutaway view of the Outotec TankCell machine.

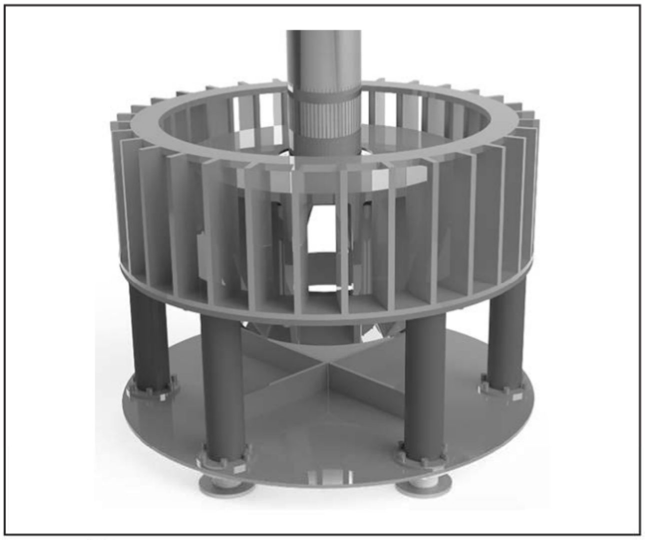
Cell Mechanisms

The mechanisms in all Outotec cells are mounted near the bottom of the cell. For many years, Outotec offered two mechanisms, the FreeFlow and the MultiMix. Each was designed to maintain solids suspension, disperse the bulk gas flow from the shaft into small bubbles, and provide the acceleration required for the particles to attach to the bubbles. These mechanisms are described in detail in Nelson et al. (2002). The MultiMix design was recommended for fine and middlings particles (<100 µm), while the FreeFlow design was recommended for coarser particles. These mechanisms may still be found in older Outotec machines.

Outotec introduced the FloatForce® mechanism in 2009. This mechanism was designed using CFD simulation, with the intent of reaching an optimal combination of aeration and mixing, the two functions of a flotation mechanism. In the FloatForce mechanism, shown in Figure 11, the lower portion of the rotor functions primarily for slurry pumping, and air is introduced through the six air ports in the upper portion of the rotor that are connected through channels to the shaft. The air from these ports is discharged into six dispersion slots on the



Courtesy of Outotec
Figure 10 Outotec TankCell with FloatForce® mechanism



Courtesy of Outotec

Figure 11 Outotec FloatForce mechanism

periphery of the rotor so that air is dispersed closer to the stator. This minimizes the influence of the introduction of air on the pumping function of the rotor so that the mixing capacity remains high even when a high air feed rate is used.

The FloatForce mechanism was designed to provide improved metallurgical performance. It also provides decreased wear. Stator blades up to a certain size are individually bolted and light enough for one person to handle without a lifting device, which simplifies change-out. For larger sizes, blade sets are provided for one-quarter of the stator. This makes replacement of damaged blades quicker and less expensive than for conventional mechanisms, in which all stators were changed one-half at a time. Size, shape, and lining thickness of the stator blades have been optimized to provide maximum wear life.

The FloatForce mechanism can be retrofitted to existing Outotec flotation cells. It is available in the same sizes, configurations, and connecting dimensions as all previous mechanisms. For new projects, the FloatForce mechanism does not use different stator designs or bottom clearances, as was the case for the previous mechanisms. Instead, the adaptation for particle size is done by selecting the size and speed of the mechanism. For finer particles and easier duties, a mechanism one size smaller than normally used at higher speed is selected. For coarse particles, a larger mechanism at lower speed will provide sufficient mixing but minimize the high turbulence that breaks the connection between a large particle and a bubble.

Current Machines Offered

Table 5 shows rectangular (OK-R) and U-shaped (OK-U) machines; Table 6 shows cylindrical machines. The motor sizes shown are typical and may change as application conditions require.

Woodgrove Technologies

Woodgrove Technologies offers the staged flotation reactor (SFR) as an alternative to the large tank cells offered by other suppliers (Figure 12). Woodgrove notes that the trend in increasing tank cell sizes can result in "longer residence

Table 5 Outotec OK-R (rectangular) and OK-U (U-shaped) cells

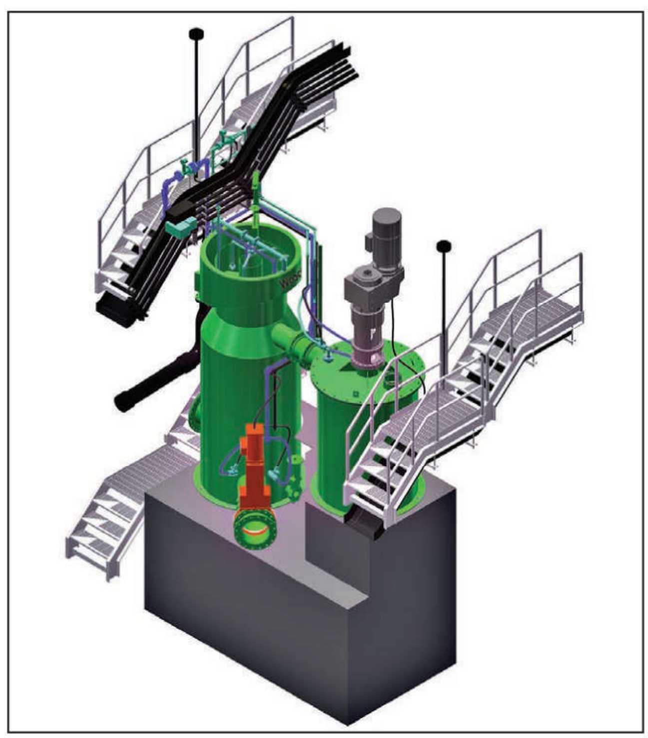
Model	Effective Cell Volume, m³	Installed Power, kW
OK-0.5-2R	0.5	7.5, dual drive
OK-1.5-2R	1.5	15, dual drive
OK-3-2R	4.3	11, single drive; 22, dual drive
OK-8-U	8	22, single drive
OK-16-U	18	30, single drive
OK-28-U	28	45, single drive
OK-38-U	38	55, single drive

Courtesy of Outotec

Table 6 Outotec TankCells

Model	Effective Cell Volume, m³	Motor, kW
TankCell e5	5	11
TankCell e10	10	30
TankCell e20	20	30
TankCell e30	30	45
TankCell e50	50	110
TankCell e70	70	110
TankCell e100	100	110
TankCell e130	130	150
TankCell e160	160	175
TankCell e200	200	225
TankCell e300	300	315
TankCell e500	500	400
TankCell e630	630	500

Courtesy of Outotec



Courtesy of Woodgrove Technologies Inc.

Figure 12 SFR machine installation

times, massive infrastructure, and challenges in controlling froth drop-back" (Woodgrove Technologies 2015).

The SFR incorporates features of both conventional mechanical cells and flotation columns. Like the Eriez StackCell machine, it provides separate chambers for different subprocesses. The SFR, however, employs three chambers where the Eriez cell has only two. The three SFR chambers enable independent optimization of the subprocesses that make up the complete flotation process: bubble–particle contact, particle attachment, particle detachment, and froth recovery as shown in Figure 13.

Another notable difference from the Eriez cell is the location of the agitator. In the StackCell machine, the agitation chamber is *inside* the froth separation chamber, whereas the chambers of the SFR are side by side.

Froth drop-back is minimal and tightly controlled. The constrained froth recovery zone results in better recovery and upgrading. Benefits of the SFR compared with conventional mechanical cells are said to include the following:

- No power is used for solids suspension, so when combined with fewer stages, the SFR reduces circuit power consumption by 40%–50%.
- Required floor space is reduced to 40%–50% of that used by conventional mechanical cells, with corresponding savings in installation costs.
- Air consumption is significantly lower, typically 10%–20% of the air consumption of conventional tank cells.
- Fewer stages are needed to achieve equivalent concentrate grade.
- Underfroth water wash is introduced below the froth zone. This is effective in minimizing gangue dilution of the concentrate product by entrainment without limiting froth mobility.
- Operating with low air rate greatly enhances flotation selectivity. For example, this is very effective in the rejection of pyrite in copper circuits.
- Froth washing on roughers is an option in high-clay applications.
- High solids flux and low air consumption create high solids concentration in the froth as well as lowering downstream pump, piping, and even regrind sizes.
- High solids concentration in the froth creates a stable froth zone, minimizing froth drop-back and, in some cases, improving coarse-particle recovery.
- An isolated collection zone, in a separate vessel, allows addition of power for fine-particle collection without significantly affecting the overall footprint.
- Circuit control is improved.
- Wear and maintenance costs are reduced because of lower impeller tip speeds.

Five parameters are used in the design and sizing of SFRs: three hydrodynamic parameters, one slurry flux parameter, and one solids flux parameter. There are no standard sizes; rather, SFRs are custom designed to best match the variation of metal units over the life of the mine in each operation. It is this custom design for each application that allows the SFR to provide the stated benefits. To date, Woodgrove has carried out fabrication drawings for flow rates ranging from 20 to 2,850 m^3/h and has SFR designs to handle up to 4,600 m^3/h.

Courtesy of Woodgrove Technologies, Inc.

Figure 13 SFR machine, with agitation chamber on the left and separation chamber on the right

Flash Flotation Machines

The flotation of coarse, high-grade particles was investigated at North Broken Hill mine in 1932 (Garrett 1933) but not incorporated in routine operation (Lynch et al. 2010). The Denver Equipment Company introduced "unit cells" in the early 1940s (F. Seeton, personal communication), with the intent that "the mineral should be recovered as soon as it is liberated." A single, mechanical machine was often used in a ball mill–classifier circuit to recover the liberated, coarse mineral before further processing (Denver Equipment Company 1953). The concept reappeared many years later in a modified form, and was called *flash flotation* (Lynch et al. 2010). Flash flotation is designed to produce a high-grade concentrate by recovering liberated coarse particles from the circulating load of the grinding process. Flash flotation machines, shown in Figure 14, are offered by Metso and Outotec.

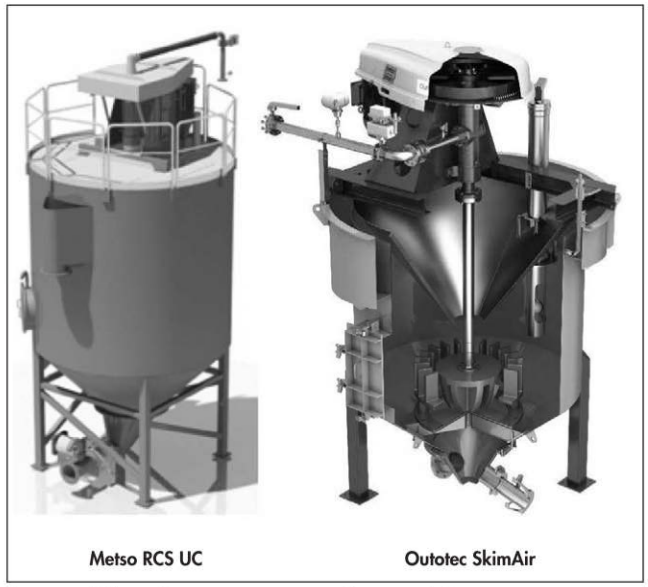
The Outotec SkimAir machine uses the MultiMix mechanism, which is designed to suspend coarse particles. It is designed with a deep froth crowder to accelerate froth removal and two outlets to provide options for separating middlings and tailings. The SkimAir is offered in six models, the SK-80, SK-240, SK-500, SK-1200, SK-1800, and SK-2400, where in each case the model number indicates the treatment capacity of the cell in tons per hour. The Metso RCS UC machine uses an RCS mechanism and integrates specific designs to handle coarse particles.

OPERATIONAL FUNCTIONS OF FLOTATION MACHINES

As discussed earlier, flotation machines are structurally classified by the design of their mechanisms. In operation, machines are classified by their functions. The simplest scheme classifies machines as roughers, cleaners, and scavengers. In some applications, additional categories are used, such as rougher-scavenger and cleaner-scavenger, unit cell, or flash flotation cell. In most cases, cells that have a given function are installed in groups or *banks*. The definitions and descriptions given here are those commonly used in the United States. In other locations, the nomenclature is different. For example, Chilean operators never use the terms *rougher-scavengers* or *cleaner-scavengers*. In Chile, the term *scavenger* is used only for cleaner-scavengers, while rougher-scavengers are understood to be the last few cells at the end of a row of roughers.

Roughers

Roughers are typically the first bank of cells in a flotation plant. They are designed and operated to achieve high recovery with acceptable selectivity, and to recover both coarse and fine particles of the valuable constituent. In complex ores, especially in a plant that produces more than one product, the roughers may be operated to achieve higher selectivity. Rougher operation is characterized by medium- to high-energy density, a medium to thick froth layer, and rapid froth pull. Rougher concentrate reports to the cleaner section; rougher tailings report either to the rougher-scavengers or to the final tailings.



Courtesy of Metso Group Courtesy of Outotec
Figure 14 Flash flotation machines

Rougher-Scavengers

Rougher-scavengers are operated to attain high recovery of values from the rougher tailings. Depending on the mineralogy and the rougher operation, these values may be coarse, fine, or locked particles, or combinations of the three. Concentrate from rougher-scavengers reports either to a regrind circuit (for liberation of the value from locked particles) or to the cleaners. Scavengers operate with a shallower froth layer, and aeration may be changed to obtain the desired recoveries.

Rougher-scavengers may be a separate row or bank of cells, or many cells at the end of a row of roughers that are operated as scavengers. In the overall rougher section of a plant, the allocation of individual cells between the rougher and the rougher-scavenger function may be changed to accommodate changes in the feed.

Cleaners

Cleaners are operated to improve the concentrate grade to meet downstream specifications for content of product values and avoid penalties for unwanted constituents. They are much smaller than roughers and rougher-scavengers, because they are treating the combined products of the roughers and the regrind circuit from which most of the tailings have been eliminated. Cleaners are characterized by a thicker froth, which usually provides a higher-grade concentrate.

Cleaners also operate at a lower pulp density, with a finer particle-size distribution than that found in roughers and rougher-scavengers. Thus less energy is usually required from the cell mechanisms, which are operated at lower rotational speeds and, in self-aerating cells, with less submergence of the impeller in the draft tube. However, some applications, such as the flotation minerals bearing platinum group metals, require high energy input to cleaner cells to recover extremely fine, dense particles. In many applications, cleaning is accomplished in several stages. Final cleaners may be columns.

Cleaner-Scavengers

Cleaner-scavengers are similar to rougher-scavengers in that they are operated to attain high recovery values from cleaner tailings. They are different in that those values are almost always fine particles. Operation of cleaner-scavengers is similar to that of cleaners, with less intense agitation and sometimes a thicker froth layer.

Reverse Flotation

Reverse flotation refers to a process in which the gangue is floated away from the valuable constituent. It is most common in the concentration of iron ores, where silica is floated away from iron oxides (Lynch et al. 2010), and it is also used in coal processing where, in some cases, pyrite and ash are floated away from coal. In some reverse flotation processes, the concentrate volume will be larger than that of the tailings. Appropriate care should be exercised in the design of concentrate handling equipment—launders, pumps, and so forth.

Split-Feed Flotation

In some applications—notably the flotation of phosphate ores—feed to the flotation plant may be split into coarse and fine flowstreams, each of which is treated differently in the flotation process.

PROCESS DESIGN

The selection of flotation machines for a given application requires specification of the number and sizes of machines for each part of the flotation circuit. The residence time required to achieve the desired grade and recovery in the concentrate is determined in laboratory tests, and appropriate scale-up factors are applied to find the number and size of machines. In addition, the machine design must account for the physical requirements of froth removal to achieve adequate concentrate recovery. Cell sizes, numbers, and circuit configurations are determined by laboratory tests and the application of scale-up factors based on experience. The design of froth removal and froth handling systems cannot be based on laboratory tests because, in those tests, the froth is removed manually by scraping and thus does not exhibit the same behavior it will in operation. Furthermore, there is no reliable method known for the scale-up of froth transport distance.

Residence Time

The following discussion is summarized from Nelson et al. (2002). Residence time is the time that a unit volume of slurry takes to travel through a process or machine. If there is no short-circuiting or "dead volume" in the process, then residence time in minutes (min) is simply process volume in cubic meters (m^3) divided by the flow rate to the process in cubic meters per minute (m^3/min).

The required residence time for a given application is determined from laboratory or pilot-plant testing. The laboratory data are then used to calculate the parameters for a kinetic model, such as the one proposed by Klimpel (1980), where recovery, R, is given by

$$R = R_0 [1 - (1 - e^{-kT})/kT] \quad \textbf{(EQ 1)}$$

where

R_0 = recovery at time zero
k = flotation rate constant
T = time

When the required residence time is known, the flotation capacity is determined by a simple calculation (Poling 1980) and is summarized here:

$$C = Q_{\text{pulp}} \cdot R \quad \textbf{(EQ 2)}$$

where

C = total required flotation capacity, m^3
Q_{pulp} = volumetric flow rate of pulp, m^3/min
R = required residence time, min

In this calculation, the solids feed rate to the mill, the solids specific gravity, and the pulp density are used to calculate the volumetric flow rate of the pulp.

When the required total tank volume is determined, the number of machines of a given size is found from the following equation:

$$\tau = V_{\text{eff}}/Q_{\text{pulp}} \quad \textbf{(EQ 3)}$$

where

τ = theoretical residence time, min
V_{eff} = effective cell volume, m^3

The effective tank volume must subtract the volumes of the froth layer and the internal tank components. It must also account for the air holdup, which is the amount of air suspended in the pulp during machine operation.

In the past, when rectangular cells were used with no partition between several adjacent units (hog-trough configuration), there was extensive discussion of connection patterns for those cells. It was typical to connect two to four cells in "open" configuration, and connect one group to the next through a step-down junction box, with level control. There was much discussion of the best way to configure rows of flotation cells, to achieve the best mixing and minimize short-circuiting.

With the advent of large, cylindrical machines, the grouping of cells has become less common. Large machines are now often connected to one another individually, through connection boxes and level control valves. Extensive residence-time-distribution studies have shown this configuration poses no problems regarding retention time or short-circuiting, but it does limit the operator's options in dividing the froth for selective retreatment. Further, the minimum number of cells required in a row or section will typically be fewer than with smaller cells. For closed circuits (typically used in cleaning stages), where the tails are circulated back to other stages, only one cell per row may be needed, because the tailings may be further treated as required.

Froth Recovery

Froth removal is critical to the satisfactory function of any flotation circuit. Recent theoretical analyses have considered kinetics for *two* processes in flotation: (1) particle–bubble attachment and transport to the froth interface, and (2) froth recovery. Froth recovery is the fraction of particles reaching the froth interface that finally reports to the froth launder. In some cases, this has been reported to be as low as 10%.

The froth that develops at the top of a flotation cell must be removed to the next stage in the process. Because froth is continually being formed in the cell, the froth at the top will naturally overflow at the top. Froth recovery is characterized by the froth carry rate, measured in dry metric tons of concentrate per square meter of froth surface area per hour (t/m^2/h), and froth lip loading in dry metric tons of concentrate per meter of froth lip per hour (t/m/h). The two parameters are clearly related. If the lip length is too small, the thickness of the froth layer will increase until the froth layer begins to collapse. In addition, froth carry rate and froth lip loading are also related to the *pulling* rate at which the cell is being operated. The pulling rate affects the recovery and grade of the concentrate, which will be discussed further.

As mentioned earlier, designs of froth removal and froth handling systems cannot be determined by laboratory testing. Froth removal systems are usually sized by experienced personnel, who make calculations for each application and compare the results with their previous experience. Outotec recommends the following froth carry rates, all in (t/m^2/h): for roughers, 0.8–1.5, for scavengers, 0.3–0.8, and for cleaners, 1.0–2.0 (Heath 2013). Note that the *froth carry rate* must not be confused with the *froth factor*, which is discussed in detail later in the "Launders and Froth Removal" section.

SIZING AND DESIGN OF MACHINES AND CIRCUITS

A carefully planned laboratory test program is essential for the sizing of mechanical flotation cells and for proper circuit design in both rougher and cleaner applications. In addition, a good testing program requires properly selected samples. The importance of obtaining representative samples, along with careful preparation and preservation, cannot be overstated. The most careful and comprehensive test programs are worthless if the samples used are not representative. A successful sampling program requires detailed discussions with and cooperation from geology and mining groups. This is particularly important if the mineralogy of the ore body is highly varied. Diamond drill-core samples are preferred, but care must be taken to ensure that drilling or cutting fluids do not contaminate the core.

A laboratory testing program for flotation usually begins with a series of tests on several ore-type composites to evaluate appropriate reagent schemes and delineate optimum rougher flotation conditions such as primary grind size, flotation pulp density, flotation pulp pH, and retention time.

Once these parameters are established, a comprehensive ore variability program is undertaken to determine the response of various ore types to the optimum conditions established.

These ore variability programs often test hundreds of samples to ensure that the ore body is well understood.

Cleaner parameters, such as regrind size requirements, cleaner pH, pulp density, and number of stages, are defined. Semicontinuous locked-cycle tests are performed using the parameters established in the batch tests to determine the effect of the recirculation of middlings streams on flotation performance. The data generated and the experience gained in locked-cycle tests may be used to design and operate a continuous pilot plant if relatively large amounts of concentrate are required for further process development, such as optimization of by-product molybdenum production from bulk Cu-Mo concentrate.

The interpretation of data from the flotation test programs indicates the size of the rougher flotation circuit based on the single most important variable for sizing: retention time. Interpretation of laboratory test data is also the basis for cleaner circuit design and sizing. See Chapters 7.7 and 7.8, "Sulfide Flotation Testing" and "Non-Sulfide Flotation Testing," respectively, for detailed procedures.

SPECIFICATION OF NEW MACHINES

Drive

Large flotation machines use AC motors. The motors for machines larger than 250 m^3 may require medium-voltage power, which changes power-supply requirements and motor control configurations for the entire mill. The relative costs and advantages of medium-voltage power must be carefully considered for each site. Variable-frequency drives (VFDs) are often used for development and testing, but their high installed cost may preclude use in operations.

For machines with volumes up to 200 m^3, multiple V-belt connections are more reliable and easier to maintain. For larger sizes, gearbox drives are used by some suppliers. However, for externally aerated machines, additional cooling of the drive may be required to compensate for the heat added by the air being blown through the shaft. When belt drives are used for machines larger than 200 m^3, a redesign of the drive is required to transmit the large amount of torque required by the mechanism.

Power Density

Power density, usually measured in kW/m^3, characterizes the intensity of mixing or agitation in a flotation cell. Again, the important consideration is *absorbed* power density, as contrasted with *installed* power density. Installed power is based on the nameplate ratings of the drive motors, which in every case are oversized to account for atypical or upset conditions. Absorbed power uses the measurement of *actual kilowatts* (not just amperage and power factor) during routine operation and is thus determined by measuring voltage, current, and power factor, so the complex power relationships can be calculated. It is preferable to make these measurements for all three phases of a three-phase power system, because three-phase circuits may be unbalanced, especially after motors have operated for a long time.

In all cases, power density decreases as cell volume increases. In externally aerated cells, the tank diameter, and to some extent the tank's horizontal cross-sectional area, determine the required mixing intensity. Power is not consumed in moving pulp vertically because the buoyant gas bubbles carry the floatable material to the top of the cell. Sanding can be a problem in large cells when scale-up is not done properly and the power density is too low.

Experience has shown that higher density ores respond better to flotation in cells with higher power density. For example, in platinum flotation, 3 kW/m^3 is a standard value, while in copper flotation, the values range from 0.7 to 1.2 kW/m^3. This factor must be carefully analyzed for each application; the optimum power density is often not intuitively obvious. For example, in platinum cleaners, power density is greater than in platinum roughers; in copper cleaners, power density is lower than in copper roughers.

Mechanism

Mechanism designs vary widely among manufacturers. In all cases, it is important that the lower portion of the mechanism (shaft and rotor) be statically and dynamically balanced, *after* the installation of liners and *before* use. Careful balancing is especially important in the case of large cells, where small imbalances in the mechanism can cause large vibrations in the supporting structure. Vibration measurements should be made on each mechanism immediately after installation, and operating vibration should be checked against the baseline on at least a quarterly basis so that corrections can be made as needed.

Mechanical loading forces in the mechanism are easily calculated using first-order theoretical mechanics. Unfortunately, vibration characteristics are much more difficult to predict, and a systems approach is required. In mechanical flotation cells, besides mechanical properties (dimensions, masses, forces, etc.), the rheology of the slurry, the effects of air dispersion, generic and local flow patterns, and wear must be taken into account.

There are no standards for specifying allowable vibration levels in mechanical flotation cells. The closest applicable ISO standard is for rotating machines with excitation frequencies between 2 and 2,500 Hz, or 120–15,000 rpm (ISO 10816-3), but most large flotation cells operate below 2 Hz. Nonetheless, Outotec has found the guidelines for response to vibration given in ISO 10816-3, shown in Table 7, to be useful for flotation machines.

Table 7 ISO 10816-3 guidelines for response to vibrations

Vibration Level	0.0–1.4 mm/s	1.4–2.8 mm/s	2.8–4.5 mm/s	>4.5 mm/s
Condition and suggested response	Newly commissioned machine	Okay for normal, continuous operation	Maintenance needed on next shutdown	Maintenance required immediately

Dart Valves

Dart valves are the standard device for controlling flow between cells, and thus for regulating the pulp level in a cell. Dart valves typically use a conical closing mechanism, or plug, that fits against a circular seat. As the conical mechanism is moved by the valve rod, the opening gets larger, and flow through the valve increases. This characteristic is not necessarily linear and should be analyzed in combination with the characteristics of the controller to ensure that flow control can be maintained in the desired region. Plugs with a specially designed taper provide a more nearly linear response characteristic. On large cells, two valves are often used—one with high gain for large changes, and one with lower gain for fine control. A detailed description of dart valve design and operation may be found in Nelson et al. (2009).

Flotation cells cannot operate without correctly functioning dart valves. Dart valves must be carefully installed and correctly adjusted, calibrated, and tuned for level control after installation. Furthermore, dart valve systems must be diligently maintained. The valve rods and rod guides should be inspected and lubricated regularly. If the valves are pneumatically actuated, the air supply lines must be blown down regularly.

Tankage

The tankage associated with a machine includes feed boxes, the cell itself, connection boxes, and discharge boxes. Feed boxes provide a constant head for feed to a machine or row of machines. A feed box is usually designed to admit feed at the top and pass it out to the flotation process at the bottom through an open connection. The box should be designed to accommodate process upsets and should fit as closely as possible to the machine, minimizing required floor space. Each feed box typically has a sloping bottom to enhance flow into the flotation cell. The size of the opening that connects the feed box to the cell is based on the minimum linear velocity required to maintain slurry suspension. Of course, high velocities can cause high wear, so connections should be lined with wear-resistant materials. In concentrators with semiautogenous grinding (SAG) mills in the grinding circuit, large fluctuations in grinding output are common. In such installations, large feed boxes can provide valuable surge capacity in the flotation circuits.

Flotation cells come in two basic shapes, rectangular and cylindrical. Rectangular cells are usually of the hog-trough design to provide longer retention time and often have a U-shaped or horseshoe bottom to conform to hydrodynamic flow patterns and to minimize wear and sanding. The largest installed rectangular machine is the 85-m^3 WEMCO® 1+1®. Rectangular cells are still supplied for some portions of flotation circuits in smaller-volume plants. Cylindrical machines are symmetrical and thus provide better hydrodynamics. They eliminate stagnant areas found in the corners of rectangular cells and the turbulence resulting from corner effects. Plant layout using cylindrical cells requires careful consideration to minimize required floor space. However, some advantages can be achieved by configuring the layout so that connections can be modified using bypasses, allowing one cell to be taken out of service for maintenance without shutting down an entire section.

Connection and discharge boxes are practically the same. Both use dart valves to control the flow through the box. Connection boxes installed between adjacent cells have a lower hydrostatic head, usually just enough to maintain flow through the bank of cells and accommodate changes in throughput. Discharge boxes have a higher hydrostatic head to provide the required flow to the tailings circuit. The inlet to a feed box should be designed and positioned to avoid excess frothing and bubbling in the box, and every feedbox should be provided with an overflow to the froth launder system. Both boxes should be designed using the minimum linear velocity required to maintain slurry suspension. Again, high velocities can cause high wear, so connections should be lined with wear-resistant materials.

There are four designs for connection and discharge boxes used with cylindrical tanks. The first, most conventional design is based on the design still used with rectangular cells. These are rectangular boxes attached to the outside of the associated cell or cells. The second design, which saves floor space and provides easier access, is a small, cylindrical box that is again attached to the outside. The third design places the dart valves inside the cell. In this design, the discharge box is below the floor level and smaller. The advantages of this design are reduced floor space, lower equipment cost, easier access to the valve and seat wear parts, and no accumulation of air and froth in a separate box. In the three cases just described, the dart valve moves vertically. In the fourth design, the dart valve is inside the tank, but the tanks are connected directly on their adjoining walls. The valve plug is connected to the valve stem by a linkage that allows the valve stem's vertical motion to swing the valve plug in and out of an opening connecting the tanks. This fourth design saves both vertical and floor space but requires a more complex dart valve mechanism. It is available only from FLSmidth.

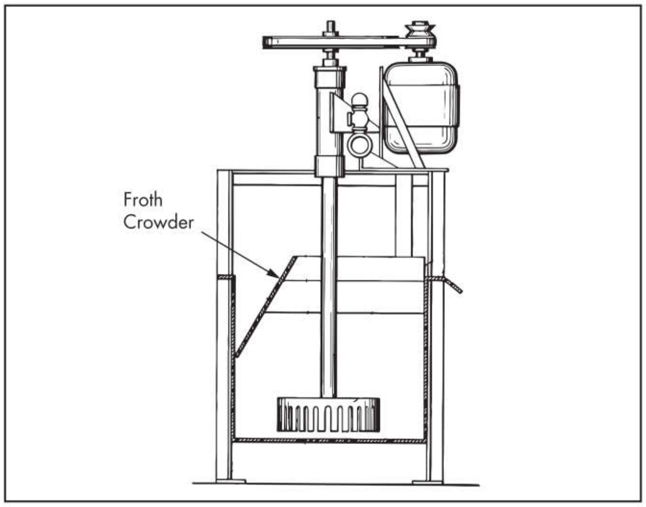
Launders and Froth Removal

Froth removal is critical to satisfactory function of any flotation circuit. *Froth recovery* is defined as the fraction of particles reaching the froth interface that finally report to the froth launder. As previously mentioned, this has been reported to be as low as 10%. In early flotation machines, froth transport occurred as a result of the natural mass flow through the cell. As cells became larger, and as new applications led to more voluminous froths, rotating paddles of various designs were used to accelerate removal of froth from the machine. Figure 15 shows froth flowing over the lip of a rectangular cell, aided by a froth paddle.

To further enhance froth recovery in a rectangular cell, a device called a *froth crowder* could be added to the far side of the cell, opposite the launder. As shown in Figure 16, the first froth crowders were plates welded to the back of the cell and inclined toward the mechanism, crowding the froth to the overflow lip on the opposite side of the cell. The presence of a crowder accelerated the flow of the froth as it rose to the surface of the cell, and decreased the distance on the surface

Courtesy of Dariusz Lelinski

Figure 15 Froth overflow in a cell with a froth paddle



Source: Sayers 1956
Figure 16 Froth crowder in a rectangular cell

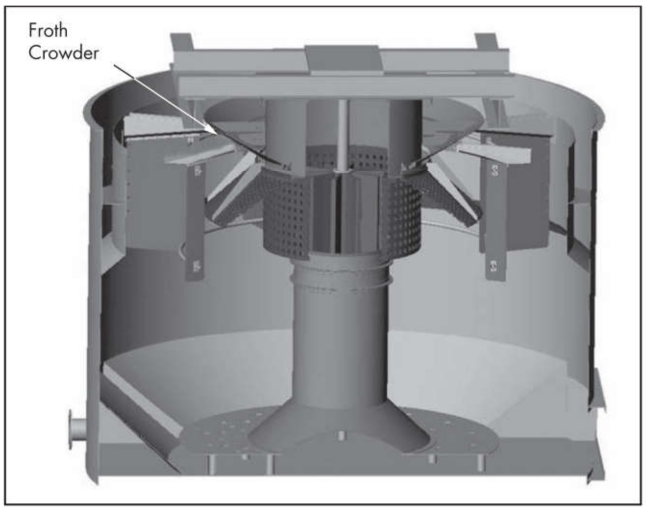


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Figure 17 Froth crowder in a WEMCO® SmartCell® machine

over which the froth had to travel to reach the launder. A modified crowder design, in which an inverted, truncated cone is installed around the mechanism, was developed in the 1990s (Degner 1997). Figure 17 shows a cylindrical cell with a froth crowder installed.

In large, cylindrical machines, froth recovery is more difficult for three reasons. First, the distance to a froth launder on the perimeter of the machine is larger. Second, in large cylindrical cells, the ratio of the surface area at the top of the cell, through which the froth flows, may not increase proportionally with increased volume, unless the aspect ratio of the cylinder is kept constant. Third, the circumference of the cell, over which the froth must flow for recovery, increases as the square root of the volume increases. This circumference is equivalent to the lip length in a rectangular cell. Flotation residence time is naturally related to volume, and gas flow rate through froth removal is related to surface area. Thus as cells become larger, concentrate flow rate does not increase proportionally to cell volume. Nonetheless, as lower-grade ore bodies are mined, more tonnage has to be treated to yield the same

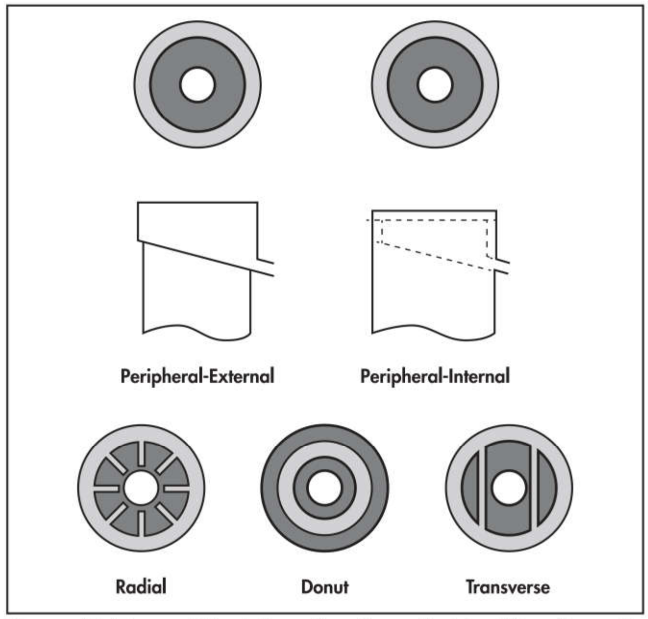

Figure 18 Types of froth launders for cylindrical flotation cells

amount of concentrate, and larger cells are better suited to this task. These constraints have led to the use of froth crowders on virtually all cylindrical machines.

The large quantity of froth produced in a big, cylindrical machine often requires additional launder capacity. Figure 18 shows five general types of launder design for cylindrical machines. In the figure, the dark shading indicates areas where froth is forming, the light shading indicates launders into which the froth moves, and the unshaded area indicates the froth crowder. Also, for the peripheral-internal launders, the lower drawing shows how the launder is mounted in the tank. Peripheral and radial launders are the most frequently used.

There are additional combinations of these five basic designs. All launders are sloped to direct the flow of concentrate to one or two discharge points. Peripheral-external and peripheral-internal launders are usually referred to as *external* and *internal* launders. They are simply attached to the outside or inside of the tank, respectively. Radial launders are always used in combination with a peripheral launder. Donut launders are often used alone but may also be installed in combination with an external or internal launder. The latter two systems are sometimes referred to, respectively, as a *double external launder* or a *double internal launder*.

The internal launder design is easy to install, requiring no additional structural support. The froth crowder directs the froth to the launder. Internal launders are widely used, but they reduce the effective volume of the flotation cell, which decreases residence time.

External launders are similar to internal launders in ease of design and installation; they are also widely used. They provide more lip length than peripheral-internal launders. Unlike internal launders, they do not decrease the effective cell volume but do require that cells be more widely spaced, thus increasing the overall footprint of the installed flotation equipment, and possibly requiring a larger building. External launders are often used on smaller cells with volumes less than 100 m^3, but may also be used on larger cells, where increased lip length and froth area are required. External launders should be designed to provide sufficient lip length for required froth flow, based on cell mass balance and froth surface area. Typical slope for froth launders is 12°–15° below horizontal, with steeper slopes used for sticky froths.

Radial launders are used where a larger lip length is required—for example, in the recovery of high-mass concentrates in iron ore processing. Like donut launders, they are more difficult to install and require additional internal supports. Figure 19 shows a 660-m^3 FLSmidth SuperCell® machine with radial launders installed. To provide adequate flow at a uniform rate, internal launders are often devised using previous external launder design. The use of internal-radial launders offers one distinct advantage in that launder capacity can be modified (usually increased) with relative ease by changing the number of radial launders.

Donut and transverse launders can also increase lip length, especially when used in combination with external or internal launders. Installation of both requires additional internal supports. Furthermore, both donut and transverse launders divide the upper portion of the froth layer into segments that tend to pull unevenly. This can lead to uneven loading of the launders.

Internal launders should be designed for relatively easy modification, for two reasons: first, to accommodate changes in froth extraction rates; second, to allow repairs after cell inspections and modification, when internal launders are often damaged. In addition, launder design should take into account the fact that that workers may stand on internal launders when conducting inspections and repairs.

The entire froth handling system must have adequate capacity to handle the highest anticipated volume of froth produced. This includes launders, piping, and pumps used to transport froth product to holding tanks or thickeners. The design of a froth handling system involves the use of the "froth factor," which is a semi-empirical quantity based on experience. It is essentially a multiplier for the volume of all equipment and parts that handle froth, as listed earlier. Froth handling equipment and parts are sized by volume. The volume of the solids in the concentrate is calculated based on the dry mass of the solids, the solids concentration, and the solids specific gravity. This volume is then multiplied by the froth factor to estimate the volume of the froth. For example, if the froth factor is estimated at a value of 3, and the calculated volumetric flow rate for the concentrate discharge pipe is 10 m^3/min, the pipe should be designed for a flow rate of 30 m^3/min. A froth factor of 3 is conservative and will almost always ensure that the sizing of the froth handling equipment (piping, valves, pumps, etc.) is adequate. Lower froth factors are sometimes used to save costs in the froth handling system, but this is not recommended.

Circuit design should include an estimation of the froth volume produced from each cell in a given time. Although only the dry mass concentrate flow for each section is typically provided for each section of the circuit, the dry volumetric flow rate can be calculated, and the froth volume estimated, by application of the froth factor. Dry mass concentrate flow is used to calculate the launder *lip length loading* in dry metric tons of concentrate per meter of froth lip per hour. To allow adequate removal of froth from the machine, lip length loading is typically below 1.0–1.5 t/m/h. As process flow moves down a row of cells, the amount of concentrate produced decreases dramatically from one cell to the next. The distribution of the concentrate produced in one row among the cells in that row varies among applications and operations. For example, in the row of 11 cells shown later in Figure 23, the distribution of the concentrate is apportioned thus: cell 1, 45%; cell 2, 26%; cell 3, 18%; cell 4, 5%; cell 5, 3%; cell 6, 2%; and cells 7–11, 1%.

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Figure 19 FLSmidth 660-m^3 SuperCell® machine with radial launders

Froth crowders are frequently used to decrease the surface area at the top of the cell, forcing the froth to move more quickly to the launders. This can be especially important in scavenger cells, where the froths are relatively thin. Note however that in large cells, the decreasing ratio of surface area to cell volume can result in a condition of *overcrowding* in the froth, where particles that have attached to bubbles cannot travel through the froth for final recovery to the concentrate.

Liners

Liners are usually installed in two locations in flotation cells: the tank and launders and the mechanism. The tank and launders are lined to prevent corrosion and abrasion of the steel, so the liner should be robust, but not too thick. The most common liners used are hand-laid natural rubber and sprayed-on polyurethane, with a suitable, corrosion-inhibiting primer. Lining of larger tanks, and of tanks that are fabricated and shipped in segments for on-site assembly, requires special surface preparation and installation skills. These lining jobs should be done only by qualified contractors. In locations where large daily temperature fluctuations are expected, the lining system should be selected to withstand the *cold wall effect*, which is caused by a temperature differential across the interface between the liner and the substrate.

In all cases, metal surfaces must be properly prepared for liner installation. After cleaning and blasting the metal, the surface must be properly cleaned of grit and solvents. Liner application must be done in scrupulous conformance with the specifications given by the supplier of the liner material. In particular, some liner systems can only be applied in a narrow range of temperature and relative humidity. Finally, the chemistry and mineralogy of the flotation slurry must be considered in selection of liner material. This is particularly important with highly abrasive ores, unusual reagents, or process water with high or unusual ionic content. A detailed discussion of liners for mineral processing equipment is given by Nelson and Truss (2009).

Lifting and Transportation

Although often overlooked, lifting and transportation are key to smooth, successful installation and maintenance. With large cells, manufacturing location and methods for welding, applying liners, and other manufacturing functions must be analyzed very carefully in relation to the size of the tank or tank sections.

Lifting lugs should be installed before cell linings so that welding of lugs does not compromise lining integrity. Lugs or other lifting aids should be installed on all components that may need to be separately removed, including belt guards, mechanism components, launders, dart valves, and tank sections. Belt guards and other components should be designed so they can be separated into easily handled pieces. All bolt holes and connection points should be checked for alignment and compatibility before cell components are shipped to the plant site. For components that are lined with elastomer or other protective coatings, this check should be made before the lining is installed, and again afterwards.

Similarly, with large cells, method of shipment, shipment route, and shipping schedule must be carefully considered. Large cells must often be manufactured in sections to facilitate transport because they are usually shipped in pieces and assembled and leveled on-site. On-site assembly may include welding the tank components and installation of the cell linings. These operations must be carefully planned, with appropriate measures taken for working in confined spaces. In some cases, special permits for over-the-road shipping must be obtained, and the large sizes may make shipment by rail impossible. Where large cells are installed in existing plants, designers should carefully consider the sizes of doorways, overhead clearances, bridge crane capacities, and other factors, to ensure that the manufactured sections can be put into place as required.

INSTALLATION AND INFRASTRUCTURE

Safety

Of course, safety is the first consideration in the installation of all equipment. Particular mention is made here of the special precautions involved in the installation of large flotation cells. In such installations, large cranes and special handling techniques are required. All personnel should be trained in the lifting and movement of large, heavy loads, and all operations should be carried out by experienced, competent individuals.

Foundations

Any foundation for a large cell should be designed by a competent structural engineer. Large cell mechanisms generate high torque. For cells that have rotors near the bottom, this torque can cause flexing in the tank bottom if the support given by the foundation is inadequate. This can lead to failure of welds in the tank bottom or the parts of the mechanism attached to the bottom. The previously used mushroom design for cell foundations may not be suitable for larger cells.

The dynamic requirements for cell foundations are related to the excitation frequencies of the equipment installed and to the nominal or natural frequency of the entire system. Here, *the system* means the foundation structure supporting the cells, the cells *holding slurry*, and the cell mechanisms that provide the main excitation frequency. The system must be supported so that the nominal frequency is higher than the lowest excitation frequency by a safe margin. As previously mentioned, this margin is defined in ISO 10816-3. Support is considered stiff if the nominal frequency of the entire system is 25% higher than the main excitation frequency. Standard practice for most flotation cell installations falls into this category, but special care must be taken if the underlying earth is unstable because of moisture, permafrost, or some other anomalous condition. In any case, the cost of foundations for a given cell increases if the rotational speed of the flotation cell increases.

Flotation Buildings

Buildings and shelters should be designed with careful consideration of the local climate and possible extreme weather conditions, such as severe storms or wildfires. Building design should also consider both normal and upset operating conditions. Elevated floors should allow overflowing slurry to flow through to the lowest level, which should be designed for easy capture and recycling of overflowing slurry, with sloping floors, sumps, pumps, wash-down water, and so forth.

Buildings must have cranes large enough to lift all parts of the flotation cells and auxiliary equipment, including pumps, launders, and sampling devices. Roofs must be high enough to allow lifting and movement of cell components and auxiliary equipment. Maintenance and replacement of mechanisms, motors, dart valves, and dart valve boxes must be carefully considered, especially in the case of very large cells. If the flotation mechanisms are designed to be lifted out of the cells for maintenance, one or more maintenance bays should be included in the building design. Maintenance bays should provide for worker access on several levels, and for access by forklifts or other equipment on the lowest level. Each maintenance bay should have a stand on which mechanisms may be mounted for maintenance. One or more auxiliary cranes should be considered for use in maintenance. If the access to the mechanisms is through a port in the cell wall (as may be the case with large cells), the layout of the access level must allow travel by the maintenance equipment and workers.

The locations of control rooms should be carefully considered. Central control rooms, with live video feed from throughout the plant and video displays from a distributed control system, have great value. However, it is also beneficial for operators to regularly walk through the plant, observing the conditions in the cells. Visual observation of froth conditions and cell performance can be especially useful in plants where there are frequent changes in the feed. The installation of one or more satellite control rooms, strategically positioned among the flotation cells, can be useful when operators are making rounds.

Almost all concentrators eventually increase capacity above the original design level, so that sumps, launders, and pipelines can become undersized. It is preferable to oversize sumps and other utilitarian structures, in anticipation of the inevitable.

Walkways, Platforms, Stairways, and Railings

Walkways should be installed to provide access to all locations that may require attention from operating or maintenance personnel. This includes sampling ports; motor connections; drive belts; instrument mountings; manual and automatic control valves for slurry, air, or wash water; and drainage ports. Of course, all structures designed for human foot traffic must comply with applicable health and safety codes.

Access to the interior of the cells is frequently necessary for inspection and maintenance. In smaller cells, permanent ladders are often installed. In larger cells, access is through a maintenance hole near the bottom of the cell. In both cases, when operators enter the cell, the cell must be locked and tagged out, and operators must wear safety harnesses for recovery, as required by local health and safety codes.

Power Connections

As previously mentioned, the motors required for larger cells may require medium-voltage power and motor control centers. This possibility should be carefully considered in combination with the costs of power and installation at each site.

All machines should be provided with instruments to indicate real power consumption to the control operator. To a large degree, power consumption can indicate what is happening in the cell—whether it is sanded, the air intake is plugged, or some other issue—especially when power consumption is compared with feed rate.

VFDs are recommended by most suppliers for cells larger than 300 m^3. VFDs allow greater control of cell hydrodynamics, and when properly used, they can optimize recoveries and grades. They come at an additional cost, which must of course be considered.

Sampling Connections

Sampling connections have two purposes. First, they must provide a representative sample of a given flow stream; second, they must be capable of connecting to an online analysis system. Each connection should be configured so that even if it is connected to an online system, a separate sample can be manually removed at any time for independent laboratory analysis. Sampling connections are easily installed during construction, and connections for samplers should be installed so that every stream can be sampled if necessary. This is true even if there is no plan to sample a given stream when the operation is started. Sampling ports should be designed to be easily cleaned of blockages, and for easy attachment of connections to the sampling device or analyzer.

START-UP

Detailed, site-specific start-up procedures should be developed well in advance. All involved personnel must be trained with regard to the equipment, process, and procedures involved in the start-up. All procedures must follow local safety procedures for lockout and tagout, personal protective equipment, and so forth. Certain simple testing procedures during start-up can obviate serious problems during operation. These tests are first conducted with empty cells, then with water-filled cells, then with water-filled, fully aerated cells. All checkout procedures are made *before* slurry is introduced to the cells. (The checkout and start-up of the systems for reagent addition and process control are not covered in this chapter.)

On occasion, a project may be put on hold after the equipment is purchased. In this situation, it is important to maintain the full operability of the equipment while it is in storage. Electrical motors and equipment containing bearings must be especially considered. Both should be stored in a climate-controlled buildings at low humidity, and regularly rotated.

Empty Cell Tests

Electrical Systems

At the beginning of the start-up, a preliminary check of electrical components should be made. Bump the cell drive motors, blower motors (where used), and all pump motors, and check each for correct rotation direction. If motors start and rotate correctly when bumped, run each one long enough to confirm that its power draw is in the expected range. Finally, confirm correct operation of any VFDs.

Mechanical Systems

First, check each cell mechanism, by hand rotation on smaller machines and using appropriate tools on larger machines. Make sure each mechanism rotates freely and that the bearings are not binding. Make measurements to confirm that the rotor is concentric within the stator or draft tube following manufacturer's specifications. (This is done for two reasons: to make sure that the stator will not interfere with the rotor and to ensure that all the shaft flange connections are properly installed.) At the same time, check the height relationship between the rotor and the stator and draft tube, if present. Make a final inspection of welds in the structure and cell lining. Make sure that the bearing housing is greased according to the manufacturer's specification; if the cell is equipped with a gearbox, ensure that it is filled with the correct oil and that there is enough gear oil on-site for the first refill. (Manufacturers often require that the oil in a gearbox be changed shortly after start-up.) Be sure to install the breather valve or check valve on the gearbox—it is not usually installed when the gearbox is delivered.

Next, while the cells are still empty, power up each cell mechanism and check for vibration, visually and with a vibration sensor. After the mechanism has run for about 30 minutes, shut it down and again check the concentricity of the mechanism and the welds on the mechanism structure.

Control Systems

First, check the dart valves. Remember, dart valves are not designed to stop the flow out of the cell, only to control it. Typically, a procedure for seating the dart valve is provided by the supplier. It includes checking the stroke, concentricity, and calibration of all the dart valves. The dart valve must be very close to the seat or grommet when it is at the lowest possible position, but it should not touch the grommet. If the valve touches the grommet during operation, the shaft will be bent and the dart valve and the grommet can be damaged. While seating the dart valve, make sure that valve shafts are moving freely and not binding in the valve guides. Confirm that the valve plugs are concentric in the seats and that the plugs seat properly. Blow down the air lines for the valve control systems, then check the instrument air pressure and make sure that it functions over the correct pressure range.

Next, check control loop calibration and function, and confirm that control loop parameters are set as specified by the supplier. The final control loop calibration will take place after start-up and must be performed by a qualified person.

Where blowers are used, confirm the correct function of the blower control system. Cycle the blower through its prescribed range and make sure the blower and the flow sensors respond correctly. Also, confirm that any control valves or dampers in the flow control system function correctly.

Finally, if the cell mechanisms or pumps are fitted with VFDs, confirm that each VFD is functioning correctly. Cycle the motor through its design speed range and confirm that the VFD and all associated instruments are functioning correctly.

Water Test

In the water test, the electrical, mechanical, and control systems are tested simultaneously. Fill the cell with water. (Air is not introduced to the machine at this point. Self-aerated machines will draw in some air when the mechanism rotates, but this should be minimized by keeping the air control ports at the top of the draft tube closed.) Make a careful visual inspection to locate any static leaks in the feed box, cell, connection and discharge boxes, auxiliary tanks, and piping. Any leaks should be repaired before proceeding. After confirming that the water-filled system has no static leaks, start the mechanism and make another careful inspection for leaks throughout the system.

Now start the blower or open the air control ports at the top of the draft tube. When a blower is used, once again check the flow control function and confirm the correct operation of flow control valves or dampers in the air supply system. Run the fully aerated, water-filled machine for the time suggested by the manufacturer, and check the temperatures of the gearbox, shaft bearings, and air supply piping (in systems with blowers), and of all pump motors, couplings, and gearboxes. Finally, confirm the correct function of the level control system.

Slurry Test

After all the preceding checks have been made and everything is confirmed to be satisfactory, begin to introduce slurry to the feed box. Allow slurry to replace water in the system at its natural flow rate. As the slurry replaces the water, start the metallurgical operation and recheck the system functions: Vary the airflow, vary the level, and check the dart valve response. During this time, continue to monitor all temperatures and power draws, and frequently walk around each cell checking for leaks, vibration, or any other unusual circumstances.

The correct start-up sequence and timing are more important for the WEMCO® machines, where the mechanism is off the floor. This is because after the resuspension time guaranteed by the manufacturer for emergency shutdowns (usually 3 hours), it may not be possible to fluidize the settled solids below the bottom of the impeller. Similarly, before a routine shutdown, the slurry in these cells should be gradually diluted to only a few percent solids before stopping the mechanism.

CELL OPERATION

Successful and optimized flotation plant operation relies on human understanding, observation, and intervention. In particular, these control points should be monitored: pulp level, froth thickness, froth pull, airflow, and reagent addition. All are important in determining flotation response, but in every operation, *regardless of the machines being used*, they are closely interrelated, and no one variable can be changed without influencing the others.

Pulp Level

In self-aerating machines, pulp level is the variable most commonly changed by operators to influence the process outcome. If the pulp level is raised, the cell is said to be "pulling hard," and cell performance will move toward higher recovery and lower grade. The thickness of the froth layer will decrease, and the process will move toward increased recovery on the grade–recovery curve described in a following subsection. If the pulp level is lowered, the opposite occurs. If the pulp level is raised too high, the pulp will overflow into the froth launders, and the machine will not function properly. Operators should take special care not to pull the cells too hard if the froth/pulp interface is unstable.

Airflow

In externally aerated machines, it is more common to change airflow than pulp level. Increasing the airflow will make the machine pull harder, and move again toward increased recovery and lower grade. Decreasing airflow will have the opposite effect. Of course, there is a limit to the amount of air that can be distributed in the pulp. If this limit is exceeded, *burping* or *geysering* will occur on the surface of the cell, and stable operation will be disrupted.

In both types of machines, there is a combination of pulp level and airflow that will provide the best recovery for given feed conditions. Only experienced operators can consistently operate at the optimum point.

Reagent Addition

Reagent addition is not usually changed in routine operations. It is usually set based on experience and laboratory testing for the various ore types known to exist in the mine. Often it is impossible to know in advance when the ore type in the mill feed will change. Thus changes in the reagent addition scheme are usually made based on visual observations of the froth structure and the tailings, and on the online tailings analysis, after discussion among operations and engineering personnel.

Grade and Recovery

The grade–recovery relationship is one of the most important parameters in industrial flotation. It is unique for each operation and even for each ore type. The combination of grade and recovery is the most typical measure of separation performance. Both are expressed in terms of the valuable constituent in the ore. Recovery is the percentage of the valuable constituent, by mass, in the concentrate from the feed. Typical recoveries are between 60% and 95%. Grade represents the purity of the product. In the mill, the grade indicates the purity of the concentrate. The maximum grade of a concentrate is determined by the chemical composition of the mineral being recovered.

The grade–recovery relationship is associated with the mineralogy of the ore, the comminution process, and the flotation equipment and circuit design. Although the relationship can vary considerably in a given process, there is generally an inverse relationship between the two variables, as shown in Figure 20. In a higher-grade concentrate, the recovery will be lower, and the value left in the tailings will be higher. For example, in Figure 20, the concentrate grade at a 60% recovery is 22%, as shown by the first diamond-shaped point. When the recovery increases to 80%, the concentrate grade decreases to 13%.

It is crucial to monitor the grade–recovery curve of each part of the flotation plant on a regular basis. This curve is the most commonly used assessment of metallurgical performance, and knowledge of the grade–recovery curves for

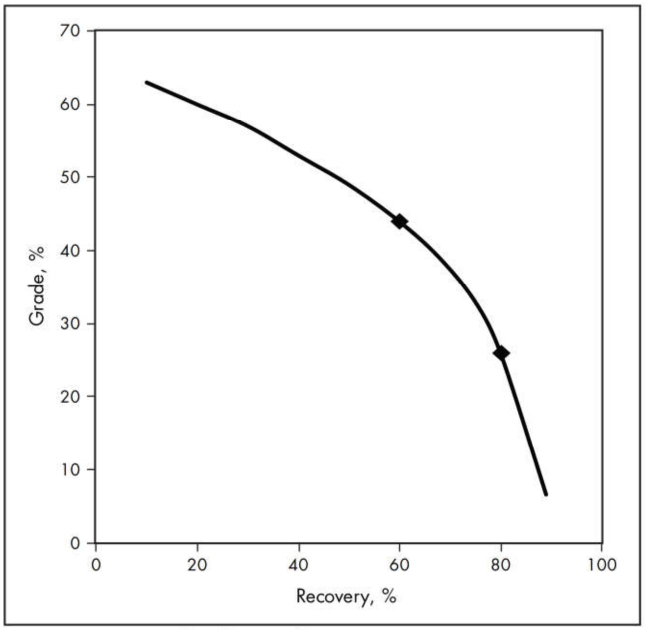

Figure 20 Example of a grade–recovery curve

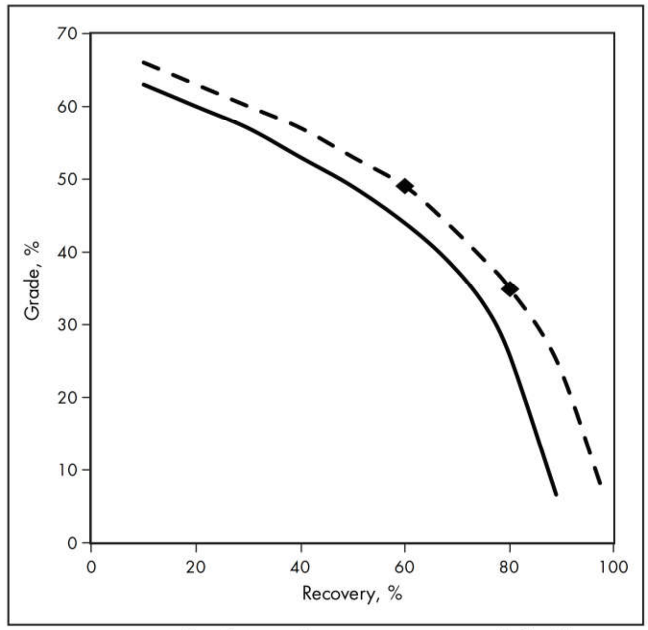

Figure 21 Example of a grade–recovery curve shifted by a change in practice

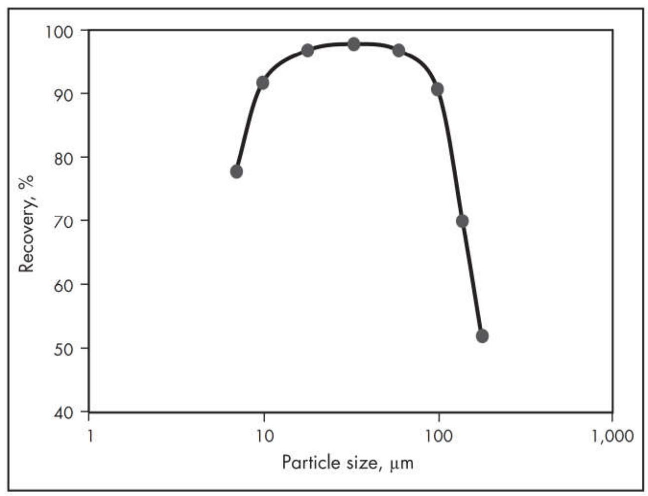

Figure 22 Recovery–particle size relationship

a given deposit allows the operator to know the achievable limits for different ore types and conditions. In most cases, changes in flotation operational parameters, such as froth depth and airflow (where applicable), will move the performance of the flotation process to different positions on the curve; if recovery is increased, then grade drops, and if recovery is decreased, then grade increases. Typically, shallower froth and/or higher airflow result in higher recovery and lower grade; deeper froth and/or lower airflow produce lower recovery and higher grade. However, if there is no change in ore mineralogy, comminution practice, or flotation circuit design, the flotation process will operate somewhere along the same curve. Higher recovery will be traded for lower grade, and vice versa, as shown in Figure 20.

Changes in ore mineralogy may often result in a completely different grade–recovery curve. However, certain changes in plant practice can cause a grade–recovery curve shift, resulting in higher recovery and higher grade at the same time. In Figure 21, the dashed line shows the new curve, shifted to the right of the earlier curve. With the new conditions, the concentrate grade at 60% recovery is 24%, and that at 80% recovery is 17%.

One way to shift the grade–recovery curve is to change comminution practice to achieve better liberation (smaller average particle size) of the valuable element. Improved liberation reduces the number of particles with grains of valuable mineral locked with gangue, which exposes hydrophobic material reporting to the concentrate, either naturally or after collector absorption.

A second way to shift the grade–recovery curve is to improve the flotation kinetics. This can be done by improving the reagent scheme, increasing the probability of bubble-to-particle contact, or increasing residence time. Reagent selection and testing is described in detail in Chapter 7.5, "Flotation Chemicals and Chemistry." Higher probability of contact can be achieved by improvement in the flotation mechanism. Residence time can be increased by adding more flotation volume to the circuit, typically by installing supplementary flotation machines.

A third way to shift the grade–recovery curve is to improve the froth recovery. Froth recovery has been the focus of extensive research, and its importance cannot be overestimated. Recovery in the slurry phase has no effect if the resulting froth is not recovered, which means that if the froth recovery is zero, the overall recovery is also zero. Froth recovery has been observed to vary from 10% to 50%, depending on application. Typical improvements in froth recovery are mostly related to improvements in the froth carry rate and lip loading.

Of course, the goal is to have ultimate grade and recovery, but there are drawbacks associated with all approaches to the grade–recovery curve shift:

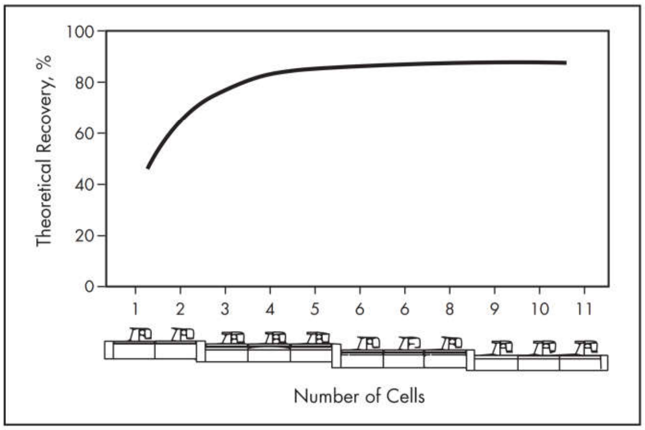

Figure 23 Theoretical recovery in a row of 11 perfectly mixed flotation cells

- Better liberation means smaller particle size entering the flotation process, resulting in a higher concentration of fines (particles smaller than 10 µm). It is well known that there is a particle-size range at which flotation gives the best results. Flotation response to particle size was described by Gaudin et al. (1942) and is shown conceptually in Figure 22. Note that particles between 10 and 120 µm float the most readily. Particles finer and coarser, outside the easy floating range, require specific conditions and higher residence time.
- Higher kinetics are often achieved with increased cost, associated with the use of more reagents, better flotation mechanisms, the cost of higher power required for increased contact frequency, or the purchase of additional flotation machines.
- Froth recovery is still the least understood part of the flotation process, in spite recent of research efforts by scientific institutions and flotation equipment suppliers. Even the measurement of froth recovery is associated with significant uncertainty. Improved understanding of froth recovery may increase the cost–benefit ratio of process changes that can shift the grade–recovery curve.

Recovery and Residence Time

The relation between recovery and residence time is usually determined during laboratory testing. Industrial flotation circuits are designed on the basis of this relationship, with the application of the appropriate scale-up factors. A theoretical recovery–residence-time relationship is shown in Figure 23; this example is based on a row of cells, as shown in the figure.

Total recovery in this example is 88%. In the first cell, 45% of this material is recovered; 94% is recovered in the first four cells, and the last 6% is recovered in the final seven cells. This example can be understood by referring to the size–recovery relationship shown in Figure 23. Material that floats easily is recovered quickly and is typically high grade. The last part of the flotation row is used to capture material that floats slowly because of liberation, particle size, or both.

For a given application, the detailed design of the flotation plant includes specifying the number of rows of cells, the number of cells in each row, and the allocation of the cell functions as roughers, cleaners, scavengers, and so forth. The design is almost always done with the assistance of a simulation software package. Such packages are available from several sources. In these models, the relationship shown in Figure 23 is accounted for by specifying several particle classes, ranging from fast- to slow-floating.

SAMPLING

The basis for evaluation of metallurgical performance of any process is a mass balance around the concentrate. Thus representative and regular samples, and accurate and timely analyses, are necessary. Each plant will have its own specific sampling schedule.

Routine Sampling

In large mills, it is typical to sample concentrates and tailings for online analysis two to four times per hour. Once or twice per hour, separate samples, taken by hand or with an automatic device, are also taken and composited into shift or daily samples. It is typical in many large operations to split the composite samples, with one split being analyzed for elemental composition and the other analyzed for mineralogy and mineral liberation, using a system that combines electron microscopy and X-ray spectroscopy.

Special Sampling

Routine sampling may not indicate long-term changes in the feed, the process, or the process equipment. Special sampling, or metallurgical auditing, should be undertaken on at least an annual basis to reestablish performance baselines for the plant. Special sampling includes down-the-row sampling, grind-release or size-by-size sampling, and residence-time-distribution analysis.

Down-the-Row Sampling

Down-the-row sampling is preferably conducted on two or three rows of each section (rougher, cleaner, scavenger, etc.) in a plant. Feed, concentrate, and tailings samples are taken from each bank in a given row. (A bank is a group of cells with common level control, and a row will include one or more banks.) The tailings from one bank are the feed to the next. In the evaluation, mass balances are calculated for each bank and each row. Down-the-row sampling is an arduous and time-consuming process. It requires preparation and careful forethought, especially in determining how and where to take representative samples. A carefully conducted, down-the-row sampling campaign can indicate long-term, gradual changes in the mechanical conditions of the cells, the properties of the ore, the performance of the grinding circuit, and other variables. By comparing results of down-the-row sampling with the results of grind-release studies in the laboratory, down-the-row sampling can give the metallurgist a good indication of where the plant is operating, in relation to the ideal grade–recovery curve. This, in turn, can provide worthwhile ideas for improving plant performance.

Grind-Release Sampling

Grind-release sampling can be conducted in the plant or in the laboratory. In-plant sampling, perhaps the more important method, includes sampling feed, concentrate, and tailings for the entire plant or any portion of the plant; screening the samples into appropriate size fractions; and analyzing each size fraction for content of the constituent of interest. For example, in a copper concentrator, a grind-release test may show that all the chalcopyrite particles larger than 200 mesh are reporting to the tailings. The results of grind-release sampling are especially valuable when used in conjunction with analysis by a mineral liberation analyzer.

Residence-Time-Distribution Analysis

Residence-time-distribution analysis has been previously described in detail (Nelson et al. 2002). Residence-time analyses are usually conducted by manufacturers on new flotation machine designs. It is important to realize that similar analyses can be conducted in the plant, using salt tracers, dyes, or radioactive tracers (where allowed). Ideally, the tracer is added *not* at the head of a flotation row, but in the feed distributor for a number of rows. Samples are then taken from the feed to each row to determine how well the feed distributor is working. Tailings samples are taken at the end of each row, and the residence time for each row calculated by the standard method. The tailings analyses can indicate gradual changes in the conditions of machines, connection and discharge boxes, and dart valves. These analyses also allow ready comparison of individual rows with one another, derived from baseline residence-time-distribution measurements performed on new machines.

All sampling programs should be statistically rigorous. Statistical design is especially important for in-plant sampling programs, which are almost always complex and expensive. Here it is important to ensure that samples are representative of the conditions in the plant at the time of sampling, and that the operating conditions at which samples are taken are characteristic of the range of conditions experienced in the plant. It is also important that there be a well-designed system for labeling, transport, preparation, and analysis of samples. A discussion of the design of flotation sampling programs is beyond the scope of this chapter. The general principles of statistical experimental design may be found in any one of many excellent texts available. For the design of laboratory flotation test programs, refer to Chapters 7.7 and 7.8, "Sulfide Flotation Testing" and "Non-Sulfide Flotation Testing," respectively. The design and execution of in-plant flotation tests has been thoroughly described in publications by Napier-Munn (1998, 2010, 2012), and Lelinski et al. (2014) offer a detailed description of one such test.

MAINTENANCE

The importance of good maintenance is obvious and cannot be overstated. Modern instruments and control systems make routine monitoring of important parameters, such as power draw, vibration, and bearing temperatures, relatively easy. However, regular and thorough visual inspections during shutdowns, performed by experienced operators and mechanics, remain an important component of a well-designed maintenance program.

Proper maintenance ensures optimal working conditions and increases the life span of the equipment, enabling high machine efficiency and ensuring high product quality. The most important part of regular and properly scheduled maintenance is ensuring that all equipment operates safely, with identified risks eliminated or minimized.

There are two conceptual approaches to maintenance: proactive and reactive. Proactive maintenance is planned maintenance and requires scheduled interruption of production; reactive maintenance is unplanned and takes place when machines or systems fail. Scheduled production interruption is preferable to the downtime caused by an unplanned breakdown and the required reactive maintenance. Because production interruptions are planned, they can occur at optimal times, and the workforce can almost always anticipate all issues that may be related to production interruption. In virtually all cases, planned maintenance takes less time and costs much less than emergency repairs and replacements. For example, mobilizing crew, equipment, and spare parts can be done ahead of time, reducing costs.

Proactive maintenance may be further divided into preventive, detective, and predictive approaches. Preventive maintenance is scheduled using parameters such as operating time or production quantity. For example, concentrators often have more than one "processing line," with each line comprising a SAG mill, one or more ball mills, and one row of rougher flotation cells. Such a mill might shut down one line for a few days each month, conducting routine inspection and maintenance on all the equipment in that line while the other lines continue to operate. Detective maintenance uses testing and measurement to locate equipment or components that have already failed but may not have yet caused shutdown of part or all of the plant. For example, instrumentation on a flotation cell mechanism may indicate that the motor for that cell has failed. The feed to the row can then be shut off before the cell in question sands in by filling with solids. Predictive maintenance uses condition monitoring to look for the indication of incipient failures. For example, high vibration on the drive for a compressor may indicate that a bearing is about to fail, so that the machine can be shut down and the bearing replaced before its failure results in further damage to the mechanism.

Clearly, predictive maintenance is the preferred approach, and even detective maintenance is superior to reactive maintenance. Predictive maintenance requires higher initial investments for condition monitoring equipment and for parts outfitted with the monitoring sensors, but it pays off very quickly.

Following are some specific recommendations for flotation cell maintenance based on the authors' experience.

Drive Assembly

Temperatures of the motor, bearings, and gear drive (if used) should be checked regularly. Statistical quality control methods may be used to detect important changes or long-term trends in readings.

Mechanism

Regular lubrication of shaft bearings is important, and bearing temperatures should be checked manually on a regular basis. The linings on the shaft, rotor, and stator should be inspected in each shutdown for wear, cracks, and chunk-type failure. Components with severe damage should be removed and replaced. Concentricity of the rotor inside the draft tube or stator should also be checked in each shutdown.

Mechanism rotation should be reversed every shutdown, to achieve even wear on both sides of the rotor blades. If rotation is not reversed regularly, symmetry will not be maintained, and then, when rotation is reversed, the motor may trip out because of excess current draw. Vibration should be checked against baseline values at least quarterly.

In self-aerating machines, the air openings should be checked regularly to ensure that they are clear. Similarly, in forced-air machines, the air intake openings in the rotor should be periodically cleared of any residual slurry or debris.

Liners

The integrity of tank liners should be inspected during every shutdown. Deterioration of liners can lead to liner failure over small or large areas, which in turn leads to increased corrosion and wear of the steel substrate, causing eventual failure of the tank. Liner integrity is especially important at the flow-through points between various tankage components—feed boxes and cells, or cells and connection or discharge boxes.

Dart Valves

Dart cones and seats should be carefully inspected for wear, proper alignment, and concentricity. Movement of the valve shaft in its guides should be checked to make sure that the shaft is not bent and that there is no binding or misalignment. The air lines and moisture traps on the dart valve controllers should be checked and blown down weekly. The flotation circuit need not be shut down to complete this operation.

Launders

Cell overflow lips and froth launders should be checked and washed down regularly to prevent accumulation of concentrate and ensure equal flow along the entire length of the lip. In large cells, connection points between the various components of interior launders may experience high wear and should be inspected on each shutdown.

Cleanout

Regular cleanout of the cell and its mechanism is important. Occasional upsets in the grinding circuit cannot be avoided, and oversize material will almost always accumulate in flotation cells. There is a limit to the amount of material that can be accumulated in any cell before performance is adversely affected. To ensure satisfactory operation, this material must be removed periodically.

The easiest way to remove oversize material is with water. In some cases, much of the oversize material can be removed by pumping water at a high flow rate through the circuit. In some plants, operators insert handheld, high-pressure water pipes into the cell to assist in moving oversize material into the flow. However, this practice should be used with caution, as it can damage the linings of the cell and mechanism. At points where the lining is damaged or detached, the high-pressure water tends to raise the lining and increase the damage and detachment. When oversize material cannot be removed with water, one alternative is the use of shovels and buckets. Large cells should be provided with access ports to allow easy access to the cell floor for cleanout.

ECONOMICS

Economic factors should be considered in the purchase and operation of flotation machines. Economics should be analyzed with a global perspective, considering capital costs, operating and maintenance costs, and metallurgical performance. Following are some examples.

First, in the design and construction of a new concentrator, the cost of the flotation equipment is usually a small part of the total capital cost for equipment. In some cases, a vendor may offer the flotation equipment for little or no additional cost if the customer agrees to purchase the comminution equipment from that vendor. While this option offers an attractive reduction in initial capital cost, it may not provide the best flotation equipment for the application.

Second, some flotation experts believe the only thing that matters is retention time, and the selection of flotation equipment can be made solely on the basis of cost per unit volume—literally, dollars per cubic meter. It is, however, important to ensure that all the performance parameters for the machines selected meet the requirements determined by laboratory tests, such as adequate power density to maintain slurry suspension, correct launder design to ensure rapid froth removal, and so forth.

Third, a given type of equipment may offer the lowest capital cost and best metallurgical performance, but its vendor may have limited presence in the operating location. Experienced service personnel may require several days to arrive on-site, and delivery of spare parts may be similarly slow. Such delays can outweigh other perceived advantages.

Finally, economies of scale often result in the design of very large mining and milling complexes, and in the use of the largest possible pieces of processing equipment. However, designers should carefully consider the challenges in fabricating, transporting, and installing large processing machines. They should also bear in mind that commodity prices are always subject to cycles, and that it is more difficult to reduce throughput in large plants that are fitted with large pieces of processing equipment.

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