CHAPTER 12.10

Diamonds

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AGE, ORIGIN, AND EMPLACEMENT OF DIAMONDS

Diamonds originate in kimberlites (and lamproites, a subtly different but related rock type), which are deeply derived and volcanically emplaced structures. Diamonds also occur in alluvial deposits, which are formed when such primary deposits weather over millennia, releasing diamonds (and other heavy minerals) to be subsequently concentrated again through river and marine currents.

Until the 1980s, there was little comprehensive understanding of the age, origin, and manner of emplacement of diamonds into minable environments. No plausible mechanisms had been proposed that could explain how diamonds were created within the kimberlite or lamproite deposits. Subsequent advances in geochemical analytical methods, however, led to studies of the geochemistry of inclusions found in diamonds. What emerged were conclusions that are now widely accepted (Kirkley et al. 1991):

- Diamonds are derived from either of two rock types, eclogite and peridotite, typical of carbon sources associated with subducted oceanic crust (basalt) and upper mantle zones, respectively.
- Diamonds are almost always much older (1,000–3,300 million years) than the kimberlite or lamproite in which they are found (>50 million years but varies widely).
- The temperature and pressure at which the diamond form of carbon is preserved intersect at favorable locations approximately 150 km below stable continents (the “diamond stability field”). Oceanic areas have a geothermal gradient that is too high, pushing the zone of diamond stability farther down.
- Kimberlite pipes originate from areas deeper than the diamond stability field (except in oceanic areas), and the kimberlite rock serves simply as the transport vehicle for diamonds. It collects diamonds and conveys them upward, expanding explosively as it approaches the surface. The journey from the mantle to the surface must be at a velocity that is fast enough to prevent the diamonds from converting to graphite or carbon dioxide or dissolving in the magma itself. Russell et al. (2012) suggest that extremely high magma velocities are achieved by the interaction of alkaline carbonates, native to the kimberlite, with acidic silicate rocks entrained during the ascent. The acid–base chemical interaction releases carbon dioxide, which then acts in a manner similar to a rocket propellant.

NATURAL DIAMOND PRODUCTION

Reported data (Table 1) show that in the period 2014–2016, just over half of the global rough diamond production by value was from just two countries, Russia and Botswana. If Canadian, South African, and Angolan production are added to Russia and Botswana, five countries accounted for more than 80% of global natural diamond production in 2016.

Natural Gem Diamonds

The main factor driving the diamond mining industry is the market for diamond jewelry. Concerted marketing efforts over many decades have focused on creating an emotionally driven attitude to the acquisition of diamond jewelry, underpinned by celebration of personal life events. Attempts to commoditize diamonds as tradable investments have been generally unsuccessful for many reasons, including the essentially “non-fungible” nature of diamonds. No two are the same, diamond grading systems are complex, and the difference in value can vary significantly between adjacent grades.

Other Uses of Diamonds

The application of diamonds to a wide variety of uses is underpinned by their physical properties, some of which are also exploited in the diamond recovery process. These physical properties include the following:

- **Hardness:** Diamond is the hardest known natural material, leading to its use as an abrasive and enabling it to survive for millions of years through geological weathering processes. The hardness of diamond relative to other ore components is particularly employed in the liberation process.

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Table 1 Rough diamond production by country

	2014			2015			2016		
	Volume, carats	Value, US$/carat	Value, US$	Volume, carats	Value, US$/carat	Value, US$	Volume, carats	Value, US$/carat	Value, US$
Russia	38,303,500	97.47	3,733,262,920	41,912,390	101.15	4,239,585,340	40,322,030	88.75	3,578,732,550
Botswana	24,668,091	147.84	3,646,952,179	20,778,642	143.73	2,986,469,130	20,501,000	138.82	2,845,948,820
Canada	12,011,619	166.78	2,003,267,161	11,677,472	143.52	1,675,936,000	13,036,449	107.18	1,397,308,512
South Africa	7,430,956	164.76	1,224,311,494	7,218,463	192.57	1,390,033,447	8,311,674	150.26	1,248,912,618
Angola	8,791,340	149.86	1,317,456,072	9,016,343	131.11	1,182,128,882	9,021,467	119.65	1,079,411,359
Namibia	1,917,690	602.57	1,155,536,792	2,053,095	591.08	1,213,539,148	1,717,658	532.60	914,827,141
Democratic Republic of the Congo	15,652,015	8.72	136,505,486	16,016,332	8.28	132,539,972	23,207,443	10.63	246,700,973
Australia	9,288,232	32.76	304,319,165	13,563,935	22.73	308,356,848	13,957,722	15.50	216,337,288
Sierra Leone	620,181	357.50	221,713,243	500,000	308.51	154,253,129	549,086	289.34	158,872,778
Zimbabwe	4,771,637	50.00	238,581,841	3,490,881	50.00	174,544,058	2,102,873	50.00	105,143,675
Other	1,323,213	388.37	513,900,646	1,171,810	362.04	424,240,130	1,343,284	453.04	608,560,880
Total	**124,778,474**	**116.17**	**14,495,806,999**	**127,399,363**	**108.96**	**13,881,626,084**	**134,070,686**	**92.49**	**12,400,756,594**

Source: KPCS n.d.

- **Density:** Diamond has a specific gravity (sg) of 3.53. Graphite has a specific gravity of 2.26. Because the host rocks within which diamonds are found typically have a density less than 2.65 g/cm^3, the relatively high density of diamond is the basis for its concentration using gravity separation techniques.
- **Dispersion:** Because of their high refractive index (2.42, versus glass, 1.52), diamonds separate the colors of light to a greater extent, providing the "fire" in a cut gemstone.
- **Transparency:** Diamond is transparent from the ultraviolet (225 nm) to the far infrared range, which it retains at very high temperatures and radiation intensities. This makes it an ideal material for use as a protective "window" for optical devices in extreme conditions (e.g., lasers and sensing devices in missile nose-cone assemblies).
- **Electrical conductivity:** Although a few diamonds are electrical semiconductors, the vast majority are electrically nonconducting.
- **Thermal conductivity:** The thermal conductivity of diamonds is four times that of copper at room temperature, leading to their use as heat sinks in powerful electronic devices.
- **Fluorescence:** Approximately 98.5% of all diamonds will fluoresce when exposed to X-rays. This is used as a basis for final diamond recovery. Type II diamonds are unique in that they do not fluoresce reliably under X-ray stimulation but are recoverable using X-ray transmission (XRT).

Grade of Diamond-Bearing Deposits

A good diamond deposit may contain less than 0.2 ppm diamond or 1 carat/t (per metric ton) ore mined. Diamond ore concentrations are so low that they are often quoted in carats per 100 t. This is far below concentration levels typical of base metal mines, and hence very high efficiencies are required to render the operation economic. Diamonds are not fungible; the value increases exponentially with size and varies with color and clarity. Therefore, the fundamental processing task is to remove 999999.8 ppm of non-diamond without losing or damaging the 0.2 ppm that represents the value.

MINERAL PROCESSING FOR DIAMOND RECOVERY

Mineral processing in the diamond industry follows four basic steps:

1. Diamond liberation (through comminution)
2. Concentration (gravity separation)
3. Recovery (X-ray, grease)
4. Cleaning/removal of non-diamond material (acid, caustic)

Given both the correlation between diamond size and value, and the very high recovery efficiencies required for successful operation, the principles of "diamond value management" are woven throughout the diamond recovery process design and operation. This involves a suite of analytical tools serving to identify the "total content curve" and hence value by incremental size range of the deposit. The tools are populated and calibrated to a deposit by ore sampling and the application of statistical methods. The tools are then verified and improved by monitoring the actual value recovered into the final diamond production. Target recoveries of at least 99% of the contained value are typical, and investigation and mitigating action will follow if unmet, to determine where in the process chain the value is being lost and why (Rider and Roodt 2003).

A typical flow sheet for a modern kimberlite treatment plant for the recovery of diamonds in the most common size range of 1–25 mm is shown in Figure 1. Although diamonds outside this size range are recovered in some installations, the core size range represents the overwhelming proportion of value for most operations (Popplewell 2007).

A typical flow sheet for the recovery of diamonds from an alluvial diamond deposit is shown in Figure 2. This is a simpler process, not requiring any comminution circuit to liberate diamonds. The following sections describe processes pertaining to this common size range, unless otherwise noted.

Not all diamond recovery operations utilize all processing steps shown. Combining primary and secondary scrubbing into a single operation and omitting reconcentration and single-particle X-ray sorters are both common variations. Although the use of dense medium separation (DMS) as the principal separation process is almost ubiquitous outside Russia, the use of bulk X-ray sorters (which are, in contrast, extensively used

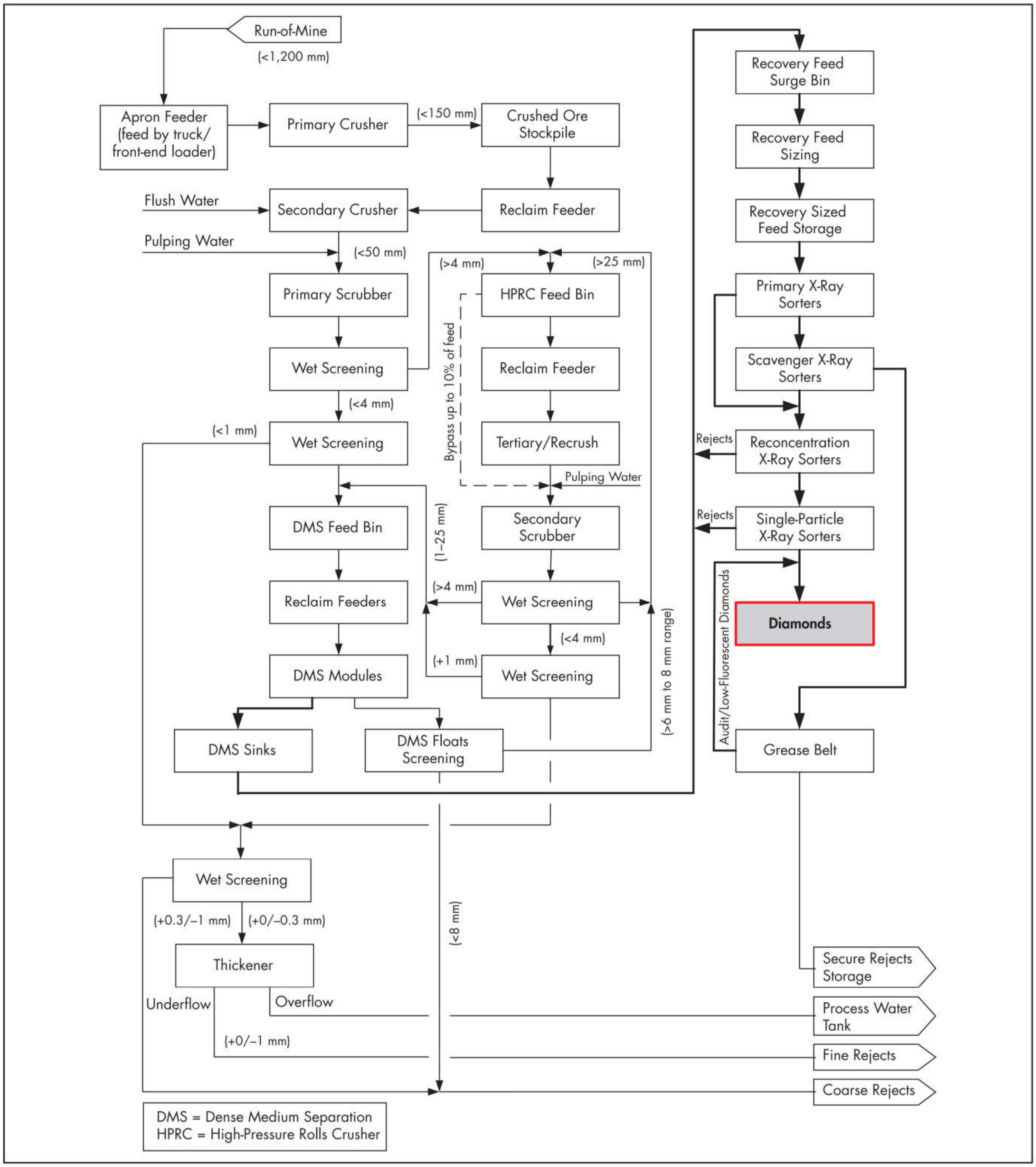


Figure 1 Kimberlite diamond recovery flow sheet

in Russian diamond recovery plants) is emerging as an alternative, where the deposit is statistically determined to contain economically recoverable large diamonds (generally accepted as >25 mm). DMS processing is then restricted to the size fraction below approximately 8 mm, for which X-ray sorting is not currently considered cost-effective. Increasingly sophisticated geological modeling has supported the introduction of such "large" diamond recovery processes in some recently developed mines. These are exclusively based on XRT sorting. Diamonds that would previously have been broken during size reduction before DMS, through a lack of knowledge of their potential presence, are now being recovered (Van Niekerk et al. 2016).

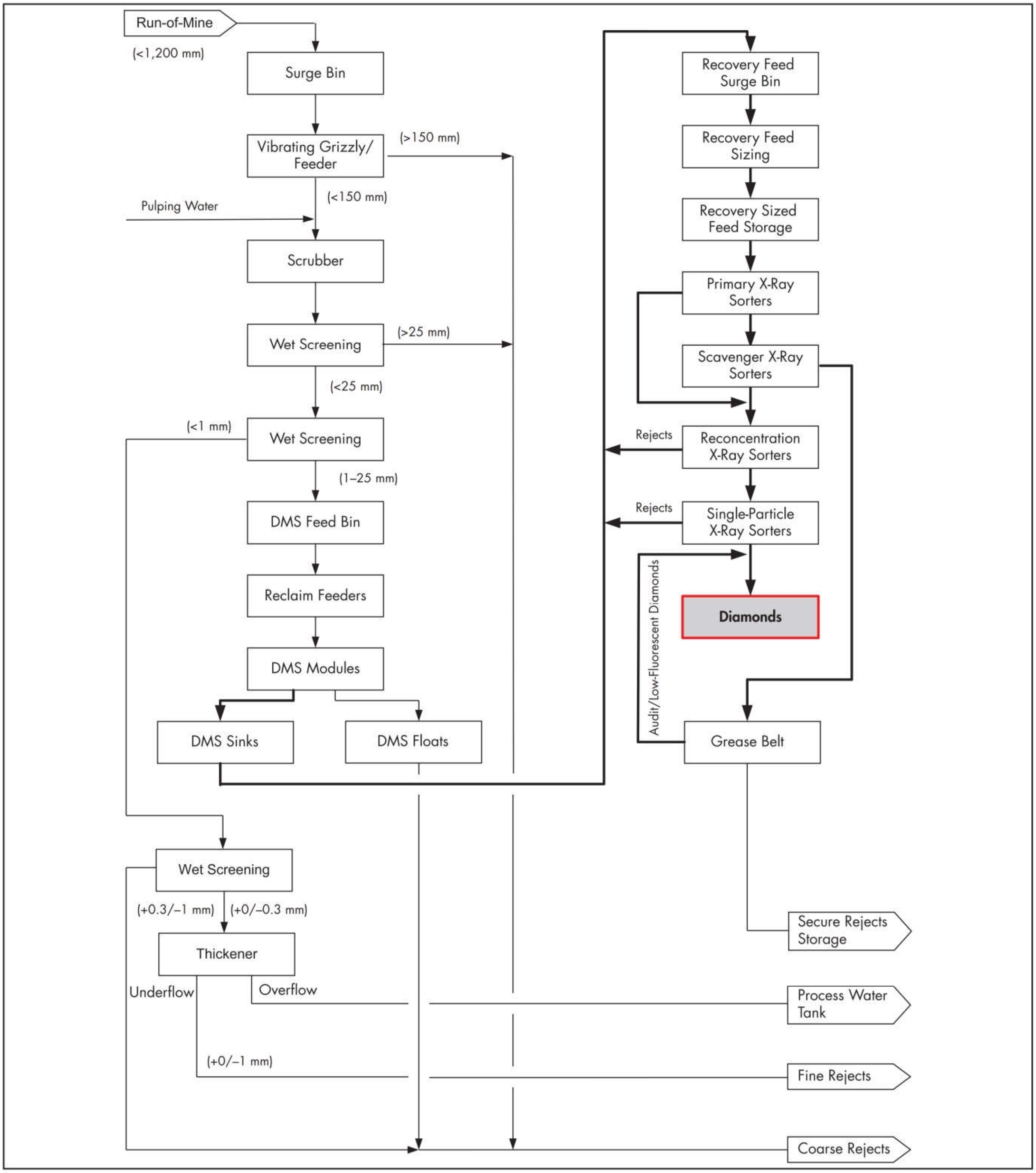


Figure 2 Alluvial diamond recovery flow sheet

Diamond Liberation

Only "free" diamonds are cut and sold. Free diamonds exist naturally, in alluvial deposits, but most have to be liberated from the kimberlite rock host. Beyond this basic requirement, the purpose of the comminution section of a diamond recovery plant is to prepare the ore for a separation process that extracts contained diamonds, either directly via X-ray luminescence or XRT sorting, or via a gravity separation process where the difference in density between the diamonds and the other host rock minerals is exploited. (The diamonds contained in the concentrate are typically also recovered using X-ray sorters.) Currently, gravity separation is by far the most common separation process outside Russia, and DMS is the dominant technology.

Following comminution, the ore feed contains particles, including diamonds, from the target diamond top size down to "dust." However, the smallest rough gem diamonds that are considered marketable are approximately 0.8 mm (DTC [Diamond Trading Company] no. 1 sieve size). Therefore, although DMS applications for other minerals range to below 0.5 mm, for diamonds the bottom size limit is almost always in the range of 0.8–1.5 mm, the actual value being deposit specific or the result of variation in the market for the diamond product.

Although some ore deposits either have been well-washed by nature (a few alluvial diamond deposits) or consist of competent rock (some primary diamond deposits, e.g., Argyle in Western Australia or Letlhakane in Botswana), most contain clay-forming minerals, which complicate the process of establishing a reasonably sharp cutoff at the desired bottom size. Without disagglomerating such clay-bound ore prior to screening, clumps of small particles stick together and report to the dense medium cyclone, where they are likely to break up under the high shear forces present. The result is contamination of the circulating medium with low-density fine material, and this leads to higher medium viscosity, which compromises the separation.

Primary Crushing

A variety of comminution devices are available. Run-of-mine primary crushing unit selection is largely driven by throughput capacity and feed hardness, with high-capacity gyratory crushers giving way to lower-capacity jaw crushers, and roll "mineral" sizers or even "roadheaders," capable of a wide range of capacities on relatively soft, friable ore. The purpose of primary crushing is to produce a conveyable ore stream. The key output from primary crushing is a maximum lump size for the downstream process. This is usually around 250 mm, with a P80 between 100 and 150 mm.

Following primary crushing, further size reduction is intended to limit the material to a desired top size. This is the size of the largest diamond that statistical interpretation of exploration results suggests is present in economically recoverable quantity. The top size is therefore deposit specific and can range up to 60–75 mm, although the vast majority of installations limit the top size for diamond recovery to 20–32 mm. Material characteristics become more important, particularly clay and moisture content, and the overall competence of the ore, as described by A*b and Ta parameters from drop weight testing (www.jktech.com.au). With ores such as iron ore, manganese, or andalusite, "grade" varies from lump to lump and hence is a notionally continuous concept that can be traded off against "recovery" and is typically represented as such on a grade–recovery diagram. Higher-grade product generally requires sacrifice of mass recovery and vice versa. The product specification for these other ore type examples is a bulk specification. With diamonds, it is different. Either a particle is a diamond or it is not. There is no bulk specification, and a "grade–recovery" curve does not apply. Simply put, a 2-carat diamond is desirable, whereas a 2-kg lump of gray rock containing two carats of tiny diamonds is not.

Part of the process of reducing the ore top size is therefore about liberating as many of the diamonds as possible so they can follow a density-specific pathway through the dense medium cyclone. However, broken diamonds are almost always worth less than unbroken diamonds, so care must be taken while reducing the top size to the desired value. In addition, a high size–reduction ratio is desirable, as particles reduced to below the bottom size for diamond recovery following comminution are screened out to tailings and therefore reduce the load on the DMS section of the plant.

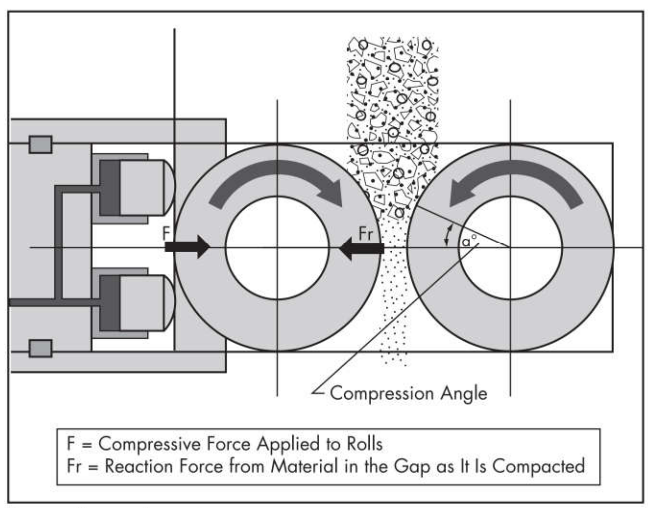
Secondary Crushing

Secondary crushers, usually cone crushers, are employed to reduce primary crushed product to a P80 in the range of 25–32 mm. Secondary crusher product is screened to scalp off material greater than the diamond top size, with oversize returned to the crusher and undersize reporting to the DMS. The need to avoid damage to larger diamonds passing through the crusher means that the crusher gap setting must be greater than the diamond top size, so that a recirculating load around the crusher is inevitable.

Tertiary Crushing

The feed to the tertiary crushing (often referred to as recrushing) section is derived from the DMS floats product, where the coarser fraction is returned for further size reduction to liberate additional diamonds not released in the secondary crushers. The target crushed product top size is usually in the range of 6–8 mm, defined as the DMS floats size below which the remaining "locked" diamond value is not significant. Prior to the widespread acceptance of high-pressure rolls crusher (HPRC) for tertiary crushing duties, cone crushers were employed for this role. For the same reason of avoiding diamond damage, crusher operating gaps were relaxed, and relatively high circulating loads (200%–300%) were common, with consequent adverse capital and operating cost impacts.

The use of HPRC (Figure 3) in a mineral processing application (as opposed to the cement industry) was pioneered in the diamond industry in South Africa, and HPRCs are used for tertiary crushing at nearly all larger kimberlite operations across Southern Africa and Canada. Early smooth and profiled roll surfaces have largely been replaced by rolls with studded surfaces (with the first installation in 1998 at Ekati diamond mine in Canada). Ore accumulates between the studs, forming an autogenous surface, which protects the studs from wear



Source: Klymowsky, n.d.

Figure 3 High-pressure rolls crusher

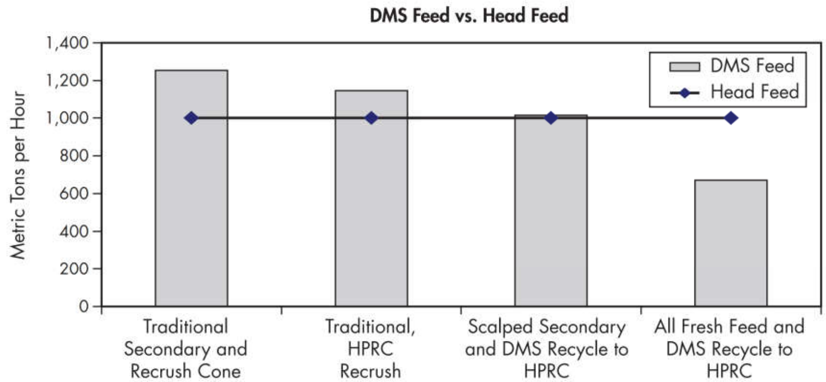
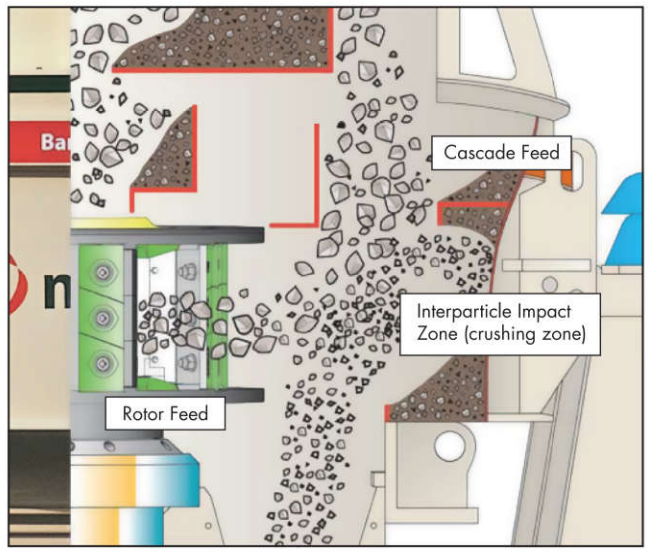


Figure 4 Benefit of maximizing comminution by HPRC on DMS capacity requirements

while increasing friction. The greater the friction angle, the greater the ability of the rolls to draw in material, resulting in a wider gap between the rolls in operation and hence higher capacity. The wider the operating gap, the less the risk of damage to any diamonds present, which obviously have to be smaller than the operating gap to avoid being crushed themselves. Since diamonds present will be the hardest component of the ore stream to the HPRC, non-diamond material is crushed around the diamonds, liberating them preferentially. The typical product from an HPRC operating in a tertiary crushing application is finer than that from a cone crusher, reducing the volume of feed to the DMS section, and drastically reducing crusher circulating load relative to cone crushers (Figure 4; Fyfe 2005).

Vertical shaft impact (VSI) crushers have been used for many years in operations where the ore is sticky and for marine operations where large amounts of shell are encountered. Although the relatively low capital cost is attractive, concerns about diamond damage greatly limited their acceptance for many years. However, recent trials conducted by one of the major diamond producers suggest that, properly controlled, VSI crushers can be a very effective comminution device in a tertiary crushing application where any liberated diamonds have already been removed. The operating principle (Figure 5) involves separation of the inflowing ore into two streams, with one stream forming a bed into which the second stream is accelerated horizontally via a vertically oriented rotor. This avoids impact of the ore stream on the crusher components, promoting instead interparticle comminution between the two streams. By adjusting the relative proportions of the two streams and the rotor speed, the crushing performance can be optimized for the particular ore being treated.



Adapted from Metso Minerals 2009

Figure 5 Interparticle crushing in a vertical shaft impact crusher

DISAGGLOMERATION

Although some ores have so little clay content that disagglomeration can be achieved by simple wet screening with washing sprays, this is relatively rare. Typically, a degree of energy input is required to loosen clay bonds (Figure 6). If jet pumps are used for material transport, the intense shear forces in the mixing chamber can result in a substantial "scrubbing" effect, and in some cases, no further disagglomeration effort is required, although, more commonly, jet pumping would complement other disagglomeration equipment. Log washers can also be used where clay bonding is weak to moderate. However, most commonly, disagglomeration is carried out in wet rotary vessels. The disagglomeration process is referred to as "scrubbing," which describes the essential nature of the process. Tumbling the ore with water in a drum disperses clay minerals, which are screened out and discarded along with any material smaller than the bottom diamond size (Figure 7). If not removed, such fine material contaminates the dense medium, increasing viscosity and adversely affecting separation cyclone performance.

Wet rotary scrubbers used in production installations vary in size from a minimum of perhaps 1.2 m up to 5 m diameter. Scrubber sizing should be based on pilot-scale test work, to determine energy input, design, and operating parameters. Shell diameter is driven by overall throughput capacity considerations, with the length selected to provide the retention time required for effective disagglomeration. Scrubber working volume is dictated by the diameter of the discharge dam ring. Scrubber absorbed power is dictated by the working volume, liner configuration, scrubber drum rotational speed, and feed slurry density. For effective scrubbing, the feed must contain sufficient competent larger ore particles (100–150 mm) to

Figure 6 Pre-disagglomerated weathered ore

Figure 7 Disagglomerated and washed ore

transfer energy to the charge. If not present in sufficient quantity, a separate charge is needed, which requires a discharge grate to be fitted to retain the coarse particles while passing the rest of the charge.

Autogenous Milling

Autogenous milling is widely practiced in the Russian diamond mining industry and performs the dual roles of disagglomeration and true size reduction, enhancing diamond liberation. Elsewhere, autogenous milling as a pre-DMS preparation stage at diamond mines has, until recently, been restricted to a relatively narrow range of softer ores and is more accurately described as "super scrubbing." Where amenable, however, the use of autogenous milling presents an opportunity to simplify the overall comminution flow sheet. The potential for a "single stage of comminution," post-primary crushing, resulting in a product consisting mainly of barren kimberlitic fines along with some grits, pebbles, indicator minerals as well as the prized undamaged diamonds, is of obvious value. Recent success in introducing autogenous mills to several Western diamond mines highlights the need to consider both scrubbing and milling as options for diamond liberation and pre-DMS mass reduction (Daniel et al. 2016). This requires a thorough understanding of the range of ore characteristics, scrubber/mill sizing, and operating parameters through pilot-scale test work.

DEGRITTING AND DESLIMING

Washed ore from the scrubbing section reports to a screening section where unwanted fines (smaller than the bottom size for diamond recovery) are removed. Sometimes, this is preceded by a scalping screen intended to generate a midsize split, to optimize the size ranges for separate DMS circuits dedicated to coarser and finer particle stream, respectively. The separate DMS circuits would typically employ different sized cyclones with different operating parameters. This scalping duty is relatively straightforward, and since the size split between the coarse and fines streams is typically driven (within a limited range) by overall mass balance considerations, the efficiency of the sizing split is not particularly important.

Although horizontal vibrating screens are still used widely, particularly for higher-capacity installations, multislope vibrating screens have become the norm for the degritting/desliming duty. The main reason is that, at the relevant apertures (to achieve a size cutoff in the range 0.8–1.5 mm), the screening duty is driven largely by drainage. A rule of thumb that has been used for many years is that the solids content of the degritting screen underflow should not exceed 7% of the total underflow stream on a volume basis. This requires that the screen passes a large quantity of water to achieve acceptable removal of undersized material from the screen feed. The design of a multislope screen is such that the high velocity and changing direction of the slurry promotes dewatering. There is a parallel between this conventional screen comparison and the greater drainage capacity performance of a circular sievebend deck relative to an inclined flat drainage panel of similar area.

Material of Construction

With a screening size usually in the range of 0.8–1.5 mm, there are few exceptions to the selection of polyurethane-based modular screening panels for feed preparation duties. A sizing split to provide coarse and fine DMS feed streams, in a more varied range from perhaps 4–10 mm, allows the alternative of rubber to also be considered. Rubber, although generally more expensive than polyurethane, has a longer wear life and greater mobility, reducing the effects of aperture blinding on efficiency.

GRAVITY CONCENTRATION

Diamonds, with a specific gravity of 3.53, occur in primary (kimberlite/lamproite) and secondary (alluvial) deposits where the density of accompanying rocks and minerals is usually much lower. Most primary deposits have average densities <2.6 sg, with usually very little (perhaps 0.2%–0.8%) >3.0 sg (meaning, in the context of a heavy medium separation, that this will report to the same product as the diamonds). Alluvial deposits are formed when primary deposits weather over millennia, releasing diamonds and other heavy minerals to be subsequently concentrated again through river and marine currents. These deposits may be reworked geologically in various ways such that the volume of accompanying higher-density material varies considerably. Even so, most alluvial deposits contain a heavy mineral content <2% by volume, with occasional "spikes" up to perhaps 10% by volume.

Concentration of diamond-bearing deposits through gravity separation is therefore an obvious technique, and gravity separation technology based on jigging and rotary washing pans has been practiced for more than a century and is still in use today in smaller operations. However, both methods rely on relatively weak enhancement of the competing effects of gravity and hindered settling, leading to relatively inefficient separations and hence the need to "cut-low" and accept contamination of the diamond-bearing product to avoid diamond loss. Both also required continuous operator attention, particularly rotary washing pans. With the evolution of heavy medium separation pioneered by the Dutch State Mines in the 1950s using magnetite (5.3 sg) for the washing of coal, interest turned to parallel application for the recovery of diamonds. Coal washing utilizes separation densities of typically 1.4–1.8 sg, which would clearly not be applicable to diamond recovery where a nominal target separation density is usually 3.0–3.1 sg. Such densities are not achievable using magnetite alone, as the magnetite content of the medium slurry would need to be so high that the resulting slurry viscosity would render the separation impractical. Ferrosilicon (FeSi) powders were therefore developed, initially as a by-product of the steelmaking industry, but they evolved over time into a specific product of 6.8 sg, based on a 14%–16% w/w silicon content. Although heavy medium separation using FeSi has been applied to many commodities (particularly iron ore, manganese, chrome, and industrial minerals such as andalusite), the production of FeSi with reliable specifications with respect to density, size analysis, magnetic susceptibility, and corrosion resistance was driven by the rapid adoption of heavy medium separation in the diamond mining industry, where consistent and predictable performance is essential. Although jigs and rotary washing pans are still employed by some small and marginal diamond mining operators, heavy media separation using FeSi medium has come to dominate the more significant production operations across the Western world.

Type of Separators

Cyclones dominate in the diamond industry. Although the steady development of high-capacity X-ray sorting technology (both X-ray luminescence and XRT) has essentially removed the need for a "coarse" heavy medium separation technology for diamonds, being essentially a "single-particle" discrimination technology requiring the feed to be presented in a monolayer, X-ray processing becomes progressively more expensive as the bottom size for treatment reduces and the required monolayer becomes ever thinner (with the unit capacity decreasing accordingly). Currently, the economic bottom size limit for bulk X-ray sorting is in the range of 6–8 mm, with heavy medium cyclones the overwhelming choice below this limit. New diamond recovery installations are therefore likely to feature combinations of X-ray separators and heavy medium cyclones for primary ore processing. The most common heavy media cyclone sizes in use are made from high-chrome cast iron, with 20-degree cone angle the overwhelming standard. The cyclone configuration is based on the original Dutch State Mines equipment specifications, with the component dimensions as shown in Table 2.

Specialist cyclone manufacturers offer units with minor variations to the standard dimensions. The density of the circulating medium required to generate the desired "cut density" of 3.0–3.2 sg varies with size of cyclone, type of medium, and the cyclone feed pressure and is usually in the range of 2.4–2.7 sg, giving a "density differential" of 0.3–0.8 sg. A narrower density differential is usually considered to represent superior separation efficiency, as the separation is spread over a larger area of the cyclone. In reality, since primary diamond separations generate very little concentrate (i.e., sinks), narrower differentials are of more interest in reconcentration duties, where much higher concentrate volumes are present and where the majority of the particles are high specific gravity. The attraction of a high-density differential lies in the fact that it allows operation at a lower cyclone feed density and this represents a lower volume of FeSi in circuit.

Table 2 Standard DMS cyclone configuration

Parameter	Relative to Diameter	Production Example
Cyclone diameter	1	356 mm (nominal 350 mm)
Inlet diameter	0.2	70 mm
Vortex finder diameter	0.41	146 mm
Cone angle	Not applicable	20 degrees
Spigot diameter	0.21–0.25	76 mm, 83 mm, 89 mm

Table 3 Gravity- versus pump-fed cyclone features

Parameter/Feature	Gravity Feed	Pump Feed
Cyclone feed pressure	Fixed and reliable	Subject to fluctuation with impellor vane blockages, etc. Pressure monitoring is essential.
	Cannot be varied to suit changes in feed characteristics.	Can be varied to suit either feed changes or general impellor wear through use of variable-speed drive.
Power failure	Most medium drains back to the circulating medium tank. No gravel solids in medium are dumped to the floor while purging the circulating medium pump.	A greater volume of medium, including feed gravel, must be dumped to the floor to avoid cyclone feed pump blockage.
Building size	High	Compact

Cyclones with 40-degree cone angles have been utilized in the past for feed containing a large number of flat particles (e.g., on marine gravels with high shell content). However, such high cone angles generate high-density differentials, leading to the need to operate the cyclone with unusually low feed densities (as low as 1.8 sg) to maintain a cut density of <3.2 sg. The high differential in turn promotes retention of coarse dense particles that do not immediately leave the cyclone but linger between the cyclone spigot zone and the vortex finder zone. This situation can potentially lead to the ejection and loss of a large diamond to the float stream.

Gravity Versus Pump-Fed Cyclones

Both gravity- and pump-fed cyclone feed arrangements are in common use. There is a tendency for small- to medium-capacity operations to pump-feed the dense medium cyclones, with medium- to high-capacity installations using gravity feed. Each has advantages and disadvantages that influence the selection in each case. Although debate is influenced by various perceptions of potential benefits and drawbacks, some of which are exaggerated, the principal differentiating features are listed in Table 3.

The most common cyclones in use and their associated capacities at different geometric feed head (multiples of the cyclone diameter) and typical feed size ranges for primary diamond recovery are shown in Table 4. Note that, when

Table 4 Diamond recovery cyclones

Nominal Cyclone Diameter, mm	Capacity at 9D Head*		Capacity at 14D Head*		Capacity at 18D Head*		Typical Feed Size Range, mm‡	M/O Ratio	FeSi Grade
	m^3/h	t/h†	m^3/h	t/h†	m^3/h	t/h†			
250	31	10	39	13	44	15	0.5–10	7:1	270D
360	61	23	77	29	87	33	0.8–20	6:1	270D
420	94	36	118	45	133	50	1–25	6:1	150D
510	134	59	168	74	190	84	2–30	5:1	150D
610	187	83	235	104	N/A§	N/A	6–32	5:1	100D

*Capacities for standard Dutch State Mines cyclone configuration. Capacity can be increased approximately 10% if an extended barrel section is fitted.
†Solids capacity at M/O ratio and average solids of 2.65 sg.
‡Cyclone size is selected based on the minimum size of feed.
§610-mm cyclones are very rarely used above 14D head.

Table 5 Ferrosilicon specification for diamond applications

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

Data from DMS Powders (Pty) Ltd.

employed in a reconcentration duty, medium/ore (M/O) ratios are typically two to three times higher relative to a primary separation. The FeSi grade listed is described further in Table 5. The capacity of large installations (higher than 200 t/h feed capacity) is provided by parallel streams.

Media Type and Specification

FeSi medium for diamond recovery is usually milled with a 14%–15% silicon content. Atomized FeSi can be used, but it is more expensive than milled and the separation densities required for diamond recovery do not warrant the lower slurry viscosity of the atomized product. Atomized FeSi is used for higher-density separations (>3.6 sg) for iron ore manganese and other high-specific-gravity minerals. The FeSi designation or grade is based on the particle size distribution. Generally, coarser grades are slightly cheaper and also result in lower medium losses, as finer particles are less efficiently recovered in screen washing and are less efficiently recovered by magnetic separators.

The three grades represented in Table 5, which refer to DMS Powders products manufactured in South Africa, cover at least 90% of FeSi used in diamond heavy medium processes.

Media Recovery Systems and Losses

Diamond recovery heavy medium cyclone floats and sinks products are processed in the same way as other heavy medium separation commodities, with the exception that the sinks product represents a very small fraction of the feed (usually <1% by mass) but contains at least 99.5% of the value of any diamonds present in the feed. Physical barriers protect the sinks product from unauthorized access, and strict security procedures and remote monitoring protect personnel from unwarranted suspicion or accusations.

In a well-run installation, the total of process plus corrosion losses should be in the range of 150–300 g FeSi per metric ton of feed solids. Smaller installations, where compromises in equipment sizing have been made to reduce capital cost, may incur losses as high as 300–500 g/t of feed solids.

Performance Monitoring

The density of separation is the key control variable to maintain plant performance. The circulating medium density should be monitored continuously by density gauges. Other common online performance measurements are the cyclone feed pressure and, naturally, the rate of feed of fresh gravel to the cyclone(s).

Regular testing of the separation efficiency is undertaken using colored beads (tracers) of closely controlled density and different sizes representing the gravel feed size range. In diamond recovery plants, the principal purpose is to confirm that diamonds are not being lost. Introducing tracers of different sizes but the same density as diamond (3.53 sg), tests can be performed integral with the gravel feed, as the volume of sinks is usually very small (<1% of cyclone feed), and the tracers hence are recovered relatively easily by placing a mesh basket over the end of the sinks screen. The expectation is that 100% of all such tracers larger than 2 mm will be recovered, with at least 95% of 2-mm tracers recovered.

Attempts have been made over many years to develop an automated system of detecting and recovering tracers, but these have not found widespread use to date. Early testing of irradiated diamonds (irradiation turns them green) has given way to potentially promising technologies such as the use of tracers containing radio-frequency identification (RFID) tags. However, the smallest size at which RFID tags are currently practical and detectable (perhaps 10 mm) is too large for measuring cyclone DMS efficiency. The presence of water on the products and rinsing screens is also a significant barrier to this technology, as water masks the radio signal.

FINAL DIAMOND RECOVERY

The final diamond recovery process usually involves the following key steps:

1. Bulk mass reduction using wet or dry high-intensity magnetic separation

2. Primary (bulk) X-ray recovery
3. Single-particle X-ray recovery
4. Grease scavenging/auditing
5. Final cleaning

Magnetic Separation

With few exceptions, diamonds are nonmagnetic. The heavy minerals that accompany the diamonds from the previous gravity concentration process (usually DMS) may have paramagnetic properties that provide a mechanism to greatly increase the concentration of diamonds in a low-cost dry process.

Although not essential in the coarser size fractions (>8 mm), the feed is usually dried because this eliminates drag and surface tension effects from entrained water. The feed is also separated into narrow size ranges (maximum 3:1 ratio) to allow the separator operating parameters to be optimized.

Either rare-earth rotating magnetic drum separators are used or a very thin continuous Kevlar belt is used by passing it over a head pulley constructed of an array of high-intensity magnets (e.g., MagRoll, Permroll). In either case, diamonds are unaffected by the magnetic field and are projected into a forward trajectory by the speed of the drum or belt. The magnetic minerals are attracted to the magnet array and follow a downward trajectory when out of the influence of the magnet. A simple splitter arrangement is used to direct the diamonds and heavy minerals into different bins. However, as the high-strength magnets are also high-gradient, this means that the magnetic field falls away very fast with distance from the magnet surface. The farther away the center of mass of a "magnetic" particle is from the surface of the magnet, the less attractive force is experienced, and only a weak change of trajectory is achieved on leaving the device. A mass rejection of 70%–90% is not uncommon in the <4-mm size fraction, falling off as the particle size increases. Design and control of typical units is described by Gehauf (2004).

X-Ray Sorting

It is in the final recovery section of a modern diamond processing plant that technology developments associated with sensor-based sorting have had a major impact. The fact that almost all diamonds (except most Type II) fluoresce under X-ray stimulation has been exploited since the 1970s, with steady advances in sorter sensitivity and discrimination. Much faster signal processing and intelligent algorithms, along with developments such as dual-wavelength sorters, have greatly improved the ability to recover smaller diamonds without unacceptable contamination from other minerals through poor discrimination or electronic noise. X-ray fluorescence (XRF) sorters have predominantly been confined to operation on DMS concentrates. However, many Russian plants use sorters in preference to DMS and up to very coarse sizes. DMS is a bulk separation process where particles follow a stream through the separation vessel determined by their specific gravity, whereas XRF is a single-particle discrimination process where each diamond must be identified and captured individually. For the sorter optical sensors to "see" the diamond, the stream of feed flowing through the sorter must also be a single-particle layer, so that diamonds are not obscured by nonfluorescing particles. As the particle size becomes smaller and the bed depth thinner, the capacity of the sorter diminishes rapidly and additional sorters are required to handle the throughput required. It is therefore unlikely that XRF will completely replace DMS in new plants, except for very small tonnage operations. Current trends suggest that DMS will remain the choice for sizes smaller than 6 mm, with XRF becoming established for sizes greater than 10 mm. Ore- and mine-specific factors will dictate whether XRF or DMS is the best selection for material in the 6–10 mm range.

A more recent development is the introduction of XRT sorting, which does not rely on detection of emitted light from the diamonds. The diamonds are detected using a dual-energy discrimination method targeting the atomic mass of the constituent carbon. This means that all diamonds are potentially recoverable. Since there is no need for the sensor to directly "see" the diamond, higher capacities are possible, as a monolayer is not essential, although bed-depths must still be controlled. An extension of this is the potential ability to detect diamonds that are unliberated (Riedel and Dehler 2010). Currently, however, signal processing limits the bottom size of diamonds recoverable by XRT to about 6 mm. Although this appears to be a retrograde step compared to XRF sorters that routinely process material down to 1 mm, the Type II diamonds that XRT sorting can also recover represent more typically the largest and most valuable diamonds in the deposit, which will hence be more reliably recovered (along with essentially all other diamonds in the same size range). Also of interest is the fact that XRT can detect diamonds that are still partially or fully encapsulated in host kimberlite particles, with the ability to detect a 10-mm diamond within a 30-mm kimberlite particle shown to be feasible.

Although sensor-based sorters using CCD color cameras (based on reflection and transparency) and photometric sorters (based on refection/absorption) have been used in diamond recovery, they have not found widespread use.

A final step in the application of sensor-based sorting is the use of laser-based sorters using the raman-shift phenomenon produced by the diamond crystal lattice to identify diamonds. This is a particularly diamond-specific technology, and it can be used as a final "confirmation" to provide certainty of final product integrity. However, the signal strength produced by the raman shift from a small diamond is very weak and requires long signal acquisition times, limiting throughput. As a defalsifying application, laser-raman sorters are also true single-particle sorters, again resulting in very low throughput rates (of the order of 250 g/h for 1–2 mm size diamonds)

Grease Scavenging and Auditing

The majority of diamonds exhibit natural hydrophobic behavior (not wettable) in a flowing stream of water), which has been exploited to recover them for more than 100 years. The diamond surface would rather adhere to grease than stay wetted in water. Most of the other minerals in diamond concentrates are wettable. This means that grease capture is a very highly specific method for recovering free diamonds because very little waste material is captured along with the diamonds.

Washed and sized gravel containing liberated diamonds is flushed in a controlled manner over a screen, continuous moving belt (rubber or plastic), or a rotating drum. The separation surface is coated with a thin film of petroleum grease. Although the vast majority of the material is flushed over the grease and discarded, most diamonds stick to the grease. The loaded grease is removed either on a batch basis by hand or, in more modern equipment, automatically. The grease is melted, and the trapped diamonds are released for cleaning in a solvent or detergent. The grease is reapplied to the separating device surface for reuse. Grease is specifically formulated for this application and is commercially available for diamond recovery use from major producers such as Shell and Mobil. It is a blend containing sufficient wax to provide a surface that is stiff enough to avoid penetration by wetted particles, but "sticky" enough to avoid adhered diamonds from being flushed away in the flowing stream of water and waste particles. Since these properties are sensitive to temperature, the temperature of the water flowing over the grease needs to be maintained within limits, usually around 25°C.

Diamond recovery using grease is, in its simplest form, a very low-cost method. However, there are drawbacks to relying purely on grease as the final recovery method of choice:

- Not all diamonds will stick to grease. The reason is usually that they have become coated over time with a mineralized layer. This can sometimes be removed using attritioners, with or without conditioning chemicals.
- Separating very small diamonds from the grease can be a lengthy process because of the high viscosity of the molten grease.
- From security principles, it is considered undesirable in most major installations to allow direct contact between personnel and diamonds, which implies it is necessary to automate the whole grease process.
- Automated grease belts and drums are relatively complex to control and maintain to a high level of performance that ensures continuous and reliable recovery of degreased diamonds, and hence are no longer as cheap and simple as the concept implies. Capital costs can be the same as for an XRF sorter treating the same magnitude feed stream.
- Failures of the system, apart from resulting in spillage of diamond-bearing material, usually result in contamination of peripheral equipment. Surrounding structures can become coated with grease over time if grease is overheated during the melting process.

However, grease is still considered to have a legitimate role as a scavenging, or auditing, process following removal of essentially all the diamonds using XRF or XRT sorters.

Diamond Cleaning

An important part of ensuring the integrity of the diamond value management chain is in ensuring that what is called a diamond product is 100% diamond and nothing else. This means that diamonds must be cleaned, preferably at the earliest opportunity, and certainly before they are certified to be "diamond." Along with the removal of any remaining discrete particles of non-diamond origin, it is also necessary to ensure that no coatings remain on the diamonds. Several processes are employed, most commonly caustic fusion followed by a "deep-boil" in a combination of strong acids. Although time-consuming, the latter has the advantage of potentially removing a very thin outer skin from the diamonds, which represents the "interface" between the diamond and the environment over many millions of years. Removing this "damaged" layer can result in a net higher value being attributed to the diamond, despite the small loss in mass.

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