

The importance of grease technology in diamond recovery

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Grease technology is still the most reliable method for recovering small diamonds. Diamonds are unique in that they are the only hydrophobic mineral, and sorting on hydrophobicity can result in the one of the lowest yields of all the diamond recovery technologies. Diamond deposits where most of the grade resides in the smaller diamonds should incorporate grease recovery in their flow sheets. X-ray sorting can miss as much as 85% of the -1 mm diamonds and 70% of the -1.5 mm diamonds. X-ray recovery is also problematic with Type II diamonds. X-ray transmission (XRT) technology is the dominant technique for the recovery of large diamonds, but is currently limited to diamonds larger than 4 mm and thus has a limited role in the recovery of smaller diamonds.

INTRODUCTION

X-ray transmission (XRT) is the latest technology used in the recovery of diamonds. The XRT technology uses X-rays to irradiate mineral particles on a belt and X-ray cameras to measure the atomic density of each particle. The atomic density data is processed to obtain an atomic density image of each particle, which is used as a basis for sorting. The high atomic density particles (diamonds) are removed from the ore stream using air ejectors (TOMRA, 2018). However, in a bulk sorting scenario, XRT can only sort particles greater than 4–6 mm (Lahee, 2017), which leaves the majority of diamonds (approx. 70%) to be recovered by conventional technologies such as dense media separation (DMS), magnetic sorting, X-ray luminescence, and grease recovery.

In Canadian National Instrument 43-101 reports, which are comparable with the South African Code for the Reporting of Exploration Results, Mineral Resources and Mineral Reserves (the SAMREC Code), we typically see graphs showing the microdiamond grades obtained from digestion processes and macrodiamond grades obtained from bulk sampling plants, as shown in Figure 1.

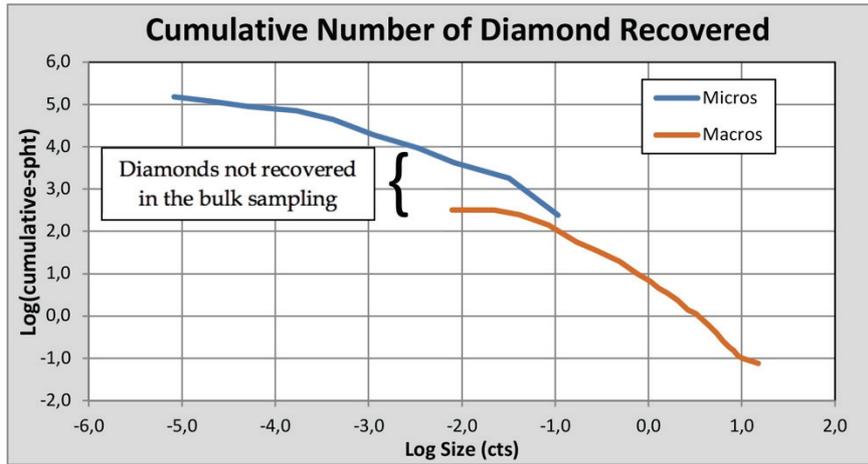


Figure 1. Cumulative recovery of micro- and macrodiamonds by number.

These diamond recovery graphs show a significant discrepancy between the recovered diamond grade and the actual diamond grade ore between 0.01 cts (1.0 mm diamonds) and 0.1 cts (2.3 mm diamonds). Although inadequate liberation of the small diamonds is partly responsible for this discrepancy, the main cause is the inefficiency of X-ray recovery for these small diamonds. This loss of these small diamonds results in a revenue loss that can cause a marginal diamond project to fail.

X-RAY RECOVERY

The majority of diamond recovery flow sheets incorporate X-ray technology as the main recovery method, assuming that all diamonds luminesce when irradiated by X-rays. However, auditing of X-ray luminescence plants reveals a high number of low-luminescent diamonds in the tailings. Diamond luminescence is a function of the diamond's size, Type, quality, and nitrogen content. Therefore, good-quality Type II diamonds are often rejected by these X-ray machines, as well as small diamonds. X-ray luminescence technology can miss as much as 85% of the 0.85–1.2 mm diamonds and 70% of the 1.2–1.5 mm diamonds, which is typically equivalent to a 9% revenue loss. Further diamond losses of 50% have been experienced in the 1.5–2.0 mm size fraction, which accounts for an additional 6% revenue loss. All the diamond losses in the size fractions between 0.85 mm to 5.0 mm can represent a revenue loss of up to 25%, as documented in Table I.

Table I. The expected diamond loss in a production environment when using only X-ray luminescence recovery technology.

Size fraction (mm)	Expected diamond loss by X-ray sorting	Occurrence of size fraction in the diamond population	Estimated revenue loss
4.0–5.0	0.5%	6%	0.03%
3.0–4.0	10%	15%	1.5%
2.5–3.0	25%	11%	2.8%
2.0–2.5	40%	13%	5.2%
1.5–2.0	50%	12%	6.0%
1.2–1.5	70%	9%	6.3%
0.85–1.2	85%	3%	2.6%
Total		69%	24.4%

GREASE RECOVERY

To improve the recovery of the low-luminescent diamonds (diamonds not recoverable using X-ray technology), grease recovery technology is often used. In such instances, grease technology is set up as a scavenger operation to treat the tailings from X-ray sorting. In this configuration, the entire ore stream is processed by both X-ray technology and grease technology. However, when grease recovery is employed in a scavenger role, little or no effort is made to optimize the technology, since the emphasis is on X-ray luminescence to recover the bulk of the diamonds. Furthermore, grease technology is often treated more as an art than a science, and as a result, negligible control mechanisms are incorporated into its operation.

Correctly operated, grease technology recovers both luminescent and non-luminescent diamonds and could (or should) be used as the main recovery technology for the -6 mm diamonds. Using a double-pass grease recovery process would enable a plant to forgo the potentially dangerous, high-maintenance, and capital-intensive X-ray section of the process plant.

In a wet/damp diamond recovery circuit, grease recovery has the added benefit of removing the need to dewater or dry the DMS concentrate. Wet DMS concentrate can be pumped to a wet magnetic separator and then to grease recovery. Removing the need for dryers and X-ray units would simplify the plant design while also removing up to two floors in a gravity fed recovery building.

THE SCIENCE OF GREASE RECOVERY

Grease recovery has been used for decades and pre-dates X-ray technology. However, comparatively little research has been conducted on the recovery of diamonds using grease technology, although it involves a significant amount of chemical and physical science. Diamonds are hydrophobic, and in practice this characteristic can be regarded as being unique to diamond. Diamonds are also oleophilic and adhere to a greased surface.

To sort diamonds from gangue using grease technology, the diamonds and gangue are first transferred to a water bath. The wet ore is then fed to an inclined greased chute, table, or belt, over which warm water is flowing. The diamonds drop through the water and, being hydrophobic (dry) and oleophilic, adhere to the warmed, tenacious sticky grease. The gangue, being hydrophilic and therefore wet, does not adhere to the grease (grease and water do not mix) and is instead washed away by the flowing water.

At the end of a shift, the grease and diamonds are scraped off the chute, table, or belt and placed in a boiler or melting tank with water. The increase in temperature melts the grease, which loses its tenacity, so releasing the diamonds which then drop into the hot water below. The melted grease floats on the surface of the hot water and is removed, leaving the water and diamonds behind.

To operate grease technology efficiently, the following parameters must be understood and controlled.

- *Water flow rate* – the water flow has to be adjusted to suit the particle size being processed: high flow rate for large particles, low flow rate for small particles
- *Water surface tension* – the surface tension should be around 72.8×10^{-3} N/m and void of any surfactants
- *Water turbidity* – water turbidity is a function of various contaminants in the water. However, most kimberlitic clay contaminants stay suspended in the water and do not adversely affect the grease recovery process
- *Water temperature* – the water temperature affects the grease temperature. Low water temperature and firm grease are required for large diamond recovery, while higher temperatures are required to soften the grease for the recovery of small diamonds

- *Grease thickness* – the function of the grease is twofold: to capture the diamonds and to absorb the kinetic energy of the diamonds as they fall from the feeder onto the greased surface. The grease thickness should be 1/8 to 1/6 the diameter of the largest diamond being processed
- *Grease softness* – the grease is a combination of wax and petroleum jelly, and should be soft enough to allow a diamond to be partially buried in the grease
- *Grease tenacity* – The microcrystalline wax has a ‘tacky-factor’ and imparts a tenacious and viscous component to the grease mixture, which is necessary for the capture of the oleophilic diamonds.

Water flow rate

The faster that water is flowing, the greater its ability to transport material. Fast-flowing rivers carry more sediment than slow-flowing rivers. The higher the water flow rate over a grease surface, the greater the probability that a diamond will be carried away (to tailings) before even touching the grease. The author undertook tests using; synthetic diamonds and different sized hydrophobic tracers with a density of 3.53 g/ cm³ (the same density as diamond) using a 200 mm wide grease chute, inclined at 36°, at different water flow rates, as shown in Figure 2.



Figure 2. The grease chute and 4 mm hydrophobic tracers used in the grease recovery tests.

The test results showed an increase in tracer recovery as the water flow rate decreased, as documented in Table II. However, the function of the water is also to remove/carry the gangue material to tailings. For the water to do this effectively, a high water flow rate is required. To optimize the water flow rate for grease recovery, the ore being fed to the grease recovery section must be narrowly sized (as for X-ray recovery) and the water flow rate set for each size fraction being processed.

Table II. The recovery efficiency of hydrophobic tracers on a grease chute at different water flow rates.

Water flow rate (ml/s)	4 mm tracer recovery (%)	2 mm tracer recovery (%)	1.5 mm tracer recovery (%)	1 mm tracer recovery (%)	-1 mm synthetic recovery (%)
355.3	100%	62%	53%	36%	20%
192.0	100%	100%	73%	71%	63%
69.6	100%	100%	100%	100%	100%

The results of the tests showed that, with this experimental set-up, a water flow rate of 355 ml/s can be used to recover 4 mm diamonds, but diamonds less than 4 mm tend to be washed away. A water flow rate of 192 ml/s can be used to recover 4 mm and 2 mm diamonds, but 4 mm gangue material will not be efficiently washed away and could 'blind' the grease. When the grease is blinded with gangue, diamonds dropping from the feeder will bounce off the gangue instead of penetrating the grease, and be washed away to tailings. Determining the optimum water flow rate for the size fraction being processed is important for maximizing diamond recovery.

Water surface tension

The surface tension of a liquid depends on the intermolecular forces at the surface of the liquid. Water is comprised of polar molecules, with relatively strong covalent bonds between adjacent molecules. In the bulk of the liquid, each molecule is pulled equally in every direction by neighbouring molecules (cohesion), resulting in a net force of zero. At the surface of the water, the surface tension results from a force imbalance. The attraction between molecules (cohesion) below the water surface is greater than to the attraction of the water molecules to the air (adhesion). The net effect is an inward force at the surface that causes the liquid to behave as if its surface were covered with a stretched elastic membrane.

When the cohesive forces are stronger than the adhesive forces, the liquid acquires a convex meniscus, like mercury in a glass container or a diamond in a water bath (Figure 3a). The adhesive force between diamond and water is what keeps the diamond dry. When the adhesive forces are stronger than the cohesive forces, the surface of the liquid is concave, like water in a glass or a mineral particle in a water bath (Figure 3b).

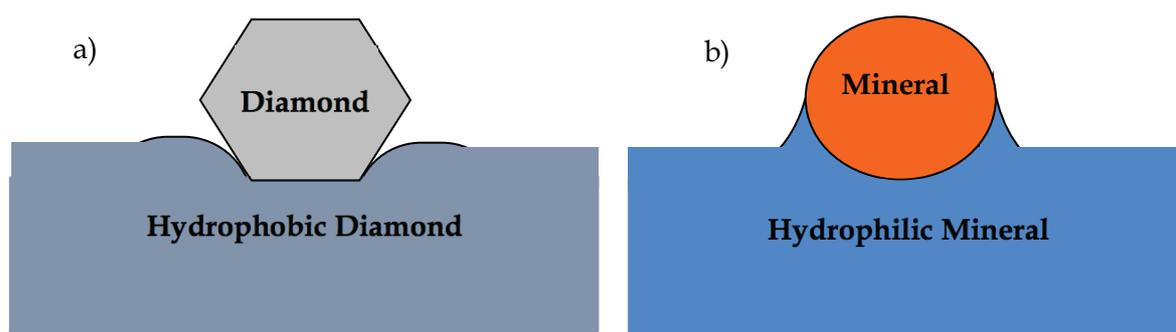


Figure 3. The interaction of (a) water and hydrophobic diamond, (b) water and a hydrophilic mineral particle.

When surfactants or soaps are added to water, the polar hydrophilic head of the surfactant bonds with the water, weakening the cohesion forces between the water molecules and thus weakening the water surface tension. Surfactants can reduce the water's surface tension by a factor of three or more (Bush, 2004). When surfactants are present in the water used in grease recovery, the cohesive forces that enable the diamonds to remain dry are weakened, and the diamonds become wet and no longer adhere to the grease.

Water turbidity

Water turbidity is a function of various contaminants in the water. Kimberlite is usually clay-rich and continually breaks down in the presence of water so, releasing clays into the water. These kimberlitic clays are suspended in the water and can increase the turbidity of the process water by as much as 1000 nephelometric turbidity units (NTU).

The kimberlitic clays adsorb cations and anions, which reside on the exterior of the clay particles (Encyclopaedia Britannica, 2018a), and these charges interact with the polar characteristics of the water molecules. The bond between the clay and water is stronger than the bond between the clay and grease, causing the clay particles to preferentially stay in suspension, then to settle out and adhere to the grease. Figure 4 is a photograph of the clay-rich water remaining on the grease alongside some diamonds and

hydrophobic tracers after a turbidity test, and shows the tendency of the clay particles to remain suspended in the water.



Figure 4. Clay-rich water remaining on the grease chute after a turbidity test.

To confirm the fact that clay particles tend to stay suspended in water rather than settle onto a hydrophobic surface like grease or diamond, water with a turbidity in excess of 3000 NTU was allowed to flow over the grease chute for 3 hours. The grease under the weir was then inspected for contamination and removed. This test was repeated using tap water. The two grease samples were then compared, as shown in Figure 5. The grease with the clay-rich process water on the left is similar to, if not less contaminated, than the grease with tap water on the right.

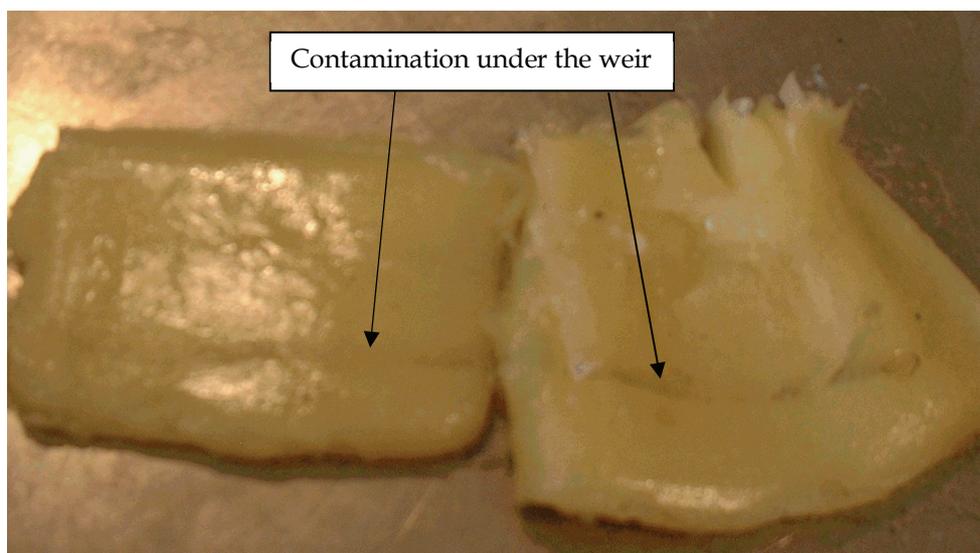


Figure 5. Grease contamination by (left) clay-rich process water, (right) tap water.

The presence of suspended kimberlitic clays in process water does not diminish the surface tension of the water and is not detrimental to grease recovery technology. It has even been recorded as improving the grease recovery process at Cullinan mine, South Africa. Cullinan now runs a closed-circuit water

reticulation system that recycles all water from no. 7 dam (tailings pond) through their plant (Petra Diamonds, 2010). Water from the dam has a high kimberlitic clay content, as shown in Figure 6.



Figure 6. The high clay content of the water in Cullinan's no. 7 dam is seen in the water sample on the far left.

Water temperature

The surface tension of water depends on its temperature. Increasing the temperature of the water increases the Brownian motion of the water molecules and the distance between the water molecules, decreasing the surface tension, which reaches a value of zero at boiling point. The warmer the water in the grease recovery section, the weaker the adhesive forces between the diamonds and the water, which reduces the hydrophobicity of the diamonds.

The grease mixture used in the grease recovery section is usually determined by the largest size fraction being processed. The larger the size fraction, the firmer the grease mixture required, to ensure that gangue does not adhere to the grease. Firmer grease is made by increasing the ratio of wax to petroleum jelly. Once the grease mixture is determined, the grease can then be made softer for the smaller size fractions by slightly increasing the temperature of the water flowing over the grease. This softens the grease and, as shown in Table III, improves the recovery of hydrophobic diamonds.

Table III. The recovery efficiency of hydrophobic tracers on grease at different water temperatures at a water flow rate of 192 ml/s.

Water temp. (°C)	4 mm tracer recovery (%)	2 mm tracer recovery (%)	1.5 mm tracer recovery (%)	1 mm tracer recovery (%)	-1 mm synthetic recovery (%)
30.0	100%	100%	93%	86%	74%
25.0	100%	95%	87%	79%	68%
21.0	100%	90%	73%	71%	63%

Grease thickness

The tendency is to use as little grease as possible, since the thicker the grease the higher the operational costs. The function of the grease is twofold: (1) to adhere to the diamond and so remove it from the water flow, and (2) to absorb the kinetic energy as the diamond falls from the feeder onto the greased surface. The deeper the particle/diamond is buried, the greater the adherence area, as illustrated in Figure 7.

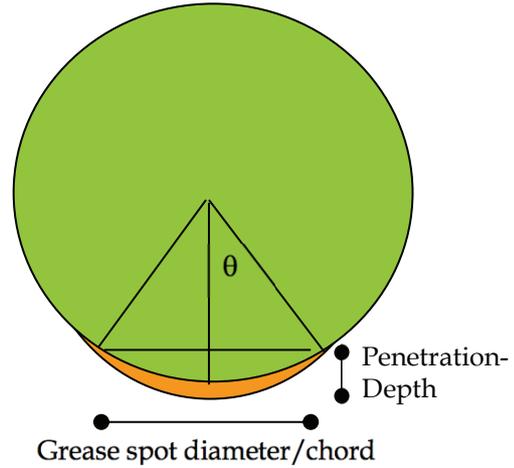


Figure 7. The relationship between the penetration depth and area of adherence of a spherical particle on grease.

The higher the feeder is positioned above the grease, the greater is the diamond's kinetic energy and the deeper it penetrates into the grease. If the grease is too thin, not all the kinetic energy is absorbed by the grease and the diamond will rebound off the greased surface and into the fast-flowing water, where it could be washed to tailings.

The author carried out tests on grease thickness requirements for feeders placed at different heights above a greased surface. Marbles weighing 22.1 g were dropped from heights of; 100, 200, 300, 400, and 500 mm above the greased surface, as seen in Figure 8. The marbles were then removed and the diameter of each imprint was measured, as shown in Figure 9. This chord measurement was used to calculate the magnitude of the subtended angle (2θ), as illustrated in Figure 7. The grease spot residue on each of the marbles is seen in Figure 10. The arc diameter (arc length) of the grease spot was measured and calculated from the subtended angle to confirm that the chord measurements were correct. The penetration depths for each drop height were then calculated, and are given as a fraction of the diameter of the marble in Table IV.



Figure 8. Marbles dropped onto a grease surface from heights of (left to right) 100, 200, 300, 400, and 500 mm, showing the progression of penetration depth.

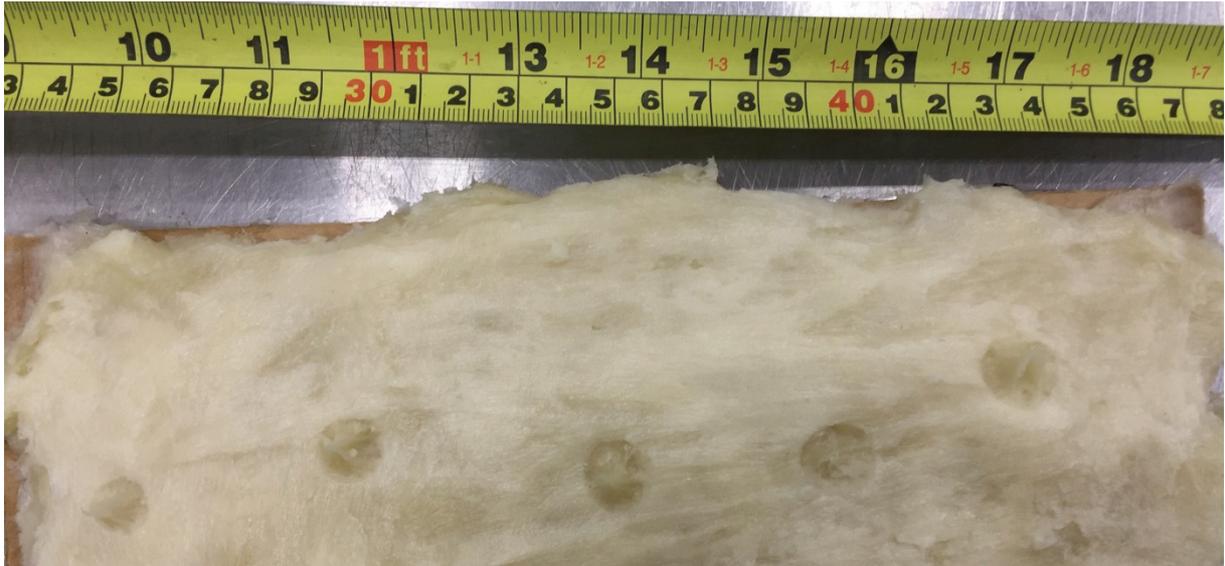


Figure 9. The imprints on the grease surface after the five marbles were removed. These imprints provided the chord measurements.



Figure 10. The grease spots/residue on the five marbles that provided the arc length measurements.

Table V. Penetration depth of a sphere onto a grease surface when dropped from different heights.

Height (mm)	Energy (J)	Chord (mm)	Arc length (mm)	Angle subtended (2θ)	Arc length calculated (mm)	Penetration depth (mm)	Fraction of diameter
100	2.17E-02	10.5	11	49.67	10.84	1.16	1/22
200	4.34E-02	14.0	15	68.11	14.86	2.14	1/12
300	6.51E-02	15.5	17	76.63	16.72	2.69	1/9
400	8.68E-02	16.5	18	82.60	18.02	3.11	1/8
500	1.08E-01	17.0	19	85.69	18.69	3.33	10/75

Diamond has a higher density than glass, and slightly higher penetration depths are expected from diamond. These tests indicate that for a drop height of 200 mm from a feeder to a grease surface, the

grease thickness should be 1/8 to 1/6 the diameter of the largest particle being processed. The additional thickness is to ensure that there is still grease between the diamond and hard surface that can absorb the kinetic energy of the fall.

Grease softness

The grease used for the recovery of diamonds is made from a combination of petroleum jelly and microcrystalline wax. Petroleum jelly is a semi-solid mixture of hydrocarbons with a low melting point around 37° C. Microcrystalline wax is a solid at room temperature with a fine crystal structure of branched hydrocarbons. Microcrystalline wax has a higher molecular weight than other waxes, is denser, and has a higher melting point between 73°C and 93°C (Encyclopaedia Britannica, 2018b).

A combination of petroleum jelly and microcrystalline wax in a ratio of 4:1, made by melting them together at around 98°C, creates a soft grease. A higher temperature can burn and discolour the grease. The higher the ratio of petroleum jelly to wax, the softer the grease. The softer the grease, the easier it is for diamonds to bury themselves in the grease. However, dense minerals such as magnetite and monazite can fall through the water and land on the grease surface, where they also become buried in a soft grease. The recovery of non-diamond minerals causes the grease recovery yield to increase. Thus, the softer the grease, the higher the yield from grease recovery and the greater the demand on the hand-sorters at the end of the process. In general, the smaller the size fraction being processed and the smaller the diamonds to be recovered, the softer the grease required. The larger the size fraction and the diamonds being processed, the firmer the grease required.

Grease tenacity

Microcrystalline wax is more viscous, denser, tackier, and more elastic than other waxes. When microcrystalline wax is mixed with petroleum jelly it forms a sticky grease that adheres strongly to oleophilic particles, as seen in Figure 11.



Figure 11. The grease mixture after hydrophobic tracers have been removed from its surface.

The viscosity and tackiness of the microcrystalline wax impart the mixture of wax and petroleum jelly with the necessary characteristics to efficiently capture and retain the oleophilic diamonds. The grease adherence needs to be stronger than the force of the water tending to dislodge the diamond and the force of gravity acting on the diamond on the incline.

Grease belts are designed so that the diamonds adhering to the grease are subjected to the water flow rate for only approximately 10 minutes before they are moved out of the stream. The diamonds captured on grease table can be removed before the end of a shift to reduce the probability of them being dislodged by the water. The grease surface can dry if left standing in the absence of water. Allowing the

grease to dry (e.g. during a maintenance period) causes a thin crust to form on the grease and a loss of tenacity. When this occurs, the grease should be re-mixed to restore its tenacity.

DISCUSSION

Grease recovery has traditionally been regarded as more of an art than a science, where operators set parameters with little or no test work. From research and tests using hydrophobic tracers to represent diamonds in the various size fractions, the correct operating parameters can be determined and optimized. Utilizing the appropriate operating parameters, grease recovery technology can recover 98–99% of liberated diamonds. This surpasses the performance of X-ray luminescence technology, which is guaranteed to recover 98–99% of only the luminescent diamonds – a significantly lower percentage than all the liberated diamonds.

The grease recovery processes is being optimized at various mines in South Africa, using rotating grease belts. Grease belts remove the need to manually apply grease to a surface as they continually apply grease via a fireball pump and an applicator positioned at one end of the belt. The grease and concentrate are removed at the other end of the belt, and drop into a hot water tank, as shown in Figure 12. When the grease is melted at 98 C to form an oil, the diamonds drop out of the grease into the water. The molten grease is then drained off via a weir, cooled, and recycled back onto the belt.



Figure 12. Photograph of the grease being removed from a grease belt and dropping into a melting tank.

CONCLUSIONS

- Hydrophobicity is a unique characteristic of diamonds, and if exploited correctly can be used to sort diamonds from diamondiferous gangue while producing low yields of concentrate.
- Grease recovery technology is a science when all the operating parameters have been correctly identified. Further tests are required to quantify the operating parameters and to develop a suitable process model to improve the performance of the technology.
- The characteristics of the diamonds and kimberlite are different at each deposit, thus the operating parameters for grease recovery need to be determined for each deposit. Making use of hydrophobic tracers will facilitate this action.

- Quality control (QC) tests must be carried out on the grease to ensure that the mixture and tenacity are correct. These QC tests would be process-dependent, but should include penetration measurements and tackiness tests. The author has carried out the latter by shaking an inverted greased board with different sized hydrophobic tracers adhering to it.
- Instrumentation for measuring the water flow rates and water surface tension should be in place, as these parameters change and fluctuations could be detrimental to diamond recovery.
- Grease recovery technology is more efficient than X-ray luminescence technology in recovering both small diamonds and Type II diamonds;
- An optimized grease recovery process can reduce the diamond losses currently incurred by most diamond mining operations.
- Grease recovery can be automated, as has been done to some degree using grease belt technology. Automation reduces the labour requirements, while also increasing security.

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