The application of XRT in the De Beers Group of Companies

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In this paper we provide a broad overview of the multiple applications of X-ray transmission (XRT) in the De Beers Group of Companies. We include localities from marine to alluvial and kimberlitic operations across the complete diamond size distribution range. XRT is a technology that is sweeping across the industry with the potential to claim the title of the single technology for all diamonds. We also describe the XRT technique and explore some of the challenges that are still to be overcome.

INTRODUCTION

X-ray transmission (XRT) sorting has become the preferred recovery technology option in several parts of diamond-winning flow sheet. This is due to its high selectivity using atomic number as the main discriminating material property, supported by major advances in the underlying enabling technologies. The latter include increased computational speeds, improved algorithm design, and advances in camera and X-ray source technology. In the De Beers Group, applications of XRT are found across kimberlite, alluvial, and marine operations. This is the result of intensive R&D conducted over the years to arrive at a suite of machine embodiments capable of fine diamond auditing and sorting, as well as large and coarse diamond recovery.

The first applications in the marine environment used the technology in an auditing mode that quantified the diamond content in the export product stream. This served as a useful early predictor of diamond content, weeks ahead of sorthouse returns. In addition to high levels of predictive accuracy, the same machines are now available with ejection capability to produce very high final product grades. The machines operate in the size range –25 +1 mm, best suited to re-concentration applications.

The next application was tests on coarse alluvial gravels as an alternative to dense medium separation (DMS). The results were very encouraging in terms of capacities, yields, shell rejection, and recoveries. Tests are planned for both green- and brownfield kimberlite environments, as well as to explore an alternative to conventional techniques in final diamond recovery.

At the Jwaneng mine Large Diamond Pilot Plant (LDPP), the objective is to recover diamonds in the size fraction –45 +25 mm, an area in which much anecdotal evidence has accumulated over the years, and is now being put to the test. This is similar to other applications across the industry looking to recover large diamonds upfront prior to secondary crushing.

The technical challenge remains in the finer sizes, for high capacity-machines as direct alternatives to conventional diamond recovery technologies. This is an area of ongoing R&D and it is only a matter of time before the breakthrough emerges.

X-RAY TRANSMISSION FUNDAMENTALS

XRT makes use of X-ray imaging techniques to analyse objects and materials, and has a wide range of applications from baggage scanning for security purposes (Martz *et al.*, 2016), to recycling of waste material (Owada, 2014). During the last decade XRT has been applied to an increasing extent in the minerals processing industry (von Ketelhodt and Bergmann, 2010; Sasman, Deetlefs, and van der Westhuyzen, 2018). Dual-energy XRT (DE-XRT), in which images of the target material are obtained at both high and low X-ray energies, allows for elemental analysis and therefore can be used to discriminate between various minerals.

A DE- XRT system makes use of a dual-energy X-ray line scan sensor to generate images of transmitted X-rays (Figure 1). Dual-energy refers to the camera, which contains two sensors, one responding to low-energy X-rays and one to high-energy X-rays. Feed material can be imaged either while on the belt, or while in flight.

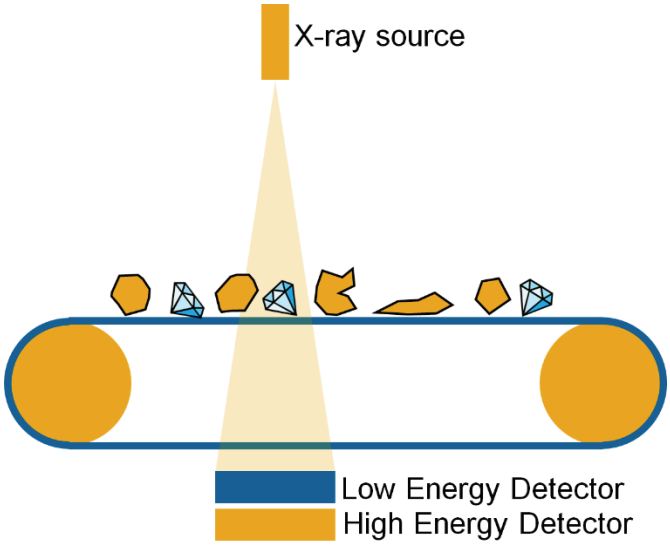

Figure 1. Schematic of a dual-energy line-scan system.

Examples of raw X-ray images of diamondiferous feed material are given in Figure 2. Particles appear as shadows in the image, as X-rays are absorbed by the particles and fewer arrive at the detector. The shadows appear darker in the low-energy image than the high energy-image, since low-energy X-rays are more readily absorbed than high-energy X-rays.

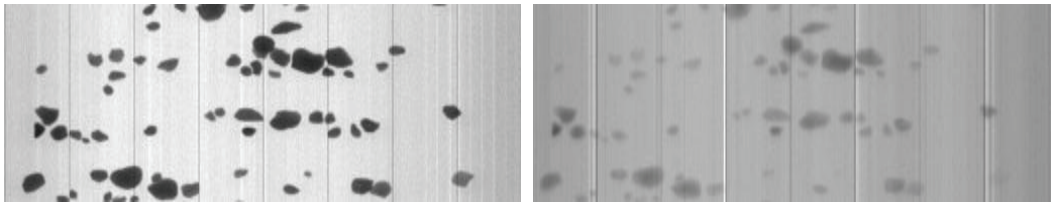

Figure 2. Examples of low-energy (left) and high-energy (right) images of diamondiferous material passing the X-ray line-scan camera.

The extent to which materials absorb X-rays depends on the types of elements present, density and thickness of the material, as well as the characteristics of the X-rays. Each mineral absorbs high- and low-energy X-rays in different ratios.

Figure Figure 3 shows the theoretically predicted absorption of high- and low-energy X-rays for various minerals of varying thickness, derived from the material properties (XCOM, 2018). It is evident that

diamond can be separated from other minerals. Note that Figure 3 represents the ideal case. In practice, detector noise and other variations result in imperfect discrimination. This is especially true for small particles.

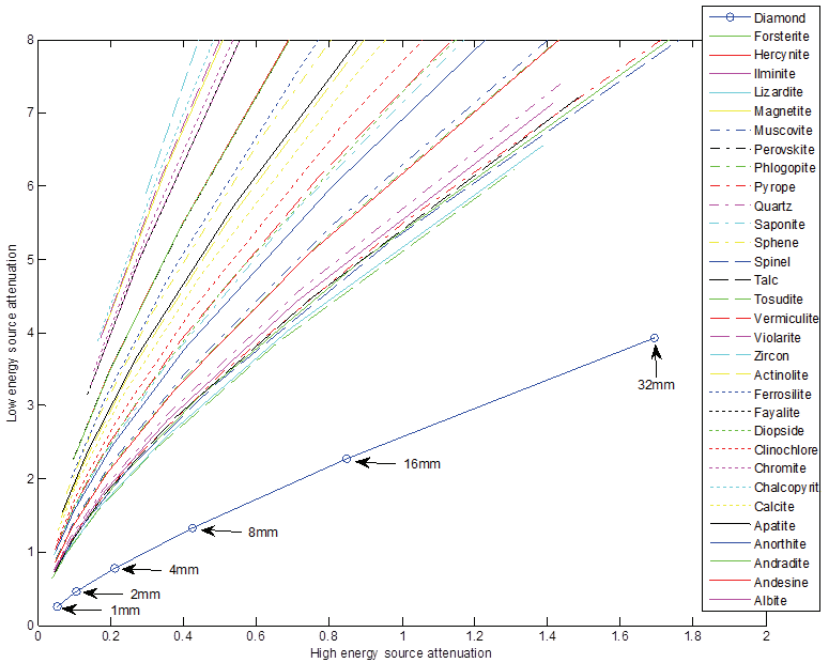

Figure 3. Result of a theoretical study of how various minerals absorb high- and low-energy X-rays. Diamonds can be separated from other minerals based on their absorption of high- and low-energy X-rays.

The high- and low-energy images can be combined, and each pixel coloured according to its classification as shown in Figure 4.

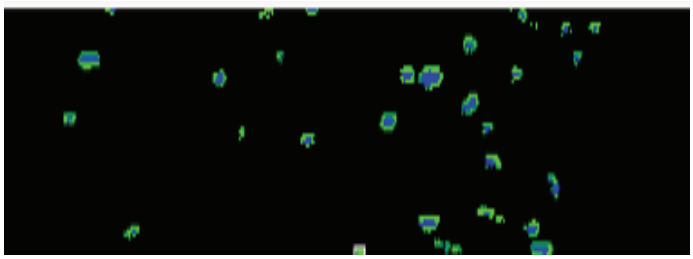

Figure 4. In this classified image, green regions represent diamond and blue non-diamond. The green rims around non-diamond particles are regions where the material is too thin to be classified correctly.

Image processing techniques are used to identify particles in the classified image. Various tests are carried out on each particle before it is identified as a target or non-target. In a sorting machine embodiment the target particles are typically ejected from the material stream using an air ejection system.

In addition to identifying particles, the XRT absorption images contain information from which the size and mass of particles can be inferred. This allows for diamond auditing applications, which are discussed further below.

A SUMMARY OF XRT IN THE DE BEERS GROUP

The first XRT system in De Beers was developed by the De Beers Diamond Trading Company in 1990. This is a laboratory system used for detecting and analysing liberated diamonds in the Kimberley Microdiamond Laboratories, and a version is still in use today.

Following this, in the early 1990s the De Beers Mineral Processing Division in Johannesburg evaluated XRT as one of the technologies for detecting unliberated diamonds within kimberlite. At that time, fast neutron radiography was identified as the preferred method for detecting these unliberated stones. During this work, XRT again showed great potential for the detection of liberated diamonds, although the commercially available excitation and detection technology was not yet mature enough for application to kimberlite processing or diamond recovery.

The major advantages that XRT offered were:

- All diamond types would be recovered with no concerns regarding low-luminescing stones
- Ultra-low yields would be possible, making new flow sheet designs feasible
- Lower sensitivity to dust and masking effects than conventional optical techniques.

However, challenges remained for XRT on multiple fronts (Buxton and Crosby, 2008):

- Predicted throughputs were low at the targeted size ranges
- The robustness of the enabling technology was poor
- The cost of developing a viable sorter to compete with existing equipment was prohibitive
- Reliable performance benchmarks were nonexistent and thus trust was low.

Nevertheless, during the next decade the underlying excitation, detection, and data processing technologies made steady progress and viable sorting machines became a possibility in the mid-2000s.

The following application areas for XRT were identified and pursued:

- To provide online diamond auditing information. The first XRT auditing trials were run in 2013 on offshore marine vessels.
- To complement X-ray luminescence (XRL) sorting machines in the recovery plants to produce concentrates containing a high weight percentage of diamonds. XRT reconcentration machines have been operating on offshore marine vessels since 2016.
- As a low-OPEX alternative to coarse DMS that would be insensitive to feed density. The first XRT pilot plant was operational in 2014 at Namdeb.
- To recover large diamonds early in the flow sheet. The Jwaneng mine LDPP will operate from 2018 to 2019.

Going forward, challenges remain as regards fine diamond recovery, particularly with wet fine material. In addition, applications in the re-deployable and ultra-coarse domains are being watched with interest and may be able to unlock further value for De Beers.

MARINE AUDITING AND SORTING APPLICATIONS

XRT can provide real-time estimates of diamond size frequency distributions (DSFD). This is because high-resolution images of the feed material are captured and the absolute X-ray absorption of a particle depends on its size and mineralogy. The carat mass of individual diamonds can therefore be estimated as they are processed.

Real-time DSFD information provides particular benefit in the marine mining environment. In a typical marine operation, the sea floor is systematically mined in well-defined sections. The final concentrates, usually the product of X-ray reconcentration unit processes, are canned on board. Consignments are exported to land on a regular basis, where they are sorted and sized in a hand-sorting facility. It is only

at the end of this process, which can take several days, that the recovery statistics for a particular mining area become known. Plant metallurgists rely on proxy measures, such as the number of ejections recorded by the diamond recovery machines. These measures vary significantly depending on the machine set-up parameters and the mineralogy of gangue material being fed to the circuit.

De Beers Marine (DBM), De Beers Marine Namibia (DBMN), and De Beers Technologies (SA) began a collaborative XRT test programme in 2013. A mine test unit (MTU) was installed on the DebMar Atlantic Mining Vessel. The final concentrate underwent XRT analysis before being canned for export.

Over a one-year test period, the XRT estimate of DSFD and total carat content was compared with the sorthouse results on a consignment basis. The tests were successful, showing that XRT provides an accurate and timeous estimate of the DSFD and carat content of the final concentrate. The XRT unit process (BDT1122) has since been commercialized and installed on five DBMN mining vessels. The machines are available in either an auditing configuration (providing carat and DSFD information), or a reconcentration configuration (where sorting functionality is included).

Figure 5. XRT reconcentration machine (BDT1122) installed on a mining vessel. The machine processes the final recovery plant concentrate before canning.

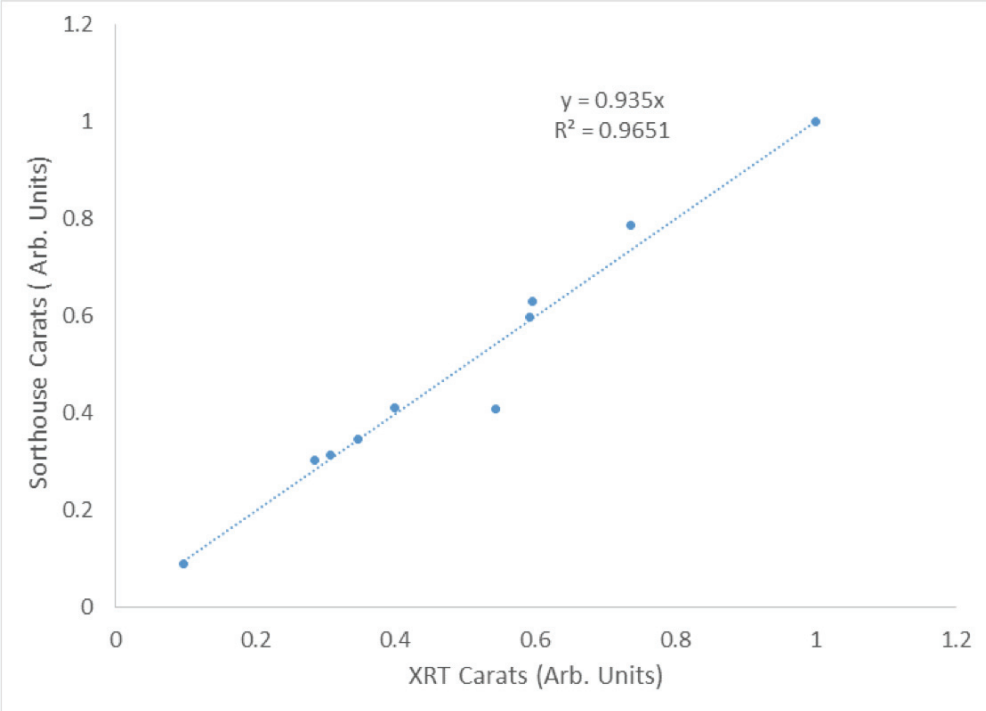

Figure 6. Correlation between the total carats recovered by the sorthouse and the XRT estimate on a consignment basis.

Figure 6 shows a typical correlation between carats recovered per consignment in the sorthouse **versus** the total carat content estimated by XRT, for +3ds material. XRT generally provides an accurate estimate of total carats recovered, and has replaced other proxy methods as a real-time measure of recoveries on many marine operations.

While the application of XRT in the marine mining environment has proved useful so far, a few challenges remain. These are primarily associated with the detection of fine (-3ds or -1.3 mm square mesh sieve) material. Such material is at the limit of the resolution capability and noise characteristics of dual-energy X-ray detectors. In order to ensure that fine diamonds are detected, and recovered, the algorithm parameters are such that a significant number of false detections occur, increasing the yield on the finer material. Indeed, the outlier cases seen in Figure 6 can be associated with a consignment that had a high incidence of dusty or gritty material in the feed. In such cases, XRT overestimates the carat content.

The reconcentration version of the machine (BDT1122) includes a multi-channel ejection system. Its purpose is to provide a high diamond by weight (DBW) product, and it is being piloted at various marine and land-based plants. The same challenge exists with fine material, as discussed in the previous paragraph.

Various initiatives are underway to address the challenges presented above. These include improved dust and grit removal systems, as well as higher resolution X-ray camera technology.

XRT AS AN ALTERNATIVE TO DENSE MEDIUM SEPARATION

New methods are required to make processing of marginal and low-grade deposits viable, and high-throughput XRT machines were identified as a lower cost alternative to DMS. These machines are predicted to run at lower operating costs and also to produce lower and more

consistent yields that will result in downstream treatment cost benefits and simplifications. A comparison is shown in

*Table I.*Table I.

Table I. An illustrative comparison of operating costs when replacing a coarse DMS with a XRT solution treating the same throughput. Values are normalized to the total DMS cost.

	Normalized cost per ton	
Cost item	XRT	DMS
Electricity	14%	36%
Labour	11%	8%
Maintenance and consumables	7%	32%
Downstream costs	2%	23%
Total	34%	100%

During 2014 to 2016, Namdeb and De Beers Technologies SA collaborated to run a joint pilot test programme with the goal of evaluating high-throughput XRT in the alluvial application as an alternative to DMS plants. A number of novel operational features were evaluated, including feed rate control loops and generation of DSFD information.

The machine used in the tests was the De Beers Technologies SA XRT Coarse Concentrator (XRT-CC) BWT1186. This containerized sorting machine has a 900 mm wide belt and is designed to process material from 6 mm to 75 mm.

The programme tested the technology with material in size ranges between 6 mm and 32 mm. Dry and wet materials were specifically tested separately to determine the effect of moisture on sorting performance. In addition, as this was an alluvial operation, the impact of marine shell in the feed was also investigated. The test programme set out to determine the following critical parameters:

- The optimal feed rate per size fraction
- Diamond recovery efficiency at these throughputs
- The availability and reliability of the XRT technology
- The operating costs of the XRT technology.

The results indicated that the XRT-CC machine is well suited as an alternative to coarse DMS. The tests also showed that feed preparation is important as increased undersize material in the feed reduces the throughput to less than the optimum for 100% diamond recovery. Wet fine material required special consideration due to the material sticking to the belt, leading to either higher-than-expected yield (for top-down ejection systems) or more frequent maintenance (for bottom-up ejection systems). It is worth noting that these findings are not XRT-specific concerns but would apply to any belt-fed sensor sorting system.

Figure 7. The XRT pilot plant installation in Oranjemund, Namibia. The system consisted of a containerized high-throughput machine coupled with a container housing the services required to run the plant.

LARGE DIAMOND RECOVERY

The high throughput and low yielding performance of XRT sorting machines enable them to be applied upstream of existing concentration circuits to target the large liberated diamonds above the conventional top particle cut-off size. This configuration allows this revenue to be recovered as early as possible and reduces the probability of damage to the large stones (Sasman, Deetlefs, and van der Westhuyzen, 2018).

The LDPP at Jwaneng mine in Botswana will undergo a 12-month test programme during 2018 and 2019 to quantify the occurrence rate of large diamonds at that operation. The plant will treat the 25 mm to 45 mm scrubber oversize size fraction with two De Beers Technologies (SA) BWT11162 machines. This containerized sorting machine has an 1800 mm wide belt and can process material from 6 mm to 75 mm.

Figure 8. The Large Diamond Pilot Plant installation at Jwaneng mine, Botswana, showing the two XRT machines side-by-side. Containerized machines simplify shipping and installation and enable pre-commissioning to be done at the factory, which shortens the on-site commissioning time.

ALTERNATIVES FOR COARSE DIAMOND RECOVERY POST-DMS

As much as the application of high-capacity XRT machines is seen as an alternative to DMS and upfront large diamond recovery, it also enables alternative flow sheet configurations (Valbom and Dellas 2010). Venetia mine is installing an XRT-CC machine after DMS, targeting the coarse (–25 +8 mm) size fraction, as shown in Figure 9.

As feed to the plant becomes harder and denser and with varying PSDs, the limitations of the current flow sheet configuration have become evident. High-throughput XRT technology will alleviate both the capacity and PSD variation challenges by a simple modification of the flow sheet as shown in Figure 9.

The De Beers Technologies (SA) XRT-CC machine will be utilized.

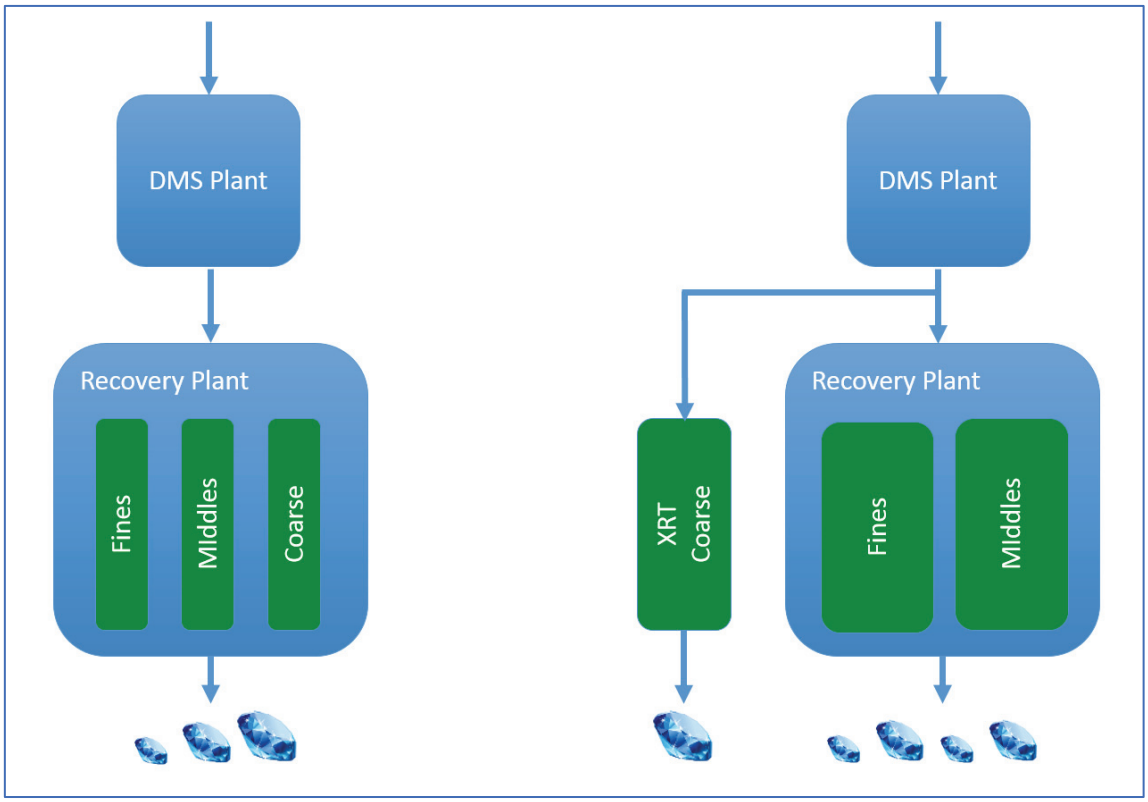

Figure 9. The current (left) and modified (right) flow sheets at Venetia mine, South Africa. Currently, the recovery plant treats all size fractions – fines, middles, and coarse – on dedicated circuits. The modified flow sheet includes XRT technology that treats the coarse fraction independently from the recovery plant, which is now reconfigured for the fines and middles fractions only.

The main advantage of the new configuration is the separation of the coarse circuit from the final recovery plant into a standalone high-capacity circuit. The recovery plant will then be reconfigured for the fines and middles size fractions at improved capacity.

FINE DIAMOND RECOVERY AT HIGH THROUGHPUT

XRT machines that treat fine material could find application in the recovery plant and as a replacement for fines DMS. However, the throughput requirements in the DMS application make any sensor-based sorting system (including XRT) commercially unviable due to the current CAPEX and OPEX estimations for such projects.

Apart from the commercial considerations, the treatment of fine material at high throughput presents various technical challenges to sensor-based sorting machines. While the demand placed on the detection and classification system is highest, the feed presentation system and the ejection system are also strained.

Feed Presentation
Systems dealing with large particles are fairly robust to dust and grit that is entrained with the material. However, as the size fraction being treated gets smaller the detection system is less able to operate effectively. Added to this is the challenge of feeding fine, wet material which sticks to the belt and tends to clump. This adversely affects the recovery efficiency and yield.

Detection and Classification
The biggest challenge presented by finer material relates to requirements placed on the detection system. Difficulties arise because finer particle sizes require smaller pixels on the X-ray sensor. In order to ensure that a reasonable signal is achieved on these smaller pixels, a number of engineering solutions are possible.

- Increasing the signal integration time, resulting in reduced throughput due to the associated reduction in the speed of the material passing the sensor
- Bringing the X-ray source closer to the sensor, resulting in reduced throughput due to reduced belt width
- Increasing the X-ray power, placing greater pressure on the engineering of X-ray safety and resulting in increased failure rates of the X-ray generation and detection components.

To achieve high throughput when treating fine material, a much higher data processing rate is required. This is due to the finer detector resolution, which requires a high number of small pixels. Another challenge associated with small pixels is that the signal-to-noise level is decreased. The resulting data is noisier, which makes the task of the classification system more difficult.

At this point in time the pixel pitch of the highest resolution dual energy X-ray sensors is 0.4 mm. Without any magnification, which could have a consequential reduction in throughput, this limits the bottom size for effective detection to approximately 2 mm. High-throughput systems capable of handling particles down to 1 mm require the development of high-sensitivity sensors with improved resolution.

Ejection
For handling fine material, the ejection system needs to be more precise. Ejectors can be thought of as having a footprint. The bigger this footprint, the greater the number of 'passenger' particles that will be recovered with each ejection of a target particle. As the material becomes finer, the ejection footprint needs to be reduced, otherwise the grade of the recovered material will be too low.

TEST FACILITY IN JOHANNESBURG

A permanent and secure XRT test facility is located at the De Beers Technologies (SA) campus in Johannesburg (Figure 10) and forms part of the Mineral Sample Treatment Plant (MSTP). Several performance parameters, including recovery efficiency, yield, throughput, and size range, as well as the interaction between these parameters, can be studied under controlled conditions.

Figure 10. The XRT test plant at the De Beers Technologies (SA) campus, Johannesburg.

CONCLUSIONS

XRT technology has had a positive, expanding impact across the De Beers Group. As we have discussed in this paper, this covers a wide range of applications from auditing in the marine environment to large diamond recovery at Jwaneng mine.

The remaining challenges are associated with the fine diamond processing applications, particularly with wet fine material. Potential applications in the re-deployable and ultra-coarse domains are being considered, and may be able to unlock further value for De Beers.

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