In recent years, the design of diamond recovery plants has undergone significant changes. The introduction of autogenous milling for diamond liberation has improved the recovery of large diamonds without significant damage. This results in a decrease in the unit processes required and therefore the simplification of the overall plant, thereby reducing both capital expenditure and operating costs. These changes impact on the much neglected interface with the mining methods used to generate the plant head feed material. Many of the other changes in plant design have been driven by the increase in computer processing power, which has enabled high-capacity sorting to become economically viable, including NIR, XRF, and XRT technologies. An area that is often neglected in the design of diamond plants is the integration of the essential security systems into the process engineering design. The impact of the new technologies on this is reviewed. Benchmarking of these new systems has indicated significant decreases in capital expenditure and operating costs, which have meant that diamond mining is one of the few industries in the minerals sector that remains relatively buoyant in the current economic climate. What does the future hold? The paper concludes with an overview of the proposed methodologies that diamond mining companies should adopt in order to improve their ability to successfully develop mines. These are considered to be highly relevant to other commodities as well.

HISTORY

Diamonds have been mined for more than 2000 years: the first known reference being a Sanskrit manuscript by a minister in a northern Indian dynasty dated from 320–296 BCE. It is believed that diamonds began appearing in European regalia and jewellery in the 13th century, and by the 16th century had become larger and more prominent as a result of the development of diamond faceting, which enhances their brilliance and fire. The earliest diamond-cutting industry is believed to have been in Venice, starting sometime after 1330, and then progressing via Paris in the late 14th century to Antwerp.

The majority of the diamonds mined in these times were from alluvial and/or eluvial deposits as the geological origins of diamonds were not understood. The discovery in 1870 of diamond deposits in South Africa changed this situation as scientists and miners began to better understand the genesis of these stones and the need to consider methods of extracting them from the host kimberlite.

Technology for the liberation of diamonds has followed an interesting path. This has included flooring, where the kimberlite was laid out over a large area to allow natural weathering to release the diamonds, through stamp mills, and more recently scrubbing and screening, jaw crushers, cone crushers, and high-pressure grinding rolls (HPGRs).
Once liberated, the diamonds had to be concentrated due to the very low concentration of the stones in the kimberlite; often measured in parts per billion. These concentration methods included hand sorting, jigs, rotary pans, dense medium separation (DMS) static cones, and DMS cyclones. Even though DMS can reject up to 99% of the barren material, there was still a need for further concentration, traditionally called final recovery. The common unit processes were hand sorting, grease belts, X-ray machines, acid digestion, and caustic fusion.

**RECENT DEVELOPMENTS**

In recent years, the design of diamond recovery plants has undergone significant changes. Technologies more associated with the recovery of other minerals have been adopted, along with new technologies.

- Autogenous milling
- Waste sorting
- Large diamond recovery
- X-ray transmission diamond recovery
- Size frequency distribution analyses
- Integration of security with process engineering.

**Autogenous Milling**

Autogenous milling has been used for a long time in many other mineral sectors such as copper, platinum, and gold; and Alrosa, the Russian diamond mining company, has used autogenous milling for over 50 years. However, it is only in the last few years that we have seen the introduction of this technology into diamond mines in southern Africa. The Catoca mine in Angola, majority-owned and operated by Alrosa, has six autogenous mills installed in two plants, and the Karowe mine in Botswana also used this technology based on the feasibility study completed on behalf of Lucara Diamonds Corp in 2010. The most recent installation is at Petra’s Cullinan Mine.

Previously, designing a diamond processing flow sheet traditionally focused on a few concepts such as:

- Upfront size preparation
- Mass balance management
- Maximizing liberation potential through grits and slimes production
- Asset efficiency (multiple tasks for equipment).

The net result has often been a plant design focused on the tactical goal of treating tonne, irrespective of the requirements for the profitable liberation, concentration, and recovery of diamonds. Autogenous milling helps to regain the focus on 'fit-for-purpose' design, and has a number of significant advantages:

- It utilises compressive, shear, and abrasive forces in a single unit process
- It incorporates internal classification and recycling of material
- It reduces the need to support large circuits and ancillary equipment
- It preferentially reduces softer components to fine sizes
- It preferentially leaves intact the harder components, which are usually waste

Due to these benefits, autogenous milling replaces several unit processes in the more conventional diamond treatment plant designs by fulfilling the same diamond liberation roles, namely:

- Primary scrubbing
- Secondary crushing
- Tertiary/HPGR crushing
- Disagglomeration scrubbing
- Recovery plant feed preparation.

A plant design based on autogenous milling has numerous advantages:

- It has the potential to remove all circulating loads, although a pebble crusher may be needed for hard kimberlites/lamproites
• It can easily treat heavily weathered kimberlite, thereby resolving the common materials handling problems relating to clay as this is removed very early in the plant flow sheet
• It can more easily handle a large jaw crusher product than conventional process flow sheets, thereby reducing the costs of the primary crushing stage
• It generates high percentages of slimes (-1mm to -2mm material) which can be immediately discarded from the plant
• It reduces the required downstream unit process capacities due to the high slimes generation and the removal of circulating loads
• It reduces the need for feed preparation systems in the recovery plant as it removes plastic, wood, wire, etc.
• It allows for flexible flow sheets that can easily be adapted to changing ore characteristics as and when required, with minimal impact on ongoing operations
• It allows for improved metallurgical control to optimize comminution conditions
• It links very easily with the use of high-capacity X-ray machines in place of DMS for the coarser size ranges
• It has a smaller physical footprint
• It reduces capital expenditure due to the simplicity of the flowsheet. The Karowe feasibility study indicated a reduction in capex of approximately 60%
• The complete plant often has lower overall energy consumption
• It reduces operating costs due to the simplicity of the flow sheet. The Karowe feasibility study indicated a reduction in operating costs of approximately 40%
• It reduces operating manpower requirements
• It has a higher overall engineering availability and metallurgical utilization than conventional scrubbing and crushing systems

Another benefit of autogenous milling technology is that it can be 'tuned' very easily for the purposes of operating at the correct level of liberation, as based on the optimal offset between revenue release and operating costs. Consequently, autogenous milling, in conjunction with a diligent strategy of process control, becomes a business tool that ensures economic productivity as opposed to simply production alone.

Historically in southern Africa, it has been believed that autogenous milling could increase diamond breakage, despite evidence to the contrary from Alrosa. This aspect of the unit process is now better understood and currently it is expected that diamond liberation will be greater than that from conventional crushing systems without incurring a significant increase in diamond damage. Recent work has indicated that up to 10% more carats could be liberated by using this technology. Discussions with metallurgists at Catoca have indicated that the level of diamond damage has been estimated at less than 4%. While this cannot be verified, the work undertaken by Alrosa over 50 years seems to support this observation.

The Karowe Mine is now successfully operating an autogenous mill in its diamond recovery plant, and it has been stated that the advantages of this technology, as outlined in the feasibility study, are being realised. Diamond breakage is estimated to be considerably lower than for a conventional crushing circuit. The fear of damage to large diamonds has also been allayed with the recovery of the second largest gem diamond in the world, the 1111 ct Lesedi La Rona, in 2015.

The technology, however, is not a general panacea. The advantages can, at times, constitute disadvantages for certain specific projects/mines. One of the main potential disadvantages is the high production of slimes, which may increase overall water consumption, and also the slimes deposition requirements in terms of volume and surface area.
The interface between mining and plant can be improved with the use of autogenous milling. The mill’s ability to treat a large size range of head feed material provides the opportunity to optimise the overall comminution system, including blasting. Usually the mining and treatment departments are considered as separate entities, but the milling plant flow sheet allows the most economical option to be implemented where the increased costs of finer blasting can be offset by greater cost reductions in the milling circuit. A finer blast fragmentation can improve a number of important mining parameters such as load factors, double handling, and secondary breaking, thereby moving towards a more integrated approach to mining and treatment which can lead to significant economic benefits.

**WASTE SORTING**

The use of autogenous milling as the main diamond liberation unit process allows for the simple and effective introduction of waste sorting into the plant design.

As noted above, the autogenous mill will preferentially reduce the softer material, which is usually kimberlite, leaving the harder waste in the larger size fractions; the mill is therefore also acting as a preliminary waste differentiator. If the difference in hardness between the kimberlite and the waste is significant, it may be possible to simply discard the mill oversize as uneconomic; however, if there is an economically viable amount of kimberlite in this stream, then a waste sorter should be installed to remove this and return it to the mill, discarding only the waste. This will significantly reduce the recycle load, reduce power usage, and increase mill throughput. Near-infrared (NIR) technology is suitable for this purpose and is based on current sorting systems.

A disadvantage of using NIR waste sorters is that they will classify diamonds as waste, and therefore if there is an expectancy of large diamonds in the resource/reserve it will be necessary to include a large diamond sorter in the circuit. It is envisaged that it would be possible to incorporate both sorting requirements into a single machine.

If waste sorting is used, then the requirement for expensive pebble crushers such as HPGRs to try to reduce the amount of critical size material can probably be eliminated.

**DIAMOND SORTING**

The most significant recent changes in plant design have been driven by the increase in computer processing power that has enabled high-capacity sorting to become economically viable. This includes waste sorting as discussed, and also large diamond recovery. Prior to the early 21st century the primary concentration of diamonds was performed using dense medium separation (DMS) which, in this application, is one of the most efficient unit processes ever, recovering in the region of 98% of the diamonds and rejecting up to 99% of the waste when properly designed and operated. However, DMS has a few disadvantages:

- High operating costs
- Limited top size
- Logistics of ferrosilicon delivery, storage, and addition
- Water consumption
- Security.

In addition, further concentration of the DMS concentrates is also required. X-ray sorting, using X-ray fluorescence (XRF) detection systems, could do this due to the low tonnages required to be treated.

The exponential increase in computer processing power over the last 50 years, along with the adoption of X-ray transmission (XRT) for detecting diamonds, made it possible to achieve a number of major step changes in sorting technology, namely:

- Increases in the rate of treatment
Treatment of larger size ranges
Lower concentrate yields.

The air ejection systems used in the old XRF machines, updated as required, are still used in the newer machines and hence the adoption of them into production facilities at the mines was relatively simple as there is a good body of existing knowledge of the technology.

The advent of XRT sorters has revolutionized the diamond mining industry in many ways. The use of XRT machines as large diamond sorters has proven that there are higher incidences of large diamonds in more mines than previously thought, and this has led to a significant revision of mineral resource estimates, as well as the potential economic value of what were previously considered sub-economic deposits: Karowe is an obvious example.

In the last few years, the use of XRT technology has allowed for the direct sorting of kimberlite down to approximately 4 mm. Very recent developments now indicate that this can be taken down to 2 mm. This effectively means the end of DMS in future diamond production plants.

It is considered that XRT technology can probably assist in the development of more efficient single particle sorters, which will eventually remove the need for any form of hand sorting.

INTEGRATION OF SECURITY

An area that is often neglected in the design of diamond plants is the integration of the essential security systems into the process engineering design; most importantly in the final recovery plant and sort-house. Many diamond mines were traditionally designed only with the process engineering in mind and the security required for diamond concentrates added on later, often as an afterthought.

Installing XRT machines in place of DMS allows for the full integration of security into the plant, along with online, remote monitoring. In a diamond mine, security is inversely proportional to the access to material: removing unit processes therefore decreases the risks. XRT generally concentrates the material adequately for the product to report directly to the sort-house.

DIAMOND ACCOUNTING

The main constraint to monitoring plant efficiencies in a diamond mine is that it is impossible to measure diamond recovery online, and that only indirect methods, such as tracer testing, can be used. This has meant that the all-important feedback of information to the operational staff is very slow and generally ineffective.

The main tool in assessing a plant’s efficiency is the diamond size distribution curve. This has traditionally been derived on an irregular basis, and often too late for any useful feedback to the operations. The next leap in technology needs to be the development of equipment that can perform online size frequency analysis whereby the production can be determined daily.

Following this, quality sorting will also become the norm at mines, which will be then able to use economic data on a rapid basis to determine their business value chain and make quick and accurate decisions regarding diamond liberation, recovery, and top and bottom cut-off sizes on a more regular and useful basis.
THE BEST BUSINESS SOLUTION

Historically, diamond treatment plant design was based on maximising recovery efficiency. In the late 1900s, diamond damage was not considered a major factor and liberation was driven by minimising the top size of the DMS final tailings stream. As a better understanding of the real value chain was gained, the emphasis moved to recovering the larger stones intact, which greatly improved the economic situation for a lot of mines. However, this change did not fully recognise the need to optimise the mine’s business model and still retained the emphasis on diamond recovery efficiency rather than net revenue generated per hour. The changes coming, especially in terms of the online diamond size and value information, will allow for a much more focused approach to diamond treatment plant design – one which maximises profits, potentially at the expense of overall diamond recovery efficiency. It may prove more profitable to stockpile currently sub-economic streams for a future business model that can better utilise the new technologies that will arise.

THE NEXT PLANT

So, what will the next major diamond plant look like?

Figures 1-3 indicate the trend. Figure 1 depicts a ’conventional’ design; Figure 2 is similar to some more recent plant designs; and Figure 3 is considered to be the future. The size of the blocks is indicative of the treatment capacity required for each unit process.

What the future promises is an overall simplicity of flow sheet design. The complexity lies within each technology, which allows for a simple, almost single-line process that reduces the engineering and operational vulnerability that can result from numerous circulating loads and unit processes.

Benchmarking of the new systems discussed in this paper has indicated that there are significant decreases in capital expenditure and operating costs due to this simplicity, which have meant that the diamond mining industry can remain competitive even in difficult economic times.
Figure 1. Conventional design.
Figure 2. Current design.
THE NEXT-BUT-ONE PLANT?

The next major diamond plant flow sheet will be an evolution of the *status quo*. However, the one after that may well be considerably different.
In recent years, the diamond industry has started to split into two very different businesses: the large diamond producers such as Letseng, Karowe, and some mines in the Alrosa stable; and the smaller diamond producers. Many companies are now re-assessing the potential of the recovery of large diamonds at their mines due to the availability of technology to do so, but the issue of breakage of these larger stones causes many headaches.

It is considered that the next leap of technology in the diamond mining industry will be the further development of diamond-within-kimberlite detection (DWIK). This was tested by De Beers in the 1980s and 1990s but was found to be too expensive to develop, had some significant health and safety problems associated with the use of nuclear technology, and could not easily be scaled up to the levels of production required. New concepts are now being investigated, linked to advances in technology in the medical industry and the previously mentioned increases in computing power, and these may see the light of day within the next decade.

The success of DWIK would then lead to another problem: how do you liberate the (hopefully) large diamond(s) that has been detected within the lump of kimberlite? Electropulse disaggregation (EPD) techniques have been tested for this purpose and are now in the process of being commercialized.

EPD is a technique that applies an electric current from a high-voltage power source to the lump of rock, immersed in a bath of water, thereby causing an ‘explosion’ that propagates along grain boundaries, resulting in undamaged diamond(s) being liberated.

These technologies are currently feasible, although commercialisation and scale up will take some time.

Jeremy Edward Clarke

Director
Paradigm Project Management (Pty) Ltd

Jeremy Clarke started his career in the mining industry with the Anglo American Corporation group of companies as a trainee metallurgist. He spent twenty years with the company gaining experience in gold, uranium, copper and diamonds and rose to the position of Consulting Metallurgist for De Beers where he was responsible for the metallurgical excellence in their plants worldwide.

He left De Beers to start his own mining companies and successfully started four new ventures in the gold, diamonds, copper and emerald industries which were all subsequently listed on the TSE and AIM exchanges between 1997 and 2003 raising over US$100m in investment. During that time, he acted as President, CEO, and Director on the Boards of these various companies.

In 1999 Jeremy founded Metcon, a metallurgical consulting business that concentrated mainly in the diamond mining arena and eventually merged with Paradigm Project Management (Pty) Ltd (PPM) in 2008.

Jeremy is now a Director and owner of PPM which has celebrated 14 years of project management in the southern Africa mining sphere. It has completed over 180 projects in that time, in 20 countries covering 20 commodities ranging in value from R2 million to R450 million.