An analysis of operating plant issues and the minimization of risk

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The mineral sands industry has a history of project implementation around the world that varies greatly in technical and financial success. The majority of operations have performed as expected and effectively as well as economically recovered the contained heavy minerals. Other operations, however, have been plagued with operating problems in areas such as the feed composition, effectiveness of mining method, the operational performance of the processing plant and/or the disposal of the tailings.

As a consequence, the operations with difficulties have generated poor economic results and in the more serious cases the problems have led to the premature closure of the operation. These negative operational and planning impacts reach beyond individual operations, affecting the reputation of the mineral sands industry and the ability of new projects to attract finance. This paper will review a number of the issues associated with some past plant successes and failures and suggest key strategies for the minimization of project risk in the future.

Introduction
The success of a mineral sands operation as with all other mineral processing operations relies on the processing plant being designed and operated to comprehensively address the specific characteristics of the orebody consistent with the owner’s objectives over the life of that operation. For the designers to deliver a suitable plant, a flowsheet and operating philosophy must be developed based on a thorough understanding of the different characteristics of the mineral grains to be processed during the life of the plant. These characteristics are used as a basis for differentiation within a separation machine and process.

The implementation of a mineral sands project presents challenges at each stage of execution due to a range of uncertainties that are unique to each project. These uncertainties encompass many factors including the vagaries of the orebody, the mining methods used and the processing route chosen for beneficiation, as well as the limitations of the available financial capital to develop the project.

In particular, the mineral sands industry has seen the premature closure of a number of operations for reasons such as:

• Difficult mining conditions leading to high mining costs and low plant feed rates
• Problems in feed preparation ahead of the wet processing plant leading to low plant feed rates
• High levels of slimes in the feed that could not be disposed of effectively
• Insufficient mineral recovery to justify the capital and operating costs
• Declining demand and commodity prices coupled with low operating margins.

The last two reasons, while not as obvious as operating the plant at less than its rated capacity, can have just as significant an impact on the overall viability of an operation, since they directly influence the cash flow of the project.

Prudent project implementation strategies include the elimination, reduction or mitigation of risk at each stage of development within the financial constraints of the project. This paper will review and discuss some of the potential risk issues associated with project development and implementation and make suggestions for addressing that risk, including three case studies which examine some particular examples that may be of interest. Although the issues discussed are not new to those with sufficient experience, they have not always been addressed by the stakeholders of a project. This paper attempts to discuss the various issues from an international perspective, where sometimes inappropriate cost cutting does occur.

Orebody issues
It is no longer sufficient, nor adequate, to design a plant and operating philosophy around a single representative sample of the proposed feed to that plant. Prudent operators are now quantifying the specific processing plant requirements by considering the characteristics of multiple orebody samples, each representing a small (for example, 12-month) section of the mine plan.

Consequently, a more comprehensive approach to the development of a mineral sands operation that seeks to identify, quantify and mitigate the risks associated with the mineral processing operation might include the following preliminary steps:

• Drilling of the orebody to collect samples across the entire deposit
• Assaying of the individual samples to determine the %+1 mm, %-45 micron, % heavy mineral, %TiO₂, %ZrO₂

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As a consequence, the operations with difficulties have generated poor economic results and in the more serious cases the problems have led to the premature closure of the operation. These negative operational and planning impacts reach beyond individual operations, affecting the reputation of the mineral sands industry and the ability of new projects to attract finance. This paper will review a number of the issues associated with some past plant successes and failures and suggest key strategies for the minimization of project risk in the future.
• Segregation of the orebody into several zones depending on the variation in the above parameters between samples
• Combining the individual drill samples into zone composites and
• Metallurgical separation tests, using laboratory and pilot scale equipment, to determine the potential grade and recovery of the contained mineral products. With this approach the true extent and characteristics of the orebody are determined, including its metallurgical separability through to saleable products. The approach taken at this step is necessary to ensure correct decisions are made as to the viability of the deposit. Notwithstanding the international location of the deposit and the relevant statutory codes, the complete metallurgical requirements are determined, thus minimizing the risk of an inappropriate plant design and commissioning difficulties.

Significant amounts of overburden can also be disastrous to the viability of an operation although this depends on the value of the minerals available, a greater quantity of valuable mineral (eg. zircon) will enable more overburden to be tolerated. The heterogeneity of the orebody is also of interest. Pockets of high value ore, if preferentially sampled for test work, would provide a positively biased interpretation of the resource available to be mined. The actual characteristics of the minerals present in an orebody are very important since it is the physical characteristics of the mineral particles that will determine how effectively they will be recovered to make saleable products that provide the cash flow for the project.

The variation in the quantity and quality of valuable heavy minerals and gangue minerals will have a significant impact on the design of the processing facilities and indeed on the viability of the operation. While high levels of the valuable minerals is always a good start, other issues such as the amount of kyanite, staurolite and monazite present as well as the particle size distribution of each of these minerals will, to a large extent, dictate whether these valuable minerals will be readily recoverable to marketable concentrates.

Factors such as the size distribution of each mineral, the liberation of each mineral grain, the quantity of each type of mineral and the level of impurities in mineral grains, including trace quantities, will affect their separation performance. The shape of the particles, whether they are well rounded, needle shaped or angular is also important as are the electrical and magnetic properties of the particles and their density distributions. A similar set of characteristics should also be determined for the waste particles to allow appropriate separator choice and process design.

Very fine material, usually called slimes (nominally -65 µm although it can be defined in the range of -38 um to -72 um), presents particular challenges because of their buoyant behaviour during transport in air and water. Slime sized material is at the physical lower limit of processing for most separators used in mineral sands operations. Fine clay particles are also very difficult to separate due to their morphology and electrical properties. Traditionally slime is considered a waste product and is removed before separation takes place.

Or characterization is a very powerful analytical tool but is only useful if the samples used are truly representative of the orebody to be mined and subsequently processed. The characteristic properties of the as-mined ore when compared to the measured properties of the characterization samples need to be within acceptable limits. These limits are determined by the operating behaviour of the mining, separation and other processing equipment used to beneficiate the orebody. If an orebody is excessively heterogeneous in its physical characteristics the beneficiation plant (if designed based on inadequate characterization samples) may not, on average, produce the necessary (financial) recoveries and grades. Consequently, it is necessary to ensure that the orebody is appropriately sampled to ensure that the subsequent test work and analysis is valid and the final design is appropriate. Another important consideration is to achieve the right balance between the capital and operating cost of the processing operation, the size of the deposit, the grade and the value of mineral in the ground. These issues are generally incorporated into the overall financial model of a proposed operation to ensure that the proposed costs are appropriate for the expected returns. The correct sizing of equipment for the required throughput has to be considered as well as the impact each of the orebody characteristics has on the ability of the plant to generate the required products.

Insufficient processing capacity may not provide sufficient dividend on the capital cost of the project. Conversely, excessive and un-utilized capacity will reduce the return on investment for the operation. Also, if this excess capacity is utilized it may either significantly reduce the life of a deposit or, in some cases, lead to a reduction in the market price for the products. Consequently, the appropriate processing capacity has to be determined when designing a plant that is consistent with the orebody characteristics, with due consideration of how it may be expanded at a later date if required.

It is also crucial that the final plant be carefully designed to ensure that all the stages of processing are designed so that they are compatible with the specific characteristics of the material to be treated at that point in the flowsheet. Much of the required information is normally generated as a consequence of a thorough flowsheet development test program where the effect of issues such as feed rate, particle size and mineralogy on product grade and recovery can be quantified. To ensure that adequate information is available appropriate sampling of the orebody is once again required. The particle size and mineralogy are a function of the given orebody and therefore outside the control of the designer but variables such as mining method, feed rate, operating hours, availability, product mix as well as product quality are key considerations.

**Mining method and feed preparation**

The data obtained from a thorough review of the orebody can be used to decide on the most appropriate mining method, mine plan and the likely quantity and quality of products. The mining method and mine plan will dictate the likely variations in feed to the processing plant and the approach to the design of the plant and its operating philosophy.

The presence of elevated levels of slimes in the orebody can have a detrimental effect on the separation performance of the wet concentration plant if not handled appropriately. Slimes occurring across the entire deposit will need to be processed through the wet concentration plant and, if present at sufficiently elevated levels to affect separation performance, removed through a desliming stage. A
number of alternatives are available for returning this slime to the tailings including thickeners, co-disposal and tailings dams but the importance of getting this step right should not be underestimated. It has been a major factor in the closure of at least one major project.

Alternatively, if the slimes are concentrated in particular areas within the deposit, either laterally or at depth, then the mining method and/or the mine path could be designed to exclude these areas from treatment. In some instances the slime is stripped off as overburden, while in others an underlying slimes layer is avoided by not mining down to that depth. For example, in a recent mineral sands project a large number of 1 tonne bulk samples were analysed as outlined above and it was determined that the average level of slime in the deposit was 30% but this varied between 15% and 50% across the various samples. As a consequence the processing plant was designed to process in the range of 26 to 35% slime with feed under and over this range sent to separate temporary storage and blended as required with the incoming feed to ensure that the %slimes in the composite feed was maintained in the correct range.

The impact of slimes on the performance of spirals within a WCP can be significant, reducing mineral recoveries by 15% or more. Figure 1 shows an example, from internal test work, of the effect of slimes on the recovery of heavy mineral from a spiral. For these separators the slimes content acts as a viscosity modifier, influencing the flow behaviour in the spiral troughs. The actual quantity of slimes that can be tolerated is likely to be different for each application.

Other issues for consideration in the determination of the most appropriate mining method for a particular operation will include:

- The level of the water table with respect to the orebody (a high water table may dictate dredge mining)
- The presence of either large rocks or indurated material (this may require dry mining)
- The proposed feed rate (high feed rates may favour dredge mining)
- The length, width and depth of the resource (very shallow deposits may indicate dry mining).

The amount of coarse material (+1 mm) contained in the feed will also have a bearing on the design of the feed preparation section of the wet concentration plant. Rotating trommels and vibrating screens can be used to remove oversize material. The oversized fraction can be returned directly to the pond if present in only small quantities or removed using the tailings system. The disposal of this material is less problematic than that for slimes as it is free draining and can easily be placed and handled in a tailing area.

In a recent mineral sands project it was determined that while the average heavy mineral content of the feed was 25% this varied between 5% and 50% across the various samples tested. Several approaches can be adopted in both the plant design and operating strategy to accommodate these variations. If the plant built to treat this material was designed based on the average grade of 25% HM (and the variations were not removed or reduced through the mining method) it could either be operated at a fixed feed rate with sufficient capacity in the scavenging and cleaning circuits to accommodate the grade changes or it could be operated at a fixed concentrate production rate by varying the plant feed rate.

Integration of wet plant and mineral separation plant design

It is generally accepted industry practice for a mineral sands wet concentration plant (WCP) to produce a single mixed heavy mineral concentrate that is then processed through a mineral separation plant (MSP). This single WCP product and single MSP feed can have a number of benefits in simplifying the design and minimizing the capital cost of both facilities. However, dependent always on the mineralogy and client requirements, it may also be advantageous to design the wet plant to produce a number of preconcentrated mineral products. These preconcentrates can then be transported separately to the mineral separation plant and treated in separate circuits specifically designed for these preconcentrated feeds. One such plant, currently under construction in India, was designed to produce preconcentrated streams from the WCP of coarse garnet/sillimanite, medium garnet and sillimanite/quartz as well as a mixed ilmenite/rutile/zircon concentrate, thickened slime, and sand tailings.

Figure 1. An example of the performance of a spiral measured by heavy mineral (HM) and very heavy mineral (VHM) recovery with feed of varying slime content

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Regardless of the number of products produced by the wet plant, it is standard practice to maintain concentrate stockpiles between the WCP and MSP. This simple design issue has a number of benefits in de-risking the operation of the mineral separation plant including the potential to blend/homogenize the feed mineralization for the MSP.

**Case A: feed preparation plant**

During the initial design phase of a feed preparation plant (FPP) and wet concentration plant (WCP) it was evident that due to the quantity of rock, clay and contained valuable heavy minerals that careful consideration should be given to the process design for this section. Insufficient design consideration in the feed preparation section of a WCP, or any plant for that matter could have serious consequences on the ability of the feed preparation section to provide a suitable and stable feed stream to the plant at the rated plant capacity.

In this instance testing revealed that the valuable heavy mineral was evenly distributed between the sand and clay fractions. To maximize the recovery of heavy mineral the design had to focus on liberating heavy mineral from the sand and clay. It was also found during the test work phase that the size and quantity of rock was highly variable across the deposit and testing small parcels of material increased the risk that the true nature of the rock would not be quantified. Without sufficient detail into the nature of the rock it would be impossible to effectively incorporate suitable engineering solutions into the plant design. While some tests were done on relatively small samples (i.e. 1–2 tonnes each) to assess the variability of the rock across the deposit; larger-scale pilot trials were also undertaken, treating 50–100 tonne parcels of ore, for better definition.

Another area that received considerable attention was the design of the chute work in this system to accommodate the handling of this ore (dominated by clays) without build-up of material or blockages in the chute work. While the importance of chute design can often be overlooked, this issue is of fundamental importance when dealing with potentially sticky material to ensure that material flows through the process as planned.

A significant amount of testing was undertaken at both small scale and pilot scale to develop an understanding of the interaction among rock, clay and heavy mineral through a feed preparation circuit. This information was incorporated into the plant during the design phase to ensure a robust and effective design of this area.

A feed preparation circuit, shown in Figure 2, consisting of two stages of scrubbing with density and speed control, a large rotary grizzly, final classification screen and surge bin was subsequently designed. The scrubbing and screening modules are shown in Figure 3. This design addresses the typical industry problems of rock, clay, and sticky ore materials handling by

- Recognizing the value of larger samples
- Installing an adequate number of stages
- Selecting robust (as opposed to low cost) materials handling equipment at the interface between mining and primary concentration.

This circuit was successfully commissioned and is now operating well at the designed throughput of 580 to 750 tph with an availability of 85%.

**Case B: surge bin design**

Continuing the theme of the importance of feed preparation, it has been demonstrated previously (MacHunter and Pax, 2007) that highly variable feed rates have a detrimental effect on the performance of a spiral plant, and hence the inclusion of an effective surge bin to stabilize feed variation can significantly improve the operability and profitability of a spiral plant.

![Figure 2. An example of a mining and feed preparation plant](image-url)
Surge bins are included in the designs of many plants to provide stable, consistent and controllable feed for the downstream processes from feed material that may be intermittent or otherwise variable (i.e. supplied by dredge, front end loader, etc.). They have been used for many years and the design of these bins has evolved to meet simple project requirements such as a particular retention time that reflects the operating requirements of the subsequent plant.

The mass flow surge bin, shown in Figure 4, was designed for a recent project. The practical implementation is shown in Figure 5. The mass flow characteristic of this surge bin design ensures that the output flow and density from the bin is fully controllable from 30% to 100% of the maximum design loading. An example of the performance is shown in Figure 6.

In Figure 6 the density of the mass flow surge bin discharge over a typical 8-hour period of operation shows how effectively the density can be controlled and how effectively a change to the controlled set point can be implemented. Techniques such as the mass flow surge bin provide an effective means of disconnecting an ‘instantaneous’ mine delivery system (e.g. dump truck loads) from the requirements of a spiral plant to have ‘continuous’ feed.

**Case C: processing high slime feeds and varying feed grades**

It is not uncommon to see variations in the heavy mineral content across an orebody. Consider a recent case where the feed grade varied between 3.6% and 6.5% HM. While the variation does not seem particularly large, it does translate to an 80% increase in the amount of contained heavy mineral and needs to be considered during the design phase.

A more obvious case of problematic feed grade variations is a plant currently being designed to handle a feed that varies from 2.5–20.0% heavy mineral, in which case the variation in nominal heavy mineral production (at a designed feed rate of 3 500 tph) is from 87.5 to 700 tph. Variations as large as this should always be reviewed carefully and reduced or eliminated if possible through blending either at the mine planning stage or through the inclusion of surge capacity. In some cases, however, such as a large, single pit dredging operations it may still be necessary to design for such variations through the processing plant.
A number of operating philosophies have been adopted to handle variations in the feed grade. The least effective approach from a metallurgical viewpoint is to run the plant at its maximum throughput without regard for the potential losses in overloaded concentrate circuits. It is also possible to design the concentrate circuits for the maximum loading scenario but this can also be problematic during times of low feed grades.

For the original project of this case study, the concentrate production (and hence the project revenue) was maximized by designing for the maximum feed grade case and then using an automatic control system to recirculate a proportion of the concentrate during periods of low feed grade to ensure optimized performance from the concentration circuits. This plant was built and the strategy to automatically recirculate concentrate was effective in stabilizing the operation of this circuit.

Conclusion

There are a number of risks associated at all stages of the development of a mineral sands project. This paper has discussed some of these. Three case studies have been presented which highlight the importance of feed preparation and slimes removal as well as the design of plants to tolerate varying feed rates.

It has also been shown that the development of new technologies can assist in the mitigation of risk if applied correctly.

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Figure 6. Controlled performance of the mass flow surge bin over a period of 8 hours

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