Pilot Testing and Plant Design Comparison of Dry VRM Milling plus Magnetic Separation with AG and Ball Milling plus Magnetic Separation for Grange Resources' Southdown Ore

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Conflict of Interest Statement:

Loesche are the manufacturer of the VRM equipment that is the main and beneficial subject of this paper. Loesche developed the novel closed circuit pilot plant described in this paper as part of their long established VRM testing facility. Grange Resources are the owners of the Southdown project, and Loesche is a potential vendor to Grange. Wood has directed all the testwork discussed in this paper, has observed the work first hand and has prepared the technical assessment. The technical assessment has been conducted independently of Loesche and Grange and reported without modifications in this paper. Grange paid Wood for commercial consulting services throughout this work, including the writing of this paper. Grange and Loesche paid registration and all expenses for Dean David to present this paper at Comminution '23 in Cape Town.

CRediT Author Statement

Dean David: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Writing – original draft, Writing – reviewing and editing, Visualisation, Supervision, Project administration, Funding acquisition

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Highlights

- VRM on magnetite ore used 41% less power than conventional wet milling
- Production of dry coarse tails reduced water consumption of the project by 26%
- Tails were rejected at coarse sizes by VRM suggesting selective liberation
- The use of VRM will allow the Southdown project to proceed

Keywords

Southdown, Grange Resources, Loesche, Milling, comminution, VRM, AG Mill, Ball Mill, Magnetite, Magnetic separation, Power saving, Water saving

Abstract:

Loesche's Vertical Roller Mill (VRM) has achieved superior pilot plant comminution outcomes on hard Southdown Magnetite ore (Grange Resources, WA) compared to a conventional AG, magnetic separation and ball milling pilot circuit. VRMs utilise hydrostatic breakage to emulate HPGR power efficiency and can also achieve selective liberation. For magnetite ores, the dry VRM classifier oversize ("grit", -3 mm+75 µm) is extracted continuously then magnetically separated. Magnetic grit is returned the VRM and non-magnetic grit is rejected to tailings. The novel Loesche VRM pilot plant rejected 31 to 41% of feed mass as coarse non-mag grits while recovering between 95 and 97% of the magnetite to the 85 µm P_{80} product. VRM piloting was 33 to 36% more energy efficient than AG/Mag/Ball pilot milling and after scale up the VRM was 39 to 41% more efficient. There is strong evidence of enhanced selective liberation by VRM milling compared to tumbling milling. This paper will compare the flowsheets, outcomes, scale up difficulties and the industrial benefits of each method.

Introduction

The Southdown Project is being developed by Grange Resources and involves the construction and operation of an open pit magnetite mine located approximately 90 kilometres east-northeast of Albany. The project location is 10 kilometres south-west of the locality of Wellstead in the Great Southern region of Western Australia. Southdown has been under development since the early 2000s and has been the subject of various feasibility studies. The 2012 Definitive Feasibility Study (DFS, Grange Resources 2012) incorporated a processing plant with a capacity to produce 10Mt/a of high-grade concentrate. The plant was designed by AMEC (now Wood) after a program of bench and pilot testing. In 2018 the scope of the project was halved from 10 Mt/a of magnetite concentrate to 5 Mt/a of concentrate (Grange Resources 2018). The process technology from the DFS was revisited by Wood in the period 2020 to 2022 and an updated Pre-Feasibility Study (PFS, Grange Resource 2022) was completed in early 2022 for the smaller project.

Figure 1: Green Fields exploration drill rigs

The deposit itself is approximately 12 kilometres in length with 6 kilometres of this included in the current study. It contains over 1.2 billion tonnes of high-quality mineral resources, including 388 million tonnes (Mt) of ore reserves (Grange Resources 2023)

The deposit is estimated to have a life of mine in excess of 30 years with a mass recovery to final product in the 34-36% range. The site is located in farmland and requires the complete establishment of all facilities and infrastructure for the mining and on-site processing of the magnetite ore. The project aims to develop an open pit mine and processing plant to treat about 15Mtpa of run of mine (ROM) feed material from which the 5 Mt/a of high-grade magnetite concentrate will be produced. The processing plant will be adjacent to the mine and the concentrate will be pumped via an overland slurry pipeline to the filtering, storage and ship loading facility located at the port of Albany. A water pipeline transports recovered filtrate water, together with new water from other sources, back to the concentrator for all applications, including processing.

The project is challenged by the lack of water and electricity. As there is no large-volume water supply in the region, the 2012 DFS proposed large scale desalination of seawater. The closest suitable capacity electricity grid is 280 kilometres away in the Collie region. These utility supply and cost restrictions contributed to the 2018 decision to reduced design concentrate production to 5Mt/a. At 5 Mt/a production rate power and water remain high-cost commodities and decision drivers for The Project.

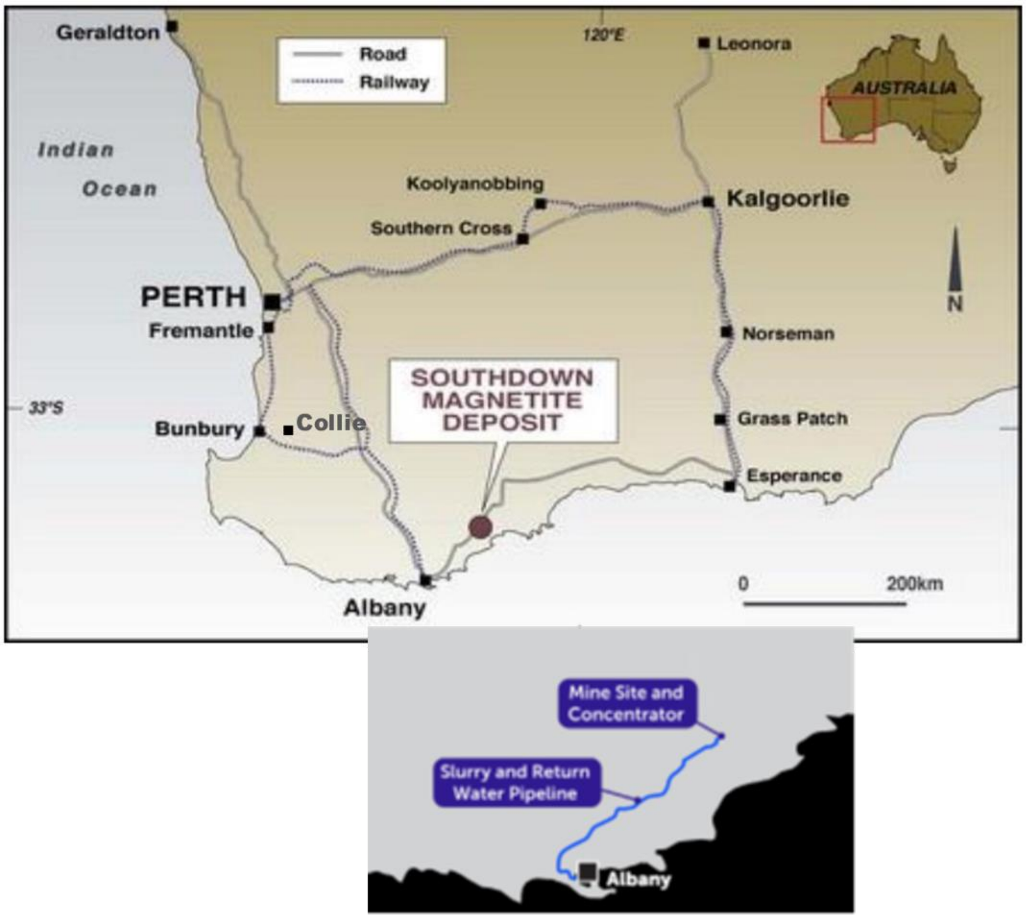

Figure 2: Project Location in Western Australia

The DFS (2012) Southdown Flowsheet

Until the 2022 update of the PFS the Southdown flowsheet consisted of a 'traditional' autogenous and ball mill grinding circuit (AG/Ball Circuit) with wet magnetic separation stages between each comminution step. The original production rate of 10Mt/a of concentrate at 45µm P_{80} required two parallel AG/Ball grinding circuits (followed by regrinding to the target P_{80} and Blaine). Reducing the production capability to 5Mt/a removed the need for one of the processing lines.

The AG/Ball mill processing flowsheet is described as follows. Primary crushed ore is stockpiled and fed to the AG mill. AG mill product is screened at 3 mm with undersize sent to rougher magnetic separation (RMS) while the screen oversize is returned to the AG mill feed. The -3 mm magnetics is pumped to the cyclones and ball mill while the -3 mm non-magnetics (n-mags) is discarded as waste. The Ball milled product, at 85 µm P_{80}, is further concentrated by an intermediate magnetic separation stage (IMS). The magnetics from IMS are sent to sulphide flotation to remove Pyrrhotite and then on to regrinding and cleaner magnetic separation (CMS). The magnetite concentrate from the CMS is thickened before being pumped to Albany for filtration and ship loading.

In this circuit there was little opportunity to reduce front end water use without significant additional capital equipment, such as dry stack tailings filtration of 10 Mt/a of n-mags. The wet RMS stage produced a large volume of dilute n-mags containing particles up to 3 mm in size. Cyclone classification was used to remove the coarse and protect the thickener which was fed the cyclone overflow. The cyclone underflow was to be combined with thickener underflow for pumping to a tailings storage facility. The thickener also received IMS and CMS n-mags. All 10 Mt/a of n-mags are pumped to the TSF and then settled to a final wet density somewhere in the range 80 to 85% solids. This pathway leads to 2.5 Gl of water being permanently lost into the TSF each year, accompanied by significant evaporative losses. Opportunities to reduce the reliance of the flowsheet on water were proposed and this commenced the investigation into dry milling in 2019.

The PFS (2022) Southdown Flowsheet

After the success demonstrated in Stage 1 of the dry milling testwork in 2021 the PFS proposed replacing the single line of AG and ball milling (described above) with two lines of dry Loesche Vertical Roller Mills (VRM). The flowsheet consists of primary and open-circuit secondary crushing followed by grinding in the VRM. Grits (-1mm +75 um) are extracted from the VRM and a grit n-mag stream (4 to 6 Mt/a of waste) is rejected using dry magnetic separation. The coarse waste stream is free of water and can be disposed of alone or mixed with other wet waste from the tailings thickener. Dry tailings disposal is projected to save between 0.8 and 1.4 GL of water each year, depending on the mass percent rejected. Magnetic grits are returned to the VRM for milling to the final 85 µm P_{80} target. The dry VRM product is then pulped and fed to the IMS stage where the bulk of the wet n-mags is generated in this circuit. Pyrrhotite is removed from IMS magnetics using flotation and the cleaned magnetite is sent to regrinding and CMS before it is pumped to the port at Albany. (note the change in the pyrrhotite flotation flowsheet position from after regrinding to before regrinding, a separate flowsheet improvement achieved during this same test program).

After the PFS was issued in 2022, Loesche were in the final stages of constructing a new closed-circuit pilot VRM at their facility in Dusseldorf, Germany. The results from closed circuit pilot testwork allowed Loesche to quantify the rejection of coarse non-magnetic waste (n-mag grit) and to quantify the power benefits this achieved. The grit waste proportion is a function of the liberation of the magnetite and the classification actions inside the VRM, and is not quantifiable by current modelling capabilities.

Vertical Roller Mill (VRM) Technology

Modern VRM technology is based on one of the oldest grinding methods known. Developed in antiquity, simple roll machines could be constructed from common materials and replace manual-labour based methods of breaking rocks. Energy to make the roll system work could be supplied by animals and unfortunate people and delivered via simple transmission systems. As time progressed larger amounts of energy could be supplied by water wheels or windmills, in the appropriate locations.

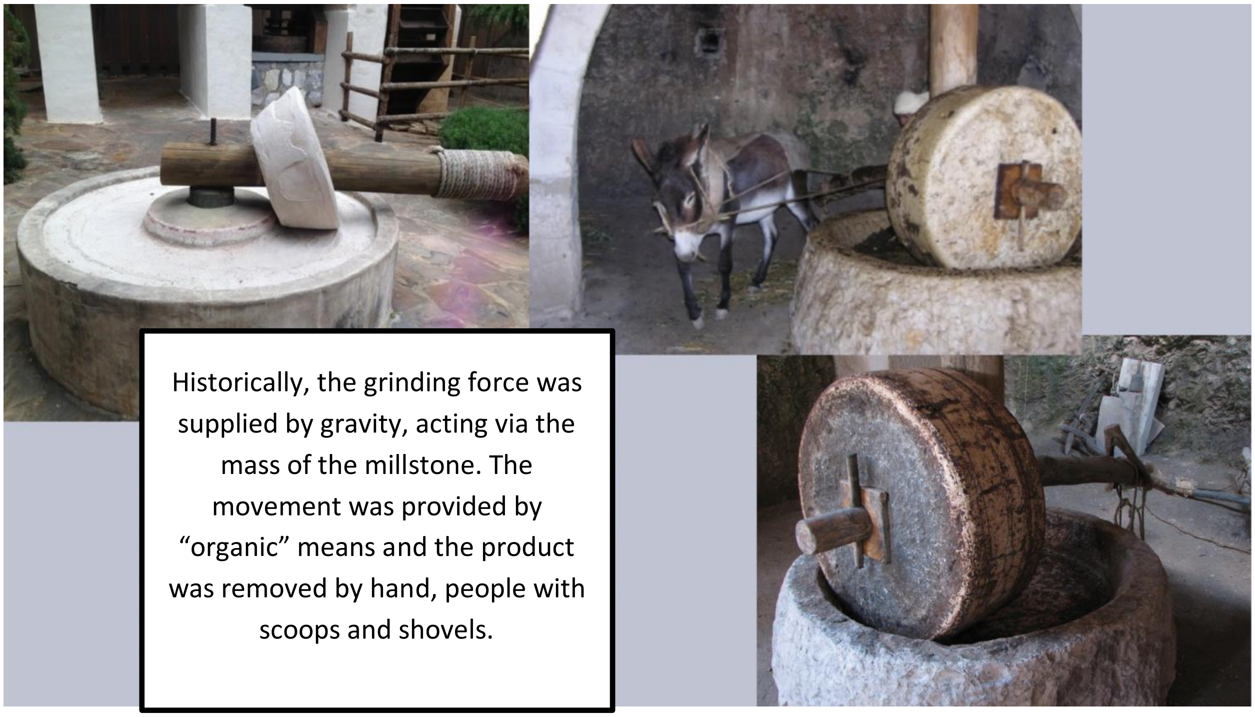

Figure 3: Historical Roller Mill Examples

Modern VRM units are much larger, motor driven and usually operated in closed circuit with a dynamic classifier mounted on top of the mill, as shown in Figure 4 at point 4. Additional grinding force, greater than gravity alone, is supplied to the roller(s) (point 2) by springs or hydraulic systems. In this design the rollers are fixed in location and it is the table underneath the rollers (point 1) that rotates. Continuous operation requires a gas flow through the machine (at points 3 and 5) and this provides a compact combination of grinding, classifying, and drying. Material that has been ground but is too large to be lifted by the gas flow falls down the chute discharge (point 6) and is returned by conveyor to mill feed.

Modern VRMs can draw up to 15 MW and treat up to 1000 t/h of feed.

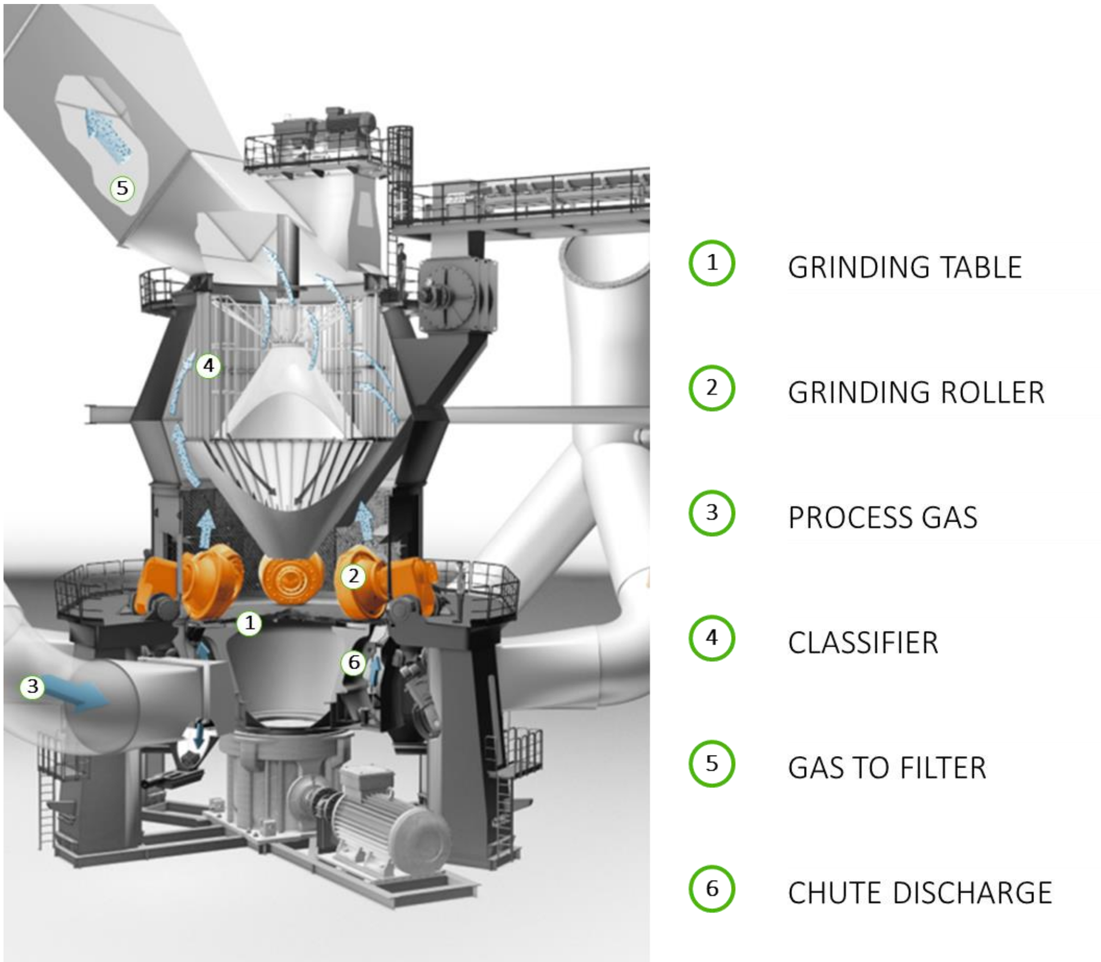

Figure 4: Schematic Loesche vertical roller mill

Detailed VRM Operating Principles

Accepting feed sizes up to F_{100} = 150 mm and grinding products down to P_{80} = 20 µm in a single unit, the Loesche VRM contains all elements necessary to achieve reduction ratios of 5000 to 7000 which will take crushed feed to the final product size in most instances.

After tramp-metal removal, material to be ground is fed into the mill and directed to the centre of the grinding table. Under the effect of centrifugal force, the feed moves outwards towards the edge of the rotating table and into the path of the grinding rollers. Under compression in the grinding gap, the particles and generated fragments are firstly displaced into existing voids within the material bed before they start to break under much higher force due to hydrostatic pressure. This process is known as compressive in-bed comminution. Breakage is induced mainly by compression, supported by small amounts of shear, resulting in optimum size reduction, high energy efficiency, and minimum wear. The advantage of the in-bed comminution principle is that through the multiple contact points applying pressure from all sides on the particle, there is a high probability for crack initiation on the mineral boundaries and at other weaknesses. This often results in an improved degree of mineral liberation when compared to conventional tumbling milling, as has been reported by Van Drunick et al. (2010), Altun et al. (2015), Reichert et al. (2015) and Jacobs et al. (2016). The liberation benefits translate to mineral separation benefits as discussed by Crosbie et al. (2005).

The ground material leaves the confines of the compressive breakage region and continues its movement under centrifugal force to the edge of the table. All particles fall from the edge of the table into the process gas stream where finer particles are levitated upwards to the classifier. The rotational speed of the classifier, in combination with the inward directed speed of the gas flow, determine the cut size of the classifier. Product-sized material passes through the classifier vanes and leaves the mill with the gas flow to be collected within the bag-house filter. Coarse material rejected by the classifier (Grit) can be returned ot the grinding table or it can be partly or completely discharged from the mill, as is done in the Southdown pilot plant testwork. However, in most VRM installations the grits are guided by the grit cone to the centre of the grinding table for further comminution.

Most particles that have undergone one or two compression events are levitated and presented to the air classifier, ensuring that any particles that have been produced at the target grind size avoid being overground. This process of rapid high energy grind followed by classification produces a narrow product size distribution (a steep cumulative particle size distribution curve) and this results in reduced amounts of ultra-fines. A stream of very coarse material, so-called reject, is not levitated at the edge of the grinding table and it falls through the upward moving gas into a chute discharge where it is removed. The rejects are recycled to the mill feed by the reject conveying system.

The air flow system can account for half of the power consumed by the VRM. In the case of wet feed (>3.5% moisture for ores like Southdown) the air needs to be heated to ensure there is no caking inside the mill and classifier. Only minor air heating costs (if any) are anticipated for Southdown.

A typical simplified flow sheet for the air flow mode is illustrated in Figure 5. Air is drawn through the VRM (8) then the baghouse (11) and out to the fan (13). If heating is required some air is returned to the VRM feed via a burner (15). The fan (13) discharges to atmosphere and is a loss point for water present as moisture in the feed (1).

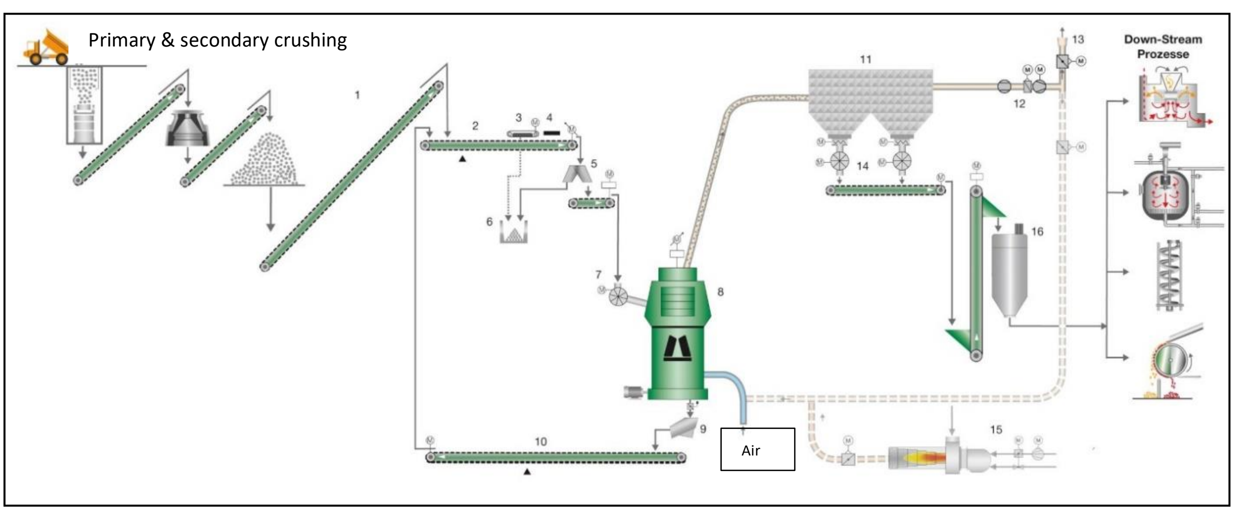

Figure 5: simplified VRM flow sheet with Air Pathways

Traditional and Emerging VRM Applications

With thousands of installations, compressive comminution technology is now a standard in the production of cement, preparing coal for power stations and grinding for various industrial mineral applications. VRM technology is arguably the compressive comminution method with the widest application globally, when all materials needing to be ground are considered. These traditional applications are not considered to be difficult duties compared to ores in the hard-rock mining realm.

An example of a difficult industrial “mineral” application, VRM technology offers a solution for cost and CO_2 savings by efficiently grinding abrasive steel slags, which can be blended into the clinker mix when producing some cement types. In 2003 there are more than 500 Loesche VRMs installed globally to grind clinker and slag for the cement industry.

Although limited, there are industrial applications of VRMs for grinding highly abrasive hard rock. Two such Loesche applications are both for VRMs grinding phosphate ores. The first example uses in excess of 25kWh/t in South Africa (Jacobs et al., 2016) and the second using 18.6kWh/t in Kazakhstan (Stapelmann et al., 2018). The South African application was the first, almost 20 years ago, and provided many valuable lessons for Loesche in regard to managing wear and improving design.

Test material and Geometallurgy

In August and September of 2010 a diamond drilling campaign for metallurgical testwork was performed at Southdown. Some cores were drilled at 150 mm diameter and some at 83 mm (PQ) size. The justification for the 150 mm diameter drilling was to ensure that the feed to the fully autogenous (AG) milling pilot trials contained realistic topsized material in the feed. Six 150 mm holes were drilled together with five PQ holes covering the western and central areas of the orebody. These drill samples have subsequently been used for all the Southdown testing across more than a decade.

The locations of these holes are shown in cross section in Figure 6. The orebody is shown in grey and the grid is 1 x 1 km. The western and central sections of the deposit are where The Project intends to commence mining.

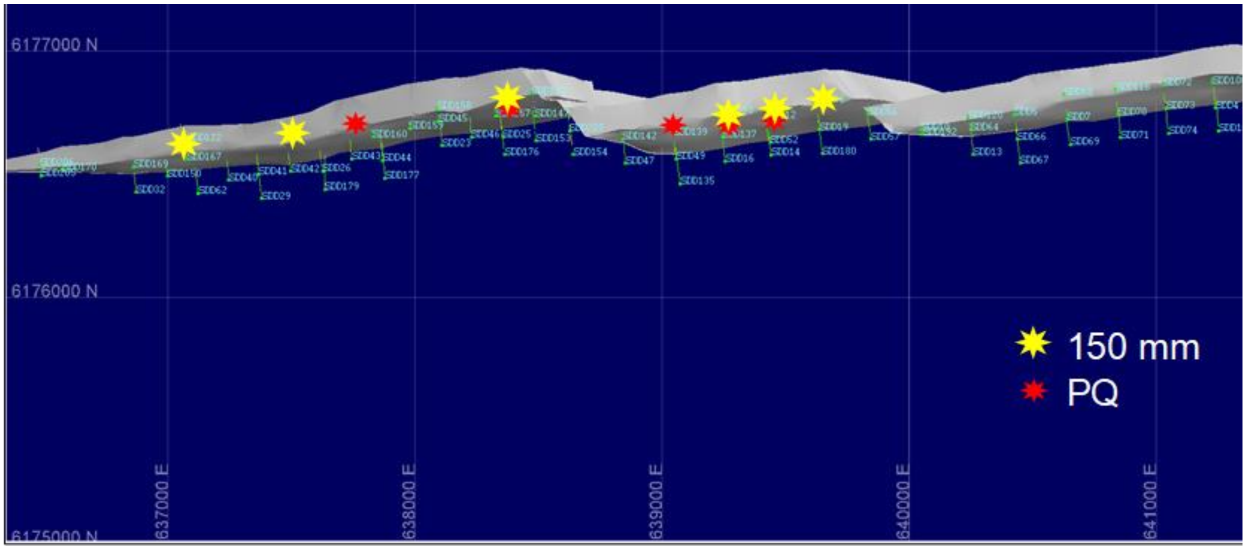

Figure 6: Location of Metallurgical Pilot Plant Holes

Typical examples of the 150 mm core are shown in Figure 7. Note the coarse-grained mineralisation. Some of the pink minerals are garnet, contributing to its abrasive nature.

Figure 7: 150 mm Diamond Core for Metallurgical Testwork

No part of the core from within the ore zones was fragmented and upon arrival at the laboratory and many core lengths had to be broken into pieces small enough to be easily handled by one person. The competence of this core was part of the reason it was useful for metallurgical testwork over such an extended period. The drilled mass from this program was more than 40 t.

The following set of properties were measured for that component of the core selected for the AG mill piloting trial. The properties are compared with the average of the variability samples selected from the core and measured at the same time. Checks were also made on the samples used recently in the VRM testwork.

Table 1: Comminution Properties of Test Samples

	Pilot Core (2010)	Variability Sample Average (2010)	VRM1 Sample (2020)	VRM2 Sample (2022)
DWi	5.60	6.16		
CWi	13.0	10.7		
RWi	12.8	13.5		
BWi	18.2	18.3		17.7
Ai	0.37	0.44		
SG	3.52	3.50	3.61	
DTR	37.7	35.4	37.0	36.1
%S	0.42	0.47	0.37	0.35

Southdown ore samples are abrasive (Ai values as high as 0.6) and difficult to grind in a ball mill (BWi values as high as 20 kWh/t). However, the large grain size makes the ore relatively easy to break at the coarse sizes that are most relevant to crushing and AG milling. The ore is more than one third magnetite as directly measured by the DTR values (Davis Tube Recovery, recognising that a small proportion of the DTR magnetics is pyrrhotite), and this is the cause of the high SG value. A notable aspect of Southdown ore is that the Bond ball mill work index (BWi) is uncharacteristically consistent across the variability samples, with all but a few results between 17 and 19 kWh/t.

Sulphur is present as the sulphides pyrite and pyrrhotite and sulphide sulphur is a problem contaminant in a magnetite concentrate. The VRM feed materials are slightly lower in sulphur than the 2010 test samples, but this is probably a sampling effect rather than the result of sulphide oxidation. It was demonstrated multiple times during pyrrhotite flotation in the VRM work that the sulphides had not noticeably degraded during 10 years in storage. It was also discovered that pyrrhotite will degrade rapidly once ore is ground below 100 µm P_{80}.

The full 40 t of core was transported to Perth in 2010 for selection of AG mill pilot feed material. Only a portion of the total sample was required and the remainder was returned, mostly uncrushed, to a storage shed at the Southdown project site. The site sample was stored in bulk bags and much of it remained as solid core. Another portion of this sample was used for a second confirmatory AG mill pilot test program under independent oversight (which gave effectively identical results as the first program described here) and the remainder was kept protected in the site shed. As the AG mill pilot sample had been selected from throughout the available core this means that the remaining unused core would be similar to, but not identical to, the original test materials. Given the consistency of the comminution properties across all variability samples, there was an expectation of consistent comminution properties across various subsamples from the 40 t of sample. The BWI value of 17.7 kWh/t measured in 2022 confirmed this, and the magnetite contents were also consistent.

For the first VRM pilot work the sample was visually assessed, subsampled, tested for degradation of sulphides and 6 t of material was selected. For VRM testwork the requirement for the feed was to be -16 mm, the standard topsize for the Loesche pilot scale grinding units. Later, a second sample for VRM testing was required and both feed lots was contract-crushed to this size in Australia then despatched to Germany. The check BWi measurement in 2022 was made on the second VRM sample.

Testwork Methods

Magnetite Ore Processing

Magnetite and hematite are the two main iron ore minerals. Hematite, common in the Pilbara Region of Western Australia, mostly exists as direct-shipping ore (DSO) and is ≥55% Fe in the ground. Hematite rarely exists as DSO and is normally found in relatively low grade (30 to 50% Fe) deposits from which a saleable concentrate must be made. Magnetite deposits like Southdown require grinding and magnetic separation to remove waste (siliceous gangue) and make a high-grade concentrate. Magnetite concentrates are generally targeted at >65% Fe and this compares to theoretical pure magnetite which is 72.4% Fe. Note that pure magnetite rarely occurs in nature because the magnetite mineral matrix contains substituted elements such as Ti and Al. Natural magnetite is usually between 71 and 72% Fe. Southdown magnetite is low in impurities and consistently achieve a premium grade of magnetite concentrate containing 69.5 to 70% Fe, making it suitable as feed to Direct Reduction Ironmaking (DRI).

At the heart of magnetite processing is the ability to reject a waste stream that is essentially free of magnetite. At very coarse sizes, above 20 to 40 mm, most magnetite is not liberated from the non-magnetic minerals, so it is almost never an option to make a coarse (lump) high grade magnetite concentrate. As crushing and grinding progresses more of the non-magnetics are liberated from the magnetics and are available for rejection as clean waste. The normal path for magnetite concentration is to progressively liberate and reject the non-magnetics until all that remains is liberated magnetite. This is shown conceptually in Figure 8. Note that while liberation of waste and magnetite grade increases with reduction in particle size, it is unlikely to be a regular progression as suggested in the diagram.

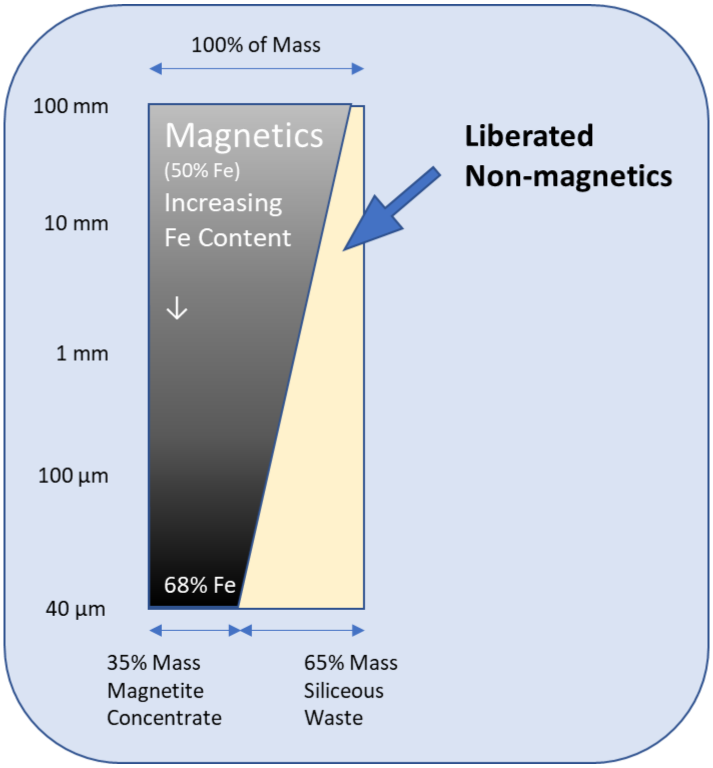

Figure 8: Conceptual Liberation of Waste from Magnetite Ore

Coarse dry separations (often termed cobbing, within the top section of Figure 8) at particle sizes from 4 mm to 20 mm can be made using a strong magnetic field to ensure that that the only particles sent to waste are those that have no magnetite content at all. The waste rejection generally needs to be greater than 20% of the feed mass to make such a coarse separation worthwhile.

In the bottom section of Figure 8 it is necessary to grind ore to something like 40 µm and then perform a separation to make the final magnetite concentrate. One option is to ignore the progressive liberation and grind the entire feed to 40 µm P_{80} and conduct magnetic separation. However, the comminution energy requirement to do so is far from optimal because much of the gangue has been ground much finer than it needs to be for rejection. The testing and design process works with the increasing liberation by seeking to reject clean waste at a number of progressively finer sizing points. The coarser the waste is rejected the less energy is required to achieve the 40 µm P_{80} magnetite. An example of a multi-stage energy-efficient comminution and separation process to make a magnetite concentrate is shown in Figure 9. Note that this is a descriptive diagram and does not represent the actual separations performed in this work.

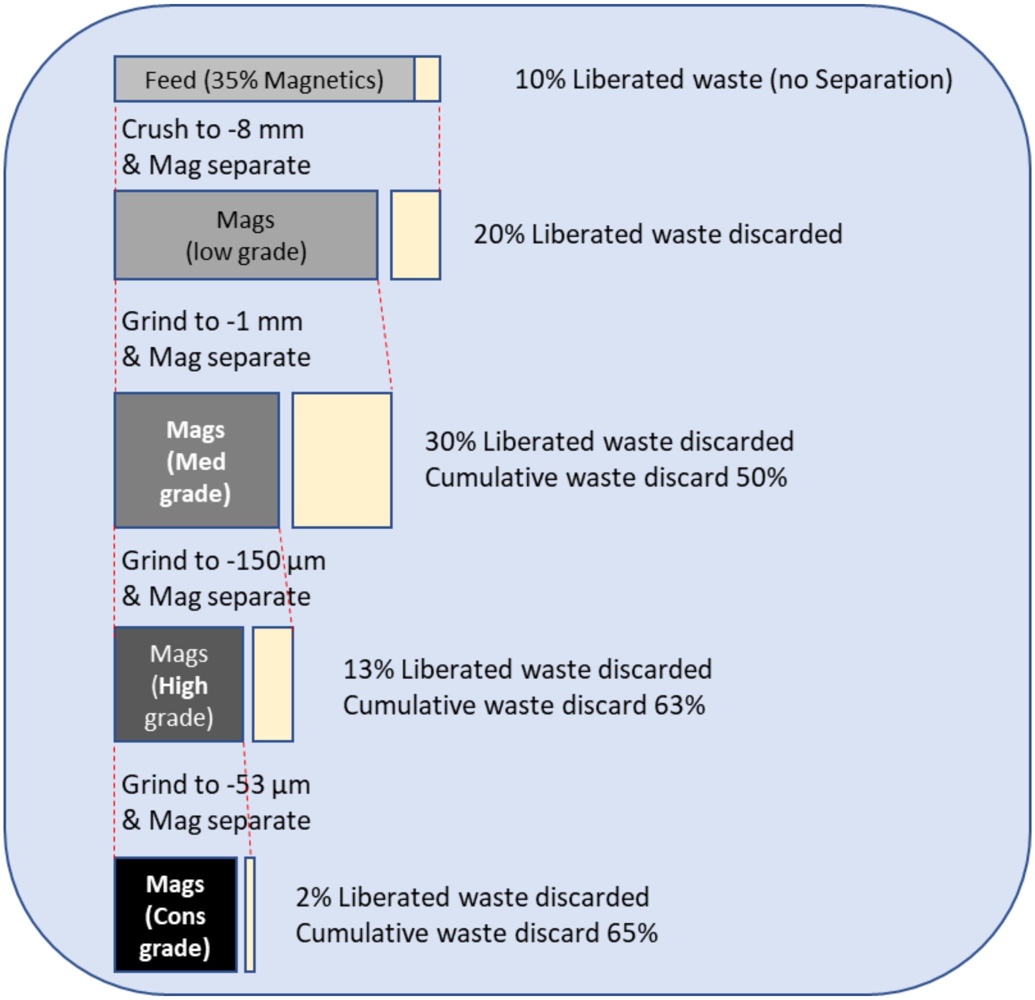

Figure 9: Progressive Comminution and Magnetic Separation Example for Magnetite

Each of the test programs described in this paper is ultimately trying to achieve the same endpoint, maximum recovery of high-grade magnetite concentrate at 35 to 40 µm P_{80}. However, each approach reaches its own natural grind and separation stop points based on equipment types, numbers and unit capacity. To simplify the comparison between methods, both comminution systems tested produce an intermediate grind product at about 80 to 100 µm P_{80} and the comparisons in this report are made from plant feed sizing to an 85 µm P_{80} grind.

AG and Ball Milling (2010/11)

Pilot AG milling was performed in the ALS (Perth) 1.6 m diameter continuous AG/SAG mill. A realistic feed size distribution was prepared by selective crushing of core into a range of different coarse and fine sizes. The pilot mill feed was manually constituted throughout the pilot run by placing a predetermined recipe of the crushed fractions onto a slow moving feeder. The AG mill component of the pilot flowsheet (no pebble crushing) is shown in Figure 10.

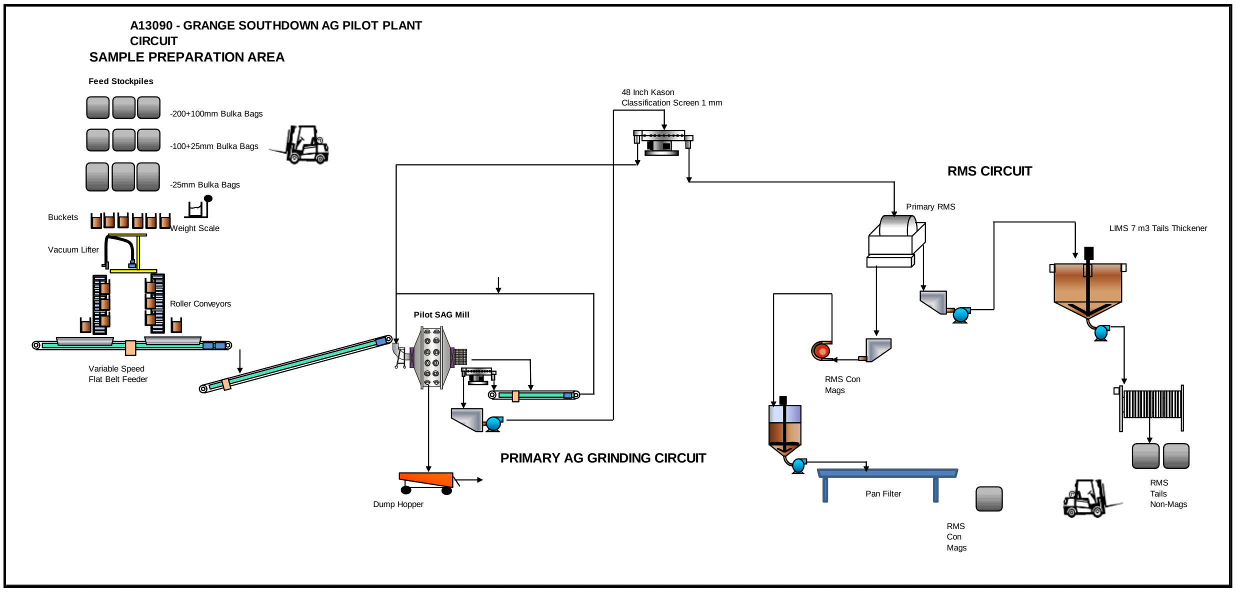

Figure 10: ALS Pilot AG Milling Flowsheet

AG mill throughput was controlled to maintain a relatively constant mill charge mass and the milled products, fine pebbles and slurry, were sampled and analysed. Pebbles and all +1 mm was recycled to mill feed and slurry product was separated in the RMS circuit (rougher magnetic separation) using Wet Low Intensity Magnetic Separation (WLIMS). The magnetics (product) and non-magnetics (waste) were filtered. At the conclusion of testing the mill was crash-stopped and the AG mill rock charge was “dropped“, weighed and its size distribution measured.

AG milling relies on the ore forming good grinding media inside the mill. It also relies on those grinding media particles wearing down reasonably rapidly so that they don’t persist and overload the mill with very coarse or “critical sized” material. Southdown ore forms excellent rounded media, as can be seen in Figure 11, and the media was self-grinding at an acceptable rate. The largest particles visible in Figure 11 were originally 150 mm diameter pieces of core. An almost intact cylindrical core piece can be seen in the upper right of the image. This piece would only have entered the mill in the last minutes before the AG mill was shut down.

Figure 11: AG Mill Charge showing Rounded Media

The mill was instrumented and calibrated for power consumption and the results of the definitive milling run are shown in Table 2. The pilot AG Mill specific power is the basis for estimating power requirements in the industrial AG mill.

Table 2: Pilot AG Mill Power Evaluation

AG Motor Input Power (kW)	8.97
AG Power at Shell (kW)	6.73
AG Feed Rate (kg/h)	847
AG Specific Power at Shell (kWh/t)	7.95

During industrial design, corrections are needed to this pilot scale power result for three scaleup factors:

- 0.954x power reduction as the industrial AG mill produces a coarser product (-3 mm industrial, -1 mm pilot)
- 1.05x power increase for the difference in aspect ratio of the pilot and industrial mills
- 1.19x power increase to design for AG mill operating headroom to accommodate more competent ore than the (average) feed processed in the pilot plant. Scaling was based on the

difference in DWi values between the pilot tested ore and the 80th percentile of the variability sample results.

The first two correction factors effectively cancel each other out in this instance multiplying to 1.002 or an increase in power of 0.2%. This is well below the accuracy of measurement in the testwork and has been assumed to be 1.0. The final correction factor takes the specific power (also known as specific energy) for AG milling to **9.48 kWh/t**.

It is important to note that AG mill operation is much more sensitive to the feed competence compared to crushing and fine milling unit operations. Therefore, competence power correction is not needed for VRM milling because its efficiency is determined by crushing and fine milling response.

The pilot AG mill slurry product, the feed to RMS, had a P_{80} of about 330 µm. However, this P_{80} is based on pilot screening at 1 mm and this means that a correction must be applied for expected industrial RMS performance and for subsequent ball milling. The pilot ball mill feed was the RMS magnetic fraction which had a P_{80} of 410 µm. Scaling to the industrial 3 mm screening case was performed using JKSimMet simulation and this raised the ball mill new feed F_{80} to 770 µm.

The pilot RMS rejected 39% of the mass of the AG slurry product and this means that the ball mill pilot operation was based on treating 61% of the plant feed mass. However, as the RMS feed will be coarser in the industrial scale, the proportion of liberated waste will be less than the pilot result. Again, a correction is needed to make the design realistic. By simulation, the RMS rejection rate was reduced from 39% to 32.3% at the realistic coarser screen separation size.

The pilot plant ball milling flowsheet is shown in Figure 12, outlined in red. Outside the red outline are all the downstream operations necessary to make final magnetite concentrate.

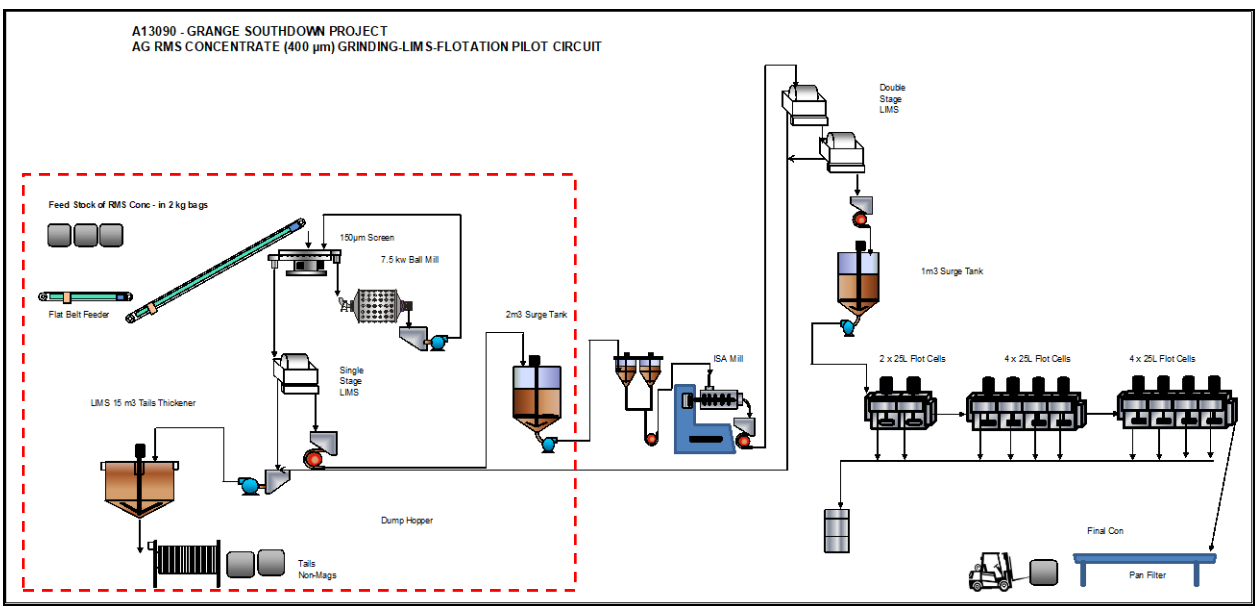

Figure 12: ALS Pilot Ball Milling, Intermediate Magnetic Separation, Regrind Milling and Flotation Flowsheet

The Ball mill pilot test gave a calculated operating work index (OWi) of 18.73 kWh/t, remarkably close to the ball mill work index which confirms pilot ball milling performed efficiently. The OWi was scaled up by a factor of only 1.014x to 19.0 kWh/t to adjust from the pilot feed BWi value to the 80th percentile design BWi value. The adjusted OWi was then applied to the industrial grinding duty envisaged at the time, which was from F_{80} of 770 µm to a P_{80} of 103 µm, and this results in a specific energy requirement of 11.9 kWh/t for ball milling. For comparative purposes this value must be further adjusted to match the same P_{80} as the VRM test product, which is targeting 85 µm P_{80}. The required factor (using Bond calculations) is 1.159 times, and this results in an industrial specific energy for ball milling RMS magnetics from 770 µm to 85 µm of **13.7 kWh/t**.

The combined AG and Ball mill circuit power at industrial scale is summarised in Table 3.

Table 3: AG and Ball Mill Scaled Industrial Circuit Summary

Stage/Stream	Mass% of Feed	Stage S.E. (kWh/t)	Feed S.E. (kWh/t)
Feed	100		
AG Milling	100	9.84	9.84
RMS Non-Mags	32.3		
RMS Mags	67.7		
Ball Milling	67.7	13.7	9.28
Total Comminution energy to 85 µm P_{80} (kWh/t)			**19.12**

The combined specific energy requirement of 19.1 kWh/t of fresh feed will be used for efficiency comparison purposes.

VRM Testing and Design

As previously indicated, VRM testing was conducted in two stages. In Stage 1 (for all cases except the final test) the ore was subjected to the standard VRM procedure in the standard VRM test machines. The exact test has been applied by Loesche over 10 000 times to evaluate materials and design industrial VRMs. The last test in Stage 1 was non-standard as it was the beginning of the exploration of grit extraction and processing and required modification to the standard test machine.

The standard VRM procedure is a pilot scale test that includes crushing and grinding as well as classifying using a dynamic air classifier. Because the classification processes used in the pilot test emulates classification in the industrial size equipment, the material properties of the pilot products are ideally suited for assessment of the performance of downstream processes (Note that this is not the case with wet milling, which often uses fine screening in the pilot plant and cycloning in the industrial environment).

The standard VRM procedure is an empiric approach, emulating industrial operation. The test and associated data analysis determine the throughput of the test material in an industrial installation. Scaleup factors are inherent in Loesche's design procedure and are not disclosed for commercial reasons. The test does not measure specific material characteristics (like BWi, for example) that are normally used in mill scale-up calculations.

The results of the pilot test are compared with an extensive database of pilot results to place it in the hardness and throughput spectrum. A second extensive database exists of industrial size VRMs treating the same materials tested at pilot scale. By relating their pilot and industrial databases Loesche is able to make precise mill size selections for new materials such as Southdown ore.

To determine the mechanical power consumption during the pilot test, the torque at the grinding table and the angular speed of the grinding table are measured. When combined with the continuously measured throughput, the specific power consumption can be directly calculated (Schmitz et al).

The Standard VRM test flowsheet is shown in Figure 13, together with the simple modification for open-circuit grit extraction. New -16 mm feed (1) is dropped into the centre of the horizontal grinding table and the two conical rollers crush and grind it. Air then carries smaller and medium particles to the classifier at the top of the unit and coarse particles (2) gravitate to a recycle system (typically this recycle is 10% of the mass). The product classifier only allows target sized material out to the baghouse (on the right) and it is then available as ground Product (6). The grit fraction from the product classifier falls and is guided by the cone into the centre of the grinding table.

To achieve optional open-circuit grit extraction, modification to the test unit is necessary to intercept and capture the grits and take them outside the mill (5). In this mode the mill produces two products, (5) and (6), rather than one. When using this modification all the grits are extracted and none are returned to the grinding table.

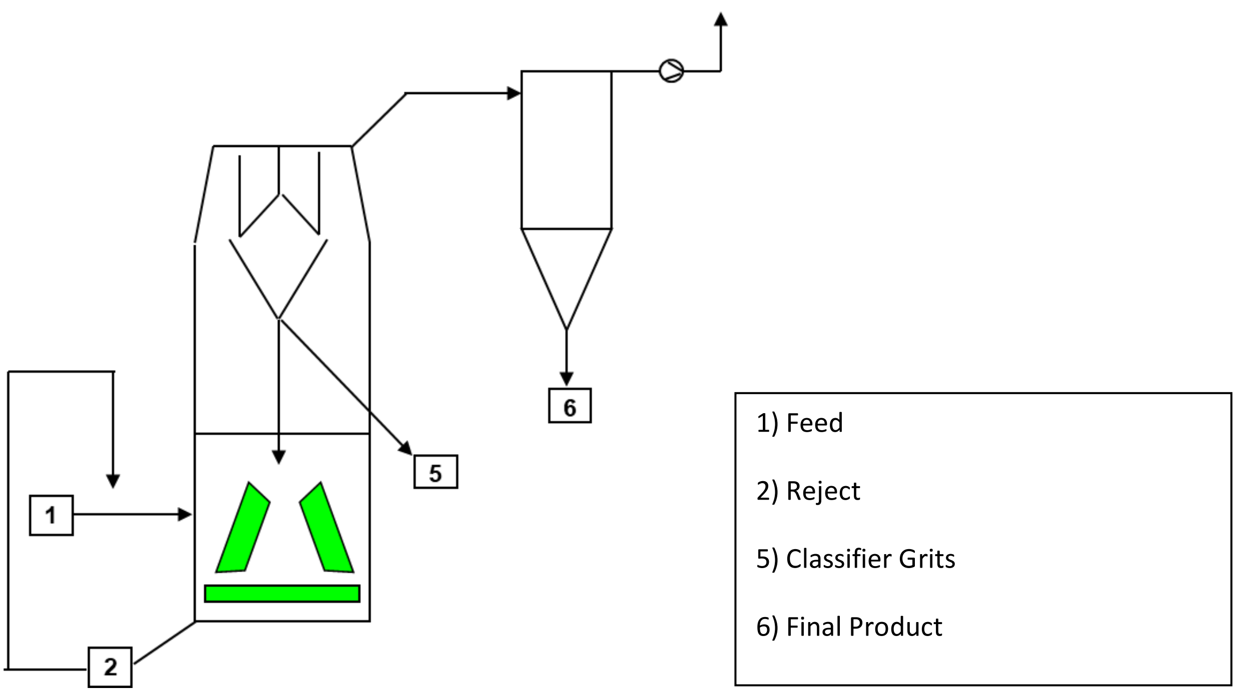

Figure 13: VRM Test Flowsheet with Optional Grit Extraction

Neither the normal single product test nor the grit extraction dual product test emulate the desired industrial flowsheet. Nor was it possible to utilise the information generated by the single and dual product tests to predict closed circuit operation in the desired industrial flowsheet. The required design information could only be generated by a purpose-built closed-circuit pilot plant.

In Stage 2, Loesche prepared a continuously operable closed circuit pilot plant able to extract and process grit from the VRM, discard barren waste and return the magnetic grits to the mill for further comminution.

VRM Stage 1 Testwork

A 6.7 t sample of Southdown Ore was crushed to -16 mm and delivered to the Loesche VRM testing facility in Dusseldorf, Germany in 2019. The initial aim was to estimate the power for the VRM to complete the full grinding duty from -16 mm feed to 36 µm product. In this approach there is no rejection of non-magnetics at any stage as the VRM receives 100% of the feed and grinds it all to 36 µm.

The pilot VRM is fully automated and the test procedure has been refined and repeated over many years. Expert operators are able to achieve nominated grind targets after only brief initial testing and adjustment. The degree of standardisation of the Loesche test method is such that it can be considered similar to (or even superior to, given the much greater test mass) a Bond grinding work index test in terms of repeatability and reliability.

The results of the initial total-grind fine-product tests are presented in Figure 14.

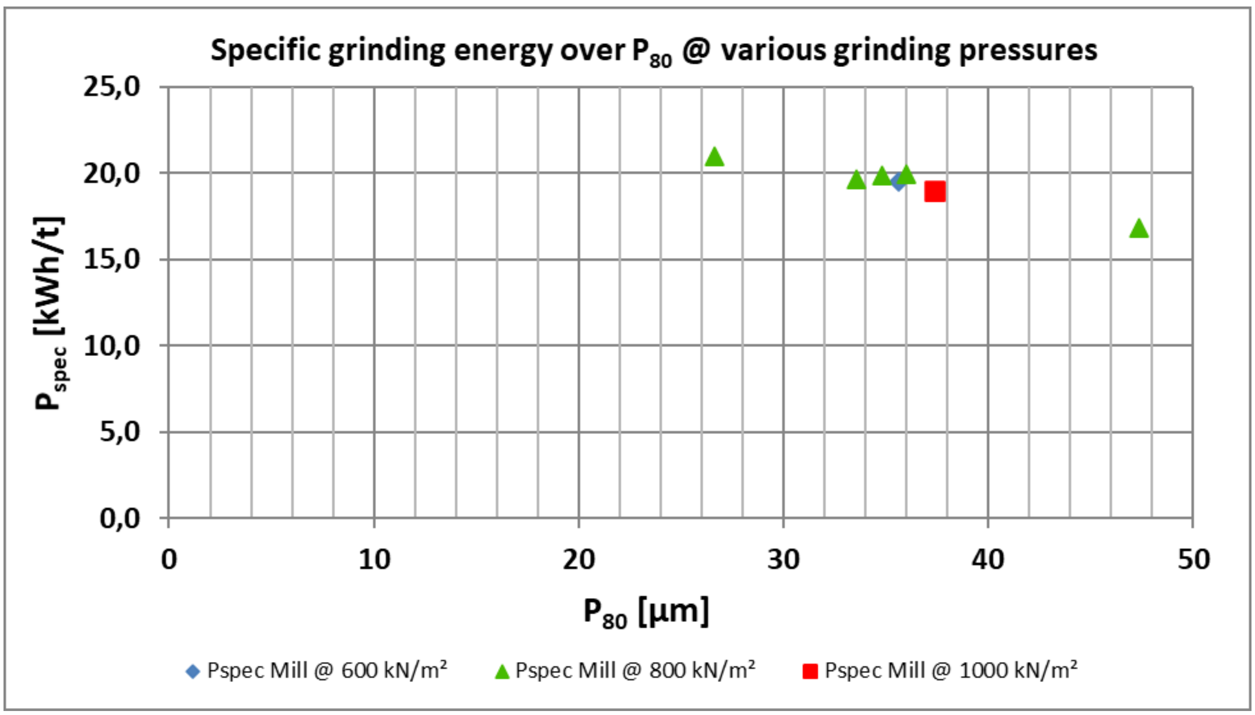

Figure 14: Initial VRM Tests – Product Size Grinding

All products were between 27 and 48 µm P_{80} and all power requirements are between 17 and 21 kWh/t. All of the results that achieved sizes close to 36 µm P_{80} are between 19 and 20 kWh/t. Note that this refers to comminution energy and does not include the power to run the main air fan, to rotate the classifier and to run other peripherals in the VRM plant. All of these factors are calculated later by Loesche in their proprietary industrial scale-up procedure.

It was quickly concluded that grinding in a single stage to 36 µm consumed too much energy and the practical effect was to excessively limit the throughput of large VRM installations. The implied effect was to require four or five VRM installations to achieve the required project feed rate.

Another issue was that it did not allow any rejection of non-magnetic waste before making the final magnetite product. Fully grinding the ore to 40 µm was certainly going to make the VRM option less attractive than conventional wet milling with progressive n-mag rejection. On review, the VRM testing aims were changed and a range of coarser products were generated. The results are summarised in Figure 15 and include the data points from Figure 14 in the upper left.

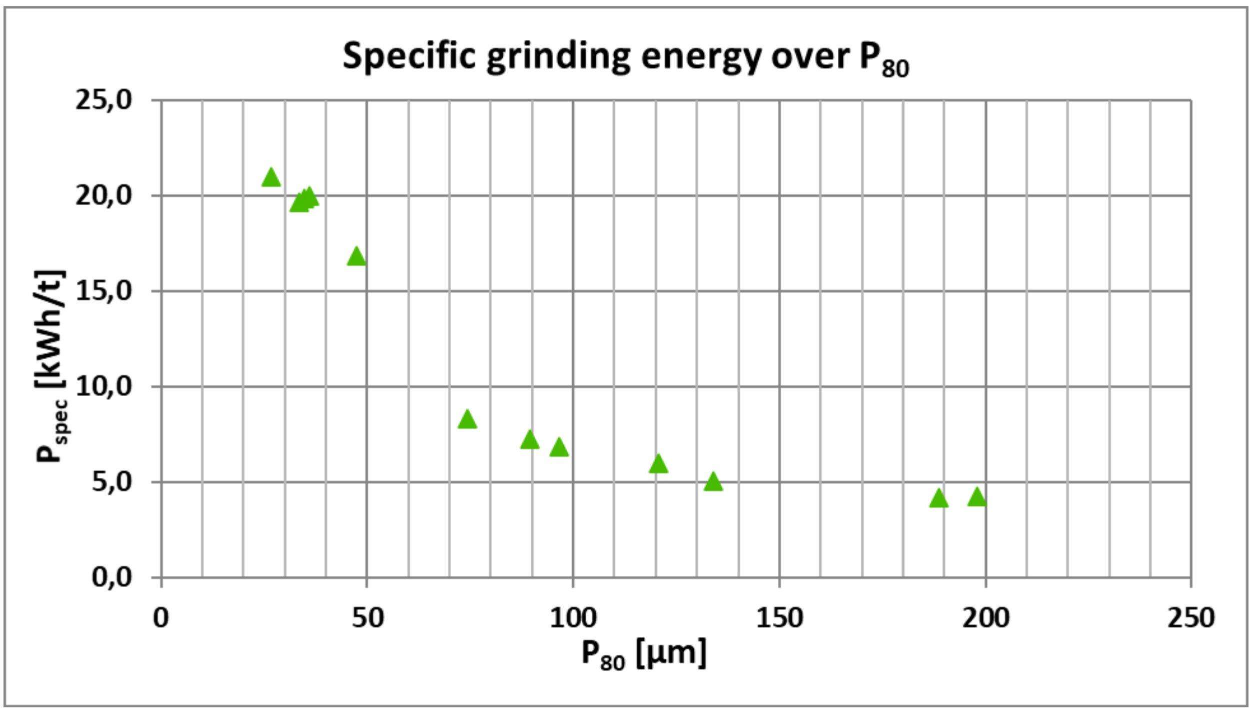

Figure 15: Fine and Coarse VRM Tests

The change to coarser grind sizes more than halved the grinding energy requirement and dramatically increased the throughput capacity of an industrial VRM treating Southdown ore. The coarser grinds were a positive development for the Southdown project.

After detailed assessment of the open-circuit results it was concluded that 95 µm was a reasonable compromise between the positive aspect of reducing comminution energy demand and the negative aspect of decreased waste liberation at coarse sizes. However, any size between 75 µm and 120 µm was considered acceptable for ongoing investigations. The industrial unit capacities inherent in these results reduce the number of operating units required from four or five down to a much more acceptable two or three.

Open circuit VRM grinding from 85 mm to 95 µm P_{80} would allow the majority of the n-mag waste to be rejected at the IMS stage. The VRM IMS mags, which feed the regrind stage, would be comparable to the AG/Mag/Ball circuit IMS mags stream. In this comparison the VRM would remain at a grind-duty disadvantage because the AG/Mag/Ball circuit incorporates the RMS waste rejection step on the path to making a 95 µm product. To insert an RMS step into the VRM flowsheet requires grit extraction and magnetic separation.

Loesche have several industrial VRM units where classifier grit is extracted, generally to be sold as a separate coarse product. The concept of grit extraction followed by magnetic separation was a known possibility for magnetite ores but had never been practiced or tested. The attraction of being able to extract and reject non-magnetic waste at coarse sizes was that the grinding energy requirements could be reduced further and the individual machine throughput capacity could be further increased.

The last component of Phase 1 work involved collection of grits from within the VRM. A standard VRM test unit was modified to make this possible, but only in open circuit arrangement as shown in Figure 13. A test was performed so that a sample of grits could be extracted and then tested for size distribution, magnetic separation response and production of a barren non-magnetic waste. It was recognised that the modified Stage 1 test rig had no possibility for further modification to allow grits to be processed and the magnetic grits continuously returned to the VRM for grinding.

The grit extraction test was successful and size distributions of the two products from the test are compared in Figure 16.

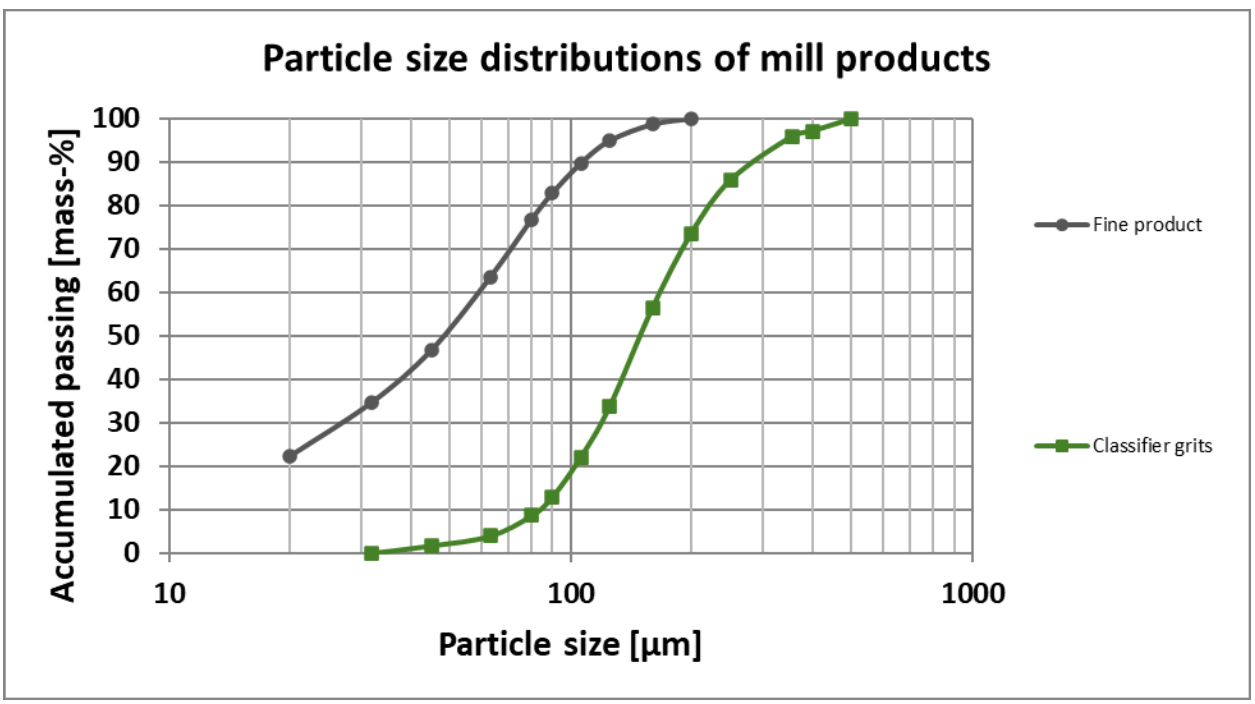

Figure 16: 85 µm P_{80} VRM product and Grit Product

The grit produced by this method has a P_{80} of between 200 and 250 µm and a top size of 500 µm. It is also devoid of fine material (with nothing finer than 32 µm) which means that it is dust-free and will behave like dry coarse beach sand. The two products from this test are compared in Figure 17.

Figure 17: VRM Final product and Grit Product

The grit material was sent to SGA laboratory (Germany) and separated magnetically. A medium intensity dry drum magnet (3800 Gauss) was used in the separation to ensure that particles of gangue containing only small amounts of magnetite reported to the magnetics fraction. The results are summarised in Table 4.

Table 4: Magnetic Separation of VRM Grits

	Mass %	Magnetite Grade (Satmagan)	Magnetite Recovery
Magnetics	55.9	74.9	99.6
Non-Magnetics	44.1	0.4	0.4
Feed (grits)	100	42.1	100

Magnetic separation was highly successful with 44% of the grit being able to be discarded as fully liberated waste and 56% retained as high-grade magnetics. The recovery of 99.6% of magnetite to magnetics exceeded expectations. Full liberation of non-magnetic waste at grit sizes was confirmed.

Although this procedure demonstrated both the extraction of grits and their magnetic separation, it does not provide guidance on the possibilities that are available when both processes are connected in a closed-circuit pilot test program. Approximations of what an industrial VRM may achieve when connected to magnetic separation capability were made for PFS design purposes, but it was based on numerous assumptions. A working VRM test unit in closed circuit with dry magnetic separation was needed before accurate assessments of capability could be made.

Modelling was considered as a pathway to estimation of pilot and industrial requirements based on the Stage 1 results. However, as the relationship between gangue liberation and grind size was not known even the first steps of modelling had to be based on assumptions. For a successful model, a liberation model would need to be coupled with a comminution model, two classification models and a magnetic separation model. Worse again, liberation characteristics are ore-specific and would require detailed calibration for each ore under consideration. It was evident that before developing a model it would be necessary to generate some calibration data, and this would only be possible by having a suitably configured pilot plant. In this instance, having a pilot plant also negates the need for a model.

VRM Stage 2 Testwork

Over a period of about 12 months Loesche designed and installed a closed-circuit VRM/Mag Separation pilot plant into their VRM test facility in Dusseldorf. Commissioning was possible in April 2022 and the Southdown Stage 2 testwork was conducted in the final days of that month.

The pilot plant configuration is shown in Figure 18. This is similar in all ways to Figure 13, except the grits (5) are magnetically separated, the barren waste (8) disposed of and the magnetics (7) returned to VRM feed.

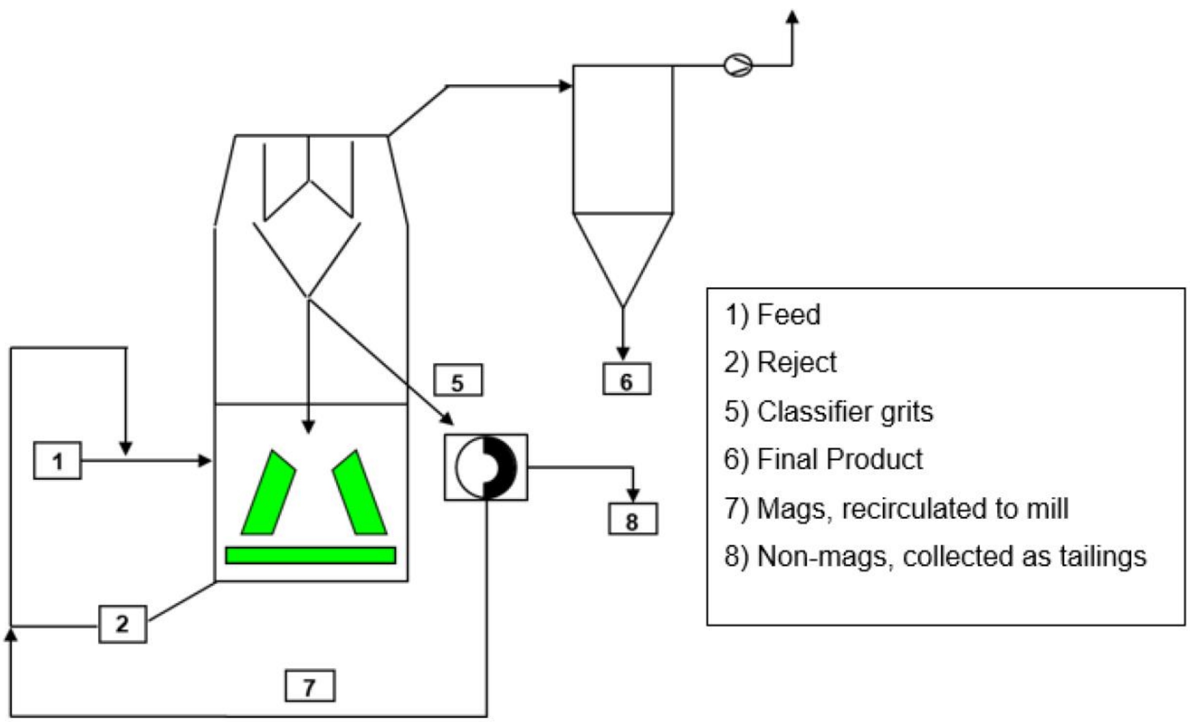

Figure 18: Continuous VRM and Grit Magnetic Separation Pilot Plant Flowsheet

The physical test arrangement at Loesche's facility is shown in Figure 19.

Figure 19: Continuous VRM and Grit Magnetic Separation Pilot Plant

Like the open circuit test unit, the closed-circuit unit was run by Loesche's test facility expert operators under automatic control and quickly achieved target performance on Southdown feed. The final VRM product size distributions varied between 81 and 83 µm over a number of continuous operating hours, during which six samples of products were collected. The results of the definitive test run are summarised below.

	Value	Comment
Feed Rate %	100	
Magnetite Content of Feed %	35	
Non-magnetic Grits Discarded %	41	Higher than expected
Grits extracted as fraction of feed %	252	Much higher than expected
Recycle Mags as fraction of feed %	212	Much higher than expected
82 µm product as fraction of feed %	59	
82 µm product Magnetite Content %	56	Excellent upgrade from feed
Magnetite loss to non-mag as fraction of feed	6%	Higher than hoped for – small diameter mag drum overloaded and drum feed rate too high and topsize too coarse
Specific Comminution energy (kWh/t of feed)	4.5	Very low for grinding from 16 mm to 83 µm

In this test some of the outcomes were excellent and some produced design difficulties for the dry magnetic separation circuit. The rejection of non-magnetic waste grits at a rate of 41% of feed was well above expectations. However, this came at the expense of a large extracted load of grits (252% of feed) and higher than expected losses in magnetic separation. Tests at SGA showed that half or more of the magnetic separation losses were of liberated magnetics confirming that the dry magnetic separation drum was overloaded. Fortunately, these are losses that can be avoided in industrial design.

An aspect of this particular pilot test that resulted in excessive magnetite losses was the coarse particle sizes extracted as grit. The unit extracted grit as coarse as 2 mm rather than the 0.5 mm topsize that was extracted in the open circuit trial at the end of Stage 1. Liberation and magnetic response at 2 mm is worse than at 0.5 mm.

Loesche were able to conduct a further trial under improved conditions about four months later and demonstrated lower magnetite losses.

Results Comparisons

VRM design outcomes will be compared to two equivalent design outcomes using AG/Ball mill comminution. The first comparison will focus on comminution to the IMS feed size of about 95 µm P_{80} without any removal of n-mag waste. The second comparison is to 85 µm P_{80}, but with coarse n-mag waste removal. It is also possible to construct some comparisons for grinding without n-mag waste removal to the initial fine grind size of 36 µm, but this involves many more corrections and assumptions to the definitive pilot results at 85 to 95 µm P_{80}. As such the 36 µm VRM work performed early in Stage 1 has not been used for industrial comparison purposes.

Industrial design outcomes are preferable to pilot outcomes for comparative purposes. This is due to the inconsistent conditions (such as F_{80} and classification methods) necessarily imposed on the two, quite different, pilot test programs.

The first grind-energy comparison assumes no magnetic separation in either circuit. In both cases all feed is ground to an intermediate size of 95 µm P_{80}, ready for IMS separation. In the AG/ball pilot plant the RMS n-mags were never subjected to grinding, but for this comparison the RMS stage is taken as having not occurred. Material rejected as non-mags in the test are considered to have been ground to 95 µm in power calculations. It has been assumed for this purpose that the specific energy to grind the non-mags (in kWh/t) is the same as measured for the RMS Mags. The RMS siliceous n-mag was finer than the mags, but it is safe to assume that it is harder to grind than the magnetite (Note that the fineness of the RMS siliceous component is not because it is softer in AG milling, it is because larger silica particles containing small amounts of magnetite report to mags rather than n-mags).

VRM power (total duty) is supplied by Loesche in their industrial design recommendations. The split between comminution and other power is approximate and is based on the pilot comminution power results and scaled to industrial values based on Loesche’s extensive correlated database of pilot and industrial performance measurements (>10 000 pilot tests and >17 500 related industrial data sets). The accurate value in the table is the total VRM duty power.

The power comparison is shown in Table 5.

Table 5: VRM vs AG and Ball Mill 100% Intermediate Grind to 95 µm P_{80}			
	AG/Ball		**VRM**
AG SE (kWh/t) 100% of Feed	9.84	Comminution SE (kWh/t)	6.9
Ball Mill SE (kWh/t) 100% of Feed	13.7	Fan, Classifier, etc (kWh/t)	7.3
Base Case P_{80} (µm)	78		
Comparison P_{80} (µm)	95		
Bond Correction for P_{80} SE (kWh/t)	-2.0 kWh/t		
Classification and internal conveyors 5% allowance (kWh/t)	+1.7 kWh/t		
Total Duty Power(kWh/t)	**23.2**	**Total Duty Power (kWh/t)**	**14.2**

The VRM provides a 39% reduction in overall power compared to the AG/Ball circuit. A power reduction of this order is sufficient to shift the project economics towards using VRM technology, even without grit extraction and processing.

The second grind energy comparison is between the closed circuit VRM and the pilot result for the AG/Ball Mill circuit, both scaled to industrial installations. Both cases are designed to grind to an intermediate size of 85 µm P_{80}. Both of these cases are very close to the final configurations of the actual pilot testing circuits. This analysis provides the best comparison between the circuits as they are each intended to be operated in practice.

Table 6: VRM vs AG and Ball Mill Intermediate Grind to 85 µm P_{80} with			
	AG/Ball		**VRM**
AG SE (kWh/t) 100% of Feed	9.84	Comminution SE (kWh/t)	4.5
Ball Mill SE (kWh/t) 67.7% of Feed	13.7	Fan, Classifier, etc (kWh/t)	6.8
Base Case P_{80} (µm)	78		
Comparison P_{80} (µm)	85		
Bond Correction for P_{80} SE (kWh/t)	-2.0	Mass Rejected as Waste Grit (% of feed)	35
Classification and internal conveyors 5% allowance (kWh/t)	+1.7	Internal Conveyors and Mag Separation (kWh/t)	+1
Total Duty Power(kWh/t)	**20.8**	**Total Duty Power (kWh/t)**	**12.3**
Mass Rejected by IMS (% of Feed)	27.7	Mass Rejected by IMS	27.1
Mass of IMS Concentrate for Regrinding (% of Feed)	**40.0**	**Mass of IMS Concentrate for Regrinding (% of Feed)**	**37.9**

In grit extraction and processing mode the VRM achieves a 41% reduction in power compared to the AG/Ball mill circuit and also reduces the mass to be processed and ground in the final stages of the flowsheet by 5%. The 85 µm P_{80} IMS concentrate is subjected to flotation to remove pyrrhotite, then ground to approximately 40 um P_{80} before cleaner magnetic separation generates the final magnetite concentrate.

The greater power benefits achieved when the VRM is operated in grit extraction mode confirms the benefits seen in the first comparison, confirms the promise offered by the grit circuit and confirms that VRM technology has the attributes to shift project economics in a positive direction.

Design Implications

The change from AG/Ball grinding to VRM brings with it many advantages, other than reduced power consumption, for the Southdown project.

The power benefit of changing from AG/Ball to VRM reduces the maximum and average amount of power that needs to be supplied to the operation and also means that a given renewable energy installation will account for a greater proportion of the total power.

The ability to reject 35% of the feed mass as dry non-magnetic grit is estimated to reduce the water supply requirements for the project by 26%. Not only is the dry disposal of coarse tailings possible, but it is also possible to mix thickened fine tailings with the coarse material to produce a conveyable and compactable tailings with minimal water content (<13% moisture). It may be necessary to dispose of a small proportion of the fine tailings as slurry to ensure that the remainder of the tailings is always conveyable, but the amount of wet tailings disposal required with VRM technology will be at least one order of magnitude below that required with AG/Ball milling. It is also possible to filter minor excess fine tails without a major capital investment in filters.

In the AG/Ball circuit the RMS tails with a topsize of 3 mm were cycloned to separate the coarse from fines. The fines feed thickening and the coarse bypasses thickening before mixed coarse and fines are pumped to a tailings dam or to filtration. In the VRM circuit the lack of wet coarse tailings means that cycloning is no longer required. Instead, a simple drum mixer will be used to combine dry grit tailings with thickener underflow before it is conveyed and trucked to tails stacking or used elsewhere for construction purposes.

Testwork also showed that flotation performance after VRM is superior to that achieved in the AG/Ball pilot plant. Very low sulphur levels were achieved in the magnetite concentrate after VRM grinding and pyrrhotite was removed by flotation. The levels achieved were 0.02 to 0.03% S, well below the target value set to minimise SO_2 gas production in pelletising. In addition, the pyrrhotite flotation rate for VRM product was very fast and this is likely to result in a smaller flotation section.

The enclosed nature of the VRM means that even though dry milling is employed, the process will not emit dust. This is important given the siliceous nature of the non-magnetic gangue at Southdown. Immediately after VRM grinding the 85 µm material is slurried ahead of IMS and then flotation. Even the dry magnetic separation section will be essentially dust free due to the lack of sub 38 µm in the grit stream.

A second crushing stage is needed ahead of VRM compared to AG/Ball. However, as the VRM topsize only needs to be less than 100 mm (specifically for Southdown, even coarser is allowed for softer ores) an open circuit secondary cone crusher is sufficient. This compares less favourably with the AG/Ball circuit which only requires an open circuit primary crusher. It compares more favourably to High Pressure Grinding Roll (HPGR) preparation which requires closed circuit secondary crushing to 50 or 60 mm topsize in order to protect the tungsten carbide roll studs.

Conclusions and Recommendations

The testwork and comparisons provide the following conclusions:

Open circuit VRM milling to achieve 85 to 100 µm P_{80} proved highly energy efficient for Southdown ore

Indicative crude grit testing (grit generated by open circuit pilot VRM) showed a high degree of liberation of barren gangue within the grit stream and that magnetic separation of the grit produced barren waste with minimal magnetite losses

A pilot plant was required to accurately evaluate closed circuit VRM with grit extraction and magnetic separation.

Loesche designed, constructed and successfully commissioned such a pilot plant and integrated it into their test facility in Dusseldorf

Based on pilot testing by Loesche and earlier AG/Ball mill piloting by Wood, the program produced the following results when elevated to industrial scale.

Comparing whole ore milling to a common P_{80} of 95 µm demonstrates a power benefit to the VRM circuit of 39% (the industrial VRM circuit will only require 61% of the AG/Ball mill power to achieve the same outcome). In this comparison case there is no rejection of coarse tailings in either circuit.

Comparing the two circuits, when both incorporate RMS removal of non-magnetic waste before generating an 85 µm P_{80} product, gives a power benefit of 41% to the VRM. This is a similar power benefit magnitude to the open circuit case (the industrial VRM circuit only requires 59% of the power of the AG/Ball circuit to achieve the same outcome). Between 35 and 40% of the feed is rejected as dry waste grits in the case of the VRM.

The benefits of applying VRM technology extend beyond power reduction to important project factors such as reducing water consumption and simplifying tailings management.

References

Altun, D., Gerold, C., Benzer, H., Altun, O., Aydogan, N., (2015): 'Copper ore grinding in a mobile vertical roller mill pilot plant', *International Journal of Mineral Processing,* 136, p. 32-36.

Crosbie R, Robertson C, Smit I, Ser V (2005) , The Benefits of Inter-Particle Comminution on Flotation, Centenary of Flotation Symposium, Brisbane, QLD, Australia 6-9 June 2005.

Grange Resources (2023), Accessed 12.2023, https://www.grangeresources.com.au/operations/southdown

Grange Resources, (2022) ASX release 22 March 2022, Southdown Magnetite Project Prefeasibility Study, https://cdn-api.markitdigital.com/apiman-gateway/ASX/asx-research/1.0/file/2924-02501498-3A590204?access_token=83ff96335c2d45a094df02a206a39ff4

Grange Resources, (2018) ASX release 23 February 2018, Market Update - Southdown Magnetite Project, https://cdn-api.markitdigital.com/apiman-gateway/ASX/asx-research/1.0/file/2924-02501498-3A590204?access_token=83ff96335c2d45a094df02a206a39ff4

Grange Resources, (2012) ASX release 30 April 2012, Southdown Magnetite Project One Step Closer with Completion of Definitive Feasibility Study, https://cdn-api.markitdigital.com/apiman-gateway/ASX/asx-research/1.0/file/2995-01293107-6A588225?access_token=83ff96335c2d45a094df02a206a39ff4

Jacobs, P., Seopa G., Mofokeng, M., Nienhaus, D., Gerold., C., & Mersmann, M., (2016, April): '16 Years of successful operation of a Loesche Vertical-Roller-Mill Type LM 50.4 in a Hard Rock Application at Foskor Pty (Ltd) in Phalaborwa [Conference paper]', *Comminution 16 Proceedings*, Cape Town, South Africa.

Reichert M., Gerold, C., Fredriksson, A., Adolfsson, G., & Lieberwirth, H., (2015): 'Research of iron ore grinding in a vertical-roller-mill', *Minerals Engineering*, 73, p. 109–115.

Schmitz, C., Gerold, C., A Fundamental Change in Approach - Grinding Ores in Vertical Roller Mills: Presentation of Test Results, IMCET 2019, Antalya, Turkey, ISBN: 978-605-01-1273-3

Stapelmann, M., Gerold, C., Smith, J., Successful Applications of Vertical-Roller-Mills in Phosphate Processing, Proceedings Beneficiation of Phosphates VIII, ISBN: 978-1-5108-7022-2.

Van Drunick, W., Gerold, C. & Palm, N., (2010): 'Implementation of an energy efficient dry grinding technology into an Anglo American zinc beneficiation process [conference paper]', *XXV International Mineral Processing Congress (IMPC) Proceedings*, Brisbane, QLD, Australia, p. 1333–1341.