COMMISSIONING OF THE 375ktpm AUTOGENOUS MILLING CIRCUIT AT NKOMATI NICKEL

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ABSTRACT

Commissioning of the 375ktpm concentrator at Nkomati Nickel began in August 2009 with the first ore reporting to the mill on the 15th of September 2009. The flow sheet was designed to treat the main mineralised zone (MMZ) arising’s from both underground and open cast operations and incorporates a fully autogenous grinding (AG) circuit.

The selection of the MMZ concentrator milling circuit has followed a comprehensive route over the preceding 10 years. Many knowledgeable parties have contributed and assisted in developing the milling circuit according to the best available information. Over and above the pilot test work and design simulations that were performed, an understanding of the geology and mineralogy of the ore body, as well as possible variations in the characteristics of the ore body over the life of mine were assessed during the feasibility study.

The final selection of the flow sheet was completed after DRA conducted a techno-economic study on four possible comminution circuits ranging from conventional crushing and ball milling to fully autogenous (AG) milling. The results from all the above mentioned work indicated that it is possible to treat the MMZ ore at the desired throughputs to the desired grind sizes in a fully autogenous grinding circuit.

This paper illustrates the subsequent performance of the milling circuit during and after commissioning, and compares initial operating performance to the design expectations.
1. INTRODUCTION

Nkomati Nickel is a joint venture between ARM (50%) and Norilsk Africa (50%), who jointly manages the mine and project. Nickel, copper, cobalt and platinum group metal (PGM) sulphide mineralization at Nkomati occurs in a number of zones within the Uitkomst Complex, which is exposed in a broad valley dissecting the Transvaal Sequence in the Mpumalanga escarpment region. The Uitkomst Complex is situated between Badplaas and Nelspruit in the Mpumalanga Province of South Africa, approximately 300km east of Johannesburg.

![Figure 1 - Nkomati Expansion Project Location](image)

There are four distinct zones of Ni-Cu-Co-PGM sulphide mineralization within the early Bushveld age (2 billion year old) Uitkomst Complex, which is a layered, mafic-ultramafic body intruded into the basal sediments of the Transvaal sequence. The complex outcrops for about 9km on the farms Vaalkop, Slaaihoek and Uitkomst in a broad valley in the Mpumalanga escarpment region.

The four zones of sulphide mineralization comprise the following:

- The Main Mineralised Zone (MMZ), which is hosted by the Lower Pyroxenite Unit (LrPXT) and which contains a diversity of pristine to altered, hybrid mafic-ultramafic rocks with small to very large quartzite and dolomite xenoliths.
- The Chromititic Peridotite Mineralised Zone (PCMZ), which is hosted by the talcose and highly altered Chromititic Peridotite Unit (PCR).
- The Massive Sulphide Body (MSB), which is exploited by the current Nkomati mine.
- In a very few places, the more copper-rich Basal Mineralised Zone (BMZ) in the Basal Gabbro (GAB) has been included in the evaluation, but only where the mineralization is high-grade and contiguous with the MMZ.
2. CIRCUIT SELECTION

DRAMP was contracted by the ARM/Lion Ore JV during July 2006 to conduct a feasibility study and Control Budget Estimate (CBE) for a new Greenfield’s project for their NKOMATI Ni mine 45km east of Machadodorp. The scope included the evaluation and review of previous studies as well as a techno-economic trade off on four possible comminution circuits ranging from conventional crushing and ball milling to fully autogenous milling. This paper encapsulates the thought process, decisions and the references used in selecting the final comminution route for the new 375ktpm MMZ concentrator.

Design simulations from a number of sources as well as performance data from a recently commissioned 100ktpm MMZ concentrator were incorporated into this selection. These considered possible variations in the characteristics of the ore body over the life of mine, as well as pilot test work already completed to generate grinding parameters. The results generated by this work indicated that it would be possible to treat the MMZ ore at the desired throughputs delivering the desired grind sizes in a fully autogenous grinding (ABC-type) circuit. Autogenous milling is generally considered as being one of the higher risk milling circuits. This is mainly due to the fact that the ore, which is utilised as the grinding media, could be variable in terms of hardness and mineralogy / geology. Nevertheless, it is a very popular route as the cost benefits, more specifically the operating cost, are very attractive, especially when large low grade ore bodies are evaluated. In North / South America, autogenous and semi-autogenous grinding circuits have been successfully employed during the past 20 years on large scale low grade operations.

Taking all these factors into account, the project team recommended an autogenous circuit for the new operation with the option to add steel to both the primary and secondary mills. This should create the opportunity for significant operating cost savings. One has to bear in mind that all the design simulations and decisions were based on previous work and that the potential unknown variations within the ore body will only be fully understood once the pit is operational for some time.

3. DESIGN

3.1 Upfront Selection

The MMZ milling circuit comprises of a primary FAG mill and pebble crushing circuit followed by a secondary hybrid pebble/ball mill and classification cyclone cluster in a MMF (mill mill float) configuration. (Fig. 2)
A generic flow diagram of the MMZ milling circuit is indicated in Figure 2 below:

![Figure 2 - Nkomati 375ktpm MMZ Comminution Circuit](image)

A single 34ft x 17.3ft, grate discharge FAG mill with 2 x 5.2MW installed power is utilised for the primary grinding duty. The mill shell is designed to carry up to 4% steel load should it be required to run in SAG mode. The feed to the mill is approximately 574tph for a 24 hour, 363 day/year operation at 90% availability to achieve the 375ktpm design tonnage.

The secondary milling circuit is designed to treat the total primary mill product through a single 23ft x 31.5ft, grate discharge ball mill also fitted with dual 5.2MW drives. The mill grinds the primary mill product to the required flotation feed size of 67% - 75µm and is designed to take up to 32% steel balls if required.

The milling circuit from the stockpile to the float feed is controlled by an FLSmidth expert control system which will be discussed in another paper at SAG2011.
3.2 Process Description

3.2.1 Primary FAG/SAG Mill Circuit

Ore is withdrawn from the conical stockpile via 2 of 4 apron feeders and delivered to the primary mill feed conveyor.

A semi-automatic ball loading system is available to load steel balls onto the mill feed conveyor. The fresh feed ore size detection is done via a Lynxx optical size analyser.

The FAG mill feed conveyor delivers ore into the feed hopper, the hopper also receives mill dilution water at a measured and controlled rate. The mass, load and power consumption of the mill is measured by mill bearing back pressure as well as an online acoustic device (SAG analyser).

The mill is equipped with 70mm pebble ports and discharges onto a 30mm trommel screen. The +30mm trommel oversize is delivered onto a conveyor supplying pebbles to the secondary mill pebble feed bin. When this bin is full, the pebbles will be routed to the pebble crushers via an overflow chute on the pebble bin.

The trommel underflow passes over a double deck vibrating screen with a 16mm top deck and a 4mm bottom deck. The oversize from both decks is combined and reports to the pebble crusher feed bins via the pebble crusher feed conveyor. The -4mm material flows into the common mill discharge sump.

3.2.2 Pebble Crushing Circuit

Pebbles from the secondary mill pebble feed bin are withdrawn at a controlled rate by a belt feeder and delivered to the secondary mill via a pebble transfer conveyor. The rate of feed is controlled by a weightometer linked to the expert control system on the secondary mill.

The +4mm -16mm primary mill product in the pebble crusher feed bins is withdrawn by vibration feeders at a controlled rate, and fed into two 450kW pebble crushers. The product from the crushers (80% passing 12mm) is delivered onto the primary FAG mill feed conveyor. Only one crusher is utilised under normal conditions.

3.2.3 Secondary Pebble / Ball Mill Circuit (Hybrid)

The feed to the secondary mill consists of:

(a) Primary mill –4 mm product
(b) Pebble mill cyclone underflow
(c) -70mm pebbles from the primary mill circuit.

The mill product flows over a trommel screen fitted to the mill discharge end for the removal of scats and oversize material, which discharges into a tramp material skip.
The undersize from the trommel screen flows into the common mill discharge sump and is mixed with the –4 mm product from the primary mill. The slurry is then pumped to a 16-way cluster of classifying cyclones by one of two sets of mill discharge pumps.

The cyclones underflow product gravitates back to the secondary mill feed hopper while the overflow gravitates to the flotation section. The final grind is monitored via an ultrasonic online particle size analyser.

*Figure 3 – 3D View of Comminution Circuit Layout*
3.3 Simulation Model of Nkomati Milling Circuit

Population balancing techniques and crusher transfer functions were used by DRAMP to model the FAG and closed-circuit regrind milling circuits. The model was used to estimate the degree of variation in circuit parameters and to effectively hone in on a plant design that will cater for typical variations during operation.

The breakage parameters for the ore, including breakage rates were determined from numerous test work methods, milling trials and piloting campaigns that were conducted over several years of testing.

The pebble crusher was modelled with the Excel™ programme using characteristic crusher performance tables from the manufacturer, to generate transfer functions related to the crusher closed-side setting. Simulations using coarse liners indicated that the crusher could under-perform if it was not being choke-fed. Certain modifications to the feed chute and liner profile had to be done before the crusher performed according to expectations.

A typical pebble crusher performance simulation is given below (Figure 4) showing the comparison between actual and modelled results, with modified fine liners.

![Figure 4 – Pebble Crusher Simulation Using Transfer Functions](image-url)
The simulation exercises highlighted the importance of the pebble crusher. It was found to be crucial to maintaining the fully-autogogenous nature of the primary milling circuit. One of the key drivers for adopting this circuit was a reduction in operating costs; therefore the success of the primary circuit would clearly be driven by pebble crusher performance.

These milling models were also used during the optimisation process, to ascertain the best operating conditions necessary for achieving stability.

The primary circuit model (Fig.5) effectively incorporates a mill (population balance breakage model) in closed circuit with a screen (Lynch-Rao tromp curve) with recycle oversize being “pebble crushed” (Transfer Function Model) prior to reintroduction to the mill.

The regrind circuit model (Fig.6) is simply a reverse fed mill (primary circuit product) and hydro cyclone in closed-circuit, using population balance breakage modelling and Lynch-Rao tromp curves, generated from hydro cyclone performance models.

Figure 5 – AG Milling Circuit Simulation in Closed Circuit with Screen and Pebble Crusher
3.4 Milling Plant

The following photos of the milling circuit taken during construction illustrate the configuration of the primary and secondary mill as well as the layout of the overall comminution circuit.
4. COMMISSIONING

Commissioning commenced in August 2009 with IO checking, bump/direction tests on motors, leak tests, calibration of instrumentation etc. and subsequent control sequence testing in preparation for hot commissioning. Slurry commissioning of the circuit commenced on the 15\textsuperscript{th} September 2009.

The expert control system was not available during commissioning as it first requires a database to be built-up. The commissioning team therefore had to rely on monitoring of the power draw and mill bearing back pressure to calibrate the mill load. The mill was stopped on several occasions during the initial filling to measure the ore level in order to establish the relationship between the bearing pressure and load. An initial slow response from the bearing pressure instrument caused a major overload that led to a lengthy delay while digging the load out.

A conservative approach was taken regarding the FAG mill load with the control algorithm used for feeding the mill stopping the stockpile feeders when the mill load reached a pre-determined maximum. They were only restarted once the mill load dropped sufficiently.

The milling circuit was affected by poor lubrication system temperature control and an assortment of niggling greasing system trips. Following a series of corrective actions and modifications to the pebble crusher feed spout design….
(aimed at improving choke feed conditions as previously noted) accompanied by the commissioning of a mill power control loop, the performance of the in-circuit crusher greatly improved the stability of the primary milling circuit. The resultant performance was encouraging enough to vindicate the circuit selection of pursuing FAG milling.

As a consequence of repeated gyratory crusher chokes and inclement weather which affected the ore supply to the ROM stockpile, a concerted effort was put in to conduct the milling performance test during December 2009 with the aim of achieving 72 hours of uninterrupted milling, at design throughput, with 90% utilisation.

The first day of the performance test was delayed by having one of the barring gear brake mechanisms disintegrate just before the test was due to start. The cause was determined as being a “freakish incident” due to the barring gear being partially engaged, as a consequence of poor barring procedure on behalf of the operator.

Coarser hard ore was fed to the mill 12 hours before the test run began and for the following 26 hours. Thereafter it was admixed intermittently into the mill feedstock, which greatly affected the Primary mill throughput. As a consequence the mill continuously went into a controlled overload condition, which generally took about 7~8 minutes to grind out and reduced the continuous throughput of the circuit. The mill stockpile was low during this initial period as the primary crusher was choked. A bulldozer was used to push material into the feeders on the stockpile to keep the plant running while the primary crusher was being “dug out”; however there were periods when the required feed tonnage could not be met by the rate of supply.
It was observed that during the test the mill throughput was gradually improving after the feed set-point philosophy was changed to avoid unnecessary overloading, to one of controlling and steady primary mill load. It was then possible with continuous coaxing and monitoring to ‘maximise’ the throughput (Refer Fig. 10).

It became evident during the test that overloading of the primary mill was the throughput bottleneck, and that by increasing the grate open-area, the accumulation of material in the mill should be reduced. The additional open grates were installed early in 2010/11. The lowest average feed rate value shown on Fig. 10 (1796min ~ 33 min) occurred during a period of poor feedstock availability. Shortly afterwards a 1.2m boulder was accidentally tipped onto the mill feed conveyor and caused a lengthy delay as it choked the mill feed hopper. After a number of weather related interruptions the mill then ran for a period of 27 hours before the test was abandoned.

The 72 hour performance test was finally achieved over the Christmas period, 25th - 27th December 2009.

During commissioning, it was confirmed that the simulation models developed by DRAMP adequately described the performance of the milling circuit and clearly identified its constraints.

The relationship between the gyratory crusher product size (CCS/F_{80} mm) and the milling circuit feed rate are illustrated in Figure 11.

![Figure 11 – Mill Feed Size vs. Throughput](image)

\[ y = 6261.2x^{-0.471} \]
\[ R^2 = 0.9994 \]
5. POST COMMISSIONING RECOMMENDATIONS MADE FOR IMPROVING THROUGHPUT

The following main recommendations were made to the mine to improve the throughput of the circuit:

- Increase the grate slotted open area by replacing the remaining blank grates in the primary mill discharge.
- The pebble crusher gap should be maintained below 18mm to achieve design tonnage, as a continuous operation of the ICC is of paramount importance in maintaining a steady-state milling circuit. A minimum sustainable gap setting of 16.5mm (CSS) was achieved under a control strategy using 80% motor full load during commissioning, with satisfactory crusher throughput.
- Gradually replace a percentage of the mill discharge screen bottom deck panels, starting from 4.5mm and increasing up to 7mm. It may be necessary to add ‘flushing’ water to the hydro cyclone underflow ‘kill pot’ to encourage better flow into the regrind mill. The effect of this will be to increase the “transfer size” which in time will alleviate the load on the primary milling circuit.
- Full implementation of the mill expert control system

6. 4 STEPS TO OPTIMISATION

The aim of the optimisation process was to achieve an increase in throughput whilst achieving the same target mesh of grind. In order to achieve this it was necessary to transfer more of the milling duty onto the regrind mill and lessen the load on the pebble crushing circuit, by gradually increasing the transfer size thus reducing the “fines” unnecessarily fed to the crusher. The sequence of events involved changing the sizing screen bottom deck from 4mm to 7mm and then to 10mm apertures.

The optimization of the Nkomati Milling circuit followed a four step approach based on the following parameters:

1. FAG mill discharge open area – Pebble Port / Grate Configuration.
2. Pebble Crusher efficiency
3. Transfer size
4. Mill Expert Control

When ore characteristics such as hardness, size distribution or composition vary, it can be expected that there will be a ±30% fluctuation on the performance of an AG circuit, with changes limited to a number of control alternatives. To improve the operability of such a circuit it is imperative to install equipment such as:

- Variable Speed Drive
- Online Size Analysers (Feed and Product)
- Expert Control Systems
Where the majority of the feed characteristics are difficult to control, the FAG mill parameters can be directly manipulated by the operator or expert control system. Many of these variations occur naturally as a result of wear on the FAG mill and pebble crusher liners. Adjusting the FAG mill parameters is normally the first option for circuit optimization.

Over the past 18 months the Nkomati Milling Circuit has increased its throughput with 12% (565 to 635 tph) whilst maintaining the required product size. Table 1 below presents the outcome of the optimization study related to various process parameters.

<table>
<thead>
<tr>
<th>DATE</th>
<th>Mill Feed (tph)</th>
<th>Pebble Rate (tph)</th>
<th>Screen Discharge Rate (tph)</th>
<th>Combined Crusher Feed Rate (tph)</th>
<th>SAG Mill Power (mW)</th>
<th>Ball Mill Power (mW)</th>
<th>In-Circuit Crusher #1 Power (Amps)</th>
<th>SAG Mill Average Bearing Pressure (Mpa)</th>
<th>Recycle Load (tph)</th>
<th>Recycle Load (%)</th>
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</thead>
<tbody>
<tr>
<td>Dec '09</td>
<td>565</td>
<td>134</td>
<td>234</td>
<td>376</td>
<td>8.0</td>
<td>4.6</td>
<td>231</td>
<td>47.0</td>
<td>368</td>
<td>66</td>
</tr>
<tr>
<td>Mar '10</td>
<td>612</td>
<td>104</td>
<td>256</td>
<td>486</td>
<td>8.5</td>
<td>4.1</td>
<td>364</td>
<td>46.5</td>
<td>360</td>
<td>59</td>
</tr>
<tr>
<td>Jul '10</td>
<td>609</td>
<td>189</td>
<td>243</td>
<td>427</td>
<td>8.8</td>
<td>5.5</td>
<td>353</td>
<td>46.1</td>
<td>432</td>
<td>71</td>
</tr>
<tr>
<td>Dec '10</td>
<td>624</td>
<td>154</td>
<td>301</td>
<td>514</td>
<td>8.1</td>
<td>6.1</td>
<td>368</td>
<td>45.4</td>
<td>455</td>
<td>73</td>
</tr>
<tr>
<td>Mar '11</td>
<td>635</td>
<td>118</td>
<td>224</td>
<td>387</td>
<td>7.5</td>
<td>6.5</td>
<td>386</td>
<td>43.3</td>
<td>341</td>
<td>54</td>
</tr>
</tbody>
</table>

*Table 1: Optimisation results on various process parameters.*

In summary the mill throughput increased from 564 tph to 634 tph by manipulating the FAG mill configuration, increasing the pebble crusher efficiency, transferring load to the secondary mill and finally allowing the expert system to take full advantage of all controls within certain set process limits. (Refer Figure 12 & 13)
Figure 13- Mill throughput vs. Power

6.1 AG Mill Discharge opens area – Pebble Port / Grate Configuration.

Figure 14 below represents the basic configuration of the Nkomati FAG mill discharge arrangement. The discharge end consists of 24 segments of which the total open area can be manipulated by changing the ratio of pebble port plates vs. grate plates.

Figure 14- Basic configuration of Nkomati FAG mill discharge grate and pebble ports
The pebble port size determines the top size of rock that may leave the mill. Pebble ports are installed to remove critical sized material for more effective size reduction in a crusher. The pebble ports must be significantly larger than the critical size fraction to be effective. However if the port size is too large, wear is accelerated on the pulp lifters, discharge cone, trommel, discharge screen and crusher. The optimum pebble port size will be a compromise between throughput and wear. Crusher limitations may dictate the optimum pebble port size and the total open area necessary for maximum production.

The total grate open area includes both the grates and pebble ports. As the number of pebble ports were gradually increased from 4 to 12 over 18 months, the absolute area increased from 7% to 9% on with new liners. With worn liners the total open area increased to 10.5%. Larger open areas lead to a reduction in the residence time of the slurry in the mill. When the pulp lifters have excess capacity as they normally do, the mill throughput capacity will increase. (Refer Table 2 below)

<table>
<thead>
<tr>
<th></th>
<th>Available Open Area (Per Grate)</th>
<th>Installed Quantity (Design)</th>
<th>Installed Quantity (Current)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grate Open Area</td>
<td>0.206 m²</td>
<td>20</td>
<td>12</td>
</tr>
<tr>
<td>Pebble Port Open Area</td>
<td>0.370 m²</td>
<td>4</td>
<td>12</td>
</tr>
<tr>
<td>Total Area</td>
<td>77 m²</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Open Area (New liners)</td>
<td></td>
<td>7 %</td>
<td>9 %</td>
</tr>
</tbody>
</table>

Table 2 - Nkomati FAG mill – Discharge Configuration

Whilst the throughput rate increased, the amount of fine grinding occurring in the FAG mill decreased and the workload was transferred to the secondary mill. This situation is ideal when additional power is available in the secondary mill as in the case with Nkomati. It is crucial not to design an autogenous milling circuit ball mill limited from day one. Optimization will only be possible if power is available in the secondary mill especially when the final product grind tolerance is low.

Figure 15 below illustrates the FAG mill power draw and bearing pressure at various throughput rates. It is clear that the mill efficiency decreased when operating above loads of 44 Mpa. This information was critical during the optimization process. The result of this dictated the expert control system process limits.
6.2 Pebble crusher optimization

Autogenous grinding is not an efficient way to break material when it is in the size range of 30 to 60mm. As particles of this size cannot pass through the 30mm discharge grate (30mm) this material accumulates in the mill and forms a large portion of the load mass. Consequently they are responsible for a significant portion of the power draw. This size material is not efficient at breaking other rocks and therefore the energy consumed by having this as part of the load is not well used.

The obvious process route to counter the above mentioned effect is by installing a robust pebble crushing circuit. Pebble crushers are far more power efficient to break down critical size rock before recycling them back to the FAG mill. It is essential to design for a running and a standby crushing unit in order to achieve the desired overall circuit utilization of +90%. A single crusher installation will significantly decrease the overall circuit availability.

The optimization of the pebble crusher circuit probably resulted in the highest benefit in terms of mill throughput. Figure 16 below it shows how sensitive the mill throughput is to the pebble crusher efficiency.
6.3 Transfer Size

The transfer size by definition is the P80 (80% passing size) of the FAG mill product which is transferred to the ball mill circuit. This size is highly influenced by the mill discharge screen aperture and can be manipulated by changing the screen panels on the bottom deck.

The transfer size also determines the power requirement of the secondary milling circuit to achieve the required product size distribution. As part of the optimization process it was necessary to transfer some of the primary mill load to the ball mill circuit as the circuit was FAG mill limited at that point in time. This was done by increasing the screen aperture of the bottom deck from 4mm to 10mm. The result of this was a lower recycle load to the FAG mill and higher ball mill power draw to obtain the required product size of 70% passing 75µm.

Due to the practical constraints of taking a representative screen undersize slurry sample, the effect of increasing the screen aperture is illustrated by the cyclone feed size distribution over time (refer Figure 17 below).
6.4 Mill Expert Control (PxP)

The final step to optimization is to rely on a robust expert control system which will strive to maintain production objectives within specific process limits. Nkomati installed an FLSmidth PxP product to assist with this goal. The control applications are designed to duplicate human reasoning and perform control strategies over most common operating conditions. Competing objectives (i.e. maximum production and quality) are resolved by a sophisticated priority management system.

The Process Expert control system is a general tool for implementation of high-level control strategies, i.e., control schemes that make decisions and execute actions on the same level as the human operator.

The Process Expert control strategy works with objectives, rather than set points on specific measurements. Examples of objectives are "stability," "maximize production" and "maximize quality". Because objectives are often in conflict, the control system works with priorities that specify which objectives are the most important to attain.
The PXP control at Nkomati Nickel Mine has been split into two different sections; SAG Mill PXP Control and Ball Mill PXP control. SAG Mill PXP Control includes the Control of the SAG Mill and Pebble Crusher and the Ball Mill PXP Control includes the control of Sump, Pumps, Cyclones and Ball Mill (See Figure 18 below).

A multi-input multi-output control problem requires continuous and coordinated actions

These controllers can be switched ON or OFF individually during operation without any interruption in the process. At Nkomati the PxP objective is to maximize throughput whilst maintaining certain process limits such as: FAG Mill Load and cyclone feed density and pressures. Figures 19 & 20 illustrate the advantage of PxP control over normal human intervention for maximizing Nkomati mill throughput.

During Operator control (Fig. 20) there are two individual mill feed stoppages. This occurs when the operator reaction on mill load is too slow and the mill goes into overload conditions. The mill fresh feed will then stop for some time until the load has dropped sufficiently to introduce feed again. The PxP control on the other hand will continuously monitor mill load and introduce small adjustments on the mill feed in advance, hereby preventing the mill from overloading.

Figure 18 – Milling Circuit Control Diagram
Figure 19 - PxP Control on Mill Feed

Figure 20 - Operator Control on Mill Feed
7. ACKNOWLEDGEMENTS

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