BUILDING THE WORLD'S LARGEST HPGR – THE HRC™3000 AT THE MORENCI METCALF CONCENTRATOR

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ABSTRACT

The newly constructed Metcalf Concentrator at Freeport-McMoRan's Morenci site commenced operation in May 2014. This 63,500 tpd (70,000 stpd) expansion includes Metso's HRC™3000, which is the result of collaboration between Freeport-McMoRan Inc. and Metso Minerals Inc., and is to date the largest HPGR ever put into operation. In addition to the sheer scale of this machine, there are a number of unique design features which improve machine performance and circuit capacity. This paper discusses the development process of the HRC™3000, presents commissioning and start-up challenges and methods of resolution, and concludes with the latest operational data for the HRC™ HPGR circuit.

KEYWORDS

HPGR, HRC, Morenci, Metcalf, HRC3000, flanges, efficiency, equipment design, comminution, crushing, grinding

INTRODUCTION

Freeport-McMoRan Inc. (FMI) is a premier international natural resources company with headquarters in Phoenix, Arizona (AZ). FMI operates large, long-lived, geographically diverse assets with significant proven and probable reserves of copper, gold, molybdenum, cobalt, oil and natural gas. FMI has a dynamic portfolio of operating, expansion and growth projects in the copper industry. FMI is the world's largest publically traded copper producer, the world's largest producer of molybdenum and a significant gold, oil and natural gas producer. Its global workforce includes approximately 35,000 employees.

Metso Minerals Inc. (Metso) is the world's leading industrial company in the mining and aggregates industries and in the flow control business. Products range from mining and construction equipment and systems to industrial valves and controls. Metso's solutions are delivered and supported by decades of process knowledge and a broad scope of services, backed by a global footprint of over 90 service centers, thousands of service employees, and an extensive logistics network. Metso employs approximately 14,000 industry experts in more than 50 countries.

The Metcalf concentrator at FMI's Morenci, AZ mine started operation in May of 2014. This plant is designed for an average of 63,500 tpd (70,000 stpd), increasing the total Morenci concentrator complex production to a nominal 113,400 tpd (125,000 stpd). The ore is a porphyry copper deposit that has a Bond Ball Mill Work Index ranging from 11.5 – 19 kWh/t and an ore hardness with an Axb value of 45 - 67.

Due to diminishing ore grades and rising energy costs, FMI and the industry have been driven to find more energy efficient solutions. It is well documented that crushing circuits are more efficient than traditional SAG milling circuits. However, in large operations, crushing circuits tend to have a greater number of lines and are more challenging to operate. On the other hand, SAG milling, while less efficient, tends to be simpler to operate and require less ancillary equipment. In developing the Metcalf concentrator, FMI and Metso created a revolutionary crushing circuit that challenges traditional expectations.

The goal of this project was to develop a highly efficient HPGR crushing circuit for the Metcalf concentrator capable of processing the total plant capacity. In addition, this HPGR would not simply be a larger scale version of what was currently available to the market, but would seek to eliminate some inherent concerns typically associated with traditional HPGRs, including skewing and edge effect. This paper will highlight the development process of the HRC™3000, including pilot plant testing, engineering design, installation and commissioning. In addition, the latest operating data will demonstrate how a flanged tire design, which will be described later in this paper, increases the efficiency and throughput of the circuit.

The design concept came to fruition in the HRC™3000, the largest HPGR in the world with a total installed weight of 900 tons. This machine was the result of a close cooperation between FMI (operation and maintenance experience) and Metso (mechanical design and automation). The HRC™3000 includes 3.0 m diameter by 2.0 m wide tires and a total installed power of 11,400 kW. Depending on the application, the total capacity of this machine can exceed over 5,400 tph of ore.

Prior to installation of the HRC™3000, a pilot scale plant was installed at the Morenci Concentrator to use as a proving ground for the HRC™ HPGR. Originally, the plan was to use the data and observations from the pilot plant to help design the Metcalf concentrator. In actuality, the pilot plant testing, the Metcalf plant design, and the design of the new HPGR were run concurrently, as shown in Figure 1. While this expedited the overall project, this also resulted in the team having to revise parts of the HRC™3000 that were already designed or manufactured, due to observations made while operating the pilot plant. Throughout the entire process, Metso and FMI collaborated through their teams of experts to draw on their unique perspectives.

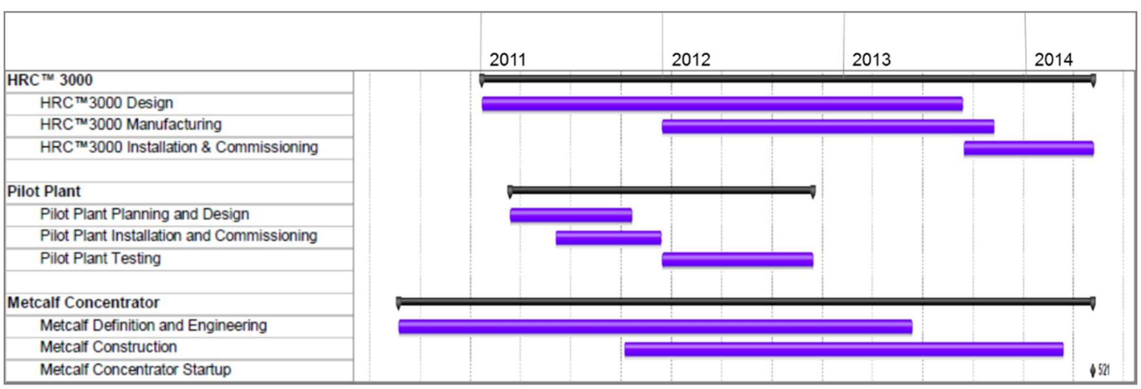

Figure 1 – Gantt chart of the Metcalf project

INITIAL CONCEPT AND DESIGN WORK

Prior to the design of the HRC™3000, the Metso design team was tasked with developing an HPGR to meet the specific needs of hard rock mining applications. After a review of the existing technology, it became clear that certain inherent design problems such as tire skewing, edge effect and uneven tire wear needed to be eliminated to ensure the concept was successful. In order to properly address these problems the design team decided to go back to the basics and began with a new frame design that became the basis of Metso's HPGR. A prototype unit with this concept was first built and tested at a quarry in Brazil. This unit eventually was used for testing at the Morenci pilot plant.

General Overview of HRC™ HPGR Concept

The initial concept of the HRC™ HPGR began with what would become the patented Arch-frame, which mechanically absorbs unbalanced loads in order to eliminate downtime caused by skewing. Skewing is a condition where the axes of the tires do not stay parallel due to uneven feed distribution. With the HRC™ HPGR, the two sides of the Arch-frame are mounted into the base frame with pins. Hydraulic cylinders at the top of the frame apply the crushing force. The cylinders only need to apply roughly half of the required force at the tires due to the mechanical advantage of the pivoting Arch-frame. This idea was based on how a nutcracker uses a mechanical lever to multiply the crushing force. Figure 2 shows a model of the HRC™ HPGR and its main components.

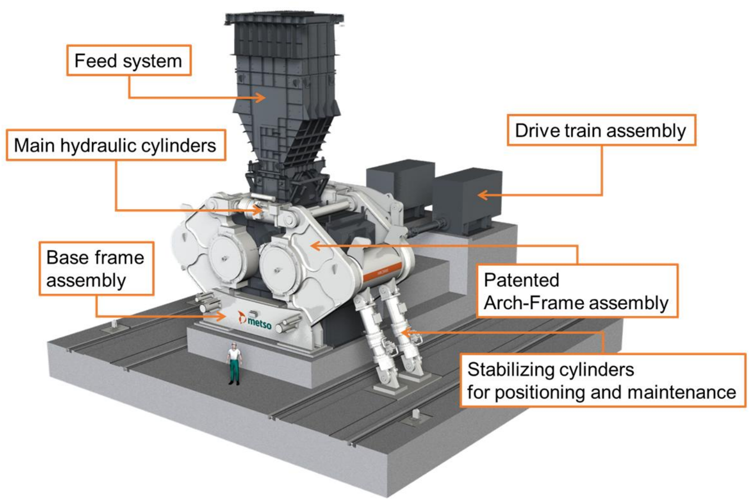

Figure 2 – Main components of HRC™3000

In addition to the Arch-frame eliminating downtime caused by skewing, this feature also allows for the use of a flanged tire design. With this design, one tire includes a set of flanges, which are bolted onto the side of the tire, as seen in Figure 3. The flanges are designed to combat edge effect, a problem with traditional HPGRs in which comminution is reduced at the edge of the tire. Because the flanges are bolted onto the tire, the flanges move in the direction and speed of the ore and therefore pull material into the crushing zone. This is in contrast to a traditional cheek plate arrangement in which stationary cheek plates are mounted near the edge of the tires. Figure 4 shows a comparison of a traditional cheek plate arrangement versus the Metso HRC™ HPGR arrangement with flanges.

Figure 3 – HRC™3000 flanged and non-flanged tire assembly

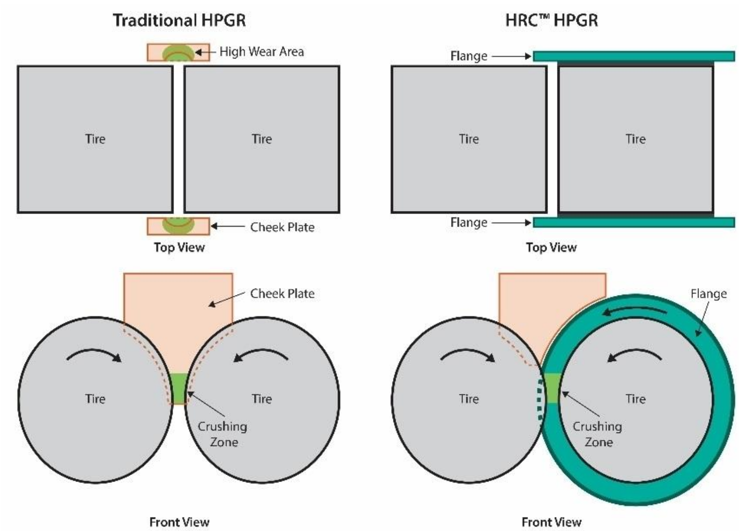

Figure 4 – Comparison of a traditional HPGR with cheek plates versus Metso's HRC™ HPGR with flanges

Metso performed a series of tests on a lab scale HPGR which was fitted with pressure sensors embedded in the tire. As shown in Figure 5, when operating with the traditional cheek plates, the pressure at the edges was much lower than the pressure at the center. This corresponds to the region of the tire which would generally produce a coarser product. Conversely, when flanges were installed, a much more consistent pressure across the full width of the tire was observed, indicating the full width of the tire is utilized for crushing.

It is important to note, that when crushing ore there is an optimum pressure for a given feed. Below this optimum pressure, less breakage will occur, while above the optimum pressure the energy efficiency will decrease. Therefore, it is important to have consistent pressure across the full width of the tire, so that an optimal pressure can be applied to the full bed of material. In the case of the traditional cheek plate design, the total pressure to the system is commonly raised to increase the amount of breakage at the edges of the tire. However, this results in higher pressure being applied to the center of the tire, leading to wasted energy and added wear in the center area of the tire. In addition, the higher localized pressure associated with the cheek plate design needs be considered when selecting the stud hardness and composition in order to prevent stud breakage. The results of this test gave the engineering team the confidence to proceed with the flanged HPGR design on the pilot scale unit.

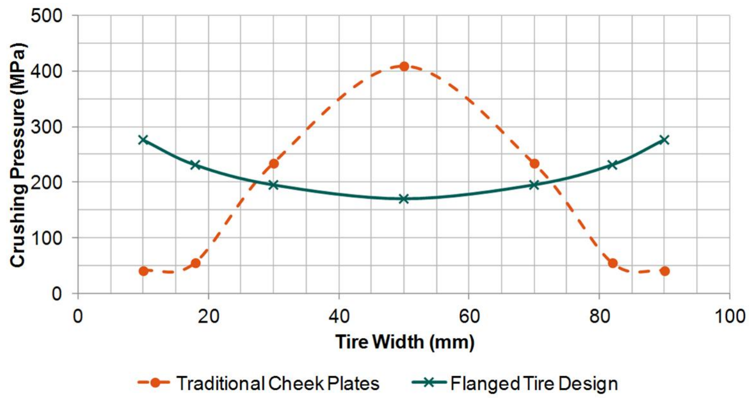

Figure 5 – Pressure profile across width of tire for flanged and non-flanged lab scale

A series of twelve process surveys were performed at the Morenci pilot plant to better understand how the flanged tire design affects the performance of the HRC™ HPGR circuit. These surveys, identified as the edge effect testing series, showed that in all conditions and pressures, the flanges clearly provided more breakage across the width of the tire and increased the throughput of the HRC™ HPGR relative to a traditional cheek plate HPGR design. On average, the flanges were shown to reduce circuit specific energy by an average of 13.5% and to lower circulating load by approximately 24%, while increasing the specific throughput of the machine by 19%. The details of this edge effect testing can be found in Knorr, Herman, Whalen (2014). These benefits later were observed upon start-up of the HRC™3000 circuit, referenced in the Operating Results section of this paper.

Pilot Scale Testing

There were three main goals for the pilot plant. The first goal was to test the design of the HRC™ HPGR, particularly the Arch-frame, flanges, and tire wear surface. The second goal was to better understand the performance of the circuit via objective testing. A total of 114 process surveys were taken under various circuit conditions and the results of this testing are discussed in greater detail in the separate paper Knorr, Elkin, Mayfield, Mular, Whalen, 2015. The third goal was to give the plant personnel experience operating and maintaining an HPGR circuit.

The pilot plant included an HRC™ HPGR with 750 mm x 400 mm tires, a primary wet screen, and a secondary wet screen. The HRC™ HPGR was fed by the primary and secondary screen oversize. The primary and secondary screen undersize was then transferred to the downstream process. The capacity of the plant varied depending on the circuit configuration, but in most conditions it could process approximately 50 - 70 tph. During the pilot plant testing, the plant operated for over 11,950 hours and processed over

667,000 tons of ore. Since the completion of the testing program in 2013, this plant continues to operate for production purposes.

Challenging Feed to the Pilot Plant HRC™ HPGR

The F80 to the HRC™ HPGR varied significantly and ranged from 11 mm to +16 mm. In addition, oversized tramp metal and oversized ore routinely entered the machine. This was especially prevalent during the initial operation of the plant; a grizzly screen was installed between the primary screen and the HRC™ HPGR to address this concern.

Based on the survey results, approximately 3% of the feed to the HRC™ HPGR was greater than 16 mm, while the measured operating gap of the machine ranged from 15 – 19 mm. This high percent of material larger than the operating gap is particularly challenging for HPGRs. It increases the amount of point loading on the wear surface and consequently increases the amount of wear on the tire and the chances of stud breakage. In comparison, the HRC™3000 was expected to have an operating gap of around 100 mm and a top size of 50 mm.

Another challenging aspect of the pilot plant was dealing with segregated feed into the HRC™ HPGR. Due to the circuit layout, the drier and coarser primary screen discharge was delivered toward the drive end of the tire while the wetter and finer material was delivered to the non-drive end of the tire. The feed arrangement can be seen in Figure 6. While segregated and oversize feed is typically not ideal for HPGR application, for the mechanical testing this condition gave the design team greater confidence when scaling up to the full scale plant because it showed the robustness of the machine.

Figure 6 – Feed segregation at the pilot plant

Pilot Plant Mechanical Testing and Redesign

Although the entire HRC™ HPGR unit was being tested at the pilot plant, there was a particular focus on the tires, edge protection and flanges. The first tire installed at the pilot plant had four different stud types installed to test multiple carbide compositions. It was evident the harder studs had better wear life. In fact the softest studs had such a high a wear rate that harder studs needed to be installed to prevent tire damage, making it clear the harder studs were necessary.

In order to understand the limits of the harder studs and simulate the forces on the full size unit, the HRC™ HPGR was tested at high forces, up to 8 N/mm^2. Despite running at higher forces and introducing feed larger than the gap, all of the studs remained intact. The hardest stud type being tested had a HV10 hardness greater than 1550 and was able to withstand the crushing application without chipping.

As discussed earlier in this paper, the flanges increase the amount of pressure at the edge of the tires, maximizing the amount of particle breakage. This additional pressure, while good for the process, did make the design of the edge protection more challenging. The edge protection on the pilot plant tires went through a number of design iterations before it could withstand the high pressures. On the first set of edge protection, the carbides cracked almost immediately, destroying the edge protection and the edge of the tire.

In order to get the plant back into operation as quickly as possible, the existing tires were machined at the edges so that a steel segment populated with carbide edge blocks could be bolted onto the tire. With this design, in the event a carbide edge block is damaged, the block can be replaced with minimal downtime. A series of different edge block designs were tested until a solution was found to be both reliable and provide good wear life. Figure 7 shows the progression of design iterations. The concept of bolt-on edge blocks worked extremely well and ultimately this design was incorporated into the HRC™3000 tire design.

Figure 7 – Progression of edge block designs at the pilot plant

Although there were few mechanical issues with the pilot plant flanges, the design team focused on improving wear life in order to ensure they last as long as the carbide studs and edges. Alternate types of abrasion resistant material were tested with varying degrees of success. Ultimately the life of the flanges greatly improved after carbides with very high abrasion resistance were imbedded into the flanges. Moreover, the added texture of the carbide components seemed to draw in more material and further increase the amount of breakage in the machine. Figure 8 shows the progression of flange designs.

Figure 8 – Progression of flange designs at the pilot plant

After 12 months of operation at the pilot plant, the hydraulic cylinders were damaged during maintenance. Upon replacement, rapid fatigue failures were observed, leading to an in-depth study of hydraulic cylinder design and HPGR loading conditions. After extensive analysis of material properties, manufacturing procedures, strain gauge readings, and operating conditions, the main cylinder design specification was refined to account for all modes of operation and cylinder loads.

Additional aspects of the HRC™ HPGR concept also were tested at the pilot plant. The hydraulic system, cheek plate design, stabilizing cylinders and bearings all were tested and found to operate successfully at this scale. This comprehensive testing also allowed specific calculations and projections to be verified. For example, a tire fit test confirmed the design calculations for the required hydraulic pressure needed to disassemble the tire from the shaft. Similarly, a series of tests varying the opening of the control gates confirmed that the aperture would not impact the performance of the machine as long as the gates were set beyond the nip angle of the machine. These tests provided confirmation that the overall concept was sound, and also allowed improvements and tweaks to be made as needed.

Communication plan

The pilot plant had setbacks early in the program. During the first few weeks, the machine experienced a number of failures which initially raised concern as to some aspects of the design. However, these failures ultimately provided experiences that strengthened the viability of the machine. Many of the problems required a diverse team from both Metso and FMI to solve and implement solutions quickly. It was at this point that both parties learned the importance of good communication and set up regular weekly conference calls with a defined agenda and clear action items. The team became effective at promptly notifying the appropriate parties, identifying the root cause of the problem, developing a potential solution and quickly implementing it to test on the machine. This model for communication carried over to the development of the full scale HRC™ HPGR and proved to be an important lesson learned from the pilot scale program. These lessons were put to good use in developing the HRC™3000.

ENGINEERING AND MANUFACTURING

The HRC™3000 is the largest HPGR in the world and the first large scale HPGR to operate with flanges. The HRC™3000 includes 3.0 m diameter by 2.0 m wide tires, and has a total installed power of 11,400 kW. Based on an application with a specific throughput of 300 $t{\cdot}s/m^3$-hr, this size unit can crush approximately 5,400 tph of feed instantaneously. Details of the HRC™3000 are found in Table 1.

Table 1 – HRC™3000 specifications

HRC™3000	
Tire dimensions	3.0 m x 2.0 m
Installed power	2 x 5,700 kW (2 x 7,644 HP)
Tire speed range	5.73 – 21.01 rpm (19.1 rpm nominal)
Tire speed range (%)	30 % - 110 % nominal speed
Operating pressure	4.5 N/mm^2 (maximum)

Engineering Design

The initial design of the HRC™3000 was particularly challenging, not only due to the new machine concept, but also the large size of the machine. The total weight of the machine is over 900 tons and it stands 15.2 m from the base of the foundation to the top of the hopper. Fundamentally, due to the sheer size of the components, manufacturing and shipping limitations needed to be considered. For example, one side of the patented Arch-frame alone weighs approximately 75 tons. The large components were manufactured in a number of different countries including South Korea, China, Germany, Holland, Finland, US and Canada. Due to the overall scale of major components, shipping logistics from these locations across the globe was extremely critical. Installation and maintenance also needed to be considered early on in the design phase of the project.

The HRC™3000's capacity is approximately double the capacity of the largest preceding HPGR in operation. It was unknown what issues would arise when scaling up to a machine that is over 50 times larger than the design prototype. In order to ensure the proper design of the Arch-frame, a series of structural analyses were performed prior to the final design of the HRC™3000. Structural analysis constraints and loading assumptions were validated at the pilot plant by comparing Finite Element Analysis (FEA) with measured strain gauge values at various operating conditions. This data was then used to refine the HRC™3000 FEA models. The same strain gauge tests also were completed on the HRC™3000 upon start-up to validate the FEA analysis. The actual stress values all were within an acceptable range.

While the new machine concept eliminated some traditional HPGR design concerns, it did require new design considerations. For example, the interface between the pivoting Arch-frame/tire assembly and the stationary dust enclosure and feed chute needed to be carefully designed. Ultimately the solution included a movable and adjustable liner that moves with the position of the stabilizing cylinders. This "floating" cheek plate pivots on the same arc as the Arch-frame, ensuring material is directed into the crushing chamber just above the tire nip.

Hydraulic System and Tramp Bypass System

An integrated tramp bypass system was developed in order to eliminate the requirement for additional infrastructure typical of HPGR installations (bypass chute with material diversion capability). The HRC™3000 bypass system detects an uncrushable object in the feed while sequentially opening the gap between the tires to the necessary bypass width. This system allows the uncrushable object to pass through the gap. Metal detectors on the discharge conveyor determine when the uncrushable object has passed through the gap and the HRC™3000 then commences the typical start-up procedure.

The tramp bypass design requirements were defined to require an open tire gap to a width of 253 mm (10 inches) in less than 10 seconds. This rapid response and resulting high oil flows led to a unique hydraulic design which incorporates the use of a regenerative hydraulic circuit. The regen circuit utilizes the potential energy from the crushing operation and diverts high pressure oil from one side of the main cylinders to the next, requiring only additional pumps to make up the difference in volume between both sides of the cylinders.

The hydraulic system on the HRC™3000 not only controls crushing force and tramp bypass, but also is responsible for the control of all hydraulic components throughout the HRC™3000 including: control gates, stabilizing cylinders, main cylinders, holding brakes, main cylinder rod lubrication and oil cooling / conditioning circuit. Due to the criticality and uniqueness of this design, a third party vendor was brought into the project to assist in implementing the required hydraulic control strategy.

Stabilizing cylinders are another unique design feature that was not part of the original HRC™ HPGR design. However, based on FMI operating experience and concerns regarding feed alignment with the centerline of the tires, stabilizing cylinders were included in the HRC™3000 final design. Due to the unique geometry of the HRC™ HPGR arrangement, the centerline operating gap can maintain alignment with the centerline of feed regardless of gap width or tire diameter. The design tolerance while operating was defined as +/- 5 mm maximum allowable tire centerline deviation. To date, the tolerance is maintained consistently below +/- 1.5 mm.

Maintenance considerations

Other aspects of the machine were considered in order to ease maintenance and ensure a safe change-out of components, including:

- The reducer torque arm assembly eliminates the need to have a link arm connected to the foundation.
- The reducer carts, used to retract the reducer assembly during a tire change-out, attach to the foundation to ensure the reducer is secure.
- The reducer and main shaft connection was designed to reduce the time to connect and disconnect these components.
- A bracket system was developed so the pins, which connect the Arch-frame and the base frame, could slide in and out during maintenance without having to be handled.
- A special harness system was designed to secure the cylinders during tire change-outs and cylinder maintenance.
- A separate transporter was developed to rotate the Arch-frame and tire assembly into and out of the base frame during a tire change-out.

INSTALLATION AND COMMISSIONING

Installation of the HRC™3000 at the Metcalf concentrator started in September of 2013. For the installation of the HRC™ HPGR, Metso provided the installation crew and field service supervision. This allowed for very close communication between the HRC™ HPGR engineering team and the installation team.

The size of the large components needed to be considered for the installation phase of the project. Transporting the shaft from the laydown yard to the Metcalf building required coordination with site personnel to arrange for the use of the truck needed to move the 97 ton component, as well as the use of the overhead crane needed to lift it.

Part of the installation process included verifying the shaft and tire fit, which is critical to the operation of the machine, and therefore was carefully considered. The shafts and tires were dimensioned using a 3D laser measuring device, which measures actual dimensions within a 0.02 mm tolerance. The tire then was blued to recheck the fit and installed on the shaft. For the main bearing installation, the taper on the bearings and the shaft also were checked with the 3D laser measuring device to confirm the dimensions.

Infrastructure Surrounding the HRC™3000

A machine as large as the HRC™3000 requires a significant infrastructure to support it, as shown in Figure 9. In multiple cases, the actual dimensions between the structural steel and the machine were different than originally designed. In some cases, the remedy was not a simple solution. For example, when installing the hydraulic cylinders, the amount of room between the steelwork was not enough to install the cylinders as originally planned. A different lifting fixture had to be designed to move the cylinders into place. Moreover, maintenance had to be carefully considered in order to safely access and handle the large components. A 20 ton gantry crane was installed inside the steelwork tower to handle the hopper and feed guide plates. In addition, 0.5 ton robotic arms are used to handle the maintenance for the edge blocks and flange segments.

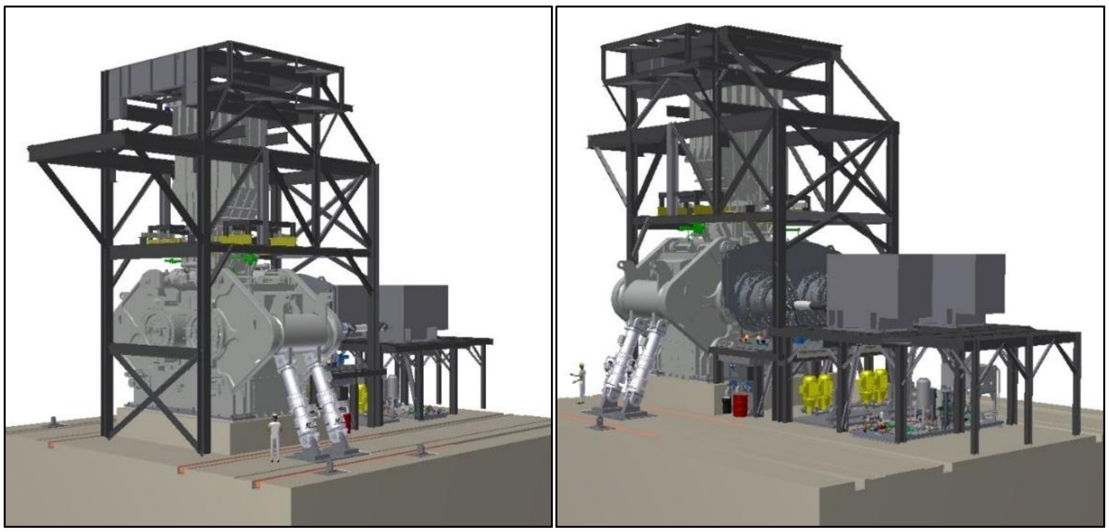

Figure 9 – Steelwork around the HRC™3000

Similarly, in order to reduce the size of the building and decrease the amount of field piping, the motors were installed on structural steel so that the hydraulic system could fit under the motor platform. Traditionally, motors of this size are installed directly onto a concrete foundation, so care needed to be taken to ensure the structure was properly designed. When the motor baseplates were installed, the footing was found to be "too soft" and outside of acceptable limits. A third party consultant was hired to review the structure and ultimately recommended additional bracing and welding to stiffen the structure.

The transporter, as shown in Figure 10, was specially designed to install and remove the 270 ton Arch-frame/shaft/tire assembly onto the base frame. The transporter was assembled at site and first tested when installing the Arch-frame/tire assembly into the machine during the initial installation. It took a total of 14 weeks to assemble this unit. During the installation of the Arch-frame it was identified that the stroke on the cylinders that extends the Arch-frame into position needed to be lengthened 75mm for the transporter to function properly. Once this modification was made to the cylinders, the transporter worked as designed and was able to align the centerline of the two tires within 1 mm.

Figure 10 – Morenci transporter for tire removal and installation

Commissioning

Initial start-up was attempted while the hopper was 60% full and the gates were fully open, causing the tires to be fully loaded. This resulted in the disengagement of the torque limiting couplings and showed the importance of the start-up procedures and utilization of control gates.

The automated start-up procedures were modified to incorporate using the control gates within the feed assembly to gradually introduce feed after the hopper level is achieved. By integrating the control gates, smoother start-ups were observed when the feed was first nipped. The control gates were an original part of the HRC™3000 design. Based on past experience, FMI was not confident that these gates would be reliable. However, these gates have worked without any issues since commissioning and have since become an integral part of the machine's functionality. In addition, the nitrogen pressure was reduced in the accumulator to soften any pressure spikes. Subsequently, larger accumulators were installed on the hydraulic cylinders to ensure a smooth start.

There were other challenges in addition to the large scale of the equipment and the experimental design of the machine. The work area was very congested. This meant that sometimes one crew needed to wait until another crew completed their tasks due to safety concerns and/or physical interferences. Weather was another unavoidable challenge and the team had to deal with thunderstorms and flooding which suspended operation. Despite all these challenges, the equipment was assembled without any major safety incidents.

OPERATING RESULTS

At the time of writing, the HRC™3000 has operated for over 7,000 hours. During that time, a total of 27,400,000 tons have been crushed by the HRC™3000 and the HPGR circuit has processed over 18,400,000 tons of ore. The HRC™ HPGR is fed with the secondary cone crusher product and has a F80 of 26 mm and a top size of 50 mm. The HRC™ HPGR is in a closed circuit with an 8 mm wet screen. Table 2 shows the typical conditions of the plant and machine and Figure 11 shows the flowsheet and mass balance of the Metcalf comminution circuit used for design.

Table 2 – Typical plant and machine conditions

HRC™3000	
Feed size, F80	26 mm
Product size, P80	15 mm
Screen closing size	8 mm
Ball Mill Feed, F80	5.1 mm
Moisture	2.2% - 3.0% (4.9% design)
BWi	16.5 design, 14.5 nominal
Operating speed (at tires)	14 – 17 rpm (19.1 rpm nominal, 21 rpm maximum)
Operating pressure	3.0 N/mm^2 (4.4 N/mm^2 maximum)
Power draw	5,729 kW*
Machine throughput, total feed	4,700 tph*

* Values based on typical operating parameters of 80% nominal speed and 3.0 N/mm^2

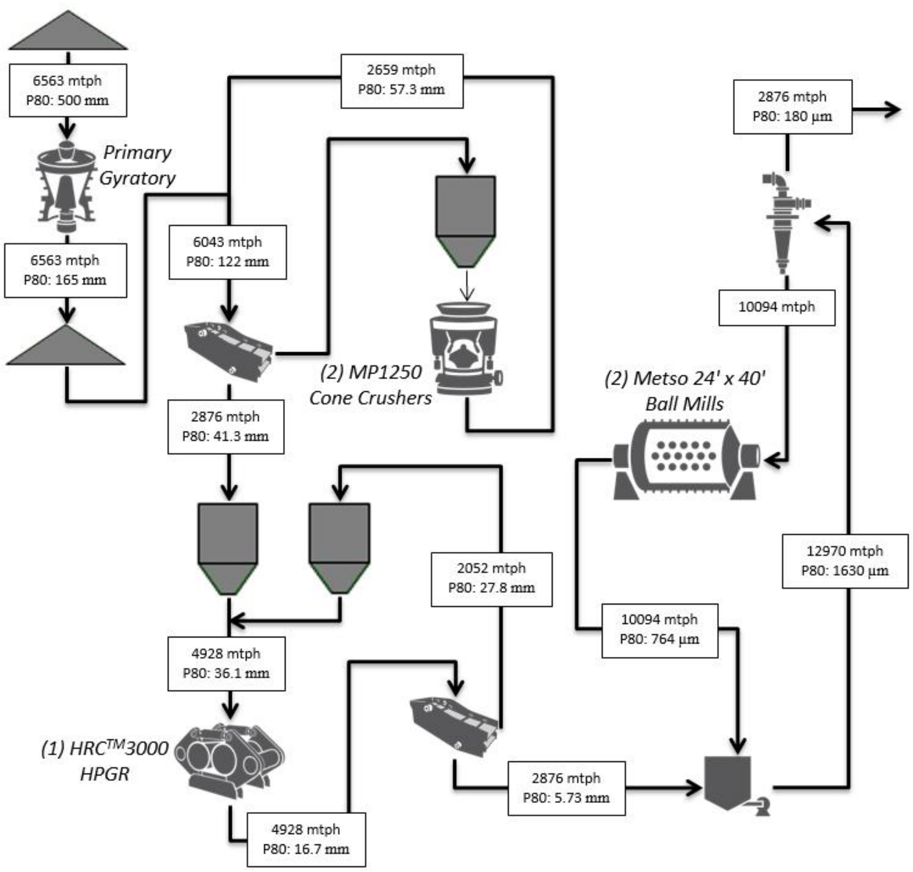

Figure 11 –Metcalf concentrator design flowsheet

Operating results show the benefits of flanges, first shown during the pilot plant edge effect testing, are exceeding the original predictions. Table 3 shows a comparison of the predictions based on the pilot plant surveys versus the actual operating results at the HRC™3000. In addition to these general findings, many of the expected results were validated and in some cases refined. Due to the lower than expected circulating load and higher specific throughput, the HRC™ 3000 is able to operate at an average of 70% nominal speed and still meet the capacity of the plant.

Table 3 – Operating results

	Predicted (based on flanged pilot plant tests)	**Actual***
Operating gap (mm)	99	99 – 101
Specific throughput (t·s/m^3-hr)	276	320 – 328
Circulating load (%)	58 – 85	41 – 55
Specific energy (kW·h/mt)	1.5	1.2

* Values based on typical operating pressure of 3.0 N/mm^2

As referenced in Table 3, the operating gap of the HRC™3000 is approximately 100 mm or 3.3% of the tire diameter. For a given feed and operating condition, the operating gap is greater for larger diameter machines. This large operating gap makes the HRC™3000 less susceptible to single particle breakage and tramp oversize material.

Additionally the HRC™3000 provides circuit flexibility compared to a traditional milling circuit. Both the speed and pressure can be changed online to meet the changing needs of the downstream circuit. The pressure can be increased, for example, if the plant is processing a harder ore. The HRC™3000 is capable of running at 30% nominal speed, which effectively reduces its capacity by the same amount. Under normal plant operations, the single HRC™ HPGR feeds two 7.3m (24 ft) ball mills. During times when one of the ball mills is offline, the plant can still operate at reduced capacity by turning down the HRC™ HPGR and feeding only one of the ball mills.

Segregated Feed to the HRC™ HPGR

Due to the arrangement of the feed bins and conveyors, feed to the HRC™ HPGR was segregated. Figure 12 shows the feed conveyor to the HRC™ HPGR. This resulted in finer and wetter material reporting to the non-drive end of the HRC™ HPGR while coarser drier material reported to the drive end.

As discussed earlier in the paper the Arch-frame acts as a spring to ensure that the two tires maintain alignment and does not result in any damage to the machine or its components. Nonetheless, the amount of skew is still monitored and alarmed so an extreme event would signal a potential problem. Despite the presentation of segregated feed, the Arch-frame maintained the alignment of the tires. During operation a 3 mm maximum between the drive end and non-drive end of the tire is observed. This is well within the acceptable limits of the mechanical design of the machine and within the clearances required for the successful operation of the flanges.

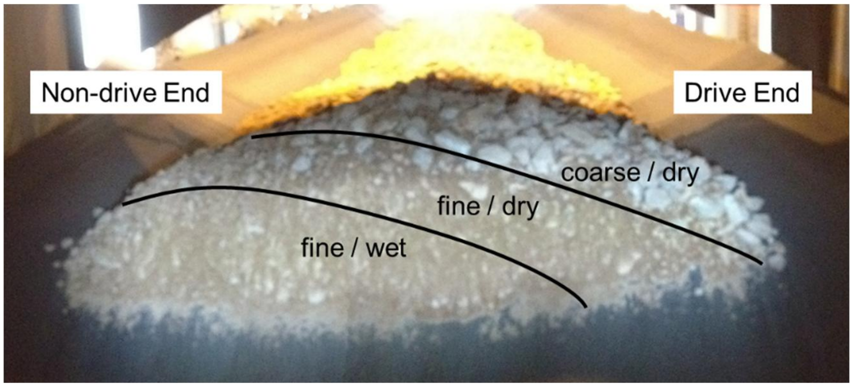

Figure 12 – HRC™ HPGR feed conveyor

While segregation did not pose a concern for the mechanical limits of the machine, it is impacting the wear surface, namely the tire, edge blocks, and flanges. For reference, Figure 13 shows a diagram of the feed to the HRC™ HPGR. On the drive end side, where the material is coarser and drier, there is less of an autogenous layer built up on the surface of the tire. This is causing the base material of the drive end side of the tire to wear at a faster rate than the studs. It was observed that the distance between the top of the stud and the top of the tire was greater on the drive end side than the non-drive end side. As a result of the higher protrusion of studs and the coarser material, the drive end side of the tire in turn has experienced some broken studs.

Conversely, the non-drive end side of the tire, which is crushing finer and wetter material, has a more competent autogenous layer. On this side, while the studs are wearing at approximately the same rate as the drive end, the base material of the tire is better protected. This results in the studs protruding out less on the non-drive end side of the tire and the studs remain intact. The concern however, on the non-drive end is the exaggerated buildup of the autogenous layer which increases the pressure on the edge of the tire. This has required refinement of the tire wear protection, as is discussed in the next section.

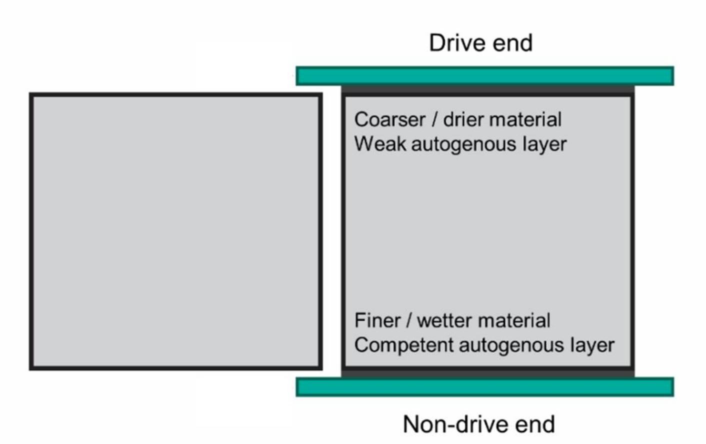

Figure 13 – Diagram of Feed to the HRC™ HPGR

Further Design Modifications and Improvements

Edge Blocks and Flanges

Although the edge block and flanges went through a number of design iterations at the pilot plant, additional design modifications were required upon start-up of the HRC™3000. It was noticed shortly after commissioning that the edge segments and flanges began to bend away from the tire surface, indicating the forces at the edge of the tire did not scale up linearly.

In review of the original design, it was determined that a combination of insufficient material properties and inadequate side protection design resulted in the failure and early removal of edge protection segments. A new set of flanges and edge segments was fabricated from high strength alloy and reinstalled. The new flanges were monitored using strain gauges to better understand stresses involved at the edges. As a result it was revealed that packing between tire surface and flange correlated to higher bending stresses. Scrapers were installed in order to remove excessive packing material and decrease the associated stresses.

After approximately 3500 hours of operation the upgraded flanges and edge segments required replacement. Flanges experienced excessive wear at each joint between segments, and carbide wear bodies began to dislodge themselves from the wear surface, resulting in premature wear. The flanges once again were upgraded to incorporate a more rigid design along with additional carbides to protect the high wear areas. At the same time, edge segments installed on the non-drive end of the non-flanged tire began to experience fatigue failure, initiating at the bolted connection between segment and tire. After further evaluation of the drive end segments it was apparent that the non-drive end segments were exposed to higher loads compared to the drive end, as both sets of edge segments were operating for the same quantity of cycles. This higher loading was attributed to material segregation, where fine material with higher density was predominately located on the non-drive end compared to the coarse material with low density on the drive end. The decision was made to install spare edge segments as an interim solution, knowing they would most likely need to be replaced in the upcoming months.

After installation of the spare segments, carbide blocks began to fracture quickly. Once again this was only located on the non-drive end of the non-flanged tire. These failures were attributed to the segregated feed combined with the fact that new, full-height edge segments now were installed on a slightly worn tire. The relatively taller edge segments resulted in increased pressure and premature failure. Spare edge segments once again were installed however with carbide blocks cut down to a lower height in order to accommodate the current tire diameter in its worn state. After lower height edge blocks were installed and changes were made to combat the segregated feed, operations resumed with no additional edge segment issues.

In parallel to the ongoing edge block and flange maintenance, Metso engineering worked on an upgraded design intended to withstand higher loads due to segregated feed. Due to the long life of the carbide wear surfaces on both the tire and edge blocks, designs had to incorporate a more aggressive approach to combat extremely high cycle fatigue failures. The new designs are scheduled for installation during the third quarter of 2015. Metso continues to evaluate the flanges, edge segments and scraper designs to ensure wear parts match the required duty of the HRC™3000 operation.

Reducer Bearing

In mid-August 2014, after approximately 1300 operating hours, a bearing failure occurred in the Siemens planetary reducer of the Metso HRC™3000. Two additional bearing failures occurred through the end of October 2014. The failures were limited to the cage of the matched set tapered roller bearings on the high speed input shaft. All were on the non-flanged (floating) tire side of the Metso HRC™3000.

Investigation concluded that the matched set tapered roller bearings became unloaded under the forces encountered, leading to random fatigue-initiated bearing cage failure. To support site operations, an interim solution was installed in November 2014, incorporating springs to preload the matched set tapered roller arrangement. In February 2015, the permanent solution for the HRC™3000 replaced the original bearing arrangement with a combination of radial bearings and a dedicated thrust bearing. At the time of this writing, no reducer bearing failures have occurred since the interim solution was implemented.

<u>Guide Plate Aperture</u>

During commissioning, the aperture of the guide plates in the feed hopper is set to ensure material is fed to the tires in a controlled manner. Based on pilot plant testing, we learned the plates should be positioned far enough apart so that the feed covers the nip angle and the machine is not starved of feed. Opening the gates beyond this point, however, normally only will result in added wear on the tire. Typically these plates would not need to be adjusted once set. However, sometime during start-up, the aperture increased as the bolts holding the gates were insufficient. This problem was fixed but the operators noticed that when the plates were set further apart, the machine capacity was higher. After this observation, the aperture of these plates was increased in order to maximize the capacity of the machine. This illustrates the importance of keeping the control gates set far enough apart to ensure the machine is reaching the full capacity.

Plant and Machine Availability

Since start-up, Metso and FMI have been working closely to fine tune various aspects of machine design, wear component development and improved control philosophies. Plant throughput has been increasing towards the design tonnage of 63,500 tpd. During the first year of operation, the plant has tracked along the McNulty I start-up curve. The McNulty Type I start-up curve is generally reserved for mature technology, while projects which include novel technology are generally classified in the Type 2 or 3 series and target approximately 80% or 60% of design tonnage by the end of the first year (McNulty, 2004). Since this circuit has a number of unproven technologies, including the HRC™ HPGR, this puts the Morenci Metcalf start-up well ahead of industry standards. Figure 14 shows the daily tonnages during the first year of operation against the McNulty Type 1 start-up curve.

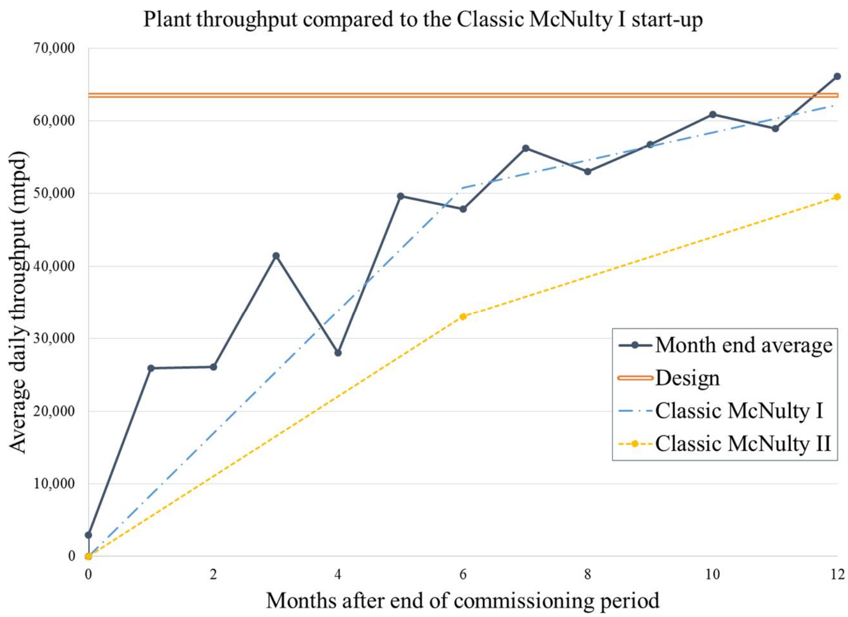

Figure 14 – Metcalf Concentrator daily tonnages versus the Classic McNulty Start-up curve

As expected, during the first year, there were a number of planned inspections that took the HRC™ HPGR offline for discrete periods of time. These inspections were necessary, as with any large installation, to ensure the machine was/is installed and working as expected. The reducer bearing failures, and edge block and flange replacements, also resulted in the machine being offline. Figure 15 shows the availability of the HRC™3000 during the first year of operation. Going forward, the availability of the HRC™3000 is expected to exceed 96%.

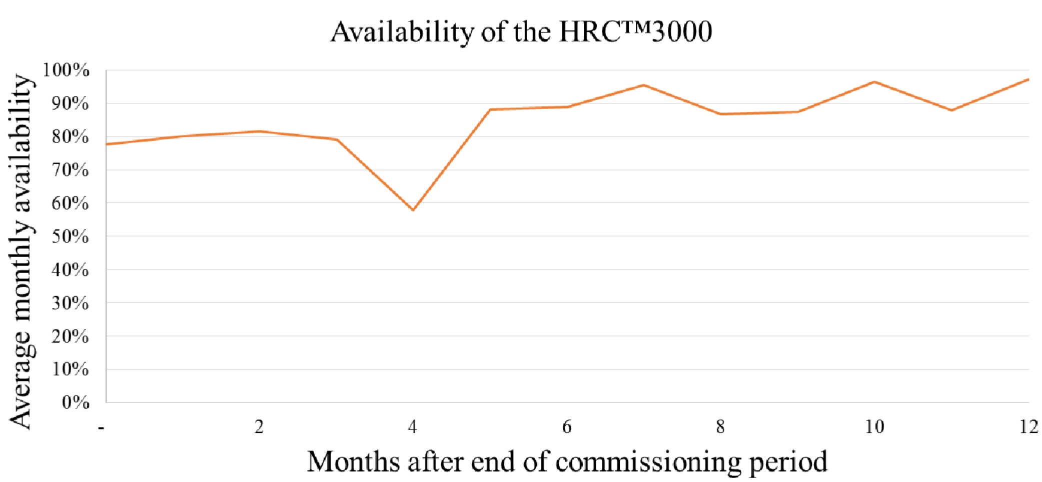

Figure 15 – Availability of the HRC™3000 during the first year of operation

Tire Wear Results

At the time of writing, the HRC™ HPGR has operated for 7,000 hours and is still running with the original set of tires. During this time, the 65 mm studs have worn only approximately 3 - 5 mm. There have been no signs of a bathtub effect, although the segregated feed, as mentioned earlier, has resulted in a slightly higher wear on the base material of the drive end side of the tire.

The first tire change-out has not yet been scheduled because the tires have over 75% of the remaining life. The current tire replacement plan includes supplying new tires instead of used or refurbished ones. In this case, the old tire is removed from the shaft using a hydraulic oil pump. A new tire is then heated using an induction heater, installed onto the shaft and allowed to cool. All these tasks are performed in the maintenance bay located adjacent to the operating HRC™ HPGR and can be performed by either FMI personnel or a Metso field service team.

When considering the option between supplying new or refurbished tires, the economics of both options were similar. In the case of supplying new tires, it is important to ensure a replacement supply is readily available. With the refurbished option, there is a greater risk for rework due to the large amount of weld (over 20,000 kg) that needed to be applied to each tire in order to restore it to its original diameter. Also, by supplying new tires, a specialized service center and a long term contract no longer is needed. Furthermore, by eliminating the need to refurbish the tires, the design of the tires can be further optimized. Without the requirement to re-weld the tires after service, a harder base material can be used.

FUTURE WORK

Metso and FMI have been working closely to fine tune various aspects of machine design, wear component development and improved control philosophies in order to maximize capacity and availability. The largest focus will be on maximizing the life of the edge blocks and flanges. The wear on the first and subsequent tires will be monitored closely to better understand wear rates in order to fine tune how long a tire will last during operation. Additional process survey results also will provide a greater understanding of how flanges affect the operation of HPGRs.

CONCLUSION

The HRC™3000 at the FMI’s Morenci Metcalf concentrator is the result of collaboration between FMI and Metso. In approximately 4 years, the team went from a design concept to the largest fully operating HPGR in the world. The HRC™3000 is the first full scale HPGR to incorporate revolutionary design features like the flanged tire design and the patented Arch-frame. This paper highlighted the various stages of development, including pilot plant testing, engineering design, installation and commissioning of the HRC™3000.

The importance of the pilot plant cannot be emphasized enough, as this allowed for approximately 12,000 hours of testing and design iterations that would not have been possible on a full scale operation. The pilot plant testing and manufacturing of the HRC™3000 were run concurrently. Although this expedited the overall project schedule, it also resulted in additional engineering time and expenses due to the re-evaluation of the designed components. With the fast pace of the project, efficient communication was vital between the parties and various groups.

While the pilot plant tested many aspects of the mechanical design, there were some challenges that still arose with the HRC™3000, namely the edge blocks, flanges and reducer bearing failures. Despite these failures, the Metcalf concentrator continued to track along the McNulty type I start-up curve and the HRC™ HPGR availability has averaged over 93% during the three months prior to the writing of this paper.

The operational benefits of the flanged tire design, first tested on the pilot plant, were shown to exceed predictions on the HRC™3000. For example, the specific throughput of the HRC™3000 was approximately 15% higher than the predictions from the flanged tire pilot plant tests. Other benefits to the circuit include increased energy efficiency and increased breakage. Ultimately, these benefits resulted in a higher circuit capacity due to the combination of the higher machine tonnage and the lower circulating load. In addition, the flanges seem to increase the overall life of the tire by allowing installation of harder studs in the center of the tire.

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NOMENCLATURE

tpd: metric tons per day
stpd: short tons per day
tph: metric tons per hour
HV10: Vickers hardness HV10
rpm: rotations per minute
N/mm2: HPGR specific force, Newton per mm squared
$t{\cdot}s/m^3$-hr: HPGR specific throughput, tons seconds per cubic meter hour
F80: Feed size 80% passing
P80: Produce size 80% passing

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