A closer look at increasing HPGR efficiency through reductions in edge effect

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Abstract
Edge effect is a condition widely observed in High Pressure Grinding Roll (HPGR) operations that gives rise to reduced comminution at the edges of the roll surfaces. This effect is caused by a reduction in the local crushing pressure at the edges of the rolls resulting from the sliding friction between the static cheek plates and HPGR feed material. Practically, this has an impact on equipment sizing, as the edge effect leads to coarser particles reporting to downstream equipment in open-circuit operations and increased circulating load and diminished HPGR circuit capacity in closed-circuit operations.

To address this, Metso's HRC™ HPGR incorporates an Arch-frame to maintain a parallel relationship between the rolls and allow for the use of a flanged roll design. We conducted a series of pilot-plant tests with a 750 mm by 400 mm HRC HPGR to compare the performance of the flanged roll design against that of a traditional cheek plate arrangement under similar operating conditions. The edge effect was found to be significantly reduced with the flanged roll design. Based on the pilot-plant results, the implications for circuit design, energy efficiency and overall plant performance in a full-scale application were investigated and discussed.

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Introduction

Global trends such as lower ore grades and rising operating costs are driving the market toward more energy-efficient mineral processing solutions, most notably in comminution circuit design. High pressure grinding rolls (HPGRs) have been recognized as an energy-efficient solution relative to more conventional circuit designs. The basic operating principle of HPGRs, in which a fairly uniform pressure is applied to a bed of material in the compression zone, lends itself to this improved energy efficiency (Morley, 2006). Studies have estimated that savings of 10-15 percent are possible when comparing an HPGR circuit with a traditional SABC circuit (Rosario and Hall, 2008).

While HPGRs offer a more energy-efficient solution than tumbling mills, there is still room for improvement in many aspects of the design. Edge effect, in particular, is one such aspect that limits the effectiveness of the machines. Edge effect is the impaired performance at the edge of the rolls due to a reduction in crushing pressure (Morley, 2010; van der Meer, 2010). As described in our prior work (Knorr, Herman and Whalen, 2013), edge effect is caused by the interaction between the ore entering the crusher and the relatively static cheek plates positioned at the edges of the rolls. As the material is drawn into the crushing zone, the sliding friction between the ore and the cheek plates inhibits the ability of material to be effectively drawn into the compression zone at the edges of the rolls. This reduces the crushing force in those edge regions relative to the center of the roll where material is being drawn into the compression zone at a higher rate. In addition, the cheek plates of a traditional HPGR design are held in place by spring-loaded brackets that are adjustable to manage the clearance. This spring-loaded cheek plate design prevents full compression of the material in the edge regions of the roll as there is relief at the outer edges.

To address this, Metso developed its HRC HPGR, whose flanges bolt onto the edges of one roll and rotate with the bed of material through the crushing zone. Using this arrangement, the flanges move with the ore and draw it into the crushing zone while closing off the edges of the rolls. This arrangement with a flanged roll assembly is shown in Fig. 1.

In the literature, Morrell et al. (1997) covered accurate modeling and van der Meer (2010) covered scale-up, but ef-

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forts have been minimal on enhancing HPGR comminution performance. This paper tests the hypothesis that an HPGR with flanged rolls can measurably reduce the negative impacts of edge effect.

Consequences of edge effect. There are three main problems associated with edge effect: (1) coarser particles discharging from the roll edges; (2) uneven wear patterns across the roll due to the differential pressure profile across the center and edges; and (3) decreased energy efficiency due to higher-than-optimal pressure applied to material crushed in the center of the roll. These problems cumulatively have a negative impact on operating efficiency, availability and operability, making any reduction in edge effect beneficial to a plant's performance.

One of the benefits of HPGRs is that the specific force can be adjusted to optimize the particle breakage based on the material being fed into the machine. However, an HPGR that has the standard cheek plate design will inevitably have lower pressure at the edges of the roll, resulting in an overall coarser product size distribution. In closed-circuit applications, edge effect will increase the circulating load and reduce the HPGR circuit capacity. In an open-circuit application, edge effect reduces overall crushing efficiency and sends coarser particles to the downstream equipment, increasing the demand on those machines. In an attempt to reduce the impact of edge effect, some open-circuit applications use a dividing chute to separate the center product and recirculate the edge product back to the HPGR feed (Gerrard, Costello and Morley, 2004).

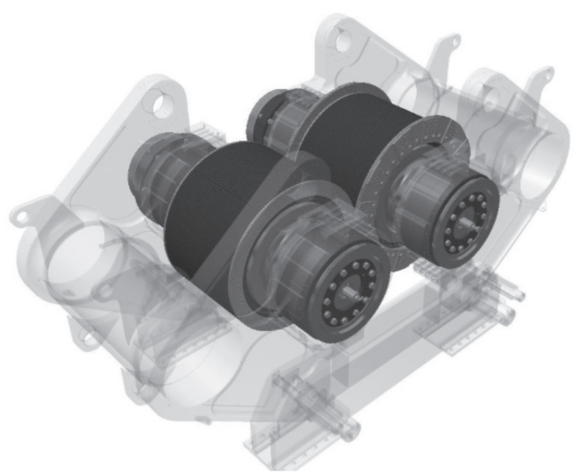

Figure 1 — HRC HPGR arrangement with flanged roll design.

The uneven pressure across the width of the rolls also creates an uneven wear profile, as the higher wear rates in the center of the roll create a twin-concave profile, known as a "bath tub" (Morley, 2006). The higher pressure exerted on the center of the rolls also increases the risk of stud breakage, limiting the hardness of the studs that can be used. In some hard-ore applications, like at Newmont Mining's Boddington operation, stud hardness needs to be reduced to minimize chipping (Hart et al., 2011). If a more consistent pressure can be applied evenly across the width of the roll, it will likely allow for harder studs to be used, increasing roll life and machine availability.

Moreover, the uneven pressure profile across the width of the roll reduces the energy efficiency of the HPGR. Traditional cheek plates create localized inefficiencies, with less-than-optimum pressure at the edges and higher-than-optimum pressure in the center. The excess pressure applied at the center of the roll does little useful work as the material cake approaches a fully compressed condition and excess energy is converted to heat. For an in-depth description, refer to Knorr, Herman and Whalen (2013).

Testing methodology

Flanged roll concept. The HRC HPGR uses flanges to minimize the amount of material bypassing the crushing zone and ensure a consistent pressure profile across the width of the roll. The bolt-on flanges are made possible by Metso's patented anti-skewing Arch-frame design, shown in Fig. 2. The Arch-frame mechanically connects both bearings of the roll assembly together, which allows the entire assembly to pivot in the base frame, absorbing any uneven forces in the frame. Due to this rigid structure, the Arch-frame ensures that a parallel relationship is maintained between the two roll assemblies, in contrast to more traditional HPGR designs, thereby making the flanged roll concept feasible.

Pilot-plant testing. Large-scale pilot testing of the HRC HPGR was completed in a collaborative research and development project between Freeport-McMoRan Inc. and Metso at Freeport-McMoRan's Morenci Concentrator. The Morenci pilot plant was designed to allow for the process and mechanical performance of the HRC HPGR to be tested in a range of operating conditions. During testing, the pilot plant operated for more than 11,950 hr and processed more than 667,000 metric tons of ore. Freeport-McMoRan and Metso jointly developed

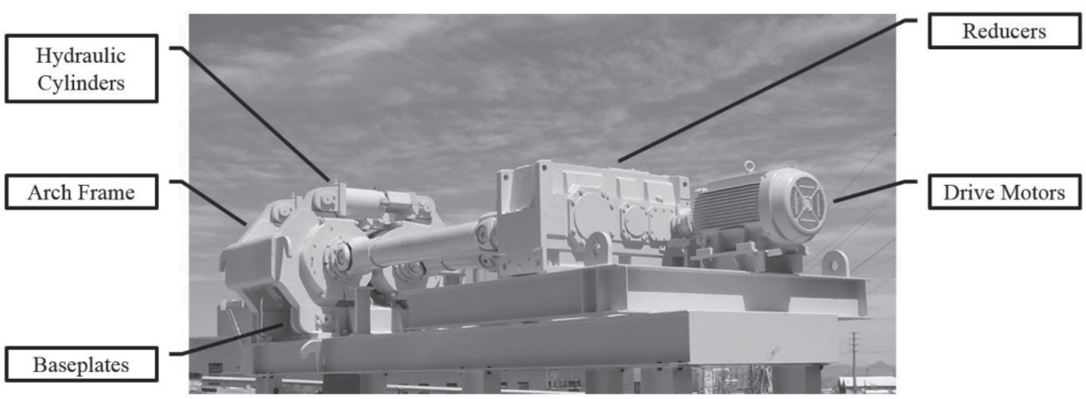

Figure 2 — Pilot-scale HRC HPGR with key components identified.

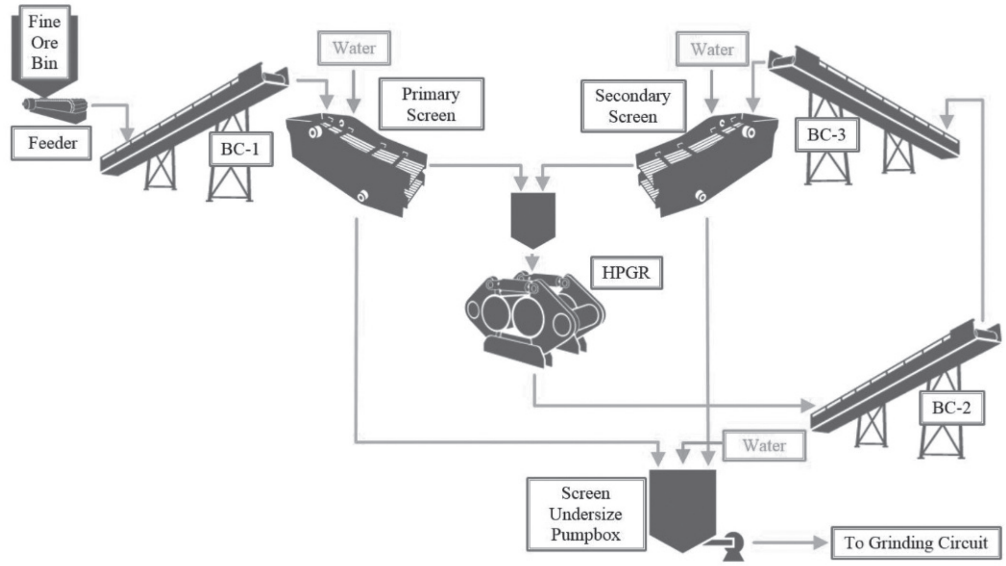

Figure 3 — The Morenci pilot plant's HRC HPGR circuit flowsheet.

and executed an experimental design, resulting in the completion of 114 individual process surveys. Since completion of the testing program in December 2013, the pilot plant has continued to operate for production purposes.

The HPGR crushing circuit at the pilot plant includes two wet vibratory screens, primary and secondary, along with an HRC HPGR with 750 mm by 400 mm rolls operating in closed circuit, as shown in Fig. 3. The fresh feed to the HPGR crushing circuit is tertiary-crushed material with a top size of approximately 25 mm. This material is drawn from the fine ore bin by a variable-speed belt feeder and conveyed to the pilot plant. Material with a particle size less than 3 mm is removed from the fresh feed in the primary screen prior to feeding to the HPGR. The combined stream of primary and secondary screen oversize is collected in the hopper and fed to the HPGR. The HPGR operates in a variable-speed mode to control the hopper level to an operator-controlled setpoint. The HPGR discharge is conveyed to the secondary screen. The primary and secondary screen undersize are collected in a product tank and pumped to the downstream grinding circuit (Knorr, Herman and Whalen, 2013).

The Morenci pilot plant is a fully controlled, monitored and automated plant. The programmable-logic-controller (PLC)-based control system was provided by Metso with an integrated camera system, dedicated historian and remote monitoring access through a Remote Desktop Protocol (RDP) connection. The pilot plant was also fitted with automated samplers on all sampled streams in the HPGR circuit and additional instrumentation to monitor plant stability, all aimed at providing the best possible process surveys.

A specific testing series was completed at the pilot plant as part of the overall experimental design, consisting of 12 process surveys, to quantify the changes in the process performance when operating with two different edge designs: a traditional cheek plate design, and the flanged roll design of the HRC HPGR. This testing series was identified as the "edge effect testing series." First, six tests were completed with a traditional cheek plate design installed on the HPGR. Then, the operating conditions were repeated in six corresponding tests with the flanged roll design. The specific force and relative wear of the flanges or cheek plates were varied during the testing. The primary and secondary screens were fitted with 3-mm and 5-mm aperture screen panels, respectively, throughout the edge effect testing series. The HPGR was fitted with a specially designed discharge chute with pneumatic flop gates capable of collecting fractional samples across the width of the HPGR discharge. This allowed for a direct assessment of the crushing performance at the edges of the HPGR rolls with the two different edge designs.

For each of the survey conditions, the pilot plant was monitored for plant stability prior to the start of the sampling campaign. The coefficient of variation for key operating parameters such as HPGR roll speed, HPGR discharge mass rate, screen undersize flow and screen undersize density were calculated and monitored continuously through the control system. Once an acceptable level of stability was established, composite samples were collected over a 2-hr period with data collection at 10-sec intervals. The samples collected from the process surveys at the pilot plant underwent a range of laboratory testing analysis, focused on both the individual sample and feed ore characterization. Mass-balanced survey results were generated by Freeport-McMoRan and Metso using the laboratory testing results and historian data, allowing for analysis of the circuit performance for each test run condition.

Results and discussion

Figure 4 shows comparisons of the mass-balanced HPGR feed and discharge particle-size distributions from test Z2B, with the cheek plates in new condition, and test Z8A, with the flanged roll design in new condition, both operating at a specific force of 4.5 N/mm^2.

The HPGR feed was a combination of the primary and secondary screen oversize streams, calculated in the circuit mass balance. The HPGR discharge was sampled during the survey in several different streams: total, edge and center. The total discharge sample was collected with an automated belt cut sampler on the HPGR discharge conveyor. Separately, individual samples of the material discharging from the edges of the HPGR were collected with pneumatic flop gates positioned directly below the rolls. These flop gates collected material from a width of 100 mm at each edge of the HPGR roll.

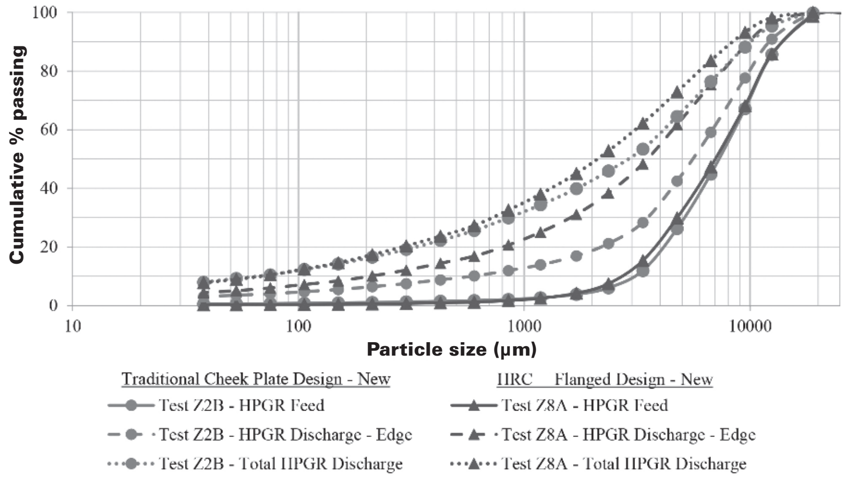

Figure 4 — Comparisons of mass-balanced HPGR feed and discharge samples from tests Z2B and Z8A.

From the comparison in Fig. 4 of the HPGR discharges at the edges of the rolls, it is evident that the flanged roll design significantly increased the particle breakage at the edges, relative to the traditional cheek plate design. This resulted in a finer total HPGR discharge with the flanged roll design, most notably in the coarser end of the size distribution. Test Z2B, with the traditional cheek plate design, had an HPGR discharge P80 of 7.5 mm, while test Z8A, with the flanged roll design, had an HPGR discharge P80 of 6.0 mm, both operating at the same specific force with nearly identical feed size distributions. The use of the flanged roll design does not appear to have an appreciable effect on the fines generation in the HPGR.

The process conditions during tests Z2B and Z8A are summarized in Table 1. In the upper section of the table are the variables that were held relatively constant between the tests. The feed conditions, HPGR specific force and HPGR roll speed were held relatively constant, and the circuit product P80 was very similar as a result of the closing screen aperture of 5 mm. Despite these comparable operating conditions, the use of the flanged roll design and subsequent reduction in edge effect had a significant impact on the overall circuit performance. As seen in the lower section of the table, plant capacity was increased by approximately 21 percent due to a reduction in the circulating load. In addition, specific throughput and operating gap were increased when operating with the flanged roll design. Overall, this resulted in a measurable reduction in the circuit specific energy.

This observed benefit of the flanged roll design was not limited to the two tests described above. Across the entire edge effect testing series with varying wear conditions and specific force setpoints, the flanged roll design exhibited improved comminution circuit performance, as seen in Table 2. Across the entire edge effect test program, the use of the flanged roll design resulted in a circuit specific energy reduction of 13.5 percent and a circulating load reduction of 24 percent, while the HPGR specific throughput was increased by 19 percent on average relative to the traditional cheek plate design.

In order to assess the change in net power draw across the

Table 1 — Balanced plant survey results for new cheek plates (test Z2B) versus new flanges (test Z8A).

	Test Z2B (cheek plates – new)	Test Z8A (flanges – new)	% change
HPGR discharge percent solids (%)	95.9	96.2	+0.3%
HPGR specific force (N/mm^2)	4.49	4.51	+0.3%
HPGR roll speed (rpm)	23.2	22.3	–3.7%
Circuit feed F80 (µm)	11,825	12,133	+2.6%
HPGR feed P80 (µm)	11,577	11,502	–0.7%
HGPR circuit product P80 (µm)	1,700	1,697	–0.1%
Plant feed tonnage (dry mtph)	35.3	42.8	+21%
HPGR throughput (dry mtph)	57.7	61.7	+6.9%
HPGR operating gap (mm)	15.6	17.2	+10%
HPGR specific throughput (ts/m^{3}h)	215.6	240.0	+11%
HPGR net power (kW)	107.4	116.4	+8.4%
HPGR net circuit specific energy (kWh/t)	3.04	2.72	–11%
Circulating load (%)	111%	87%	–22%
HPGR product P80 (µm)	7,491	6,004	–20%

Table 2 — Balanced test results summary for all 12 tests of the "edge effect testing series" matrix.

Test no.	Cheek plate/flange – wear	Specific force (N/mm^2)	Specific throughput (ts/m^3h)	Net circuit specific energy (kWh/t)	Circulating load (%)	Force acting angle (deg)
Z1B	Cheek plates – new	3.49	178.5	2.82	107%	2.7
Z4A	Cheek plates – half worn	3.49	203.9	2.82	135%	2.7
Z5A	Cheek plates – fully worn	3.50	210.7	2.81	122%	2.7
Z2B	Cheek plates – new	4.49	215.6	3.04	111%	2.6
Z3A	Cheek plates – half worn	4.51	213.5	3.34	124%	2.6
Z6A	Cheek plates – fully worn	4.49	223.4	3.05	114%	2.6
	Average cheek plate results		**207.6**	**2.98**	**119%**	**2.7**
Z7A	Flanges – new	3.50	231.6	2.67	93%	3.1
Z9A	Flanges – half worn	3.49	279.8	2.35	102%	3.1
Z12A	Flanges – fully worn	3.50	256.5	2.35	102%	3.1
Z8A	Flanges – new	4.51	240.0	2.72	87%	2.9
Z10A	Flanges – half worn	4.51	239.7	2.65	80%	2.9
Z11A	Flanges – fully worn	4.49	236.6	2.71	78%	2.9
	Average flanged roll results		**247.4**	**2.57**	**90%**	**3.0**

range of test conditions, the force acting angle from each test was compared. The force acting angle, β, is related to HPGR power draw by (Klymowsky et al., 2006):

$$P = 2 \times \sin \beta \times u \times F \qquad (1)$$

where P is the total net power in kW, u is the circumferential speed of the rolls in m/sec, and F is the applied press force in kN.

This allows for a comparison of the HPGR's ability to draw power across a range of operating speeds and crushing forces. The force acting angle for each test is presented in Table 2. The increase in force acting angle when operating with the flanged roll design demonstrates an increase in power for a given crushing force and roll speed.

Implications for large-scale operations. These results on the pilot scale have implications for the design and operation of HPGR circuits. A detailed scale-up analysis was completed, including simulation and modeling, to provide predicted results for a full-scale HRC HPGR operation. Based on this analysis, significant improvements in the areas of comminution efficiency, roll wear and circuit design were predicted for full-scale HPGRs with flanged rolls. The first opportunity for demonstrating these benefits has been in the tertiary HPGR crushing circuit at Freeport-McMoRan's Metcalf Concentrator at the Morenci operation.

The HRC3000, which is the world's largest HPGR and the first large-scale unit operating with a flanged roll design, was installed in this tertiary crushing circuit. This unit has been in operation since May 2014 and at the time of writing has run for more than 10,200 hours, crushing over 42 million metric tons of porphyry copper ore. The HRC3000 includes rolls with a diameter of 3.0 m and width of 2.0 m, driven by a total installed power of 11.4 MW. The plant is designed for nominally 63,500 t/d (70,000 stpd).

Preliminary observations indicate the predictions from the flanged roll testing at the pilot plant have scaled up well to the full-size operation. The observed circulating load, operating gap and specific throughput with the HRC3000 all met or exceeded the predicted performance from the pilot-plant analysis, as shown in Table 3. Future work will provide more details on the performance of the HRC3000 in this application.

Table 3 — Observations of HRC3000 at the Morenci operation.

	Prediction based on flanged-roll pilot plant	HRC3000 observations
Specific throughput (ts/m^3h)	276	315-350
Operating gap (mm)	99	93-112
Circulating load (%)	58-85	45-55

The observed improvements in particle breakage and increased unit capacity resulting from the flanged roll design can have an impact on equipment selection during plant design. The finer product size improves the open-circuit performance of the HRC HPGR, potentially allowing for open-circuit arrangements to be applied in a broader range of applications. In closed-circuit applications, it might be possible to reduce the size of the HPGR, as well as the screening and conveying equipment, for a given plant capacity due to the lower predicted circulating load. This translates into savings in both capital and operating costs. Of course, plants also have the option of maintaining the same equipment size and realizing the benefits of flanges through a higher plant capacity.

The ability of a flanged roll design to provide an even pressure distribution across the width of the roll also has potential implications for roll design and wear life. A more even wear rate across the roll could avoid the negative effects of a bathtub wear pattern. The lower peak pressure at the center of the roll could allow for harder, more wear-resistant carbide studs to be embedded on the roll surface without risk of fracture. Fewer roll change-outs would result in a lower cost of wear parts and increased machine availability.

Overall, the cumulative benefits in operating efficiency, increased roll wear life and circuit design would appear to support the use of a flanged roll HPGR design on a larger scale.

Additional work

These findings are based on a pilot testing unit with a 750-mm diameter. Future work will include continuing to refine our understanding of how flanges affect the crushing efficiency of larger units. In addition, the knowledge gained in this study will be used to incorporate the effects of flanges into simulation and modeling tools.

Additional updates covering other aspects of the HRC HPGR development program include a presentation of the full scope of the pilot-plant HPGR study by Knorr et al. (2015) and detailed reviews of the installation, commissioning and operation of the HRC3000 at the Metcalf Concentrator by Mular, Hoffert and Koski (2015) and Herman et al. (2015).

Conclusion

Pilot-plant testing using a 750 mm by 400 mm HRC HPGR with and without a flanged roll design demonstrated that the flanged roll design resulted in a measurable reduction in HPGR edge effect. The primary outcome of this reduction in edge effect was a finer HPGR discharge, which in turn provided a significant reduction in the circulating load and circuit specific energy. The flanged roll design also drew more material into the crushing zone, resulting in a higher specific throughput and an increase in net power draw.

The use of a flanged roll design yielded better particle breakage at the edges of the HPGR roll by increasing the compressive forces at the edges.

Observations with the large HRC3000, with a diameter of 3.0 m, at Freeport-McMoRan's Metcalf Concentrator suggest that the pilot-scale benefits have scaled up as predicted. These findings have implications for the unit capacity, energy efficiency and roll wear life of the HRC3000 relative to HPGRs with a traditional cheek plate design.

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Disclosure statement

Metso sells the HRC high-pressure grinding rolls as commercial equipment.

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