CRITICAL ASPECTS OF LOW GRADE ORE BENEFICIATION

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ABSTRACT

Beneficiation of low grade ores is the process of increasing the grade of a mineral through unit operations that remove and separate the waste (or gangue) material from the valuable mineral that can then be used for further processing or direct use. Important factors when deciding upon a beneficiation program are the feed grade, mass yield and the metal recovery. As lower grade ores are being processed beneficiation is a critical process. How predictive is laboratory test work for “as built” operating projects? Beneficiation includes all or some of the available unit operations to produce a beneficiation flow sheet i.e. associated unit operations including but not limited to optical sorting, radiometric sorting, crushing and screening, coarse cobb ing, jigg ing, dense media separation (DMS), spirals, magnetic separation, flotation, thickening, filtering and drying. Reference to specific projects and the approach developed in formulating a beneficiation flow sheet and a comparison of difficult and simple beneficiation flow sheets are cited.
INTRODUCTION

Reserves of high-grade iron ores are reducing all over the world, at an alarming rate, over the years as a result of the rapid increase in demand for steel particularly from Japan and then China. The recovery of mineral value from the low-grade ores using present technology is more expensive than DSO ores due to high energy and capital costs. Beneficiation is defined as a variety of processes whereby extracted ore from mining is reduced to particles that can be separated into mineral and waste.

Various physical properties of an ore can be exploited to separate a low grade fraction including variation in hardness, density, reflectance, conductivity and magnetism.

"Beneficiation" of iron ores includes concentration, generally by physical removal of unwanted gangue. Also considered beneficiation is the regulation of product size, or other steps such as agglomeration to improve its chemical or physical characteristics prior to smelting.

GEOLOGY & ORE CHARACTERISATION

Over 300 minerals contain iron but there are five primary minerals that are commercial sources of iron: magnetite (Fe₂O₄), haematite (Fe₂O₃), goethite (Fe₇O₈·H₂O), siderite (FeCO₃) and pyrite (FeS₂). Mineralogy using Qemscan at an early stage of development is critical in determining test programmes and developing flow sheets.

METALLURGICAL TEST WORK

Beneficiation of an iron ore can be considered in different methods such as milling (crushing and grinding), thickening, filtration, sizing, gravity concentration, magnetic separation, flotation and agglomeration (pelletizing, sintering, briquetting, or nodulizing).

Most beneficiation operations will result in the production of three materials: a concentrate; a middling or very low-grade concentrate which is either reprocessed (in modern plants) or stockpiled and a tailing (waste), which is discarded.

A common metallurgical test work requirements for magnetic iron ore beneficiation, developed by METS, is presented in Figure 1.

Test work will normally begin with blending, splitting and control crushing of the samples. Following the sample preparation, coarse cobbing, wet magnetic separation test (WHIMS), Induced Roll Magnetic Separation (IRMS), cyclo-sizing, etc. can be performed on the sample. In addition, Mineral liberation Analysis (MLA) provides very detailed information on the minerals present and the liberation size which can point to the most suitable beneficiation process. A Davis Tube is normally used to determine the yield of magnetite from those ores (Connelly, 2009).

CRUSHING AND SCREENING

Crushing and screening play an important role in dry beneficiation of iron ores. Crushing and screening can be the first step of iron ore beneficiation. In most ores, including iron ore, valuable minerals are usually inter-grown with waste minerals, so the minerals to be separated have to be liberated as an essential preliminary step prior to their separation into concentrate and tailing. Size reduction is achieved by crushing and grinding and the degree of reduction required is determined by the extent of mineral intergrowth.

Crushing and screening can result in an upgrading of the iron ore. The fines fraction is usually lower grade and contains more waste.
Figure 1 – Iron ore (magnetite) beneficiation test plan
High Pressure Grinding Rolls (HPGR) are increasingly being used in iron ore circuits because of power savings. The HPGR replaces a SAG mill, has a similar CAPEX and can result in a lower Bond Ball Mill Work Index due to fine cracking of the particles.

COARSE COBBING

In the case of magnetite ores, a magnetic cobbing machine can be employed to upgrade the magnetite ore at a coarse size. The machine can treat ore with a particle size of 1 – 3.5 mm, increasing the iron grade by 2 – 3 percent and discharging a tailing accounting for 10 – 15 per cent of the feed (Connelly, 2011a).

Magnetic drums used in coarse cobbing are designed to obtain maximum rejection of a non-magnetic product and maximum recovery of the iron mineral. Typically, they are applied on a rod mill discharge product. Since the objective is to obtain maximum capacity, these drums are 0.9 – 1.2 m in diameter and they incorporate wear covers on the drum shells to take the wear introduced by the relatively coarse feed size.

Laboratory or pilot-plant tests are usually conducted on individual ores to determine the number of drums required to obtain optimum concentration results.

JIGGING

Jigging is an old separation technology which has been used over the years in iron ore beneficiation. Due to the recent advances in jig control and a better understanding of the separation processes they are still in use. The use of jigging in South Africa has been driven by the need to beneficiate lower grade ore (typically 40 – 60 per cent Fe) to a product grade of 63 per cent Fe or higher.

Jig technology offers low capital and operational costs in comparison with other technology currently used for iron ore beneficiation.

The size range that is applicable for this technique extends from 25 mm down to 0.8 mm. In this size range the density difference between the iron ore and the gangue is used as the basis of separation. When particles separate on the basis of density in water, the light and heavy particles both move in the same direction, the only difference being that the heavier particles move faster than the lighter particles. So in this technique the particle size also plays an important role. Figure 2 illustrates the segregation between heavy and light minerals due to the vertical pulsation of water.

![Figure 2 – Jigging mechanism (heavy mineral in black)](image)

The Gekko Inline Pressure Jig (IPJ) is a recent innovation which may have application at a coarse size.
HEAVY MEDIA SEPARATION

In terms of tonnes produced, the beneficiation of iron ore has traditionally been dominated by dense medium separation technology (Iron Ore 2007). The size range for this technology is the same as jiggling but heavy media separation, as the name implies, takes place in a heavy or dense medium made up of a mixture of water and ferrosilicon. In this technique, since the density of the medium is between the density of the iron minerals and the waste, the waste and iron particles move in opposite direction (floats and sinks). Size plays a less dominant role and provided that all the particles are larger than a certain maximum size, which is equipment specific, dense medium separation, can be regarded as being size independent. Clays in the ore present operating problems and ferrosilicon loss is an important cost consideration.

Figure 3 – 2-Compartment heavy media drum for coal

One type of coarse heavy media separator is the drum separator shown in Figure 3.

CENTRIFUGAL CONCENTRATORS

Knelson and Falcon concentrators are used to recover free heavy mineral particles by the motion of a high-speed centrifugal force against a fluidisation water (in the case of the Knelson), and are mainly used in gold recovery. Knelson concentrators consists of a concentrating cone, drive motor, water chamber and fluidisation water unit. The concentrating cone is a conical shape that incorporates a series of rings, increasing in diameter towards the top of the cone. In the vertical wall of each ring section there is a series of holes from which water is pumped into the concentrating ring.

The Knelson concentrator operates in a batch or semi batch sequence. Firstly, the fluidisation water flows into the water cavity through the rotor shaft. Once the cavity fills to capacity, the static pressure forces the water through the fluidisation holes and into the concentrating rings. This injection is tangential and counter-clockwise as shown in Figure 4.
Spiral separators vertically separate the feed slurry in the launder (channel) according to density differences. The heaviest feed particles fall to the bottom of the launder, where frictional forces slow their velocity. As a result, the heavier grains are less subject to the centrifugal forces (generated by the flow of slurry through the spiral-formed channel) than are the lighter grains higher up in the flow. This creates a horizontal density differentiation of the feed grains, with the heavy particles flowing along the inside walls of the channel, and the lighter particles travelling higher up towards the outer rim. The discharge outlets are located on the inside of the channel for removal of the heavier particles (concentrate). Separation precision can be improved by adding additional water during the sorting process.

The launders (channel) are made of rubberized fibreglass or cast-steel or, in more modern constructions, also of fibreglass, urethane or ceramic. The design involves numerous pipes for supplementary-water intake and discharge outlets, making the spiral separator a fairly complicated construction (Figure 5).

Critical construction parameters are: launder (channel) cross-section and spiral diameter, number of windings, inclination and number of discharge outlets.
LOW INTENSITY MAGNETIC SEPARATION

The magnetic separation process is complex in many respects due to the varying magnetic susceptibility of the different ores, the amount of middlings and the particle size distribution of the processed ore. The magnetic force acting on a specific particle is dependent upon these factors as well as other properties such as magnetic flux and magnetic field gradient, which are created by the magnetic system in the separator. The product of magnetic field strength times gradient, also called the magnetic force index, varies between different magnetic system designs and is a factor when selecting the most suitable magnetic system for a particular process.

As in all applications, the magnetic force is competing with other forces such as gravity and hydraulic drag, therefore, the feed volume and tonnage must be balanced to obtain a suitable level of performance.

Generally speaking, the smaller the particle size being processed, the lower the feed capacity of the equipment. By selecting a higher magnetic field strength (magnetic flux) the feed capacity can be increased considerably, in many cases the recovery of the fines increases significantly with the field strength.

RARE EARTH DRUMS

There are two main suites of rare-earth magnetic separators (REMS) – rare-earth rolls and rare-earth drums. Process widths are usually 1 m to 1.5 m, with 2 – 4 magnetic stages.

In a rare-earth roll, (Figure 6), material is fed evenly on its separator belt and is transported over a uniquely designed magnetic roll. As the feed material moves through the magnetic field, all magnetic particles are attracted to the roll. Depending on the magnetic susceptibility of the particle, it either becomes attracted to the surface of the belt (magnetic particles) and its trajectory altered or it is unaffected by the field (non-magnetic) and is thrown from the roll through centrifugal force. The separation is optimized with the proper selection of magnetic roll design, belt thickness, roll speed, feeding position, splitter position and number of stages of separation.
With a rare-earth drum (Figure 7), the principle is somewhat similar. The feed is introduced onto a rotating metal shell and the magnetic particles are attracted towards the rare earth magnets in the drum, while the non-magnetics are thrown away from the drum by their centrifugal force. With both separator configurations, magnet design and magnetic force are customized for each application.

In iron ore beneficiation, REMS is used to separate weakly magnetic iron ore (magnetite mixtures) from a variety of less-magnetic and non-magnetic materials.

For this technique crushed ore should be less than 0.5 – 1 mm. The magnetic field is medium intensity of about 2000 – 5000 gauss for REMS.

By maximizing the use of rare-earth magnets in a process flow sheet, the following main benefits can be established:
- Reduced operating costs, often in the range of 30 – 50% compared to induced roll magnets, and even lower compared with cross belt separators
- Enhanced product qualities
- Optimized product yields
- Augmented economic recovery of valuable minerals from waste materials
- Increased overall dry processing efficiency
- Decreased plant size and lower capital costs
- Reduced need for operators as well as the associated skill levels
- Enhanced ore reserves due to overall greater efficiencies, resulting in a greater pit to product yield
- Reduced equipment footprints of up to 90% over electromagnets
- Optimized capacity

**WHIMS**

When the ore is primary milled to approximately 6 mm or less, it may be directed to a wet cobbing magnetic separator such as a Wet High Intensity Magnetic Separator (WHIMS). In the Jones WHIMS (Figure 8) the separation takes place on the plate boxes on the periphery of one or two rotor attached to a central shaft. The well-mixed feed enters the separator via pipes at the leading edge of the field in the form of slurry into the plate boxes. The plate boxes are grooved to concentrate the magnetic field and the feeding is continuous as the plates are rotated. The magnetic particles are held by the plate, while the non-magnetic material passes through into the launder below. The non-magnetic materials are washed before leaving and are collected as middling product.

The magnetic material then is finely ground in secondary mills such as ball mills. In silicate bearing ores the fines may be sent to hydro separators, where fine silica is removed. A finisher magnetic separator can be utilized prior to fine screening and a subsequent final concentration in a 'concentrate thickener'. The underflow from the thickeners is called 'filter cake', and is ready for mixing with a binding agent before pelletizing.

![Diagram of WHIMS separator](image-url)

Figure 8 – Jones wet high intensity magnetic separator
SLon MAGNETIC SEPARATOR

SLon magnetic separators utilise the combined force fields of magnetism, pulsating fluid and gravity to continuously beneficiate fine weakly magnetic minerals. They possess the advantages of high efficiency, low operative cost and high reliability. Until now there are about 600 SLon magnetic separators widely applied in processing oxidised iron ores, or other minerals (Figure 9). SLon magnetic separators mainly consist of the pulsating mechanism, energising coils, magnetic yoke, separating ring, feeding and product boxes. Expanded metals or round bars made of magnetic stainless steel are used as a matrix. While a direct electric current flows through the energising coils, a magnetic field is built up in the separating zone. The ring with the magnetic matrix rotates around its horizontal axis. When slurry from the feeding boxes enters into matrix located in the separating zone, magnetic particles are attracted from the slurry onto the surface of the matrix, brought to the top of the ring where the magnetic field is negligible, then flushed out into the concentrate box. Non-magnetic particles pass through the matrix and enter into the tailing box under the combined actions of gravity and pulsating hydrodynamic force.

As the ring rotates vertically, the flushing direction of the mags is opposite to that of the feed so that coarse particles can be flushed out without having to pass through the entire depth of the matrix pile. The pulsating mechanism drives the slurry in the separating zone up and down, keeping particles in the matrix pile in a loose state. Magnetic particles can therefore be more easily dragged to the tailings box through the matrix pile. Obviously, opposite flushing and pulsating prevents the matrix from being clogged, and most importantly, pulsating helps to purify the magnetic product.

![SLon vertical ring and pulsating high gradient magnetic separator](image)

Figure 9 – SLon vertical ring and pulsating high gradient magnetic separator

FLotation

Flotation is a technique where particles of one mineral or group of minerals are made to adhere preferentially to air bubbles in the presence of a chemical reagent. This is achieved by using chemical reagents that preferentially react with the desired mineral. Several factors are important to the success of flotation activities. These include uniformity of particle size, use of reagents compatible with the mineral, and water conditions that will not interfere with the attachment of the reagents to the mineral or air bubbles.
Historically, flotation was used to recover magnetite from taconite ores but with large resources of high-grade iron ores worldwide, flotation today in iron ore processing is primarily used to upgrade concentrates resulting from magnetic separation. Over 50 percent of all domestic iron ore is upgraded using this technique. Flotation, when used alone as a beneficiation method, accounts for approximately 6 percent of all ore treated.

Several factors are important when conditioning ore for flotation with chemical reagents. These include thorough mixing and dispersal of reagents through the pulp, repeated contact between the reagents and all of the relevant ore particles and time for the development of contacts with the reagents and ore particles to produce the desired reactions.

**OPTICAL SORTING**

Optical Sorting is applicable to large projects where the grade is low and vein type systems exist. The differences can be colourimetric, reflectance or radiometric differences. The typical size range is -300 +10 mm material. The ore needs to be graded with respect to size. The benefits of ore upgrade are significant. High speed automation and solid circuit electronics have seen great improvements in the machines available.

Typical applications are nickel, uranium, taC, gold and diamonds. The upgrade of scheelite ores using ultraviolet light is one very efficient application.

**IRON ORE CASE STUDY**

![Iron Ore Case Study Diagram]

Figure 10 – Low grade iron ore beneficiation


ROM Handling Prior to Scrubbing

Ore materials characteristics, handling prior to scrubbing and distribution to scrubbers, determines the number of scrubbers and their size. The ore contains wet sticky clays (Connelly, 2011b).

The predominantly fine nature of the ROM size composition, with high moisture and clay content, negates the need for major primary crushing equipment such as gyratory crushing facility. To minimize handling costs, ore receiving will be direct tipping from haul trucks into the primary sizer feed bin.

Primary crushing would mostly be required to break down large lumps of consolidated clay ore, to enable overland conveying from the primary tip and crushing station to the processing plant. The difficult handling nature of the ore, and high clay content, dictates the use of a primary mineral sizer, able to break up large particles of agglomerated soft ore, as well as making handling of clay possible.

Overland conveying is limited to a single conveyor, to minimize costs, thus requiring a facility to distribute the ROM feed to the number of scrubbers. Stockpiles to allow for surge, and distribution via apron feeders were considered, but the extreme difficult handling characteristics of the ore made such a facility impractical, as the ore would compact and consolidate, and ore extraction from the stockpile with apron feeders would fail.

It would be ideal to feed ROM ore directly into scrubbing, without requiring transfer points or stockpiles as it is taken that, with proper scrubber design, the difficult handling characteristics of the ROM ore post scrubbing would be eliminated. Distribution of ore from the single overland conveyor into a number of scrubbers is expected to be difficult, hence limiting of scrubber units to the minimum.

The minimum number of scrubbers which could be considered for this duty is driven by the number of screens required to practically handle scrubber product. Calculations indicated that eight screens and two scrubbing units would be required to enable practical distribution of scrubber product.

A facility is thus required, to distribute the ROM from the single overland conveyor to two scrubber units continuously, and to provide “offloading” capacity in the case when one scrubber requires to be stopped. In such a case, ore on the distribution facility needs to be accessible with a FEL.

SCRUBBING AND SCREENING

Screening of scrubber product – scalping of oversize, gravity feed between screening stages as opposed to pumped transfer.

The scrubber product will require screening directly after exiting from the scrubbing units, to enable sizing and dewatering of the ore, and handling of water effluent and fines passing through the scrubbers.

Post scrubbing, four size fractions need to be produced:

1. Oversize +32 mm – material for pebble circuit
2. 32 x 8 mm fraction – feed to secondary crushing
3. 8 x 1 mm fraction – feed to “natural fines” DMS modules
4. < 1 mm fraction suspended in pulp – not suitable beneficiation, tailings feed

To achieve the above, three separate screening surfaces would be required. The DFS design was based on a pumped transfer of the < 8 mm ore to the 1 mm screening surface, in order to limit the height at which the scrubber required installation to gravity feed onto the screening units.

Additionally, the design rested on the ability of trommel screens, mounted onto the discharge of the scrubber units, to achieve the 32 mm screening duty. It was established that the capacity of the trommel
screens were not sufficient for the duty. As a result a dedicated screening surface for the 32 mm cut would be required.

It was considered in the FEED that pumping of <8mm ore, as produced by the 8mm screening surface, on the scale of the Marillana plant, would pose significant risks in terms of operability, maintainability, operating costs and achieving annual nameplate capacity. Abrasively of the ore, in combination with the high velocity required to maintain mobility of the coarse ore particles, are the main concerns. Pumping of <1mm ore in slurry format fundamentally de-risks this.

The FEED design therefore includes sufficient screening capacity to enable screening with 3 screening surfaces by gravity, and pumping of the <1mm slurry. Water utilised in the scrubbers and sizing screens, is essentially recirculated water from the DMS plant, thereby reducing the load on the Thickener.

PEBBLES HANDLING

The > 32 mm fraction of the ROM will constitute the “pebble” fraction, which will essentially be discarded. Test work during the FEED has indicated that pebbles in the scrubber load will be essential to provide scrubbing media to ensure that difficult clay agglomerates will be broken up and dispersed sufficiently.

The design therefore includes a pebble recycling facility which will ensure a constant pebble load in the scrubbers up to 10% of these solids load. The circuit is designed to distribute the recycled pebbles evenly to the two scrubber feed points. Pebbles not recycled will exit the circuit to the coarse rejects conveyor. This is a unique design but essential to ensure functionality of the scrubber process at all variations of ROM particle distribution consistency.

SECONDARY CRUSHING AND SCREENING

Availability and Utilization – Linking with Scrubber Plant

The 32 x 8 mm fraction from the scrubber screening process requires crushing and wet screening to produce the remaining DMS feed stock at 8 x 1 mm. The crushing circuit is in closed loop with the wet screens to ensure the top size of 8mm.

There are only minor differences between the DFS and the FEED design of the plant. The main consideration in the FEED design was the significant difference in expected utilization of the crusher plant, in comparison with that of the scrubber plant, from where its feed originates. To overcome this, the cost of a surge stockpile against a standby crusher unit was considered.

The secondary cone crushing and wet screening circuit is conventional, employing feed bins to enable distribution of the crushing feed stream between the numbers of crushers, as well as choke feeding to maximize crushing efficiency.

The wet crushing screening process will produce a > 32 mm fraction to be recirculated to the cone crushers, the crushed 8 x 1 mm DMS feed fraction, and a < 1 mm fraction in pulp, which will be pumped to the Spiral Plant for beneficiation. Pulping water utilized on the screen, is recirculated water from the DMS effluent.

CRUSHER FINES BENEFICIATION

The < 1 mm fraction produced by crushing and wet screening, can be beneficiated with mineral spirals. At the scale of throughput of the Marillana plant significant amounts of this fraction is inevitably produced. However, the spiral plant is equipped with a bypass facility, to ensure that the scrubber, crushing and screening plant can continue operation if the spiral plant requires to be shut down.
The spiral plant feed from the crusher screens is dewatered in hydrocyclones and classified into separate coarse and fine feed fractions to maximize efficiency of beneficiation. The coarse and fine circuits both employ separate straightforward rougher and cleaner stages, which are pump fed and transferred, to limit the height of the spiral plant structure.

Product of the coarse and fine circuits are jointly dewatered via conventional cyclone and dewatering screen, and the rejects will be combined and pumped to the tailings section of the plant. The spirals plant is not a significant consumer of process water.

**DMS BENEFICIATION**

- Surge between scrubbing and crushing plant and the DMS section.
- DMS cyclones gravity feed, against pump feed configuration.
- Featuring various improvements in the DMS circuit design.

Natural and crushed sized 8 x 1 mm ore will be stockpiled ahead of the DMS plant, on a specially designed stockpile facility to enable distribution of feed ore between the DMS modules. In addition, the stockpile facility will also provide the required surge to allow for the difference in planned utilization between the DMS beneficiation plant and the up-front mining, scrubbing and crushing sections.

Natural and crushed DMS feed will be conveyed separately to the DMS feed stockpile. This provides the option to stockpile the different types of ore separately, or combined. Test work has shown the natural and crushed 8 x 1 mm fractions require different separation parameters in the beneficiation process; hence this was the primary consideration. Notwithstanding, blending or feeding both types of ore to the same DMS module, will be possible. This will enhance the utilization of the DMS beneficiation plant, and negate the effect of difference in ROM particle size distribution on the operation of the plant.

The DFS design employed pumping as the mode of feeding the DMS cyclones. The FEED considered that given the scale of throughput of the Marillana plant, this would have a significant impact on the maintainability and availability of the DMS section, as wear is a major consideration. Furthermore, pumping causes attritioning, and significantly increases degradation of ore particles, thereby contributing to medium contamination. By utilising gravity feed configuration, the DMS plant was de-risked from these issues, and a number of pumps eliminated also.

Each DMS module is equipped with a dedicated Feed Prep Screen, to ensure the ore is suitably prepared prior to entering the DMS circuit, thereby ensuring optimum chances of medium preservation. The inclusion of a medium cleaning circuit should prove essential for the removal of magnetic ore contaminants which have been found during test work and are expected to be present in the Ferro medium.

Various other improvements in the FEED DMS design include a more robust densification circuit to improve control, and increased throughput per module, thereby reducing the number of modules. Improved chute design, as well as access to all pumps and drives has been addressed.

The DMS plant is the primary user of process water. Effluent from each module is recirculated to the modular Feed Preparation Screen, and finally to the Scrubber plant via a distribution circuit.

**PRODUCT REJECTS AND TAILINGS HANDLING**

Products and rejects handling from the screens in each DMS module, features individual conveyors, discharging onto the main conveyors. These allow improved maintenance access, and start up procedure after main conveyor trip, as the Ferro circuit starting and stopping will be de-linked from the operation of the main rejects and product conveyors. Sampling of individual modules for grade control is also possible.
Tailings handling involves pumping of all fine tailings to the FRS (Fine Rejects Storage) facility. The total < 1 mm fraction of the ROM removed from the ore at the scrubbing and screening operation, reports to the tailing section, as well as the spiral tailings (or bypass), and the underflow from the Thickener (< 100 micron) (Connelly, 2012).

The tailings pumping facility design allows transfer of < 1 mm ore to the FRS. All tailings streams will be thickened in Hydro cyclones, and cyclone overflow will be thickened. This results in dense tailings slurry, which could be diluted with tailings cyclone overflow to suit the pumping operation.

CONCLUSIONS

Low grade ore sources can be profitably mined provided the ore is amenable to beneficiation. Beneficiation is the process of increasing the grade of a mineral through unit operations that remove and separate the waste (or gangue) material from the valuable mineral that can then be used for further processing or direct use. Important factors when deciding upon a beneficiation program are the grade of concentrate, mass yield and the metal recovery. For some rare earth ores where beneficiation is not achievable the project is not viable.

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