Performance of Mine Water Treatment Innovations to the High-Density Sludge Process at MacLeod Mine

Bernard C. Aubé[1], Stefano Cerilli[2], Giulio Grossi[3], and Riccardo Schiavone[3]

[1]Envirobay Inc., 116 Tremblay, Ste-Anne-de-Bellevue, QC, Canada, bernard.aube@envirobay.com
[2]Ontario Ministry of Mines, 933 Ramsey Lake Road, Sudbury, ON, Canada, stefano.cerilli@ontario.ca
[3]Anmar Mechanical & Electrical Contractors Ltd., 199 Mumford Rd Lively, ON, Canada, giulio.grossi@anmar.ca, riccardo.schiavone@anmar.ca

ABSTRACT

The MacLeod Mine, near Wawa, Ontario, was an underground iron mine operated by Algoma Steel until 1998. Since closure, the mine voids have been filling with acidic water containing high iron concentrations due to the presence of pyrrhotite. In order to protect the local environment, this water must be pumped out and treated to strict environmental requirements before discharge. In 2017, a high-density sludge (HDS) treatment plant was constructed to meet these high discharge standards. While the traditional HDS process was applied, this plant contained a number of innovative designs for improved operational efficiency and reliability. These improvements included a clarifier designed to deal with viscous sludge, positive displacement pumps for the clarifier underflow sludge, a lime slaking and slurry system design that improves reliability through a gravity-feed, peristaltic pumps for lime dosing, and an innovative design for the Lime/Sludge Mix Tank. After five years of operation, the success rate of these innovations is discussed. Also discussed are lessons learned for future improvements after dealing with issues regarding operation, the raw water feed, and grit management, for example.

Key Words: acid mine rock drainage, lime treatment, operational efficiency

INTRODUCTION

The MacLeod Mine, near Wawa Ontario was an underground iron mine operated by Algoma Steel until 1998. Since closure, the mine voids have been filling with acidic water containing high iron concentrations due to the presence of pyrrhotite. To protect the local groundwaters and surface waters, it was stipulated that the water level in the mine workings must be kept below the elevation of a local subsidence zone (Block D subsidence), which is a mining-induced rock failure zone visible as a large, caved-in area on surface. The subsidence zone intersects a local fault (the Walbank fault) which presents a potential conduit of underground mine water to Wawa Lake.

The water from the underground mine workings is pumped up to the treatment plant via boreholes that intersect the mine. The pumps are suspended in the boreholes on a vertical threaded pipeline. The pump intakes are set deep enough to try and maintain a consistent water quality as feed to the HDS plant.

The MacLeod Mine HDS treatment plant uses lime to precipitate metals out of the influent mine water. Once the raw water is treated and meets the discharge criteria, the treated effluent is piped to the Magpie River, at a 5 kilometer distance. The average raw water and treated effluent concentrations from 2023 are given in Table 1.

The MacLeod HDS Plant, shown in Photo 1, was designed to treat 295 m^3/h (1,300 USGPM or 4,921 L/m). Operations were planned to occur within a window from early spring to late fall, as needed to treat the required annual volume. Before construction, it was estimated that up 995,455 m^3 could require treatment, but this would also be a factor of the amount of precipitation received in the year. To treat this at the design flowrate would require approximately 5 months of operation annually, excluding down time and maintenance shutdowns.

Table 1. MacLeod HDS Plant feed and effluent chemistry

MacLeod Water Characterisation		Raw Water	Treated Effluent
Averages in 2023			
pH		5.7	8.2
Sulphate	mg/L	3821	3669
Fe	mg/L	442	1.3
Ca	mg/L	414	760
Mg	mg/L	469	406
As, Co, Cu, Ni, Pb, Zn	mg/L	<0.5	Non-detect

Photo 1. The MacLeod HDS Plant

HDS Process

The HDS process, as applied at MacLeod, is illustrated in Figure 1. In this process, lime is first contacted with recycled sludge from the clarifier in a “Lime/Sludge Mix Tank”. Sufficient lime is dosed here to neutralise the AMD to the desired pH setpoint, of approximately 9.0. Mixing the lime and sludge together forces contact between the solids and promotes coagulation of lime particles onto the recycled precipitates. This mixture then overflows to the Reactor #1 (R1) where pH is controlled and the precipitation reactions are initiated. As the MacLeod AMD contains principally ferrous iron, aeration is provided to the reactors to oxidise ferrous iron to ferric and form the more stable ferric hydroxide. With the lime particles and sludge particles coagulated, this promotes the precipitation reactions to occur on the surface of the existing precipitates in the reactors, thereby creating growth in particle size. This in turn increases the density of the produced sludge, reducing the volume of sludge waste that must be stored onsite. Promoting the precipitation reactions to occur on recycled particles also inhibits scale formation on reactor surface and impellers.

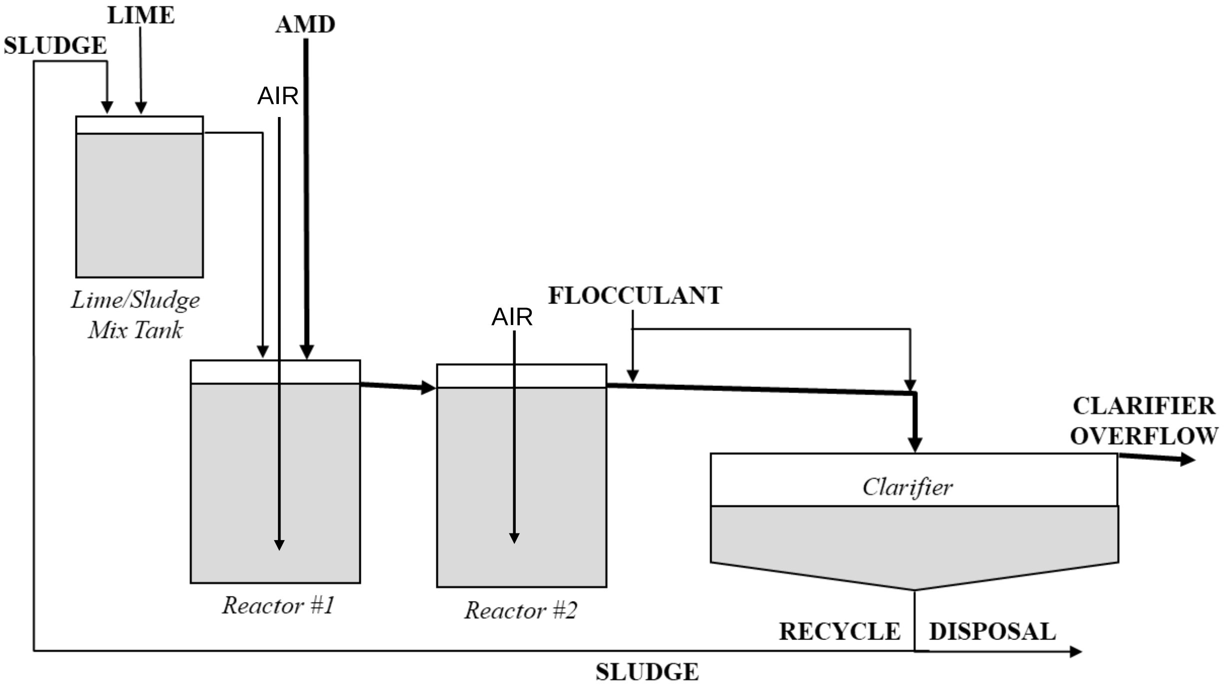

Figure 1. Illustration of the HDS Process as applied at MacLeod

The slurry then overflows to Reactor #2 (R2), to offer more retention time. Aeration is continued in R2, but there are no reagents or controls other than air.

The slurry overflowing from R2 is then contacted to a flocculant solution in a launder where some turbulence is provided, prior to reaching the center feed well of the clarifier. The flocculant serves to agglomerate all precipitates and promote efficient settling in the clarifier. The solids settle to the bottom of the clarifier to form a sludge. Clean and clear water overflows from the clarifier via an external ring containing v-notches along the entire clarifier circumference.

This clarifier overflow is collected in an Effluent Tank (not shown), where the pH and turbidity are continuously monitored in order to ensure quality of the treated water. When the pH is in the desired range (6.5 to 9.5) and the turbidity sufficiently low, the treated water is allowed to overflow to a Parshall Flume for flow measurement, then by gravity through the pipeline to the permitted discharge point in Magpie River. If the pH or turbidity are not within specifications, the off-spec clarifier overflow is instead directed towards the nearby Boyer Basin and into the mine workings, in a closed loop that eventually reports back to the feed. The target pH, besides the regulated limits, for confirmation of proper treatment, should be between 8.5 and 9.5. The turbidity is a proxy reading for total suspended solids, which must be of less than 15 mg/L.

The solids produced via precipitation in the process are mechanically “raked” towards the center cone of the clarifier as they settle. Below the clarifier, sludge pumps are used to draw this material and direct it continuously to the Lime/Sludge Mix Tank and periodically to purge it from the system and control the HDS plant sludge inventory. The sludge, consisting primally of ferric hydroxides and gypsum, is stored in nearby Boyer Basin, which is contained within the catchment area of the mine workings. Therefore, even though the sludge here is considered to be highly stable, any drainage in contact with it eventually flows back to the raw water pumps for treatment.

The HDS process presents significant advantages in operating costs over conventional lime addition, due the increased sludge density, decreased lime consumption, improved metal removal, and better solid/liquid separation (Aubé and Zinck, 1999). The higher sludge density means less waste is produced but also that more water is treated and released. Another advantage of the HDS process is that with proper design and operation, gypsum precipitation can also be optimised, which decreases the final concentration of sulphate in the treated effluent.

Background Chemistry

To neutralise the raw water containing sulfuric acid and high concentrations of iron, lime is used. The HDS plant uses quicklime (CaO) and the first chemical reaction to occur in the process, is the hydration of quicklime to hydrated lime ($Ca(OH)_2$) which produces a lime slurry. At MacLeod, a lime slurry of 10% to 25% is formed with a target of 20% solids. This lime is then dosed to Lime/Sludge Mix Tank to coagulate with the sludge solids, as explained in the previous section. In R1, this mixture is contacted to the raw water, where the lime dissolves (reaction 1) to precipitate primarily as ferric hydroxides (reaction 2) and gypsum (reaction 3).

$$Ca(OH)_2 \rightarrow Ca^{2+} + 2OH^- \qquad (1)$$

$$Fe^{3+} + 3OH^- \rightarrow Fe(OH)_3 \qquad (2)$$

$$Ca^{2+} + SO_4^{2-} + H_2O \rightarrow CaSO_4{\bullet}2H_2O \qquad (3)$$

DESIGN INNOVATIONS

In recent years, autonomous operation has become increasingly necessary to reduce costs and to compensate for the lack of availability of skilled operators. This has been compelling owners to automate their plants and operate remotely as much as possible. In order to enable this, systems must be as rugged and reliable as possible, requiring minimal maintenance and operator intervention.

This was the case for the MacLeod mine, where the basis for design was that the plant would have a single operator present five days per week, eight hours per day. This means that the plant would operate independently during evenings, overnight, and weekends. While an operator would always be on call, the plant was designed to shut down automatically for any critical problems, particularly those that could affect the effluent discharge quality. Unless levels were critically high in the shaft, the operator could resolve the problem during their next scheduled shift.

Over the past 30 years, efforts have been expended by the lead author to define weaknesses in mine water treatment plants with the aim of minimising costs and downtime. This started with an internal technical review and audit of 9 mine water treatment plants within the Noranda group in the 1990’s (Aubé, 1999b). These efforts to identify systems and equipment that fail, cause downtime, and increase operator maintenance have continued over years of operating, designing, troubleshooting, and optimising HDS plants globally.

The sections of HDS plants that typically cost the most downtime and maintenance are the lime and sludge systems. These are two problematic slurries for different reasons. For sludge, it is mostly related to the sludge viscosity. For lime, it is mostly due to grits. At MacLeod, another challenge was the minimisation of gypsum scaling in the 5-km effluent pipeline. The potential scaling issue, the different parts of the lime and sludge systems that can be problematic, and what was done to minimise these risks, are detailed in the sections below.

Gypsum Scaling

In a 5-km effluent pipeline, gypsum scaling is a significant risk because its accumulation can limit the flow and force a lower treatment rate. It is a very hard scale that is not easily removed by mechanical means. It is often easiest to replace the pipeline entirely, which is very expensive. At MacLeod Mine, the raw water sulphate concentrations have often exceeded 4,500 mg/L, while 2023 averages were 3,800 mg/L (Table 1). A high lime dosage is required to increase pH, neutralise acid, and precipitate metals, particularly iron. Sulfate and calcium (from lime) combine to form a significant amount of gypsum.

There are a few reasons why gypsum scaling is prevalent in mine water treatment plants. The problem is partly caused by the fact that gypsum is a slow-growing crystal. While the metal hydroxides formed in the plant will nucleate or form rapidly, crystalline precipitates tend to grow or form onto existing crystals. The gypsum precipitation reaction is much slower than that of hydroxide precipitation, often resulting in a treated effluent water quality that is super-saturated for gypsum precipitation. Because the calcium and sulphate tend to precipitate on existing gypsum crystals, it can cause growth on equipment surfaces, including pipelines.

Experience has shown that the best way to minimise gypsum scaling downstream of a lime treatment plant, is to promote gypsum precipitation in the process itself, and remove it from the system as part of the sludge. This will minimise the supersaturation level of the treated effluent. Considering the slow rate of precipitation and the tendency for gypsum to form on the surface of existing gypsum, promoting precipitation in the reactors requires the provision of greater gypsum surface areas and longer retention times.

Reactor Retention Times

The early HDS plants often had reactor retention times in the order of 20 to 50 minutes (Aubé, 1999a; Kuit, 1980). Since the turn of the century, the trend has been for longer retention times, particularly when sulphate is an issue (Aubé et al. 2018). The MacLeod HDS plant was designed to have two reactors, each with a one-hour retention time for a total of 2 hours. This allows time for the crystallisation reactions to occur, which increases the particle growth (and hence, sludge density) and decreases the effluent sulphate concentrations.

Sludge Recycle Rates

In order to increase gypsum surface areas and promote precipitation of calcium and sulphate, the sludge recycle rate needs to be maximised. Essentially, what limits the amount of sludge that can be recycled is the effluent quality. Higher sludge recirculation rates result in greater solid contents in the reactor slurry. If the reactor solid contents are too high, flocculation efficiency will be limited and solid-liquid separation will be incomplete, leading to high suspended solids in the clarifier overflow. Note that a setpoint reactor solids content is considered to be controlling mechanism for proper HDS operation (Aubé et al. 2018), replacing the old concept of “solids recycle ratio”.

The sludge recycle pumps at MacLeod were designed to provide sufficient sludge to have at least 35 g/L of solids in the reactors. This is because experience has shown that flocculation remains efficient at this solids content. With sludge density improvements and optimisation of other parameters in the system, it may be possible to increase the reactor solids content further and enhance gypsum removal without compromise on clarifier overflow suspended solids and effluent quality.

Lime System

The lime system includes the quicklime storage, slaking system, lime slurry storage, and dosing system. All these systems historically have challenges that can result in downtime and significant maintenance.

Quicklime Storage and Slaking

The MacLeod HDS plant uses quicklime (CaO) which contains grits – unreactive sand-sized particles of hard calcium carbonate or silicates. Typical quicklime quality in Northern Ontario can contain in the order 5% grits by weight. Although the slaking systems are normally equipped to deal with grits, they are not 100% effective and these particles tend to settle in difficult places. The lime is received from trucks and stored as a powder in a 104-tonne lime silo, from which it is transferred to a slaker by a screw conveyor to hydrate the quicklime, produce a lime slurry and remove the grits via an inclined screw. The product is transferred to a lime slurry storage tank while grits are accumulated in a bin and disposed of on-site. This equipment is shown conceptually in Figure 2, where the silo is outside, the screw crosses the building wall with the rest of the lime system all contained in the HDS building.

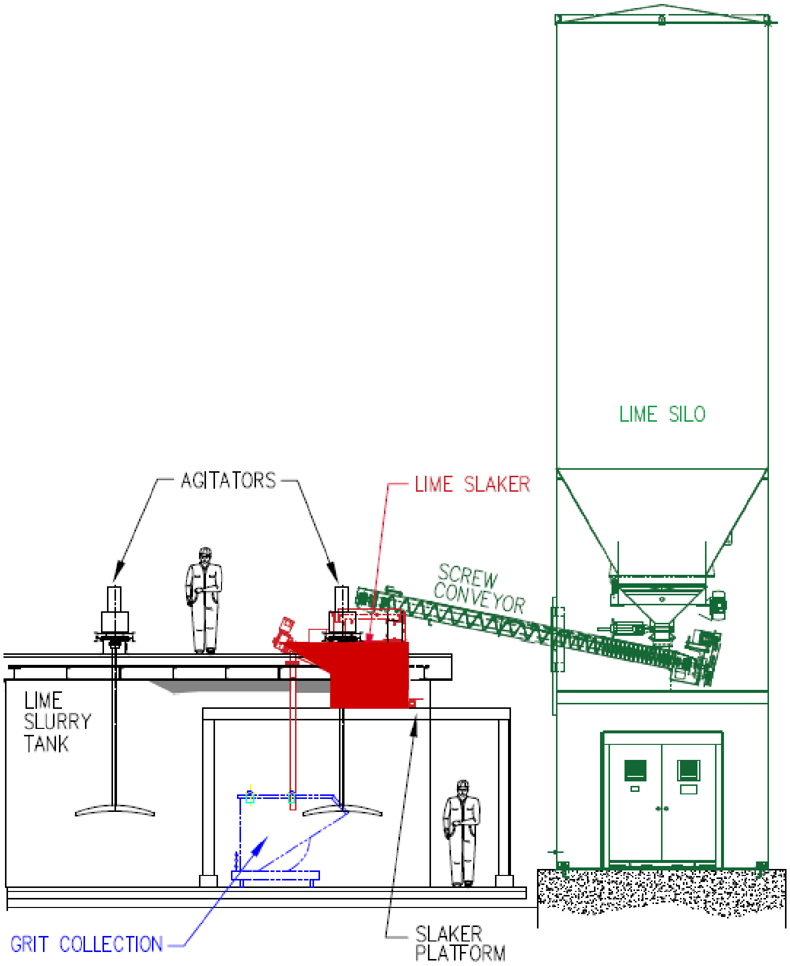

Figure 2. Lime silo, slaker, and lime slurry tank, front view

One of the most problematic areas of producing lime slurry is the transfer from the overflow of the slaker to the lime slurry storage tank. These often use small pump tanks and centrifugal pumps. Due to the small size of the tanks, the pumps speeds are often difficult to control to maintain a desired level in the tank, preventing either overflow or running the pump dry. The tanks often end up sanding up due to the small fraction of grits that by-pass the grit removal.

To circumvent this, some sites have opted to have an in-ground lime slurry storage tank and feed it from the slaker by gravity. While this works well, dosing the lime slurry in these cases has been done using inefficient cantilever centrifugal pumps and lime loops – as discussed in the dosing section.

At MacLeod, it was instead decided to elevate the silo, install the slaker on an elevated platform, and feed an above-ground steel tank by gravity. This also allows the grit removal screw (from the slaker) to drop the grits directly into a bin installed beneath the platform. Figure 3 shows a different perspective of the lime slaking and slurry storage system. By eliminating a transfer pump box and two pumps (one installed spare), the added cost of this design if mostly off-set. But the greatest advantage is in operation, where a problematic system is removed and the fresh lime slurry transfer is seamlessly done by gravity.

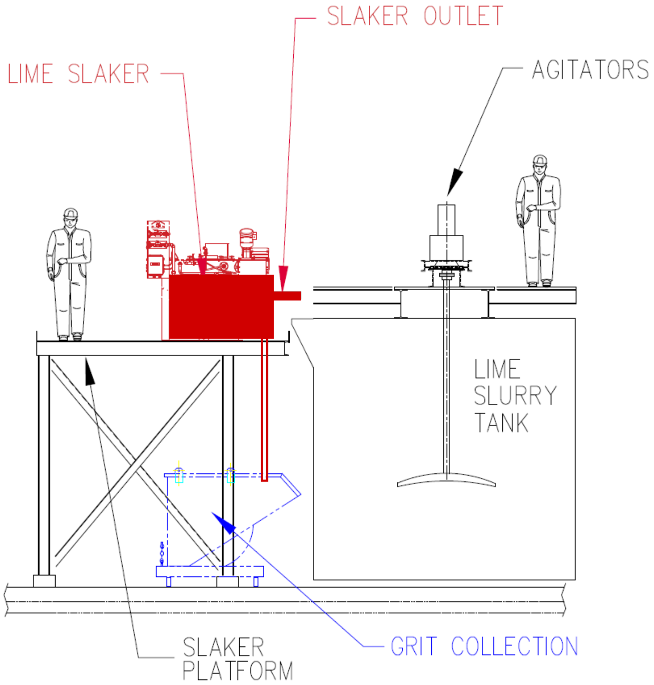

Figure 3. Lime slaker and lime slurry tank, side view

Lime Slurry Storage

The above-ground steel tank shown in both Figures 2 and 3, was designed to operate with infrequent batching. It is large, containing approximately 86 m^3, which allows for at least 8 hours of independence when the tank is full. This means that the plant can continue normal operation for a full shift while routine maintenance or troubleshooting is completed on the slaker, thus reducing downtime.

During start-up, the slaking rate was then set to be only slightly higher than the HDS lime consumption rate. This allows for batching to occur less than once per day. This is a key component to the design as quicklime slaking is inefficient during ramp-up of the slaker, which means that the lime slurry quality can be negatively impacted by frequent batching (slaker start/stop).

Lime Slurry Dosing

Conventional lime slurry dosing systems were designed using slurry pumps on a recirculating loop with a valve at the dosing point. Typically, these are pneumatic pinch valves operating on/off on a split-time proportional control. This is still commonly used in mining, as concentrators have multiple lime dosing points in the crushing and recovery circuits and this type of lime loop is an efficient way to deliver lime slurry to several locations. In contrast, as per theory and practice, an HDS plant has one single dosing point: the Lime/Sludge Mix Tank. By adding lime directly to reactors, you risk creating unwanted nucleated hydroxides, which can cause issues with settling and with sludge viscosity (as discussed later).

Although lime loops have advantages when multiple dosing points are used, when there is one single dosing point, the disadvantages become more important. The grits from lime tend to settle in problematic areas, particularly in front of valves that remain closed and in piping elbows. In order to minimise these settling problems, the standard is to provide a lime slurry velocity of at least 2 m/s in the pipe. This not only requires a lot of energy, but the aforementioned grits also tend to wear down the piping prematurely.

An alternative that has been applied at several sites for the past 15 to 20 years is to use variable-speed peristaltic pumps to dose the lime slurry. These are low-power, high-pressure, positive displacement pumps that simply and reliably deliver the lime in a straight line directly to the Lime/Sludge Mix Tank. The plant automatically controls the speed of the pump on a standard PID (proportional, integral, derivative) loop maintaining the pH within 0.15 pH units of the setpoint at the R1 overflow. There is no need to maintain a high velocity of the lime slurry as even small peristaltic pumps can provide very high pressures, thus preventing any clogging and pushing through any potential grit accumulation.

Another design feature applied at MacLeod is that there are two pH probes installed at the R1 overflow for pH control. The measured pH used to control the lime addition rate normally uses the average of the two probes, but can be set to use either one or the other during maintenance, calibration, replacement, or due to instrument failure. This allows for continuous normal operation at times when pH control would have been impossible had there been only a single probe. Although not always applied, this feature is not new (Aubé, 1999a).

Sludge Handling

The HDS process was named as such because it produces high density sludge, which when stored on site, can take less than 10% of the volume as compared to low density sludge. This is a very important advantage on the cost and liability of long-term sludge storage. The HDS process also maximises gypsum precipitation, which can be of critical importance in many situations where either scaling must be minimised or sulphate is a regulated parameter.

But the formation of a high-density sludge comes at a cost, as this sludge can be viscous and difficult to manage. There are three situations where this has been shown to be problematic in operating HDS plants: 1) the clarifier raking, 2) sludge pumping, and 3) in the Lime/Sludge Mix Tank. In the following sections, the root causes are discussed followed with the issues and design innovations for each of the three problem areas mentioned above.

Causes of Sludge Viscosity in HDS Process

There are three primary causes of high sludge viscosity: over-flocculation, mixed-particle sizing, and stagnant sludge. Over-flocculation can occur due to operator error or equipment issues. Mixed-particle viscosity can occur during plant upsets but also regularly occurs during plant commissioning or annual start-ups. As illustrated in Figure 4, low-density sludge, of less than 5% solids, is free-flowing. Shown at the bottom, well-established high-density sludge contains mostly dense particles that tend to respond more like a metallurgical slurry, with much less interaction between particles, and is therefore only slightly viscous. Mixed-particle viscosity occurs at mid-density (shown in the middle) while building up the high-density sludge, before sufficient established particles are recycled to the process to serve as precipitation sites for all new precipitates. The mid-density sludge cannot be avoided during build-up of the high-density sludge inventory. Process upsets or operator error can also cause the creation mixed-particle viscosity.

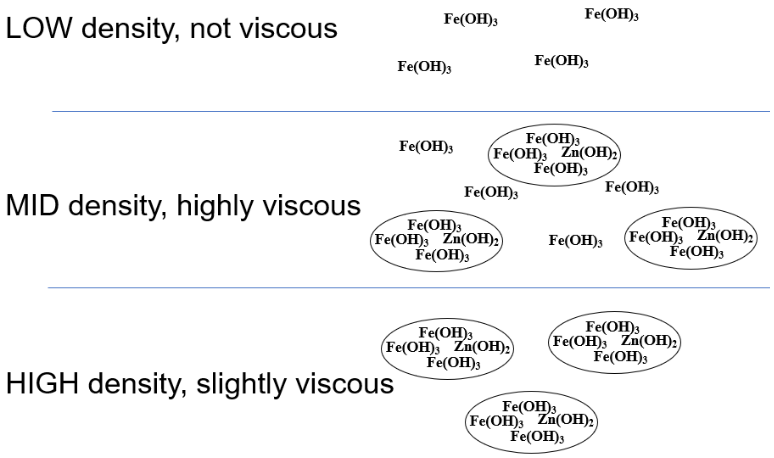

Figure 4. Conceptual representation of mixed-particle viscosity

The issue with stagnant sludge is due in part to the thixotropic nature of HDS sludge. Whenever this sludge is left stagnant, it congeals and consolidates to form a gelatine-like substance. When in constant movement, an established high-density sludge exhibits low viscosity, but if it is allowed to rest in a pipe, in a clarifier, or in storage, it essentially becomes a gel and is very difficult to pump. This can occur for example due to power outages that last more than a few minutes. In the design of an HDS plant, it is important that the sludge piping be maintained either in movement or drained. For this reason, whenever a sludge pump is shutdown, the line is automatically rinsed with treated water, then the drain valves are opened to leave the pipe empty. This rinsing cannot be provided during sudden power outages.

Proper automation and operator training can prevent viscosity due to over-flocculation. The two other potential causes of high viscosity cannot easily be avoided, as the ramp-up to form HDS is required after any prolonged shutdown and because power outages occur. In order to minimise downtime and maintenance, the solution is therefore to design the plant to be able to handle this type of sludge.

Clarifier Sludge Handling

Conventional water treatment clarifier rakes are designed to turn slowly and push the sludge towards the center cone at the bottom of the sloped clarifier floor. These are often outfitted with torque-controlled lift mechanisms to lift the rakes out of the sludge bed and prevent kicking out the drive. High torque is a risk in HDS plants because what is termed a “donut” can form. A donut occurs due to sludge viscosity, as the sludge congeals in front of the rake arms, and these start pushing sludge around instead of raking it toward the center. With the sludge on the clarifier bottom not flowing towards the center cone and the sludge recycle pumps operating, fresh slurry from the previous reactor ends up being drawn from center, creating what is essentially a hole in the middle, hence the name donut. It is also sometimes called ratholing and can cause the loss of steady state conditions in the process and affect pH control, subsequent sludge formation, and turbidity.

Any of the three major causes of viscosity can result in donut formation and the problem is not only self-sustaining, but even self-aggravating. This is because the resulting recirculation of fresh particles, essentially low-density sludge, from the center cone of the clarifier results in mixed-particle viscosity (Figure 4).

To minimise the risk of donut formation, three conventional designs were modified:

1. The bottom slope was increased from the standard 1 in 12 (4.76°) to 1 in 6 (9.46°);
2. The rake drive was provided with a variable-frequency drive; and
3. The distance between rake blades was increased, removing any overlap.

The increased slope of the bottom helps propel the sludge towards the center cone. This modification is one that has been applied in the past and follows trends in the metallurgical industry where high-rate thickeners have had increased slopes as compared to conventional thickeners.

Providing the rake drive with variable speed allows the speed of the rakes to be optimised with the process. The rake drive pushes the sludge solids towards the centre cone at a rate proportional to its speed and the angle of the rake blades (in this case, 45°). If the rake is too slow in comparison to the sludge removal rate (controlled by the sludge recycle), undensified slurry can be drawn by the recycle pumps and cause mixed-particle viscosity. If the rake is too fast in relation to the pumping rate, the sludge can accumulate in the center bottom and require a higher purge rate – which in turn can prevent the sludge density from attaining optimal or target densities. Detailed calculations are possible, but essentially, trial and error during operation can be used to find the “sweet spot” for the clarifier rake drive.

Removing the overlap between rake blades is a key innovation not previously applied in HDS plants. This strategy had been applied for a different water treatment process at Bloom Lake Mine in 2013 (Aubé et al. 2014). Standard rake designs have blades that are positioned at near 45° angle, are often curved, and tend to overlap. This means that when the rake arm is viewed from the front, you do not see the far end of some blades as they are behind the front end of the next blade. When sludge viscosity occurs, this design promotes the formation of a donut as sludge can accumulate in front of the rake arm and move with the rake instead of being moved towards the center cone.

To minimise this risk, a space was left open between the rake blades. This ensures that some of the sludge will flow through the blades as one rake arm passes. The placement of the rake blades on the following arm are staggered to ensure that the entire clarifier bottom is raked at least once per revolution.

Sludge Pumps

In conventional designs, the clarifier underflow sludge pumps were typically standard centrifugal slurry pumps as per those used in mine concentrators (typically known as SRL “slurry rubber lined” pumps). The accepted belief was that, as those pumps can easily convey slurries of 60% solids in the mill, they should not have issues with 20 to 30% sludge from a treatment plant. Unfortunately, due to viscosity, this is not the case. Standard SRL pumps do not provide sufficient suction to deal with issues like stagnant sludge or mixed-particle viscosity. Still today, some designers suggest that when viscosity issues occur, the solution is to simply add water on the suction side in order to dilute the sludge and render it pumpable by a centrifugal pump. This not only defeats the purpose of the HDS process, it is a manual, problem-related temporary fix to a common issue, while preventative measures are preferred. It will also affect the reactions occurring in the Lime/Sludge Mix Tank and can impact pH control.

Instead, a fully automated and reliable option is to use positive displacement pumps. At MacLeod, progressive-cavity pumps were chosen for the purpose. In a smaller plant, peristaltic pumps may be chosen, but these are large and were too tall for the planned clarifier tunnel, given the sludge recycle design flowrate of 45 m^3/h. While these pumps are more expensive than SRL pumps at purchase, the savings in reliable and unattended operation pay off the difference in costs quickly.

Lime/Sludge Mix Tank

As stated in sections above, the lime slurry can be problematic to handle and the sludge is certain to be difficult to manipulate at certain stages. In this vessel, those two problematic slurries are mixed together to form an even more difficult mixture. Lime/Sludge Mix Tanks have traditionally been equipped with conventional axial agitators. Experience has shown that this often resulted in only a small part of the tank remaining active while part of the Lime/Sludge mixture would congeal along the walls of the tank. Occasional sloughing off of these congealed solids could cause the riser or exit channel of the vessel to get plugged up. Many HDS plant operators have learned that continuous operation with good pH control requires frequent regular cleaning of this tank as a preventative measure.

To allow for lower maintenance and remote operation, this tank was designed differently and equipped with counterflow agitation. Counterflow impellers have a larger diameter and instead of only pumping the slurry down towards the center of the vessel (as per axial agitators), the external ends of the counterflow impellers pull the slurry up. The agitator was equipped with two impellers at different depths. This design imparts more energy to the slurry and maintains a larger fraction of the tank active, preventing the lime/sludge mixture from congealing along the tank walls.

As illustrated in Figure 5, the vessel was also equipped with a feed well (30 cm depth) to ensure that the lime and sludge were put in contact from the very beginning and to prevent any risk of short-circuiting. There are four pipes coming into the feed well as both the lime and sludge have completely independent piping related to each of the pumps. The two larger orange ones are the sludge recycle and the two smaller ones are lime. The riser (or upcomer) was designed very short (15 cm depth) to prevent any risk of plugging or congealing in this part of the tank.

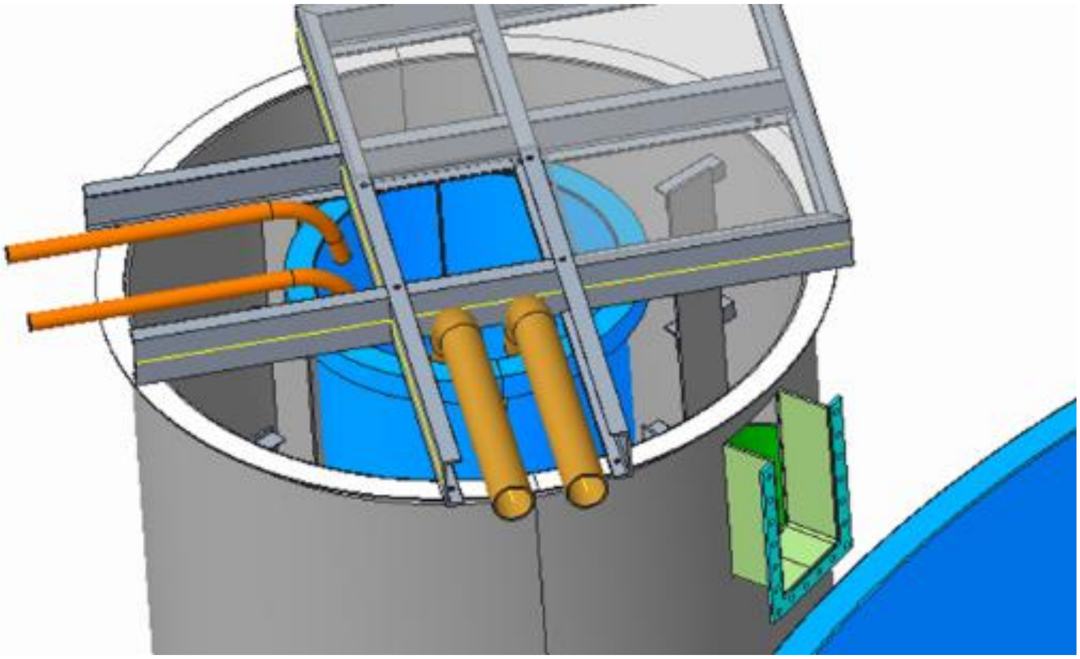

Figure 5. Innovative design of the lime/sludge mix tank

Overall, this design forces the lime and sludge to mix and be in full contact immediately upon entering the tank. The counterflow impeller ensures that this mixture flows to the bottom of the tank and is fully contacted before any slurry can overflow.

OPERATION RESULTS

Challenges arise when operating water treatment facilities on abandoned or closed mine sites. The reduced availability of a workforce, equipment, and site access challenges are drivers for innovation. As stated earlier, the MacLeod HDS plant was designed to operate with an operator present only on a Monday to Friday, 8-hour per day schedule. With the exception of plant start ups or shutdowns the plant has operated successfully under this schedule since 2018.

Overall, operations have been very successful as the water level in the mine workings has been maintained, the plant has operated semi-autonomously, and the discharge to the Magpie River has consistently met the regulatory permits. These objectives were met despite the fact that the raw water concentrations have doubled over the design concentrations, which had been based on pilot tests done 2 years prior. This means that the lime consumption rates and sludge production rates roughly doubled from the initial design criteria for the plant. The flexibility, contingency in design, and robustness of the HDS plant has allowed for continuous operation despite this unexpected increase in raw water concentrations.

Some challenges have been encountered during operation; these are discussed in the sections below, as well as how the design modifications have held up.

Operating Challenges Encountered

Specific operational challenges are listed below, but one of the greatest challenges is operation itself. It is not a simple task to recruit qualified personnel for operating a remote HDS plant with no other activities on site. With the current shortage of qualified personnel in all aspects of mining (among others) the MacLeod HDS plant has also been faced with difficulties. It took more than two years of operation to eventually establish steady reliable operation. In these first two years, there were operator errors encountered, negligent equipment maintenance, and poor communication. Some of the maintenance issues that were neglected may have reduced the expected life of equipment parts.

Raw Water Pumps

The most important cause of downtime in the MacLeod HDS plant in its first five years of operation has been the raw water pumps. There have been pump failures and times where the pumps could not provide the required flowrate to discharge the targeted volumes. One of the reasons downtimes have been important is that new parts have been needed at times and because external equipment and operators are required to pull the pumps up the well. Obtaining fast delivery or service has at times been complicated by availability issues due to the COVID-19 pandemic.

The choice and design of the pump systems were not part of the mandate of the authors of this paper. The problems with the pumps themselves are not completely understood but the higher than expected concentrations of iron in the raw water may have played a part, because the inlet screens have been shown to be clogged up upon inspection. Some problems are thought to be related to the power sourcing design, the types of cables, connections, and clamps used. Reactions with the materials may also be occurring, resulting in ferrous iron oxidation and precipitation.

As the raw water pumping is not yet optimised, there are on-going attempts to rectify the situation. These attempts are under study and may include changing the type of the pumps; putting in a permanent sheltered hoist and support system to remove or replace the pumps by the operators themselves; or changing the depths at which the pumps are located.

Grit Removal

The second most important challenge has been related to grits from the quicklime. It is unclear if the quicklime delivered has contained more grits than what was expected, but it is clear that the grit removal system integrated with the slaker is no longer performing as required. Operators have pointed out that the flights on the grit screw may be worn down to a point that it no longer performs as expected and removes only a fraction of the grits. This screw is to be replaced and it is believed that more frequent inspection and potentially regular replacement of the screw will solve the issues related to grits. As discussed below, the lime system itself has not shown any problems handling the excess grit, but it does impact the longevity of the sludge recycle pumps.

The issues with the slaker may in part be due to poor maintenance, particularly in the first two years of operation. Improved operation of the slaker and grit removal is to be a focus of the 2024 operating season.

Total Suspended Solids

Although the effluent has been maintained within regulatory limits, the total suspended solids (TSS) in the final effluent has been high. The TSS limits for MacLeod have both a grab sample limit of 30 mg/L and a monthly average limit of 15 mg/L. The monthly limit has been exceeded on grab samples, suggesting that this can be optimised. As discussed below, the sludge recycle pumps required maintenance due to wear and in 2023 could not recycle the amount of solids for which the plant was designed. This may have affected the solid-liquid separation efficiency.

Also due to low recycle, the sulphate concentrations were not brought down as low as expected. This suggests the possibility that the laboratory TSS results may not be entirely representative, because gypsum precipitation may have continued in the sample. Samples collected for TSS are not acidified or preserved in any way. Precipitation of gypsum can occur in treated water samples with high calcium and sulphate concentrations. This is to be investigated – samples can be measured for TSS immediately on site and compared with laboratory results taken at their usual delays.

Despite this possibility, efforts have been made to improve effluent TSS through cleaning process equipment such as the clarifier overflow launder and improving the flocculant formation and dosage. These measures have shown improvements at least on site.

Gypsum Scaling Measures

The amount of gypsum scaling in the effluent piping has not caused any issues to this date. This suggests that the increased sludge recycle and longer retention time in the HDS design have served to minimise gypsum scaling in the effluent, as desired. Unfortunately, there is no way to know what would have occurred without these measures, as every site is different with their own specific chemistry. That said, there are examples of other sites with similar raw water sulphate concentrations that have had issues with scaling in the effluent in the first five years of operation.

Sulphate removal performance in the HDS plant was less than expected in 2023, the year being used here for evaluation. The problem indirectly relates back to the grit removal and inadequate preventative maintenance. The sludge recycle pumps, being progressive cavity pumps, are excellent for pumping sludge but can wear when confronted with abrasive media like lime grits. While operation continued, due to this wear on the rotor and stator, the pumps could not provide the required flowrates to attain the target of 35 g/L of solids in the reactors (2023 average, 12.5 g/L). As shown by the sulphate concentrations in Table 1, there was only 152 mg/L of sulphate removed in the process. Previous years had better removal and this would be expected to be at least 500 mg/L in optimal operation.

Sludge Handling Measures

It should first be noted that sludge densities of more than 30% solids have been produced in the plant, in part due to the very high iron concentrations in the raw water, as well as the design of the plant itself. This means that the modifications made to the MacLeod HDS plant have been demonstrated as effective.

Lime/Sludge Mix Tank

The Lime/Sludge Mix Tank has performed as designed and has not required frequent cleaning or caused plant stoppages. This design, which has since been applied at another HDS plant, is an important improvement over the conventional designs.

Clarifier Sludge Handling

The rakes have been successfully conveying the sludge to the center well. While an operator error once allowed the sludge inventory to nearly fill up the clarifier, the clarifier modifications and the rakes themselves have proven to handle sludge viscosity well.

Sludge Pumps

The progressive cavity pumps have been reliable and have not required any sludge dilution to pump back the required volume of sludge, even at times of mix-particle viscosity. This is, as mentioned previously, until 2023, when the wear on the rotor and stator became important enough that the pumps could no longer provide the required flowrates.

The wear on the progressive cavity pumps is believed to be partly due to inefficient grit removal in the lime system. A large amount of abrasive grits would also have worn down impellers for other types of pumps, including the conventional SRL pumps. In both cases, the solution is to periodically inspect and replace the parts that are wearing out. This is part of normal operations with periodic replacement of wear parts. The state of equipment should be monitored more closely to replace these parts before they affect treatment.

Another type of pump that can handle both high viscosity and grit content is a peristaltic pump. As mentioned, the peristaltic pumps that would have met the needs at MacLeod would have been more expensive but also much taller. The physical height of these pumps would have required that a much larger space be made available under the clarifier, which would have impacted costs significantly. In other cases where the height is not an issue, peristaltic pumps should be considered for sludge recycling in an HDS plant. These have been shown to work well at some smaller HDS plants.

Another type of pump being investigated at a different mine water treatment plant is lobe pumps. These pumps are much smaller than peristaltic and are reputed to being capable of handling some abrasives when the right materials are used for the lobes. The authors are not aware of lobe pumps currently in use at any existing HDS plants.

Lime System

It is clear that the increased height of the silo and the gravity feed of the lime slurry storage tank have been very successful in removing a potential bottleneck in the production of lime slurry. By far, the greatest issue in the lime system has been related to the lime slaker itself. This is an off-the-shelf detention slaker of a type and model that has been in application worldwide for more than 30 years. It is proven to generally work reliably, with regular maintenance and replacement of worn parts. But lime is difficult to handle and all slakers require regular maintenance. It is suspected that, during the first two years of operation, the slaker operation and maintenance was less than ideal. This could have caused premature wear of some slaker parts (i.e. the grit screw) as well as allowing grits to enter the HDS process and affect other parts of the plant.

Despite issues with the slaker and grit removal, the large lime slurry tank has allowed for continuous operation during numerous slaker stoppages for troubleshooting and cleaning.

The peristaltic pumps delivering the lime have been operating very well at controlling pH and seamlessly handle the abrasiveness of the grit. The primary maintenance this system has required is occasional replacement of the pump tubing, which is an easy replacement accomplished by a single operator. It is clear that this lime dosage system is considerably more reliable and requires less maintenance than the conventional lime slurry loop.

CONCLUSIONS

Overall, the MacLeod HDS plant treated the required annual volumes and met discharge requirements, despite raw water iron concentrations double those expected at the design phase. As with any water treatment operations on closed mine sites, there are challenges.

All of the measures applied have been shown to decrease maintenance and downtime as compared to conventional designs. The gravity feed for the lime system, the large lime slurry storage tank, and peristaltic pumps have been shown to be considerably more reliable than conventional designs.

The innovative design of the Lime/Sludge Mix Tank has performed seamlessly, ensuring proper mixing, preventing the need for frequent cleaning, and eliminating the risk of plugging.

The progressive cavity pumps for sludge recycling have performed well in the first few years of operation but have shown wear due to the abrasiveness of the grits from lime. While their performance significantly exceeds what would be expected from conventional centrifugal pumps, other options could be evaluated for future plants. Perhaps the progressive cavity pumps remain the best choice, but must have regular replacement of the rotor and stator built into the preventative maintenance and operating costs.

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