# Oversized HDPE liners to combat internal corrosion and erosion in mining industry pipelines

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## Abstract

Internal corrosion and erosion of carbon steel pipelines in the mining industry have been analyzed and modeled for years in the hopes of determining the most practical and economical means of mitigation for a particular application. While there are many options available to mitigate, control, prevent or eliminate internal corrosion or erosion in mining industry pipelines, the use of tight fitting, oversized high density polyethylene (HDPE) liners has proven successful at combating both corrosion and erosion in specific circumstances throughout the world over the past 25 years.

Not only is high density polyethylene resistant to a broad range of chemical and biological attack, its physical properties are often favorable for increased resistance to erosion compared to bare carbon steel. Furthermore, the extrusion process of manufacturing HDPE liners creates a significantly smoother pipe wall surface than new carbon steel which can lead to improved flow characteristics and lower pumping costs for a pipeline. Finally, HDPE resin is a global commodity and is generally available at a cost comparatively lower than other corrosion and abrasion resistant alternatives.

This paper examines the use of oversized HDPE liners in corrosive and abrasive applications, provides a comparison with other alternatives, discusses improvements in the industry, and briefly describes the first use of oversized HDPE liners in Brazil.

## Nomenclature

| | |
|---|---|
| **t** | HDPE liner wall thickness (mm) |
| **E** | HDPE liner Young's modulus (MPa) |
| **R** | Average radius of HDPE liner (mm) |
| **Pc** | Collapse pressure (bar) |
| **p** | Absolute pressure (pascals) |
| **V** | Volume (cubic m) |
| **n** | Amount of gas (moles) |
| **R** | Universal gas constant (J/ºK mol) |
| **T** | Temperature (Kelvin) |

# Oversized HDPE Liners to Combat Internal Corrosion and Erosion in Mining Industry Pipelines

## 1. INTRODUCTION

Internal corrosion and erosion of long distance, carbon steel, slurry pipelines have been a concern of the mining industry since this mode of transport came into existence over 40 years ago. Combating internal corrosion and erosion has required significant financial and intellectual investment along with ongoing operational and maintenance diligence. Even then, inspection of pipeline internals is difficult and costly to accomplish leaving an ongoing risk of expensive shutdowns, repairs, or sometimes priceless leaks and environmental damage. While there are many alternatives to preventing, mitigating, controlling, and allowing for internal corrosion and abrasion, the use of polymeric liners has proven to be very effective at internally protecting carbon steel pipelines and providing significant life-cycle cost advantages. High density polyethylene (HDPE) is often the material of choice for thermoplastic lining due to its excellent chemical and abrasion resistant properties along with global availability and a comparatively low cost. As such, the use of interactive, oversized HDPE liners is utilized in higher pressure corrosive and abrasive applications often found in slurry transport pipelines. These applications typically include abrasive tailings lines and pipelines containing corrosive concentrates, acid, pregnant leach solution, and water.

## 2. HIGH DENSITY POLYETHYLENE LINER BACKGROUND

Although the problem of internal corrosion and abrasion has been an issue worthy of consideration since pipelines were utilized for slurry transport, the use of HDPE liners did not begin to reach prominence until the early 1990s. Smaller projects were completed for a Newmont Gold tailings line and a Kennecott copper concentrate line in the United States. Then in 1994/1995, a 167 km x 9 5/8" OD high pressure (3700 psig design) copper concentrate slurry pipeline was lined with an oversized HDPE liner. This was a direct result of the internal corrosion experienced in Mina Escondidita Limited's first bare steel pipeline installed in 1989 (1). Use of an oversized HDPE liner system resolved or mitigated many of the previously existing operational issues including:

- Heavy internal scaling
- Acid cleaning of the pipeline
- Galvanic corrosion during extended downtime
- Microbiologically Influenced Corrosion (MIC)
- Excessive wear in the six-o'clock groove and slack flow areas

Since that time and successful installation and operation, oversized HDPE liner use has expanded in Chile, Argentina, Peru, Columbia, and across the globe. Significant projects of note include but are in no way limited to Antamina (301 km x 8" - 10" in Peru) (2), Century Zinc (303 km x 12" in Australia) (3), Collahuasi and Pelambres (Chile) as well as additional installations in Canada, China, Indonesia, Madagascar, and on the North Slope of Alaska.

## 3. BENEFITS OF OVERSIZED HDPE LINING

HDPE liners have been used for decades to line carbon steel pipelines for protection against a corrosive or abrasive attack. The global acceptance and increasing use of oversized HDPE liners should come as no surprise. First and foremost, HDPE is a comparably inexpensive and readily available material with excellent chemical-, corrosion-, and impact-resistant properties. HDPE -- typically specified as ISO PE-100 or ASTM PE 4710 -- is chemically resistant across a broad range of chemicals, and its physical properties are often favorable for increased resistance to erosion compared to bare carbon steel. Additionally, the polymeric nature of HDPE and the resulting properties lends itself to use as a means of rehabilitating existing pipelines since HDPE is excellent for bridging holes and spanning gaps often caused by corrosion and erosion. In addition to eliminating corrosion and reducing abrasion within the carbon steel pipelines, HDPE lining can also improve the flow characteristics of the pipeline because although there is a slight reduction in pipeline inside diameter (ID), the inner wall of newly extruded HDPE is smoother than new carbon steel. This advantageous comparison has often and empirically been found to hold true over the life of a pipeline.

### 3.1 Chemical resistance

For chemical resistance, the Plastics Pipe Institute (PPI) provides six dense pages of tables (4) to document the chemicals against which HDPE is resistant to attack in varying degrees. HDPE is a high molecular weight, non-polar, paraffin hydrocarbon. This leads to its high chemical resistivity especially versus salts, acids, and alkalis over a broad range of temperature and duration of time. In comparing HDPE to other thermoplastic piping material (5), thirty eight pages are provided by the PPI. While HDPE is not resistant to all chemical attacks, it performs exceedingly well in acid service at the concentrations usually encountered in industrial/mining applications. In fact, HDPE containers are often utilized for the storage and transportation of acids.

### 3.2 Abrasion resistance

Oversized HDPE liners were initially developed to prevent internal corrosion in oil & gas fields, but the excellent abrasion resistance properties of HDPE make it a reliable and now proven method of internally protecting pipelines from corrosion *and* abrasion under the appropriate conditions. Although the wear rate of a slurry pipeline is affected by factors including size, shape, and concentrations of solids as well as fluid velocity, fluid flow characteristics and angle of impingement, laboratory tests have shown the HDPE wear resistance "to be three to five times longer than normal or fine-grained steel pipe at a typical velocity of under 15 ft/sec" (6). Numerous studies have been conducted regarding the wear rate of certain materials, including HDPE, and under different conditions (6, 7, 8). This speaks to the huge economic impact of extending the service life of slurry pipelines, and the performance of HDPE in these studies oftentimes illustrates the economic value of an HDPE liner in slurry transport pipeline service.

The Saskatchewan Research Council tests used a coarse silica sand slurry (D50 = 0.58mm; 30 mesh, 3mm; 40% by weight in a water slurry) pumped at velocities of 7 fps and 15 fps in a closed loop of test pipe.

**Table 1. Wear rates of HDPE and steel under abrasive slurry**

| Wear Rate (mm) | | |
|---|---|---|
| **Material** | **Coarse Sand** | |
| | 15 fps | 7 fps |
| Steel | 1.81 | 0.65 |
| Polyethylene | 0.46 | 0.06 |

From the Schreiber and Hocheimer study regarding the effects of bends (straight pipe to 6D bends) on the relative wear rates for HDPE and bare steel, tests were conducted with 7% and 14% by volume quartz sand to water mixtures with an average flow velocity of 23 fps. Although real concentrations today are generally higher, HDPE was found to have a wear resistance about four times better than steel in this particular study (9). More recently, a paper was written specifically regarding the wear rate prediction for long distance slurry pipelines (10), and this study took into account that wear is a combination of both chemical corrosion and mechanical abrasion. Furthermore, it highlighted that the wear rate can change over the length of a pipeline due to a reduction in oxygen concentration and solids' sharpness reduction and degradation.

### 3.3 Surface roughness

The corrosion and abrasion resistant barrier that is the oversized HDPE liner does come at the cost of a slightly reduced inside diameter compared to a bare steel pipeline. Fortunately another beneficial property of HDPE is the smooth inner wall created by the liner. Extruded HDPE liner has a surface roughness that approximates drawn tubing, and this is approximately 30 times smoother than that of new commercial steel (11).

**Table 2. Values of surface roughness**

| Material | Surface roughness (mm) |
|---|---|
| Drawn Tubing (Brass, Lead, Glass, and the like) | 0.00152 |
| Commercial Steel or Wrought Iron | 0.04570 |

For the vast majority of slurry pipelines, the fractional loss in ID is more than offset by the large reduction in surface roughness of the inner wall. This results in improved operating efficiencies for the pipeline with all else remaining equal. Over the life of the pipeline operation, there is some recent debate as to the extent HDPE liners are expected to prevent scale deposits due in part to the very smooth surface (3). There is no debate, however, that corrosion of the steel pipe increases the roughness of a steel pipeline while an HDPE liner resists corrosive attack and retains its smooth surface especially in fine slurry (-100 mesh or < 0.15 mm particle sizes) service. The qualitative beneficial effect this would have on pumping costs over the lifetime of a pipeline's operation is evident.

### 3.4 Biological resistance

The problem of bacterial corrosion does not appear that frequently in slurry transportation pipelines; however when MIC appears in any pipeline service, preventative, downtime, and maintenance costs can be astronomical. Suffice it to say that HDPE liners are resistant to biological attack since polyethylene is not a nutrient medium for bacteria, fungi, and the like. Furthermore, HDPE lining has proven itself time and time again in the oil & gas industry as an effective method for not only preventing MIC in newly constructed pipelines, but also for rehabilitating existing pipelines that have been compromised by bacterial corrosion despite the best and costly efforts of chemical biocide treatment.

## 4. DESIGN CONSIDERATIONS

### 4.1 Specifications

For interactive, oversized HDPE liners, it is important that the liner is custom sized for the specific pipeline(s) under consideration. By definition, an oversized HDPE liner is designed and manufactured with an OD larger than the ID of the host pipe to be protected. Based on the ID of the host pipe, the appropriate HDPE liner size is calculated, and the HDPE wall thickness can be determined based on extrusion capabilities and the desired service application. To save raw material cost of the HDPE liner (namely, the amount of HDPE resin required) the thinnest practical wall thickness is usually chosen. Limitations are encountered, however, during the HDPE extrusion process in determining the actual minimum allowable wall thickness. If an industry "standard" exists, interactive HDPE liners are typically extruded with a desired Standard Dimension Ratio (SDR) of OD to wall thickness around 41. This is more difficult to achieve for smaller diameters (2" to 8" or so) and easier to meet and exceed for larger diameter HDPE liners.

While the minimum wall thickness is often a function of manufacturability, there is usually an option to provide a thicker HDPE liner if the pipeline design engineer desires for reasons such as:

- Optimum fluid velocity
- Increased protection from abrasion
- Increased collapse resistance

It is important to note that for nearly every HDPE liner installation in the mining industry, the OD of the liner should be larger than the ID of the host pipe. This results in the HDPE liner operating in the hoop-compressive state. This also results in the highest surface friction at the interface between the liner and the host pipe which, in turn, prevents the axial extension caused by the greater thermal expansion of the HDPE vs. the steel host pipe. Additionally, oversized liners possess the highest radial critical buckling pressure (12, 13) compared to close- or loose-fitting HDPE pipe liner.

If liner collapse and/or accelerated wear are critical design considerations, oversized HDPE lining technology obviously allows for an increase of the HDPE wall thickness. Wang, Mason, and Yu illustrate that "the critical liner collapse pressure increases monotonically with increasing tightness" (13), and for tight-fitting HDPE liners, design and engineering practice in the oil and gas industry considers that:

$$\mathbf{Pc \propto E(t/\underline{R})^2} \qquad \mathbf{[1]}$$

rather than the cubed relationship of Timoshenko's classical formula. By virtue of increasing the wall thickness, the inherent collapse resistance of the HDPE liner is also increased. Young's modulus, **E**, may not be considered as well defined by some, but it is undoubtedly an inverse function of temperature such that collapse pressure decreases at higher temperatures without a corresponding increase in HDPE wall thickness. This issue, however, is of greater concern when

HDPE is being used in pressure containing service such as in either a stand-alone or a "slip lining" application. In slip lining, the HDPE OD is smaller than the existing host pipe ID, so that the host pipe essentially acts as a conduit for a smaller diameter, fully structural HDPE pipe. Hoop strength of HDPE is considerably lower than carbon steel, so the HDPE pipe must be very thick to contain increasing amounts of pressure, and the pressure rating of the HDPE is lowered at temperatures above ambient conditions. Additionally, in slurry applications, erosion can cause a reduction in HDPE wall thickness thereby necessitating a reduced maximum allowable operating pressure and corresponding reduction in flow. For these reasons, the use of interactive, oversized HDPE liners is recommended in higher pressure corrosive and abrasive applications often found in mining industry pipeline service including those transporting tailings, corrosive concentrates, acids, pregnant leach solution, and/or water.

### 4.2 Length

Unlike bare welded steel, the HDPE liner can not be installed as one complete, long distance protective barrier. Installations need to be broken into separate "pull lengths" joined together by connections along the pipeline route into one long distance slurry pipeline. The lengths of the individual pull sections vary widely based on numerous factors including but not limited to: pipe diameter, internal condition of pipe, quality of steel welds, pipeline bends, elevation changes and degree of change, as well as any existing valves/fittings, etc. Pull section length can range from 500 m to 1.2 km although longer and shorter pulls are possible.

### 4.3 Bends

Pipeline bends are a necessary consideration of most pipelines. For coarse slurry pipeline design, bends create an area of accelerated wear both at the bend, itself, as well as in the area closely downstream of the bend. With HDPE lining, the concern regarding accelerated wear is combined with the potential for shortened installation lengths or the outright inability to field install the liner (depending on the severity of the bend). If a slurry pipeline is normally designed with a minimum bend radius of 20D (10), installation of an oversized HDPE lining is feasible although pull section length may need to be shortened. Tighter bends may be possible but at a definite cost of shorter installation lengths. Otherwise as a rule of thumb, if a host pipe contains field constructed bends, field installation of oversized HDPE lining will be possible.

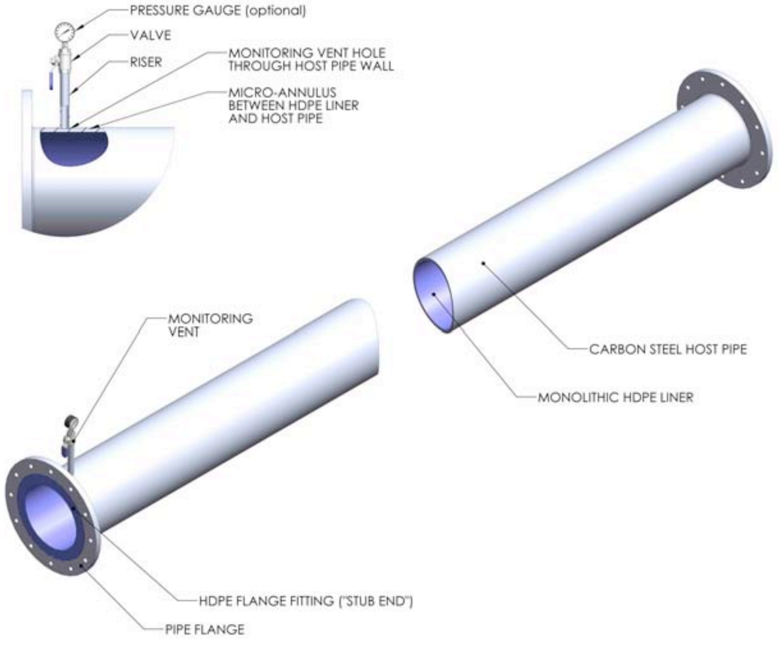
## 5. INSTALLATION

Before field installation can begin, a steel pipeline must be constructed using traditional methods and *almost* as though no HDPE liner will be installed in concert with the steel. Then, the new (or existing) host steel pipeline is sectioned to allow for the insertion of the HDPE liner, and connections are welded into place. Once the HDPE liner is manufactured and delivered to site for the field installation, the short (12 m to 18 m or so depending on road or rail transportation limitations) individual liner lengths are thermally fused into long, monolithic sections particular to each length of host pipe previously constructed and sectioned to accept the HDPE liner. The external thermal fusion weld beads are removed and inspected, and for slurry service, the internal weld beads are typically removed/inspected as well. A blow-down pig and sizing plate are then attached to a cable and sent through a particular section of the host pipeline. Once the blow-down pig reaches the other end, the section of pipe is ready for HDPE liner installation since the steel sizing plate confirms a clear path. The cable is then attached to a fabricated pull-head on the corresponding length of HDPE liner pipe to install the liner.

A specially constructed winch or wireline then pulls the oversized HDPE liner through a specially designed diameter reducing mechanism. This mechanism may be either fixed or may have moving functionality such as with the roller reduction process. This mechanism is positioned at the insertion end of the host pipe usually in direct line with the host pipe entry point either above or below grade. The HDPE liner is temporarily compressed radially as it passes through the diameter reducing mechanism, and it is also placed under axial tension via the wireline pulling it through the equipment and into the host pipeline. Both of these effects cause temporary reduction of the HDPE liner OD so that it may fit inside the otherwise impossibly small ID of the host pipe. Even after the HDPE liner pipe exits the diameter reducing equipment, the thermoplastic properties of HDPE as well as the continuing axial tension of the wireline prevent the HDPE from immediately returning to its original OD.

Once the HDPE liner has been completely installed inside the host pipe, the axial tension is released, the liner pipe begins to expand, the HDPE liner returns to its near original geometry, and a tight fit against the inner wall of the host pipe is created. Following relaxation of the liner pipe, custom manufactured HDPE flange-fittings ("stub ends") are thermally fused to each end of the lined section. The flanged sections and the HDPE stub ends isolate each installed, lined section of pipe from one another. Customized low turbulence slurry flanges have been developed and successfully installed so that the flanged connections do not introduce excessive turbulent flow and the resulting accelerated wear at or near the connection points. Monitoring vents are placed near each flange to confirm that the monolithic HDPE pipe lining system is intact and the inside of the pipeline is completely and continuously isolated from the host pipe and the monitoring vent (**Figure 1**). The two steel flanges are then positioned together, and the line is pressure tested and bolted-up before placing in service (14).

**Figure 1**
**Internally HDPE Lined Steel Pipe with Monitoring Vent Hole**



## 6. ALTERNATIVES

For fine slurry transportation, corrosion rather than abrasion tends to be the dominant concern, while for medium coarse slurry with particle sizes less than 1 mm (-18 mesh), abrasion is more significant (10). The slurry pipeline design engineer is usually the individual most knowledgeable and best positioned to recommend the appropriate measures to take against internal pipeline corrosion and abrasion. Depending on the severity of the application and the need to fight internal pipeline corrosion and abrasion, there are numerous options available along a spectrum including bare steel at one end and corrosion and abrasion resistant alloys at the other end with chemical treatment and/or other mitigating steps possible in between. Metal loss of the pipe wall due to corrosion and/or abrasion can be estimated, and allowance can be factored into the design over the expected useful life of the pipeline (3). If no internal wall loss is expected, then a bare steel pipeline is sufficient for a pipeline operating at pressures high enough to dictate steel construction. Once internal corrosion or abrasion is factored into the design, costs increase to varying degrees over the life of a pipeline.

### 6.1 Thicker steel and chemical treatment

Internal corrosion can be offset by designing the pipeline with a thicker steel wall to account for the expected wall loss, and chemical injection of corrosion inhibitors can be utilized to lower the rate of corrosive wall loss. Thicker steel obviously has the economic ramifications of higher raw material costs as well as increased construction time and cost. Chemical inhibition has some increased capital cost for the injection facilities, but operating costs are usually very high to continuously treat the process stream over the operating life of a pipeline. Even then, diligent monitoring of the chemical treatment program and equipment is required, and operational upsets must be managed appropriately and immediately when they undoubtedly occur. A conservative approach to chemical injection can result in increased pipeline wear while aggressive treatment will result in higher chemical/operating costs. Inventory levels must always be adequately maintained so that the process may be continuously treated.

If abrasion is a dominant factor largely in the absence of excessive internal corrosion, a thicker steel wall can be specified and/or a pipe rotation schedule can be implemented. Pipe rotation has proven to extend the operation of a pipeline (15), but the costs involved are very high since the pipeline must be shut down each time the procedure is performed, it must be constructed in separable and manageable lengths with frequent connections to allow for the physical process of rotation, and it must remain above ground for access. The strategy and process is very inefficient, and the workforce must spend more time in the right-of-way while the labor intensive procedure is safely performed.

### 6.2 Steel treatment and alloys

Metallurgical enhancements including cold working, heat treatment, and induction hardening can “transform steel pipe into high strength, abrasion resistant products, suitable for the transport of abrasive slurries encountered in mining applications” (16). The use of corrosion and abrasion resistant alloys (CRA) for pipeline construction is also a proven method to ensure the long life of a mine’s production infrastructure. Along with its documented effectiveness, it is also well known to be one of the most expensive methods to combat corrosion (17) and abrasion.

### 6.3 Rubber and elastomer lining

The advent of rubber lined steel brought about an additional option offering both chemical and erosion resistance. It has been used in the industry for a long time, but some of the inherent drawbacks have never been overcome. Namely, the rough rubber surface increases frictional losses and corresponding operating costs, plus the pipeline must be constructed in short length (15 m or so) flanged sections due to the limited length spools that can be rubber lined and transported to site. Polyurethane and other similar elastomer lined pipe systems have been accepted in the industry as an improvement over natural rubber. The chemical and abrasion resistance is maintained or improved, and the frictional loss is reduced with the smoother wall elastomer. However, a polyurethane lined steel pipeline still must be constructed by connecting one short lined spool at a time. One comparison of rubber or polyurethane lining to bare steel (3) estimated a five-fold increase in pipeline cost.

## 7. HDPE LINING CONCERNS AND MANAGEMENT

Use of an oversized HDPE lining system is often called a “fit-and-forget” solution against internal corrosion and abrasion. While this is an easy-to-understand concept and predominately true, there are certain aspects of an HDPE lined system that should be understood and monitored depending on the slurry pipeline operation and operating conditions. HDPE is abrasion resistant under the proper conditions, and if those conditions become too aggressive, the wear rate can accelerate for HDPE just as with any material. Additionally, the formation of scale in an HDPE lined pipeline is possible, and consideration should be given to the proper operation and maintenance if scaling may occur. Although rare, mining pipeline operation should prevent the possibility of liner collapse caused by permeation of molecules trapped by the host pipe combined with significant and rapid operational pressure swings. Finally, even though sections of HDPE lined pipe are exceptionally longer than rubber or elastomer lined pipelines, there is a finite length to the installation sections, and those sections are traditionally joined by a mechanical flanged connection rather than constructed as a continuously welded steel pipeline.

### 7.1 Wear

Under the correct operating conditions regarding solids size, shape, and concentrations as well as fluid velocity, and fluid flow characteristics, HDPE lining is a superior material for wear resistance and for the extension of the pipeline operating life. Still, HDPE lining only resists abrasion, and can not prevent it under all operating conditions. Therefore, a certain amount of performance monitoring may be warranted. The slurry pipeline engineering community has done a far better job than the HDPE lining industry in analyzing the appropriate conditions and theoretical and empirical performance of HDPE liners. References to some of that analysis are contained within this paper. Additional joint research – including the HDPE and HDPE lining industries – is warranted in part because of HDPE resin improvements. Within the last three to four years, the industry has migrated from the use of PE- 80 or PE 3408 to PE-100 or PE 4710. This is a higher density (0.964 gm/cc vs. 0.956 gm/cc, typical), bimodal HDPE resin with an up to 10X increase in stress crack growth resistance and an increased stand-alone pressure rating for the same SDR. Further information on the differences and superior properties of the PE 4710 is available in the public domain, but it is important to note that the new material now available for use in HDPE lining has greater toughness and better resistance to abrasion, chemicals, and improved elevated temperature performance than the material previously studied and used.

### 7.2 Scale

In the era of early adoption of HDPE liner use, it was believed that scale would not form on the HDPE liner (3). Recently, there have been a small number of instances where calcium carbonates and calcium phosphates have formed incrustations and adhered to the HDPE liner wall of concentrate pipelines. This paper will not go into the detail already described in previous articles by Ghandi (3), and Altmann (18), but it will mention that soft material (foam, polyurethane, etc.) pigging has been successfully performed for many years in oil & gas industry HDPE lined pipelines. This is occasionally done to clean HDPE lined pipelines of paraffins and/or asphaltines that can lay down in the pipelines. Similar to scaling witnessed in the concentrate pipelines, the buildup is much lower than ever experienced with bare steel pipe, and removal of them is significantly easier because there is markedly less adhesion to the HDPE liner. Additionally, just as a chemical wash is possible in HDPE lined oil & gas pipelines, so too may an acid wash be confidently performed in HDPE lined concentrate pipelines. The HDPE liner protects the steel host pipe while the acid can help to remove any scale and revert the pipeline back toward normal operating conditions. If there is concern that scaling may occur, facilities should be considered in the pipeline design and procedures should be included in the operating manual to mitigate the scaling and maintain the pipelines with special consideration for the HDPE liner as provided by the installer.

### 7.3 Collapse

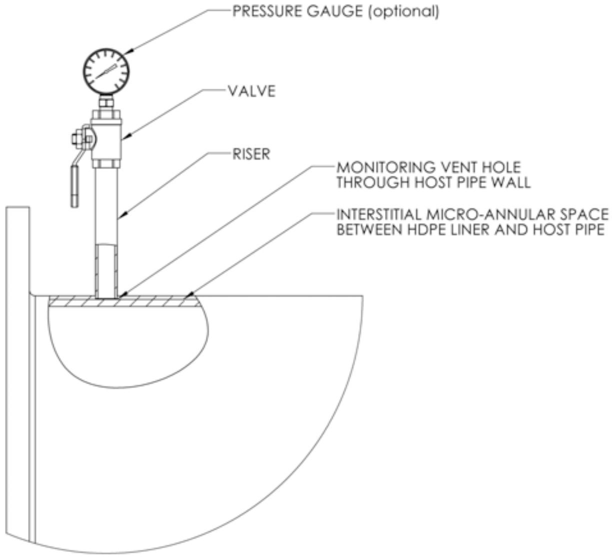
A concern sometimes raised with HDPE liners is the threat of a liner collapse since the HDPE liner is not bonded to the host pipe. Although HDPE liner collapse is rare, there is a greater risk of an occurrence in more severe, higher temperature, gaseous applications with operational upsets causing significant and rapid pressure fluctuations. The theory and process was recently described (14) for these conditions sometimes found in oil & gas applications. The collapse possibility is caused by the permeation of gaseous molecules driven by the pressure differential between the pipeline and the HDPE/steel micro-annulus over time and at elevated temperatures. All HDPE plastic pipe liners used in gaseous applications are susceptible to the permeation of gas into the annulus between the liner and the carbon steel pipe. Smaller molecules are more prone to permeation than others, and all molecules tend to permeate at greater relative rates under higher pressure and temperature conditions. The higher temperatures provide individual molecules more energy to permeate through the solid HDPE material, and the partial pressure differential creates a concentration gradient, hence a greater driving force for the molecules to migrate through the HDPE liner.

The gaseous molecules will continue to permeate until equilibrium is reached between the micro-annulus and the pipeline. If the pressure of the pipeline decreases significantly and quickly enough, that is at a greater rate than the molecules can permeate back from the micro-annulus to the pipeline, then the gas molecules in the micro-annulus will expand to reach a new equilibrium assumed to closely follow the ideal gas law of $\mathbf{pV = nRT}$. As the pressure decreases, the volume must increase at a constant temperature and number of molecules in the micro-annulus. The expansion of the gas in the annulus will exert force on the HDPE liner in the direction away from the host pipe and toward the center of the pipeline. There are certain design characteristics and physical properties of the HDPE liner that can prevent or resist collapse, namely wall thickness of a liner, but if there are enough molecules in the micro-annulus and if the pressure drop of the pipeline is not adequately controlled, the HDPE liner will be forced away from the host pipeline.

Empirical and theoretical (13) evidence has shown that on many occasions, a first collapse may be relatively small and insignificant such that it is not noticeable and does not materially affect pipeline operation. When the pipeline is returned to normal operating pressure, the increased pressure forces the HDPE liner back toward the host pipe. However, the tight fit of the liner may not be as tight as the initial installation such that the micro-annulus has grown in volume. This then allows more molecules to permeate into the larger micro-annulus, and should another operational upset and uncontrolled pressure drop occur, the increased number of molecules will need to expand to fill the larger void. Subsequent collapses will become larger and more pronounced to the point that deleterious operational effects may be incurred.

In long distance slurry pipeline applications, the slurry rarely operates at elevated temperatures near the empirical upper limit of the HDPE liner technical envelope, say 82 – 85C. Furthermore, any amount of vapor would be low, and if present, would probably consist of large molecules such as $H_2O$, $N_2$, and $O_2$. Their size, geometry and the polarity of water vapor contribute to low permeation rates through HDPE and a smaller chance of causing collapse. Furthermore and as evidenced by testing and proven by experience (4), HDPE is very tolerant of the effect of pressure surges such as those described above in the micro-annulus attempting to force the liner away from the host pipe. Directionally, the use of the higher density PE 4710 HDPE will also reduce (but not eliminate) the permeation of molecules, and it has a higher Young's modulus to inherently resist collapse better as well as a higher long-term hydrostatic strength that resists fatigue better than the previously used HDPE resin. If significant permeation is expected to occur, monitoring vents placed on the line during installation and used in the leak testing process can be utilized to monitor annular pressure and/or vent gas that has permeated the HDPE liner (**Figure 2**). This is standard method of not only confirming that the HDPE liner remains leak free, but it also allows an operator to vent any vapor that has accumulated in the micro-annulus as well as determine how often the permeated gas should be vented to protect the liner from collapse in the event of a rapid pressure drop in the pipeline. Finally and as discussed previously, the use of an oversized HDPE liner (i.e., in the hoop-compressive state) provides added resistance to collapse.

**Figure 2**
**Venting of Permeated Gas Through Monitoring Vent**



### 7.4 Connections

Although the distance between connections is greatly increased in comparison to rubber or elastomer lined spools, connections are still required on long distance HDPE lined pipelines. The end result is an entire pipeline protected by a monolithic HDPE protective barrier; however, just like lined spools, flanged connections have predominately been used to construct the pipeline. The issue sometimes raised is that a flanged connection introduces a "weak link" for containing the pipeline contents over-and-above a singular welded pipeline. While this may be true in theory, thousands upon thousands of HDPE lined flanged connections have been successfully installed by multiple HDPE liner installers and are currently operating in leak-free service. Steel flanges were designed to contain pipeline pressures under various environmental and operating conditions, and the use of HDPE liner with "the special flange designs…that resist the pipeline pressure and also retain the HDPE material in the flange assembly" (3) maintains this design philosophy to ASME code and provides a leak free seal/connection.

## 8. IMPROVEMENTS

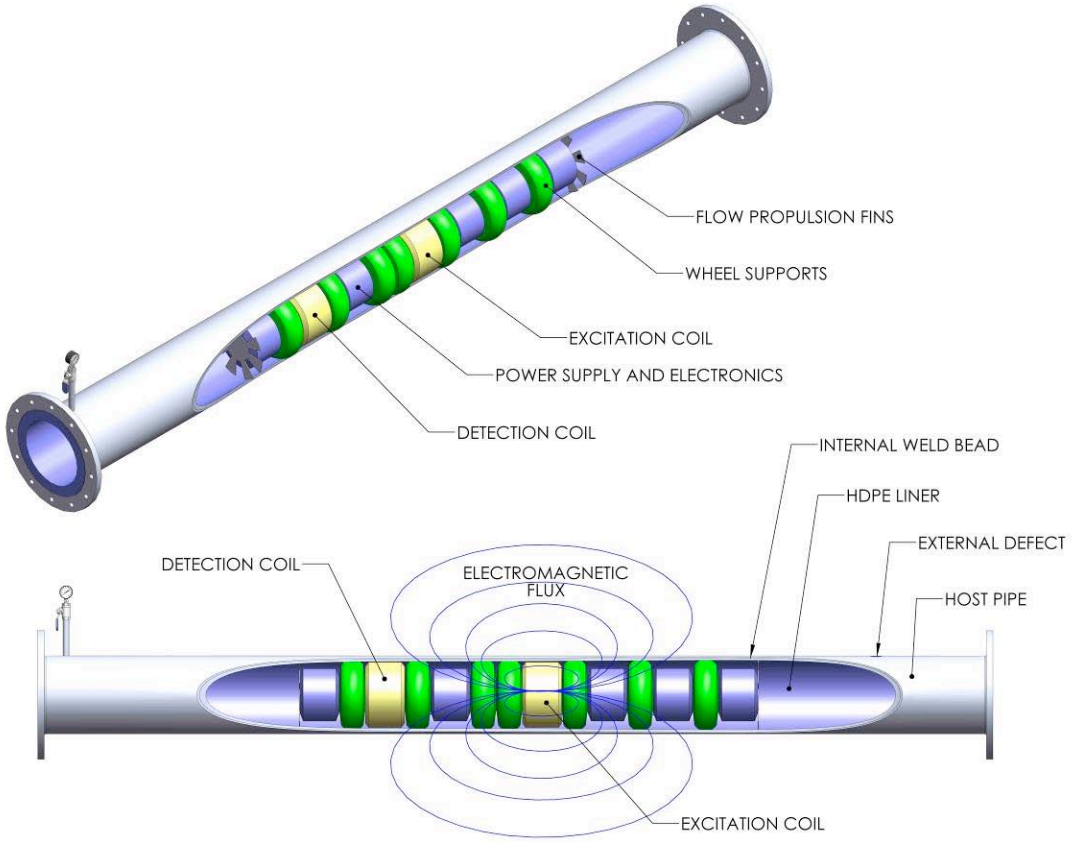
HDPE lining of steel pipelines is still relatively new and only beginning to reach wide acceptance and use in the mining industry. The use of oversized HDPE liners, however, has been in practice for over 25 years. In that time, advancements in the "technology" have been slow to take place. That is not to say that technological advancements and improvements are impossible or even improbable. On the contrary, there are a number of areas ripe for improvement and additional concerns that can be further addressed/resolved with the proper amount of industry attention, interest, and involvement. Some areas where improvement already has or can be realized are briefly discussed.

### 8.1 Wear -- inspection

Laboratory based models can always be constructed to theorize the wear rate of an HDPE liner in service, but the only way to confirm the accuracy of those models – and determine how much of an HDPE barrier actually remains to protect the pressure containing host pipe – is to inspect the pipeline and liner in the field. Visual inspection of the HDPE liner during a shutdown is probably the most common method of determining the condition of an HDPE liner, but this requires a shutdown and access to the inside of the pipeline as well as a limited viewing area rather than knowledge of the entire pipeline. Although not that common, local inspection ports can be installed along the pipeline during initial construction. This will allow operators the ability to perform in-service spot inspections on an HDPE liner to measure thickness remaining at specified and static locations. To determine the remaining ID along the entire length of the pipeline, a caliper pig can be utilized for this purpose. The results of a pig run can be compared with (a) expected results based on known steel pipe ID and HDPE liner wall thickness or (b) known data from a previous run, perhaps conducted upon commissioning of the pipeline.

One additional method can be utilized to determine the overall integrity of an HDPE lined pipeline by measuring anomalies on the inside or outside of the host steel pipe. The technology available for this use is Remote Field Testing (RFT) which is an electromagnetic method of nondestructive testing. The technology utilizes a probe that generates an alternating current magnetic field while it travels down a pipeline. The field extends outward from the probe, through the HDPE liner and then the steel pipe wall and along the pipeline. The detector portion of the probe then measures the magnetic field that has traveled along and then back through the steel and HDPE walls. The "time of flight" and magnetic field amplitude are measured to determine the steel wall thickness disregarding the HDPE liner (**Figure 3**). The technology is sometimes referred to as Remote Field Eddy Current (RFEC) or Remote Field Electromagnetic Technique (RFET), and eddy current discriminators can be utilized to differentiate between internal or external defects along the steel pipeline.

**Figure 3**
**Representative Drawing of a Remote Field Testing Probe**



## 8.2 Leaking – manual and automatic detection

The monitoring vents of an oversized HDPE liner system can be very important for ensuring and confirming the overall integrity of the corrosion and abrasion resistant HDPE barrier. Although this is not new technology, it is still the most common and lowest cost method to guarantee that the host steel pipe is protected from a corrosive or abrasive attack. Electrical and/or mechanical systems can be designed to automatically relieve any accumulated pressure in the annular space or merely to alert an operator of the higher than normal pressure. These systems can and must also be designed to prevent the venting of liquid if the higher pressure is a result of a breach of the HDPE liner.

Other advanced technologies can be used to detect a leak in the HDPE liner -- in the rare event a leak occurs after testing and commissioning -- or monitor the annular space between the liner and host pipe. Leak detection can be accomplished in a number of ways including the use of a coaxial cable. The coaxial cable can be used to send energy pulses down the center and then measuring the reflected energy in the outer braid. This Time Domain Reflectometry (TDR) can measure a change caused by liquid in the annulus where the cable would reside. Another type of detection technology utilizes Brillouin scattering based fiber optic sensors placed in the micro-annulus to measure temperature and distributed strain for leak detection and pipeline damage. These technologies have been utilized in other pipeline situations but never with an HDPE liner. There is additional cost that has never been justifiable mainly because of the reliability of HDPE lining and the low cost, manual means of confirming its leak-free operation.

### 8.3 Connections – welded

Oversized HDPE liner systems were developed and have prospered with the use of specialized flanges to join individually lined sections of pipe. More than ten thousand oversized HDPE liner flanged connections are estimated to have been successfully installed and are operating in leak-free service. Nevertheless, improvement was necessary for the installation of oversized HDPE lined pipe for the oil & gas industry's subsea installations. Not only were flanges inefficient during the subsea pipeline installation process, but there would be no practical method of tightening the steel flange nuts if a loose flange connection occurred thousands of feet below the sea surface. Instead, welded CRA HDPE liner connections were developed by multiple sources to allow for an entirely welded, HDPE lined pipeline. Although the cost for these specialized connections is appreciably higher than the cost for similar sized and rated carbon steel flanges, there are certain instances (such as the high consequence subsea installations) where the cost can be justified.

For onshore pipelines used in the mining industry, the pipeline engineer would need to conduct an analysis determining if the higher cost welded connections could or should be recommended, and the HDPE lining industry would be wise to develop lower cost welded connections. To the latter point, future improvements in the HDPE lining industry are undoubtedly possible, and it would behoove all interested parties to work closer together to identify additional concerns and problems with the intent to develop, test and implement solutions. For example, the typical wear pattern of a coarse particle pipeline is described in Shou (2007) (10). Rather than uniformly increasing the steel wall thickness for an initial section of a pipeline or replacing that section of the pipeline later (necessitating a shutdown and risking a premature failure), might it be possible to line the initial section with an asymmetric oversized HDPE liner that has a thicker wall along the bottom of the pipeline to allow for increased wear around the 180 degree position? Matters such as this one and others that could bring additional economic, operational, safety and environmental benefit to the mining industry should be further explored.

## 9. An Application – HDPE lined carbon steel pipelines in Brazil

A zinc processing facility in the Tres Marias area of Belo Horizonte was reaching maximum capacity in their tailings pond. Additionally, the polyurethane lined pipelines used to transport the tailings and disposal water had experienced leaking at the connections which existed every 6 to 12 meters. Leaks were not acceptable and there was an added concern about them because the pipeline route passed over creeks that fed into the nearby São Francisco river. To combat the leaking joints, the owner installed specialized collars that would capture any leaking, corrosive material. At the bottom of each collar along the route, a tube was connected that directed the acidic liquid into a trough installed directly below each of the two pipelines and constructed along the entire length of the pipelines. Special concrete collection pits were also constructed periodically along the route to allow an area for the trough to drain.

To resolve both of these problems, two new carbon steel pipelines would be constructed along an altered route and lined with an oversized HDPE liner. The modified route would allow expansion of the tailings pond, while the HDPE liner would prevent internal corrosion and abrasion as well as the potential for leaks at the low turbulence flanged connections. The new pipeline system design consists of a 10” water disposal line approximately 6 km in length and a 10’ zinc tailings pipeline over 7.5 km long both routed in parallel to the newly expanded tailings pond. Both the tailings and water disposal lines are acidic, hence corrosive in nature. Although the zinc tailings design conditions are not expected to result in an aggressively abrasive service – the tailings are to be transported as a fine slurry at low velocities – the use of a thicker liner (SDR < 26) for this service was considered along with internal debeading while there is no compelling reason to incur the additional material and labor costs for the disposal water pipeline liner.

In other countries, oversized HDPE liners successfully operate in conditions similar to this, and HDPE liners are an economically and environmentally beneficial choice in this situation. The existing pipelines need to be at least partially relocated due to the expanding tailings pond, and the operating pressures dictate that steel pipelines are required. Because operating costs would be prohibitively high to chemically neutralize the disposal streams, a protective liner is ideal. Furthermore, the project’s pipeline lengths are long enough to justify the use of an oversized HDPE lining system which allows for installation lengths closer to an average length of 800 meters rather than the 6 - 12 meter lengths of the previously utilized polyurethane spools. Not only are HDPE lined flange connections theoretically and empirically proven to provide a leak-free connection, but the use of an HDPE liner system on this project results in over 1,000 fewer connections.

Oversized HDPE liners have never been installed and operated in Brazil, and although common industry practice might recommend burying these pipelines, it is expected that these pipelines will remain elevated in pipeline racks at an additional project cost. This will allow confirmation of successful operation and visual monitoring of the pipeline and the leak-free flanged connections. As of the writing of this paper, the mine owner remains undisclosed, and there is no indication that the HDPE liner installation has commenced. If installation begins, it will be interesting and educational to monitor the progress, installation, and operation of this first oversized HDPE liner in the Brazilian mining industry.

## 10. Conclusions

The internal corrosion and erosion of carbon steel pipelines in the mining industry have been analyzed and modeled for years in the hopes of determining the most practical and economical means of mitigation for a particular application. While there are many options available to mitigate, control, prevent or eliminate internal corrosion or erosion in mining industry pipelines, the use of tight fitting, oversized high density polyethylene (HDPE) liners has proven successful at combating both corrosion and erosion in specific circumstances throughout the world over the past 25 years. There are few reasons and fewer valid concerns preventing increased use of this technology that has proven benefits including:

- Prevention of internal corrosion from continuous chemical and/or bacterial attack

- Prevention of possible galvanic corrosion during extended downtime
- Abrasion resistance
- Increased pipeline life and reduced operational downtime
- Probable improved hydraulic flow properties and reduced operating costs
- Significantly longer distance HDPE lined lengths and fewer connections compared to elastomer lined spools
- Reduction or practical elimination of internal scaling with the inherent ability to utilize acid cleaning and/or soft pigging

An oversized HDPE liner "never stops working" to protect the host pipeline, and HDPE liner use is often (a) superior to bare steel pipelines at a slightly increased construction cost but lower operating costs and (b) superior to elastomer lining at a fraction of the cost. The concerns that do exist with the use of HDPE liners are known, and they have been and continue to be addressed with recent improvements in HDPE material and advanced technologies on the horizon. This should result in longer installation sections, reduced likelihood for collapse, improved connections that eliminate potential leak points, and technology to monitor/inspect the liner and pipeline integrity as well as detect any possible liner leak.

Just as oversized HDPE liner use has been investigated, approved, and successfully installed and operated around the world, it has recently been investigated and approved for use in Brazil. A brief review of that planned use is provided, and the progress and performance should be closely monitored.

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