Higher Ground Consulting

Performance Analysis of Engineered Liner Systems Used to Store Saline Fluids in the Canadian Oil and Gas Industry: Physical and Environmental Influences

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Executive Summary

PTAC retained HGC to investigate the impact that liner material selection, construction techniques, operational techniques, and environmental conditions may have on the performance of engineered liner systems. The investigation focuses on the specific application of synthetically lined earthen ponds in western Canadian climates. The objective of this study is to close existing knowledge gaps not currently addressed in the industry, bring consistency to produced water pit construction, and mitigate overall industry risk. The work included a literature review, case study reviews, and interviews with industry representatives, regulators, researchers, and geosynthetic vendors.

Common liner failure mechanisms include physical liner damage (particularly during operations), welding deficiencies, and stress cracking. Stress cracking represents a significant concern for many operators that were interviewed. In the case study reviews, there were two instances where stress cracking behavior was observed, despite the fact that a third-party laboratory determined the stress crack resistance of failed samples met the requirements of industry standards (GRI-GM13).

The root cause of stress cracking is generally related to compounding factors, rather than one single independent factor. Potential contributing factors include the following:

- applied stresses, which may include: local indentations, differing liner temperatures prior to welding, and fluctuating ambient temperatures during welding;
- welding deficiencies; and
- chemical and thermal exposure post installation.

Each of these factors can contribute to the mechanism of failure. Cold-weather conditions are of particular concern as they exacerbate the brittle nature of most plastics, like HDPE. Welding in cold temperatures can be of particular risk as the temperature variances can elicit thermal shock, resulting in additional stresses which may lead to stress cracking. Fortified liners may help achieve desired performance characteristics based on the expected chemical constituents in the stored water. These may be used in tandem with composite liners to provide an effective and reliable form of containment. LLDPE is also a good alternative to consider in installations where stress cracking is of potential concern, as LLDPE's appear to be less susceptible to stress cracking. .

Research has shown that during installation, issues with welded seams are responsible for nearly 80% of leaks, with 61% of these leaks related to extrusion welds (Nosko et al. 1996, 2000). General liner damage caused during operations were associated with the majority of post-construction liner failures based on industry interviews. Based on available research, very few instances of leaks and defects have been associated with liner installation projects with a rigorous QA program (Giroud & Bonaparte 1989). Similarly, experience shared by industry members indicate significantly less holes, defects, and failures following implementation of third-party QA. Post-installation QA/QC tests assist in identifying liner defects and serve as an additional risk mitigation as they may be conducted at any point in the lifecycle of the pond.

In Alberta, Directives 55 and 58 provide guidelines for the design, construction, and operational requirements associated with storing process-affected waters in Alberta. The AER's application process follows a risk-based, case-by-case approach whereas the BC OGC has issued a document titled Management of Saline Fluids for Hydraulic Fracturing Guideline, which follows a more prescriptive approach. Saskatchewan regulates produced water under Information Guideline 97-01, which notes a preference towards steel for primary containment over synthetics, as "punctures and tearing problems have been experienced in the field with synthetics as primary liners" (IG 97-01).

Improperly investigated or constructed pond earthworks can lead to settlement issues that place the geosynthetic liner under stress and may ultimately lead to failure. Generic specifications, such as those provided by the GRI, are often appropriate for routine, low-risk projects but may not be adequate for the storage of aggressive solutions including brine. Appropriate geotechnical investigation, site selection, engineering design with double-liner systems and groundwater management, the inclusion of construction QA/QC programs, and contractor prequalification can dramatically reduce the likelihood and consequences of liner failure. Limiting access to lined areas, managing liquid levels, frequent leak detection monitoring, and ongoing inspections are good practices to incorporate to further reduce the frequency and severity of liner failure.

Moving forward, further research is recommended in the following areas:

- an investigation into failure mechanisms and mitigation methods for extrusion weld failures;
- supercooling of welds in cold-weather installations;
- use of bituminous geomembranes in saline water storage pond applications;
- the use of GCLs and composite liners for saline water storage pond applications;
- quantitative analysis of the successes and failures of previously constructed ponds; and
- a risk-based guideline for siting, designing, and constructing of saline storage ponds in Alberta may serve as valuable information for the industry.

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1 Introduction

1.1 Background

Higher Ground Consulting Inc. (HGC) was retained by the Petroleum Technology Alliance Canada (PTAC) with funding under the Alberta Upstream Petroleum Research Fund (AUPRF), to perform a study entitled "Performance Analysis of Engineered Liner Systems used to Store Saline Fluids in the Canadian Oil and Gas Industry: Physical and Environmental Influences" (15-WIPC-09).

Produced water pit structures (PWPS) are constructed as storage and delivery hubs to assist in the reuse of produced water and hydraulic fracturing flowback fluids, collectively referred to as saline fluids. They provide an accessible alternative to freshwater, reduce the number of water transport trucks on roadways, and help to reduce costs associated with water sourcing and disposal. As a result, they are an economical asset to the industry which may facilitate growing production by supporting the hydraulic fracturing process. These structures are exposed to environmental and physical changes during operating cycles on a continuous year-over-year basis and to elements that may cause stresses not encountered in other geosynthetic applications.

1.2 Purpose and Scope

The scope of this work is to investigate the impact that liner materials, construction techniques, operational techniques and environmental conditions have on the performance of engineered liner systems for storage of saline fluids. Answers to these questions are intended to close existing knowledge gaps not currently addressed in industry guidelines or standards.

The scope of work included undertaking an investigation consisting of the following:

- table-top / literature review;
- interviews with regulators;
- interviews with industry representatives and vendors;
- interviews with engineering specialists; and

- case study reviews.

Factors affecting the performance of saline water pit structures that were investigated, but not limited to, include the following:

- extreme heat and cold fluctuations (seasonal changes);
- extreme heat and cold fluctuations (seasonal changes) along with addition or withdrawal of saline fluids with varying temperatures;
- earthworks construction during frozen and un-frozen ground conditions;
- geosynthetic installation during frozen and un-frozen ground conditions;
- hydrostatic head pressure changes;
- subgrade conditions; and
- slope stability.

The scope is limited to earthen excavations only and is not inclusive of aboveground walled storage systems (AWSS's), commonly known as "c-rings".

1.3 Study Methodology

The methodology employed to complete the study included the following:

- a literature review, which included material from journal articles, government and symposium publications, and white paper reports from various industries and jurisdictions;
- interviews with regulators including the Alberta Energy Regulator (AER) and the British Columbia Oil and Gas Commission (OGC);
- interviews with PTAC members and non-member producers;
- interviews with geosynthetic vendors and contractors;
- interviews with academic and industry engineering experts; and

- case study reviews to investigate failures related to the construction, operation, and monitoring of lined ponds.

1.4 Report Outline

Within this report, liner material types and developing technologies are outlined along with the organizations and institutes that are involved with polymeric geosynthetics. Common causes and locations of liner failure are reviewed, then four case studies from western Canadian saline water storage pond applications are investigated and their failure modes are discussed. The current regulations are subsequently outlined as well as standards and guidelines for other industries and jurisdictions. Based on findings of the report, recommendations are provided for siting, design, construction, and operations. Finally, areas which require further investigation are proposed.

2 Liner Technologies

2.1 Liner Materials

Containment liners need to be compatible with the fluid they are storing and fit for environmental conditions. There are various types of geosynthetic liners that are frequently used for the storage of fluids in industrial applications, including high density polyethylene (HDPE), linear low density polyethylene (LLDPE), polypropylene (PP), bituminous, and polyurea (PUR) liners. The most commonly used materials for the storage of saline fluids in the oil and gas industry include HDPE and LLDPE. For the purposes of this report, a geosynthetic material intended to contain fluid is referred to as a geomembrane or a geosynthetic liner, which is essentially impermeable when properly installed. A geosynthetic drainage layer refers to a permeable product that is designed to allow for water to move into and through the product, such as a geocomposite. A geotextile is a geosynthetic material that is intended to allow water to pass through it, while preventing fine particles (such as clay or silt) from entering a drainage pocket, acting as a filter. These liner systems generally require in-field installation, including a team of skilled labourers to weld geomembrane panels together.

The selection of geosynthetic liner products and the design of the overall liner system is a critical component of pond design and construction. The liner system can include the following layers and components (from top to bottom):

- primary containment;
- leak detection;
- secondary containment;
- subgrade protection;
- groundwater management; and
- redundant fluid management layer(s).

Currently the regulations in western Canada require the use of synthetic liners for the storage of saline fluids such as produced water and flowback fluids. Regulations in western Canada currently do not allow clay based liners to be used for primary or secondary containment liners. Liner system design and material properties need to be carefully assessed during the engineering design stage. Identifying the risks and associated costs of containment failure can assist owners in evaluating liner system products and making an informed decision. Based on the interviews, some operators are choosing to conduct immersion testing to determine chemical compatibility with various liner types to ensure the most appropriate geomembrane materials are selected.

There are several products that can provide varying degrees of groundwater management and can protect the liner system from subgrade irregularities and hazards. These products include non-woven geotextiles, geocomposite drainage layers, subdrain piping, and bituminous geomembranes. These liner system components vary greatly in cost and part of the design process is balancing the requirements of the site, risk tolerance, and construction costs.

As a risk mitigation measure, some pond owners and operators have elected to install an additional liner and leak detection layer above the primary liner, often referred to as a fluid management layer. The purpose of this fluid management liner layer is to provide an additional layer of redundancy and limit the volumes and pressure head that the primary liner is exposed to.

The following sections provide more detail on the different types of geomembrane materials.

2.1.1 Medium Density Polyethylene (MDPE) and High Density Polyethylene (HDPE)

Medium density polyethylene (MDPE) is a mixture of low-density polyethylene and high density polyethylene (HDPE), and therefore has a property profile somewhere between these two materials. Historically, HDPE has been the go-to product for primary and secondary liners in oil and gas applications. It is readily available, has a long design life (>20 years), and the quality of welding is generally good, in comparison to other traditional geomembranes. HDPE provides good chemical resistance and toughness, but is a semi-crystalline material with a relatively low ductility that has difficulties conforming to uneven subgrades and movement. Thicker HDPE liners are also more rigid and difficult to handle and weld.

Generally speaking, the higher the density of the polyurethane material, the higher the chemical resistance but the lower the resistance to stress cracking. Stress cracking, which is discussed in more detail in Section 4.1.4, involves the brittle failure of the material under specific conditions. It is important to note that since some older HDPE resins had a history of failures attributed to stress cracking, most geomembrane materials that are currently marketed as HDPE are in fact MDPE or HDPE-MDPE blends. Thus they are able to greatly reduce the risk associated with stress cracking while still maintaining a relatively high chemical resistance. For the purpose of this report, HDPE will refer to the blend of HDPE and MDPE materials, as it is commonly referred to in the industry.

2.1.2 Linear Low Density Polyethylene (LLDPE)

LLDPE based blends provide a more flexible alternative to HDPE and are frequently used within the oil and gas industry. LLDPE generally does not provide the same chemical resistance as HDPE and has a lower tearing resistance in laboratory materials testing. LLDPE can deform and elongate significantly more than HDPE before failing, however this is still a plastic resistance; the deformation is inelastic and any thinning and weakening in the liner is permanent. LLDPE is often used where higher degrees of settlement are expected. The design life and puncture resistance of LLDPE can be slightly less than that of HDPE.

All polyethylene liners have a relatively high coefficient of thermal expansion, which necessitates that expansion wrinkles are built into liner systems. These expansion wrinkles make liner construction and welding more difficult, and have historically been a high area of failure (Peggs 1997). Polyethylene liners used in pond applications are thermally welded, which is a process that has inherent challenges and potential for operator error.

2.1.3 Composite Liner Systems

Composite liners consist of a geosynthetic liner (such as HDPE, LLDPE, or PUR) installed in direct contact with an underlying compacted clay liner (CCL) or Geosynthetic Clay Liner (GCL). These liner systems are common in the design of landfills. Western Canadian regulations currently do not allow these types of systems as primary or secondary containment on their own for pond applications, but they can be combined with other liner systems for added protection. This was the case in at least one of the saline water pond case studies HGC evaluated.

Composite liner systems have the special advantage of the inherent redundancy in the system, and consequently the significant reduction in leakage. Should a penetration occur, the geomembrane serves to decrease the leakage rate while the underlying CCL (or GCL) increases the amount of time required for the liquid to flow through the soil layer. Additionally, due to the fact that the layers are in direct contact, the rate of leakage that would result from a hole in the geomembrane is decreased since the clay below acts as a plug (Giroud & Bonaparte, 1989).

A GCL requires specific installation and operating conditions to maintain its low permeability properties. Standard GCL's currently on the market must be hydrated with a fresh (non-saline) water source during installation, prior to covering GCL with a ballast material to provide confining pressure during hydration. A confining pressure must also be maintained on the GCL at all times. These requirements are often difficult to achieve in pond applications and furthermore these systems tend to be more expensive and take more time to install.

Published research has shown that GCLs are less effective at containing saline water than fresh water, and in order to be effective, the GCL requires hydration with fresh water while under a confining load, before being put into service (Petrov & Rowe 1997). Even when hydrated with potable water, salt exposure increases hydraulic conductivity of a GCL, therefore GCL exposed to saline solutions must undergo a higher confining stress to help reduce the increased hydraulic conductivity caused by salt exposure (Petrov & Rowe 1997).

2.1.4 Polypropylene

Polypropylene geomembranes (PP) are highly inert thermoplastic polymers made by creating a copolymer blend of ethylene and propylene rubbers. PP geomembranes have low levels of crystallinity when compared to polyethylene, and are therefore more flexible than HDPE and less susceptible to stress cracking. The design life and puncture resistance are slightly less than that of HDPE, however they may be reinforced with a polyester scrim for enhanced dimensional stability, tear and puncture resistance.

The chemical and ultraviolet (UV) resistivity of PP are generally much lower than that of HDPE or LLDPE, and therefore their use in saline storage applications is not common. . The market for PP is smaller than it is for HDPE and LLDPE, therefore a longer lead time for ordering may be required. Additionally, PP is generally more expensive than HDPE. To HGC's knowledge PP liners have not been utilized for the storage of saline fluid associated with hydraulic fracturing in western Canada.

2.1.5 Polyurea

Polyurea is a spray applied elastomer that has historically been used in the industry as a coating film and secondary containment option, especially in brownfield construction and in areas with challenging access for construction, such as piles. An appealing property of polyurea is that it is an elastic material, unlike traditionally used plastic liners. This can potentially offer a much higher tolerance to subgrade movement, and long-term resistance to mechanical damage. Another significant advantage of polyurea is that when properly installed, the in-field seams have almost identical properties to prefabricated material, unlike thermally welded plastics.

Polyurea based liners for pond construction is still a relatively new and developing application. Historically, using polyurea for large scale applications has been cost prohibitive, however the cost gap relative traditional materials has been closing. Developments in production, such as the prefabrication of polyurea panels in a controlled environment have contributed to the efficiency and available quality assurance and quality control measures for this technology. Polyurea has high puncture resistance and good chemical compatibility, however it has not been extensively used for primary containment largely due to economics.

2.1.6 Bituminous Geomembranes

Bituminous geomembranes are comprised of a thick non-woven geotextile saturated with bitumen to create an impervious flexible sheet. As the geotextiles range in weight, the thickness and amount of bitumen on the roll ranges correspondingly. Once the bitumen is applied to the roll, sand is placed while the material is still hot. This sanded surface provides increased friction angles and a safer walking surface during installation and operations. In general, bituminous geomembranes have a high puncture resistance but are more expensive than polyethylene and research on their effectiveness in fluid storage applications is limited. They tend to take longer to install and have a shorter design life than HDPE.

Based on industry interviews, bituminous geomembranes are rarely used for saline storage pond applications, possibly due to the limited extent of research, development, and testing that has been conducted to verify their performance. However in HGC’s opinion, their usage in combination with more standard geomembrane materials in circumstances with shallow bedrock subgrades is worth further investigation.

2.1.7 Polyvinyl Chloride

Polyvinyl chloride (PVC) is a chain assemblage of vinyl chloride (itself produced by a reaction of ethylene and hydrochloric acid). It has good workability, is easy to seam, and can be prefabricated and folded in very large sheets, minimizing field seaming.

PVC is an elastic, amorphous material and therefore is not subject to environmental stress cracking. When compared with HDPE, which exhibits a sharp peak in their stress-strain curve and consequently undergo abrupt failure, PVC undergoes a large amount of elongation before failure, which may be advantageous in scenarios where some settlement may be expected. It should be noted however that in the case of fire, highly toxic fumes of hydrochloric acid may be formed (Huggett & Levin 1987). PVC liners have not been utilized for the storage of saline fluid associated with hydraulic fracturing in western Canada. PVC does not have the same range of chemical resistance as HDPE and tends to become brittle when exposed to extreme cold.

2.1.8 Ethylene Propylene Diene Monomer (EPDM)

Ethylene propylene diene monomer (EPDM) is a terpolymer of ethylene, propylene, and a diene-component. It displays good performance in low temperatures, has high UV resistance, and is an extremely flexible material. Seam quality for EPDM however can be poor, as does its resistance to hydrocarbons, solvents, and punctures. EPDM is not currently being used for saline water storage generally does not appear suitable for oil and gas applications.

2.2 Manufacturing Standards and Specifications

The Geosynthetic Institute (GSI) is a consortium of organizations involved with all types of polymeric geosynthetic materials, including: geotextiles, geomembranes, geogrids, geonets, geocomposites, and geosynthetic clay liners. It is an umbrella organization which includes the Geosynthetic Research Institute (GRI), Geosynthetic Information Institute (GII), Geosynthetic Education Institute (GEI), Geosynthetic Accreditation Institute (GAI), and Geosynthetic Certification Institute (GCI), among others.

The Geosynthetic Research Institute (GRI) creates and publishes specifications, guides, and practices for polymeric materials, including geomembranes. These specifications are reviewed at least every 2 years, or on an as-needed basis. They heavily reference a large suite of American Society of the International Association for Testing and Materials (ASTM) standards to quantify acceptance and/or performance criteria. The GRI specifications have been widely adopted by industry as acceptable standards for the manufacturing and installation of geomembranes, although the GSI and its constituent organizations have no legislated authority.

3 Liner Performance and Failure Analysis

3.1 General

A liner failure is defined as either a breach of containment due to a failure of the earthworks (generally consisting of localized slope stability failure), liner integrity, or both. Peggs (2003) described the durability of a HDPE geomembrane to be a function of the following:

- The knowledge of the design engineer in selecting and specifying the most appropriate liner material, and designing the liner for minimum stress on slopes, at sumps, at penetrations, and in anchor trenches.
- The knowledge of the engineer in specifying adequate puncture protection for the geomembrane (i.e. subgrade protection).
- The smoothness, uniformity, and density of the subgrade.
- The ability of the manufacturer to produce a consistent homogeneous material with a minimum number of internal and surface flaws and with effective antioxidant additives.
- The stress crack resistance and oxidation induction time of the resin used and of the geomembrane itself.
- The quality of the installation – lack of wrinkles, intimate contact with subgrade, seams, penetrations, minimum extrusion welding, minimum shear stress on slopes.
- Quality of construction Quality Assurance (QA).
- Ongoing operations.

According to Peggs (2003), once a liner has successfully been installed and there is no leakage, the internal influences that can cause additional leaks are such items as:

- Wrinkles and protrusions causing stress crack before stress relaxation can occur.

- Wrinkles at seams causing slow peel separation and propagation of critical flaws in seams.

- Crazing (surficial fissures), induced by peel separation, initiating stress cracking at the stressed seams.

- Shear and peel stresses at overheated or over-ground seams adjacent to wrinkles initiating stress cracking.

- Elevated geomembrane temperatures causing oxidation and accelerating stress cracking if stress relaxation is not accelerated in proportion.

3.2 Common Causes of Liner Failure

Unfortunately, very little academic research has been conducted on geomembrane liners in saline water applications in Canada to date. Extensive research has been conducted for landfill applications internationally, and some relevant information can be reasonably applied to exposed pond-type applications.

Based on interviews, correlated research, and experience in a variety of industries, liner failure in general can be caused by a variety of conditions that include:

- Siting that does not properly identify or avoid geotechnical hazards such as shallow bedrock, high permeability soils, or unstable slopes.

- Inadequate, or the absence of, engineering design.

- Inadequate, or the absence of, groundwater control systems.

- Inadequate moisture control and compaction during earthworks construction.

- Use of geosynthetic liner materials that are too thin or not appropriately selected for the given application and site conditions.

- Deficiencies and workmanship issues in the seaming of geomembrane liners.

- Insufficient involvement of QA/QC professionals and engineers in the construction phase of projects.

- Inconsistencies and errors made in the operation of liner systems, including leak detection and groundwater control systems.

- Physical damage to liners caused by equipment and human traffic.

3.3 Common Failure Modes

Specific failure modes for geosynthetic liners are outlined below. Investigation into liner failures has found that multiple failure mechanisms often act concurrently, compounding the stresses on the material and leading to failure.

3.3.1 Physical and Mechanical Liner Damage

Differential settlement can be detrimental to the pond liner system due to the elongation of material from the inconsistency in the material subgrade. Traditionally used plastic based liners, such as polyethylene, are sensitive to settlement and subgrade movement. Plastic based liners are relatively tough materials that resist tension, however once loaded and deformed, they become thinned and permanently weakened. The short-term studies of the strains in geomembranes typically show strains in excess of the 3% suggested by Seeger and Müller (2003) as a maximum allowable strain. Abdelaal et al. (2014) found that the locations of stress cracks (to be discussed further in Section 4.1.4) were directly related to the location of local indentations caused by gravel particles.

Mechanical damage to the geomembrane liner can cause a breach of stored fluids into the leak detection system and/or through the secondary liner. There are several different ways that mechanical damage can occur, including:

- Human error while working on the liner surface. This can include dropped tools, dragged equipment and hoses, driving mobile equipment directly on the liner, and stepping on sharp rocks or other objects while on the liner surface. This type of damage often goes unreported and can be missed during visual inspections.

- Deformities in the subgrade or presence of sharp objects such as rocks have the ability to puncture liners under stress, specifically where the liner is stretched due to settlement or uneven subgrade.

- Placing equipment directly on top of the liner, such as pipes or pumps. Methods exist to cushion and protect liners from damage, however whenever mechanical equipment is resting directly on top of liners, the potential for damage exists.

Liners are designed to act as impermeable barriers and not to be load bearing members. Even the most robust liner systems are dependent on the uniformity of the subgrade for support and are susceptible to damage from stress concentrations such as sharp objects of concentrated loads.

3.3.2 Welding Deficiencies

Welding polyethylene involves locally heating the material up to a melted flow state where the material from the two surfaces can mix together and form new molecular bonds in the cooling process. The strength of the weld is dependent on the temperature of the material, the heating time, the degree of mixing in the melt flow, and the absence of introduced impurities. If the material is too cold during the welding process, the materials do not melt properly and reconstitute new molecular bonds. The result can be that the material does not form a full strength weld. Overheating the plastic during welding can lead to an undesired change in the material's molecular structure, reorganizing the polymers into a more crystalline structure resulting in a more brittle and locally weakened weld. Overheating also causes accelerated consumption of antioxidants in the polymer, which increases the susceptibility of the geomembrane to stress cracking (Scheirs 2009).

Extrusion welds have the highest incidence of failure of the welding techniques investigated. According to Nosko et al. (1996, 2000), of the liner failures that occur during installation, 61% are directly attributed to extrusion welds. While there is no way to eliminate the use of extrusion welds completely as they are used for patching, liner repairs, penetration details, and detail welds in sumps, their use may be limited with proper installation techniques. Rigorous and careful inspection during the extrusion welding process is critical to reducing the number of failures attributed to extrusion welds, which includes the following:

- Ensuring that the technician who is grinding and tacking the patch in preparation for the extrusion weld is using only enough heat from the hot air welder to tack the patch without excessively melting the materials. A fine grinding wheel is generally used and the grinded area should be slightly narrower than the extrusion bead width.

- The extrudate in the barrel of the extrusion welder should be purged to ensure the "old" extrudate is removed prior to commencing welding.

- The length of the extrusion bead should be kept to a constant width and height and should not become overly thick. An overly thick bead will create too large of a heat sink and blister the materials being welded, which realigns the polymer chains thereby weakening the material. Generally, the weld should be twice as wide as it is tall and there should not be excessive squeeze out along the edge of the bead.

The quality of polyethylene welds is highly dependent on the welding personnel, which introduces a high potential for human error. Proper welds are dependent on correct surface preparation, control of ambient moisture, setting the equipment at temperatures suitable for the ambient conditions, running the welding equipment at appropriate speeds, and welder skill in determining weld contact locations and weld conformity.

Proper welding quality assurance can dramatically reduce the frequency and severity of weld defects and failures, however does not always eliminate them completely. Polyethylene welds are more brittle than the surrounding material, and the heat-affected zone immediately adjacent to the weld is a common area of weakness. The heat-affected zone is affected by the welding process, however does not have the added thickness in the cross-sectional area that the weld does. Although the tensile strength of the seam itself is sufficient, weak points in the heat-affected zone can become areas of stress concentration (Peggs and Carlson 1990).

A weakened area in the weld or the heat-affected zone immediately adjacent to the weld can visually appear normal and pass initial standard non-destructive quality assurance testing methods, however can fail once the liner is placed into service. This is a situation that was encountered in at least one of the case studies, which is discussed later in the report.

3.3.3 Oxidation

LLDPE has a lower density and hence lower crystallinity than HDPE, which allows oxygen to diffuse faster into LLDPE than into HDPE. As a result, the antioxidants in LLDPE geomembranes are depleted faster than the antioxidants in HDPE geomembranes (Koerner et al. 2005 and Gulmine et al. 2003).

Laboratory accelerated aging tests were conducted by Allen et al. (2000) to investigate the oxidative stabilities of additive-free LLDPE and HDPE. The results showed that additive-free HDPE was less stable than LLDPE with respect to thermal and photo-oxidative degradation. So while LLDPE loses its antioxidants faster than HDPE, LLDPE may age slower after the antioxidants have been depleted (Islam et al. 2011).

3.3.4 Stress Cracking

Stress cracking is essentially a brittle cracking phenomenon that occurs at a constant stress lower than the short-term yield strength of the material (Peggs 2003). Macroscopic cracks form, creating a route for absorption of stress cracking agents and moisture. The absorption of the liquid through the crack plasticizes the polymeric matrix and causes the crack to expand (Seaman Corporation 2012). Oxidizing agents such as chlorinated water can cause oxidative degradation to the polymer resulting in its embrittlement. This leads to stress cracking under very low stresses (Scheirs 2009), and is referred to as oxidative stress cracking.

Stress cracking is a consequence of the semi-crystalline microstructure that gives the HDPE its good chemical resistance and high strength. Accordingly, LLDPE does not have the same predisposition to stress cracking, however it is still possible to occur once the materials antioxidants have depleted and the material oxidizes. This is more common in exposed lining systems where restrained contraction stresses are cyclic and the geomembrane is not confined (Peggs 2003).

Stress cracking can occur at any time in the lifecycle of the geomembrane. Cold-weather conditions are of particular concern as they exacerbate the brittle nature of HDPEs. Welding in cold temperatures can be of particular risk as the temperature variances can elicit thermal shock, resulting in additional stresses which may lead to stress cracking.

The typical pattern of geomembrane degradation begins with antioxidant depletion, followed by a time lag, then subsequently geomembrane degradation. However Ewais & Rowe (2014) observed changes in the stress crack resistance of an HDPE before the antioxidants were depleted. They attributed the change to morphological changes during aging due to annealing and chain disentanglement mechanisms which act to weaken the material. Additionally, they concluded that surfactants (substances which reduce the surface tension of a liquid) may have enhanced the rate and the extent of chain disentanglement, further accelerating the time to which a lower stress crack resistance is reached. This may help explain the occurrence of stress cracking in the field when geomembranes have been in service for relatively short periods of time.

The most common method of testing stress crack resistance is ASTM D5397, “Standard Test Method for Evaluation of Stress Crack Resistance of Polyolefin Geomembranes Using Notched Constant Tensile Load Test”, often referred to as the NCTL test. Specimens are notched to 20% of their overall thickness, loaded at 20-50% of the tensile yield strength for the material, and placed in a solution containing 10% surfactant at 50°C to accelerate aging. The time until failure is measured and the data is reported in a plot of load versus failure time. The transition between ductile and brittle failure indicates the stress crack resistance of the material.

Based on case study reviews, there was at least one instance where stress cracking behavior was observed in the field, despite the fact that a third-party laboratory found the stress crack resistance of the material met the requirements of GRI-GM13. This apparent contradiction is likely due to the fact that not all environmental factors can be applied in a laboratory setting, therefore some lab tests cannot guarantee that a stress cracking failure will not occur in the field. Furthermore, there are currently no correlation studies to relate this lab-based index test to actual field performance.

3.3.5 Chemical Degradation

If stored fluids contain high concentrations of oxidizing acids, chlorinated solvents, or detergents, environmental stress cracking is more likely to occur. Upon immersing HDPE geomembrane into various leachate components including volatile fatty acids, salts, and trace metals, it was found that of the three, the presence of salts had the greatest effect on the time to nominal failure and resulted into the shortest time to nominal failure based on stress crack resistance (Abdelaal 2013). Premature failures may be instigated in regions of induced stress such as wrinkles and stone protrusions. The susceptibility of the liner to these stresses is a function of the stress crack resistance of the specific resin used (Peggs 2003), which can vary between differing geomembrane manufacturers.

3.3.6 Thermal Degradation

Thermal degradation causes changes in the physical and chemical properties of geomembranes (Koerner 2005). Elevated temperatures accelerate both ultraviolet and oxidative degradations. Abdelaal et al. (2014) found that as geomembrane temperature increased, time until rupture decreased and tensile strain at the location of ruptures increased as well. This may have a significant impact on liner performance in ponds with inlet water temperatures in excess of 60ºC.

3.3.7 Ultraviolet Degradation

Qureshi et al. (1989) conducted an outdoor weathering study using geomembrane with no UV stabilizer in a climate with solar radiation comparable to Arizona, USA. They determined that of all the weather-induced degradation mechanisms including solar radiation, temperature, wind, rain, and thermal cycling, UV degradation is the most harmful for an exposed geomembrane. High energy photons cause a series of reactions to geomembrane polymers that are exposed to sunlight which liberates free radicals and eventually makes the polymer brittle and susceptible to stress cracking. To slow this process, carbon black or other light stabilizers are added, which are subsequently depleted with increasing exposure time (Suits and Hsuan 2003). However, in higher latitudes such as Canada, failures associated with UV radiation are of relatively low risk.

3.3.8 Earthworks Failures

Indicators of earthworks failures may include sinking, low spots, slumping, and sloughing. The prepared surface may appear non-uniform, hummocky, rolling or undulating. Depending on the cause, these problems can act slowly over time, such as settlement, or propagate quickly (slope instability, for example) and may lead to a complete failure.

Although the pond side slopes may appear stable, improperly investigated or constructed pond earthworks can fail and lead to settlement issues that place the geosynthetic liner under stress. This can be attributed to the geotechnical properties of the underlying soil, improperly compacted pond berms, or both. Differential settlement occurs when the loading or bearing capacity of underlying soil is variable, and results in varying degrees of settlement throughout the pond.

Side slope failure in a pond can be attributed to a variety of factors, most often including one or more of the following:

- improperly compacted fill;
- placement and compaction of poor quality fill;
- side slopes constructed at unstable grades;
- construction within a weak stability zone (i.e. weathered shale, sand, etc.); and
- inadequate groundwater collection system (or the lack thereof) or inadequate operation of the groundwater collection system.

Side slope failures can be limited to isolated sections of the slope, in which case a repair might consist of slope reinforcement or by replacement of soil in a localized area. If the issue is recognized on a larger scale, much larger remediation may be required such as a full pond berm reconstruction.

During the interview process with industry representatives, it was confirmed that lack of proper siting investigations in advance of construction have directly contributed to past pond failures. However, it appears that it has now become common practice to conduct full geotechnical investigations prior to designing produced water storage ponds, thus reducing the occurrences of earthworks failures.

3.4 Common Failure Locations

Nosko et al. (1996, 2000) has identified the leading causes of liner damage with respect to the installation phase (Table A) as well as the most frequent locations of liner damage (Table B). The data was collected from several thousand failures from 16 countries, representing more than 300 sites and approximately 3,250,000 m^2 in total lined area. It should be noted that these sites included landfills with a protection layer installed above the liner. Consequently, stones and heavy equipment related to the protection layer were responsible for a significant proportion of damage.

Table A: Causes of Liner Damage During Installation

Cause of Damage	Amount
Extrusion Welds	61%
Overheating / Melting Faults	18%
Stone Puncture	17%
Cuts	4%

Table B: Locations of Liner Repairs

Location of Repairs	Amount
Flat Floor	78%
Corner, Edge	9%
Other (Road Access, Storage, etc.)	7%
Under Drainage Pipes	4%
Pipe Penetrations	2%

From Table A, it is apparent that during the installation phase, nearly 80% of leaks occur on seams for exposed liner systems. For the data presented in Table B, the liners studied were covered with a protection layer for the purpose of landfilling. Saline water storage ponds generally do not have a protection layer. However, based on HGC's experience and the interviews conducted, the trends for location and frequency of repairs are similar to those reported in the studies.

3.5 Effects of Temperature on Liner Installation

Liner installers' QC manuals list the preferred installation temperature at 0ºC or warmer, but no higher than 40ºC. In Alberta, that would represent a time frame of approximately April 1 to October 31 (Alberta Agriculture 2015). Cold weather construction can amplify the impact of quality issues for both earthworks and liner, some of which may not become apparent until spring thaw.

Based on interviews from geomembrane installers, the general consensus is that productivity will decrease by about 20-40% for winter work, primarily due to ambient temperatures and precipitation. Coordination of snow removal, dewatering, and material handling also tend to delay progress.

The GRI Test Method GM9: Standard Practice for Cold Weather Seaming of Geomembranes (Geosynthetic Institute 1995) provides guidelines for thermal fusion and extrusion fillet field seaming of geomembranes in cold weather. The applicable temperature range of the geomembrane sheet is from 0° to -15°C and recommendations are summarized as follows:

- Seaming at temperatures below -15°C is not recommended, from both a material and personnel perspective.
- Seaming is not to take place when it is snowing, sleeting or hailing.
- All frost must be removed from the surface of the geomembrane sheets where seaming is to be performed and residual moisture wiped dry.
- It may be necessary to use a rub sheet beneath the area being seamed to separate the geomembrane from frozen soil subgrade.
- The rate of seaming should decrease with decreasing sheet temperature.
- The number of trial seams (trial sections of seamed geomembranes used to establish machine settings under existing conditions) should be increased by one per day for each 7.5°C less than freezing.
- More destructive testing on production seams may be conducted at the discretion of the construction quality assurance (CQA) engineer.
- For extrusion welding, the profile of the base of the extrusion gun barrel may be shaped more rectangular than when seaming at temperatures

above freezing. The reason for this is to minimize the cooling rate in the thinner extrudate regions.

The rapid changes in temperature undergone by liner materials during welding procedures produce a significant temperature shock to the liner material. The wedge temperature of the welder is typically in the range of 300-400°C, in contrast to the temperature of the liner material, which may be -15°C or lower during winter installations. Increased temperature differentials between the liner material and the welding mechanism increase the potential thermal effects on the liner. This is a significant factor in why liner installation is not recommended in conditions below -15°C and why wedge welders should be run at a slower rate in winter installations.

Cold, sunny days are common in many parts of western Canada and can present additional challenges with winter welding. Polyethylene liners used in exposed pond applications are typically black from UV stabilizing carbon additives. Once the liner panels are deployed, the large surface area of the black panels absorb energy from the sun which can produce temperature changes of several degrees in the liner material. Furthermore, most plastic liners (especially polyethylene) have a high coefficient of thermal expansion, and therefore the liner panels may shift as they heat and cool. As the liner material changes temperature, the welding temperature and machine rate may need to be adjusted, which could go unnoticed if ambient conditions do not change drastically. Similarly, differing sunlight exposure may heat two adjacent panels unevenly. Ideally, the two liner panels should be at the same temperature so that they both undergo the same degree of melting in the welding process and have similar cooling rates as well.

Winter time liner installations require additional vigilance and more frequent welder qualifying. The number of sheets deployed prior to welding should be limited as much as practically achievable.

3.6 Effects of Temperature on Liner Performance

The material may potentially be exposed to temperature shock again by the inlet water temperatures which can be over 50°C. These rapid temperature swings cause the geomembrane to rapidly expand and contract. Peggs (2003) found that the kinetics of stress crack initiation and propagation increase at elevated temperatures as they speed the consumption of antioxidant additives. These conditions, coupled with the chemicals in the contained liquid, can have a significant effect on the integrity of the liner.

3.7 Canadian Shale-Gas Industry Experience

HGC produced a report titled Pond Liner Failure Mechanisms (HGC 2015) which provided an overview of the most common types of failures observed in lined ponds, a high level cost analysis for multiple pond construction scenarios, and a brief section on risk mitigation. This report was founded on HGC’s experience in working with over 30 lined ponds in western Canada.

Differential settlement was determined as one of the leading contributing factors to containment breaches in the lined ponds examined. This occurs when the loading or bearing capacity of underlying soil is variable, and results in varying amounts of settlement throughout the pond. Differential settlement can be very detrimental to the pond liner system due to the elongation of material from the inconsistency in the material subgrade.

Side slope failure was another common mode of failure, which may be attributed to improperly compacted fill, poor quality fill, unstable grades, weak or low stability sites (such as weathered shale or sand), or inadequate groundwater collection systems.

Physical damage to geomembranes was also a commonly observed mode of failure, which can happen in a variety of ways. Methods in which geomembrane liners were commonly damaged included mechanical equipment in the pond contacting the liner, inadequate subgrade preparation, and human error while working on the liner surface, including dropped tools, dragged equipment and hoses, driving or placing vibrating equipment directly on the liner, and tracking foreign debris such as rocks into the pond.

Lastly, geomembrane welding deficiencies were found to be a major source of failures. A weakened area in the weld or the heat-affected zone immediately adjacent to the weld can visually appear normal and pass initial non-destructive testing, however can fail once the liner is placed into service. The quality of polyethylene welds is highly dependent on the welder workmanship and the welder’s ability to adapt to the environmental conditions.

Risk mitigation and recommended practices are addressed later in this document.

4 Case Study Review

The following case studies are based on information collected by HGC through interviews with producers and regulators, review of collected documents, and in some cases post-incident investigative work that HGC was hired to conduct.

4.1 Case Study 1

In this case study, the pond liner design comprised of a primary and secondary HDPE liner over top of a geocomposite underlay, which was over top of a GCL liner. The pond was filled and leaks were immediately identified in the primary and secondary liners based on high inflow rates in the interstitial leak detection systems, specifically the primary leak detection layer and subdrain sump (beneath the secondary liner) .

The pond was emptied and large tears in both the primary and secondary liners were identified and inspected; some were estimated to be as large as 50mm long slits. Additional defects occurred along wedge welds adjacent to the expansion joint. The defects occurred in the squeeze out zone, which is just outside the welded joint, underneath the flap of overlapped liner material.

An electrical leak survey was performed on the installed conductive HDPE liners, however, likely due to the location of the liner defects and their proximity to the wedge welds, the leak location survey technology did not have identified the defects. Based on the timeline and the analysis of the pond monitoring records, it is likely that the tears in the liners existed from initial construction, and may possibly be attributed to stress cracking related to the initial welding.

Given the inflow rates and salinity measured in the subdrain sump, it appears that the produced water was flowing through the GCL layer nearly as fast as it accumulated. During installation, the GCL was not pre-hydrated with fresh water or covered with a ballasting material, which may have contributed to the poor performance of the GCL. The GCL was also placed underneath the geocomposite underlay, which created a permeable layer between the secondary liner and the GCL. The GCL may have been more effective if it had been installed immediately below the secondary liner, creating a composite liner system. Furthermore, installation defects were noted in the GCL in the leak detection sump area.

The ponds were engineered; however, the design engineer was not involved during the construction phase. The liner contractor performed QA/QC activities, however no third-party liner inspector was involved in construction. Costs for the investigation, repairs, and recommissioning in this particular case were estimated to be in the range of $4 million.

4.2 Case Study 2

A produced water pond was lined with HDPE for the primary line and LLDPE for the secondary liner. Installation of the liner system took place during cold winter conditions. Shortly after construction, defects in the liner were suspected based on high inflow rates into the primary leak detection layer as well as the subdrain sump (located beneath the secondary liner). The pond was emptied and the liner was investigated to determine the location and cause of the breach.

The majority of liner failures identified were located on the floor of the pond. Evidence of stress-cracking was observed immediately next to a wedge weld seam, including a straight slit running parallel to the seam. Samples of failed seams were submitted to an independent third-party laboratory for investigation and analysis.

The lab examined failed locations to determine failure mechanisms. Electronic microscopy indicated the typical, staged stress-cracking mechanism of polyethylene (Choi et al. 2007), consisting of brittle failure on the stressed surface, followed by propagating cracks and subsequently, ductile failure.

Another liner failure was found at the end of the extrusion weld, which displayed clear evidence of grinding but no evidence of melting. The weld was located on a fold, which supports the conclusion that the welder was not able to apply sufficient pressure to adequately melt the liner material, resulting in inadequate adhesion. Further along in the same weld, there was indication of a pull-off force which resulted in a hole, despite the fact that in that location the material was properly adhered. The third-party analysis determined that the failures may have been a result of the presence of excessive moisture, too cold of a surface at the time the extrusion bead was applied, dust, excessive speed, or a combination of these factors.

Costs for the repairs and recommissioning for this case study were estimated to be in the range of $1 million.

4.3 Case Study 3

In a dual lined pond, an operator reported finding and pumping out fluid from the leak detection sump and subdrain sump (beneath the secondary liner), which was unexpected because the pond had not been put back into service since completing previous liner repairs. The adjacent groundwater monitoring wells were not collecting water at that elevation, leading to the conclusion that groundwater was not responsible for the inflows. During the winter months the leak detection pump was frozen in, however later in the spring, the leak detection sump was thawed and a substantial volume of fluid was pumped out in a single day.

For the next month and a half, large volumes of water were pumped daily from the leak detection sump. Over this period, there was no water accumulating in the pond subdrain sump. When the leak detection sump pumping was stopped, fluid would start appearing in the subdrain after the leak detection sump accumulated fluid to a particular elevation. The pond was inspected visually along with a vacuum assisted acoustic leak survey, which revealed holes in both the primary and secondary HDPE liners. These holes were sufficiently large enough to explain the presence of fluid in the leak detection sump and subdrain sump.

While the pond was not in service, it collected snowfall over the winter months. Black HDPE liners absorb solar energy on sunny days, and can melt snow and ice in direct contact with the liner. This snow melt was believed to be the source of the water in the leak detection system and subdrain. The snow melt was not detected by the operators because the snow at the bottom of the pond did not appear to be melting when viewed from the top of the pond berms.

The holes in the primary and secondary liners were unexpected because the liner had been tested with a vacuum assisted acoustic leak survey the previous year and had not been placed back in service since the leak survey. As part of the investigation, it was determined that during the previous repairs and leak surveys, the liner contractor performed their own QA/QC and no third-party liner inspector was involved. External consulting engineers experienced in liner construction were engaged to support the investigation and provide onsite third-party liner inspection for the current repair work. While overseeing the most recent vacuum assisted acoustic leak survey, the third-party liner inspector observed the liner contractor conducting extrusion weld repairs on the primary liner while the liner system was still under vacuum. In one observed location, the suction force of the vacuum underneath the primary liner pulled the still molten HDPE extrusion bead down into the interstitial space, leaving a pinhole in the newly completed repair. The liner contractor did not notice the pinhole in the weld until it was identified by the third-party liner inspector, and further admitted to completing welding in the same fashion during previous leak surveys and repairs at that pond location. Examination of some of the holes in the primary and secondary liners showed characteristics of weld deformation that could likely be explained by welding while the liner system was still under vacuum.

The largest holes in the liners showed characteristics of molten weld deformation, however during the investigation and repair work, scratches and small indents were also noted in several locations, particularly on the primary liner. In some instances, the surficial scratches and indents had propagated into pinholes in the liner. The scratches and indents in the liners were consistent with mechanical damage caused by dropped or dragged objects including vacuum hoses, tools, and debris such as rocks or ice sliding down the slopes and impacting the pond bottom. A higher concentration of mechanical damage was noted in areas near the toes of the pond slopes, supporting that assumption that debris could have been sliding down the slopes of the pond.

One outcome of the investigation was the development of new operating procedures for the pond that included monitoring and pumping the subdrain and interstitial space even when the pond was not in service. The operating procedures also included maintaining a minimum liquid level in the pond to protect the pond bottom from falling rocks and ice.

Costs associated with the repairs for this pond were estimated to be in the range of $1 million.

4.4 Case Study 4

Construction of a produced water pond was completed in difficult winter conditions. Shortly after commissioning the pond, leaks in the primary and secondary LLDPE liners were suspected based on recorded inflow rates in the primary leak detection system and the salinity of the extracted fluids. A dye test was completed, which consisted of putting a dye into the subdrain pipes, turning off the subdrain pump, and monitoring the interstitial space. Doing so revealed the dyed water was entering the interstitial space, confirming a leak in the secondary liner. The pond was then emptied in order to inspect the liner, determine the cause of the leakage, and to repair observed defects in the liner.

Based on inspections, there were concerns regarding the quality of the extrusion welds. The most significant failure was attributed to an extrusion weld located on a fold. Third-party lab testing of the failure indicated that the weld did not adhere, likely due to insufficient operator pressure or welding temperature. The poor quality welds were likely related to poor working conditions encountered during construction, including excessive moisture, cold temperatures, and possibly operator error. The pond site also had a high groundwater table, with high recharge rates. Dewatering was a challenge throughout construction and during pond operation.

Costs for the repairs for this case study were estimated to be in the range of $750,000. A vacuum assisted survey was completed and the pond was placed back in service. No further liner integrity issues have been since noted.

5 Current Regulations and Standards

Lined water storage ponds are frequently used within the Oil and Gas and Precious Metal Industries throughout western Canada for the temporary and permanent storage of water that has been, or may have been, impacted by industrial operations, as well as for storage of brine and naturally saline water solutions.

Separate regulatory bodies in Alberta, British Columbia and Saskatchewan manage the licensing, design, construction, operation and use of water storage ponds within their jurisdiction. Included in this mandate are rules surrounding the use of synthetic (and non-synthetic) liners as part of a pond system such as installation requirements, operational requirements, liner specifications, allowable fluids and on-going inspection and monitoring requirements.

Alberta's Water (Ministerial) Regulation (1998) defines saline groundwater as having a total dissolved solid (TDS) concentration over 4,000 mg/L. This also applies to British Columbia (British Columbia Ministry of Environment 2005) and Saskatchewan (Saskatchewan Water Security Agency 2009). Furthermore, Manitoba Conservation and Water Stewardship released a discussion paper on June 30, 2015 with proposed regulations to support Manitoba's new Groundwater and Water Well Act. Within this document, saline water is defined as having a concentration of TDS in excess of 3,500 mg/L (Manitoba Conservation and Water Stewardship 2015). The chemical composition of produced water is operator-dependent, varies with ongoing use, and not made publicly available, however the TDS of saline water stored in lined ponds is often upwards of 50,000 parts per million (ppm).

A brief examination and comparison of the respective frameworks has been conducted to determine what information the regulators are focusing on when licensing and inspecting synthetic lined structures.

5.1 Alberta

Within the oil and gas industry, the Alberta Energy Regulator (AER) (formerly the Energy Resources Conservation Board) regulates the construction and use of most water storage ponds. To do so the AER has issued a series of "Directives" applicable to various operations within the oil and gas industry, which are discussed below.

5.1.1 Directive 55 – Storage Requirements for the Upstream Petroleum Industry

Directive 55 – Storage Requirements for the Upstream Petroleum Industry outlines the minimum storage expectations that the upstream petroleum industry must meet, including storage of process-affected waters. This document, although not currently applicable to storage of saline water associated with hydraulic fracturing, is often used as a reference baseline for industry best practices for pond design, construction, and operation.

Section 8 of Directive 55 sets the requirements for Lined Earthen Excavations. Included in the list of acceptable designs are excavations with a primary and secondary containment device, which may be synthetic liners, with a leak detection system in between (Directive 55, 8.1). When the storage system is below grade the secondary containment system must include an impervious synthetic liner (Directive 55, 8.2). The secondary containment liner must be protected by being placed over an appropriately prepared excavation and having sand or other suitable material laid on top. According to the AER, the systems described in Section 8 are typically used to store oily wastes, to receive oilfield wastes or store process solids, or to receive blowdown fluids (Directive 55, Section 8).

When a synthetic liner is used, Section 13.3 outlines additional requirements for liner specifications. To determine the suitability of a type of synthetic liner for a given application, the most important attributes to consider are: thickness, density, mass per unit area, tensile properties, tear resistance, hydrostatic resistance and puncture resistance (Directive 55, 13.3). While the AER requires liner specifications and installation details to be documented, the actual regulatory requirements are limited. Directive 55 simply requires that installation follows the manufacturer's specifications, is conducted by qualified personnel, and, if used for secondary containment, has a minimum thickness of 30 mils (Section 13.3).

5.1.2 Directive 58 – Oilfield Waste Management Requirements for the Upstream Petroleum Industry and the New Oilfield Waste Management Application Requirements Checklist

Generally speaking, the AER currently defines flowback water containing hydraulic fracturing fluid as a "waste". As such, Directive 55 would not apply, but rather *Directive 58 – Oilfield Waste Management Requirements for the Upstream*

Petroleum Industry. Directive 58 is used as the guidance document and includes requirements for oilfield waste management facilities, waste storage areas / facilities, waste transfer stations, and waste processing facilities. Directive 58 was released in 1996, prior to the development of the shale gas industry and has not undergone a substantial update since. As such, the document is void of specific references and guidance on the fluid waste associated with the shale gas industry.

To compliment Directive 58, the AER has also published a checklist titled the New Oilfield Waste Management Application Requirements (AER 2015). For facilities involved in the water and waste treatment and the use of storage ponds, this checklist is intended to guide the licensing requirements. Specifically, it outlines the requirements for site-specific information including plot plans, surface waters within 3km, regional geology and hydrogeology, baseline soil parameters including chemical analyses, groundwater monitoring (if required), and surface water management. Additional submission requirements include a process flow diagram and a list of proposed waste streams to be received and how they will be handled. Public consultation and financial security must also be addressed as part of the application. This checklist references requirements outlined within Directive 55, 56, and 58.

HGC's understanding of AER's application process is that it follows a risk-based approach, leaving it up to the operator or operator's engineer to conduct the appropriate due-diligence in site and material selection. From the operator's perspective, this can create an element of uncertainty in the application process. Based on interviews with operators, the interest and potential for water re-use exists, however many feel that the uncertainty and risk associated with the current process prohibits perusing this option. To date, PWPS have not been used to store saline water in Alberta.

5.1.1 Dam Regulations

The construction and operation of dams in Alberta is regulated by the AER under the Water Act. According to the *Alberta Dam and Canal Safety Regulation*, a dam is defined as:

> *"…a barrier constructed for the purpose of storing water, including water containing any other substance, that:*
>
> *(i) provides for a storage capacity of 30,000 cubic metres or more, and*

(ii) is 2.5 metres or more in height when measured vertically to the top of the barrier,

a. from the bed of the water body at the downstream toe of the barrier, where the barrier is across a water body, or

b. from the lowest elevation at the outside limit of the barrier, where the barrier is not across a water body, and includes a works related to the barrier."

There are three provincial level regulatory frameworks that apply to dams in Alberta:

- Water Act;
- Water (Ministerial) Regulation; and
- Dam and Canal Safety Guidelines.

As a result of the separate regulations, there are also more requirements and responsibilities in constructing and operating a dam, and consequently, higher costs. It is important to note that depending on the design of the saline water storage pond, these regulations may be applicable.

5.2 British Columbia

The British Columbia (BC) Oil and Gas Commission (OGC) regulates ponds used for the storage of hydraulic fracturing returns in BC. The OGC has recently developed and issued a detailed guideline for how to site, design, construct and operate ponds titled Management of Saline Fluids for Hydraulic Fracturing Guideline, Version 1.1 (OGC 2015). HGC worked with the OGC and was involved in the review and development of this document.

The document outlines siting requirements for storage systems using synthetic liners including both containment ponds as well as above-ground walled storage systems (AWSS), commonly known as “c-rings”. In addition to liner specification requirements, the Management of Saline Fluids for Hydraulic Fracturing Guideline has additional requirements including:

- that ponds must be designed by a professional engineer;

- construction must be overseen by professional engineer;
- a geotechnical investigation is conducted, and
- it must include a double lined system complete with a leak detection system, a sub-drain system, and site fencing.

The document also outlines requirements for monitoring groundwater and samples collected from the leak detection and sub-drain systems. With respect to liner specifications, the requirements are distinct for AWSS and containment ponds.

Chapter 3 specifies the requirements for containment pond design and construction, including provisions regarding the use of synthetic liners. Section 3.2 outlines that the pond design must be certified by an engineer in good standing with Association of Professional Engineers and Geoscientists of British Columbia (APEGBC) and meet the following additional requirements specific to the liner system:

- Liners must be tested and have quality assurance/quality control reports form the manufacturer.
- Design must include measures to ensure the liners are not damaged during the course of operations.
- Primary and secondary synthetic liners must have a minimum thickness of 60mils and hydraulic conductivity below 10^{-7}cm/s and be fit for the intended purpose and conditions that are likely to be encountered.
- The liners must be separated by an engineered seepage system that prevents direct contact between the liners.
- The design must include a leak detection system.

Chapter 3 also includes additional monitoring and operational requirements for containment ponds.

Under Section 3.4, the OGC incorporates usage of the Action Leakage Rate (ALR, as discussed in 1.7) as a monitoring provision. Should leakage in excess of the ALR be detected through a primary liner for a period of 3 consecutive days or more, or any indication of leakage through the secondary liner be detected, the OGC must be notified and remedial action taken.

5.2.1 Potential Dam Classification

Under the new BC Dam Safety Regulations (DSR Reg 40/2016) the definition of a dam is as follows:

> ***"dam"*** *means*
> *(a) a barrier constructed for the purpose of enabling the storage or diversion of water diverted from a stream or an aquifer, or both, and*
> *(b) other works that are incidental to or necessary for the barrier described in paragraph (a);*

Although the BC DSR (Reg 40/2016) does not specifically mention produced or hydraulic fracturing storage ponds, the BC Oil and Gas Commission (BCOGC) recently issued a document entitled “Water Sustainability Act Application Support for Operators” (OGC WSA Support 2016) that clarifies produced water structures would not be subject to regulation as dams.

5.3 Saskatchewan

Saskatchewan Ministry of Economy (SME) (formerly Saskatchewan Energy and Mines, SEM) regulates waste materials contaminated with crude oil or produced water and that are generated from exploration, drilling or production activities. Approvals are issued by SME under Information Guideline 97-01 (IG 97-01) to store contaminated materials, water and other produced fluids in Oily By-product Storage Structures (OBSST) until a final disposal method can be implemented.

Under IG 97-01, the application for approval to construct an OBSST must contain detailed design drawings and specifications which bear the seal of a Professional Engineer licensed to practise in Saskatchewan. OBSST’s are required to have a primary and secondary containment system as well as a monitoring system for each.

At the time of issuance in 1997, SEM explicitly noted a preference for steel as the primary containment system over synthetics. While synthetics are allowed as both primary and secondary containment, SEM noted “punctures and tearing problems have been experienced in the field with synthetics as primary liners,” (IG 97-01).

If a synthetic liner is to be used as either a primary or secondary containment system it must be compatible with waste products to be stored, placed on a stable, compacted subgrade with a sand-bedding layer, anchored in place and seams constructed and tested as per manufacturer's specifications. Care must also be taken during construction and cleaning to protect the liner. In addition to the regulations surrounding the construction and use of liners, IG 97-01 also contains sampling and monitoring criteria and requirements for leak detection systems.

5.4 Summary of Western Canadian Frameworks

The regulatory bodies in Alberta, B.C., and Saskatchewan all address the use of synthetic liners in the oil and gas industry in their respective regulations. Saskatchewan's relevant Information Guideline was issued in 1997. In Alberta, Directive 55 was issued in 2001 and in British Columbia the Saline Fluids Management Guideline were issued in 2015. Despite the differences in the regulations and the changes in synthetic liners over the past 20 years some similarities should be noted.

All three jurisdictions defer to manufacturer's specifications and standards. None of the regulations contain specific quality control procedures or installation requirements except to ensure compliance with manufacturer's specifications. Similarly all the regulations are rather limited in specific requirements for liner properties. A maximum value on hydraulic conductivity is placed in all three provinces, and B.C. and Alberta to specify liner material thickness minimums for specific uses. However, beyond these provisions the regulations are rather general in all areas and simply require that the properties be appropriate to the use and conditions. This too gives a large amount of discretion to the operator to choose liner systems in the design based on manufacturer's specifications. This discretion is limited within BC and Saskatchewan by a requirement for detailed professional engineering design to ensure proposed synthetic liners are properly vetted by someone with the appropriate expertise.

It is important to note that when the specific liner provisions are viewed in context with the entire regulatory framework for pits, ponds or storage structures, the newly issued OGC Saline Fluid Guideline contains more detailed requirements than what is typically represented in regulations. So while the regulation of the geomembrane liner installation continues to default to manufacturer specifications, the regulation of the structures themselves have evolved and developed in BC.

5.5 Other Jurisdictions, Industries, and Organizations

5.5.1 Colorado Regulations

The Colorado Oil and Gas Conservation Commission (COGCC) has jurisdiction over the regulation of the development of Colorado's oil and gas natural resources. As part of this mandate, the COGCC seeks to develop the resources in a manner "consistent with the protection of public health, safety and welfare, including the environment and wildlife resources," and maintaining working relationships with all interested parties.

The COGCC establishes operational standards for the industry through the issuance of Rules applicable to activity throughout the state. Of particular importance to the use of lined storage systems is the 900 Series: Exploration and Production Waste Management (E & P Waste Management). The 900 Series establishes the requirements for permitting, construction, operation and closure of "pits" as well as other waste management procedures and processes.

Specifically section 904 of the E & P Waste Management details pit lining requirements and specifications. For pits defined in 904(a) as required to be lined, 904(b), 904(c) and 904(d) detail more specific requirements of the liner system. The synthetic material must be "impervious", have high puncture and tear strength, and be resistant to the elements as well as the substances it will be used to store. The liner system must also be "designed, constructed, installed and maintained" in accordance with manufacturer's specifications as well as sound engineering practices. All field seams must be tested in accordance with manufacturer specifications and good engineering practices, and results maintained and made available to COGCC on request.

In addition to the above requirements, section 904(c) and 904(d) outline specific requirements for liner thickness and foundation preparation. For lined pits, the subgrade must have a minimum thickness of 12 inches after compaction, a hydraulic conductivity not exceeding 1.0×10^{-7} cm/sec, and a minimum liner thickness of 24 mils. For lined pits at centralized waste management facilities, the subgrade must have a minimum thickness of 24 inches after compaction, a hydraulic conductivity not exceeding 1.0×10^{-7} cm/sec, and a minimum liner thickness of 60mils. The remainder of the 900 series deals with the requirements regarding other aspects waste management and associated facilities.

5.5.2 Canadian Association of Petroleum Producers (CAPP)

The Canadian Association of Petroleum Producers has published the Hydraulic Fracturing Operating Practice: Fluid Transport, Handling, Storage and Disposal (CAPP 2012). This document outlines operational requirements that CAPP member companies are expected to meet or exceed when transporting, handing, storing and disposing of produced water. These include maintenance and safety protocols, following the applicable storage regulations in the operating jurisdiction, restricting wildlife from the area where produced water is stored, and safely disposing of spent fluids at approved waste management facilities. Member companies are expected to make their process for transport, handling, storage and disposal publicly available. There are no specific guidelines or recommendations with respect to synthetic liners except that storage of fracturing fluids, produced water and other fluids will follow the applicable storage regulations.

5.5.3 International Association of Geosynthetics Installers (IAGI)

The International Association of Geosynthetics Installers (IAGI) is an association of geosynthetic professionals with a goal of advancing installation and construction technologies. IAGI has instituted a Certified Welding Technician (CWT) program which serves to train and certify geomembrane liner installers. The CWT candidate must provide a resume showing a minimum of 90,000 square meters of welding experience then pass an exam which consists of a written portion and a hands-on welding test. The hands-on portion is evaluated by a third-party testing laboratory.

Based on interviews with geomembrane vendors who have hired CWTs, the program does not necessarily produce installers with sufficient competency and therefore vendors generally resort to internal training programs. Interviewees commented on the fact that a minimum amount of welding experience, if not under the guidance of a competent master welder, will not produce a suitably competent welder.

5.6 Other Industries

5.6.1 Mining

Since 1985, the US Environmental Protection Agency (EPA) has been examining the use of liners in the mining industry throughout the United States (see 1985 Report to Congress on Wastes from the Extraction and Beneficiation of Ores and Minerals, EPA 1985). The EPA found in the 1985 investigation that large mine wastes were not generally lined and that doing so may be “infeasible.”

In 1997 the EPA released a follow-up report (see Feasibility of Lining Tailings Ponds, EPA 1997a) based on data collected since the 1985 report finding that it is feasible to line certain types of mining units and that liners were in fact being used by industry.

A companion study on different types of large scale mining waste units found that of the sites studied, all used a 60 mil geomembrane regardless of whether it was required by applicable regulations or if a single or double liner system was used or required (see Feasibility Analysis: A Comparison of Phosphogysum and Uranium Mill Tailing Waste Unit Designs, EPA 1997b).

5.6.2 Industrial Landfills

In 2006 the Canadian Council of Ministers of the Environment published the National Guidelines on Hazardous Waste Landfills (CCME 2006). In addition to recommending siting and monitoring requirements to offer increased environmental protection, the Guidelines found that a combination of synthetic and natural liners to form a composite liner is the best system to reduce overall leakage. Furthermore, the Guidelines stated that “the contemporary design standard for an engineered hazardous waste landfill facility is a double composite liner system with a natural attenuation layer” (CCME 2006).

With respect to the synthetic liner itself, high density polyethylene (HDPE) was found to be the most popular material due to its strength, puncture resistance, and compatibility with many types of waste and weather conditions. While the Guidelines contain no further recommendations with respect to type or specifications of the synthetic liner, they do recommend an extensive quality assurance program by qualified personnel to ensure the proper construction and installation of all parts of the liner.

A 1995 review in the United States found that HDPE was used almost exclusively in commercial hazardous waste landfills. With one exception, a minimum thickness of at least 60 mil was used in each of the composite liners and more commonly, 80mil liner thickness (Neidorf 1995).

The Standards for Landfills in Alberta (AENV 2010) include the following investigation requirements for the construction of a new or expanding landfill: characterization of geology, hydrology, hydrogeology, and geotechnical settings, identification of groundwater and surface water regimes, description of potential contaminant flow paths, and a description of potential for impacts on groundwater and surface water regimes. The applicant must also provide a characterization of the variability, depth and engineering properties of the soil, a stability assessment, geologic data, and a topographic survey. They must confirm that the near-surface water-bearing zones do not comprise a domestic use aquifer or an exceptional aquifer and that the local near-surface water-bearing zones are hydraulically connected to permeable zones that are used for domestic water supplies. The liner system for a class II (non-hazardous waste) landfill may consist of compacted clay, compacted to at least 1 meter thick, or a composite liner system (as further discussed in Section 4.3.3), of which the clay must be compacted to at least 0.6 meter thick. The aforementioned compacted clay must achieve a hydraulic conductivity of less than $1x10^{-9}$ metres/second.

5.7 Allowable Leakage Guidelines

The definition of what qualifies as an allowable leakage rate varies by both region and industry. Alberta Environmental Protection (1996) defines the action leakage rate (ALR) as the amount (rate) of leakage through a primary liner in a double lined system that is deemed acceptable before remedial action should be taken. It is based on the liner performance method developed by Giroud and Bonaparte (1989). The ALR is calculated based on having a maximum of two pinholes per hectare of liner, each with a diameter of 2mm. The underlying assumption of the liner performance method is that the liner was properly installed and maintained.

The Geosynthetic Institute (Koerner and Koerner 2009) conducted a Survey of U.S. State Regulations on allowable leakage rates and found that the regulated allowable values range from as low as 120 liters per hectare per day (L/ha/d) to as high as 32,000 L/ha/d. The maximum regulated allowable leakage rate is approximately 4,700 L/ha/d is acceptable for wastewater ponds in most States of the USA, regardless of the water depth.

The US EPA defines the allowable leakage rate for hazardous waste landfills as the maximum flow rate that the leak detection system can remove without the fluid head on the bottom liner exceeding 0.3 m (US Code of Federal Regulations, 40 CFR Part 264.222). As a point of reference, the EPA suggests an allowable leakage rate of nearly 10,000 L/ha/d (1992).

According to the equations presented by Giroud et al. (1997), a 5 mm thick geonet leak collection layer with 0.3 m allowable head on the secondary liner would allow a leakage rate of 36 liters per minute from a single defect. With one such defect per hectare, the ALR would be approximately 50,000 L/ha/d.

Since flow through defects in a liner is directly correlated to the depth of water (i.e. the pressure head), a hole that would cause the ALR to be exceeded when a pond is full will have a fraction of the flow when pond water levels are low. Based on that principle, it would be reasonable to conclude that the criteria for allowable leakage in a pond should be calculated over incremental depths, effectively scaling the ALR to the hydraulic head. However it may only be effective up to a maximum inflow rate, as ponds with significant hydraulic head will have a correspondingly significant inflow rate into the leak detection system. In these cases, engineering mitigative measures may be implemented, such as the inclusion of a third liner.

6 Recommended Practices and Discussion

The current standards for pond liners do not provide an infallible system that will never leak under any circumstances. The constraints of current technology, construction practices, operational practices, and project economics leaves some risk for failure. However, there are excellent risk mitigation measures within current industry practices and technology that can dramatically reduce the likelihood and potential consequences of a pond failure. These measures include proper planning, site selection, engineering design, geosynthetic liner selection, onsite QA/QC inspection, pre-commissioning leak surveys, and appropriate operating and monitoring procedures. When all of these measures are adopted, the level of risk can be dramatically reduced to a point that is acceptable to most operators and regulators.

The potential frequency and severity of pond liner failures are dramatically reduced when experienced and qualified personnel are involved in the design, construction, and operation of the asset. Good practices include:

- allowing adequate schedule and resources for site selection, site investigations and contractor selection;
- detailed pond design completed by engineers experienced in the design and construction of lined ponds;
- properly selecting the materials, products, and components of a liner system. This may include chemical resistance testing of proposed liner materials submersed in the fluid to be stored (i.e. immersion testing);
- implementing a QA/QC program that includes carefully selected contractors and the onsite involvement of an experienced independent firm;
- avoidance of cold weather construction;
- using pre-commissioning leak detection surveys (as discussed below); and
- developing and following appropriate operating and monitoring procedures and practices.

6.1 Siting

Site selection can have a significant impact on the pond design, stability, environmental protection and overall cost. Sites with shallow groundwater tables and/or shallow bedrock can create risks to the stability of the pond that can be mitigated with engineered solutions, but where possible, these sites should be avoided. Sites with competent clay based soils are ideal for pond construction because they reduce the likelihood of subgrade issues, and provide better environmental containment for potential leakage.

A geotechnical investigation is essential to help identify weak stability layers, low bearing capacity soils, and geotechnical hazards which present challenges that can often be mitigated during the pond design. Up front investigations coupled with engineering design of the pond allow the owner to make adjustments to pond dimensions to minimize or mitigate subsurface hazards.

A geotechnical investigation should be completed to identify and test the soils located immediately within the proposed pond footprint. The information from the geotechnical investigation is used to properly design the pond, including:

- material suitability for use in construction;
- engineering specifications – material, compaction, moisture content; and
- construction quality assurance (CQA) to verify construction materials and methods.

Based on HGC's interviews with industry members, all participants currently conduct a geotechnical investigation prior to the design and construction of storage ponds.

6.2 Engineering Design

Regulations for ponds are continuing to advance and are trending toward having qualified professionals involved in every aspect of the pond lifecycle, including site suitability, design, construction and operation. Completing a proper site investigation and having qualified professionals design the pond help mitigate unforeseen site-specific issues and provides a pond design that is appropriate for the site. There is also benefit in having continuity in engineering support throughout the lifecycle of a pond project, so that the information revealed in the site investigations are reflected in the design, construction, and operation of the facility.

Considerations that go into the engineered design of a pond include:

- suitability of local soils and borrow source requirements;
- slope stability assessments;
- depth of excavations and fills;
- location of pond relative to groundwater and bedrock;
- groundwater management systems;
- liner material and construction specifications;
- incorporation of pumping systems and associated liner protection measures;
- liner system selection and installation details;
- leak detection systems; and
- monitoring instrumentation and wells.

Dr. Kerry Rowe concluded that generic specifications, such as those provided by the GRI, are good for routine, low-risk projects but may not be adequate for the storage of aggressive solutions such brine or surfactants (Rowe 2015).

6.3 Earthworks

A firm foundation below the liner system is necessary to minimize any settlement that may translate to strain on the geomembrane. Subgrades with soft spots may cause the liner to “sink” into low areas and put excessive stress on welds, while rocks and stones may puncture or weaken liner materials.

Pond berms must withstand substantial forces including those from traffic as well as hydraulic forces when the pond is full. As such, their appropriate construction and stability is critical to the success of the structure.

Properly compacted material provides a greater hydraulic barrier and is important to ensure engineered fill remains stable under loading. Compacted fills should be tested by a third-party using a nuclear densometer. Laboratory testing of the fill material will determine the maximum density that the soil can be compacted to, and at what moisture content the material needs to be at to achieve the maximum density (called a Standard Proctor Maximum Dry Density or SPMDD). Compacting a soil to a minimum standard (e.g. 95% SPMDD) and within a certain range of the optimum moisture content (e.g. +/- 2%) helps confirm that the material placed is uniform and cohesive, maximizes its stability, and minimizes settlement. Adequate subgrade preparation is critical in preventing extensive deformation of the geomembrane. This is apparent from Table A, Section 4.2 which indicates that stones in the subgrade are responsible for 17% of the damage that occurs during installation (Nosko et al. 1996, 2000).

High groundwater pressure can cause uplift against the base of the pond system and disrupt the structural integrity of the design. In these situations a subdrain system may be required. The system works by allowing groundwater seepage along the pond berms/bottom to drain via an interstitial space to a dedicated groundwater collection system where it can be collected and pumped out. Groundwater elevations are not static and fluctuate seasonally, and from year to year. The installation of some type of subdrain system for all lined ponds is therefore recommended, as installing subdrains after initial construction is largely unfeasible and the impact of unmanaged groundwater is significant. Industry interviews indicate that most operators choose to incorporate subdrain systems for groundwater management as part of the pond design. In British Columbia subdrains have been a regulatory requirement since 2015.

6.4 Liner System

Although regulations vary by region, the generally accepted industry practice is to store impacted or potentially impacted fluids within a synthetically lined storage pond consisting of, at a minimum, each the following:

- primary geosynthetic liner;
- interstitial leak detection layer; and
- secondary geosynthetic liner.

A secondary leak detection sump, and/or a subdrain system are commonly installed below the secondary geosynthetic liner. The guidelines and regulations to date rarely mandate the exact type of geosynthetic liner that must be used in this application, often leaving the selection of geosynthetic material to the owner. There is a wide spectrum of geosynthetic materials available, all of which can provide excellent containment if specified properly and used in the correct application. Based on industry interviews, most operators elect to include a double-liner system for pond construction and some include third-party QA during liner installation.

Liner penetrations should be avoided whenever possible as they create a weak point in the containment system due to potential differential settlement of the pipe versus the liner and the difficulties surrounding welding and testing of the weld. Sumps, riser pipes, and pipe penetrations through geomembranes are typically located in areas with the highest sustained hydraulic head on the liner (Bonaparte et al. 2002). All liner installers interviewed recommend avoiding penetrations of polyethylene liner whenever possible.

Every possible effort should be made to construct the containment system in fair weather conditions. If a winter construction window cannot be avoided, ensure the liner temperature differential is kept to a minimum. This can be challenging at the start of a new shift because the geomembrane that was previously rolled out must be welded to geomembrane material coming off the roll. If the two liners are different temperatures, it will introduce tension in and around the welds, increasing the likelihood of failure.

Both the geomembrane manufacturer and the installer should be prequalified prior to bidding, including their experience and track record in the industry and verified against a list of projects that particular company has completed in the past several years. This process should be more rigorous if winter construction is to take place.

Furthermore, a geomembrane testing program should be designed, initiated, and executed prior to starting the project. This should involve the use of a chemical compatibility test such as the EPA 9090 test or ASTM D5747 or D5322, as well as Stress Crack Resistance testing (ASTM D5397).

Fortified liners utilize additives to achieve desired performance characteristics, similar to the use of admixtures such as super plasticizers in concrete mix design.

Based on the anticipated chemical constituents in the stored water, the operator may choose to work directly with the liner manufacturer to determine if a fortified material may be appropriate for the anticipated site conditions. If stress-cracking is of significant concern LLDPE is a viable option worth investigating.

6.5 Quality Assurance and Quality Control

Quality assurance (QA) and quality control (QC) are quality programs established to ensure the work is executed according to the design and project specifications. An effective quality program does not guarantee a good product; it only serves to ensure the structure is constructed as it was designed.

Construction quality assurance and construction quality control (CQA/CQC) includes inspections and evaluations of the materials and workmanship in order to determine and document the quality of the constructed facility. CQA/CQC often starts before the contractors are selected. It is important to have individuals and parties that are knowledgeable and experienced in civil and liner construction to be involved in the procurement and construction planning processes. Ideally contractors should be selected based on not only their proposals, but based on third-party feedback based on recent project experience.

CQA/CQC is important for both the earthworks portion of the project and the liner installation. As outlined previously in this document, both the construction of the subgrade and the liner material can contribute to, or directly cause, a pond containment failure. Having qualified professionals on-site to monitor the construction process will significantly reduce the likelihood of earthworks and liner failures.

An engineered pond that is not constructed within the boundaries of the engineering specifications can completely negate the benefits of having a pond engineered to begin with. Left unsupervised, there is a long history of pond failures due to improper construction techniques, unreported changing site conditions, and minimal material inspection. A proper CQA/CQC program also provides auditable documentation recording construction conditions. This can prove to be a very valuable resource in the future if there are any issues with the pond.

QA for earthworks usually involves a representative of the engineering company who monitors the material, compaction and moisture content of the fill and ensures compliance with the pond design drawings and specifications. In addition to monitoring compaction, ongoing visual inspections are also completed to further monitor and document quality. The on-site representative provides a direct line of communication to the design engineer regarding construction progress, reports unexpected site conditions back to the engineer, and provides technical support during the construction process. An earthworks CQA program should be developed in consultation with the designing engineer, and include at least the following:

- sampling and testing of fill sources;
- visual onsite inspection to monitor material conformity and fill lift thicknesses;
- moisture content and density testing of fill to ensure the parameters of the design are met, typically using a nuclear densometer; and
- survey control.

In liner installation, proper CQA and CQC can dramatically reduce the frequency and severity of weld defects and failures, even if it does not eliminate them completely. Liner contractors have their own CQC programs, which should be evaluated during the procurement and contracting processes, and monitored for compliance during construction. Research has shown that ensuring that the contractor is using adequate QC and including QA from an independent firm can reduce the frequency of defects in field seams 30 fold (Giroud & Bonaparte 1989).

Forget et al. (2005) obtained statistics from geoelectric leak detection surveys for more than 89 projects and determined that 80% of the projects where the liner installation was performed using a rigorous CQA program had very low leak densities (an average of 4 leaks per hectare). For ponds constructed without a CQA program, an average leak density of 22 leaks per hectare was calculated. Similarly, experience shared by industry members in the interview process also supports this research; owners are finding significantly less holes, defects, and failures following implementation of third-party QA.

The components of a liner CQA/CQC program are dependent on the liner system design, materials used, and intricacies of the project. It is important that the CQA/CQC program is developed well in advance of construction, and that an independent firm is used that is both knowledgeable and experienced in liner construction and proper CQA/CQC methods.

The majority of operators interviewed as part of this study indicated that they currently employ external third-party CQA/CQC services and most also choose not to carry out any construction activities in the late fall or early winter in order to avoid the risks associated with freezing temperatures.

6.6 Post-Installation Quality Assurance

Post-installation quality assurance is a method of testing a completed liner installation to ensure all deficiencies have been located and repaired. These tests may be conducted at any point during the lifetime of the installation but may require temporary decommissioning of the pond. There are a variety of techniques that may be utilized and are discussed below.

6.6.1 Conductive Geomembrane

Conductive geomembrane is used for the purpose of spark testing an installed geomembrane to discover defects in the geomembrane. In general terms, the HDPE and LLDPE geomembranes are coextruded so that a thin layer on the bottom of the geomembrane contains a higher percentage of carbon black, which is an additive used at the manufacturing stage to provide the geomembrane with an effective UV block. It also acts as a highly conductive material. Normally the carbon black content is specified in the range of minimum 2% to a maximum of 3%. The conductive layer in a conductive geomembrane has a carbon black content in the order of 8%.

Once the geomembrane installation is complete, the perimeter of the liner sheets are welded to effectively seal them and the conductive layer is grounded. The test operator uses a high voltage, low amperage wand device to scan the surface of the geomembrane. Damage, defects and/or discontinuities in the geomembrane will cause the wand to spark through to the upper surface of the geomembrane from the underlying conductive layer. In this way, the entire surface of the geomembrane installation can be inspected by spark testing. Below are some of the advantages and disadvantages of this post-installation QA technique:

Advantages:

- conductive geomembrane has been available for about the last 20 years. Hundreds of conductive geomembrane installations have been completed and successfully tested.
- conductive geomembrane is widely available from several manufacturers.
- the premium for conductive geomembrane versus standard geomembrane is not overly excessive - adds about 20% to the cost of an installation.
- no difference in installation techniques, procedures and CQC activities.
- areas which would normally be difficult to test such as penetrations, sumps, grade changes and wrinkles can be non-destructively spark tested.

Disadvantages:

- although the cost premium for conductive geomembrane over standard geomembrane is not large, it still adds to the cost of the project.
- primary and secondary liners must be welded together along the edges to provide electrical isolation. This additional step adds time and cost to the project versus a typical installation where the liners would not be welded together at this location.
- weather can restrict or constrain the effectiveness of the spark testing.
- although it is possible to test every geomembrane layer in a multi-layer installation (double or triple liner), from a construction sequencing and perspective, it is sometimes not feasible – particularly when installing “vertically” due to earthworks delays or concern over inclement weather. In those cases, only the top geomembrane installation of a multi-layer system may be cost effectively and efficiently tested.
- a higher risk of stress cracking is associated with poor carbon black dispersion (Scheirs 2009). Interviews have indicated that operators have found higher instances of stress cracking when using conductive geomembrane, which contains between 2 to 4 times more carbon black as other polyethylenes.

6.6.2 Electrical Leak Location Surveys

Electrical leak location surveys are used to detect electrical pathways (leaks) through a geomembrane, regardless of the type of geomembrane liner material. An electrode is placed in the water above a liner installation and another is placed in the leak detection zone and a voltage is applied to both electrodes. Since the geomembrane is an insulator and water is a very good conductor, current will flow only through a breach or defect in the liner being tested. Equipment is used by the leak survey operator to locate the areas of high current flow.

There are three basic methods to perform leak surveys on exposed geomembrane installations: Water Puddle Test, Wading Survey, and Towed Array Survey.

The Water Puddle test is typically used for single liner installations where the geomembrane is installed directly on top of, and therefore in contact with, the supporting subgrade or Geosynthetic Clay Liner (GCL). Water is sprayed over the geomembrane and the “puddles” are surveyed for leaks. The Wading Survey is conducted by personnel who are physically wading in the water on the liner, while the Towed Array Survey (often performed from a boat) is used when the water is too deep to wade in or when the water quality is unsuitable or unsafe for personnel. Typically, only the top geomembrane liner of a double or triple geomembrane liner installation can be tested by either the Wading Survey method or the Towed Array Survey method. In order for these latter two methods to be successful, the top of the liner needs to be completely covered with water and the interstitial space in the underlying leak detection zone needs to be either completely filled with water or an alternative conductive layer, such as a conductive geotextile, must be installed in the interstitial space. Below are some of the advantages and disadvantages of this post-installation QA technique:

Advantages:

- very accurate and successful at finding defects and leaks in the upper liner of a double / triple liner system;
- can find very small leaks consistently;
- companies have been successfully conducting liner leak surveys since the 1990's;

- the application of the method is not costly in itself; and
- the survey methods have a long and successful track record.

Disadvantages:

- although the actual leak survey services provider is a relatively low cost, the cost to fill the pond with water and to fill the interstitial zone with water or add a conductive material below the liner adds significant cost;
- further to the above, a large source of water is required;
- the water filling operations adds significant time to the project timeline;
- testing is limited typically to only the uppermost geomembrane liner;
- most leak survey companies are from the USA, therefore mobilization times and logistics are more complex;
- penetrations in the liner (if present) must be isolated;
- once the leak survey is completed and leaks have been located and mapped, both the pond and the interstitial zone need to be drained in order to make the necessary repairs;
- weather conditions can significantly restrict or constrain the testing; and
- adding water above the liner must be closely monitored and measured so that when water is added to the interstitial zone, the primary liner does not lift due to the added hydrostatic head.

6.6.3 Acoustic Leak Surveys

Sometimes misinterpreted as an ultrasonic test method, this method works on the principle of detecting the sound signature of air being pulled through a defect by a strong vacuum exerted on the interstitial zone between two liners. Vacuum trucks (typically 1-3, depending on the pond size) are used to apply a vacuum to the interstitial space between the liners through specially designed fittings welded to the primary liner. The surface of the liner is scanned using sensitive microphone and amplifier equipment tuned to a specific frequency to detect the sound of air leakage through a hole in the liner. In order for this system to work as intended, the complete perimeter edge of the liner system should be welded and water should not be present either above the liner being tested or in the interstitial zone below the liner being tested. Existing ponds that do not have the primary and secondary liners welded together at the anchor trench have been tested, however additional vacuum trucks are typically required to make up for suction losses in the anchor trenches. This, combined with the additional background noise than can be expected with more vacuum trucks, can reduce the accuracy of the acoustic survey, although it can still be a valuable tool.

Some sources indicate that both liners of a double lined system or the top two liners of a triple liner system can be tested at the same time since the detection of leakage is done by sound. Therefore, a leak can be also located in the lower liner as holes in the lower liner will exhibit a marked change in the type of sound signature or volume of the sound signature as it is isolated and insulated from the area above the uppermost liner as the lower liner is covered by the uppermost liner. Acoustic leak surveys can frequently detect defects in a covered secondary liner, however not necessarily with the same high degree of accuracy as defects in the primary liner. Below are some of the advantages and disadvantages of this post-installation QA technique:

Advantages:

- cost is relatively low;
- does not require any conductive media in the interstitial space or above the liner;
- relatively simple and easy to set up;
- is not particularly time consuming when compared to electrical leak survey methods;
- uses locally available materials and equipment (vac trucks);
- can detect leaks in primary and secondary liners;
- effective if the design and installation are created to accommodate the Acoustic Leak Survey; and
- provided by a number of installers in western Canada.

Disadvantages:

- cannot have any water above the liner being or in the interstitial space;
- need to develop at least 10 psi vacuum in order for the method to work - if the surface area of the pond is large, this may require numerous vac truck units to work in unison; and
- for maximum effectiveness, the perimeter edge of the liner system needs to be welded / sealed which adds cost to the installation.

6.6.4 Ultrasonic Testing

This method has been used since the early 1990's to non-destructively evaluate materials and structures, including geomembranes. Ultrasonic wave travel time and waveform energy are measured to evaluate the condition of the geomembrane. Typically, the Pulse-Echo method is used to transmit ultrasonic waves through the geomembrane from the top surface of the installed material. The as-received characteristics of the ultrasonic waves allow the operator to determine the material's properties, condition and defects or discontinuities in the material. Below are some of the advantages and disadvantages of this post-installation QA technique:

Advantages:

- simple, fast and accurate assessment;
- used extensively in the energy industry to evaluate the condition of pipelines, pipeline welds, pressure vessels and storage tanks;
- can be used to evaluate installed geomembrane panels and seams;
- relatively low cost; and
- can be used to evaluate geomembrane thickness.

Disadvantages:

- wave characteristics are subject to interpretation by the testing company personnel;

- although used to evaluate pipelines, pipeline welds, etc. - not aware of any company in western Canada that performs the service on geomembrane installations;
- inspection surfaces (the geomembrane) must be clean;
- high temperatures will affect the propagation and attenuation of waves and therefore the technique can be weather dependent; and
- requires considerable effort to create the baseline (i.e.: laboratory testing) testing to provide the standard for measurement and evaluation.

6.6.5 Pre-Installed Geomembrane Monitoring Systems

Pre-installed geomembrane monitoring systems are an innovation to the standard electrical leak survey system. The liner monitoring system is based on installing a large number of sensors in a grid beneath the geomembrane liner. These systems are permanent and must be installed during the installation of the geomembrane liner. Like the water based method of leak location and detection, this technology exploits the fact that an impressed electrical current will follow moisture through a defect. The sensor grid system can be installed either above or below the geomembrane liner that is to be monitored. These systems can be configured to allow for periodic monitoring events performed at the site on an as-required basis (passive) or can be fully automated where the system can be monitored continuously from a remote location (active).

Two examples of the system include Leak Location Services Inc.'s, ELIM (Electrical Leak Imaging and Monitoring) System (active); and Sensor Group's Sensor DDS Fixed Systems (either passive or active). LLSI is based in San Antonio, Texas, while Sensor Group is based in Europe. Sensor's first system was installed 23 years ago and is still fully operational today. Below are some of the advantages and disadvantages of this post-installation QA technique:

Advantages:

- can be monitored passively or actively, depending on the client's needs;
- very small (pinhole) sized leaks can be located with 10% of the monitoring system spacing (i.e.: 10 m spacing = 1 m location accuracy) according to LLSI;

- can be tied into an alarm system if the system is an active system. Alerts can be sent via SMS / email / supervisory control and data acquisition (SCADA); and
- compatible with modern communications devices (iPad / iPhone).

Disadvantages:

- systems' high capital cost;
- Sensor Group's projects appear to be concentrated in Europe, Asia and Africa;
- one (1) monitoring system is required for each layer of geomembrane; and
- North American systems are limited to what LLSI can provide as there are no known competitors in North America.

6.6.6 Infrared Thermography

Infrared thermography offers a rapid and direct method of evaluating seam bond strength and internal flaws non-destructively (Peggs et al 1996). The surface of the weld must be heated about 10ºC and the surface temperature is monitored for a couple seconds as heat is conducted by the geomembrane. Heat is rapidly absorbed at good seams and appear blue in the thermogram. Heat is not absorbed where the bonding is poor and appear red in the thermogram. Voids and grains of sand in the seam can clearly be seen, along with blockages in the air channel.

With the appropriate artificial intelligence (AI), seams could be surveyed at about 10 km/hr and flaws analyzed in real time. A hard copy of all seams would be available for further examination. Such technology is available for special investigations, but AI needs further development for routine CQA (Peggs 2001).

Advantages:

- inspection provides a visual documentation of the weld quality over the entire length of each weld;
- no difference in installation techniques, procedures and CQC activities; and

- does not require any conductive media in the interstitial space or above the liner.

Disadvantages:

- the appropriate AI is not yet widely available and may be cost prohibitive;
- testing is limited to only the uppermost geomembrane liner; and
- thermogram characteristics are subject to interpretation by the testing company personnel.

6.7 Operational Considerations

Based on industry interviews, the majority of failures occur as a result of damage to the liner during operations. In most cases, people accessing the lined areas aren't aware of the precautions that must be taken when working around geomembranes, therefore this type of damage frequently goes unreported.

Regularly inspecting and monitoring pond parameters can provide an opportunity to intervene before a liner fails, and reduces the potential severity of a liner breach by shortening the response time. Some requirements for pond operation, monitoring, and documentation will be driven by regulations; other requirements will be driven by engineering, good practices, and risk mitigation.

The primary containment liner should be inspected for evidence of leaks and damage on a regular basis. Records of corrective actions and any issues pertaining to inspections should be kept on record and maintained for the life of the pond. Visual inspections should include but are not limited to documenting any:

- sloughing or visible changes to the shape of the earthworks underneath the liner;
- cracks or noticeable settlement in the pond berms;
- debris or foreign objects on the liner that could cause damage;
- signs wildlife was near the pond;

- dents or punctures on visible/exposed sections of the liner, particularly after maintenance events; and
- the fence and other security measures are in good condition and properly closed off to the public and wildlife.

Operating and monitoring procedures should be developed for each pond prior to commissioning. Operating procedures have frequently been developed by the pond owner, however they should include input and consultation with the designing engineers. Typical operating procedures include:

- limiting access to the pond to an absolute minimum. This may include placing all infrastructure equipment a certain distance away from the pond to ensure no access is permitted to the lined area unless they are trained liner inspection personnel;
- utilizing wildlife fences to minimize wildlife access;
- keeping vibrating equipment, piping, and hoses off the surface of the liner;
- regular equipment inspection and maintenance;
- visual inspections for signs of damage to the liner system, or indications of potential hazards such as debris or subgrade cracking;
- monitoring of leak detection and subdrain sumps, including periodic sampling and testing;
- liquid level management, including ensuring minimum and maximum volume thresholds are maintained; and
- documentation of conditions.

Some additional potential mitigative measures could include: the use of a sacrificial liner, constant visual monitoring of all construction activities in, near or around the pond after the containment system is installed, and performing regular liner maintenance inspections.

Care must be taken while working within or around lined areas. Workers should avoid placing hoses, couplers, piping, etc. into the pond or around the pond area and avoid dragging items along the liner. Sharp edges, falling objects, and vibrating items must also be avoided on the liner. These “good housekeeping” practices help ensure the integrity of the liner system is maintained. A visual inspection should be conducted after any maintenance near the liner is completed. If a puncture is suspected, the operator should contact a liner contractor to inspect and complete QA/QC and repairs if necessary.

Given the climatic conditions of western Canada, ice build-up on the surface of ponds is a possibility, despite the lower than 0ºC freezing point of saline waters. Based on interviews with vendors, industry representatives, and experts, HGC found no instances of failure caused by forces imposed by rapid drawdown of water with surficial ice frozen to the lining material. As long as there are no protrusions in the liners and there is a protective layer of ice or water on the bottom of the pond, the ice should slide up and down the pond side slopes without damaging the liner.

7 Closure

7.1 Conclusion

Lined ponds provide an economic and effective method for large volume fluid storage as required for hydraulic fracturing and water recycling programs. Some lined ponds have historically failed due to issues with site selection, liner material selection, pond design, construction, and pond operation.

Common causes of failures included liner damage (particularly during operations), welding deficiencies, and stress cracking. Research has shown that during installation, issues with seams are responsible for nearly 80% of leaks (Nosko et al. 1996, 2000). Cold-weather conditions are of particular concern as they exacerbate the brittle nature of most plastics, like HDPE. Welding in cold temperatures can be of particular risk as the temperature variances can elicit thermal shock, resulting in additional stresses which may lead to stress cracking. Failures after installation may be attributed to wrinkles and protrusions causing propagation of critical flaws, shear and peel stresses at overheated seams adjacent to wrinkles initiating stress-cracking, or elevated temperatures accelerating oxidation and stress cracking if stress relaxation is not simultaneously accelerated in proportion. General liner damage caused during operations were associated with the majority of post-construction liner failures based on industry interviews.

Excellent risk mitigation measures exist which can dramatically reduce the likelihood and potential consequences of a pond failure. These measures include:

- proper planning including a geotechnical investigation prior to finalizing site selection, so that hazards can be avoided as opposed to mitigated;
- engineering design and project support provided by professionals qualified and experienced in pond design;
- careful liner selection for climatic and service conditions, which may include immersion testing;
- project scheduling to avoid winter construction;
- thorough contractor evaluation and selection;

- third-party QA/QC inspection for both earthworks and liner installation;
- pre-commissioning leak location surveys;
- operation and maintenance procedures prepared by an experienced and qualified professional;
- strictly limiting pond access; and
- rigorous leak detection monitoring, subdrain system operating, and pond inspections.

When all of these measures are adopted, the level of risk can likely be dramatically reduced to a point that is acceptable to most operators and regulators.

7.2 Areas for Further Investigation or Research

Based on this work, including interviews and discussions with members of the industry, the following topics were highlighted as areas for further research:

- Supercooling of extrusion welds during cold-weather installation: the most appropriate cooling rate is 15ºC/min since it's most similar to that found during liner production (Peggs 1992). If extrusion welding must take place in winter conditions, how would the ambient temperature and therefore the accelerated cooling rate, affect the strength of the weld.
- More research on extrusion welds in general: the bulk of research is generally focused on wedge welding and stress cracking, however from Nosko et al. (1996, 2000) it has been shown that during the installation phase, 61% of leaks occur on extrusion welds for exposed liner systems. This is a significant source of failures which additional research may help reduce.
- More research on bituminous geomembranes: a very limited extent of research, development, and testing has been conducted to verify its performance ability.
- The use of GCLs and composite liners for saline ponds: the National Guidelines on Hazardous Waste Landfills (CCME 2006) found that a

combination of synthetic and natural liners to form a composite liner is the best system to reduce overall leakage. Many GCLs have compatibility issues with saline fluids, however further research on composite liner systems using saline-resistant GCLs may reduce risks associated with the storage of saline water.

- A risk-based guideline for developing saline fluid storage ponds in Alberta: current regulations have created confusion amongst operators. A guidance document that outlines key risks and methods that can be employed to mitigate these risks would assist Alberta operators who are planning to construct saline fluid storage ponds and help reduce the risk of future pond failures.

- Central data collection and research on the success and failures associated with saline water storage ponds: a compiled resource is not currently available.

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