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# Husab Tailings Storage Facility Containment Design

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## Abstract

Construction of what will become the second largest uranium mine in the world, Swakop Uranium's Husab Mine in Namibia, is currently underway. As part of the development, a Tailings Storage Facility (TSF) is required to retain a projected twenty years of tailings production. The main objectives of the TSF design are to protect the environment and maximize water returns to the plant. The design of the TSF basin utilizes a number of geosynthetic materials to achieve these objectives.

Design considerations for the geosynthetic lining system include seepage attenuation performance, durability, dam-slope stability, constructability and cost. The following paper provides a summary of the design considerations and presents an update on progress at the time of publication, together with lessons learnt so far.

## Introduction

Husab Mine is located within the Erongo Region, approximately 50 km northeast of Swakopmund, Namibia, southern Africa. The site lies within the Namib Naukluft National Park.

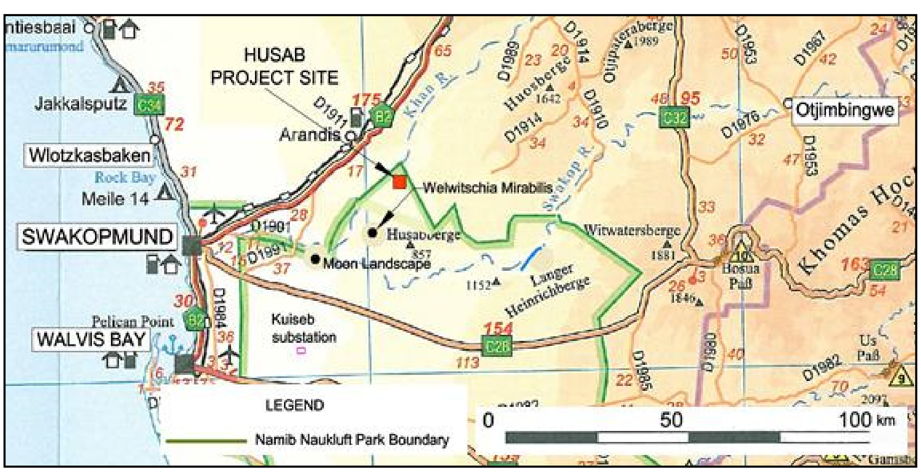

**Figure 1: Regional Setting of Husab Mine**

Annual rainfall within the Erongo Region ranges between 0 and 50 mm at the coast to 400 mm in the northeast of the region, with the estimated mean annual precipitation for the site being 76 mm. The average temperature in the summer months is 35°C, with extreme peaks of over 40°C. The area experiences predominantly west-south-westerly to westerly winds with stronger northerly winds during the winter period.

The mine site is underlain by red gneissic-granites of the Abbabis Metamorphic Complex and rocks of the Damara Sequence. Superficial deposits, in the form of colluvial soils, alluvium and fluviomarine deposits, overlie the bedrock to varying depths. The proposed Tailings Storage Facility (TSF) site is characterized by large areas of calcretized and colluvial soils with the limited existence of the shallow, alluvium-filled channels.

The mine has a design life of twenty years, with an estimated 300 million tonnes of uranium tailings being produced and deposited in the TSF. The TSF covers an area of 4.3 $Mm^2$, approximately 2.2 km by 2.1 km, and will eventually reach a maximum height of 65 m. Figure 2 shows an aerial photograph of the mine site, during the initial stages of construction just after site clearance.

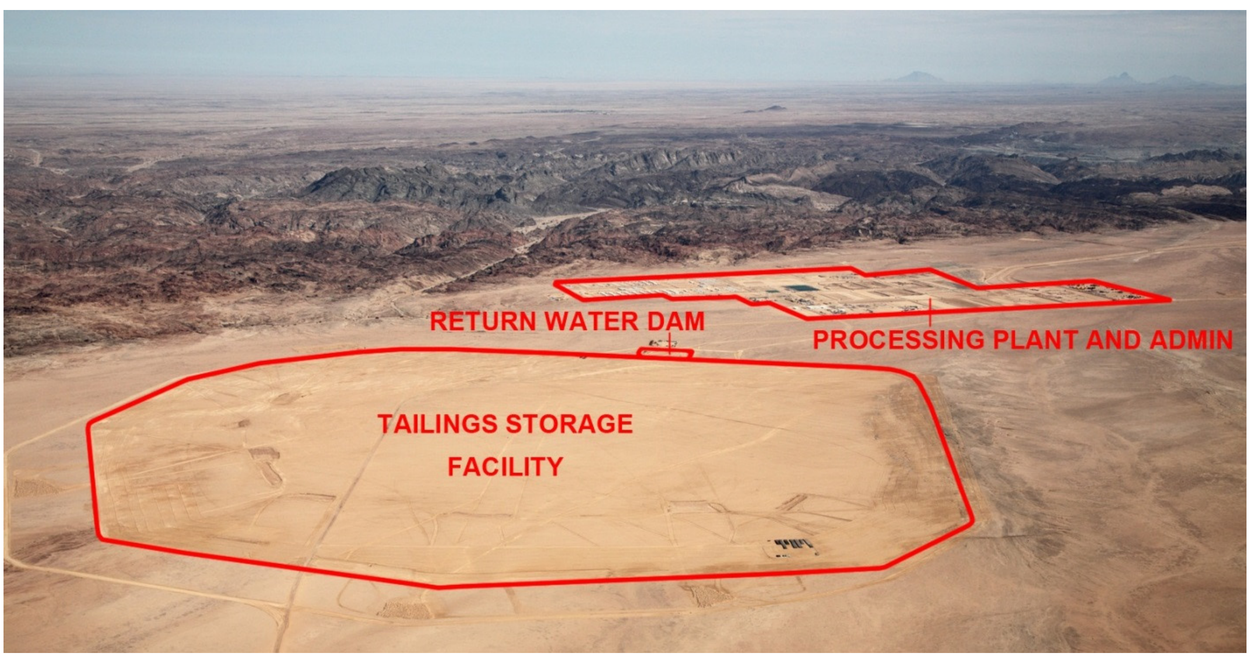


**Figure 2: Husab TSF January 2014, after Site Clearance**

## Outline of TSF Design

The containment system of the TSF consists of a geosynthetics liner, which extends across the entire basal area and beneath the starter embankment. At the outside perimeter of the starter embankment a 1 m high kicker berm will be constructed. The geomembrane will extend up to the crest of the kicker berm, where it will be anchored in a trench.

In areas where structures such as the starter embankment, main drains, pipework trenches, decants towers, and access causeway will be built, additional protection will be provided. In these areas additional protection against damage is provided by the inclusion of a needle-punched geotextile immediately above the geomembrane, which in turn is overlain by a 500 mm thick cushion layer of selected fill material. A Geosynthetic Clay Liner (GCL) beneath the geomembrane in these areas provides further hydraulic containment. In other areas a smooth- or double-textured geomembrane will be laid down on a prepared 300 mm thick protection layer. The two liner systems are shown in Figure 3.

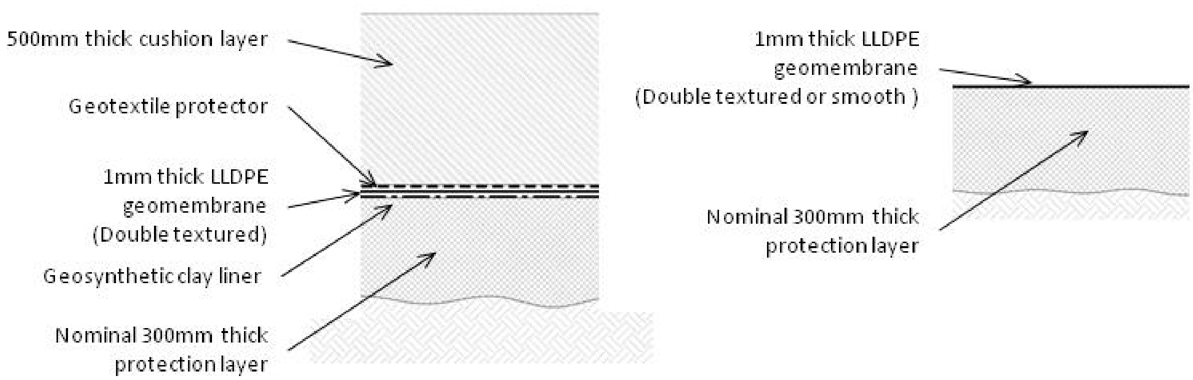


**Figure 3: Containment System Construction Details**

The underdrainage system lies above the lining system and is designed to reduce the phreatic surface within the tailings below the upstream raise, thereby increasing stability and maximizing return-water collection. The design of the underdrainage system utilizes three sets of drains, namely, toe drain (outside toe of the starter embankment), chimney drain (center of the starter embankment) and main drains (~150 m from the inside toe of the starter embankment within the TSF). Figure 4 presents the layout of the drainage which utilizes, where possible, the natural topography to drain via gravity to the south of the TSF.

The drains comprise 160 mm diameter perforated collection pipes installed within, with non-calcareous drainage material with a filter geotextile to prevent the ingress of fine particles into the drain which may block the drain. The perforated pipes feed 160 mm diameter plain pipes which flow by gravity outside of the TSF, penetrating the lining system, where they discharge into manholes from which water flows via a 450 mm diameter pipe to one of five lined seepage-water collection sumps located around the perimeter of the facility.

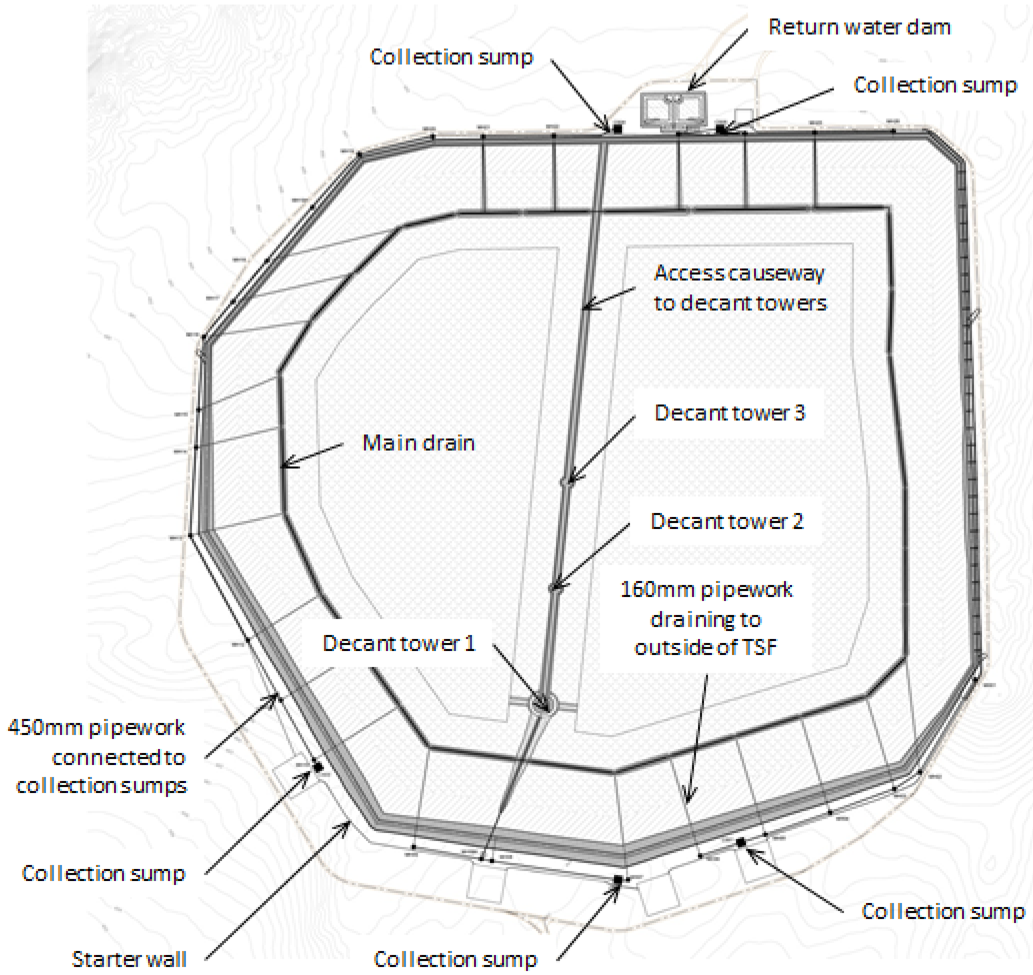


**Figure 4: Layout of Tailings Storage Facility**

All waters collected from the sumps and decant system will be pumped to the return-water dam which lies to the north of the TSF, immediately adjacent to the silt trap. The lining system of the return-water dam comprises a geomembrane liner underlain by a GCL. The perimeter slopes to the return-water dam have a gradient of 1V:2.25H for long-term stability and to facilitate the installation of the lining system.

The starter embankment height varies around the perimeter of the TSF according to the elevation of the natural ground, with a maximum height of 18 m at the southern end of the facility and a minimum height of 3 m. The final crest width of 10 m is sufficient to allow safe working during operation and the construction of the initial upstream lift above the level of the starter embankment, where it is envisaged that the construction plant will need to pass on top of the embankment. The inclination of the starter embankment slope is designed to be 1V:1.75H. However, once the tailings dam is being raised above the level of the top of the starter embankment, the downstream slope will be graded back to 1V:4H to reflect the upstream raise portion of the dam and to minimize run-off erosion in the longer term.

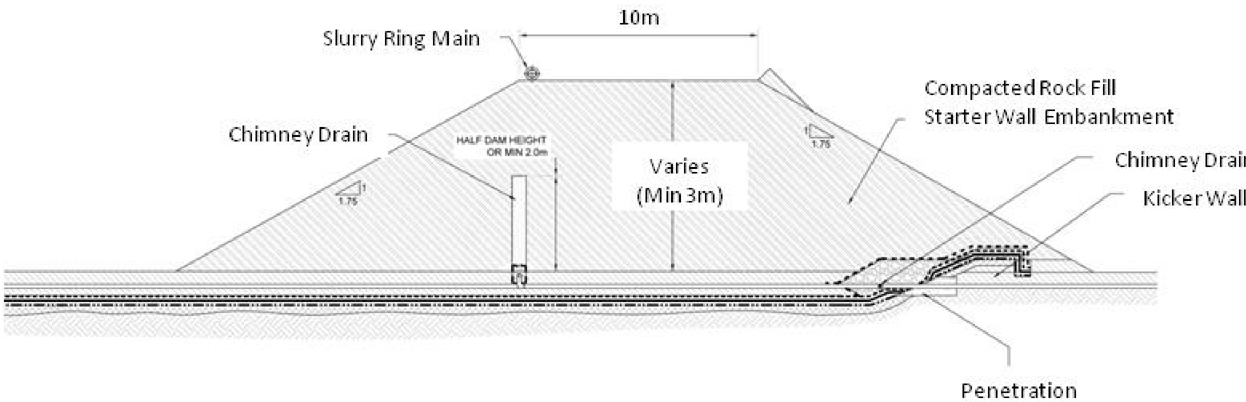


**Figure 5: Schematic Section through Starter Embankment**

The starter embankment is to be constructed over the geomembrane liner to eliminate inaccessible penetrations through the lining system. Given the granular nature of the materials used in the construction, this design also allows for the starter embankment to be utilized as part of the overall drainage system for the TSF. To achieve this, a chimney drain is included in the center of the starter embankment. In addition to this a toe drain along the outside of the embankment has been included, where the height of the embankment exceeds 3 m, in line with the lowest edge of the TSF on the southern perimeter.

## Stability

Seepage and stability analyses have been carried out to confirm the stability of the proposed TSF side slope configuration. The analyses were carried out using Seep/W and Slope/W, both of which form part of the overall geotechnical package GeoStudio 2007 Version 7.19.

Within the model, tailings were subdivided to represent permeability and shear strength variations resulting from sub-aerial deposition, in respect of grading and stress level. For the purposes of the analyses, the permeability and shear strength of the tailings were obtained from the laboratory test results for the tailings. Porewater pressure regime within the tailings was governed by the size of the operational pond and by the underdrainage system.

The permeability and shear strength of the fill forming the starter embankment was estimated based upon experience of this type of material and published data.

Of particular importance to the stability of the overall tailings is the interface friction between the various geosynthetic materials and soils, since they represent a relatively weak planar interface at the base of the model. Repeatability of shear strength test results for the geosynthetic liner interfaces is notoriously difficult to achieve, and in addition at the design stage the geosynthetic products to be used were not known. Hence, rather than undertake a laboratory-testing program, conservative values for the critical interface were selected based on published data and previous experience. Subsequently a requirement of the contract is for the supplier of the geosynthetic materials to demonstrate that their proposed materials exceed the minimum shear strength criteria assumed in the stability analysis.

The results of the seepage and stability modelling indicate that the factor of safety against a failure of the overall dam is not less than 1.3 at the end of the operating life of the TSF (the most critical time in terms of stability); and in the long term a factor of safety greater than 1.5 is achieved for all of the cross sections examined. Figure 6 presents the critical cross section which passes through the starter embankment on the southern boundary of the TSF with the maximum elevation of the tailings.

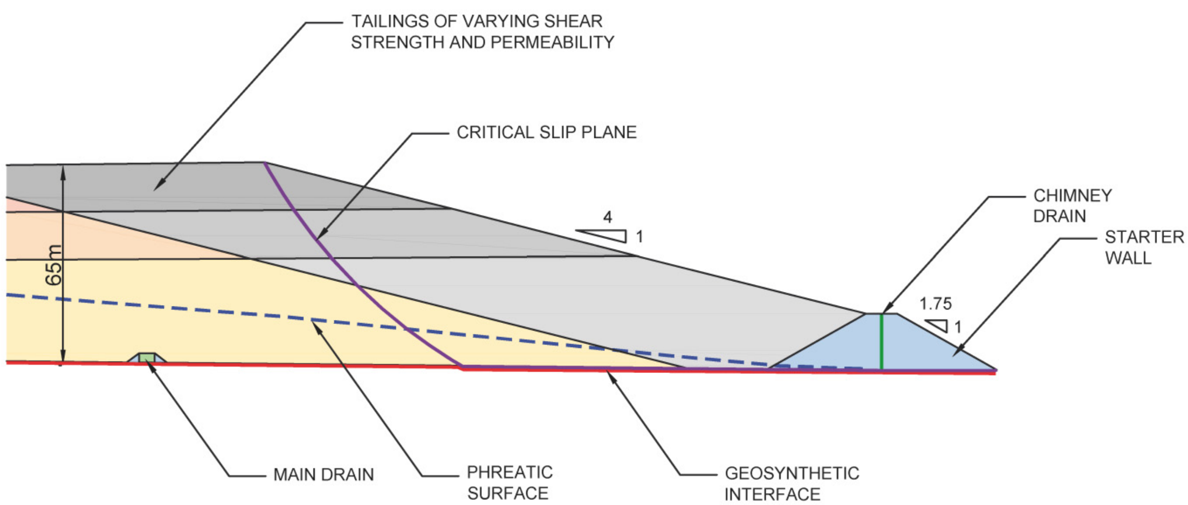


**Figure 6: Analyzed Critical Section**

However, the analyses did indicate that to ensure stability, double-textured geomembrane is required beneath the starter embankment and extending 75 m beyond the toe of the embankment into the base of the TSF. Textured geomembrane is also utilized beneath earthworks structures that sit above the liner, such as the main drains, decant towers, and access causeway, to ensure stability prior to tailings deposition.

## Geosynthetic Materials

There are a number of geosynthetic materials utilized in the construction of the containment and drainage systems to the TSF. The following provides a summary of the materials used and the logic behind the selection of each.

## Geomembrane Liner

The lining system extends across the entire basal area and beneath the starter embankment. At the outside perimeter of the starter embankment a 1 m high kicker berm is to be constructed. The geomembrane will extend up to the crest of the kicker berm and be anchored in a trench. Geomembrane liners will also be used to provide containment to the seepage collection sumps and the return-water dam.

Both high density polyethylene (HDPE) and linear low density polyethylene (LLDPE) materials were considered for the geomembrane liner. The resins used for the manufacture of both materials are closely related thermoplastic materials, with very similar chemical structure, and as a result the physical properties and durability of the materials are also similar. In selecting the type of geomembrane the physical properties and durability of the materials were considered.

HDPE geomembranes have a density greater than $0.940 g/cm^3$, whereas the density of LLDPE geomembranes is less than $0.939 g/cm^3$. Properties such as tensile and yield strength, puncture and tear resistance increase as the density of the polymer increases, whereas properties such as flexibility, elongation, and multi-axial strain tend to increase as the density decreases.

With respect to durability there are three principle causes of degradation in geomembranes, namely, environmental stress cracking, chemical attack, and oxidation. LLDPE resins were developed to overcome stress cracking, as the lower crystallite content of LLDPE is not susceptible to stress cracking. The chemical resistance of both materials is relatively comparable, and with regard to the acidic conditions within the tailings dam HDPE and LLDPE geomembranes will perform identically. With respect to weathering and thermal ageing (oxidation) HDPE has slight advantages over LLDPE, but only in regard to UV resistance, as LLDPE loses its antioxidants faster than HDPE (Islam et al., 2011). While the geomembrane could be exposed for a period of years prior to being covered by tailings, the durability in a covered application is comparable for both.

As discussed above, HDPE performs better than LLDPE with respect to a number of parameters, such as tensile strength, puncture resistance, and UV resistance. The difference in performance between the LLDPE and HDPE in respect of these parameters can be overcome by good design. For example, ensuring that no tension is generated in the geomembrane; ensuring that there is a high level of construction quality assurance (CQA) to minimize the risk of puncture; and managing the discharge of the tailings to ensure the geomembrane is covered quickly. On the other hand, the advantage LLDPE has over HDPE in respect of stress crack performance and a better ability to accommodate settlements and uneven sub-grades, is more difficult to engineer out. On this basis a 1 mm thick LLDPE geomembrane liner has been specified to provide primary containment to the TSF and the seepage collection sumps. A 2 mm thick LLDPE geomembrane liner has been specified for the return-water dam since it will be exposed for the lifetime of the mine (~20 years). Due to the climate all geomembrane products were also specified with an ultra-violet-stabilized upper white surface.

The white surface of the geomembrane not only provides an extra level of protection against UV degradation of the LLDPE, but also reduces the problem of wrinkling of the geomembrane. Due to the thermal elongation coefficient in polyethylenes, black geomembranes show wrinkles when installed and exposed to high temperatures, such as those experienced at Husab. The white surface of the geomembrane reflects the sunlight, keeping the geomembrane sheet cooler than if the surface was black, with a reported reduction in surface temperatures of between 20 percent and 40 percent (Pelte et al., 1994; Koerner and Koerner, 1995; Koerner et al., 1993). The wrinkles are significantly reduced allowing for better welding quality, longer installation times, and easier installation of subsequent materials. In addition, by reducing the surface temperature of the lined area, desiccation of the sub-base layer (clay /GCL) is reduced.

### Geosynthetic Clay Liner

In locations considered to be at risk of damage by overlying structures, i.e. starter embankment, main drain, return-water dam, etc., a higher level of containment was considered necessary. In these locations, even with a geotextile protector and cushion layer, there is a higher risk of construction damage, due to either the presence of oversize material or mechanical equipment.

To reduce the risk of damage, both increasing the thickness of the geomembrane and installing a GCL beneath the geomembrane were considered. In selecting the best option the theoretical leakage rates through the lining system were considered. While increasing the thickness from 1 mm to 2 mm thick would improve the robustness of the geomembrane element of the containment system, and CQA would minimize the number of holes upon completion of construction, installation damage would still occur. Whereas a GCL installed beneath the geomembrane significantly reduces the leakage rates through a defect as the GCL and geomembrane act as a composite liner.

When water leaks through a hole in the geomembrane, the hygroscopic montmorillonite within the GCL draws in the water molecules and swells, effectively plugging the hole. The ability of the montmorillonite to swell is dependent upon a number of factors, one of which is the pH of the permeant water passing through the GCL. The seepage water at Husab is anticipated to have an initial pH of 2.5. It has been demonstrated that as the pH of the water decreases the hydraulic conductivity of the GCL increases, with the increase being up to several orders of magnitude (Shackelford et al., 2010: Bouazza et al., 2013). However, even with the hydraulic conductivity of the GCL increased by three orders of magnitude (i.e. $10^{-8}$m/s), the theoretical leakage rate through a GCL/geomembrane liner, using Giroud and Bonaparte (1989), is two orders of magnitude better than a single geomembrane liner.

There are four main methods of manufacturing GCL, namely adhesive-bound bentonite, stitch-bonded bentonite, needle-punched bentonite, and adhesive-bound bentonite to geomembrane. As the GCL is to be installed beneath various structures within the TSF, stability is an important consideration when specifying the material since bentonite, especially when saturated, has low internal shear strength (Zornberg et al., 2005). A needle-punched GCL, where the bentonite is held between two geotextiles using needle punching, was selected for this application as the punched fibers of the geotextile effectively act as reinforcement and subsequently lead to a higher internal shear strength.

### Other Geosynthetic Materials

A number of other geosynthetic products have been used within the design, namely geotextile protector, geotextile separator, and geocomposite drainage layer.

Additional protection was installed over the geomembrane liner to provide protection from overlying layers of fill material. It was not considered necessary in the open TSF basin to provide protection to the geomembrane since the basin only receives fine grained tailings, a geotextile would degrade rapidly due to UV exposure, and sandy soils would be eroded by wind and rain. A needle-punched nonwoven geotextile protector with a mass per unit area of 540 g/m$^2$ was specified based upon the methodology set out in Koerner (1998) and assuming a protrusion height of 15 mm for the overlying protective layer of soils. Given the overlying soil layer is a silty sand material which had been screened to remove any oversized particles, this approach was considered conservative.

The geotextile separator was also used to separate the drainage stone within the underdrainage system from surrounding general fill and/or tailings. The geotextile is intended to prevent finer particles from passing into the free-draining granular materials within the drain.

## Construction Details and Considerations

### Temporary Surcharge/Wind Loads

Prior to the placement of overburden materials, geomembrane liners are exposed and endure wind damage, both during and after construction. The uplift force from an unfavorable wind blowing across the surface of a geomembrane can be considerable and result in significant damage. The forces that can be generated not only depend on the speed of the gusts, but also on the direction and topography of the landscape. Metrological data, and conditions already experienced during the construction of the processing plant at the mine, have highlighted the probability of high winds at the site. During construction the temporary surcharging of the geomembrane is the responsibility of the installer. However, after construction the design must address the likelihood of wind damage by including features which will effectively hold the geomembrane in place.

Upon completion of construction at Husab only 10 per cent of the lined area will be covered with overlying earth structures, such as the starter embankment and main drains. To prevent wind damage the exposed geomembrane in the base of the TSF needs to be anchored. Originally it was envisaged that this would be achieved by constructing anchor trenches beneath the lining system. However, the frequency of the anchor trenches and associated extrusion welding was felt to be difficult and inefficient. Hence, the design has included the placement of 1,000 kg aggregate bags, filled with selected site-won material, on a 20 m grid. Consideration must be given to the sequencing of the deployment of the geomembrane liner and the placement of the bags, as access over the installed geomembrane will be difficult and costly.

### Penetrations

Penetrations through a geomembrane liner are the weakest point in any lining system; therefore designers must consider both the integrity of the seal around the penetration and future accessibility if a repair is required. In total there are over seventy penetrations through the lining system at Husab.

The penetration design utilizes a concrete block to provide a rigid support to the pipework as it passes through the geomembrane liner. A geomembrane stud liner will be cast into the face of the concrete block onto which the geomembrane liner and boot detail can be extrusion welded. A stainless steel clamp with a rubber gasket is fitted over the boot detail and pipe, sealing off the penetration.

The design of the containment system, with the liner installed beneath the starter embankment, has enabled all the pipework penetrations to be through the kicker berm around the perimeter of the TSF. Locating the penetration at the perimeter of the TSF, rather than immediately beneath a drainage feature, ensures that maintenance can be undertaken should there be concerns about leakage. Another advantage of locating the penetration at the perimeter is that the penetration is subjected to lower loads than it would be at the center of the facility.

### Animal Damage

In deserts water is at a premium not only for humans but for animals too. This is of particular concern in respect of the drainage features outside of the TSF as any standing water, contaminated or not, will attract animals. Animals which access the lined lagoons will find it difficult to get out, due to the steep slippery sides, inevitably causing damage as they clamber to get out.

To address this, the seepage collection sumps have been filled in with drainage stone and manholes to allow pumping of the seepage water to the return-water dam. Due to the volume of through flow it is not possible to adopt this approach at the return-water dam, hence the design requires an open lagoon. Although the return-water dam is surrounded with a fence and human activity at this area will discourage animals, the possibility of animals trying to access the lined area is high. To minimize the risk of damage to the geomembrane liner by animals, access ramps and rope nets have been included.

### Construction Quality Assurance

Leakage through geosynthetic lining systems results from the presence of defects that arise during construction. These defects are generally termed pinholes, holes, and tears, and the accepted standard for calculating leakage rates is based upon a probabilistic approach that assumes a range of sizes for these defects (in $mm^2$) together with a range for the number of defects per Ha of liner according to whether or not CQA was adopted during the installation process. Table 2 presents the type, size ranges, and frequency of defects assumed within the LandSim V2.5 model (2003), which is used to undertake hydrogeological risk assessments.

**Table 1: Geomembrane Defects**

| Defect Type | Size Range ($mm^2$) | | Number per Hectare | |
|---|---|---|---|---|
| | Minimum | Maximum | Good CQA | No CQA |
| Pinhole | 0.1 | 5 | 0 to 25 | 0 to 750 |
| Hole | 5 | 100 | 0 to 5 | |
| Tear | 100 | 10,000 | 0 to 2<br>(most likely 0.1) | 0 to 10<br>(most likely 0.5) |

On the basis that the installation of the lining system is to be undertaken under full CQA supervision, numerical modeling indicated that the leakage rates per ha of liner per day are ~$2m^3$ when the dam reaches its highest elevation during operations, and $0.12m^3$ after the draw-down period of the dam (i.e. once the former pond has dried out and the phreatic surface within the tailings reduces over time to a steady state condition. This has been estimated to be around 125 years).

## Closure

At this point in time the construction works are underway, with the earthworks performed by Fraser Alexander of South Africa and the installation of the geosynthetic materials by Aquatan. So far the works have concentrated on constructing the starter embankment and in particular the installation of the underlying geocomposite lining system, which is critical to the program for the whole TSF project.

With respect to the geosynthetic materials installation a number of minor issues have been encountered, such as: termites in the subgrade beneath the liner, wind damage to exposed geosynthetic materials, and saturation of unprotected GCL due to a rain storm. All of these issues have been addressed easily on site.

Looking into the future, once the starter embankment is complete, the installation of the single geomembrane liner over the basal area of the TSF is critical to achieving the deadline. To meet the program, in excess of $20,000m^2$ of geomembrane will need to be installed on a daily basis. Although installation of geosynthetic materials is labor intensive in Africa, production rates of this magnitude are achievable given enough teams of geomembrane installers. However, programming of subgrade preparation, surcharging, and the construction of the drainage system which lies above the lining system, need to be carefully considered to keep in front of the lining works whilst maintaining access without crossing the installed liner.

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