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Appendix H – Geosynthetic Liner Design Details

I-CORP INTERNATIONAL Inc.

6072 North Ocean Boulevard, Ocean Ridge, FL 33435 USA +1-561-369-0795 (vox) +1-561-369-0895 (fax)
icorp@geosynthetic.com www.geosynthetic.com

REPORT

Geomembranes for McArthur River Mine (MRM) Covers

Prepared for

Drew Herbert

McArthur River Mine

Darwin, Australia

Co-Authored by

Ian D. Peggs
I-CORP INTERNATIONAL, Inc.
Ocean Ridge, FL, USA

J.P. Giroud
J.P. GIROUD, INC.
Paris, France

Drew Herbert
McArthur River Mine
Darwin, Australia

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GSLs for MRM Covers

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Document Author	Drew Herbert Ian D. Peggs (I-CORP INTERNATIONAL, Inc.) and J.P. Giroud (J.P. GIROUD, INC.)
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1.0 Table of contents

IN PERSPECTIVE

When asked how long they need a geomembrane liner containing waste to last, most people would want to say ”forever”, but nothing lasts “forever”. A thousand years seems to be a (more) realistic alternative. Even that is probably unnecessarily high: for how many infrastructural practices that were used in the year 1017 AD, are still in use today? Better ways to deal with what is presently considered waste will be found, not the least of which is recovering the valuable part of it. Now that does not mean one should not try to achieve maximum lifetime in that lining system but one must be realistic. Much can happen in 1,000 years.

2.0 Glossary

ASTM	American Society for Testing and Materials
BGM	Elastomeric Bituminous Geomembrane
CSPE	Chlorosulfonated Polyethylene
CI	Carbonyl Index
DSC	Differential scanning calorimeter
EPDM	Ethylene Propylene Diene Monomer
fPP	Flexible Polypropylene
FTIR	Fourier-transform infrared spectroscopy
GCL	Reinforced Geosynthetic Clay Liner
GMB	Geomembrane
GSI	The Geosynthetic Institute
GSL	Geosynthetic Liner
GTX	Geotextile
HDPE	High Density Polyethylene
IR	Infra-red
LLDPE	Linear Low Density Polyethylene
PVC	Polyvinyl Chloride
RPP	Reinforced Polypropylene
SC	Stress Crack
SCR	Stress Crack Resistance

3.0 Introduction

3.1 Background

MRM will have several overburden emplacement facilities (OEFs) that will remain on the surface as a final landform. To meet MRM's Closure Objectives, these facilities must be protected from infiltration of water and air for the assessment period of 1,000 years. To better achieve this, a cover system with a barrier layer has been specified in the conceptual designs and models.

As part of the Draft EIS investigations, section 5.5.3.5 Cover System Design undertook a Multi-criteria analysis (MCA) of several alternative cover systems. Most were based on having a compacted clay liner (CCL) as the barrier layer, but one option nominated a bituminous geomembrane (BGM) as the barrier layer.

Figure 1 Cover system alternatives assessed as part of the Draft EIS

The evaluation arrived at the following recommendation:

"The overall MCA scores for all of the cover systems with a barrier layer were comparable, with the top three scores as follows:

1) Alternative 5 – BGM cover system 46.0/60 (77%);

2) Alternative 3 – Oxygen barrier cover 45.0/60 (75%); and

3) Alternative 2 – Enhanced store and release cover system 45.0/60 (75%).

The highest score was attained by the BGM cover system. The high environmental performance of this alternative is due to anticipated very low net percolation (NP) and oxygen ingress rates, whilst moderate construction complexity and relatively high cost did not penalise the scoring significantly. However, there are a number of risks associated with this cover system design including:

□ *the durability has been rated very highly in the nuclear industry, however their emplacement conditions are expected to be materially different to the interior of the MRM OEFs;*

□ *no construction trials have been undertaken at MRM or by McArthur River Mining, leading to a higher uncertainty in this area; and*

□ *the risks of a limited friction angle and high runoff rates in high rainfall events may present a risk of geotechnical instability of the cover layer on the steeper upper batters of the NOEF.*

The durability has also been rated highly in buried applications, however the number and duration of testing is limited compared to geomembranes such as high-density polyethylene (HDPE). No site specific testing has been completed on the product for the expected MRM application.

For these reasons, it was felt prudent to defer selection of this cover system until the confidence in these areas can be increased through site specific trials of both the sheet material and its welds. The perceived additional performance of this cover will make it preferred for OEF areas of higher risk (such as where larger stored loads may be expected) if trials prove its capabilities."

This document provides an update on the BGM and other geosynthetic liners (GSLs) that may be applicable to the barrier layer in the cover systems planned for MRM. Although initial consideration was given to BGMs, there are many different geomembrane barrier materials such as HDPE, LLDPE, fPP, RPP, PVC, CSPE, and EPDM, that can provide barrier functions in different environments. They may have rough, smooth, colored, or electrically conductive surfaces to enhance different performance factors, including the ability to locate very small leaks. There are also many geosynthetic products that function as cushions, filters, separators and reinforcement that may also be incorporated in the lining system.

3.2 Report Structure and Authors

This report has been prepared for Mr. Drew Herbert of McArthur River Mine (MRM), in the Northern Territory, Australia by Dr. Ian D. Peggs of I-CORP INTERNATIONAL, Inc., USA, and Dr. J. P. Giroud of J.P. GIROUD, INC., Paris, France. In November 2017, Mr. Herbert requested that Dr. Peggs provide advice on the structure and construction of a geosynthetic liner (GSL) which is commonly called a geomembrane (GMB) - based cover system for the mine's extensive overburden emplacement facility (OEF). The information generated will be used to support MRM's EIS.

Since Dr. Peggs is a polymer materials scientist he invited Dr. Giroud, a geotechnical engineer with extensive experience in the design of geomembrane-lined structures, to contribute his expertize.

In this report, MRM provided the information in the barrier layer context section. Further background information was provided in the following draft reports:

- The memorandum titled "MRM NOEF Preliminary Settlement Estimation" dated 2017.11.25 by GHD;
- The report titled "Updated Preliminary Geotechnical Assessment NOEF" dated 2017.11 by Pando; and
- The report titled "NOEF Geosynthetic Liner Cover System - Preliminary Soil Plant Atmosphere Modelling and Analysis" dated 2017.11.23 by O'Kane Consultants (OKC).

Dr Peggs and Dr Giroud used their specialist knowledge and experience to review the suitability of various GMBs and even alternate cover systems for the MRM application.

Five lining systems containing geomembranes have been considered:

1. Single geomembrane as part of the conceptual cover system identified in OKC (2017);
2. Single composite liner;
3. Double liner;
4. Exposed cap/cover; and
5. Geosynthetic clay liner (GCL).

This report discusses the single geomembrane options.

4.0 Barrier Layer Context

4.1 Objectives of the Barrier Layer

The key performance criteria for the barrier layer are discussed below.

In order to limit the risk of advection currents transporting oxygen through to the core of the OEF, the bulk air permeability must be 1 x 10^{-11}m^2 or less.

Whilst waterways modelling indicates that with mitigation strategies, average Net Percolation (NP) of 11% of rainfall through the main North OEF (NOEF) cover system (the modelled performance with a CCL as the barrier layer) can still meet the closure objectives, it is desired to operate in the Very Low (< 5% of rainfall) NP category (OKC, 2017).

The GSL must provide a stable substrate for overlying cover materials in all parts of the OEF, with slopes up to 1V:3H and for the maximum rain design event (defined as a 1 in 1,000 year 72-hour rain events in section 3.3.1.2 of OKC (2017)).

The evaluation period for the Project is 1,000 years. Due to the costs and complexities of liner replacement, a service life of at least 500 years is desired.

4.2 Barrier Layer Setting

The conditions in which the barrier layer will need to perform are described in this section. The main OEF on site is the NOEF, with a cover area of around 525 ha. It will be up to 140m high, with trilinear concave batter slopes from 1V:4.5H on the lower third of the slope, 1:3.5 in the mid-batter and up to 1:3 for the top third. Free-draining coarse rock will be incorporated into the cover system above the barrier layer, connecting to surface drains (Figure 2). Whilst the closure plan for the 190 ha Tailings Storage Facility (TSF) is to reprocess the tailings and remove the TSF landform, there is a chance that it may remain on land. Therefore, the top of this structure may also require a cover system with a barrier layer in it.

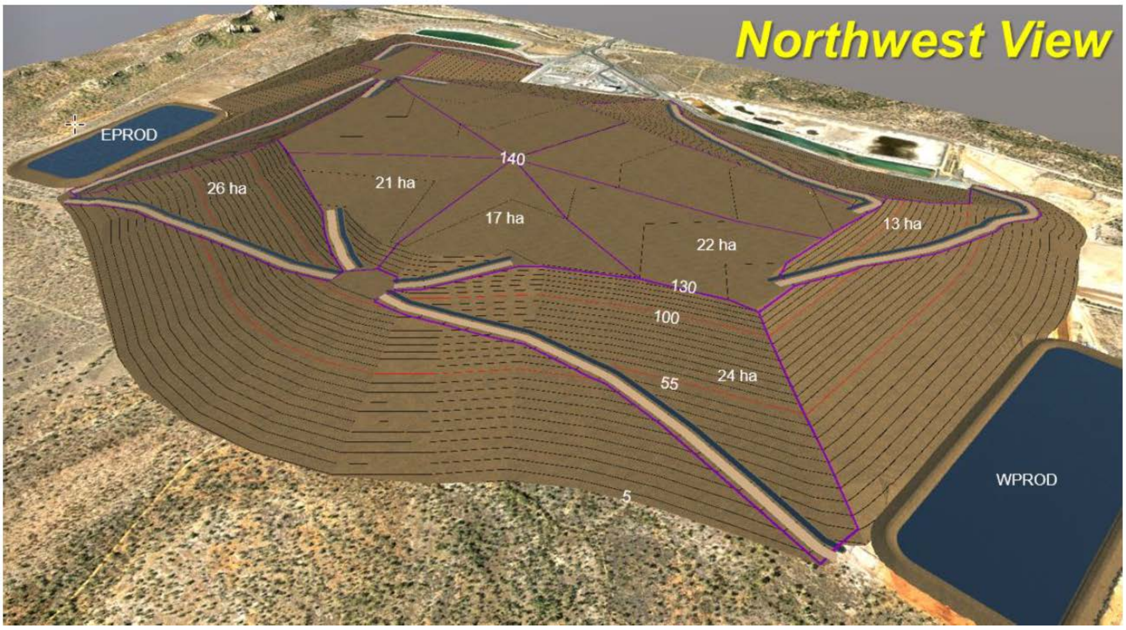

Figure 2 – Impression of the completed NOEF showing drainage catchments

4.2.1 Climate

OKC (2016) Chapter 3 describes the climate that the OEFs will be subject to, with the following two tables extracted from this report.

Table 1 - Monthly and annual climate averages for 125-year climate database developed for MRM (from OKC(2016))

Month	Temperature (°C)		Relative Humidity (%)		Rainfall	PE	AET*
	Max	Min	9 AM	3 PM	(mm)	(mm)	(mm)
January	35.8	24.8	90.0	49.0	188	173	118
February	35.0	24.5	92.7	52.0	172	147	104
March	34.7	23.2	92.6	49.6	141	159	104
April	34.2	20.3	87.2	40.1	32	155	44
May	31.9	16.5	82.6	33.7	7	144	22

Month	Temperature (°C)		Relative Humidity (%)		Rainfall	PE	AET*
	Max	Min	9 AM	3 PM	(mm)	(mm)	(mm)
June	29.4	12.7	82.5	30.8	5	126	17
July	29.3	12.0	81.0	28.9	1	136	16
August	31.6	13.5	80.6	27.8	0	160	16
September	34.6	16.9	82.0	29.7	3	181	30
October	37.2	20.9	80.7	32.2	14	209	60
November	38.1	23.9	80.5	36.3	42	204	74
December	37.5	24.9	85.9	42.8	109	195	95
Annual	34.1	19.5	84.8	37.7	715	1989	700

*AET from BOM website which estimates regional evapotranspiration rates; will vary based on cover system performance.

Figure 3 provides the cumulative deviation from the mean annual rainfall, and shows the site has experienced extended periods of drying, but is currently in an extended wetting period (although not included in the graph, the 2015 model year was also wetter than average with 800 mm of rainfall).

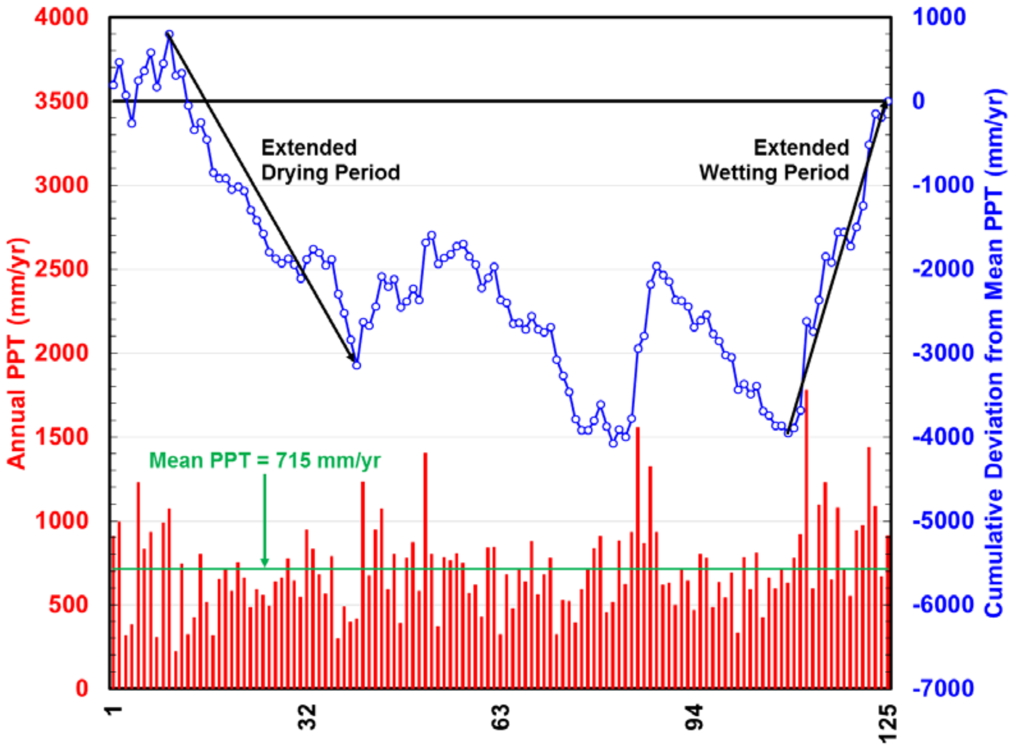

Figure 3 - Annual precipitation (PPT) and cumulative deviation from the mean from 125-year MRM climate database (from OKC(2016))

It can be seen that there is a distinct dry season with minimal rainfall; cover system construction works will typically be planned during this period and the cusps, between April and November. The daytime temperatures can get high all year round – welding of HDPE liner on site has often been undertaken on nightshift to avoid the daytime high temperatures that cause high wrinkles in HDPE geomembranes, which makes welding difficult. Good welding is just as important as good geomembrane material.

Construction of the cover will need to contend with winds (Table 2). Wind conditions are typically calmer at night during the dry season.

Table 2 - Average monthly wind speeds

Parameter	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Annual
Mean 9 am wind speed (km/h)	6.9	5.9	5.5	6.9	8.7	8.7	8.1	8.6	9.4	9.3	8.2	7.2	7.8
Mean 3 pm wind speed (km/h)	10.2	9.4	10.1	10.7	10.2	10.5	11.0	11.8	13.1	13.2	12.5	11.4	11.2

The OEFs are in operating mining areas, meaning they will be subject to typical mining environments: dust, small hydrocarbon spills, and trafficking by heavy rubber-tyred and tracked equipment such as haul trucks and dozers. However, the detailed cover construction will be undertaken by smaller civil construction machines.

4.2.2 OEF Construction Materials and Cover Design

The overburden materials to be stored in the OEFs under the cover are typically moderate to high strength sulphidic shales and breccias. These are typically sized from fines to +1m, and are too coarse to form a substrate for the application of a liner. However, the shales can be packed down reasonably smoothly once rolled (Figure 4). The addition of -20mm crushed Heavy Media Rejects (HMR) – a by-product of the processing operations – will assist in closing up the pore spaces of the underlying surface in preparation for cover construction. The sulphidic materials in the NOEF can oxidise and generate heat, and commonly the gases SO_2, CO, CO_2, NO_x and H_2S. In the past, spontaneous combustion occurred inside the pile, resulting in gas venting cracks in the top of the NOEF. The core of the rock pile remains hot in places, so gas venting will be an ongoing issue to manage for a number of years until the oxygen supply is cut off and the mass cools down. Temperatures of the rock close to the liner in the cover system could reasonably be expected to be in the 45°C to 65°C range.

Figure 4 - Rolled shale and alluvial materials on the NOEF

Alluvial materials such as clay, silts, sand, gravels and cobbles will be mined from the upper benches of the open cut (Figure 5). These are planned to be stockpiled and used both within the OEF and in the cover system as underliners, overliners, and growth media layers. Conceptual profiles for the NOEF cover have been developed by OKC (2017) for both the batters and plateau (refer to Figure 6 and Figure 7), using these materials. The drainage layer breccia is expected to be blasted run-of-mine (ROM) waste rock from the open cut, with no screening or processing. The mechanical compatibility of soil/rock and the geomembrane will require testing.

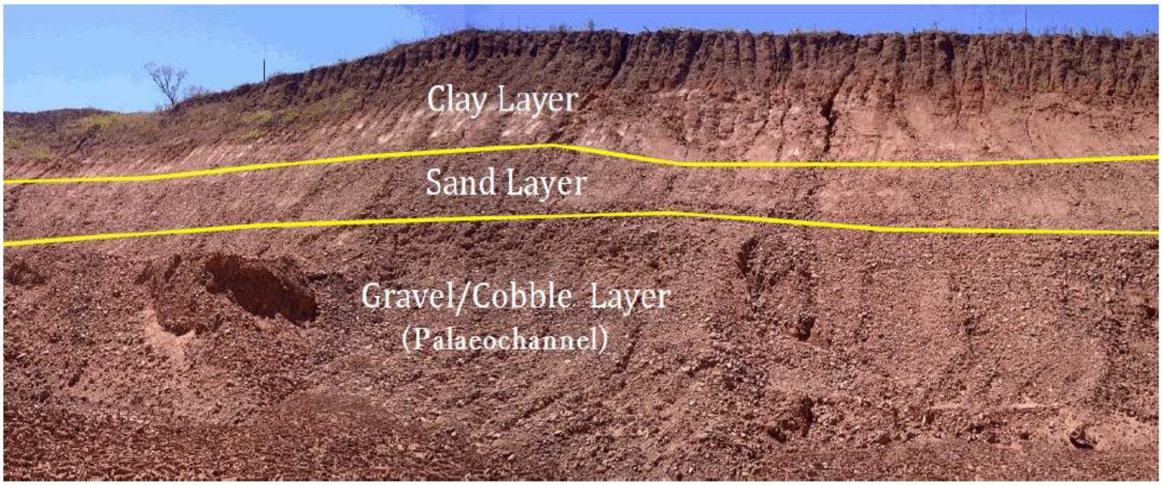

Figure 5 - Profile through the open cut showing zones of alluvial materials

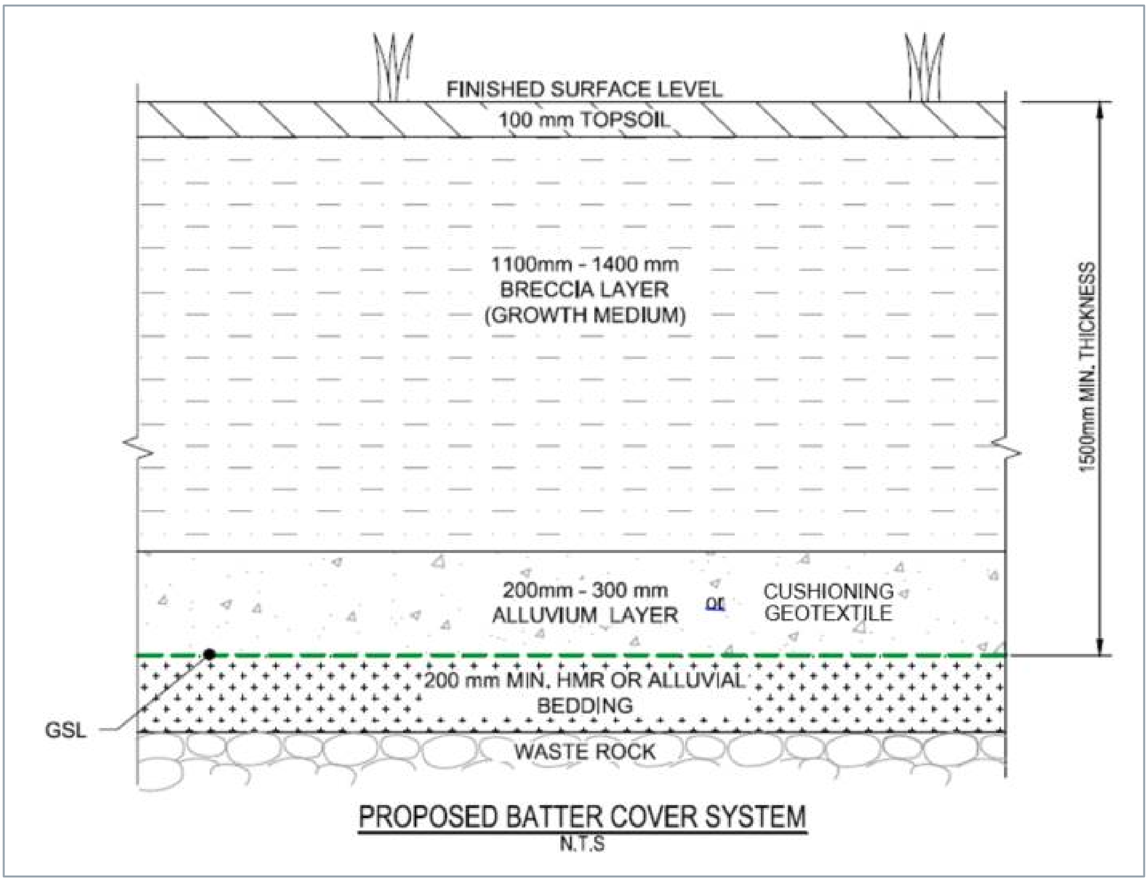

Figure 6 – Conceptual cover system profile for the NOEF batters

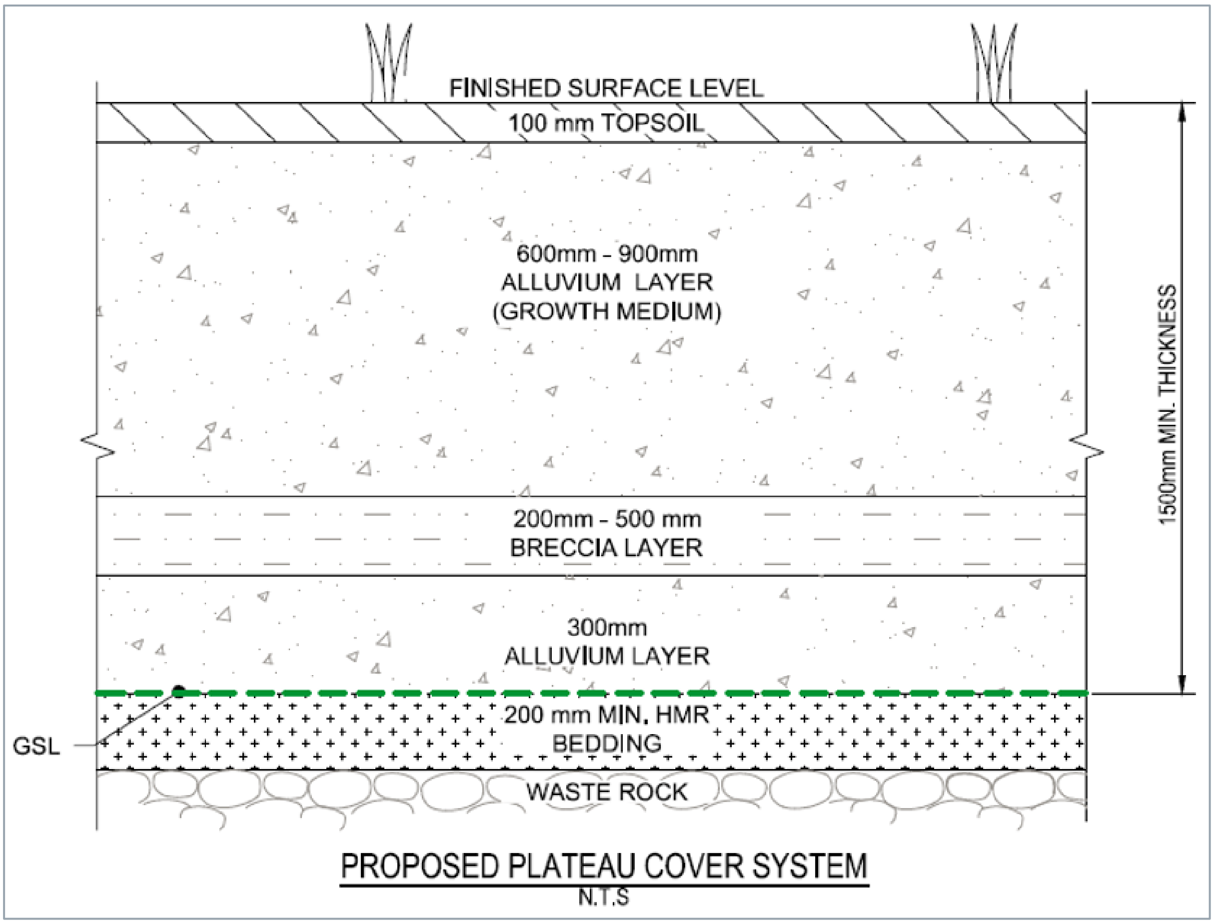

Figure 7 - Conceptual cover system profile for the NOEF plateau

Preliminary settlement analysis of the NOEF has been completed by GHD (2017). Assuming that the Immediate Settlement is irrelevant due to delayed application of the liner, long-term creep and strains in the cover liner is summarized in the table below.

Table 10 Estimates of Differential Creep Settlements

Differential	Creep Settlements at End of Design Life (1,000 years)			
	140m Upper Bound – 130m Upper bound	140m Best Estimate – 130m Best Estimate	140m Upper Bound – 130m Best Estimate	140m Upper Bound – 130m Lower Bound (*)
Creep in mm	450	300	2,400	4,350
Strain over 40m	1%	1%	6%	11%

Geotechnical stability modelling of the slopes, including alluvial layers in the batter cover, is described in Pando, 2017. This showed a risk of alluvial layers in the batter area becoming saturated in very wet periods and having a reduced Factor of Safety. Further work is required to confirm material properties.

Leachate generated from water infiltration into the OEF core is likely to be neutral pH, with high levels of Ca and Mg sulphates as a result of acid neutralisation within the rocks. Zinc is likely to be from 5 to 850 µg/L.

4.2.3 Biological Agents

The OEFs will be rehabilitated to contain native vegetation focussed on grasses and low shrubs. However, it is reasonable to expect trees will establish themselves over time. The low moisture retaining capacity of the coarse batter rock will increase the likelihood of tree roots extending deeper into the cover system in an attempt to gather more moisture – the barrier layer will therefore be at risk of penetration by these roots. However, in many cases roots have been seen to turn parallel to the geomembrane.

The MRM area has termites around the NOEF, as evidenced by mounds on the surface. Termites may establish themselves in the OEF covers, and create burrows and mounds within and out of the alluvial materials.

Other fauna known in the area that burrow for food or shelter include Echidnas, Sand Goannas (Varanus gouldii), Rainbow Bee-eater bird, Striated Pardalote bird, bandicoots and rats. These all would not be expected to excavate down to and through the barrier layer. Arguably the biggest threat to the liner would be posed by feral pigs, digging deep for food.

It is unknown if MRM has any unusual bacteria that may affect any potential liners. This will have to be investigated further for short-listed materials.

Note that the NOEF landform is not considered to be a "walkaway" proposition, and ongoing maintenance will be required. Resources and finances for this will be provided for in an agreed long-term security bond funding mechanism. Therefore, periodic removal of high-risk trees and other biological threats can be considered to manage risks associated with these potential failure mechanisms.

4.2.4 Constructability Considerations

The mine is located in remote Australia. Labour costs are high in Australia, so options with high labour components for installation will have higher costs. The project does have a long life though (OEF lining could be expected from 2019 to 2032), so specialised training and equipment for cover construction can be considered.

The rate of cover construction will typically be from 20 to 40 hectares per year. If a 6-month window of liner placement is considered (i.e. during the dry season only), installation rates of 3.3 to 7 ha per month will be required. This should not be a problem for an experienced installation company.

The NOEF is already approximately 70m high, with individual slope lengths of over 200m in places at 1:4 gradients. There are no berms on these slopes. The liner must be able to be applied on these geometries.

The primary difference between the various candidate materials in relation to constructability is whether their thickness and weight allow large panels to be prefabricated under a controlled environment in a plant, or whether all welding must be done in the field and subject to the vagaries of the weather – wind, rain, dust, etc. Prefabrication will speed installation, and reduce the number of field welds to test.

Welding/seaming of most materials is done thermally and should not be a problem. BGMs are welded with a handheld propane torch which is reported to require only a little operator training.

However, detail work and large pipe penetrations require additional expertize. One of the BGM manufacturers has a small tractor with an array of ultrasonic transducers to continuously ultrasonically non-destructively test all the weld area.

A few difficulties occur in welding conductive backed HDPE geomembranes, in that special equipment has to be used to ensure the conductive layer through the weld is destroyed and made non-conductive to avoid false positive signals along cut edges. Welding a "conventional" HDPE to one of the new "high temperature" geomembranes requires extra care. When there is a nonconductive layer, such as a drainage layer, under the geomembrane the conductive layers between panels must be connected electrically.

MRM will be required to verify the installed performance of the cover system over the OEFs. Therefore, the ability to conduct Quality Assurance/Quality Control (QA/QC) of the liner product and its installation will be required. The ability to detect, locate and repair defects will also be advantageous, and may impact the design details to ensure that leak surveys are feasible.

4.2.5 Liner Installation & Quality Assurance

Of course, the most durable, best performing and most appropriate geomembrane material is wasted if the design is not good and if installation is poorly done. The design should be peer reviewed by an independent, knowledgeable engineer. There should be a written construction quality assurance (CQA) plan with which all parties agree. This should include manufacturing QA (MQA). Note that the intent of CQA is not to ensure that perfection is achieved, rather it is to ensure that what was designed and approved is built. Therefore, if the design is inadequate so too will be the finished product, unless CQA has caught and resolved the defficiencies before construction starts.

The CQA Plan should act as the glue that integrates all plans and instructions to ensure nothing falls through the cracks nor are there any conflicting overlaps.

CQA, both polymeric and geotechnical, should be done on a full-time basis during installation.

During construction, visual inspection for damage must be conducted. This can be aided if multi-coloured GMBs such as white-surface black-core HDPE are used. CQA should also include geoelectrical testing of the geomembrane (where compaitble) for holes after any soil or rock has been placed on the liner, since this is when most damage (up to 80%) to a geomembrane is done. (Nosko, et. al., 1996). The method and protocol used for the survey will have to be agreed beforehand to ensure that an effective survey is possible. Note that for the geoelectric method to be successful the geomembrane must be an electrical insulator, therefore EPDM and GCLs cannot be surveyed this way.

When construction is completed, primary (upper) geomembranes can be tested for leaks using infra red (IR) spectroscopy tuned to detect gases generated from the rock pile below the GMB.

The IR spectroscopy technique for remote gas sensing has been used in the United States a number of times to locate leaks in landfill caps. Three remote sensors detect landfill gas plumes from several metres, show their source, and measure flow rate and concentration. The two primary requirements are a characteristic tracer gas and a positive gas pressure under the liner. A big advantage of this approach is that 100% of the liner can be surveyed.

Repairs can only be made by excavation to the geomembrane.

It is good practice to install a series of coupons of GMB that can be easily removed so any degradation can periodically be assessed.

5.0 Geosynthetic Liner Options

There are many geosynthetic liners that are available on the market for barriers. The following descriptions were sourced from Rowe (2004) and Scheirs (2009):

- **High density polyethylene (HDPE)** geomembrane is a polymeric compound made from polyethylene resin, carbon black and additives. There are many different HDPE resins with the manufacturer's proprietary additives formulation. Therefore, all HDPE geomembranes are not the same. HDPE is commonly used for waste containment as it exhibits high chemical resistance to a wide range of chemicals. HDPE geomembranes are stiff. They are susceptible to stress cracking to different degrees depending on the polyethylene resin. HDPE is susceptible to accelerated environmental stress cracking in oxidizing acids, chlorinated solvents, aromatic hydrocarbons and detergents.
- **Linear low density polyethylene (LLDPE)** geomembrane, similar to HDPE, is also made from polyethylene resin, carbon black and additives. The key differences from HDPE are that LLDPE has a lower crystallinity, lower stiffness and lower density, which make it more flexible and less susceptible to stress cracking.
- **Ethylene propylene diene monomer (EPDM)** geomembrane is a vulcanised rubber (thermoset rubber) geomembrane. The rubber molecules crosslink during the manufacturing process to give an elastic, flexible and chemically stable geomembrane. Un-reinforced EPDM geomembranes are extensible and readily conform to subgrade contours.
- **Chlorosulfonated polyethylene (CSPE)** geomembrane is a thermally weldable geomembrane based on chlorosulfonated polyethylene synthetic rubber and is only available in a number of reinforced versions (CSPE-R)
- **Polyvinyl chloride (PVC)** geomembrane is made from polyvinyl chloride resin, plasticiser(s), fillers, carbon black and additives. PVC geomembranesliners are very flexible. Also, they are very extensible and readily conform to subgrade contours.
- **Flexible polypropylene (fPP)** geomembrane is made using a polymeric compound made from polypropylene resin, other resins (ethylene propylene), carbon black and additives. fPP geomembranes have low crystallinity making them very flexible and less susceptible to stress cracking than HDPE geomembranes. They have lower thermal expansion coefficients (fewer wrinkles) than HDPE.

Other geosynthetic liners to be considered are:

- **Elastomeric bituminous geomembrane (BGM)** is an alternative to the traditional and more commonly used polymeric geomembranes. Bitumen is a tarry residue obtained from the distillation of crude oil and is a thick, highly viscous hydrocarbon. Modern bitumen products have been developed that are less viscous and more flexible than traditional bitumen and can be used as flexible membranes. Bitumen is susceptible to the development of cracking with time and it must be associated with a certain amount (approximately 10 to 15%) of elastomer to eliminate the risk of cracking. Bituminous geomembranes are always reinforced with a nonwoven geotextile. BGMs are relatively heavy.

- **Concrete PE hybrid –** this product consists of a cement-sand mix inside two needle-punched geotextile layers so that the mix is encased in the fibres. A geomembrane of the user's choice (commonly HDPE or LLDPE) can then be bonded to the underside. After rolling out the product, it is wetted down so that the concrete sets, achieving a strength of about 40MPa after 28 days. This protects the geomembrane from damage and degradation.
- **Reinforced geosynthetic clay liner (GCL)** is comprised of layers of woven or nonwoven geotextiles encapsulating a thin layer of sodium bentonite clay, which has been reinforced (usually via needle punching) to improve the performance. A GCL may have a PE film on one side to improve impermeability. The bentonite may have polymer additives to improve impermeability to specific chemicals.

Scheirs compiled a simple comparison table of the material properties of the polymeric geomembranes. A modified version is shown in Table 3.

Table 3- A comparison of polymeric geomembranes

Property	HDPE	LLDPE	EPDM	CSPE-R	PVC	fPP-R	fPP
Water tightness	A	A	A	A	A	A	A
UV resistance	A	D	A	A	D	A	A
Service Life	A	C	A	A	D	A	A
High temperature resistance	B	D	A	B	D	A	A
Flexibility	D	B	A	A	A	A	A
Extensibility	D	C	A	D	A	D	A
Chemical resistance	A	B	B	B	C	B	B
Resistance to hydrocarbons	B	C	D	D	C	C	C
Stress crack resistance	D	B	A	A	B	A	A
Yield point	D	C	A	B	C	B	B
Resistance to plasticizer extraction	A	A	A	A	D	A	A
Root resistance	A	A	A	B	B	A	A
Resistance to microbiological attack	A	A	A	A	C	A	A
Puncture resistance	C	B	B	B	B	B	A
Surface friction	D*	D*	A	B	B	B	B
Slope stability	C*	B*	A	B	A	B	B
Wrinkling	D	B	A	A	A	A	A
Dimensional stability	D	D	A	A	B	A	B
Mutliaxial strain	D	C	A	C	B	C	B
Resistance to settlement	C	B	A	C	A	C	B
Seamability	C	B	A	B	B	A	B
Seam strength	A	A	A	A	B	A	A

Property	HDPE	LLDPE	EPDM	CSPE-R	PVC	fPP-R	fPP
Seam testing	A	A	A	B	A	B	A
Ease of installation	C	C	A	B	A	B	B
Permeability	A	B	B	B	C	B	B
Environmental properties	A	A	A	B	D	A	A
Repairability	C	B	B	D	C	B	B
Details, design & installation	D	C	B	B	B	C	B
Conformance to substrate	D	C	A	B	B	C	B

A-excellent; B-good; C-fair; D-poor * - unless textured

Each product will be discussed in the context of its suitability for use at MRM.

5.1 HDPE

HDPE is a commonly used geomembrane in the mining industry, including at MRM. It has been used at MRM for dam and drain lining, in thicknesses from 1.0mm to 2.0mm. It will meet the permeability objectives, and will manage the risks associated with chemical attack well. Note that if the Langelier saturation index of the water is below zero, one may have to be careful in the use of thermoplastic polyolefin geomembranes. (Thermoplastic polyolefin is a class of polymers that include polyethylene and polypropylene). Preliminary estimates of MRM leachates indicate this index is around zero. There are many companies in Australia capable of supply and/or installation of the product. Also, the QA/QC processes are well understood but need knowledgeable and experienced practitioners.

There are several downsides to HDPE though. As experienced at MRM, its dimensional stability under temperature changes is poor – works have been conducted at night in the past to reduce these issues. Note that this is a construction issue, as the liner should remain at a fairly stable temperature and under confinement stress once buried under the cover. The wrinkles that can form due to the dimension changes are due to HDPE's high stiffness. Large wrinkles can become locations of stress cracking. White surface sheet has far fewer wrinkles than black sheet due to its lower temperature when exposed to the sun. Wrinkles are not dispersed when covered.

HDPE geomembranes have a very low yield strain (typically 12 to 15%). Due to this low yield strain and the parabolic shape of their stress-strain curve, their strain in the field should be limited to about 5 to 6%. Using a factor of safety, it is often recommended to limit their strain to 3%. As a result of this tensile strain limitation, HDPE geomembranes do not cope well with differential settlement.

HDPE geomembranes are stiff and they do not conform to subgrade contours, which reduces their resistance to puncturing under high normal stresses. However, this is not an issue in a cover.

It is important to note that, when an HDPE geomembrane liner fails, the failure occurs generally within a few years after installation due to stress cracking, or shortly after the liner is put in service (e.g. at first filling of a reservoir) due to the poor mechanical properties of HDPE geomembranes. Design and installation that minimize stresses is essential to avoid premature failure of HDPE geomembranes in structures where stresses could develop if the design is not adequate.

The life of HDPE can be quite variable – it can be affected by heat and constant or cyclic stresses, but the use of specialised formulations can extend the life into the desired range. Some key research into liner life is discussed below.

Unfortunately, geomembrane lining systems were first installed only about 40-50 years ago, so there is little confirmation of the proposed calculated lifetimes being practically achieved. Most quantitative durability work has been performed on HDPE because of its predominant use in waste containment lining systems. A significant amount of work has been done by Prof. Kerry Rowe's research group at Queens University (QU) in Kingston Ontario.

Prof. Rowe's research group has incubated HDPE geomembranes for 17 years in air, water, and simulated municipal solid waste leachate at temperatures of 40 to 85ºC (Ewais, A.M.R, Rowe K., Rimal, S., Sangam, H.P., to be published) and, by Arrhenius modelling, projected half-lives as shown in Table 4. Note that the half-life is arbitrarily defined to be the end of the service life, and is defined as the time to reach 50% of original strength and/or break elongation. Break elongation is used because it is sensitive to surface damage. The results show that temperature has a significant effect on durability. However, lifetimes exceeding 500 years are achievable with HDPE.

Table 4 – Half-lives of incubated HDPE

Half Lives (yrs) of Incubated HDPE		
Temperature	20ºC	60ºC
Air	1700	170
Water	1500	18
Leachate	660	~13

The research also showed that there is a wide range of performance characteristics, even though the materials tested were all "HDPE". For instance, the high pressure oxidation time (HP-OIT) used to evaluate the remaining additives that protect the HDPE against oxidation mostly will drop to a low residual value before material starts to degrade, but in other cases degradation will commence before the HP-OIT reaches its low residual value. Clearly, all "HDPEs" are not the same.

Prof. Koerner, at the Geosynthetic Institute (Koerner, et. al 2016), projects that extrapolations of HDPE geomembrane tests conducted at 55 to 85ºC then adjusted back to the standard 20ºC reporting temperature have half-lives of 70 years when exposed and 450 years when buried.

However, all of these studies present caveats such as the following from Koerner:

> *"It must be cautioned, however, that the results of this fourteen-year long study on laboratory incubation and subsequent strength and elongation testing is based on the specific type of geosynthetic, i.e., polymer and its formulation, of the products evaluated. In general, the formulation specifics (antioxidants, additives and/or fillers) were not known to the authors. Conclusions must be tempered and utilized accordingly along with the assumptions stated and the specific products evaluated. "*

This again confirms that all HDPEs are not the same.

In some cases degradation of mechanical properties begins before all the stabilizers have been consumed. However, in most cases degradation starts when all of the additives have been consumed.

Both Peggs and Giroud have been involved with workshops and discussion sessions at international conferences to develop a protocol to determine the remaining lifetime of in-service geomembrane lining systems. Refer to the Glossary for an explanation of the acronyms used. In principle it is quite logical to do, but in practice it is difficult:

- Define benchmark reference parameters – original specifications or measured on sample from the anchor trench
- DSC analysis to show amount of stabilizers left in the liner
- FTIR to determine Carbonyl Index and to confirm extent of oxidation that has occurred.
- This CI is 0.1 or O.2 in the HDPE pipe sector
- Critical CI at which SC is initiated

The end of life is defined in a number of ways:

- Time to loss of 50% of a given property such as break elongation using the reference value from GRI.GM13 (for HDPE)
- As above but using the measured value of the material prior to installation
- Appearance of the first stress crack
- Appearance of the first penetrating hole

In summary, there is simply no general rule for determining the lifetime of a given geomembrane, even for different grades of the same material such as HDPE. This is not surprising since there are so many different resins, different manufacturers, different formulations of additives, and extrusion equipment.

There is a new class of HDPE geomembranes made using different resins (a. bi-modal, and b. PERT: polyethylene of raised temperature), that can increase the service temperature from about 45^{0}C up to 60^{0}C, 80^{0}C, and even 100^{0}C for short times. The resulting GMBs have a somewhat higher density than the average GRI.GM13 HDPE but also a higher SCR. They are a little stiffer and need more care in welding such as at pipe penetrations.

Specialised and properly specified HDPEs will be considered for use at MRM.

5.2 LLDPE

LLDPE geomembranes start yielding at a strain of 30 to 40%, depending on resin density. As a result, LLDPE geomembranes conform to subgrade contours and protruding stones better than HDPE geomembranes (which yield at 15%). Therefore, LLDPE geomembranes are more suited to an OEF barrier layer, with its variable surface shapes and settlement, than HDPE geomembranes. However, this product is more affected by heat, with a limited lifespan relative to the design criteria at MRM temperatures.

Even though they have a high coefficient of thermal expansion, LLDPE geomembranes exhibit smaller wrinkles than HDPE because LLDPE is less stiff than HDPE. As a result, LLDPE geomembranes are easier to install than HDPE geomembranes.

As the relevant mechanical properties are better than those of HDPE geomembranes, LLDPE geomembranes are generally preferred to HDPE geomembranes in landfill covers, where differential settlement often occurs.

As with HDPE, durability can be changed by modifying the additive formulation.

LLDPE has not been investigated to the same extent as HDPE for its service lifetime, but typically it would not be used exposed without an upgraded additive package. In this way one might get 20 years of exposed service at the equator.

LLDPE geomembrane should be considered for the MRM cover.

5.3 EPDM

As indicated in the table above, these 1.15 to 1.5mm thick EPDM geomembranes seem well suited to the OEF application at MRM. They have high extensibility (e.g. 300%, which is far superior to the 15% of HDPE and the 30% of LLDPE), which allows them to respond well to dump movements, and conform well to an irregular surface, including protruding stones. Tests under high normal loads show that EPDM geomembranes have a higher resistance to puncturing by stones than geomembranes that are less extensible such as HDPE and bituminous geomembranes, and even LLDPE geomembranes.

Due to good dimensional stability under temperature changes, EPDM geomembranes are easy to install. However, because they are relatively insensitive to temperature, they cannot be welded. They are seamed in the field using a special tape system. The long-term performance of this seaming method seems satisfactory, based on available information. No electric power is needed with the tape method, which is an advantage in remote areas over geomembranes that are joined by welding, since welding requires electric power. However, thermal welding of EPDM has been performed in Europe but requires a special coating on the material surface.

EPDM geomembranes can be fabricated in a factory or workshop to create large panels, which reduces the amount of seaming done in the field. This is not possible with stiff geomembranes such as HDPE, LLDPE and bituminous geomembranes.

Due to their excellent mechanical properties, EPDM geomembranes could be considered for the MRM cover if the cost is acceptable.

5.4 CSPE

The key points related to CSPE are listed below:

- CSPE geomembrane is not as chemically resistant as other suitable geomembranes;
- CSPE geomembranes have a 'shelf life' and need to be fabricated and installed within an estimated 6 months in hot and humid climates;
- CSPE geomembrane continues to cure over time and loses its ability to be easily welded which may adversely affect the ability to joining the progressive staging of the cover installation works. The cured surface layer must be removed;
- CSPE cannot be used without reinforcement. Therefore, CSPE geomembranes are always reinforced with a scrim (a kind of a light woven fabric). As a result, CSPE geomembranes have limited extensibility (e.g. 15% with the most typical scrim). Therefore, CSPE geomembranes do not conform to subgrade contours;
- CSPE geomembranes are relatively expensive when compared to other suitable geomembranes;

- CSPE resins are no longer manufactured by the original manufacturer (DuPont). The quality of currently available CSPE geomembranes may vary depending on the manufacturer. However, the geomembranes are still made by the same manufacturer that used the DuPont resin. Warranties for 30 year lifetimes are available; and
- About 25 years ago, fPP-R geomembranes started to replace CSPE for liners and floating covers in potable water reservoirs. However, there were several problems with the additive formulations, resulting in stress cracking failures. Consequently there has been a resurgence in the use of CSPE.

For several of the above reasons, CSPE geomembranes are not recommended for the MRM cover project.

5.5 PVC

The key points related to PVC are listed below:

- PVC geomembrane is not as chemically resistant as some other suitable geomembranes;
- The plasticisers used in the manufacture of PVC geomembrane are susceptible to migration and leaching which can make the material brittle. The quality of PVC geomembranes depends significantly on the quality of plasticizers, which depends on the manufacturers. Only a few manufacturers can be recommended worldwide;
- They can be susceptible to microbial attack if not formulated with biocides;
- They have low tear strength compared to HDPE geomembranes;
- PVC geomembranes have excellent extensibility (e.g. 400%). As a result, they readily conform to subgrade contours, in particular protruding stones;
- PVC geomembranes have a high coefficient of thermal expansion, Therefore, PVC geomembranes tend to exhibit wrinkles. However, these wrinkles are much smaller than HDPE wrinkles because PVC is much less stiff than HDPE. As a result, PVC geomembranes are much easier to install than HDPE geomembranes;
- Like bituminous geomembranes, they have low seam strength compared to HDPE geomembranes. There is an ASTM seam test D7177 “Air channel testing PVC Geomembrane thermal welds” that allows inflation of the air channel in a double track weld and to look for disbonding incursions into the weld track, thus avoiding doing seam peel tests;
- The service life of most PVC geomembranes is below that required at MRM. PVC geomembranes that are about 3 mm thick and contain excellent plasticizers (available from a few manufacturers) have a service life of 50 years exposed and more than 100 years buried; and
- PVC geomembranes can be fabricated in a factory or workshop to create large panels, which reduces the amount of seaming done in the field. This is not possible with stiff geomembranes such as HDPE, LLDPE and bituminous geomembranes.

Based on the above discussion, PVC geomembranes have adequate properties for the short-term, but their long-term performance may be questionable, especially if there is no first class supplier in Australia.

It should be added that the best geomembrane currently available from the standpoint of mechanical properties is a thick PVC geomembrane (2.5 to 3.5 mm thick), containing first class plasticizers, heatbonded to a nonwoven geotextile (with a typical mass per unit area of 500 g/m^2). Its mechanical properties are ideal. However, its durability is that of PVC with excellent plasticizers, i.e. about 50 years exposed and 100 years buried.

PVC is not recommended for the MRM application due to the limited life.

5.6 Flexible Polypropylene (fPP)

- Polypropylene geomembrane is not as chemically resistant as some other suitable geomembranes
- Without reinforcement polypropylene geomembrane exhibits lower tear strength than other suitable geomembranes.
- Un-reinforced polypropylene geomembranes have excellent extensibility (e.g. 400%). As a result, they readily conform to subgrade contours, in particular protruding stones.
- Polypropylene geomembranes can be susceptible to oxidative stress cracking, particularly along folds and creases. However, this is not frequent because the degree of crystallinity of polypropylene geomembranes is low. It was a problem in the early days of PP geomembranes when geomembrane manufacturers were formulating their own additive packages. This issue has been resolved.
- Polypropylene has approximately half the thermal the expansion coefficient of HDPE. Furthermore, polypropylene geomembranes are much more flexible than HDPE geomembranes. Therefore, at high temperatures, the polypropylene geomembrane wrinkles are much smaller than the HDPE geomembrane wrinkles. This makes polypropylene geomembranes easier to install than HDPE geomembranes.
- Polypropylene geomembrane is relatively expensive when compared to other suitable geomembranes, though not as costly as CSPE.
- The durability of polypropylene geomembranes depends significantly on their composition. It should be noted that polypropylene geomembranes contain only 20% polypropylene, the remainder is ethylene propylene rubber. For UV protection it contains carbon black, as do PE geomembranes. Therefore, the composition of the considered polypropylene geomembrane should be discussed with the supplier.
- Installers like fPP due to its low expansion coefficient and its high surface friction.

Based on the above discussion, polypropylene geomembranes have adequate properties for the short or intermediate terms, but their long-term performance may be questionable. They are not recommended for further consideration.

5.7 Bituminous Geomembranes (BGMs)

A BGM is a composite material with several constituents to attain the desired overall material properties. They typically consist of non-woven geotextile and glass fleece layers impregnated with and encapsulated in elastomeric bitumen, with a sanded surface on one side for enhanced friction and an anti-root layer on the other. The geotextiles dictate the mechanical properties of the BGM, while the elastomeric bitumen provides waterproofing, chemical resistance and protection from ageing. The glass fleece is used for manufacturing purposes. It ensures stability of the geomembrane during impregnation of the geotextile with hot bitumen. The geotextile is then temporarily too soft to support the weight of the bitumen without large deformation. It will be seen below that, although, the glass fleece is used for manufacturing purposes, it has an impact on the properties of the bitumen geomembrane.

Typical thicknesses are from 3.5mm to 5.6mm. The BGM is supplied in rolls from 4.0m to 5.0m wide, typically up to 90m long.

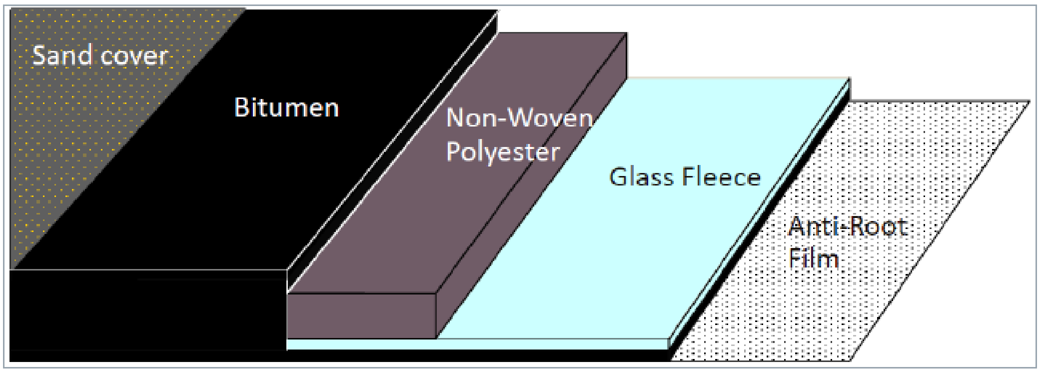

Figure 8 - Schematic of a BGM

Key points relating to issues relevant to the MRM application are listed below:

- Air permeability – Very low – oxygen transmission rate of 13.8 x 10^{-7} m^3/m^3/day
- Water permeability – Permeability of 4 x 10^{-14}m/s, which is a little more than for polymeric geomembranes (e.g. 10^{-15}, even 10^{-16} m/s for polymeric geomembranes).
- Temperature resistance – Softening point approximately 120°. Can be increased to 145° as a special order.
- Service life – Chosen by the Atomic Energy Commission in France for a design life of a minimum of 300 years (see Appendix A – Bituminous Geomembrane Cover for a low to Medium Level Radioactive Waste Disposal Site). Chosen by the Nuclear Safety Agency in the USA with a design life of 1,000 years. Based on current knowledge, it is the geomembrane with the longest service life, along with HDPE geomembrane.
- Friction angle – approximately 20-25° on root barrier side, 30-35° on sanded side, but is dependent on the subgrade and overliner material utilised. A High Friction Angle BGM product with sand on both sides is available if required. However, the polyester root-barrier film is considered an important consideration in MRM's application because bitumen is highly susceptible to root penetration. Laboratory testwork is required with specific MRM materials to determine actual friction angles.
- Seepage chemical resistance – no issues with expected pH, metals
- Cover leachate chemical resistance – not affected by leachate waters.
- Fuel & oil chemical resistance – Low. Diesel will soften the bitumen. Nevertheless, BGM has been used under highways and in roadside ditches to protect an underlying critical aquifer (Coppinger, J., et. al. 2002). Note though that the root barrier is polyester and will not dissolve.
- It is an electrical insulator so it can be electrically surveyed for leaks.
- Gas chemical resistance – not affected by oxidation gases. High temperature gas will melt the bitumen.
- Tear resistance is high due to the presence of the nonwoven geotextile in the middle of the bituminous geomembrane.
- Extensibility is limited because the glass fleece causes great stiffness of the bituminous geomembrane between 0 and 3% strain. The glass fleece breaks at 3% strain. Beyond 3% strain, the bituminous geomembrane becomes more extensible. However, at about 30 or 40% strain, the permeability of the elastomeric bitumen increases. Therefore, the limit strain (with some safety) is about 20%, which is not sufficient for bituminous geomembranes to conform to the contours of the subgrade and to protruding stones. Bituminous geomembranes are a

little more extensible than HDPE geomembranes, a little less extensible than LLDPE geomembranes, and much less extensible than PVC, EPDM and polypropylene geomembranes. Subgrade preparation must allow for this.

- Puncture resistance – Enhanced by an internal 300-400g/m^2 geotextile. BGM will require protection from mechanical puncture by rocks. The subgrade typically is required to have pore sizes of less than 25mm. Due to the fact that bituminous geomembranes have limited extensibility, they are susceptible to puncture by protruding stones under high loads (which is not the case in a cover).
- Bioturbation resistance – Excellent resistance to animals including rats, termites, beetles, cockroaches. Anti-root barrier resists root penetration, except possibly at welds where the anti-root film is discontinuous.
- Productivity
    - High unit weight (5.8-6.8kg/m^2) reduces influence of wind on construction – though the heat torches for joining can be hindered by high winds. This is an advantage over polymeric geomembranes for wind speeds less than 40 km/h, which are the majority of cases. See Table 2.
    - Equipment is available to ultrasonically test seams for non-bonded interfaces over the complete area of the welds.
    - High dimensional stability, so limited effects due to expansion and contraction. Thanks to the low coefficient of thermal expansion of bitumen and of the glass fleece, there are no wrinkles during installation. From this view point, bituminous geomembranes are much easier to install than HDPE geomembranes.
    - Thanks to their high tear strength and high impact resistance, bituminous geomembranes are sturdy and are less susceptible to damage during construction.
    - Can get sticky to work/walk on in temperatures over 30°C.
- Joining method – standard is a flame torch to join a 200mm wide overlapped strip. The weakness of the seams is compensated by the large width (200 mm). Care at pipe penetrations, particularly large pipes, is needed, as well as where the BGM is applied to an underside surface, such as at a pipe opening invert.
- QA/QC – thanks to sturdiness and with strict construction quality assurance (e.g. working to ASTM D 7703 "Standard practice for electrical leak location on exposed geomembranes using the water lance method"), careful installation should result in very few defects/ha.
- Installed cost - High
- Strengths – long life, durable, low risk to MRM failure modes.
- Weaknesses – Slower than HDPE to install, cost, diesel spill risk.

BGMs should be considered further for the barrier layer role at MRM.

5.8 Concrete Hybrid

This product will have the barrier properties of PVC or PE, but with added compressive strength of the protective concrete layer. Commercial examples are branded as Tiltex Plus and Concrete Canvas.

These relatively new products are essentially nonwoven geotextiles carrying calcium aluminate cement powder which are laid in place and hydrated to become cured/in-place reinforced concrete. For improved barrier functioning they may have a thin PVC, HDPE or LLDPE film bonded to the underside. Rolls are 1 to 5 m wide depending on the product and manufacturer, so there may be much welding to do. Panels up to 4 rolls wide have been prefabricated.

Welding is done by peeling the powder/GTX layer back and welding the PVC/PE, as is normally done. It must be quite difficult to keep the surfaces to be welded free of powder and contamination. Placement of the alluvium layer on the concrete layer will have to be done very carefully to avoid cracking the concrete and damaging the geomembrane. Photographs show a wrinkle running along each weld. When covered this will be source of stress in the PVC/PE film and an accelerated loss of plasticizer due to the stresses, possibly leading to local embrittlement of the PVC/PE liner.

- Thickness – 7.5mm to 12.5mm
- Air permeability – will achieve the target
- Water permeability – will achieve the target
- Temperature resistance – the concrete has high temperature resistance. However, the PVC/PE would be exposed to any heat source originating within the OEF, so heat impacts on the PVC/PE could still be expected.
- Service life - Concrete is not strong in tension. Loss of plasticizer of the PVC/PE in the area of cracking would need to be investigated.
- Friction angle – No problem.
- Elasticity/tear resistance – tensile strength MD at least 20.0kN/m (+/- 10%)
- Puncture resistance – Very good. CBR puncture strength at least 3.0kN (+/- 10%). Lay and weld the product in unhydrated form. Then place rock drainage layer, before then hydrating the product.
- Bioturbation resistance – Excellent for fauna resistance. Vegetative resistance good.
- Productivity – Considering overliner process, faster than PVC/PE with a separate overliner.
- Joining method – peel back geotextile layer. Standard thermal welding of the PVC/PE. Replace geotextile layer then hydrate.
- QA/QC – PVC/PE welding uses standard PVC/PE methods.
- Installed cost – very high
- Strengths – fast and simple to install with protective overliner. Resistance to puncture.
- Weaknesses – Cost. Tensile strength. Uncertain life of PVC/PE in areas of embrittlement.

Concrete hybrid should not be considered for the MRM cover.

5.9 GCL

GCL's rely on the bentonite clay layer to absorb moisture and swell, forming a very low permeability barrier, which due to its high saturation level, would also be a barrier to oxygen movement. However, the bentonite that swells is a sodium based variety. MRM's leachate waters will be high in calcium – these waters will facilitate ion-exchange of the Na and Ca ions, resulting in the bentonite changing to a Ca-bentonite. This type of clay swells considerably less, and so the permeability is significantly higher.

GCL is not considered a suitable barrier for use in the MRM OEFs.

6.0 Other Geosynthetic Products

The OEF poses several constructability and life issues where geosynthetics may be applicable. The detailed design phase will investigate the suitability of these products to support the barrier layer:

- Geogrids for enhanced stability of soil materials, particularly on slopes;
- 3D geonet for drainage instead of ROM rock;
- Geotextile cushion layers, to protect the geomembrane from damage caused by under- or overlying layers; and
- Geocells, for holding soil and small rocks in place.

7.0 Costs

A survey of the approximate cost of some of these materials, end price to installer/client, landed and cleared to a major city in Australia, are indicated in the table below.

Table 4 Supplied cost of a variety of GSLs

Type	Thickness	Price AUD$/m2
Standard GRI.GM 13 HDPE	2.0 mm	6
LLDPE	2.0 mm	5
Elastomeric BGM	4.2 mm	12
EPDM	1.14 mm	9
Concrete hybrid + 1.2 mm PVC	5.0 mm	70
GCL (Geofabrics X1000)		5.80

8.0 Conclusions

While several geomembrane materials demonstrate the basic physical, mechanical, and chemical properties to function as a cover over the NOEF facility, only HDPE and BGM have been tested to demonstrate its ability to provide the required 500 to 1,000 year durability. Note the HDPE tests have been performed using free hanging specimens exposed on both sides and hence the test results will be pessimistic, since only one side (a lower surface area) will be exposed to the leachates in the field. However, the specimens are not under stress when they are exposed, thus precluding an assessment of stress cracking.

Taking all into consideration, the top four candidate geomembrane materials (in no order of preference) are:

- HDPE, for its demonstrated durability and cost;
- LLDPE, for its flexibility and ductility and cost;
- BGM, for its long life; and

- EPDM, for its extensibility and ability to tolerate rough surfaces.

It will take an extensive testing program to select the most appropriate product. Test will include:

- Chemical resistance
- Puncture and cushioning tests
- Rock deployment on geomembrane
- Haulroad tests
- Friction angle tests
- Tear tests
- Seam weld tests
- Test pad cyclic loading
- Drainage and permeability
- Interior and peripheral rock temperatures

The nature of several of the tests will be a function of the material selected.

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Post Office Box 36821· Winnellie · Northern Territory 0821 · Australia
34a Bishop Street · Darwin · Northern Territory 0820 · Australia
Tel +61 8 8975 8179 · Fax +61 8 8795 8170 · Web www.mcarthurrivermine.com.au

A GLENCORE COMPANY

McArthur River Mining Pty Ltd ABN 90 008 167 815

Appendix A

Bituminous Geomembrane Cover for a low to Medium Level Radioactive Waste Disposal Site

Report 2.06 (version 22 novembre 2004)

BITUMINOUS GEOMEMBRANE COVER FOR A LOW TO MEDIUM-LEVEL RADIOACTIVE WASTE DISPOSAL SITE

Every year, France produces 2.5 tons of industrial and domestic waster per inhabitant, including one kilogram of radioactive waste.

There are three categories of radioactive waste:

- Category A: Waste containing essentially short-lived (under 30 years), low-level or medium-level radionuclides (The total amount accumulated as of 2000 is under one million cubic meters. They are irreversibly stored on the surface or slightly below the surface at the La Manche radioactive waste disposal site, which is the subject of this article.)

- Category B: Waste containing long-lived radionuclides, often called “alpha waste”

- Category C: Highly radioactive waste containing large quantities of long-lived radionuclides (These are currently vitrified.)

One solution under study for category B and C wastes is irreversible disposal in deep underground geological formations.

1. THE LA MANCHE RADIOACTIVE WASTE DISPOSAL SITE

The La Manche disposal site (CSM), which is located near Cherbourg, opened in 1969 and was France’s first site designed to store radioactive waste. It accepted 30,000 m^3 a year.

ANDRA (Agence Nationale pour la gestion des Déchets Radioactifs; Radioactive Waste Management Agency) operates this disposal facility, which was designed to store short-lived, low and medium-level radioactive waste. The waste comes mainly from nuclear power plants (ion exchange resins used to purify reactor and filter cooling water. The nuclear fuel reprocessing industry, research laboratories, and hospitals also produce radioactive waste.

1.1 <u>The life of a surface disposal site has three phases</u>

- An exploitation phase of approximately 25 years, which includes the construction of storage facilities, and the reception and storage of barrels of radioactive waste (Once the center is completely saturated, which was projected to be in 1994 for the La Manche site, the permanent cap is installed, which will be described later in this article.)

- A surveillance phase of no more than three centuries during which ongoing monitoring of the radioactivity, which decreases exponentially, is conducted (Maintenance of the surface drainage system to keep rainwater from flowing through or infiltrating the waste is also performed on a regular basis.)

- A banalization phase during which the radioactivity of the waste approaches background levels (The land can then be returned to normal use.)

1.2 Disposal of barrels of radioactive waste

Barrels of radioactive waste at the La Manche site are stored either in structures called monoliths or in tumulus. All the storage structures have water recovery systems in their floors that are connected to gallery tunnels running underneath.

The monoliths are concrete vaults in which the barrels of radioactive waste are stored. Once they are filled, the monoliths are packed with special concrete. Monoliths are filled with barrels of radioactive waste placed side by side and in layers. After each layer is in place, the spaces between the barrels are filled with gravel to stabilize them. A soil cover is then spread over the monoliths to form the final tumulus, which is 10 meters high, 500 meters long, and 250 meters wide. Each tumulus contains 500,000 m^3 of waste.

2. DESIGN OF THE PERMANENT CAP OF THE TUMULUS

2.1 Three essential criteria were selected

Imperviousness
The amount of rainwater that may penetrate the cap and thus come in contact with the packages must be kept to a strict minimum of no more than several liters per square meter per year in order to avoid leaching and leakage of radionuclides.

Longevity
The cap must be flexible in order to move with the substrate but must also remain impervious throughout the surveillance phase, i.e., 300 years.

Protection
In addition to water infiltration, the cap must be able to resist stressors such as erosion, temperature fluctuations, chemical attacks, living organisms, etc.

2.2 Three essential criteria were selected

The roof-shaped cap resembles a series of sloped panels, each no more than 140 meters x 25 meters in size.

The cap is made up of (from bottom to top; Figure 1) the following layers—

A terraced earthen mound built up in sections that acts as a semi-watertight buffer layer between the packages and the cap

A drainage layer to prevent water leaking under the bituminous geomembrane

A bituminous COLETANCHE NTP4 geomembrane

A drainage layer to collect water that transits the subjacent layer and to prevent hydraulic pressure on the geomembrane

A drainage layer of compacted shale to regulate water seepage on top of the geomembrane and, mainly, to protect the geomembrane from root growth and burrowing animals

A layer of grass-cover topsoil (The topsoil in contact with the subjacent layer has a higher sand content to promote evaporotranspiration.)

The two uppermost layers form the biological barrier.

FUNCTION	DESCRIPTION
BIOLOGICAL BARRIER	TOPSOIL
	COARSE MATERIAL
DRAINAGE 1	SANDS – DRAINS
IMPERMEABLE BARRIER	BITUMINOUS GEOMEMBRANE
DRAINAGE 2	SAND – DRAINS
EARTHWORKS	COARSE MATERIAL

Figure 1: Diagram of Permanent Cap

3. COLETANCHE NTP4 BITUMINOUS GEOMEMBRANE

Before selecting the bituminous geomembrane, ANDRA asked for numerous tests in various laboratories. The testing period lasted almost three years. The structure of the COLETANCHE NTP4 geomembrane and the main properties tested are described below.

3.1 Structure of the COLETANCHE NTP4 bituminous geomembrane

COLETANCHE NTP4 is essentially a non-woven, continuous-filament BIDIM geotextile. The filaments are impregnated and coated with Shell Mexphalt 100/40 bitumen filled with 25% limestone filler with a grain size under 80 microns.

The top surface of the geomembrane is sanded while the bottom surface is a polyester anti-root film.

COLETANCHE NTP4 is 5.6 mm thick and weighs 6.5 kg/m^2.

The BIDIM geotextile provides mechanical strength. Since the polyester filaments are completely soaked in bitumen, the COLETANCHE NTP4 geomembrane has the same resistance as bitumen to water and chemical and biological agents.

3.2 Resistance of bitumen to biodegradation

The natural bitumens used for waterproofing purposes and for protecting objects in Mesopotamia has endured some 4,000 years with no evidence of any great amount of biodegradation. Natural bitumens have existed in many places around the world for millions of years.

Temperatures exceeding 180°C are used to manufacture COLETANCHE geomembranes, which results in a relatively sterile product.

When the COLETANCHE geomembrane is covered with soil, the surfaces of the membrane undergoe biodegradation.

The use of blown bitumen as radiation waste coatings led many researchers to study the biodegradation of bitumen. In particular, the tests conducted at the request of the U.S. Nuclear Regulatory Commission, involved placing samples of surface bitumen in various types of soil containing indigenous bacteria or *Pseudomonas aeruginosa* (1).

Biodegradation was monitored by measuring the release of CO_s. The researchers reported that the average biodegradation rate of blown bitumen was 5.5 10^{-4} cm/year, with a range of 2 10^{-4} cm/year to 10^{-3} cm/year, or 3 mm/300 years.

3.3 Permeation coefficient of the COLETANCHE NTP4 bituminous geomembrane

There are two coefficients for measuring the transfer of water across a geomembrane:

- The effective diffusion coefficient (De) of water in $m^2\ s^{-1}$ when no pressure is applied to the water during the test
- The permeation coefficient (K) in $m^2\ s^{-1}$ obtained when pressure is applied. Permeation is composed in part of permeability (coefficient K in $m^2\ s^{-1}$) and diffusion.

The Atomic Energy Commission built, in its Grenoble laboratory (2), a cell capable of measuring very low levels of De ($10^{-17}\ m^2\ s^{-1}$) and K ($10^{-19}\ m^2\ s^{-1}$). (Photo 1)

This laboratory, which is the only one in France capable of measuring such low coefficients, uses tritiated water ($HTO\bullet_{nH2O}$) in its apparatus. Tritium (T or H^3), an isotope of hydrogen, is a beta emitter that can be used to measure the amount of water that transits geomembranes using a scintillation counter in the 2–19 KeV energy range.

Samples of COLETANCHE geomembrane were taken from a basin in Corsica after seven years of exposure to UV radiation and/or water. Their permeation coefficients were compared to those of a new geomembrane and a geomembrane that had undergone various elongations in the laboratory. The diffusion coefficients are shown in Table 1.

Type of COLETANCHE Geomembrane	Thickness (mm)	Diffusion Coefficient De m^{-2} s^{-1}
New	3.9* 5.6**	1.3 10^{-15} 1.6 to 4.2 10^{-15}
Natural ageing		
7 years in water and in contact with UV radiation	3.9*	2.2 10^{-15}
7 years underwater	3.9*	1.7 10^{-15}
2 years exposed to the air and 5 years underwater	3.9*	5.1 10^{-15}
Samples elongated in the laboratory		
10% in width	5.6**	1.1 10^{-15}
10% in length	5.6**	11 to 14 10^{-15}
25% in length	5.6**	11 to 13 10^{-15}

* Coletanche NTP2 ** Coletanche NTP4

Table 1: Diffusion coefficient of various COLETANCHE bituminous membranes

The permeation coefficients were in the range of 120 to 130 10^{-17} m^2 s^{-1} for a 1.2-meter-high water column and 18.6 to 4.6 10^{-17} m^2 s^{-1} for 20 and 40-meter-high water columns.

The permeation coefficients of the samples stretched by 25% were twice as high as the unstretched samples. These results indicate that care must be taken when transporting and installing COLETANCHE membrane to avoid stretching or localized puncturing.

3.4 Coefficient of friction between the soil and the bituminous geomembrane

ANDRA also had the coefficient of friction between the bituminous geomembrane and the drainage material tested in order to ensure that the structure was stable (Figure 1). The box shear apparatus commonly used provided unsatisfactory results because the applied stress was too high. CEMAGREF Bordeaux, on the other hand, used the inclined plane method to determine the angle of friction of a load of sand placed on the geomembrane (sanded polyester surface). The angle of friction obtained was 29.5°. (3)

4. INSTALLATION OF THE PERMANENT CAP ON THE TUMULUS

Phase 1 of the installation was contracted to Coyne and Bellier in association with EDF (Electricité de France) Direction de l’Equipement Centre Lyonnais d’Ingénierie (Equipment Service, Lyon Engineering Center).

ANDRA made especially sure that each step, from manufacture to installation of the bituminous geomembrane, complied with particularly stringent quality standards.

The quality of the COLETANCHE bituminous geomembrane was factory certified. During the manufacturing process, the following measurements were conducted at random:

- Mass per unit area
- Thickness
- Breaking strength and elongation at break

The transportation and storage of the rolls, which weighed 1.5 tons each, was done in such a way as to avoid placing them on a heat source, which would have resulted in a localized decrease in thickness at the point of contact.

A conventional installation procedure was used. The strips of geomembrane were unrolled parallel to one another with a 25 cm (Photo 2) overlap to allow for hot air welding of the joints.

An automatic welding machine was used, and the welding parameters were constantly monitored and recorded. The data was transmitted to ANDRA (Photo 3).

All (100%) the welds were checked by ultrasound (Photo 4).

Defects totaling five square meters were detected. Repairs were performed following a statistical analysis of the size, number, and position of the defects detected during the inspection.

The repairs involved applying a 60-cm-wide joint-cover over the defect.

The joint-cover weld was checked by ultrasound.

5. CONCLUSION

The permanent cap of the La Manche radioactive waste disposal site was the subject of extensive studies and unequalled quality controls, which were amply justified by the projected service life (300 years) of the site.

BIBLIOGRAPHY

Photo 1: Permeation measurement cell at the Laboratoire du Commissariat of the Atomic Energy Commission in Grenoble, France

Photo 2: Unrolling of the Coletanche geomembrane (La Manche waste disposal site)

Photo 3: Welding of two strips of Coletanche membrane (La Manche waste disposal site)

Photo 4: Checking welds by ultrasound (La Manche waste disposal site)