Managing the Engineering, Health and Safety Aspects of Thin Spray-On Liner Application

Underground Trials at Xstrata Nickel Sudbury Operations, Nickel Rim South

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Luleå, January 2013

Patricia Boeg-Jensen
Abstract

Bolts, shotcrete and mesh are today a part of the standard ground support system, although it becomes economically challenging to combine them sufficiently to support seismically active ground that requires increased yielding and energy-absorbing capabilities. An alternative to the current ground support system is the Thin Spray- On Liner (TSL) that may possess significant yielding properties. TSL has the potential ability to support seismically active ground in terms of deformation and rock bursting, common in deep mining.

This thesis is a part of the investigation; to prove whether the current formulation of the Thin Spray- On Liner could be implemented as an alternative ground support system and improve the support capabilities for complex ground types. The thesis will complete and deliver a conclusive trial site results summary.

A qualified ground control team put together a set of 11 large-scale trials in an underground environment within an active mine, Nickel Rim South in Sudbury. Each trial examined the geotechnical capabilities with respect to the engineering and health & safety aspects of the TSL. These trials are a Proof of Concept phase towards proving the liner as a superior component in underground rock support. This TSL was developed to achieve the de-bonding, toughness and tear resistant ground support parameters.

The thesis focuses on the specific geotechnical testing conducted at the Nickel Rim South Mine during the first quarter of 2012. Subsequent testing has been completed and liner development continues that is not covered within this thesis. Out of the 11 planned tests, 8 were executed during this period, and the rest will be executed later. Some of the results from the test trials are of a long- term nature and therefore the majority of the test results are not yet available. Before any tests could be executed, the isocyanate levels were measured and the results served as a base when setting up the PPE (Personal protective equipment) safety protocol. In addition some practical concerns arose during the trials, which were successfully solved after a few adjustments. The test results available for the full composite liner material concluded that peel- back at the leading edge next to the face blast, together with fly- rock damage, was severe, due to primer adhesion failure and this test was therefore considered to have failed. A comment should made in qualification of the above statement that the leading edge of the PCM(Polymeric Composite Membrane) was not bolted which was contrary to the project scope that suggested treating the PCM much like mesh prior to a blast and the wall was not high-pressure water scaled. The same test was performed on topcoat only, with significant improvement. The coverage of the topcoat only on top of shotcrete is poor, due to the pebbly nature and fibers protruding out from the shotcrete. The robot managed to apply the TSL with sufficient coverage and consistent thickness on the walls and the pillar nose, except for the edges where the guns flip over occurred and missed large perimeter patches, which was not dealt with till later in the testing.

These results indicate the requirement of a rehab procedure for damage caused to the liner, although the damage could partly appear due to the fact that the top coat could have been not yet fully cured and in its strength building process at the time of face blast. No determination was made of the PCMs actual strength required at the time of face blast during the cure cycle. There are speculations whether
adhesion failure could be diminished by using a higher adhesion primer but without the foaming properties, which would result in a primer with lacking properties to fill the gaps for superior coverage while providing higher adhesion. In addition, bolting of the leading edge could be implemented to partially address the peeling issue. It is however important to investigate that the adhesion fails due to a rock failure and retains the loose material, unlike adhere and tear. The trial results are only investigated on the rock walls, in order to make a fair judgment on the liners performance and capability it should in addition be applied on the shoulders and the back to accomplish full rounds.
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1. Introduction

Underground hard rock mining has become more common in many mining jurisdictions during the past decade, with many of the world’s surface deposits mined out. In fact it is increasingly apparent that the mining of orebodies at greater depth is necessary to meet the demands of metals from the mineral market. Mining at greater depths is subject to higher stresses and to maintain acceptable safety, the demands of the rock reinforcement increase. Conventional rock support comprises rock bolts, most typically rebar and a surface liner of either screen or shotcrete. At greater depths, the problems of deforming and rock bursting ground are an issue that must be dealt with. There is by now significant evidence to show that existing rock support components and systems fail to manage the demands posed by these ground conditions, the reason being their lack of toughness or yielding capacity. Toughness is referred to as the materials ability to deform without cracking during an energy discharge. Shotcrete has high stiffness and high compressive strength, while screen is soft and effective at retaining loose material due to its tensile properties. In order to continue deep mining with acceptable safety, bolts and liner components with high yielding properties are required which function holistically as a ground support system.

The invention and development of a liner with the required properties has taken about 20 years and is referred to generically as a Thin Spray- On Liner or TSL. The current PCM was developed to provide a TSL product with superior tensile and elongation characteristics for Type 1 ground scenarios with further consideration for other scenarios. Conceptually the preferred TSL should obtain reinforcement and retaining function superior to either shotcrete and/or screen under highly deformable and rock bursting ground conditions. However, proof of this concept is still lacking, together with certain material health & safety and operational concerns. These concerns are currently preventing its routine implementation to an operating deep mine. In the specific case of 3M’s Polymeric Composite Membrane (PCM) TSL, much of the theoretical and laboratory proof has been completed. It remains to increase the level of proof to that of final feasibility, both in the areas of ground control and operations, which will be performed at Xstrata Nickel’s Nickel Rim South mine site in Sudbury. The TSL- Project is funded jointly by the Deep Mining Research Consortium (DMRC) together with ABB Canada, 3M Canada and Xstrata Nickel.
1.1 Objectives

The thesis aims to complete and deliver a conclusive trial results summary from large scale underground trials, required to prove the TSL as a feasible component in underground rock support and prepare it for commercialization. The trials are primarily of a health & safety and geotechnical nature. In addition the early development and research performed on TSL is presented together with the recent findings collected through the ground control and operations proof phase of the above noted DMRC- directed project. The results presented from the trials described in this thesis will serve as a basis when arriving to a decision on whether or not this particular TSL or variant thereof is an appropriate material from a ground control and operations point of view. It is anticipated that much of the geotechnical proof material will be collected during the writing of this thesis and all available results at the final phase of the thesis writing are presented. However, it should be pointed out that certain trials related to ground control proof will continue at various mine sites once this thesis is completed due to the project’s need for long-term monitoring data of the rock failure process. The thesis aim is to establish a sufficient amount of proof necessary to unequivocally demonstrate the ground control and operations acceptance of the TSL composite membrane for Type 1 ground conditions with extended testing to include various Type 2 and Type 3 ground conditions. The main focus of this report is to present some of that proof, how it was achieved and the issues encountered due to the sampling of the data.

1.2 Limitations

The nature of the ground control and operations proof necessary to gain confidence in a TSL is the greatest limitation. It requires long-term monitoring and cannot be fully predicted. The thesis only present data collected during the writing of the thesis, which barely sums up to a period of 6 months. Therefore it does not present any future data that may contain further proof due to deforming and bursting ground and other related ground conditions. The objectives were to prove the PCM using at least 60% Type 1 ground conditions and the remainder being a blend of Type 2 and 3 ground conditions. Various test sites have been chosen for each of these ground conditions which includes where deforming and bursting ground is predicted but cannot be guaranteed within the time scope of the thesis and the results from these trials are therefore not a part of this thesis. Other significant data will be collected and evaluated during the time span of the thesis, which by itself significantly can prove some of the material benefits.

The TSL development and research over the past 20 years has overcome many difficulties, leading to a basic understanding of material property specification and equipment requirements necessary to achieve the desired ground control, operations, safety, health and the environmental results. The most significant difficulties and issues will be discussed in the context of the history of TSLs in this thesis.

1.3 Targeted Readers

The thesis is of interests to any individual that wishes to achieve knowledge within the most recent research related to the future of mining. For example, the thesis may be of interest to individuals
involved in deep mining within education, research and development. More examples on some of the suggested readers are first of all the individuals involved in TSL-related projects in the past where proof of application under deep mining conditions was not achieved. For these purposes the thesis can be used as a reference for future work or as an update. It is also of high interest for commercialization of TSLs, manufacturers of autonomous, robotic equipment, the mineral market and other deep mining companies since it presents some of the results available from the final geotechnical and health & safety proof phase of a new mining ground support system.

1.4 Outline
The structure of the thesis is based upon traditional guidelines and adjusted due to the nature of the thesis’ subject. It is divided into three parts: an introductory part, the thesis and a conclusion. The background chapter will provide some basic background related to the properties of TSLs and also some of the background of the mining company and the test site. The theory chapter aims to summarize the historical research related to the development of 3M’s TSL. The focus of the thesis is on the chapters of ground control, operations proof and results since most of the practical work performed at the site, the approach used and data analyzed will be presented within these chapters. These chapters describe the approach and the results. The final chapters will provide some conclusions and recommendations based upon the results presented in previous chapters.

2. Background
The TSL project is currently funded by CAMIRO’s Deep Mining Research Consortium (DMRC), Xstrata Nickel, ABB Canada and 3M Canada. However it is not entirely the economical support that is crucial in order to execute and develop this TSL project but also the technical support and the providing of test spray sites. The basic facts of 3M’s TSL product and information about the company providing the spray sites are provided in the following section.

2.1 Thin Spray- On Liner
Based on 20 years of experience with Thin Spray- On Liners much has been learnt about its performance and properties, which are essential in achieving the desired final product. The previous experience is by observations in laboratory tests and it is also based on underground trials, to simulate real life behavior.

According to Swan et al (2012) the current 3M TSL is a 2-part composite polymeric membrane comprising a foam Primer and a tough polymer Top Coat. It can be modified to meet the demands in the mining industry in terms of its strength, elasticity, toughness, and adhesion.

Spencer et al (2011) describes the basics of current TSL- formulation. The strategy is to generally apply two layers when spraying the material since it is a 2-layer composite system. The application is
automated but can be manually applied when desirable. First the Primer should be sprayed on a cleaned and prepared rock surface. The Primer used in the tests has foaming properties and foams 3-3.5 times with respect to its original application thickness, with its final thickness between 4-5mm. The advantages of the Primer are characterized by its capability to adhere to damp rock and its foaming properties tend to smooth out the rock surface and seal gaps, allowing the Top Coat to mobilize its key physical properties such as tensile strength, elongation and toughness as the load is generated due to eventual loose rock failure. The Top Coat is preferably 3-4mm thick and comprised of a hybrid polyurea chemistry, known for its high tensile strength and toughness. In order to form an adequate ground support, the liner requires support by a standard bolting pattern as with shotcrete and screen. The basic functions of the 3M TSL and its installation is demonstrated in Figure 1.
2.2 Xstrata Nickel

Xstrata is one of the world’s largest mining corporations, in terms of metal and mineral products. They produce coal, copper, nickel, zinc, ferrochrome, platinum and vanadium as illustrated in Figure 2. Xstrata (2012) presents Xstrata Nickel with respect to the worldwide nickel production that they are currently the 4th largest nickel producer. Xstrata Nickel’s operations consist of both mines and processing facilities operating in Canada, Dominican Republic, Australia and Norway. Xstrata Nickel in Canada is operating in the provinces of Ontario and Quebec. However Xstrata Nickel is not only producing mineral and metals, sustainability is proven by their effort in recycling nickel and copper bearing materials. The total annual managed production, is nearly 106,000 tonnes of nickel, Xstrata (2012).

Figure 2. Xstrata Operations, www.xstrata.com (2012)

2.2.1 Nickel Rim South

The underground TSL trials are currently being performed at Nickel Rim South mine, Sudbury, Ontario. It is not a coincidence that the underground trials proving the geotechnical benefits of the TSL will be executed at this specific mine. Mining induced seismicity is common at the mine and therefore suitable for testing the dynamic support system, TSL. Nickel Rim South mine is located on the northeast rim of the Sudbury Basin. The basin is in fact a result of a meteor impact creating a crater that today is rich in metals at the limbs surrounding the basin.
Simser and Pritchard (2011) describe the observational ground control aspects at Nickel Rim South. The extraction of the deposit at Nickel Rim South started in 2010 and the annual ore production is estimated to a total 1.25 MT. The tonnage is a mix of both nickel and copper since the ore is extracted from two geological zones, consisting of a hanging wall nickel sulphide orebody and a footwall copper sulphide orebody that are next to each other according to Figure 3. The majority of the nickel orebody is at 1200-1400 meters depth whereas the majority of the copper orebody is between 1400-1600 meters depth. With respect to the positions and depths of the nickel and copper orebody the mine has three main levels to access the deposits by vertical shafts. Level 1280 is the nickel zone, level 1480 is nickel and copper zone and level 1660 is the copper zone only.

![Figure 3. Orebodies at Nickel Rim South mine. Orange color displays the nickel sulphide orebody, green color displays the copper sulphide orebody while the blue color represents copper orebody with lower amounts of precious metals, Simser and Pritchard (2012)](image)

The mining method at Nickel Rim South is a type of blasthole method. Primary panels as illustrated in Figure 4; are mined out with the blasthole method leaving large open stopes that are backfilled with cemented hydraulic tailings to maintain stability in the stope back and walls. The secondary and tertiary panels are mined out with the same procedure. The mining sequence requires the primary stopes to be backfilled before the mining of the secondary can begin and backfill of the secondary before the mining of the tertiary stopes can begin.
Simser and Pritchard (2011) describe the factors causing seismic activity. Nickel Rim South is still in the beginning phase of its total lifetime so that mining-induced stress concentrations have not yet raised to give any major concerns. However this will change due to further extraction and with time. The host rocks surrounding the orebodies contain brittle rock types with typically high strength such as fine grained granite breccia. The fine grained strong host rock experience more seismic activity than in the ore. The major rock mechanic issues are however due to the natural geological contacts between the orebody and host rock. Typically the strength contrast between the ore and host rock is the main reason for any seismicity. This is especially observed in the copper zone, where the contrast is even more significant due to the low strength of the high-grade copper ore and also the increased depth compared with the nickel orebody. In addition to the strength contrasts, several main fault sets run transversely through the host rock and orebodies causing fault slips. The fault slips are the main reason for seismicity with the consequence of rock bursting but also seismicity associated with fault creep. The main fault sets are north/south faults, low angle faults and southwest/northeast faults, intersecting between the main fault sets is complicated as illustrated in Figure 5 and Figure 6. Due to the further extraction of the stopes shear movements will only increase within the main faults since several stopes are designed within the main fault areas causing increased risk of these activities. There are additional rock mechanics issues related to the depth, pillars and the mining method. The increase in horizontal
and vertical stresses due to increased depth, causes spalling. When preparing the headings for primary, secondary and tertiary stopes, pillars are created and are subjected to high vertical stress, especially at the nose where spalling is common. The walls and back within the open stopes are particularly prone to failure before being backfilled since the stopes are subjected to high stress from surrounding rock. Together the wide variety of these rock mechanics issues alone provides adequate motivation for performing the test trials at Nickel Rim South.

Figure 5. Left figure displaying the north/south fault set in light green shade, right figure displays the low angle fault set in light grey shade, Simser and Pritchard (2012)

Figure 6. Southwest/northeast fault set in dark grey shade, Simser and Pritchard (2012)
Nickel Rim South is dealing with some of its rock mechanics issues by changing the standard support requirements compared to those typically used in Canadian mines. Historically screen and bolts have been accepted as a standard support system. Nickel Rim South utilizes shotcrete in addition to screen and bolts, which makes the mine somewhat unique. There are roughly two types of ground conditions and therefore two types of support: stiff and yielding. Stiff support refers to rebars or cablebolts and shotcrete in order to support stress fractured ground and preventing wedge failures. In areas that experience bursting and squeezing conditions, yielding support is required and for this purpose D-bolts and screen over shotcrete is utilized.

3. Thin Spray- On Liner
During the 20 past years of TSL developments a large amount of research has been performed in order to increase the level of its operational proof. There are many factors that have been considered and the most significant progress is summarized in the following sections.

3.1 Material Specifications
There have been various types of TSLs developed for mining purposes, during which time materials have been invented and re-invented while undergoing various laboratory tests and operational trials. Described by Swan et al (2012) the first generations of spray-on liners mainly failed due to poor tear resistance and poor toughness in combination with slow cure rate.

According to Swan et al (2012) one of the first Thin Spray- On Liner used in underground trials was a two-part polyurethane chemistry which was not modified due to the underground trials. Espley’s (1999) work resulted in that liner was being abandoned due to tensile failure occurring during laboratory pull tests and ripping and tearing failure in underground trials due to deformation and blasted fly rock and lack of adhesion as displayed in Figure 7.
Figure 7. Failure types. Tensile failure to the left due to laboratory pulls test, centre and right display failures in an underground application, ripping and adhesion failures respectively, Espley- Boudreau (1999)

Hadjigeorgiou (2000), Hadjigeorgiou (2005) and Blake et al (2006) describe the properties of the two major liners that were engineered and designed with some of the properties desired for the underground trials. Both liners were used in an underground environment subjected to stress and deformation for test purposes. One of them is a 2- part synthetic latex/ cementitous system. The main concern with respects to the health and safety issues of the liners is the airborne isocyanates. While some TSL’s do contain isocyanates there are other non- polymer types that being cementious in nature may have other curing agents and additives that may be of concern. However the chemistry did not show any traces of airborne isocyanates but the product failed due to ruptures caused by underlying stress fractured slabs, tearing failure by loose underlying rock, blasting damage caused by fly rock and detached flaps causing difficulties spraying next rounds. The second liner, a 2- part urethane pre- polymer/ water based resin system have the similar advantages and disadvantages as above and both liners had a long curing/ drying. However the available free isocyanates was too low to afford any measurement level of curing. The main reason for abandoning these two liners is due to the combination of high adhesion and low tear resistance, lack of toughness and the long curing/ drying time, some of these issues displayed in Figure 8 and Figure 9.
Figure 8. Liner failure types, left picture displaying a tear in the liner due to gravity failure, right picture shows applied liner on stressed back with visible signs of stress fracturing in the liner, Hadjigeorgiou (2000), Hadjigeorgiou (2005) and Blake et al (2006)

Figure 9. Failure types. To the left signs of poor coverage and insufficient thickness due to manual spray application, right picture shows rupture of liner due to dilating stress- fractured slabs, Hadjigeorgiou (2000), Hadjigeorgiou (2005) and Blake et al (2006)

Spencer et al (2011) describes the most recent and current of 3M’s spray-on liner as demonstrated in Figure 10. The 3M PCM liner has been designed with the desired properties that historically have not been achieved with earlier generations of TSL. Their polymeric composite membrane (PCM) is tough to possess the most desirable properties in terms of adhesion, elongation, curing rate, tear resistance, toughness and tensile strength. The 3M PCM liner has the ability of continuous application on rough, dry or damp rock surface while maintaining adequate adhesion. It is a 2- layer composite with respect to the primer and the topcoat. The primer and topcoat consist of two parts respectively, named part A and B. Part A is the part containing the isocyanate while part B is organic. These are kept separated until mixed in the spray gun creating the full primer and topcoat respectively. After application the primer and topcoat cream/ gel in a matter of seconds. The foam creams first then rises and then cures after it gets to its tack free point. Before rock bolts can be installed for a sufficient ground support system, the material should preferably cure 1-2 hours in order to reach some initial strength. Typically, the materials full strength is reached after 72- 96 hours after application but it develops considerable strength
surpassing any former TSL in the shorter term and the tensile strength peak is 30MPa. The polyurethane primer smooth’s out the rock surface and is designed to adhere on damp surfaces and provide an even layer for the topcoat resulting in overall better coverage. The hybrid polyurea topcoat is expected to possess all the desired engineering properties in order to compete with the existing ground support systems. The level of elasticity, tear resistance, toughness and tensile strength of the topcoat cannot be found in any other existing support system such as other polymer liners, screen or shotcrete. See Table 1, for property specifications within the full composite; note that once the material gels then the strength starts to build over time. The material properties confirm that the liner has exceptionally high strength, high elongation and good reinforcement ability compared to current support systems.

Figure 10. Demonstration of the new 3M PCM Thin Spray On- Liner with robot prototype, Spencer et al (2011)
Table 1. 3M PCM TSL material properties according to Rayner (2012)

<table>
<thead>
<tr>
<th>Material Property</th>
<th>3M PCM Primer (Polyurethane)</th>
<th>3M PCM Topcoat (Polyurea/Polyurethane)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness [mm]</td>
<td>3-6</td>
<td>3-4</td>
</tr>
<tr>
<td>Cream/ Gel time [sec]</td>
<td>2-5</td>
<td>2-5</td>
</tr>
<tr>
<td>Tensile strength [MPa]</td>
<td>-</td>
<td>25-30</td>
</tr>
<tr>
<td>Elongation [%]</td>
<td>-</td>
<td>300-400</td>
</tr>
<tr>
<td>Young’s Modulus [MPa]</td>
<td>-</td>
<td>200-250</td>
</tr>
<tr>
<td>Toughness [MPa]</td>
<td>-</td>
<td>50-80</td>
</tr>
<tr>
<td>Tear strength [pli]</td>
<td>-</td>
<td>600</td>
</tr>
<tr>
<td>Adhesive strength [MPa]</td>
<td>0.45-0.85</td>
<td>0.5-0.75</td>
</tr>
</tbody>
</table>

A comparison of some fully cured material laboratory properties between 3M’s PCM Topcoat, its water-based Mark 1 TSL, Mineguard™ and fibre-reinforced shotcrete is shown in Figure 11. Note that RDP Toughness refers to Round Determinate Panel test data, which in the case of a TSL has been obtained by first applying it to a standard shotcrete sample and then performing the test as per ASTM(C-1550) procedures, Swan et al (2012).

However note that comparing the properties for a brittle material as fibre reinforced shotcrete and an elastic material such as the 3M liners must be done with respect to the purposes of these materials.

Swan et al (2012) list the most favorable properties in order to deliver a liner material compatible with its predecessors and current conventional support, the properties are as follows:

- Adhesion
- Toughness
- Tear resistance
- Smoothing properties (continuity of coverage)
- Applicable to damp and/or rough surfaces
- Ultimate cure
3.2 Geotechnical Justification

The 3M Polymeric Composite Membrane’s laboratory-based properties as presented in Table 1 are exceptionally good considering the liner as an underground support system, especially compared with existing ground support systems in terms of tear resistance and toughness. However, underground tests are necessary to detect early practical design failures in a large-scale environment, to gain final geotechnical proof in terms of the liner’s ability to contain failed or failing rock, to validate the laboratory testing and to prove the PCM in Type 1 ground conditions with further input in Type 2 and 3 ground conditions. In theory the capability of TSL exceeds the capability of screen and shotcrete together, especially with respect to the ejection velocities, the liner having superior deformation properties compared with screen and shotcrete. The underground trials aim to prove the liners performance based on the results from laboratory testing compared with alternative liners under essentially the same ground conditions. The 3M PCM should deliver dynamic support due to its toughness and tear resistance. It can be applied as a support system or in case of extra support in combination with existing ground support systems, 3M (2011)

Spencer et al (2011) describes the nature of the critical ground conditions where the 3M liner should be installed in order to gain sufficient proof, validating its exceptional properties. The focus has been on Type 1 ground conditions. The ground conditions are specified as follows in Table 2 and illustrated in Figure 12 and Figure 13.

Figure 11. A comparison plot of various fully-cured material properties from laboratory tests on 3M’s PCM Topcoat Liner, its original water-based polymer liner Mark 1, Mineguard™ and fibre-reinforced shotcrete, Swan et al (2012)
Table 2. Classes of ground failure, Spencer et al (2011)

<table>
<thead>
<tr>
<th>Class Type</th>
<th>Failure</th>
<th>Proposed Solution</th>
<th>Key Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Type.1</strong></td>
<td>Gravity or moderate stress-driven local loose failure</td>
<td>Rebar with 3-4mm thick 3M Liner</td>
<td>High adhesion and toughness</td>
</tr>
<tr>
<td><strong>Type.2</strong></td>
<td>Rockbursting—weak to intensely violent impact failure</td>
<td>Yielding bolt bonded with 6-7mm thick 3M Liner</td>
<td>Liner de-bonds with rock failure, high toughness and high tear resistance</td>
</tr>
<tr>
<td><strong>Type.3</strong></td>
<td>Squeezing—slowly deforming, disintegrating failure</td>
<td>Yielding bolt bonded with 3-4mm thick 3M Liner over 20-30 mm shotcrete</td>
<td>Liner de-bonds with rock failure, high toughness and high tear resistance</td>
</tr>
</tbody>
</table>

Figure 12. Type.1 Ground failure, local loose material contained by bolted screen, Spencer et al (2011)
The 3M liner performance due to several types of ground failures has been determined in laboratory trials and the results motivate further trials in an underground large-scale environment. However before the trials can continue in a large-scale environment there is still need of further laboratory testing. Spencer et al (2011). The main testing issues with need of further investigation are as follows:

- The bagging expansion between rock bolts
- The liner capacity to carry loose load and ability to contain the ejected rock fragments
- The bolt plate design with respect to cutting edges
- The liner bonding ability with the rock surface
- Applying the Top Coat on top of green shotcrete to determine if it can be applied without interfering with the cure time for shotcrete
- Strain deformations need more investigations, especially due to rock burst (secondary interest to the scope of the program)

Once these issues are tested and investigated, the necessary modifications are to be performed in order to finalize the liner material for underground trials, Spencer et al (2011)

Swan et al (2012) is referring back to some of the previous work when addressing one of the major performance issues: adhesion. The liner must detach from the rock surface when underlying rock failure occurs in order to be able to mobilize the toughness capabilities of the TSL, the loose rock expands the liner and is retained by rock bolts. While the theory behind liner performance due to rock failure may seem very simple, historically this has been an issue due to design difficulties associated with both chemical and mechanical adhesion. The TSL design with respect to its adhesion should have the properties to resist blast damage without peeling and bond to rock surface without de- bonding other
than due to rock failure. Higher adhesion of the primer will help to limit the peeling aspects on the other hand, higher adhesion of the Top Coat does not ensure resistance to blast damage since those issues are more a function of the physical properties within the Top Coat. The issues with high adhesion of the Top Coat to rock or Top Coat to primer is that the failure mode under stress changes to one of de-bonding first followed by potential tear. Further there is what is termed a weak boundary layer between the Top Coat and primer that could release causing property change in terms of the liners tear ability. The balance between the ideal adhesion, referring to the de-bonding due to a rock failure but bonding due to any other mining induced activity is a critical design criterion. The “bagging” phenomenon or adhesion failure allows the liner to bag, as demonstrated in Figure 14.

![Diagram showing primer, Topcoat, Raw Rock, and bolts with before and after failure states](image)

*Figure 14. De-bonding due to a failure also referred as the “bagging” phenomenon*

Other issues addressed by Swan et al (2012) are related to the liner’s quality of application; pre-requisites the liner thickness must be kept as uniform as possible which is one reason why robotic application is preferred. This is because manual application does not provide the same type of reliability in terms of thickness control. Both thicker and thinner application have the similar fully cured strengths properties in terms of elasticity, but thinner applications will have less loose load-carrying capacity. To gain sufficient proof the liner must be applied at targeted areas where mining induced rock failures are to be expected. For capability as a Type 1 ground support, in cycle rounds are an accepted method of monitoring effectiveness.
3.3 Safety, Health and Environmental

Although the implementation of TSL aims to improve the overall mine safety in terms of a flexible support system there are some health and environmental aspects that need to be considered. Overall it should be mentioned that applying the liner is less labor intensive than installing screen due to the robotic application method. The liner spray application can leave manageable traces of airborne isocyanates in the form of monomer and oligomer for very short periods of time after the spray has been completed, Spencer et al (2011). The application of any underground support system has some health and safety concerns that should be put in perspective for the specific required application and should be the primary priority. Once the safety aspects are assessed and mitigated to an acceptable level, the secondary concerns are to compare the benefits and disadvantages of the candidate support systems. The comparison should be done in such a fashion that it is kept in mind that there is no available support system that is ideal and flawless. The final decision should be based on the specific situation, what kind of purposes the liner aim to serve while balancing the safety and support aspects while keeping it economically feasible.

3.3.1 Isocyanates

Spencer et al (2011) describes the safety aspects of the 3M PCM. The liner is a two layer composite, each composite consist of two parts, A and B. Part A in both composites contains Methylene Diphenyl Di-Isocyanate (MDI) which can lead to health effects due to exposure in the absence of appropriate handling and usage protocols. The health effects are skin sensitivity, eye irritation and with long-term exposure it can lead to asthma attacks. Similar polymers of this specific isocyanate are normally found due to manufacturing of typical industrial materials such as paints, lacquers and electrical insulation as well as in mining in rock bolt resins. MDI used in 3M PCM is however the least volatile compared to isocyanates used for similar purposes since it has lower volatility than TDI but not necessarily less than the likes of HDI or IPDI. Part B is a mix of flame retardants and primary and secondary amines for the most part. Part A and B chemicals are kept fully inclosed and separated until mixed with the ratio 1:1 in the spray gun, where they react immediately and the 3M PCM is fully reacted in a matter of milliseconds. The majority of the 3M PCM reacts at this point and leaves a very low concentration of airborne isocyanates in the working environment during the spraying and a short period afterwards. Rayner¹ explains the process in greater detail. The reaction time of the airborne isocyanates is very rapid in reacting from either monomer to oligomer or oligomer to polymer, in addition CO₂ gas is produced in small quantities during the application process. The particle size, post reaction are large enough that a dust mask would be able to catch the particles, although a dust mask is not a substitute for the required personal protective equipment to be used when entering the working area during spray and designated timeframe post spray. Without any airflow, any large particles would drop to the ground at the spray site. There is enough amine in the Part B that some would get vaporized and contribute to making the air in the area slightly alkaline which would aid to drive the isocyanate reaction.

¹ Terry Rayner Specialist 3M, interview on the 17th April 2012.
However, Spencer et al (2011) continues explaining the importance of the protocols and procedures to be set up for managing isocyanates and limiting the exposure. Based upon regulations by the Ontario Ministry of Labour (MOL), the following limitations should not be exceeded without respiratory protection. The time weighted average (TWA) of 5ppb over an 8 hour period and at the ceiling limit (CL) of 20ppb. Based upon MOL regulations a Control Plan has been designed. During spraying, a barricade set-up is required 20 meters downstream behind the spraying equipment, entrance within the 20 meters barricade is only allowed with full personal protective equipment including respiratory equipment. No respiratory equipment is required downstream from the 20 meters barricade during the scope of the trials conducted. The ventilation should be turned off during spray and during the waiting time 30 minutes after spraying is completed. Ventilation and water curtains actually disperses the airborne isocyanates. By following the described handling procedure the isocyanates are handled in a controlled fashion, there are however occasions where the situation may be accidental. For example due to a material spill or leak where the ratio of the part A and B chemicals may vary from the 1:1 ratio. Procedures are set up for neutralizing an isocyanate spill. Rayner² suggest that if the spill mostly contains the isocyanate part A, neutralization is necessary and is performed according to the environmental, health & safety accepted protocol. The protocol requires the use of a low volatility neutralizing agent such as water, ammonia and a surfactant. If the majority of the spill comprises the organic part B, the handling procedure should be treated as organic waste as per the MSDS. Removal by scoop or any other device available is sufficient, while wearing the appropriate personal protective equipment.

3.3.2 Fire Hazards
According to Swan & Petherick (2009), the MDI isocyanates are not considered as a severe fire or explosion hazard. Trials performed to test the flame spread and smoke developed of the liner shows that it is self-extinguishing after the external flame has been removed. However it may degrade the material in direct proximity to the flame, depending on the char mechanism which can reduce this potential. Its observed flame spread values are below the limiting value of 150, which value is thought to be low in comparison with other flammable materials used in the mining business. Currently there is not a flame spread nor smoke developed specification for TSL’s to be used in an underground environment. In order to put the 3M PCM on fire something else has to be on fire and in close proximity to the liner. While on fire it will not release any isocyanate since it cannot back degrade but will however generate two types of gases: carbon oxides and nitrogen oxides which can have severe recognized health effects. Once again, these gases are well recognized in a mining environment and the 3M liner generation of these gases is thought to be negligible in comparison with other sources for these gases in a mining environment, e.g. vehicle tires.

Neither the foam or topcoat will burn by themselves; to be set on fire the whole composite is required. The composite has a level of flame retardant, preventing the liner from propagating a fire. However the foam has porous properties and contains air and when the foam forms, it forms by liberation of CO₂ gas,

² Terry Rayner Specialist 3M, interview on the 17th April 2012.
Swan et al (2012). The 3M PCM is a polymer and has a melting point, as do most thermoplastic polymers, once reached it forms a char layer. The polymer controls the melt point while the flame retardant package controls the methods used to limit the flame propagation. The flame retardant needs to be considered with respect to the impact on physical properties, application method, impact on pumping equipment, airflow: higher amount of airflow increases the rate of propagation. Any other sources of ignition, that caused the fire, would have to be dealt with or part of the mine protocols in dealing with such situations.

3.3.3 Environmental Aspects
According to an evaluation by Tuzum (2012) performed during the flotation of the ores, the addition of the 3M liner material does not affect the flotation considerably. Due to the properties of the liner, it is not easily fragmented and may therefore cause plugging or transportation handling issues. The majority of the 3M liner seemed to end up in the tailings, with some minor parts found in the concentrate. An investigation into whether any of the 3M liner material may find its way to the smelter and the consequences of it doing so has not as yet been investigated. There is however speculation whether some of the 3M liner could be found in the hydro cyclone overflow for the backfill preparation plant.

Rayner claims that the 3M liner was designed to resist degradation through its polymer backbone since it is designed to retain its original physical and chemical properties throughout the majority of the mine life. The topcoat has sinking properties and the foam floating properties, which make it easy to separate once processing it. As mentioned it will not degrade and not leach, depending on the definition of leaching as even any removal of color could be considered leaching. It is a tight and cured polymer system and could therefore be considered to store in a landfill once it has fulfilled its purpose as a support system, the material is not biodegradable but it can be disposed as a part of the mines normal waste stream for similar materials. Recycling of the PCM have not yet been studied and need to be evaluated, although it is assumed that normal recycling procedures will not be able to recycle the PCM since it is a very highly cross-linked polymer.

3.4 Equipment Requirements
The demands on mining equipment are many and tough and needs to be considered during the design and construction phase for a TSL application prototype. To mention only some of them, the equipment needs to be well protected and robust due to the rough profiles underground and able to resist dust and vibrations, since these are common factors when mining. It also needs a certain level of flexibility since underground drifts are limited in size. The prototype should provide high capacity since mining is a large-scale operation. It is obvious that the prototype is equipped with lamps providing enough light, shock absorbers when transporting the robot and spray equipment on rough surfaces and proper reflective tapes for increased visibility. These are only some of the factors to consider when designing the TSL application prototype; fragile equipment will not be suitable in a mining environment. Keeping this in

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3 Terry Rayner Specialist 3M, interview on the 17th April 2012.
mind a suitable prototype will be designed and constructed. Meantime a skid mounted system with an integrated spray equipment will be used to collect the necessary geotechnical proof.

3.4.1 Spray Equipment
Spencer et al (2011) describes the basic functions and requirements of the skid- mounted equipment. In order to be able to automate the sprays and transport all spray equipment during collection of the geotechnical proof, an integrated spray equipment skid was constructed, containing the spray equipment and a skid mounted robot as demonstrated in Figure 15 and Figure 16. The integrated spray equipment simplifies the logistics, increases the level of safety, productivity and the material efficiency while decreasing the cost. The connecting hoses and cables are well contained on the skid. The two separate high pressure spray units, one for the primer and one for the topcoat pumps come in two part liquids with a 1:1 ratio. The two separate spray units require space but are beneficial since there is no need to purge the materials between coating application of the primer and topcoat respectively, it is time saving and guarantees the material quality. The pumping capacity can reach 17MPa. The primer and topcoat materials are pumped to the main pumps by the standard drum pumps, where it is heated, pressurized and kept separated until sprayed. Once the materials are sprayed they react in a matter of seconds. During off mode the mix chambers in the guns are blocked and purged with air to prevent clogging. The skid is hoisted underground in parts by the vertical hoisting system and assembled at one of the shops. Once assembled underground the skid is transported and adjusted to a proper position with a load haul dump (LHD) vehicle. Due to the reach limitations with this type of mounted robot, it can only spray around 2.5 meter wide patches at a time once the skid is set. In order to spray a whole round the skid needs to be transferred by a scoop. The skid requires air in order to mix the material in the drums and electricity for power supply.
Figure 15. Spray equipment and skid mounted robot, Spencer et al (2011)

Figure 16. Robot and spray equipment integrated on the skid
During the final phase of the collection of this TSL system proof a prototype will be designed and built with the objective of meeting all the operational and engineering demands. The mobile carrier for applying the TSL must include the drum carriers containing the materials to be applied, spray feed pumps and a mounted robot with adherent control package. The robot is highly sophisticated and should be protected and handled with care, especially during transportation. The mobile carrier itself must be flexible providing horizontal and vertical movement in order to move the robot and allow it to spray walls and back or any other preferred geometry. Essentially it will be sized to provide the capability of spraying an intended number of rounds common to underground mining operations.

3.4.2 Robot

ABB Canada is responsible for the design and development of the robot for the application of the 3M PCM. The sophisticated robot process starts with scanning the surface, although the surface in a mining environment is usually rough, blocky and undulated the robot will be designed to be able to scan such a surface. The scan pattern is performed vertically and horizontally, creating a grid. The pattern used has a 25cm separation between horizontal points. Once the scan is completed, the data is saved and creates a robot path; a dry run is performed to ensure that the generated path will provide a sufficient application covering the surface to be sprayed successfully. To improve the spray coverage the robot is spraying 4 different spray passes with varying directionality of the spray while maintaining approximately 30 degrees leading angle, according to Figure 17. This application procedure is performed for the primer at first and directly thereafter for the topcoat with separate guns, the primer and the topcoat are applied with different thickness and different velocity respectively.

![Figure 17. Demonstrating the vertical passes at the top and the horizontal passes at the bottom with reversed leading angles](image)
The robotic application allows for controlled thickness of the primer and topcoat respectively and promotes the benefits of automated application. It is not at this point fully determined which parameters affect the application thickness the most; the parameters required to achieve the desired thickness could to some point be determined by spray applications performed for the geotechnical proof. Since the robot is mounted on a skid it will have limited reach and will only be able to spray 2.5-3.0 meters wide and 3.5 meters high patches at a time, which equals a half round. The reach will be increased as well as the flexibility once the robot is mounted on the prototype carrier, designed by MTI according to Figure 18. The carrier will allow the robot to move upwards and downwards, back and forward with the help of an integrated rail system and to the sides. The carrier’s flexibility together with the robots operating dimensions will allow the spraying of a complete round. The idea behind the use of a robot is mainly motivated by its effectiveness in controlling the application thickness and to avoid the operator exposure due to the isocyanates present during the spraying and from exposure of unsupported ground. The robot is operated by remote control including options for scanning and spraying the desired geometry and aim to simplify the process. The robot performance is evaluated by its ability to spray with a certain consistency, a spray pattern providing successful coverage and with providing sufficient overlaps without compromising the 3M PCM properties. The robot must therefore be reliable, easy to operate and flexible in order to achieve acceptable cycle times, Spencer (2011)

Figure 18. MTI designed prototype

3.5 Operational Controls
The operational controls are those required prior to applying the TSL and all the operational difficulties faced during the application and after the application of the TSL. To assure optimum liner application, cautious blasting is preferred in terms of decreased crack lengths and decreased fractured zones along
the contour. It is of high priority to complete the necessary surface preparations that are critical to assist with surface preparation in advance of applying the primer layer. The washing and scaling process is most preferably performed by a high pressure waterscaler. The mobile carrier and the robot are fully automized and computer driven to allow minimum operator intervention to eliminate the risk of isocyanate exposure and in order to control the application thickness. Currently there are some coverage difficulties due to the limited reach of the robot while on the skid. Once a prototype is available it will be able to cover the desired areas such as the back and shoulders. Before spraying it is required to carefully set up the robot and the equipment with a set stand-off distance for sufficient coverage. During spraying, operator observation is allowed behind the 20-meter physical barricade. In case of any interruptions, the operator controls the spray equipment and the robot with a remote control. When finished spraying, a quick visual inspection can be performed and bolts installed before the next round is blasted and supported by the TSL.

4. Ground Control and Operations Proof
The following section describes the nature of the approach during underground trials performed at Nickel Rim South. The purpose of the underground trials is to gain sufficient ground control and operations proof for the TSL product in terms of its rock support abilities and practical concerns. The major focus of the thesis will be put on this section together with the section describing the results from the underground trials.

The TSL aims to provide unprecedented rock support, in terms of its deformable elastic properties and capability over the intended ground support types to maintain rock masses. In order to prove the properties and capabilities of the TSL liner, it must be exposed to whatever conditions it is designed to prevent, therefore test trials should be of a targeted fashion. The main purpose of the underground trials is to simulate such conditions and to observe what happens. Totally 60% of the underground trials were to be in the areas of Type 1 ground support and the remainder split between Type 2 and Type 3 ground types.

4.1 Methods and Procedures
The Thin Spray On- Liners 20 year long history and testing trials were mainly and are currently executed in Canada, although considerable work has been done in South Africa as well as development work has been done in the US. As a part of the thesis, data collection is required. The onsite geotechnical and health & safety data collection was performed underground at Nickel Rim South mine in Sudbury, providing not only the necessary data but also providing understanding since the data collection was performed within close proximity to the liner and the spray equipment. The data collected is summarized in the thesis with associated conclusions.

Rock mechanics and soil mechanics cannot be compared with any other materials’ mechanics. Other materials usually have well-defined properties, which is not applicable to rock and soil. The variables are
countless and many times unpredictable which must be accounted for during test trials. Each rock surface has individual properties, which causes difficulties when the capability of the conventional support is compared to the TSL under similar conditions. The test trials can only guarantee that the comparison is performed for similar rock conditions, not for the same rock conditions. The mining environment has exposed the liner to the same conditions as for regular support, such as the same humidity, temperature, dust, vibrations, fly-rock and in cycle related exposures. Some of the liner’s toughness properties can be evaluated with respect to these factors. Note should be made that the surface preparations was not per normal protocol and there was only ability to evaluate patches on a wall rather than a full heading. The overall material quality can be determined by visual inspection shortly after the application, which contributes to the geotechnical proof collection although this is only a very qualitative method of assessment. The time based performance was not available in these underground trails since the majority of the geotechnical proof will not be gained until long-term monitoring has been performed where full rounds of material have been applied. Any conclusions as to whether the liner is performing as expected due to primarily ground movements and potentially bursting conditions cannot be performed until such events occur, the results from these events are usually of long-term nature and difficult to forecast. The specific tests and type of rock conditions required to prove the liner’s ability have been revised and assessed by a qualified ground control team.

The host rock at Nickel Rim South is Sudbury Breccia with Dyke intrusions; the most critical areas in the mine are by definition where the main faults run and where the contacts between the host rock and soft copper ore is. A variety of these critical areas are selected for the test trials and in addition the areas are located at depth, contributing to the increase of the stress situation. The test sites will be exposed to ground movement and they are located in areas where bursting ground and loose failures are expected. Once the test areas are selected, the application of the liner on the walls only is performed to fulfill the specific tests. At this point the reach limitations of the robot and the rigid skid only allowed application at the walls. It was desirable to spray the shoulders and the back to get full coverage for a round but practically this option was not available at this point due to limitations related to robotic software. Most of the data is collected during the application process. To monitor the ground movement prior to eventual rock failure instrumentation is installed to detect any movement in the rock mass behind the applied liner. The instrumentation is a set-up of smart cables, multi-point borehole extensometers and camera holes which aim to measure the movement and provide a visual inspection of the rock behind the liner. It should be mentioned that some of the instrumentation was not used during the scope of the tests although it was the intent. Depending on the nature of the tests, observations are performed of the applied liner with set time intervals and are a part of the long-term monitoring.

During the trials, cancelling and interruption delayed the tests to be performed. The main reason for some of the delays was due to the fact that the mine is in its producing stage, prioritizing some of the headings for the production and not necessarily for the trials. Further delays were caused by exercising extreme caution associated with the possibility of exposure to isocyanates during spraying and due to the handling protocols that were in the process of being established based on the environmental and health & safety trials. The local ventilation is turned off during spraying and operators working downstream at the same level were requested at some times to leave the working area. If the air travels
from the spray site crossing some of the operators working areas, this procedure is required in the event that the air may contain either a monomeric or oligomeric form of the isocyanates. In order to clear some of the headings, waiting times for the operators to complete their work was sometimes required. This changed as the protocols were further refined. After the necessary headings are cleared safety procedures during spraying were as follows. Spray equipment technicians, programmer and anybody entering the designated spray area wore disposal coverall, gloves and went under supplied air since the isocyanate protocol during the underground trials was not set up and conservative safety actions were taken. The equipment available to spray the liner is a rigid skid and a robot with limited reach. Only 2.5-3.0-meter wide patches could be sprayed a time, which equals a half round. Every spray site was labeled according to the format NRS- Month-Day-Trial, for example NRS 03-18-01 which is a label for a first spray for the day performed at Nickel Rim South at the 18th of March. The skid with the mounted robot had to be turned off, unpowered and moved with a scoop before the next application. The scoop had high availability although the procedure to set the skid up with high precision required a skilled operator and instructor and could sometimes be time consuming. Before every spray the surface to be sprayed was washed, using a hand low pressure water hose, scanned and subjected for a dry run. At times this was time consuming, in cases of a rough and blocky surface or in case of elevation issues. After a while, the ABB programming became integrated in the application process although it could at some times require a large amount of time.

Sources of errors compromising the liners true capability and properties must be considered. Failure with respect to lack of continuous coverage and lack of continuous thickness, due to the initial pattern that did not ensure full pattern coverage due to the nozzle flip over mechanism, which was adjusted later in the testing, may cause weaknesses or thinner areas in the liner. Areas with poor coverage and thickness are the weak points within the liner: in the case of eventual rock failure these weaknesses may cause the liner to tear at these specific points. Poor coverage and lack of continuous thickness is a combination of the robotic speed, spray pattern overlap, spray pattern continuity of coverage and the spray pressure with addition of a rough surface. Visual inspections are necessary during all the phases of the spray to determine the surface conditions, the spray quality and the liners resistance due to fly rock, blast damage, seismicity, stress, ground movement and ability to contain failed rock fractures. Eventually it is necessary to compare the performance of the 3M PCM versus conventional rock support to be able to evaluate the liners ability and performance.

4.2 Measuring Equipment
During the underground trials, measuring equipment was necessary for collection of some of the performance data for further proof and to determine the current conditions for each specific application. To assure the coverage and validate the thickness continuity, surveying, TSL cutouts and ultrasound measurement was executed.

Surveying was executed with a surveying device referred to as a total station as displayed in Figure 19. The total station contain an electronic distance measurement unit combined with an electronic theodolite, the total station is set up on an adjustable tripod. In addition two prisms are installed on the
rock walls to triangulate the total station with two known points, referred to as the back sights. The triangulation process aim to determine the location. Once the triangulation error is acceptable two new front sights are shot with the total station and triangulated as illustrated in Figure 20. This setup will serve as a base for collection of desired points. The theodolite measures the vertical and horizontal angles and an infrared signal is emitted and reflected to the point of interest to measure the distance. This system allows for a 3 dimensional position of points by determining the angles and distances between the points of interest, able to detect changes in thicknesses. The collected thickness data is transferred to a handheld computer connected to the total station by Bluetooth connection, Kavanagh and Glenn Bird (1996). Once the total station is set up and triangulated, scanning the desired wall area collects the selected points. The scanning procedure must be performed for each layer respectively. First the raw rock, thereafter the foam layer and finally the topcoat layer. The total station measures the same points with an accuracy of ±0.2mm for every layer. By interpreting the collected raw data a determination of both layer thicknesses can be performed. The points of interest were collected by a grid pattern with the dimensions 25 x 25cm. Although the survey system offered great accuracy and simplicity unfortunately it could not be integrated in the spraying process successfully. Three total station setups were required to gain the layer thickness which would require the skid to be moved back and forward twice and interrupted between foam and topcoat application, which is time consuming and caused delays. An attempt to shoot the desired wall area was done once the skid remained in its position given the alternative to either setup behind the skid or in front of the skid. The setup behind the skid could not be performed with success since the skid blocked the desired wall area to be scanned by the total station. The only option left was to setup in front of the skid, which was possible in those locations where the rock face was further behind the skid setup. In those locations where the face were in close approximate to the skid there were no room left to set up the total station, a total station set up in front of the unsupported face and next to unsupported rock wall is neither acceptable from a safety point of view. There were no longer any options to where to set up the total station. In addition to these practical issues the triangulation and setup of new front sights could barely be performed with an acceptable accuracy, based on the level of accuracy due to installation of the back sights. The practical difficulties prevented the optimal use of the surveying equipment and therefore it was eventually abandoned.
Figure 19. The total station setup in one of the underground trials with adherent tripod and handheld computer

Figure 20. Schematic sketch of the surveying procedure
To continue the assurance of the coverage and validate the thickness continuity an ultrasound device was implemented. The ultrasound measurements were validated through the use of material cutouts. The ultrasound device contains a handheld unit connected to an adapter with a cable connected to the transducer as demonstrated in Figure 21. The transducer is electromagnetic acoustic and generates shear sound waves to determine the thickness. The accuracy is ± 0.25mm and the thickness can only be measured for the topcoat layer with the ultrasound device, which is the thickness of interest. It is a handheld unit that quickly determines thickness without removing the topcoat layer. The points of interest are of targeted fashion, which provide the flexibility to take thickness measurements where the topcoat application may be critical such as in shadowed areas from a spraying point of view or other critical areas. To assure that the unit is collecting valid thickness data, the specific surface subjected for thickness measurement must be clean and smooth.

*Figure 21. Ultrasound device with the electromagnetic acoustic transducer, [www.olympus.com](http://www.olympus.com) (2012)*

In addition the temperature and humidity measurements were taken before every application. The humidity and air temperature were measured with a Hygro-Thermometer Anemometer with data logger. The average humidity measurements were performed once the fan was turned off to avoid any dispersal of air entering from outside the drift and the same instrument were used for measuring the average air temperature. Average temperature measurements were also collected from the rock walls, the face and the back with an infrared thermometer. It was suitable for the underground trials since it has a good reach and provides flexibility. Both instruments are illustrated in Figure 22.
4.3 Underground Trials

The majority of time during the thesis’ project was spent at data collection and observations of underground trials. The large-scale trials aim to prove the true ground control potential of the TSL in a real mining environment and also to early detect any operational issues. In order to collect the remaining proof and prove the 3M PCM as a superior component in underground rock support, the underground trials are necessary. To achieve the 95% proof level, the remaining final ground control and operations proof is necessary since it is thought that the laboratory proof and the initial ground control and operations proof can only target up to a level of 70%. A qualified ground control team with experience from earlier TSL-projects determined the nature and the extent of the specific underground trials necessary to increase the level of proof and evidence by setting up a geotechnical plan. Minimum operational and ground control criterions were setup to prove the 3M PCM as a superior component in underground rock support and to prepare it for commercialization. The criterions are setup and will be compared with respect to available alternatives under a variety of rock failure conditions and loadings, where 60% of the underground trails were to be in the areas of Type 1 ground support and the remainder split between Type 2 and Type 3 ground support types, Swan (2012). Some of the issues addressed are to observe the capacity to withstand fly-rock damage and peeling of the leading edge due to blasting of the next round.

The underground trials to gain geotechnical proof are presented in Table 3, by Swan (2012). Tests that are planned but not yet performed is a consequence of low priority, lack of time and resources such as access to planned test site and obviously this is the reason for not obtaining any results from these tests yet. Before any geotechnical tests could be planned and executed, health and safety tests were prioritized. These tests contained the isocyanate level measurements, where the measurements showed no concerns to proceed with the geotechnical trials if the safety protocols and necessary personal protective equipment were used as required. In addition to the tests presented in Table 3, a water
Seepage test was planned to test the PCMs ability to withstand water seepage by backfill water from nearby stopes. This test required PCM application on both shoulder and back and was abandoned due to the robotic limitations at this point, however it should be mentioned that some of the seepage test was done at 1625 meters level in heading 287 where there was water flowing over the area that was sprayed. Since the 3M PCM requires to be supported by bolts to fulfill the requirements of a dynamic support system, possible operational limitations during bolt installation needed to be examined, called the bolt-through test. A few adjustments to the bolting equipment were performed before acceptable bolt installation could be accomplished. Most significantly to determine which drill bit is most appropriate to cause minimum damage and ripping to the liner, which drilling speed is most suitable and which drilling method to use to diminish the de-bonding around the drill hole. Once these issues were addressed, they were solved by best practice and by past experience. Bolt installation could be performed successfully for all the test sites. Cautious blasting, which is a blasting practice aiming to reduce the blast damage on the remaining rock, was not applied during any of the tests. The majority of the tests were performed in already existing drifts developed months and sometimes years before the TSL testing, this partly caused rough, blocky and over broken application surfaces. However a ground support system is to be implemented in a wide range of ground conditions.

Table 3. Planned and executed geotechnical underground trials, Swan (2012)

<table>
<thead>
<tr>
<th>Test Type</th>
<th>Method</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peel and Fly- Rock test</td>
<td>Full Composite Apply PCM and blast next round, in-cycle after 8-12 hours</td>
<td>Performed</td>
</tr>
<tr>
<td></td>
<td>Topcoat Only Apply PCM to wall of stope overcut before blasting stope</td>
<td></td>
</tr>
<tr>
<td>Stope Blast Test</td>
<td>Apply PCM to wall of stope overcut before blasting stope</td>
<td>Performed</td>
</tr>
<tr>
<td>Primary Pillar Nose Test</td>
<td>PCM will be subjected to deformation/failure when driving secondary stope access</td>
<td>Performed</td>
</tr>
<tr>
<td>Toughness Capacity Test</td>
<td>7mm versus 4mm topcoat thickness comparison</td>
<td>Performed</td>
</tr>
<tr>
<td>Topcoat over Shotcrete Test</td>
<td>Extent of increased shotcrete toughness given a rock failure condition</td>
<td>Performed</td>
</tr>
<tr>
<td>Bolt- Through Test</td>
<td>Drill- through issues with bolt holes</td>
<td>Performed</td>
</tr>
<tr>
<td>Passive Adhesion Test</td>
<td>Adhesive strength under damp and dry surface conditions, full composite and topcoat only</td>
<td>Partly Performed</td>
</tr>
<tr>
<td>Main Fault Test</td>
<td>Long-term observations on shearing faults</td>
<td>Not Performed</td>
</tr>
<tr>
<td>Wrap- Around Nose Test</td>
<td>PCM applied to 3 faces of a stope access pillar subject to failure as mining proceeds</td>
<td>Performed</td>
</tr>
<tr>
<td>Underground Large- Scale Pull Test</td>
<td>Modified MIRARCO test without paving stones to obtain in situ Force- Displacement data</td>
<td>Not Performed</td>
</tr>
<tr>
<td>Green Shotcrete Test</td>
<td>Apply PCM to green shotcrete, perform 28-day UCS test on shotcrete</td>
<td>Not Performed</td>
</tr>
</tbody>
</table>
4.3.1 Peel and Fly- Rock and Toughness Capacity Tests

The Peel and Fly- Rock Test is one of the most prioritized tests and provided results shortly after application. The results from this test aim to reveal the PCM’s adhesive and toughness properties while in cycle and at cure times of 8-12 hours. It will examine if the PCM peels back due to blasting and if any fly- rock damage appear. The tests are performed on full composite and topcoat only. Topcoat only is applied with the thickness of 4mm and 8mm although the majority was applied in the range of 2-4mm with only 2 patches applied as topcoat only at thicker level. In addition the test is subjected to the toughness capacity test, where a thickness comparison is performed in terms of peel back and fly- rock damage. To gain accurate and sufficient amount of data, the tests are of repetitive fashion and performed in- cycle. A total of three rounds, 5 meters at a time is sprayed right to the face prior to the cycle blast. Figure 23 below illustrate the principal layout of the Peel and Fly- Rock test for the full composite, the location with respect to the depth, specific heading and the label for each spray. The same layout was adapted for the Peel and Fly- Rock test and Toughness Capacity test for the topcoat only with a topcoat thickness of 4mm and 8mm as depicted in Figure 24.

*Figure 23. Test site principal layout for the Peel and Fly- Rock test, full composite*
4.3.2 Stope Blast, Passive Adhesion and Topcoat over Shotcrete Tests

The Stope Blast test is a highly prioritized test and is combined together with the less prioritized, Passive Adhesion test and Topcoat over Shotcrete test, all subjected to a stope blast. The three applications contain, the full composite, the topcoat on raw rock and topcoat over shotcrete. Before any results are available a waiting time for a couple of weeks is required since the test site access is unavailable right after the stope blast. Most importantly the test aims to compare the damage on the stope overcuts after the stope blast, between the three alternatives respectively. Since the applications are performed on copper zone overcut and its contacts, squeezing conditions, shear and failure conditions due to heavily structured rock are occurring and putting the applications to further test. In order to apply the full composite and the topcoat, the current screen had to be cut out. A minimum of 2.5 meters was sprayed and bolted for each type of application as illustrated in Figure 25. The results are visually inspected after backfill operation.

Not only is this a comparative stope blast test, the adhesive strength under dry surface conditions between the topcoat and full composite is examined as well as the extent of increased shotcrete toughness when underneath topcoat application.
4.3.3 Primary Pillar Nose Test

The Primary Pillar Nose test was of high priority and the test will be subjected to long-term monitoring where after the results from this test will be available. The PCM is applied on the pillar wall in a primary heading before the secondary heading is driven, once applied with properly installed instrumentation the driving of the secondary heading can begin and deformation measurements are collected. The PCM will be subjected to deformation and potential failure when driving the secondary stope access due to blast vibrations and cracking. The secondary heading will create a 7.5-meter wide pillar, subjected to vertical loading where spalling failure can occur. The potential to withstand all mentioned conditions will be examined. The application process is performed as depicted in Figure 26.
4.3.4 Wrap-Around Nose Test

Although the Wrap-Around Nose test is less prioritized than other tests, it is important since it shows early signs of the PCM’s capacity due to deformations and failures in the pillar. The PCM is applied to the three faces of a stope access pillar as illustrated in Figure 27 to investigate the PCM capacity. Typically primary failures occur at the pillar nose, relatively early. After full composite application at the nose, the required instrumentation was planned to be installed to record deformation in the pillar nose after which mining in the two headings could proceed. However no instrumentation was installed during this test. The pillar nose will be subjected to failures as mining proceeds, especially since the nose of the pillar is usually more slender than the remaining pillar, which most probably will subject the pillar to a nose failure. The test aims to test the operational application capabilities of the robot while spraying the nose and also to test the PCM capabilities when failure is most probable.
4.3.5 Main Fault, Underground Large-Scale Pull and Green Shotcrete Tests

These tests are of lower priority and will therefore be executed during the later phase of the testing. The tests have not yet been executed during the writing of the thesis.

The Main Fault test require a mining environment since it is a long-term observational test, where the PCM will be sprayed over the main faults where shearing can be expected. The ground control team will target these specific areas where the main faults run and this test will examine the shear capability of the PCM. There were a number of faults observed in the area.

The Large-Scale Pull test is as the name suggests a pull test where in situ force-displacement data can be obtained by pulling each ground support configuration with the same force. It is a comparative test and aims to compare several ground support configurations. Combinations of patches are sprayed and installed on a rock surface for comparison. These tests are of no need to be executed in a producing mining environment and will therefore be executed at MTI’s underground ramp excavation. Investigations of in situ force-displacement data will be obtained from following configurations.

- PCM with a constant 72 hours cure time
- Full composite with variations in primer
- Topcoat with 4mm versus 8mm thickness
- Shotcrete with a variety of curing times (steel fibre-reinforced)
• Weld- Mesh Screen
• Topcoat on steel fibre- reinforced shotcrete

The term “green shotcrete” needs further explanation. The green shotcrete is simply uncured shotcrete. The aim of this test is to apply PCM to green shotcrete and perform a 28-day UCS on the shotcrete to examine if the PCM interferes with the curing time and strength properties within the shotcrete.

The appearance of the PCM surface, fresh after application during the trials obviously depends on the grade of roughness at the rock surface underneath it and the carefulness of the preparations pre-spray. The typical appearance is however not especially different from one site to another and is typically appearing as depicted in Figure 28.

![Figure 28. Typical appearance of the PCM freshly after application](image)

### 4.4 Observations

Attendance at the underground trials provided important observations, some of them predicted, some unexpected. During the trials, the focus has been to observe any practical concerns that may arise during the application process and any primary indications of geotechnical deficiency. These observations are presented as follows.
The complexity to set-up the robot and skid equipment was experienced due to the skids low mobility and time consuming set-up. Therefore there are reach limitation since the robot cannot spray the shoulders and back and the conclusions regarding the PCM potential is therefore only based upon the PCM sprayed on the walls. However, once the mobile prototype carrier is designed and ready for utilization the mobility will be high and very flexible with allowance for full reach. It is however important to keep in mind that although the robot is intelligent, it is also fragile and requires considerate transportation.

The trials have been of a targeted fashion, which requires application at zones with expected ground movement/failure, important for the examination. This not only required carefulness and inspections before entering the working area but also sufficient planning. At some points, due to the fact that the mine is in its producing stage, access was denied to the specific test site, which required an alternative plan to accomplish the requested tests.

The local mine ventilation must be off during application and for 30 minutes after application, according to the safety protocol and in order to diminish the risk of escaping airborne isocyanates. It should not be any issues to integrate this part of the process into the application process since it is already a standard practice to shut of the ventilation during the application process of shotcrete.

The installation of deformation measurement instruments was planned for every test site, but this generally failed to be implemented due to the short time interval between PCM application and resumption of the mining activity. The instrumentation would be advantageous when determining the PCM potential.

Most of the observations have been performed on the freshly applied PCM, to examine its toughness, coverage and weak points. Future tear points will most probably occur where poor coverage is observed and focus should therefore be put on liner coverage and thickness continuity.

The minimum requirements to be able to run the application process during trials are an ABB programmer and a spray equipment operator. Once in commercial use a single trained operator will be able to run the spray equipment and robot with a remote control or in a climate controlled cabin.

The programming during the test trials was time consuming, especially during the initial phase of the trials due to the limited robot mobility. The scanning procedure could not be adequately performed due to this. However this issue will be eliminated once a mobile carrier is available. The robot provided a smooth, controlled, uniform and rapid application of the foam and topcoat. Prior to adjusting for the flip over, there were large patches around the perimeter with less than ideal thickness, which may have in part accounted for some of the peel pack issues.

4.5 Data Collection
The geotechnical and health and safety data collection was successfully integrated in the application process during test trials. The importance is great since the data collected can be used for future
references, when determining the conclusions and addressing which variables to adjust for greater success. However the health and safety data is really only valid for the air flow and mine conditions in which the data was obtained and may change with other mine conditions.

The geotechnical and health and safety referred data was collected pre- spray, during spray and post- spray application, although the majority of the data was collected pre- spray. The spray equipment recorded the data during spraying and most of the post- spray geotechnical data was not yet available since the expected ground movement/ failure has not yet occurred. The data collection sheets for pre- spray, during spray and post- spray application can be viewed in Appendix A, B and C.

The definition of a spray is related to the maximum reach of the robot, which at this point was 2.5 meters, half a round. Every spray performed during test trials has an individual data sheet with pre- spray, during- spray and post- spray application data. The pre- data includes the collection of site characteristics, temperatures, humidity, spray surface conditions and rock mass specifics. The site characteristics are constant with the dimensions: height 5.3 meters and width 5 meters. Temperatures were measured on air, walls, back and face and were usually between 20-25 degrees Celsius, with air relative humidity around 60- 70% although there was a single test site with almost 100% relative humidity (due to presence of hydraulic backfill drain water). The rock mass comprised the characteristic Sudbury breccia and with dyke intrusions within the copper ore zone. The during- spray data records the cumulative spray time, flow rates, pressure, temperatures and liters of material consumed. The cumulative spray times for a foam thickness of 1.5mm and topcoat thickness of 4mm is average 3-4 minutes for the foam and average 10 minutes for the topcoat, for a patch 2.5 meters wide and 3.5 meters high. Usually for the same spray patch the amount of material used is approximately 15 liters of primer (part A and part B) and 40 liters of topcoat (part A and part B). However a coverage analysis could partly be performed by visual inspections of the coverage in shadowed areas and examine if any holes, gaps, cracks or lines are visible. The PCM performance data due to blasting and due to conventional mining operations could also be partly collected, with any damage and adhesion failures observed and noted.

In addition to the data sheets, pictures were taken. The procedure was to take pictures pre- spray, to record the rock surface roughness and quality. For some of the sprays, videos were also recorded during spraying to observe the robotic motion and to investigate whether there is any further need of robotic adjustments for improved coverage. After every spray pictures were taken to determine the spray quality. The spray quality in terms of thickness continuity was further confirmed by thickness measurements performed with both cutouts and the ultrasonic unit.

Before any sprays could be executed a test plan was set up, presenting the necessary trials in terms of purpose, performance, requirements and comments. For each spray there was also a calculation performed for the estimated material required compared to actual material uses, to keep track of material used and make sure to not run out of material during underground trial phase. A summary of the detailed test plan can be viewed in Appendix D.
In order to visualize and easier imagine and explain each trial, principal layout drawings were created. Every principal layout drawing is as the name suggests providing the layout of the sprays, alternative spray sites and specific trial requirements.

All this data together was throughout the process updated and necessary adjustments were performed. By providing a test plan and drawing, the tests could be performed as planned by the geotechnical team and decreased the risk of misinterpretations. The data sheets are and will be useful for future references together with the pictures taken and videos recorded although an effective way of documenting such large files should be established due to the variation within the values and clarity.

5. Results
The following section presents the available results from the underground trials. At this point a part of the results are still unavailable since the time frame for the thesis did not include long- term monitoring after test trial completion, necessary for some of the tests. These long- term tests have not yet experienced rock deformation or rock failure and some tests of a relatively short term- nature have test sites not yet accessible.

5.1 Isocyanate Test
The Isocyanate test was conducted before and during the geotechnical underground trials. The results show that there are high levels of isocyanates during application in the hot zone or spray zone, but only 5 meters outside the hot zone the levels are considerably lower and beneath the time weighted average and ceiling limits as presented in Figure 29. Between 30-60 minutes after application, the isocyanate levels are beneath the time weighted average and ceiling limits both at the hot zone and downstream from the hot zone. This presumes that the ventilation is turned off during application and for 30 minutes after completed application. A water curtain did not decrease the isocyanate levels and was therefore abandoned. With respect to these results a safety protocol was set up, requiring a barricade 20 meter downstream from the hot zone, with no allowance to enter until 30 minutes have passed after completed application. The safety protocol also requires ventilation to be turned off during application and 30 minutes after completed application to avoid dispersal of any potential airborne isocyanates.
5.2 Thickness control and continuity

The thickness control and continuity is of importance to gain sufficient coverage. It is a prerequisite in order to perform any trials and to gain any geotechnical proof. In addition to the tests, targeted thickness measurements were performed during the test trials to assure the quality of robot application and thickness continuity.

The results from the targeted thickness measurements for the topcoat are based on a total of 58 points shot at 7 different spray applications for the desired thickness of 4mm. The maximum value reached 7.30mm and the minimum 1.71mm with an average 4.38mm and standard deviation 1.11mm. The results are displayed in the staple diagram in Figure 30.

For the desired topcoat thickness of 8mm, targeted thickness measurements were based on a total of 16 points shot at 2 different spray applications. Note that the majority of the trials requested 4mm thickness and only a few tests were executed with the 8mm thickness, hence the reason for fewer data points. The maximum value reached 9.10mm and the minimum 3.30mm with an average of 6.80mm and standard deviation 1.81mm. The results as illustrated in the staple diagram in Figure 31.
Figure 30. Thickness measurements variations for topcoat with desired thickness 4mm

Figure 31. Thickness measurement variation for desired topcoat thickness 8mm
5.3 Peel and Fly Rock and Toughness Capacity Test
The results from the test are immediately gained after the blasted round. The impact from the blasting caused peel back of the full composite at the leading edges and the blast also cached some of the overlaps and peeled them back. Note should be made that the PCM was not bolted right up to the face as would be done with wire. The perimeter areas; generally had a lower total coating application due to the initial spray pattern setup and the interface between panel sprays was comprising of topcoat/ foam/ topcoat rather than topcoat to topcoat. In several cases the face blast also blasted out the wall from behind where the coating was applied. In addition significant fly rock damage, few cracks and mucking operation tend to tear pieces of the PCM. The first sprays in this test were using material that was water contaminated which contributed to the majority of the small cracks. These observations together determined the test as failed as it peeled and was damaged by fly- rock and cracks. The observations are illustrated in Figure 32 through Figure 34, where the fault lines are poorly indicated.

*Figure 32. Peel back due to round blast at 1565-300 where the Peel test was executed for full composite*
The same test was repeated without the foam for 4mm and 8mm topcoat application respectively, with significant improvement. The peel back was reduced as well as the fly rock damage for both 4mm and 8mm topcoat application; see Figure 35 through Figure 37 for comparison. Although the 4mm application managed to decrease the level of peel back and fly rock damage compared to the full composite it did not provide sufficient coverage and experienced gaps, the 8mm topcoat thickness gave the best results in terms of minimum peel back, minimum fly rock damage and sufficient coverage.
Figure 35. Fly-rock damage to the left and scoop damage to the right on the lower part of the wall at 1565-250 for 8mm topcoat.

Figure 36. Leading edge at 1565-250 after round blast for 8mm topcoat.
5.4 Stope Blast, Passive Adhesion and Topcoat over shotcrete test

The Stope Blast test results between the three applications: the full composite, the topcoat on raw rock and topcoat over shotcrete test were not yet available for comparison. However the in-situ adhesive strength for the full composite versus topcoat only under dry surface conditions was comparable shortly after application and before the stope blast. It is speculated whether the adhesive strength for topcoat only was higher than for the full composite determined only by visual inspections and by pulling the materials, without any actual data to support this speculation.

Some of the results were available for the Topcoat over Shotcrete test. The shotcrete toughness underneath the topcoat was at this point not available to examine. A visual inspection showed that the coverage on top of fibre reinforced shotcrete was not as smooth as on bare rock although there was sufficient material applied with the fiber protrusions limiting a uniform coating compared. The gaps within the shotcrete had a thinner layer of topcoat while the crest had a thicker layer. This alone indicates for potential future tear points at the material applied on the gaps. The comparison between coverage of topcoat on top of raw rock versus topcoat on top of fibre reinforced shotcrete is displayed in Figure 38.
Figure 38. Left picture shows the coverage of topcoat on raw rock, right picture shows the coverage of topcoat on top of fibre-reinforced shotcrete

5.5 Wrap Around Nose Test

The results from the Wrap Around Nose test showed that the robotic programming has the capability to apply the PCM to a pillar nose geometry, as depicted in Figure 39. Some tear damage was observed at the pillar nose, mainly due to scoop bucket mucking operation, illustrated in Figure 40. Any deformation at the pillar nose did not yet occur and therefore there are no results showing the PCM’s potential due to nose deformations.
Figure 39. Successfully applied PCM to pillar nose

Figure 40. Damage mainly due to scoop bucket mucking operation, the damaged PCM had been cut out when this picture was taken
5.6 The Primary Pillar Nose, Main Fault, Underground Large-Scale pull and Green Shotcrete Test

Any results from these tests are not available at this point. Mainly since the expected rock failure condition have not yet occurred and due to lack of access to the test sites. The underground Large-Scale Pull and Green Shotcrete tests will be performed during a later phase of the trials, post the time frame for the thesis.
6. Discussions

The majority of the results from the underground large-scale trials are of a long term nature and therefore there is only a limited amount of results available to evaluate at this point. Even though there are not yet any available results on the liner’s performance when exposed to movements or failures indicating its capacity to retain loose material, there are nevertheless results available of great interest to discuss.

The primary concern has been the health & safety aspects concerning the concentration of the airborne isocyanates. Initially it was assumed that by having full ventilation on, combined with an absorbing water curtain the isocyanate levels would decrease, but the opposite turned out to provide the desired results. By eliminating the water curtain and turning the ventilation off during application and 30- minutes afterwards, the airborne isocyanates were kept localized at the working area and eventually dissipated to acceptable levels within a 30-minute period. The ventilation and water curtain turned out to disperse the airborne isocyanates further and extended the range of dissipation time. Areas that might experience draught after the ventilation is turned off may have to be isolated in order to prevent potential dispersion of the airborne isocyanates. For this purpose a type of barrier could be considered, maybe even a water curtain, although it needs to be examined whether a water curtain can provide a sealed barrier and retain the airborne isocyanates isolated. It should however be mentioned that any physical barrier must be perfectly sealed, which may be hard to achieve.

Thickness continuity was required in order to perform any tests for geotechnical purposes. The robotic application managed to control the thickness continuity to an acceptable level by providing constant speed and spray pressure during application. The sprays used a 4 pass pattern where the spray flipped over and missed large sections of the perimeter of the applied area. Other areas with reduced coverage were usually rare, occurring mainly in shadowed areas but even here some coverage was achieved. The coverage of the full composite was reduced since the foam pattern was wider than the topcoat pattern and no overlap of the topcoat on itself but rather a weak layer of the foam at the trailing edge of the spray pattern. To improve the coverage the robot was programmed to spray two horizontal patches and two vertical patches with reversed leading angles. This resulted in better coverage since each point would be sprayed from four different angles. The coverage could be improved with further programming, providing specific patches and by adjusting the spraying angles from its present setting of 30 degrees from normal. For instance, when applying the materials successfully to a complex geometry, such as a pillar nose it was proven that the robot has the ability to spray the three faces of a pillar nose, pointing in different directions.

The geotechnical results at this point are related to the peeling at the leading edges and the fly- rock damage due to the face blast. The most significant damage occurred where the full composite was applied and the severe damage was surprising. Reasons for this could be related to the method of surface preparation not being to the intended protocol and that bolting pattern did not extend to the leading edge as would be done with wire mesh. Without the leading edge being bolted, the foam layer was too weak to withstand the blast damage without peeling back. The foam has some stiffness to it and also some relatively low density with some energy absorption capability. The fly- rock damage may appear due to the soft layer of primer beneath the topcoat, making it more susceptible for puncturing.
After the first impact the foam may loosen over an area resulting in sections that have no reinforcement behind which could have made the top coat more prone to impact damage. However the mutual reason for these damages are most probably due to the fact that the face blast occurred before the materials fully cured, only 8-12 hours after application. The top coat requires about 72-96 hours to reach its full strength, prior to that the top coat cures and the toughness properties are being enhanced during the curing time. It should be mentioned that already after 1-2 hours the liner is ready for bolt installation and the curing process could continue while bolting and also afterwards to reach the full strength. The time requirement to reach the full strength does not compare favorably with that required to complete the bolting and face drilling cycles before blasting. After the primer was abandoned and some of the tests were executed with the topcoat only, the results immediately improved. The topcoat had higher adhesion to the rock, decreasing the peeling and fly-rock damage. The fly-rock damage was further decreased without the soft layer of primer beneath the topcoat. In order to diminish these damages, surface preparations could be executed more carefully and smooth blasting of the face blast could be implemented.

When investigating the application of topcoat on top of fibre-reinforced shotcrete, uniform coverage was poor due to the fibers penetrating perpendicular to the applied shotcrete that acted as accumulation points for the top coat. The coverage could be improved by applying the topcoat on shotcrete without the fibers or maybe even considering to apply the full composite, allowing the primer to smooth out the surface. It is still at this point unknown how the formulation of topcoat and shotcrete perform in a large-scale mining environment, under movements or due to failures compared with the full composite or topcoat only applied on rock.

7. Conclusions
The original aim of this thesis was to complete and deliver a conclusive trial site result summary of a new TSL-based ground support system. However the available results are not sufficient to make any fair judgment on the 3M PCM’s capability at this point and additional results and trials are necessary.

The isocyanate level measurements showed that the manageable concentrations of airborne isocyanates were present during spraying in the hot zone and dissipated between 0-30 minutes. This investigation allowed for a safety protocol to be set up: a physical barricade 20 meters beyond the hot zone, during spraying and for 30 minutes afterwards together with having the local ventilation turned off during spraying and 30- minutes afterwards. These actions were shown to assure a safe working environment while the trials proceeded.

The thickness continuity and coverage was measured during the various robotic applications and needs to be optimized based on pattern width, direction angle of the spray gun, flip over delay and all trailing edges need to be topcoat to topcoat and not topcoat to foam. The thickness had a standard deviation of ±1mm when a 4mm topcoat was applied to the blasted rock surface, though no absolute measurements of the actual surface roughness were made. No doubt improvements to this deviation can be made.
through the application of consistent perimeter-controlled drilling and blasting procedures, as well as by optimization of the robot’s scanning and spraying features. However, these actions were seen as being outside of the scope of this particular trial. Control programs were developed that demonstrated the robot’s capability to spray walls and pillar noses. However once the topcoat was sprayed on fibre-reinforced shotcrete with polymeric fibers protruding outward from the shotcrete, the continuity was poor. Thicker layers of topcoat appeared on the crests while thinner layer appeared in the gaps.

Of greatest concern during the trials was the repeated observation that significant peeling of the leading edges occurred, together with fly-rock damage to the topcoat, caused for the full composite due to a face blast. This was considered as an failure to recognize this before testing. Bolting of the leading edge should be included in the test plan. It should be stated that the protocols of high pressure water scaling, and bolting to the face were not being followed. In addition the perimeter of many of the sprays was thinner than the internal areas due to the flip-over not spraying the edges. However once abandoning the primer and applying only the topcoat with a 4mm and 8mm thickness respectively, the damage in terms of peeling and fly-rock decreased to the point of being acceptable with proper bolting at the leading edge. The topcoat with the 8mm thickness tends to provide better coverage than 4mm topcoat, although it appears a bit runny at some areas which may be related to proximity of the spray head to the wall.

To sum up what has been observed during the trials and comment upon the results, it is recognized that the liner has great potential. It is however not at this point ready to become a superior component in an underground rock support system, the liner is not yet ready for commercialization without further developments and underground trials.

8. Recommendations

There is need of further developments and further trials to fully get an understanding and be able to make a fair judgment on the liner’s true performance and capability, including monitoring the performance in full rounds.

This thesis does not provide final conclusion related to how the liner performs due to movements and failures in seismically active ground, or whether it will be able to retain loose material due to an underlying rock failure through bagging. The tests were executed to address these issues but it is unknown when the results will be available, therefore it is necessary to continue to supervise and to observe these test areas for results, further research and to gain the needed understanding.

The material formulation has been discussed, from a chemistry standpoint, the topcoat will need a primer to adhere adequately to damp or wet surfaces and also to be able to provide a contiguous coating across the rock surface. This should be investigated in future research in order to be able to suggest the optimal material formulation under different ground conditions such as: wet, dry, broken or intact prior to application. The topcoat only may seem as the solution. It should be investigated how well the topcoat only manages to mobilize the forces due to a loose failure or rock movement, whether the
topcoat will detach and bag due to a failure or will it adhere and tear. It may however be able to de-bond under low adhesion circumstances and still bag without tearing assuming it is supported with rock bolts.

It should be clarified that the Thin Spray-On Liner itself is not necessarily a replacement for current support systems. It is flexible and can be used by itself once proven and could also be integrated with existing reinforcement when required.

The results from the trials are only based on the liner applied on the walls. In order to make a fair geotechnical judgment on the liner’s capability, it needs to be further investigated how the liner performs when applied on the shoulders and back in addition to the walls as this is how it would be applied in a real mining environment.

Based on the results from the trials, it is obvious that a rehab procedure is necessary. The rehab procedure needs to be developed and to be fully integrated into the application process, since damage to the liner is expected. To prevent the leading edge from peeling, it needs to be investigated whether pinning it with bolts, using a primer with higher adhesion and overlapping it with 0.5-meter topcoat from the next round, could address the peeling issues.
9. References

Literature


Publications and Reports


Swan, G. (2012). GEOTECHNICAL- Underground & Laboratory, Targeted Proof-Seeking Test & Trials


**Electronic Documents**


10. Appendices

Appendix A- Data Collection Sheet- Pre Spray

<table>
<thead>
<tr>
<th>Pre- Spray Data Collection</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Trial Number (Month-Day-Trial)</strong></td>
</tr>
<tr>
<td><strong>Date</strong></td>
</tr>
<tr>
<td><strong>Location</strong></td>
</tr>
<tr>
<td>Nearby mining activity</td>
</tr>
<tr>
<td><strong>Present Team</strong></td>
</tr>
<tr>
<td>Site characteristics</td>
</tr>
<tr>
<td>Drift height [m]</td>
</tr>
<tr>
<td>Drift width [m]</td>
</tr>
<tr>
<td>Drift length [m]</td>
</tr>
<tr>
<td>Drift comments</td>
</tr>
<tr>
<td>Air temperature [°C]</td>
</tr>
<tr>
<td>Right wall temperature [°C]</td>
</tr>
<tr>
<td>Left wall temperature [°C]</td>
</tr>
<tr>
<td>Back temperature [°C]</td>
</tr>
<tr>
<td>Face temperature [°C]</td>
</tr>
<tr>
<td>Water curtain (on/off)</td>
</tr>
<tr>
<td>Ventilation (on/off)</td>
</tr>
<tr>
<td>Main air pressure [psi]</td>
</tr>
<tr>
<td>Air relative humidity [%RH]</td>
</tr>
<tr>
<td>Air flow [cfm]</td>
</tr>
<tr>
<td>Air flow [linear fpm]</td>
</tr>
<tr>
<td>Distance between duct and face [m]</td>
</tr>
<tr>
<td>Site characteristics comments</td>
</tr>
</tbody>
</table>

**Spray surface descriptions**

- Sprayed right wall (Y/N)
- Sprayed left wall (Y/N)
- Sprayed back (Y/N)
- Surface type (ore, shotcrete, screen, bolts, pillar)
- Surface conditions (dust, roughness, wet/dry, washed, faults, cracks)
- Spray surface comments

**Rock mass**

- Rock mass type
- Rock mass quality
- Geology
- Stress situation
- Orientation
- Ground condition (Normal, Stress failing, Squeezing and large deformation)

**Observations performed**

- Videos taken (video specifications)
- Borehole camera utilized (comments on fracturing)
- Photos taken (photos specifications)
- Convergence [mm]
- Drift scanned (Y/N)
- Additional comments
# Appendix B - Data Collection Sheet - During Spray

## During Spray Data Collection

<table>
<thead>
<tr>
<th>Trial Number (Month-Day-Trial)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Date</td>
</tr>
<tr>
<td>Location</td>
</tr>
<tr>
<td>Nearby mining activity</td>
</tr>
<tr>
<td>Present Team</td>
</tr>
</tbody>
</table>

### Primer spray

<table>
<thead>
<tr>
<th>Time to start spray (actual time)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gun average angle [°] (leading/trailing)</td>
</tr>
<tr>
<td>Fan spray angle [°]</td>
</tr>
<tr>
<td>Spray pattern width (Spray tip)</td>
</tr>
<tr>
<td>Part.A foam flowrate [lpm]</td>
</tr>
<tr>
<td>Part.B foam flowrate [lpm]</td>
</tr>
<tr>
<td>Foam exotherm max [°C]</td>
</tr>
<tr>
<td>Strokes per minute</td>
</tr>
<tr>
<td>Total strokes</td>
</tr>
<tr>
<td>Foam ratio (from pump)</td>
</tr>
<tr>
<td>Total foam sprayed (L)</td>
</tr>
<tr>
<td>Average foam thickness (mm)</td>
</tr>
<tr>
<td>Cumulative spray time [min]</td>
</tr>
<tr>
<td>Time to finish spray (actual time)</td>
</tr>
</tbody>
</table>

### Topcoat spray

<table>
<thead>
<tr>
<th>Time to start spray (actual time)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gun average angle [°] (leading/trailing)</td>
</tr>
<tr>
<td>Fan spray angle [°]</td>
</tr>
<tr>
<td>Spray pattern width (Spray tip)</td>
</tr>
<tr>
<td>Part.A topcoat flowrate [lpm]</td>
</tr>
<tr>
<td>Part.B topcoat flowrate [lpm]</td>
</tr>
<tr>
<td>Topcoat exotherm max [°C]</td>
</tr>
<tr>
<td>Strokes per minute</td>
</tr>
<tr>
<td>Total strokes</td>
</tr>
<tr>
<td>Topcoat ratio (from pump)</td>
</tr>
<tr>
<td>Total topcoat sprayed (L)</td>
</tr>
<tr>
<td>Average topcoat thickness (mm)</td>
</tr>
<tr>
<td>Cumulative spray time [min]</td>
</tr>
<tr>
<td>Time to finish spray (actual time)</td>
</tr>
</tbody>
</table>

### Equipment characteristics

#### Scan and spray parameters

<table>
<thead>
<tr>
<th>Scan pattern</th>
</tr>
</thead>
<tbody>
<tr>
<td>Row spacing</td>
</tr>
<tr>
<td>Column Spacing</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Spray pattern</th>
</tr>
</thead>
<tbody>
<tr>
<td>Row spacing</td>
</tr>
<tr>
<td>Column spacing</td>
</tr>
</tbody>
</table>

### Robot

<table>
<thead>
<tr>
<th>Spray type (handspay/robot)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Robot standoff distance [cm]</td>
</tr>
<tr>
<td>Robot travel speed, Primer [mm/s]</td>
</tr>
<tr>
<td>Robot travel speed, Top coat [mm/s]</td>
</tr>
<tr>
<td>Robot overlap [%]</td>
</tr>
</tbody>
</table>

### Topcoat/foam Components

<table>
<thead>
<tr>
<th>Part.A foam drums used (st)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Part.B foam drums used (st)</td>
</tr>
<tr>
<td>---------------------------</td>
</tr>
<tr>
<td>Top coat part. B special issues (storage/temperature)</td>
</tr>
</tbody>
</table>

**Primer characteristics**

**Gun type**  
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Hose temperature [°F]</td>
<td>Pre- mix time on type.B drum [h]</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Topcoat characteristics**

**Gun type**  
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Hose temperature [°F]</td>
<td>Pre- mix time on type.B drum [h]</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Observations performed**  
<table>
<thead>
<tr>
<th>Videos taken (video specifications)</th>
<th>Photos taken (photos specifications)</th>
<th>Convergence [mm]</th>
<th>Drift scanned (Y/N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Additional comments</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
# Appendix C- Data Collection Sheet- Post Spray

<table>
<thead>
<tr>
<th>Post Spray Data Collection</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Trial Number (Month-Day-Trial)</strong></td>
</tr>
<tr>
<td><strong>Date</strong></td>
</tr>
<tr>
<td><strong>Location</strong></td>
</tr>
<tr>
<td><strong>Nearby mining activity</strong></td>
</tr>
<tr>
<td><strong>Present Team</strong></td>
</tr>
<tr>
<td><strong>Coverage analysis</strong></td>
</tr>
<tr>
<td>Apparent area covered [m²]</td>
</tr>
<tr>
<td>Material used [l/m²]</td>
</tr>
<tr>
<td>Occurrence of any gaps (holes, lines, patches)</td>
</tr>
<tr>
<td>Topcoat deformation</td>
</tr>
<tr>
<td>Quality of spray in shadowed areas</td>
</tr>
<tr>
<td>Quality of spray in critical areas</td>
</tr>
<tr>
<td>Hardening time [min]</td>
</tr>
<tr>
<td>Temperature liner [°C]</td>
</tr>
<tr>
<td>Adherence to rock</td>
</tr>
<tr>
<td>Comments on quality of the coverage</td>
</tr>
</tbody>
</table>

**Performance TSL post completion**

| Elongations [%] |
| Tensile strength [Mpa] |
| Due to blasting (peel back) |
| Due to long term failures (sagging/deforming) |
| Due to rock bursts |
| Necessary corrections/adjustment/deviations |
| Unplanned misses |
| Damage to TSL |

**Observations performed**

| Videos taken (video specifications) |
| Photos taken (photos specifications) |
| Convergence [mm] |
| Drift scanned (Y/N) |
| Additional comments |
# Appendix D - Summary of Detailed Test Plan

<table>
<thead>
<tr>
<th>Priority</th>
<th>Test Type</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>High</td>
<td>Peel Test (in cycle)</td>
<td>Observe if TSL peels back due to blasting of next round.</td>
</tr>
<tr>
<td>High</td>
<td>Peel Test Top Coat only (in cycle)</td>
<td>Observe if Top Coat peels back due to blasting of next round.</td>
</tr>
<tr>
<td>High</td>
<td>Stope Blast Test</td>
<td>Observe how TSL behaves due to squeezing conditions (which occur at the copper ore) and due to shear and failure conditions in rock with large amount of structures. Observe the damage in sprayed overcut due to the stope blast.</td>
</tr>
<tr>
<td>High</td>
<td>Pillar Nose Test</td>
<td>Observe how TSL behaves due to vertical loading in the pillar to be carved out, i.e. spalling. Test TSL due to blast vibrations and cracking increase within pillar when development continues in the secondary heading.</td>
</tr>
<tr>
<td>High</td>
<td>Water Seepage Test</td>
<td>Observe if there will be water seepage through applied TSL. Test if spraying over wet surface gives sufficient adhesion. Long term test.</td>
</tr>
<tr>
<td>High</td>
<td>Isocyanate test</td>
<td>Collect samples to measure the levels of isocyanates during spray and decide upon health and safety actions and PPE.</td>
</tr>
<tr>
<td></td>
<td>Yield Capacity Test</td>
<td>Test the yielding capacity due to strain burst risk for TSL support of Type.1 ground conditions and Type.2 ground conditions compared to the corresponding conventional support for these types of ground conditions.</td>
</tr>
<tr>
<td></td>
<td>Topcoat Over Shotcrete Test</td>
<td>Spray Top Coat only on top of shotcrete to test the support ability of these two under areas with large amount of structures that can lead to failure. Test if Top Coat can be used without the primer.</td>
</tr>
<tr>
<td></td>
<td>Bolt Through Test</td>
<td>Test the capability of the TSL and Top Coat only due to drilling and bolting. Observe any issues during drilling and bolting of TSL and Top Coat only.</td>
</tr>
<tr>
<td></td>
<td>Passive Adhesion Test</td>
<td>Test the adhesion of Top Coat only and full composite at dry and wet rock respectively.</td>
</tr>
<tr>
<td></td>
<td>Main Fault Test</td>
<td>Obtain long term monitoring data in main fault areas where fault slip and seismic events can occur.</td>
</tr>
<tr>
<td></td>
<td>Wrap Around Nose Test</td>
<td>Test the TSL capability when sprayed on a slender pillar. The geometry of the pillar increase the probability of pillar nose failures and less resistance due to blasting.</td>
</tr>
<tr>
<td></td>
<td>Underground Pull Test (full scale)</td>
<td>Test the pull capacity of TSL, maximum tensile strength of the material before failure occurs. Observe the detachment of material due to the pull test, how it behaves and adhere.</td>
</tr>
<tr>
<td></td>
<td>Green Shotcrete Test</td>
<td>Test if TSL affect the curing of shotcrete once sprayed on top of green shotcrete.</td>
</tr>
</tbody>
</table>