Master Thesis

Design of a ContBlast unit for lining while charging with considerations for placement of detonator and primer

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Declaration of Authorship

„I declare in lieu of oath that this thesis is entirely my own work except where otherwise indicated. The presence of quoted or paraphrased material has been clearly signaled and all sources have been referred. The thesis has not been submitted for a degree at any other institution and has not been published yet."

Preface, Dedication, Acknowledgement

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Thanks to Dipl.-Ing. Christian Heiss, who supported me in every step of prototype development and the implementation of the prototype in the real scale tests. A lot of his ideas and suggestions are reflected in this thesis.

Dr. mont. h.c. Dr.tekn. Finn Ouchterlony improved my paper especially in relation to expression of the English language. Furthermore, professional discussions improved my prototype concepts.

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Abstract

The objective of this thesis is the redesign of the existing ContBlast unit to a Lining-While-Charging (LWC) unit. The thesis is integrated in “SLIM”, a H2020 project of the EC, and there the task is specified as followed:

“Design of a ContBlast unit for lining while charging (LWC) with considerations for placement of detonator and primer. Manufacture first prototypes of ContBlast unit with 3D printing, up to 40-50 units Drilling of either 40-50, Ø76 or 89 mm, 15-20 m deep blastholes, some if possible in wet ground Charging with ContBlast units and MUL-BBK emulsion pumping unit and explosives from Austin powder. Checking for emulsion leakage through rise of emulsion column during gassing. Blasting of holes while checking for detonation failures. Evaluation of design of ContBlast unit and redesign according to experience” (Executive Agency for Small and Medium-sized Enterprises, p.21)

As the ContBlast unit is a *“prototype for explosive charges centered in the borehole for the use of cautious blasting in underground applications”* (Ivanova R. 2011, p.1), the purpose of this unit is its application for cautious blasts. However, the LWC unit should support production blasts in wet or jointed borehole conditions using emulsion explosives.

The redesign of the unit started with the analysis of storage possibilities of a plastic hose inside a protection container and the development of a 3D printed device, which supports the unfolding mechanism of the plastic hose and prevents the advection of emulsion into the plastic hose storage area.

Lab tests with water and field tests with emulsion as filling medium were conducted to ensure the LWC unit capabilities. Stress tests were performed with the plastic hose to determine the strain resistance against the static load of the emulsion, the rock load and the load while unfolding. In these test series a lot of emerging problems could be examined and solved.

The design of the connection between charging hose and emulsion-pumping unit, which withstands the pressure conditions of the pumping process, completes the development.

Zusammenfassung

Die Aufgabenstellung dieser Arbeit ist es, das bereits bestehende ContBlast Einheiten Konzept zu einem LWC (lining-while-charging) Konzept weiterzuentwickeln. Die Arbeit ist in das H2020 Projekt „SLIM“ der EC integriert und dort wird die Aufgabenstellung wie folgt definiert:

„Entwicklung einer ContBlast Einheit für das Auskleiden von Sprengbohrlöchern während des Ladens. Das Einbringen von Booster und Zünder werden berücksichtigt. Mit einer selbstgebauten 3D gedruckten Einheit sollen 40-50 Bohrlöcher, mit Durchmesser von 76 mm oder 89 mm und einer Länge von 15-20 m gesprengt werden. Es muss die Mischladeeinheit MUL – BKK verwendet werden sowie Sprengstoff von Austin Powder. Auf das Austreten von Emulsion muss geachtet werden. Zünder Fehler sollen analysiert und das Design der LWC Einheit soll nach Beendigung der Versuche überarbeitet werden.“ (Executive Agency for Small and Medium-sized Enterprises, p.21)

Die ContBast Einheit ist ein Prototyp, bei dem die Sprengladung im Zentrum des Bohrlochs gehalten wird, um so beim Streckenvortrieb Untertage schonend zu sprengen. (Ivanova R. 2011, p.1) Damit unterscheidet sie sich von der LWC Einheit, die Übertage Gewinnungssprengungen im nassen oder zerklüfteten Gebirge unterstützt soll.

Die Weiterentwicklung der ContBlast Einheit begann mit der Untersuchung von Aufbewahrungsmöglichkeiten der Schlauchfolie im Prototypen und der Entwicklung eines 3D-Elements, das beim Ladevorgang das Abrollen der Schlauchfolie unterstützt und ein Einströmen von Emulsion in das Innere des Prototypen verhindert.

Um die Fähigkeit der LWC Einheit zu testen wurden Laborversuche mit Wasser und Feldversuche mit Emulsion als Füllmedium durchgeführt.

In diesen Versuchsreihen konnten einige Mängel erkannt und behoben werden. Weiters wurde die Schlauchfolie Belastungstests unterzogen, um ihre Standfestigkeit gegenüber Kräften zu testen, welche durch Eigenlast der Emulsion, Gebirge und Abrollvorgang auf selbige beim Ladevorgang einwirken.

Die Entwicklung zur LWC-Einheit wurde mit der Verbindungsgestaltung zwischen Prototypen und Ladeschlauch der Emulsions-Mischladeeinheit, welche den aufgebrachten Drücken bei Ladeprozess standhält, abgeschlossen.

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1 Introduction

The decrease of exploitation costs, health and safety improvements and the protection of the environment have always been important aspects for quarries and are momentous at the current time. Blasting is the state of the art technique to mine metals and minerals in a large scale set up. To improve the utilization of emulsion based blasts a LWC unit is developed, which wraps the emulsion in a plastic hose inside the borehole while charging.

The benefits of this unit due to the fixated position of the emulsion forced by the plastic hose are the explosive consumption reduction inside fissured rock, the increase in operating speed in unfavorable borehole conditions, the decrease of fly-rock risk while blasting and the decrease of nitrate leakage, because of less emulsion usage and the guarantee of emulsion ignition throughout the total borehole length.

This thesis is integrated in the SLIM project (Sustainable Low Impact Mining), which is supported by the Horizon 2020 agenda issued by the Research and Innovation department of the European Commission. (Executive Agency for Small and Medium-sized Enterprises, 2016; Research and Innovation – Participant Portal, 2016)

The LWC unit is a development based on the ContBlast unit which was designed for cautious underground contour blasts. The ContBlast unit is patented and the summery of the patent reads as follows: *"A device (100) for receiving an explosive material (315) comprises a receptacle unit (103) for receiving the explosive material, and an anchoring unit (104), wherein the anchoring unit is arranged on an outer surface of the receptacle unit, and wherein the anchoring unit is adapted to anchor the flexible receptacle unit in a borehole (313)."* (Moser and Ouchterlony 2007, abstract)

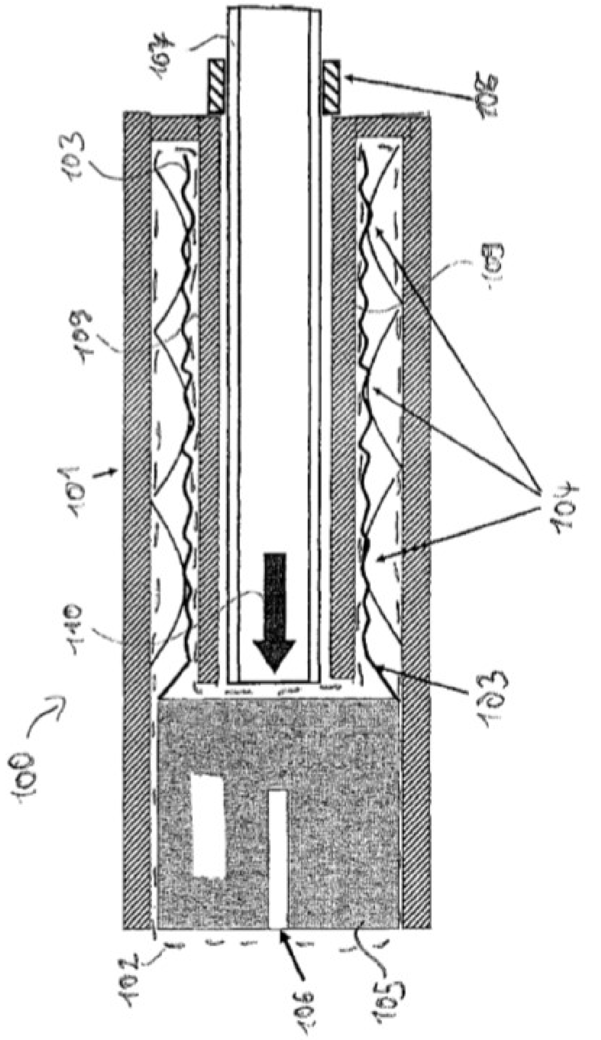

Figure 1: Patented ContBlast Prototype (Source: Moser and Ouchterlony)

In this device the primer (Figure 1, 105) is placed inside the protection container (Figure 1, 101) together with the ignitor (Figure 1,106). The wire igniting the primer runs parallel to the unit on the outside. The booster is wrapped in plastic hose (Figure 1, 102) keeping the booster inside the emulsion. The emulsion is lead through an inner pipe and a charging hose (Figure 1, 110) directly to the booster. With this technique the charging process can start from the deepest part from the horizontal borehole. The purpose of the ContBlast unit is the deployment in underground contour blasts, which require only small amounts of explosive power. Therefore, the plastic hose of the ContBlast unit is smaller in diameter than the actual borehole. The expandable centering units (Figure 1, 104) keeps the filled plastic hose in the middle of the borehole, not allowing any connection between emulsion and rock. With this technique less explosive energy reaches the rock and the contours are blasted smoothly.

Figure 2: ContBlast Charging Unit ready for filling (Source: Ivanova)

Figure 2 depicts the final product of the charging unit. The components are turned parts. The left black component connects the ContBlast unit with the charging hose of the MUL-BBK emulsion pumping unit. An inner pipe is wrapped with plastic hose and expandable centering units leading to the right black component, in which the primer and ignitor can be placed. Emulsion flows from the charging hose through the inner pipe to the primer starting to unfold the plastic hose in the progress.

ContBlast is designed for underground contour blasts, while the LWC unit is designed for open pit production blasts with rough borehole conditions. Therefore, the requirements for the LWC unit have changed.

- The LWC unit has a 70 mm outer diameter and the borehole has a 90 mm diameter. The plastic hose should fill out the borehole. This means the plastic hose has to expand outside of the unit. A lot of hose is required to enable this process. This plastic hose must be stored in the LWC unit.

  The ContBlast unit should not fill out the borehole, but only keep a small portion of emulsion in the middle of the hole. Therefore, less plastic hose has to be stored in the ContBlast unit. On the other hand, expandable centering units have to be stored in the unit.

- The LWC unit was designed for 15-20 m long boreholes. The boreholes on the Erzberg site had a length around 25-30 meters, and the LWC unit was adjusted to this length. The protection container length of the LWC unit is 163 cm. To find the right folding technique to store this amount of plastic hose in a short practical prototype was essential for the project.

The ContBlast unit was deployed in underground boreholes. These boreholes rarely exceed the length of 10 m. Therefore, less plastic hose must be stored in the ContBlast unit.

- The LWC unit is explicitly designed to get deployed under rough borehole conditions. The plastic hose must withstand sharp rocks and gaps in the rock. Therefore, the strength of the plastic hose is evaluated in this thesis.

  The ContBlast unit does not have to deal with bad borehole conditions, because the contour boreholes are drilled with care and usually in good condition.
- The LWC is designed for vertical boreholes, the problem of water inside the borehole is imminent. Furthermore, the deadweight of the emulsion in a completely filled LWC unit, loads the bottom area of the plastic hose with up to 2 bar. This stress is unavoidable.
- The ContBlast unit is designed for horizontal boreholes. The deadweight of the emulsion is negligible. There is also no option, that water can accumulate inside of the hole.

The general agreement requires the filling of the LWC unit with the MUL-BBK emulsion pumping unit. This unit is owned by the Montanuniversität Leoben and produced by Austin Powder. This pumping unit is designed for the underground deployment. Therefore, the matrix tank and the tanks for water, acetic acid and ammonium hydroxide are small, because underground boreholes are smaller in diameter and length compared to open pit boreholes. This aspect required a lot of downtime at the field tests. Most of the time the experimenter team was occupied to fill reagents inside the pumping unit and less time was available to work with the LWC unit.

Another negative aspect of using this pumping unit is the plugging of the machine with emulsion if temperatures decrease under 14°C. Because the Erzberg site is high in the mountains temperatures above 14°C are only available in the month between June to September. This limited the development and redesign face of the project, because not many field tests with emulsion could be made.

Figure 3: Controlling of the MUL-BBK emulsion pumping unit

A number of controlling points had to be done constantly. Temperature had to be checked (Figure 3, red). The amount of reagent low (Figure 3, blue) and plugging of the conduits must be checked (Figure 3, green).

2 Summary of insights

Figure 4 depicts a technical drawing of the prototype used for the second field test. This is the most developed LWC unit, in which a lot of insights and experience are incorporated. The first quarter of the unit is shown, because all important components are located in this region. Every component is named and described.

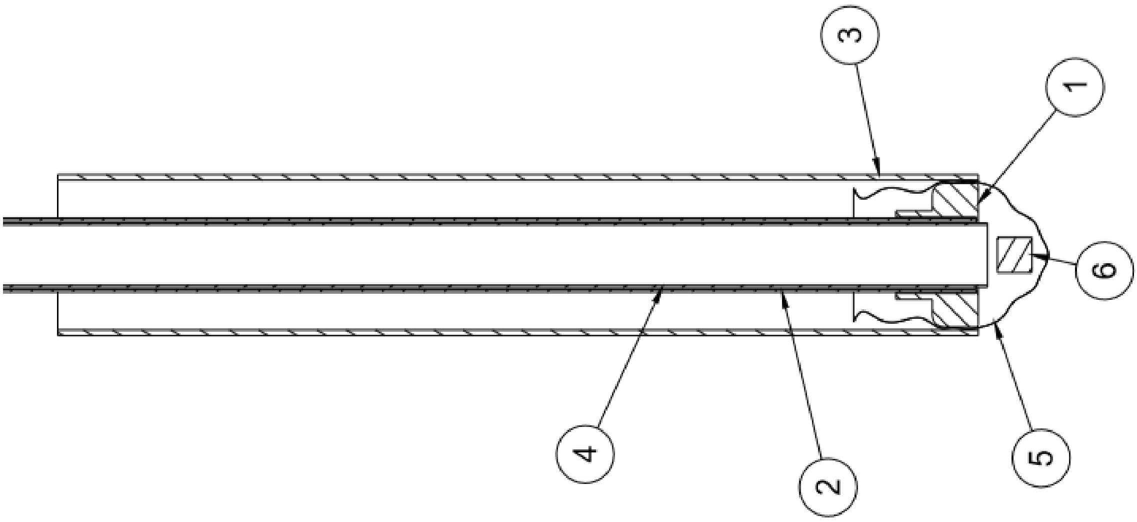

Figure 4: Drawing of the front section of the LWC unit

- The unfolding device (Figure 4, 1; Annex V) helps the plastic hose to unfold properly and protects the inside of the prototype from emulsion inflow. The outer diameter is 62,5 mm. The inner diameter is 33 mm with a narrowing to 31 mm at the bottom to hold the inner pipe in place. It has a height of 35,78 mm with a height of 20 mm at the broadened area. The edges of the broadened area are rounded and have a 5 mm radius at the plastic hose entry zone and a 1 mm radius at the plastic hose exit zone. The device is 3D printed made from PLA.
- The inner pipe (Figure 4, 2) has the purpose to guide the pumping unit charging hose through the prototype to the envelopment area of the LWC unit. The pipe has a diameter of 32/31 mm and a length if 190 cm. It is the longest part of the unit.

- The protection container (Figure 4, 3) has the goal to protect the plastic hose from damage by the borehole wall. Furthermore, it enables the LWC unit to move inside the borehole, because the Plexiglas surface is smooth. The protection container is translucent to facilitate the folding process at the production stage. The diameter of the container is 70/65 mm and it has a length of 40 cm. 4 container elements are linked in line to protect the 30 m of plastic hose. The elements are connected by 7 layers of Duct Tape, leaving a 1 cm gab between the containers. This enables the LWC unit to be a bit flexible. The length of the 4 containers with the 3 connections is 163 cm. The protection container is the broadest part of the prototype.
- The pumping unit charging hose (Figure 4, 4) runs through the inner pipe, delivering emulsion to the envelopment area. It is not part of the LWC unit, but the unit is constructed especially for this hose.
- The plastic hose (Figure 4, 5) is stored inside the protection container. It is only indicated in the drawing. The plastic hose slides between protection container and unfolding device outside of the unit. It gets closed on the outside with cable tie and forms the envelopment area. The envelopment area is the region on the outside of the unit enclosed by the plastic hose. The plastic hose is stored folded in the containers and has a diameter of 90 mm and a length of 30 m.
- The primer (Figure 4, 6) is stored in the envelopment area of the unit. Before the unit gets lowered down the borehole, the primer gets connected with the igniter wire and inserted in the plastic hose. Afterwards the hose gets closed with cable tie and the igniter cored is guided on the outside of the prototype.

To use protection containers separated to subcomponents enables an easy and fast assembly of the LWC unit. The subcomponents make the unit very flexible. Depending on the length of the borehole the length of the unit can be adjusted. If the LWC unit is not folded very heavily the subcomponents with the Duct Tape between them enable the unit to be very flexible. This will decrease the plugging risk of the unit.

Another benefit of the unit is the material demand. All components are available on the free marked and no special ones must be produced. This lowers the cost of the unit. It is possible for a worker to produce a LWC unit on its one.

It is possible to store 30 meter of 100 µm thick plastic hose in a protection container length of 163 cm. Converting this result to a factor leads to 18,4 m stored plastic hose / meter of protection container.

The plastic hose can bridge 2 cm gaps of fractured rock without concerns of raptures, due to the pressure conditions. 4 cm gaps can be managed under pressure conditions of 4,5 bar. And the static pressure of the emulsion can be handled until the point of 9,5 cm gap length. Rough rock edges in the borehole wall may decrease the capability of pressure handling by the plastic hose.

To reduce the friction between inner pipe and emulsion the charging hose with the static mixer leads to the primer guided by the inner pipe. Therefore, the emulsion is lubricated until the place of deployment and the risk of unwanted decoupling between unit and charging hose is reduced.

The unfolding of plastic hose works reliable without damaging the hose. Tests depicted, if the plastic hose is raptured by the unfolding device the unfolding will not stop, but will progress, closing the rapture on the borehole wall. The unfolding mechanism works with water or emulsion as a filling reagent. The emulsion is hold back by the unfolding device inside the envelopment area. While water bypasses the device, accumulating at the inside of the protection containers too. This accumulation does not influence the unfolding process.

The predetermined breakage point accomplished by the clamp works. If the unit plugs the experimenters can pull the charging hose apart from the unit and salvage the hose. At the first field test this breakage point failed due to the high pressure conditions created by friction.

The unit, with the cylindrical connection between inner pipe and protection container can be lowered and raised inside the borehole. The connection between charging hose and unit is revised from the ContBlast unit and works reliable. The charging hose with mixer leads through the inner pipe to the unfolding device decreasing the accumulated friction inside the inner pipe. The predetermined breakage point only opens due to heavy pulling of an experimenter.

Due to the bad weather conditions and the lack of possibilities to lower the unit in water filled boreholes no blast was conducted. Therefore, a comparison of blasts supported by the unit to blasts performed the normal way was not possible. The water must be drained out of the borehole or the prototype must be 7,25 kg heavier to blast unit supported. Nonetheless, the deployment of the unit inside a dry borehole is possible, because the lowering and raising of the unit was tested successfully as well as the unfolding process using emulsion.

The prototype developments achieved a lot of the set goals in the period covered by this thesis, but problems opened up too, which have to be solved in following projects. Water inside the borehole, very long boreholes of 20 meters and more and the limited amount of time to conduct the test, due to weather conditions are the biggest problems which are inevitable or unsolved.

To support following projects solution approaches are given to optimize the outcome.

- The opportunity to test the prototype is between June and early September, because the matrix pumping unit works only at degrees higher than 14°C. The ramp up time for the tests is high, because a special drilling rig, which is capable to drill boreholes with a diameter of 90 mm, and the matrix pumping unit must be available. The production of the prototypes is time-consuming too.

  To guarantee the functionality of the produced prototype a test series in real boreholes with water as a filling agent is recommended before the month of June. This test can be done at temperatures above 0°C and ensures the operational readiness of the prototype.

- The unfolding process works better with emulsion as a filling agent as with water. But to achieve a save connection between unit and charging hose may be difficult, because the emulsion has a high viscosity and therefore pressure tends to escalate breaking the connection.

  A test with the matrix machine can be conducted before June to validate the developed connection. The pumping unit must be stored in a temperature-controlled area to ensure the operational capability. Quarries mostly do not offer such storage areas, therefor the test may be placed on another site.

Concessions to handle with explosives must be requested early to pass before June.

- The unit is designed for borehole length of 30 meters. These long holes appeared to have many drawbacks for the project. Primarily the prototype becomes very long and thick, the risk of plugging is increased and pumping out water is difficult.

  Borehole length of 10 to 15 meter would enable the production of a prototype smaller in diameter, which increases the safeness and easiness at the on field-handling.

- Water and mud inside a borehole prevent a deployment of the unit and the mining site may not have a pump to remove the substances, if the borehole diameter of 90 mm is not commonly used.

  To acquire pumps with a static suction lift of 15 meters or more will need 2 to 3 weeks. To push the water out of the borehole with compressed air can be done at low hole length, but is not possible at lengths of 25 meter.

- The unit is not functional in water filled boreholes, because it floats instead of sinking. The weight necessary to force the unit to sink can be calculated with the law of Archimedes.

  Radius of the prototype r = 0,045 m

  Length of the prototype h = 1,63 m

  Density of the prototype made out of plastic filled with air ρ_p *~ 500* kg/m^3

  Density of mud-water mixture ρ_w *~ 1200* kg/m^3

  Earth gravity g = 9,81 m/s^2

  Required additional mass to force equilibrium m_x *= searched*

$$mx = \frac{\rho_w * r^2 * \pi * h * g - \rho_p * r^2 * \pi * h * g}{g} = 7{,}24\ kg$$

Two possibilities to increase the weight of the prototype from 5,2 kg to at least 12,5 kg come to consideration. On the one hand, the protection container material can be changed from a translucent Plexiglas tube to a metal one, which would exacerbate the folding process and prototype production. On the other hand, a weight could be attached on the inner pipe before it disembogues into the protection container, which would decrease the operational time on field. Both options are viable and the drawbacks must be considered.

The borehole diameter of 90 mm is designed for underground blasts. An increase in diameter would facilitate the deployment of the unit. Water can be pumped out easier and the risk of plugging decreases. On the backside a new plastic hose must be acquired and the space requirement to store the hose increases.

3 LWC unit development

3.1 Sequence of the project

The project starts in the development stage (Table 1, blue). In this stage the folding technique was analyzed and the unfolding device was developed. Stress tests were conducted and a laboratory test was done. All development decisions were made with considerations to the ContBlast System. All other technical design possibilities were neglected.

In the production stage (Table 1, green), the knowledge gained in the development stage was used to build prototypes for two field tests. Knowledge gained in this stage is pointed out in the summery of insights, prototype improvements and conclusion.

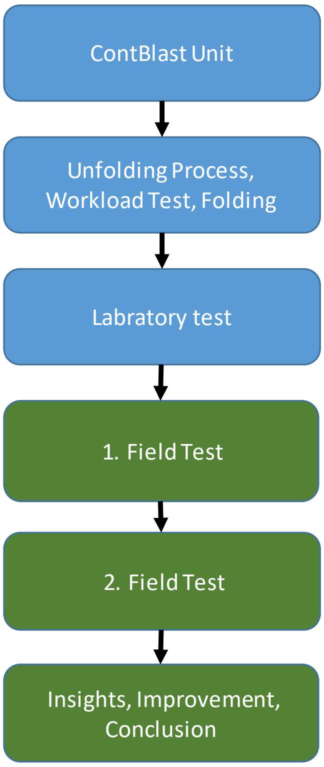

Table 1: Flowchart of the project

The following flowchart (Table 2) depicts the working process of the thesis in detail. (A) points to the ContBlast unit structure (Ivanova R. 2011). (B) describes the folding with subcomponents method for the first field prototype (Chapter 3.3.2.2.4, Page 27). (C) depicts on the inner pipe dimension change for the second field prototype (Chapter 3.8.2, Page 75). The blue squares show the development stage and green the production stage.

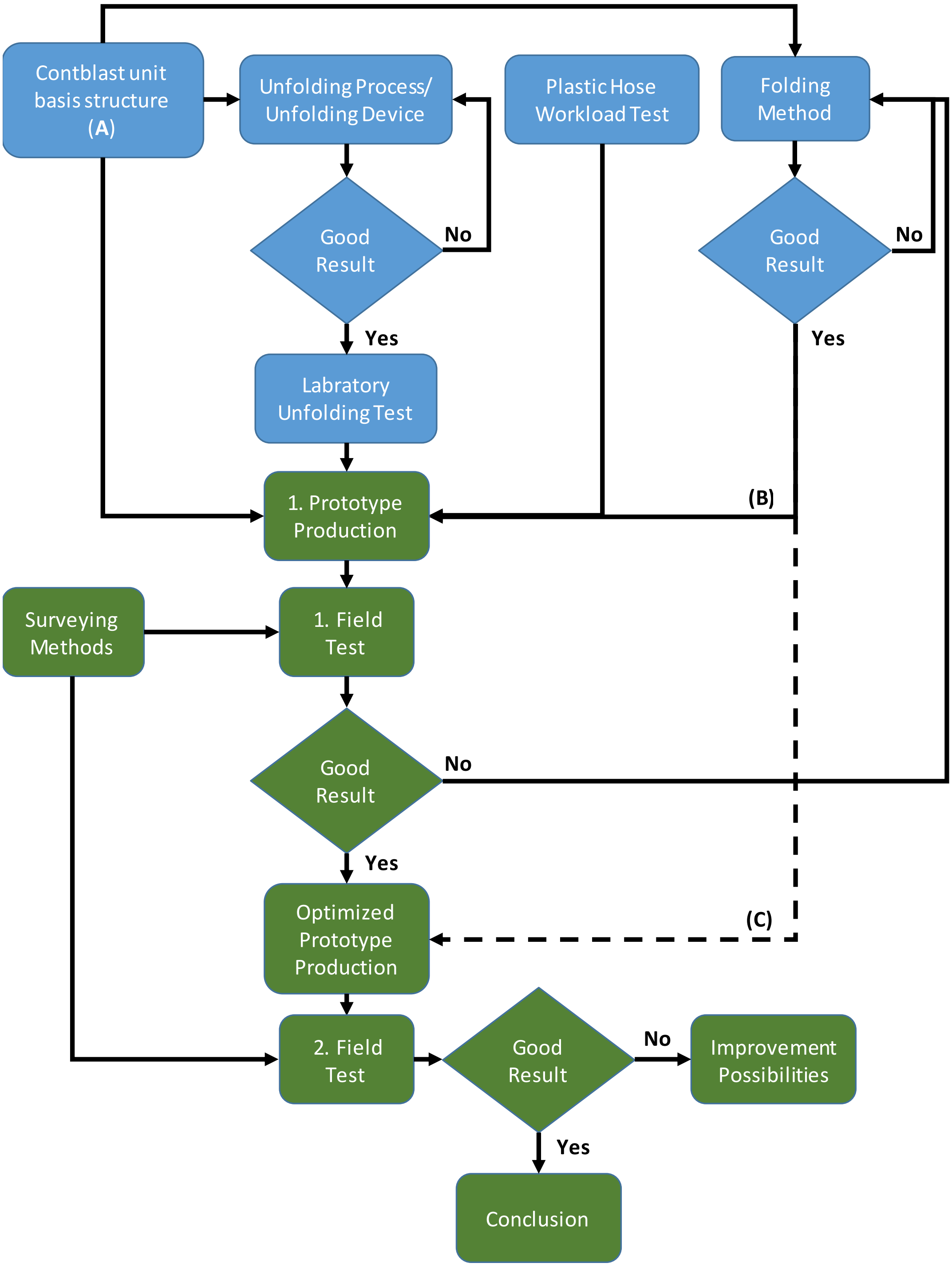

Table 2: Flowchart of the project in detail

3.2 General planning thoughts

Considerations are made about the placement of the primer. Two options are imminent. One option is the placement of the primer inside the borehole, before the LWC unit is inserted. This would simplify the folding process of the hose, because the hose would not have to carry the weight of the primer with the possible risk of unfolding. On the other hand, the unit is deployed under rough borehole conditions. Therefore, a primer sliding down the borehole could plug the hole and prevent the unit to slide down. The second option is to box the primer inside the plastic hose, sliding down with the LWC unit together.

To stay near the concept of the ContBlast unit the decision was made to implement the primer within the LWC unit. This accelerates the deployment of the unit. The ignition wire leaks from the start of the plastic hose out, connecting with the surface on the outside of the unit. While lowering the unit special attention must be given to the ignition wire, because it is exposed to the rough borehole conditions.

The unfolding mechanism shall be done by a 3D printed device, which locks the start of the unit. Only one layer of plastic hose at a time, should glide outside of the unfolding device. The unfolding device should not destroy the plastic hose, but prevent the emulsion from leaking in the inside of the unit. The envelopment area should be the only area exposed to emulsion.

The plastic hose length should fill the hole length of the borehole. While it is possible to only use plastic hose for the emulsion charging length the guidance of the plastic hose to the top enables the experimenters to analyze the unfolding process. If the plastic hose reaches the surface the experimenters can measure the remaining length and calculate if the folding process was successful. Furthermore, it is possible to let the top charge primer through the plastic hose opening directly to the emulsion before the borehole gets closed.

The connection between charging hose and unit must have a predetermined brakeage point to salvage the charging hose if the unit plugs. This point will be accomplished with a tight fit connection. A clamp will be used to connect charging hose with LWC unit.

The redundant primer will be inserted inside the plastic hose, which reached the surface. The primer can slide through the hose directly on the emulsion.

The unit shall not become longer than 2 m and have a diameter as small as possible to decrease the plugging risk.

3.3 Development of a unit for the laboratory test

3.3.1 Final dimensioning

- The protection containers have a dimension of 70/65 mm in diameter and a component length of 37,5 mm.
- The inner pipe has a diameter of 20/19 mm
- The unfolding device has an outer diameter of 31,5 mm (Annex III), made out of PLA.
- Chosen folding technique is folding within subcomponents
- The inner pipe will be connected with a garden hose, guiding the water through the inner pipe to the envelopment area. Connection will be accomplished by clamps

3.3.2 Folding development

Goal of the folding experiments is to impart the experimenters a feeling for the material of the plastic hose. The behavior of the plastic hose is specific, and therefore the most compact and reliable way how the hose should be folded and stored must be determined. A focus is oriented to folding techniques, which does not alter the plastic hose behavior through excessive stresses and strains while the folding process. The unfolding process is highly dependent on the right folding technique so no hose plugging occurs between unfolding device and protection container. Furthermore, the unit should have a small external diameter to prevent a unit plugging inside a borehole. Therefore, a lot of this thesis attention lays on the optimal folding technique.

3.3.2.1 Folding methods with short container

To facilitate the folding methods a test series with a short container was prepended to observe the starting sequence of the folding process. The approach of the series was to utilize a short 5-meter-long plastic hose piece (Figure 5, red), which can be folded and unfolded very easy and fast. With this hose numerous different folding techniques were conducted to determine the most favorable one, leading to a compact small package of the hose.

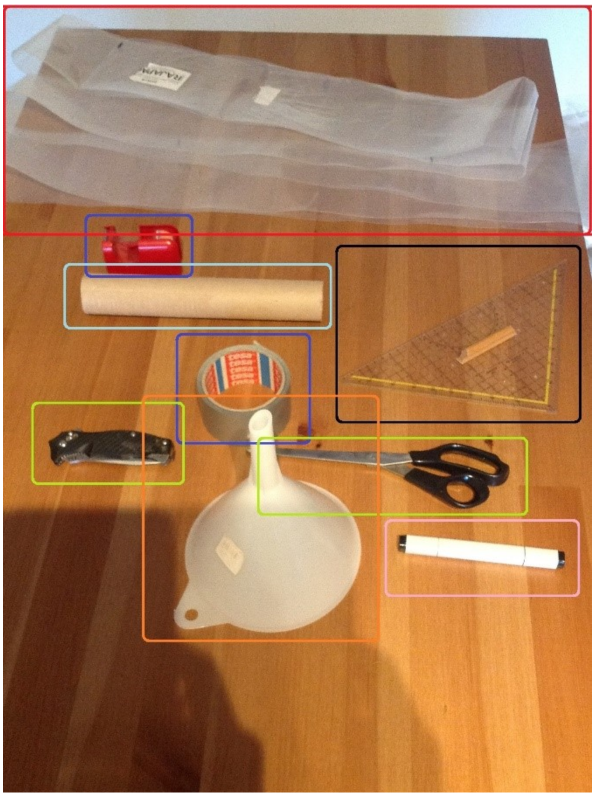

Figure 5: Material in use for the folding methods with shortened container

To conduct the tests mostly common tools were used. To note was the cardboard representing the inner pipe of the prototype. The cardboard material (Figure 5, light blue) was chosen due to its flexible behavior. While different folding techniques were performed the Duct Tape (Figure 5, blue) connections, bundling the cardboard coil, could be released and the diameter of the inner pipe represented by the cardboard coil could be changed. Furthermore, a funnel (Figure 5, orange) was used to compensate for the unfolding device. The funnel had an angle of 28,3° from the tip to the bigger end of the cylinder. This supported the folding process, because the experimenter could start the folding process at the funnel wall and achieve a predefined inclination for the folded hose. The triangular ruler (Figure 5, black) supported the folding, because it allowed the experimenter to check regularly the planed inclination of the stored plastic hose.

The general idea of the different folding techniques was to achieve an inclination of the plastic hose of 24,6° (Figure 6, right). With this slant, the hose, with a diameter of 90 mm, fit into a protection container with an external diameter of 60 mm. The inner pipe should not undercut the diameter of 14 mm. This diameter was used for a similar project called ContBlast Charging Unit (Ivanova R. 2011, p.14) (Annex II). To facilitate the emulsion flow through the inner pipe a working diameter of 19 mm was chosen. If the prototype should be viable for 25 meter boreholes and the length of the prototype should not exceed 150 cm; 1,87 windings of inclined plastic hose / cm were required to fit within a protective container with a diameter of 60 mm.

3.3.2.1.1 Folding method without geometrical validation

The first approach was to use the funnel wall to start a plastic hose folding process with a starting inclination of 28,3° (Figure 6, right). After the slightly to shallow start the inclination was sharpened manually by instinct to 24,6° and the rest of the hose should be folded the same way along the inner pipe.

The start of the folding process was accomplished according to plan. Several attempts depicted, that it is possible to fixate the plastic hose with the funnel. A starting inclination of 28,3° was achieved too. The plastic hose was compressed manually and a new layer of hose was pulled over the compressed one to create a new winding. The overlaying hose was pulled downwards the inclined hoses, compressing the under-laying hoses furthermore. This process came to a still stand at the moment an inclination of 24,6° was reached. After 5-6 windings the inclination was perfect, the diameter of the hose was 60 mm and the windings were packed enough to achieve the goal of a maximal prototype length of 150 cm.

Figure 6: Folding method without geometrical validation

Ensuing the 5 - 6 winding it was noticed, that the under-laying hose was not compressed as much at the center of the funnel as it was at the border of the funnel. These overlapping folds in the center area were requiring more space and therefore the volume requirement of hose in the center part raised. Due to the size increase near the center the inclination of the hose became steeper with every winding until the point of zero degree was reached. The only possibility to add more plastic hose was to lead it along the folded windings and to increase the diameter of the folded hose until the point of 90 mm. At this moment it was not possible to proceed the folding process without damaging the plastic hose (Figure 6, left). 20 executions of the folding technique without triangular ruler were made with the specific intend to minimize the volume increase at the center area near the inner pipe. Nonetheless, due to the lack of space in the center area, the volume increase was inevitable and the folding process stopped. For small scale folding tests this technique may be practicable, but the more plastic hose must be stored the more it loses its legitimacy.

3.3.2.1.2 *Folding with triangular ruler*

As the previous experiment depicted, folding without any kind of inclination control leads to a too steep inclination of the hose with the result of stopping the folding process. Therefore, to counteract this effect, a new folding technique was tested, using a triangular ruler to validate the inclination of the plastic hose. The plastic hose was folded in windings, comparable with the folding method with no triangular ruler. But after every winding the wanted inclination, length of folded plastic hose and the volume increase in the center area was reviewed geometrically (Figure 7). If the inclination of the hose started to deviate from the desired outcome the packaging got loosened and the plastic hose gained more room to fold perfectly. The mellowed packaging led to a longer prototype length.

Figure 7: Folding with triangular ruler set up

Figure 7 describes the course of the test. Left shows the start of the folding process. Currently the fifth winding is pulled over the fourth one. With a triangular ruler the length and inclination of every winding is tested.

Right depicts the result of the folding with triangular ruler technique. 9 windings are pulled over the inner pipe, the diameter of the package is 60 mm.

For short boreholes this technique works perfectly. The required diameter of 60 mm for the plastic hose was reached, the hose could be folded without any kind of harming stress or strain influence and the unfolding of the hose worked too. The downside of this technique was the loosened packaging. It was possible to fold 1,7 meter of plastic hose onto 30 cm of inner pipe. If this conversion factor was extrapolated to a real length unit 4,46 meter of protection container were required to store the plastic hose for a 25-meter-long borehole. This unit length is inconvenient to use, because it is difficult to transport and to deploy within boreholes. The unit length should not exceed two meters. As a result, the folding technique supported by geometrical control is adequate for boreholes of 11,3-meter length or less.

3.3.2.1.3 Folding method via vacuum

A new approach to fold the plastic hose was to draw the air out of the hose with the assistance of a vacuum cleaner. The plastic hose was put on the inner pipe and no specific attention was turned on the windings. The inclination of the windings and the assembly did not matter with this technique.

The left side of Figure 8 depicts the folding state before the air is drawn out of the plastic hose. 5 meter of hose are divided on 30 cm of inner pipe equally. In blue the top area of the hose is shown sealed by Duct Tape. In red the random folded hose is depicted, with random inclinations and irregular orientations around the inner pipe. Green shows the plastic hose sealed to the funnel. The funnel is not necessary for this test, but it simplifies the coupling of the vacuum cleaner in the variety of test processes.

Figure 8: Vacuum assisted folding set up

While the vacuum cleaner was active a clear decrease in hose volume was noticeable. Furthermore, the hose sucked onto the inner pipe blocking a vertical movement of the packed hose. The radius of the hose was 90 mm, but because of the loss in volume it was easy to pull a 60 mm protection container over the hose shifting the horizontal stored package of hose to a roughly 25° inclined one (Figure 8, right). Hence the vertical movement of the hose was blocked no transfer downwards was possible, which would had led to a tighter packaging in the area near the funnel. This effect was important, because a transfer in a small scale test might be of no consequence, but in large scale a transference could lead to difficulties of pulling the protection container over the hose at the end of the folding process, due to a lack of remaining volume.

This folding technique was fast, because no time was wasted to control the windings. Furthermore, it was possible to store 5 meters of plastic hose in 30 cm of protection container. Converting this ratio to large scale a unit used for 25-meter borehole, would have a length of 150 cm, which is an acceptable size. It was possible to have a 60 mm diameter protective container, which enables a rather flexible and plugging-free prototype movement inside the borehole.

Due to the fulfillment of all requirements and the easy applicability the folding method via vacuum was chosen for the prototype and will be tested in large scale test series.

3.3.2.2 Folding methods with one meter containers

To verify the test results from the short container folding tests three translucent Plexiglas protection containers were acquired with different inner and outer diameters (Figure 9). A pipe utilized for the transportation of electrical wires and having a diameter of 19 mm was used to simulate the inner pipe (Figure 9, 4). The protection containers with the diameter of 80/75 mm (Figure 9, 1), 70/65 mm (Figure 9, 2), 60/55 mm (Figure 9, 3) and the inner pipe had a length of one meter and the employed plastic hose had a length of 16,6 meter (Figure 9, 5). Therefore, the test was conducted with 2/3 of the length needed for the real unit. The test with 1,5-meter-long protection containers was avoided, because the acquisition of longer Plexiglas tubes than 1 meter with different diameters was difficult and more expensive. It was assumed, that all successful folding tests with one meter containers could be inherited to the real unit, because the difference in length was minor.

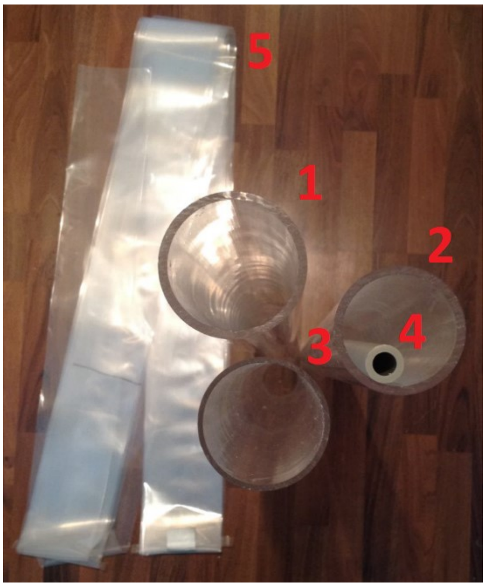

Figure 9: Test materials for the large scale folding experiments

3.3.2.2.1 Folding via vacuum

Referring to the folding methods with shortened container (Chapter 3.3.2.1.3, Page 20) the 16,6 meter of plastic hose were pulled over the inner pipe and sealed with Duct Tape on the top and a vacuum cleaner on the bottom. The activation of the cleaner resulted in a volume decrease inside the plastic hose. It was noticed that the volume reduction decreased from the top to the bottom. At the start, where the inner pipe had the first contact with the hose, the volume reduction was strong and the hose clinged on the inner pipe. After approximately 40 cm of inner pipe the volume reduction started to get limited due to the clinging effect on the first 40 cm of pipe. The plastic hose was so attached to the inner pipe, that it prevented the vacuum cleaner to draw more air out of the system until the power limit of the cleaner was reached and the volume decrease stops. To pull the 80/75 mm and 70/65 mm diameter over the packed hose worked perfectly at the first 40 cm. But after reaching this point the adhesion force was not strong enough and the plastic hose started to get striped bottomward by the protection container. At the end of the inner pipe so much plastic hose accumulated, that it was impossible to incline the hose anymore and as a result the 90 mm plastic hose did not fit into either the 80/75 mm or 70/65 mm container. The inner diameter of the 60/55 mm container was too small from the beginning and it was not possible to put it over the packed hose at all. A possible improvement of the folding technique would be the deployment of a more powerful air-drawing aggregate. Such a device was currently not owned and an even stronger one would had to be deployed to fold 25 meters of plastic hose. Therefore, this promising folding technique was discarded for the prototype development.

3.3.2.2.2 Cramming via folded windings

This approach refers to the folding with triangular ruler (Chapter 3.3.2.1.2, Page 19). The plastic hose was folded to windings with an inclination of 24,6°. After one winding was folded it was crammed as deeply as possible directly into the plastic container. The following folded winding trailed the first one and shoved it further into the container. This procedure was repeated until the whole hose is stored in the container.

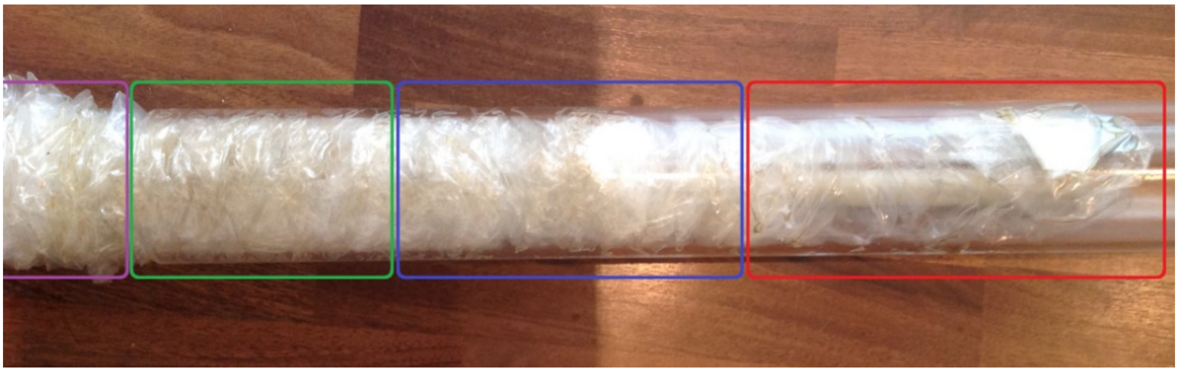

Figure 10: Result of the cramming via folded windings technique

The first windings glided inside the protection container easily, reaching a depth of 20 cm in a 70/65 mm container. Inserting more and more windings resulted in a pushback of 15 cm of the first winding. With a constant addition of windings, the connection area between plastic hose and protection container increased. In this zone the friction between the two components appeared to become very strong. The result was that the windings did not travel to the end anymore. Instead the movement through the container slowed down, clumping up more and more windings. The friction between hose and container increased, with an end result of stopping the hole progress.

Figure 10 depicts the situation perfectly. The folding progress starts with the blue area. The windings are stacked satisfactorily and move through the protection container through pressure of the succeeding windings. With more and more windings moving inside the container the friction increases to a too high amount, with the result, that the hose is pushed back barley but instead is compressed. The green area is created, in with the hose is compressed that much that no movement inside the container exists. The hose in the purple area cannot be inserted inside the container, because the hose in the green area cannot be compressed further. On the other hand, because no force is containing the hose an unfolding process starts in the red area, to the point, in which the friction of hose to container is high enough to form a counterforce.

Figure 11: Cramming via folded windings technique using a protection container with a diameter of 80/75 mm

Trying to examine the limitations of this technique the protection container with the biggest diameter was applied and the windings of the plastic hose were splashed with MoS_2 to decrease the friction forces inside the system (Figure 11). The result of the test was that, even using the biggest pipe, only 54% of the protection container was filled. Of these only 35,5% were filled with perfect or heavier folded plastic hose. 46% of the plastic hose remained outside of the protection container, which was 7,7 meter of unprotected hose. Therefore, this technique was not viable to use for the prototype.

3.3.2.2.3 Folding via wrapper

The problem recognized in the cramming tests (Chapter 3.3.2.2.2, Page 23) was the friction grooming between the layers of plastic hose and protection container. Furthermore, there was no possibility of intervention, if an area with heavy friction was building up inside the container, due to a high compression of the plastic hose. To create a possibility to overcome this friction the plastic hose was compressed preemptively, before it was inserted in the container. The compressed package of hose was wrapped with a second unfolded hose with a length of 3 meter. Together the hose and the wrapper were inserted inside the container starting with the 2 meter of wrapper, in which no packed hose was wrapped. The protection container had a length of 1 meter, hence 1 meter of wrapper poked out of the protection container. The wrapped hose was pushed inside the protection container on the on hand and on the other a traction force was applied through the wrapper to overcome the friction forces (Figure 12). Furthermore, the wrapper surrounding the packed hose was splashed with MoS_2 to decrease the friction.

Figure 12: Using a wrapper to force the plastic hose through the protection container

The folding experiment was a success (Figure 12, blue). While it was not possible to force the plastic hose through the containers with diameter 60/55 mm or 70/65 mm at all, it was possible to force it through the one with 80/75 mm. Three experimenters were required to perform this folding technique. The first had to pressure the compressed hose together with the wrapper into the longitudinal direction of the container. The second one had to splash the wrapper with MoS_2 before the hose enters the container. Furthermore, he had to decrease the radius of the compressed hose from 45 mm to 37,5 mm applying a radial compressive force directly at the entrance point, in which the wrapper enters the container. The third experimenter applied a constant pulling force via the wrapper, which was poking out of the container on the other side (Figure 12, red). The constant and straight appliance of the traction force was important, because the load on the wrapper was high. A slanted traction force, resulting in a sharp edged contact between wrapper and container, or a sudden stress could have led to the failure of the wrapper and a block on the folding progress. While the packed hose was inserted in the container the wrapper increased its length and elongation-damages were noticeable. The insertion procedure was not continuous but jumpy, which resulted in more load for the wrapper. A way to homogenize this process was not found yet. Nonetheless, in every of the ten tries the wrapper was capable to insert the plastic hose inside the container.

Figure 13: End result of the folding via wrapper method

The folding via wrapper technique can be applied to produce a prototype with an outer diameter of 80 mm.

3.3.2.2.4 Folding within subcomponents

Another solution overcoming the friction between hose and container was the folding within subcomponents technique. While testing the cramming via folded windings technique (Chapter 3.3.2.2.2, Page 23) it was noticed that the first 20 cm of cramped windings were stored perfectly within the protection container of 80/75 mm in diameter. Inserting more hose led to a partly translation but also partly extensive compression, which stoped the folding progress.

Figure 14: Arrangement of the subcomponent folding test

To utilize only the first 20 cm inside the container a 1 meter Plexiglas tube was cut into 2 pieces of 35 cm in length and a piece of 30 cm as a byproduct (Figure 14). The subcomponents of the protection container were filled from both sides of the tube, resulting in a 17,5 cm distance, which had to be filled from one side. The decision was made to use a Plexiglas tube with a diameter of 70/65 mm to reduce the plugging risk of the unit inside the borehole. Therefore, the distance which has to be managed from one side was reduced from 20 cm to 17,5 cm. Four subcomponents of the protection container would be required to store 25 meter of plastic hose resulting in a finale prototype length of 140 cm.

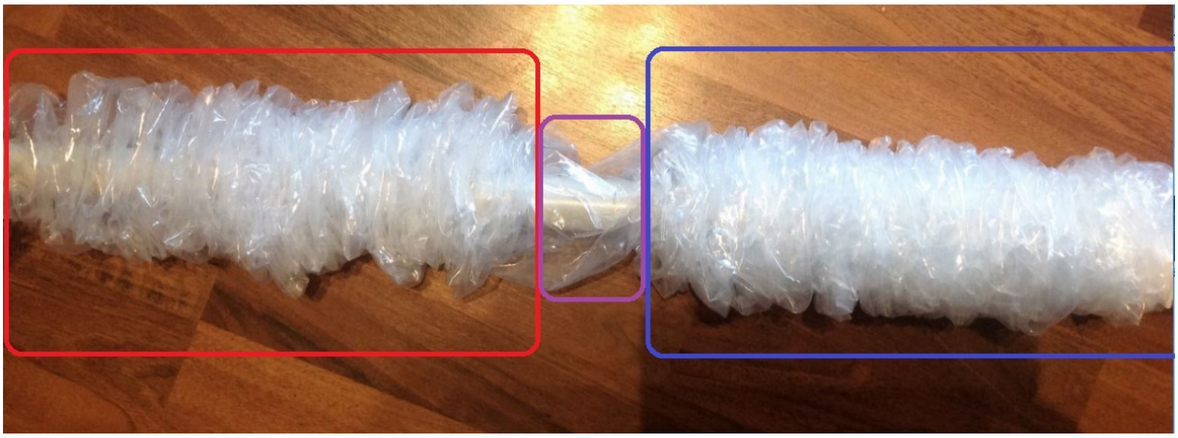

Figure 15: Distribution of the plastic hose

Figure 15 shows the distribution of the plastic hose. Red depicts the first sixth of the hose separated via estimations. Blue shows a segment of the remaining hose. In purple the inner pipe is noticeable. In this area the hose will be separated in 2 parts.

The plastic hose was pushed over the inner pipe and compressed without concern about the windings. The test protection container had 3 elements, therefore the first sixth of the hose was split via estimations from the rest. The compression of the hole hose was of importance to enable the experimenter to distinguish the dimensions of the hose and to separate it to approximately the same section size. The sixth part of the hose separated from the rest had a length of 2,76 meters and was pulled through one of the protection containers after separation. Because the folding process was conducted at the edges of the containers and these edges were sharp due to the cutting process of the Plexiglas, these edges were picked with cello-tape to prevent damage on the hose. Now the plastic hose was decompressed on both sides. Starting with the drawn through hose segment the cramming via folded windings technique was used to insert the hose inside the container.

Because the hose tent to unfold and the experimenter had to move the container further to fill the other side, a cable tie was used to bind the hose to the inner pipe to prevent unfolding. The backside of the container was filled with the same technique as the front side. The windings produced in the backside had an inclination opposing the unfolding direction of the prototype.

20 times the first container was filled from both sides and unfolded manually through traction force applied at the front side. It was noticed that the first 17 cm were the most critical one, in which the hose tent to stay compressed and move outside the container at once. After this critical area the friction between hose and container was too high and the hose unfolds consistent, without bulking of some windings. The misdirected inclination of the backside folded hose had no impact on the unfolding process.

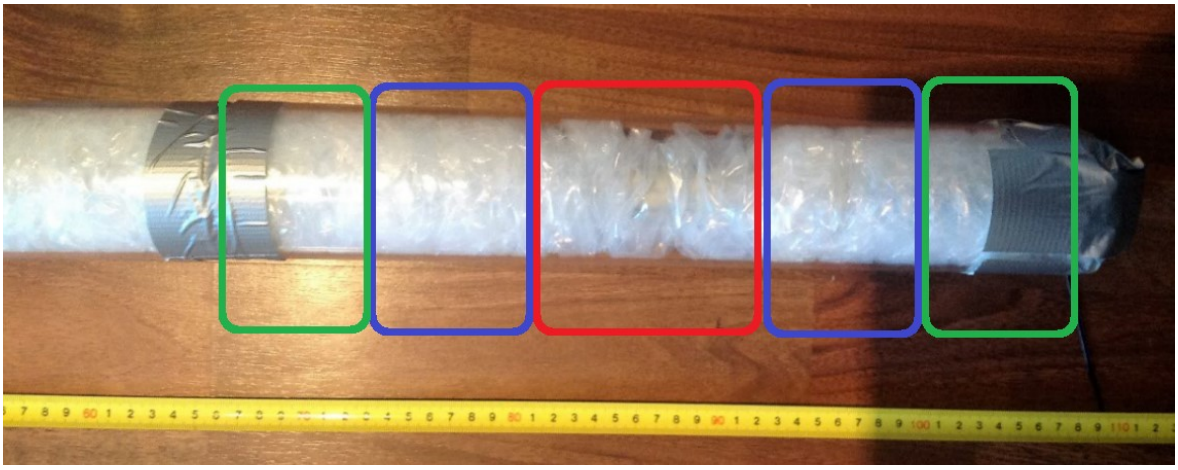

Figure 16: Protection container filled with hose

Three segments were created inside the container subcomponent (Figure 16). Green depicts a heavily compressed area, blue an area with perfect hose compression, and red a low compressed area, in which the hose unfolds.

The hose in the back was blocked from unfolding via cable tie too. It was noticeable that the 2,76 meter fit into the container and that the compression effects mentioned in the cramming via folded winding chapter were appearing again. In the red zone, in which the hose had unfolded inside the container (Figure 16) the different directions of inclinations are observable.

The next segment of protection container was treated the same way. To mention was the connection between two containers. After the front side of the second container was folded, the cable tie preventing the hose from the first container to unfold was cut without damaging the hose. The hoses pushing outside the container on each side were compressed together and the containers were connected via three layers of Duct Tape (Figure 16).

Following this technique, the three protection container segments were assembled, storing the 16,6 meter of plastic hose. Subcomponent folding was a viable option for the prototype too.

Subcomponent folding had many benefits compared to the folding via wrapper. The diameter of the protection container was 10 cm smaller, which decreased the unit plugging risk inside the borehole. The subcomponents were independent elements, having their own friction constitution. Therefore, the overall result and prototype length was independent from the friction conditions and could be altered freely to reach the required goals. A prototype used for a 25 m borehole requires 4 subcomponents and one for 15 m holes only 3 components. Furthermore, the containers were not completely filled jet (Figure 16, red), enabling the experimenters to optimize the folding technique. This would result in a decrease of length or diameter.

Storing the hose in the container of 60/55 mm in diameter was not possible, because 5,3 m of plastic hose remain outside of the protection.

Figure 17: 1 m of protection container filled via the subcomponent folding technique with 16,7 m of plastic hose

3.3.2.3 Conclusion of the folding tests

Folding techniques with vacuum assistance are the easiest and fasted way to insert plastic hose inside a protection container. For long units this method fails, due to the lack of power of the vacuum aggregate. For an industrial production of the unit, in which the aggregate can be adjusted to the required power this option may be the most viable one. For a small number of prototypes this option is too costly.

Nonetheless, the friction between container and hose prevents the sliding of many layers of hose at once and is therefore helpful. While producing the unit vacuum supported in high quantities the first 17 to 20 cm of unfolding area should be packed very lightly to prevent a simultaneous sliding of layers.

For small numbers of units, the folding within subcomponents technique is the preferable one. The production time is still short and the costs are low.

3.3.3 Unfolding process

A question needed to be solved is, how the unfolding process works inside the unit. The unfolding mechanism has to fulfill many requirements. The unfolding process needs to contain a primer to initiate the matrix from the deepest part of the borehole. The plastic hose has to unfold constantly without bulking, because the stored hose is exactly calculated for the length of the borehole. The unfolding process cannot harm the plastic hose, otherwise the unit would lose its deployment benefits. Protection container and inner pipe are reusable parts and should be salvaged from the borehole. And no emulsion should reach the inside of the protection container, influencing the unfolding process of the hose. To fulfill these functions a 3D printed unfolding device is developed and the unfolding process is tested via water charging of the unit.

3.3.3.1 Unfolding device

An unfolding device was developed, fabricated by a 3D plotter. A specific attention to the accuracy of fit was laid to solve most of the requirements. The unfolding device had an outer diameter of 63 mm (Figure 18, Annex III) leaving only 2 mm between device and the inner wall of the 70/65 mm diameter protection container. The plastic hose was capable of fitting barely through the remaining space, resulting in a medium traction force, which had to be applied to unfold the hose. This force requirement allowed the experimenter to pull out 20 to 30 cm of plastic hose and filling it with a primer. The primer was connected with an igniter cord and the cord was led through the opening of the hose on the outside of the unit to the top. The hose was closed with a cable tie holding the primer in place. The force, which was necessary to pull out the plastic hose, must be strong enough to bear the weight of the primer while the unit sinks down the borehole. Otherwise this weight would unfold the hose pulling it down the hole without protection.

The tight fitting between unfolding device and container prevented the emulsion from streaming into the storage area of the plastic hose.

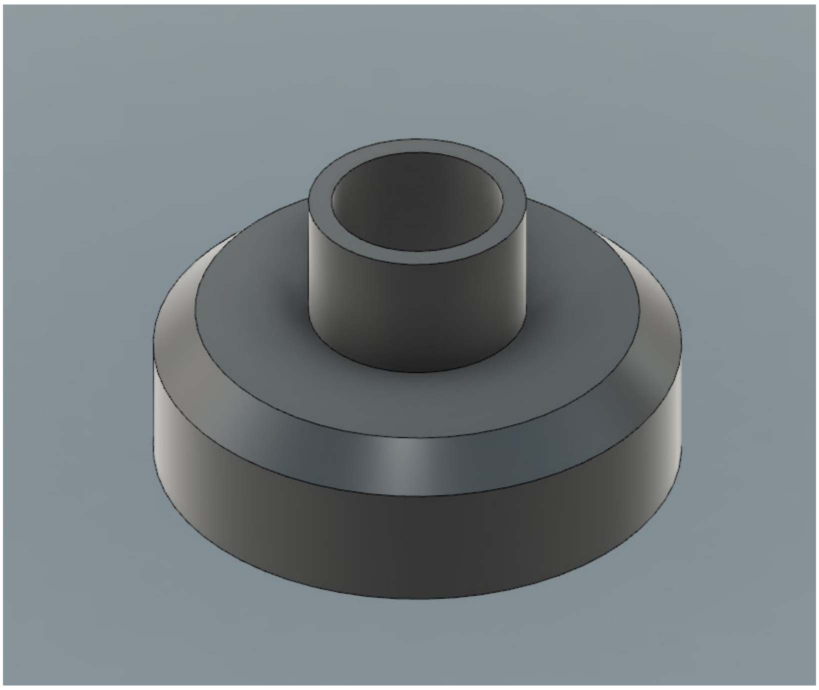

Figure 18: Computer model of the 3D printed unfolding device

The unfolding device was shaped cylindrically, hence it guided the hose gently to the area between device and container (Figure 18). This was necessary, because it was possible that bulks of hose reach the device and the cylindrical inclination separates the bulk. Nonetheless, it was noticed if the area directly above the device was filled with heavily compressed hose, more layers of hose could reach the unfolding area, got stuck and damaged by the traction force. To mitigate this effect, the zone close to the unfolding device was filled with low compressed plastic hose. Only this zone was of importance, because after trespassing the first 20 cm inside the container the friction force between hose and container became strong enough to hold the bulk of hose back. After 20 cm, within every unfolding test made, the bulk of plastic hose was restraining and only one winding was loosened. Only one layer of hose was reaching the area between device and container and no plugging occured. The low packed front part of the first protection container and the space requirement for the unfolding device within it, led to a decrease in hose storage possibilities inside it. Therefore, the remaining hose had to be divided on the remaining 3 containers.

The solution of the hose plugging problem solved the dimensioning of the hose problem too. Because the first 20 cm of the prototype were backed with low compressed hose and afterwards the friction between hose and container was holding the bulks of hose back, only one layer at a time could bypass the unfolding device. This resulted in a constant unfolding mechanism, without the unwinding of more than one layer. Therefore, the hole borehole could be filled with one layer of plastic hose.

The material used to print the 3D unfolding device is PLA (Polylactic acid). The decision to use this material was made, due to the rather high strength criteria of PLA compared with other 3D printing materials. The PLA material has a breaking resistance of 65,6 ± 1,3 MPa (Farah et al. 2016, p. 374) and an E-modulus from 2.02 – 3.55 GPa (Chacon et al. 2017, p. 144). These resistances were necessary due to the forces impacting the unfolding device. Traction force of the unfolding hose, compressive force of the emulsion, impact forces inside the borehole and the compressive force applied by the charging hose had to be absorbed by the unfolding device.

Furthermore, the PLA material is classified with a high resistance against erosion or scratches and therefore the surface can be considered as hard. PLA also has a low wettability which is helpful to handle the wet emulsion. (Jorda-Vilaplana et al. 2014, p.24)

One disadvantage of PLA is the low heat deflection temperature of 51°C (Murariu and Dubois 2016, p.26) and first deformation behaviors at 64°C (Song et al. 2017, p. 158). This low resistance was critical, because in a closed car, with direct sun exposure, the 3D device may had deformed, losing its important accuracy of fit properties. The testing sight at the Erzberg was known to be rather cold, therefore the risk of PLA deformation is small.

After the production of the 3D unfolding device an inaccuracy in dimensions was measurable and the edges existing within the plotted part were sharp. Unfolding tests using the device had a high chance of ripping parts of the plastic hose. The inaccurate result in narrow sections were hard to bypass by the hose, and the sharp edges bored into the hose at the moment clumping occurs. To improve the device sharp edges and sections too large in diameter were abraded manually. The clear defined technical drawings were blurred by this procedure, but it was necessary to obtain acceptable unfolding results.

Nonetheless, with the abrading process an approach to gain the best dimensions for the unfolding device could be made and implemented for the test series at the Erzberg site.

With the reworked unfolding device, the unfolding process was conducted satisfactorily and the plotted part was applied for the prototype.

3.4 Prototype test in laboratory experiments

3.4.1 Targets and experimental arrangement

To confirm the unfolding process using a fluid, not a traction force applied by hand, a prototype was filled with water inside a translucent Plexiglas tube, which simulates a borehole. The decision to use water instead of emulsion was made to minimize the risk of harming the explorers and to protect the environment if the test would fail. The prototype had a protection container length of 102 cm and a 180 cm length of inner pipe (Figure 19, 4). The pipe was chosen to be extremely long to simplify the working process within the 2-meter-long Plexiglas tube used to simulate the borehole. The container had a diameter of 70/65 mm and was filled with 16,7 m of plastic hose using the folding with subcomponents technique (Chapter 3.3.2.2.4, Page 27). The unfolding device (Figure 19, 2; Figure 20, A3) was built within the first part of the protection container and the following 20 cm of container was backed with low compressed plastic hose (Figure 19, red). The hose was packed perfectly (Figure 19, blue) between the low compressed zones and the highly compact zones (Figure 19, green). A 1 cm gap between the container subcomponents remained (Figure 19, 3) to enable the prototype to be flexible.

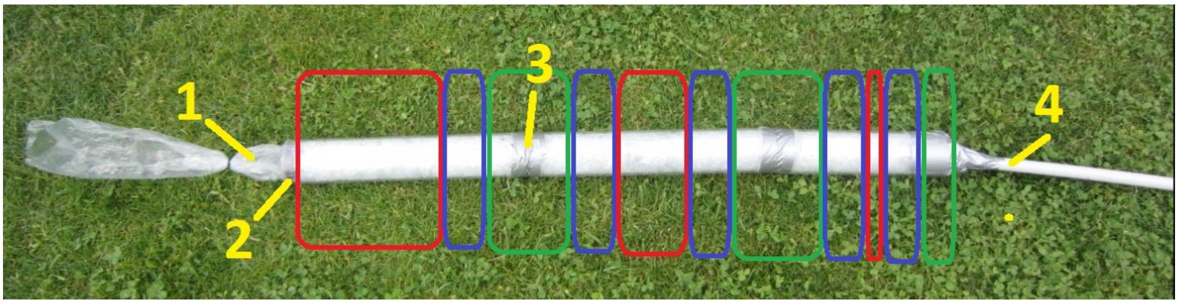

Figure 19: Prototype used for the unfolding test

The water was led through the inner pipe into the envelopment (Figure 19, 1; Figure 20, A2) in which the primer will be stored, if blasting tests are conducted. For the unfolding test no primer was required, therefor the envelopment remained empty and could be filled with water completely. A closure of hose had to be available to contain the water inside the hose and to start the unfolding process, so the hose was closed via two wire ties (Figure 20, A1).

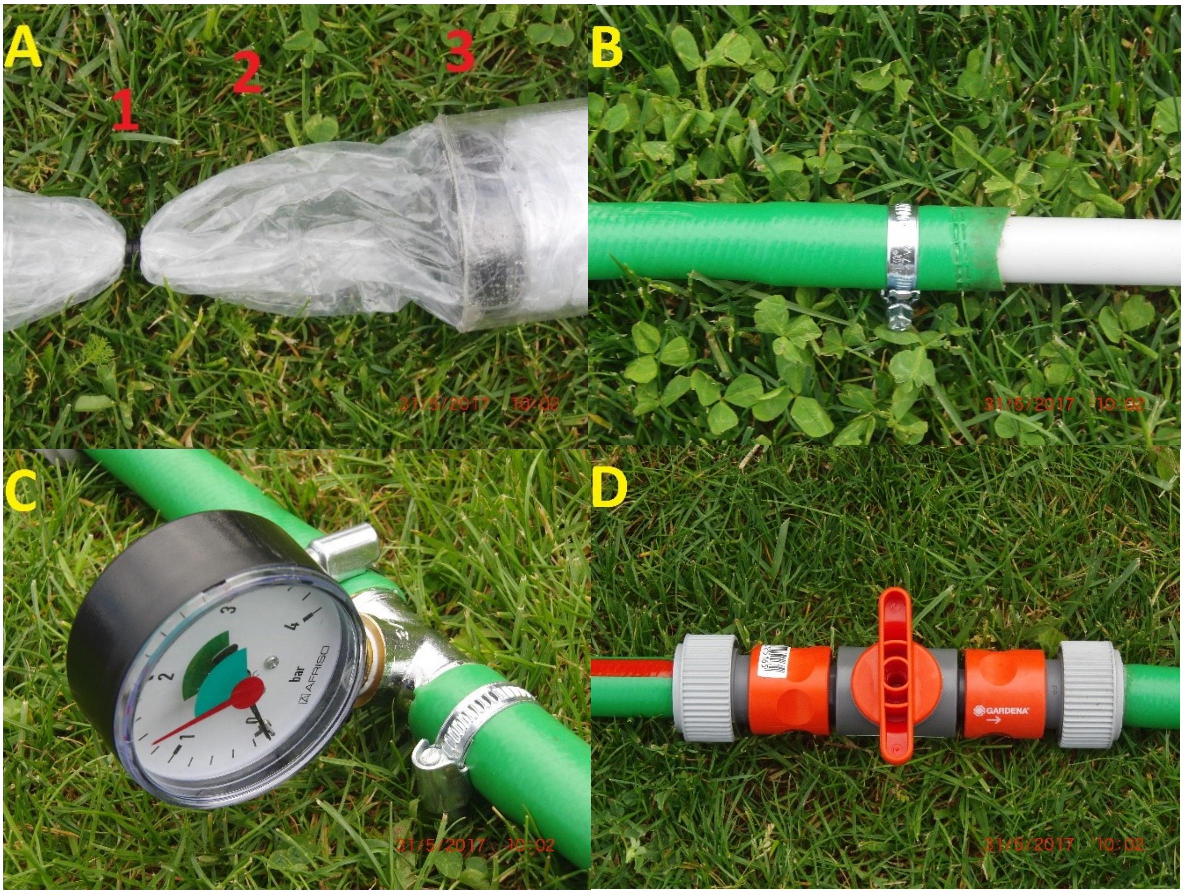

Figure 20: Unfolding test set up

The standard water supply pressure in the tested region averages around 15 bar. The unfolding test received the water of this source and was separated from it via control valve (Figure 20, D). A barometer was interposed between prototype and control valve to measure the real water pressure reaching the prototype (Figure 20, C). The barometer was fixated with a clamp on each side to prevent a disengagement due to the water pressure. The barometer was capable to depict pressures up to 4 bar, which was sufficient for the test, because the prototype begins to unfold within lower pressure conditions. The garden hose was connected with the inner pipe (Figure 20, B) enabling the water to flow in the prototype.

3.4.2 Test performance

The prototype connected with the garden hose was inserted into a translucent Plexiglas tube, with a diameter of 90 mm and 2 m in length. A high speed camera and a common one were installed on tripods to record the test series. The barometer was under observation of the experimenter, who had also the control over the control valve. 4 test series with 2 prototypes were conducted to analyse the unfolding process.

In the first test series (Figure 21), after opening the control valve completely at once, the barometer depicted a pressure increase between 1 to 2 bar. Air, which remained in the garden hose separated by the control valve, streamed inside the envelopment area starting to unfold the plastc hose. The prototype got lifted by the unfolding procedure, without the help of the experimenter. The envelopment area was closed perfectly and no air was capable to disappear. After three seconds the unfolding device got pushed half way out of the protection container and the envelopment area collapsed, releasing stored air. A bulk of plastic hose reached the unfolding divice and jammed. The traction force of the inflowing air was strong enough to resolve the plugged plastic hose windings, pulling out half of the unfolding divice too. Within this occurrence the plastic hose got damaged and air was able to stream out of the envelopment.

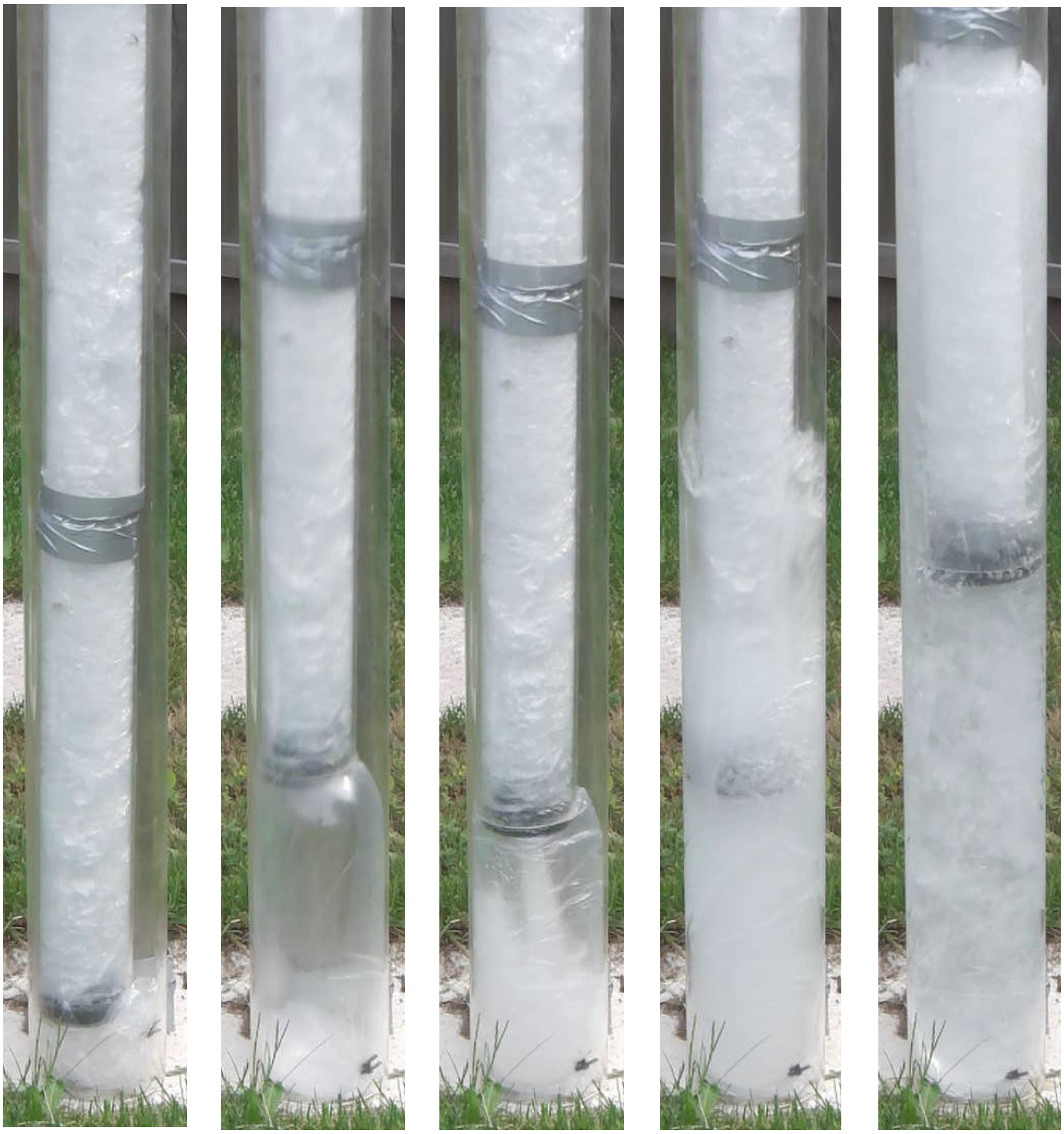

Figure 21: Progression of the first unfolding test

Afterwards the inflow of air through the inner pipe and the loss at the breach of the plastic hose were in equilibrium and the envelopment area neither collapsed completely nor grew through unfolding. At second 6 the garden hose was filled with water and no air remained, hence water started streaming in in the envelopment area. Instantly water was escaping through the rifted hose too, but due to the higher viscosity of water not all of it was able to flee fast enough and the unfolding process started again. Because the prototype was moving upwards again and the water was pressuring the hose to the surrounding Plexiglas tube, the rifted plastic hose moved from the unfolding device region to the representing Plexiglas borehole wall.

Through the pressure the rifted zone got sealed on the Plexiglas surface and the unfolding process was carried on the planed way. The barometer depicted a pressure peak of 2,5 bar at the moment the plastic hose jamed, but otherwise the pressure remains in the 1 to 2 bar region.

Three conclusions could be drawn out of this test. Firstly, air stored in the feeding lines of the prototype was a risk for the unfolding process. The air was a bad lubricant between hose and device and did not support the movement of the hose on the PLA material.

Furthermore, if air was in the system the hose had to endure more abrupt loads. On the one hand the start of the unfolding caused by air, and on the other hand the continuation done by water or emulsion.

Secondly, the prototype will not get stuck in the borehole due to plugging of the plastic hose inside it. The force of the unfolding effect was strong enough to drag the unfolding device out of the protection container and to tear the hose apart before the unfolding stops. As a result, the unit and especially the charging hose could be salvaged even if the unfolding process fails.

Thirdly, small raptures in the plastic hose did not necessarily stop the unfolding process. It was possible that the pressure inside the envelopment area forces the raptured plastic hose onto the borehole wall, sealing it and progressing with the unfolding procedure normally. This effect will be strengthened using emulsion, due to the higher viscosity of the explosive. The higher the viscosity the lesser is the possibility for the fluid to leave the envelopment area through a joint and the raptures will be closed through the upwards and sideward movement of the envelopment area. On the other hand, jointed rock could mitigate the effect, because the extension into a joint would not close the rapture and emulsion would stream out of the prototype until the joint is filled completely.

The second unfolding test was conducted subsequent to the first one. After technical documentation of the first test, the same prototype was filled with water the second time. The control valve was opened and the pressure influencing the prototype plateaus between 1 and 2 bar. Because the feeding lines were filled from the first test, water instantly streamed inside the envelopment area. The air remaining in the plastic hose from the first test was mixed with water, streaming out of the inner pipe, constituting a 40 cm long zone, in which water and gas bubbles were in heavy movement. The upwards movement of the prototype started instantly and the motion remained constant over the course of the second test. Because large parts of plastic hose were unfolded due to the first test and slumped between the first and second test, the surplus unfolded plastic hose now moved 5 cm in front of the protection container on the outside of the prototype between container and fictional borehole. Without any failure the unfolding process progressed until the 2 m borehole length is reached and the test was stopped purposely.

The conclusion of the second test was, that the unfolding process can be stopped and started again without influencing the unfolding result. Using the matrix pumping unit a start and stop filling of the hose will be standard, because the machine emits emulsion in manually adjustable steps, which must be added up by the blaster to fill the borehole.

Figure 22: Progress of the second unfolding test

In a third unfolding test a new prototype was deployed. Special attention was drawn to keeping the garden hose filled with water, hence only the air of the inner pipe would stream inside the envelopment area before the water reached the zone. Once again the control valve was opened quickly and the pressure instantly increased to 1 to 2 bar within the prototype.

Figure 23: Progress of the third unfolding test

At first, air expanded the envelopment area, starting the upwards movement of the prototype. After 1 second the inner pipe was completely filled with water, which succeeded the air in the envelopment area. The movement of the prototype and the influencing pressure remained constant while the change of air to water was happening. The records depicted, that the unfolding device was not capable to block the water from streaming into the inner side of the prototype. The water had a lower viscosity than the emulsion, therefore it was more difficult for the device to stop water compared to emulsion.

But the records showed too, that the water reaching the storage area of the plastic hose, was not influencing the unfolding in a negative way and the unfolding progress was unaffected by the liquid. The windings of the hose opened up one by one moving towards the packed area. After leaving the protection container the hose was not deposited instantly at the borehole wall but expanded, slowly reaching the wall after 2 to 7 cm of upward movement. After unfolding to the top of the simulated borehole, the plastic hose suffered a burst at the bottom of the borehole. The cable tie, used to close the envelopment area, cut with a sharply chopped edge into the plastic hose, which caved upon the water load of the filled envelopment.

The conclusions of the third test were, that the basic concept of unfolding using the unfolding device works. The cable tie used to close the envelopment area must be treated with care, the redundant tie must be cut off exactly, not leaving sharp edges back. To reduce the risk furthermore, the cable tie will be wrapped with Duct Tape in the field tests.

3.4.3 Conclusion of the laboratory test

The unfolding tests were satisfying and the unfolding set-up together with the unfolding system will be inherited in the prototype used for the field tests. Implementation of the unfolding system requires special attention in the following points.

- Air in the intake of the prototype should be avoided and the charging hose and inner pipe should be filled with water or emulsion.
- The unfolding process will continue even if the plastic hose is raptured by the unfolding device. The risk of prototype plugging inside the borehole has not increased.
- Filling the prototype in steps is possible. The hose does not have to be filled in one run.

The cable tie, closing the envelopment area with the primer, must be stored in a way, that no sharp edges are created. The remnant plastic of the cable tie should be cut off accurately and Duct Tape can be used to mask the cable tie off.

3.5 Plastic hose workload test

The unit has the purpose to get deployed in the case rough boreholes conditions occur. The plastic hose should hold the matrix in place especially in rugged rock to avoid congregations of explosives, avoiding flying rocks and reduce the emulsion consumption. Furthermore, the plastic hose is in contact with rock, which can have sharp and spiky edges. The unfolding process causes stress on the plastic hose and after filling the hose with matrix a dead load of 2 bar is applied on the bottom area of the hose by the explosive, if it is filled up to 20 meters.

To test the strength of the 100 µm thick plastic hose, it is filled with air or water inside a horizontal Plexiglas tube with a diameter of 90 mm, sparing different length of Plexiglas out. Goal is to depict the behavior of filled plastic hose without sheathing under heavy load conditions. A second test to simulate a rugged borehole with dead load of water is a vertical test series in a Plexiglas tube combined with plastic tubes to represent a borehole with many open zones.

3.5.1 Test implementation – horizontal series

Two Plexiglas tubes were deployed alongside each other with a gap between them (Figure 24). The tubes were filled with a 100 µm plastic hose, which was closed on one side with 3 cable ties and on the other connected to an air compression hose. The air pressure was activated. The point of failure of the plastic hose was recorded, together with the gap length between the Plexiglas tubes and the current effecting air pressure traced by an aerometer. To prevent movement of the Plexiglas tubes, due to the expansion of the plastic hose and the forces applied by the compressed air, one of the tubes was fixated on a solid wall and the other was hold in place by a peg.

Tries to determine the point of failure with a 2 cm gap remained unsuccessful, because the plastic hose withstood the 1,9 bar air pressure, which was the maximum pressure the compressor was able to produce.

Increasing the gap to 12 cm initiated an interesting failure behavior of the plastic hose (Figure 24). First the plastic hose expanded un-deformed, filling the Plexiglas tubes completely out and forming a straight transition between them. Appling more pressure led to a bulge in the gap with a perfect symmetry. At the moment 0,9 bar were reached the bulge lost its symmetry and shifted slightly to the right before the failure of the hose occurred. The failure developed on the top of the shifted bulge (Figure 24, red) and not on the edge between hose to Plexiglas tube, which could have been a weak point due to the sharper edge of the tube. The rapture had a length of 3 cm (Figure 26) and developed in longitudinal direction of the hose with two to three severe stretch marks parallel on each side (Figure 24, blue shows longitudinal stretch marks on the other side of the rapture zone). These stretch marks would had failed instantly, if the point of failure would not had been placed at the rapture. The rest of the expanded hose sustained an irrecoverable deformation, having many small stretch marks. The stretched material lost the smooth plastic surface and felt harsh.

In a second experiment using a gap of 11 cm the plastic hose behaved the same. This time the bulged moved slightly to the left at the moment 1,1 bar air pressure impacted, before it failed at the top of the bulk (Figure 25, red). Longitudinal stretches formed especially at the failure zone (Figure 25, blue)

Figure 24: Plastic hose between a 12 cm gap influenced by 0,9 bar briefly before the point of failure occurs

Figure 25: Plastic hose between a 11 cm gap influenced by 1,1 bar briefly before the point of failure occurs

Figure 26: 3 cm long rapture surrounded by stretch marks

To decrease the gap length and to increase the applied pressure, water out of a roughly 15 bar strong conduit was used instead of air.

Appling the pressure to a 2 cm gap led to a deformation of the plastic hose, but no failure occurs. The cable tie connection on one side of the hose failed before a burst at the gap occurs. The deformation was irreplaceable and small stretch marks in longitudinal direction were noticeable, but the stress-bearing area was considered to be in good shape.

Increasing the gap length to 4 cm, led to a point of failure at the moment 4,6 bar were applied. The behavior of the hose remained the same. First the gap was bridged via normal expansion until a strait transition was created, after a short delay the hose started to deform and formed a symmetrical bulge. The shift to one side was not noticeable, hence the gap was small and the movement minimal. The hose failed at the peak of the bulge and forms a longitudinal rapture.

A second test with a gap of 4,5 cm and a pressure influence of 4,4 bar contracted the hose behavior of the previous tests. The start remained the same and the bulge with the longitudinal stretch marks formed as expected, but the rapture occurred in a radial direction, contradicting the longitudinal direction of the stretch marks (Figure 27). This behavior may have been ascribed to a production weakness at the tested point, because this result was anomalous. The strength of the hose overall did not suffer.

Figure 27: Comparison of stretch marks (blue) to rapture (red) direction, in a 4,5 cm gap under 4,4 bar pressure

For a real statistic statement, regarding the connection between gap length and bar at the point of failure more tests must be conducted, but an estimation can be done with the gained data by this test series (Table 3). Especially tests in the range of 5 to 10 cm must be made to improve the conclusion.

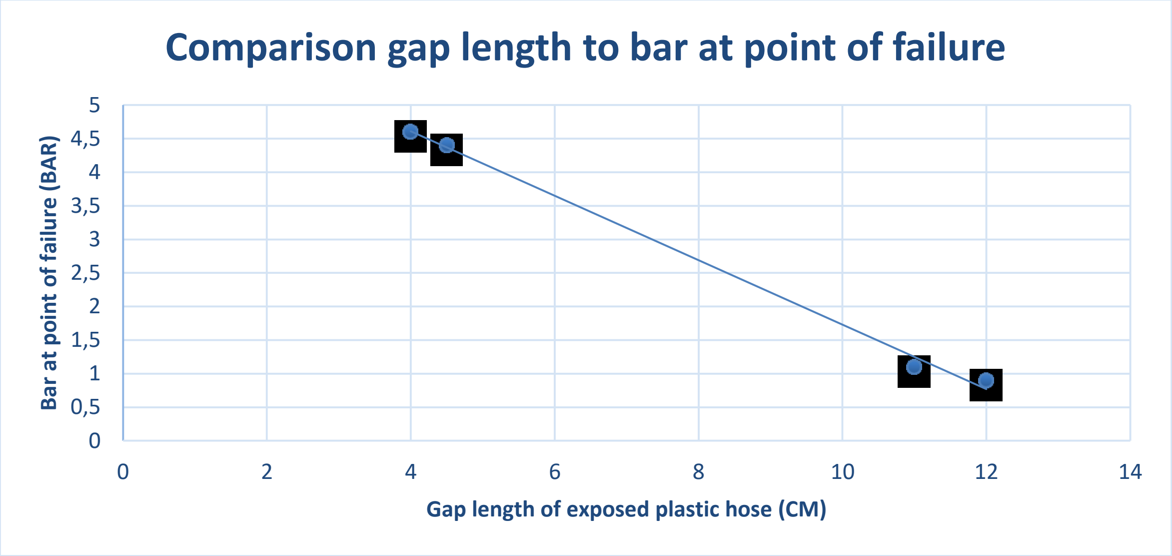

Table 3: Comparison of the gap length in which a 100 µm plastic hose is exposed from encasement to bar needed to create a rapture in the hose

3.5.2 Test implementation – vertical series

To simulate a rough and sharp borehole a 90 mm Plexiglas tube with two plastic tubes on the bottom area were placed vertically. The gap between the plastic tubes was 2 cm and the gap between Plexiglas to plastic tube was 4 cm. The edges of the plastic tubes were protected with one layer of Duct Tape, but still considered to be extraordinary sharp, even to embody sharp rock. The Plexiglas was fixated with 3 cable ties.

A prototype, produced like in the unfolding process test series (Chapter 3.4.1, Page 34) was placed inside and the inner pipe was connected with a garden hose. It was assumed, that the influencing bar will be 1 to 2 bar. A barometer was placed between prototype and valve to evaluate the exact pressure.

At the start of the test the prototype acted normally, starting to unfold and filling the two plastic tubes and the Plexiglas tube together with the gaps between the three elements (Figure 28). The prototype progressed inside the Plexiglas tube, but the plastic hose at the 4 cm transition between Plexiglas and second plastic tube started to show the bulge behavior. This behavior indicated the point of maximum stress in the system. The expansion of the plastic hose was so strong, that it started to push the Plexiglas tube upwards increasing the gap to 6,5 cm. Stretch marks were noticeable, before the system failed and a longitudinal rapture was formed at the top of the bulge (Figure 28, red arrow).

The pressure influencing the prototype at the point of failure was at 2 bar and with the overlaying water in the Plexiglas tube the effective pressure impacting the rapture zone was 2,2 to 2,5 bar, which was beneath the comparison line between gap length and effecting bar (Table 3). It was hard to define the impact of the sharp plastic tube edge or the movement of the heavily fixated Plexiglas tube on the point of failure, but the statement can be made, that every deviation of the ideal conditions decreases the expected strength of the plastic hose.

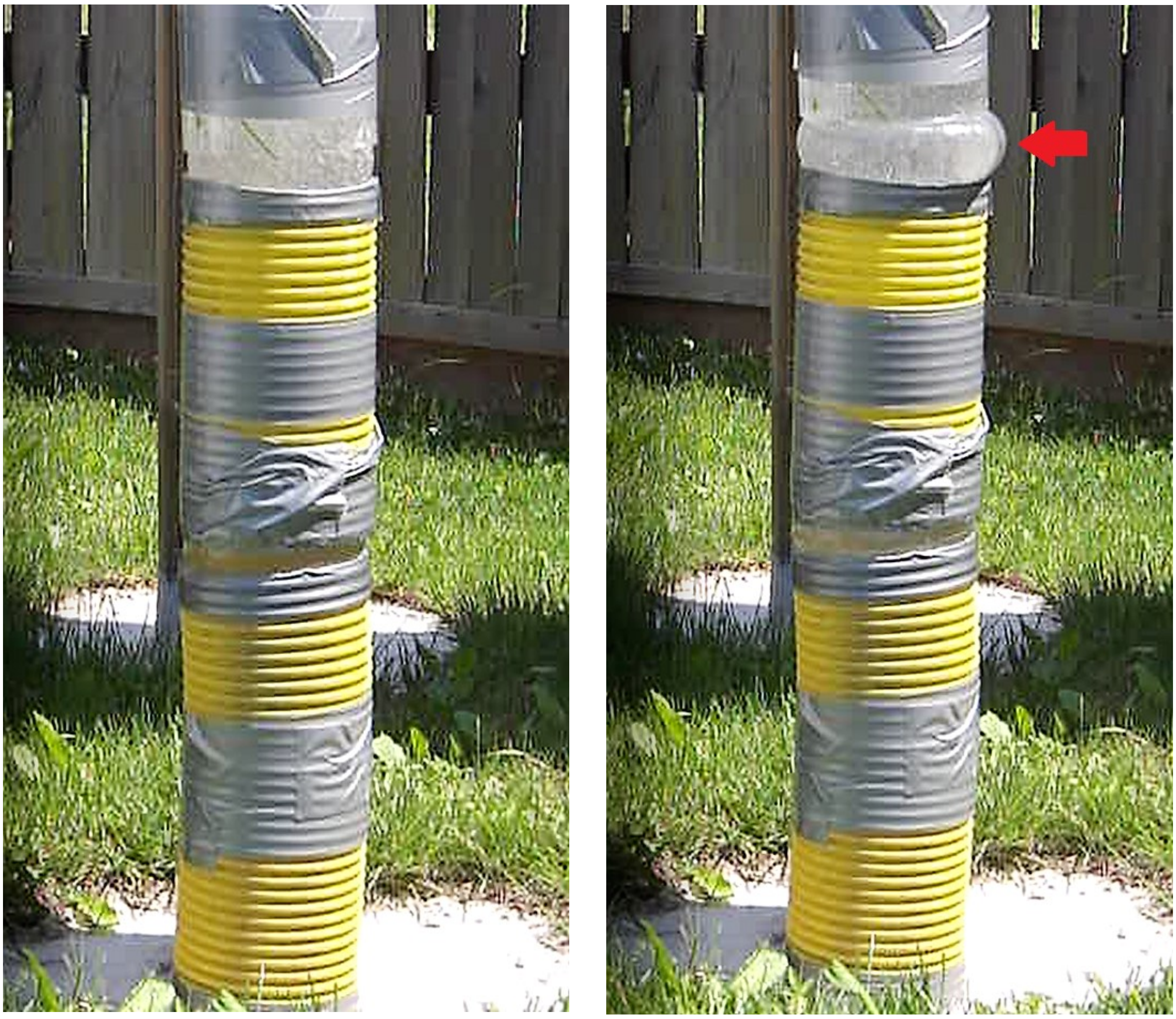

Figure 28: Test result of the vertical series

A second test, with the same setup, was conducted to increase the statistical significance. This time the prototype did not move far inside of the Plexiglas, because the plastic hose raptured at a sharp edge of the plastic tube. A small rapture was enough to enable the highly viscous water to escape and stop the unfolding process.

Because the rapture was small, an idea raised to fill the prototype with two sets of plastic hose. This would have ensured, that if one layer gets damaged by sharp edges the second would seal the rift and the unfolding process would progress.

Many tries to fill two layers of hose inside a container were conducted, but the two layers were never placed in the same region of the container. The inner or the outer layer were better stored and a part of the inferior folded one remained outside the container. This led to problems at the unfolding process, because the better folded layer unfolded faster and the overall length of the stored plastic hose decreased. Therefore, this option was discarded.

3.5.3 Conclusion

Considering ideal settings, the plastic hose is not influenced by 0 to 2 cm gaps at all and can handle 4,5 bar having a 4 cm gap. The dead load of 2 bar, created by the matrix filled plastic hose on its own, can be handled until the 9,5 cm gap length. At gap length of 11 to 12 cm the work load decreases to 1 bar.

The plastic hose is tested without any envelopment at all sides, this may not occur at a real borehole. If only one part of the hose is exposed and the rest supported the workload may increase. On the other hand, the sharp edges of stones inside the borehole decrease the overall strength of the hose. If small raptures due to stones occur the unfolding process will progress, because the matrix has a high viscosity and cannot escape as fast as water. To increase the strength of the hose using two layers is not possible, because the simultaneously folding of both is not realizable.

3.6 Development of a unit for the first field test

3.6.1 Limitation factors and final dimensioning

Limitation factors:

- Borehole length at the Erzberg site is between 25 and 30 m, which is longer than the borehole length of 15 to 20 m mentioned in the definition of tasks.
- Borehole diameter is 90 mm. The boreholes are in bad conditions in the first 5 meters but afterwards the holes are in good shape.
- 10 boreholes should be blasted. Of those 5 with the LWC unit.
- The boreholes are partly filled with water and mud.
- Temperature at the Erzberg side is above 14°C.

Final dimensioning:

- Protection container diameter is 70/65 mm and the length is 40 cm. 4 elements are lined up with 1 cm gaps between them closed by Duct Tape. Protection container length together is 163 cm
- Inner pipe diameter is 20/19 mm and the length is 190 cm.
- Stored Plastic hose has a diameter of 90 mm and a length of 30 m.
- The unfolding device has an outer diameter of 62,5 mm made out of ABS.
- Charging hose will be connected with the inner pipe with a 1-inch garden hose, holding together with clamps.
- Predetermined breakage point is the connection 1-inch garden hose to inner pipe.

3.6.2 Prototype production

The protection container and the length of the plastic hose in the development stage of the LWC unit were designed for boreholes of shorter length than 30 m, and therefore the prototype in the production stage had to be adjusted. Calculations and obtained experiences revealed that the length of 40 cm of each protection container segment with an outside diameter of 70 mm and inner diameter of 65 mm were best suitable to contain the 30 m of plastic hose. Four container elements were required to store the plastic hose completely. Once again translucent Plexiglas was used to enable the experimenters to fold the plastic hose easier inside the container and to allow an in-depth look, while the experiments were running.

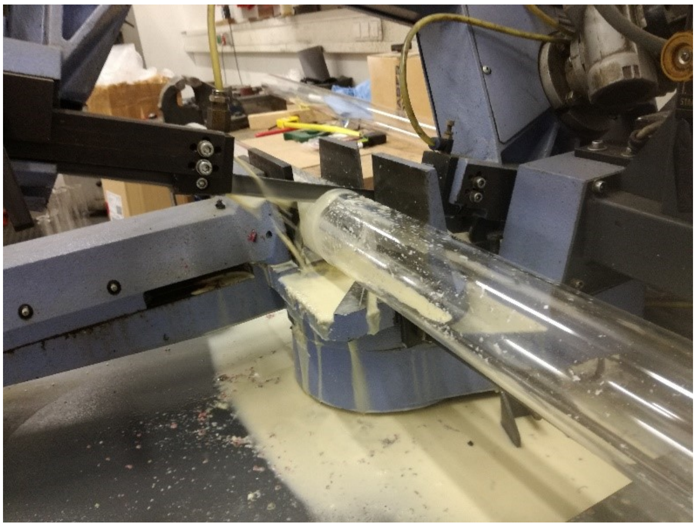

Figure 29: Automatic metal cutting saw, supported by an oil-water blend

To cut the Plexiglas an automatic metal cutting saw (Figure 29) was used to create a smooth joint face on the Plexiglas edges, hence they could not harm the plastic hose while folding and unfolding. The settings of the machinery were essential for the end result. While a slow movement of the saw blade and a fast automatic downwards movement of the saw created sharp edges or led to a burst of the Plexiglas, fast blade movement and very slow downwards movement resulted in smooth joint faces.

To transport the matrix from the charging hose to the bottom of the prototype the same inner pipe was used like in the development stage of the unit. The only divarication was the extension of the pipe to 190 cm. Because the inner pipe was the longest part of the prototype, the final product would also have the length of 190 cm in total.

Furthermore, several changes were made to the 3D printed unfolding device. First of all, the material used to print the 3D part was changed from PLA to ABS (Acrylonitrile Butadiene Styrene). The printing result from the PLA product was not satisfying. Nearly all edges of the product had to be abraded manually with abrasive paper. Since the PLA material could endure high compressive and traction forces this process was tedious, especially because the PLA material tent to dissipate in bulk of strings, which ruined the end product. Therefore, ABS was used due to the easier formability. Within the printing process of a 3D part a strong connection between the printed part and the heating table of the printer had to be ensured, otherwise the printed part may have had shift slightly and the printing process would have had to be redone. To guarantee this connection, more creation material had to be placed around the printed part and the printing table. After the printing process this material had to be removed manually. With a product like the unfolding device, which has to be extremely compatible with the plastic hose and the protection container, the ABS material appeared to be more fitting, because this compatibility can be reached easier.

The ABS material can handle lower compressive and abrasive forces. But findings gained from the development stage of the prototype depicted a ripping of the plastic hose occured earlier than the first signs of failure within the unfolding device. Therefore, the tensile strength of 37,6 ± 1,4 MPa and tensile modulus of 1,6 GPa of the ABS material were sufficient for the unfolding device (Hirajama and Saron 2018, p. 272).

Another positive aspect of ABS was the heat resistance. While PLA products tend to melt at low temperatures with a deformation temperature of only 64°C ABS material has a deformation temperature of 109,9 ± 0,4°C with a melting temperature of 139,5 ± 0,6°C (Feng et al. 2018, p.67). Therefore, within a closed car with direct insolation the ABS produced unfolding device had no risk of deformation, while there would have been a possibility that the PLA product would deform and compromise the unfolding process of the plastic hose.

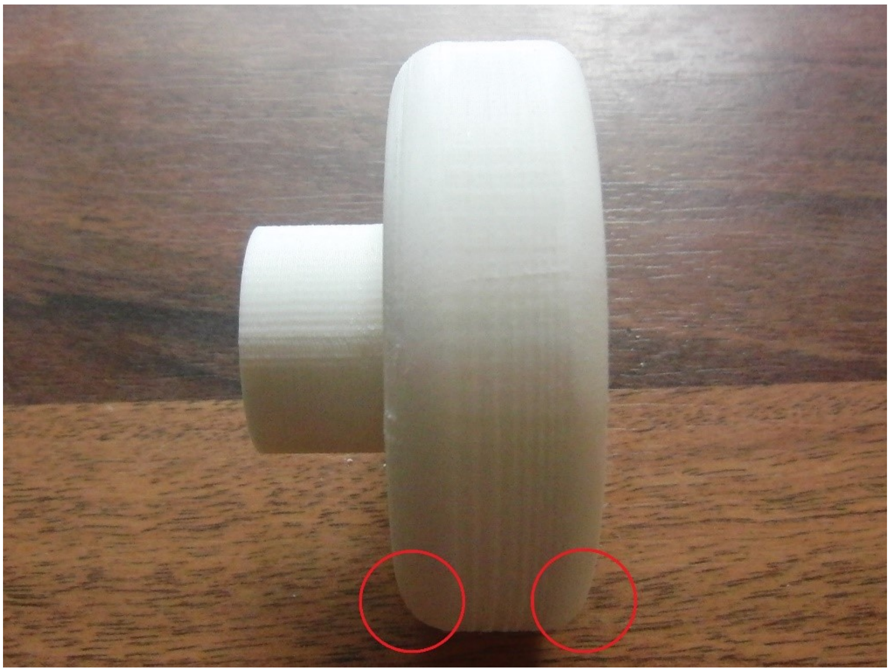

Figure 30: Unfolding device fabricated with ABS

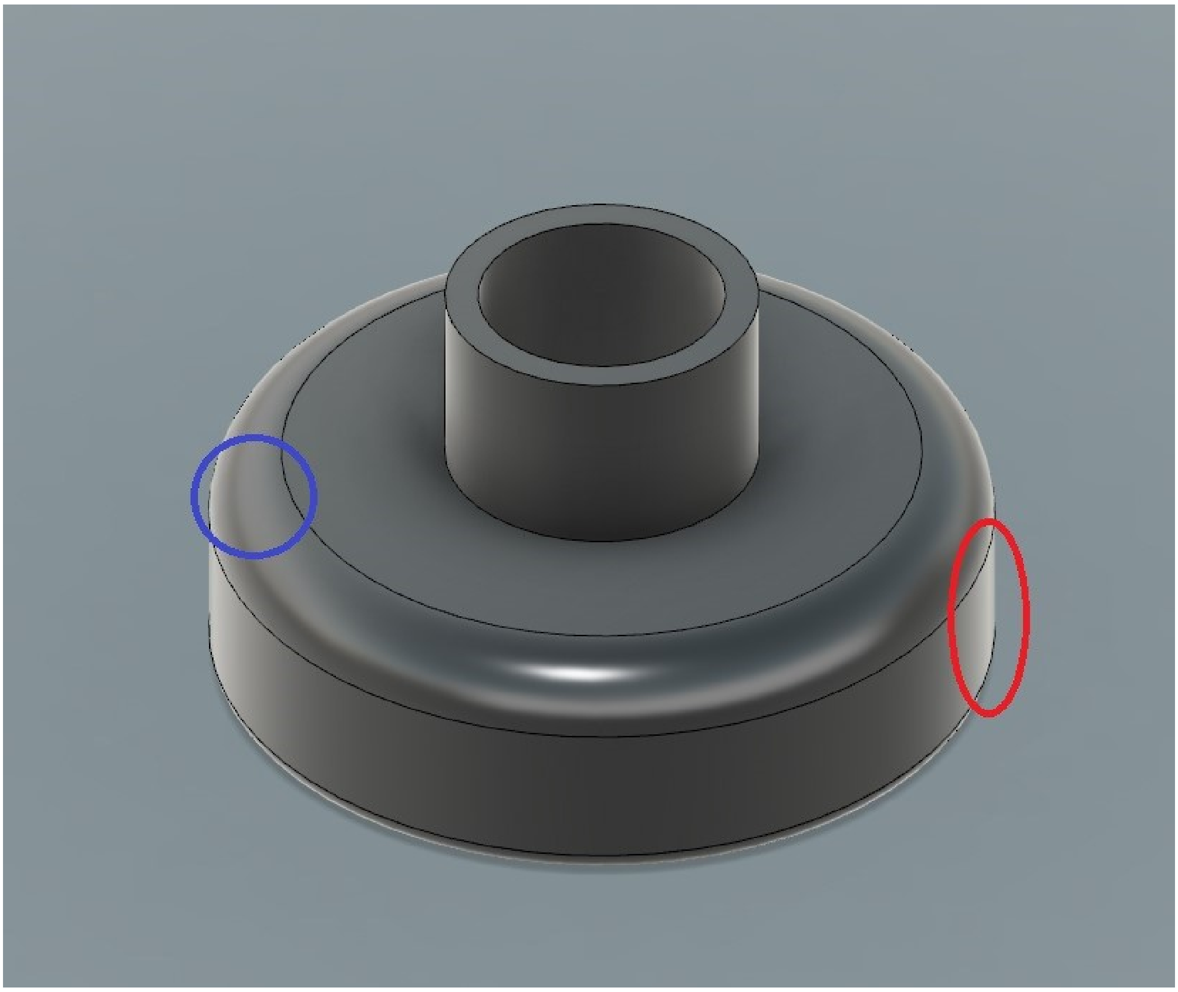

Figure 31: 3D model of the unfolding device

As mentioned previously, the most important aspect of the unfolding device was the perfect fitting with the protection container and the plastic hose. The critical part was therefore the exterior area (Figure 31, red). Due to the needed connection between printed part and the heating table of the printer the maximum size of the unfolding device was reached in the lower end of the exterior area. To reduce this unviable outcome of printing, this area was inclined to the inner side of the device (Figure 30, red). Therefore, if the 3D printer fabricated this overburden the device would not obtain a bigger radius than the now planed 62,5 mm. On the other hand, the same overburden produced by the printer evinced to be very helpful within the inner area of the device. Due to the slightly greater radius the device prevented the inner pipe from sliding through and holding it at the perfect location. Therefore, to amplify this effect an edge was planned, reducing the inner diameter for 2 mm, resulting in a fixed location of the inner pipe within the system. While preparing the unit for the development stage, it was noticed that the sharp edges on the upper part of the exterior area (Figure 18 and Figure 31, blue circle) tent to rip of parts of the plastic hose when more layers of hose reached the unfolding device at once, and therefore had to be smoothened manually. To avoid this effect and to reduce the manual interference with the unfolding device, the new 3D part had a continuous rounded shaped transition from the horizontal to the vertical exterior part (Figure 31, blue circle) (Annex IV).

In the development stage of the unit the folding of the plastic hose inside the protection container had been easy regarding the distribution of the plastic hose between the different container elements, because only two elements were used. The distribution of the 30 m plastic hose within four container elements, which was required for the real production prototype, was more difficult. Due to the fact, that the folding of the hose within the first and second element tent to be too slack and the folding within the fourth container was not possible anymore. Too much plastic hose remained for the last container.

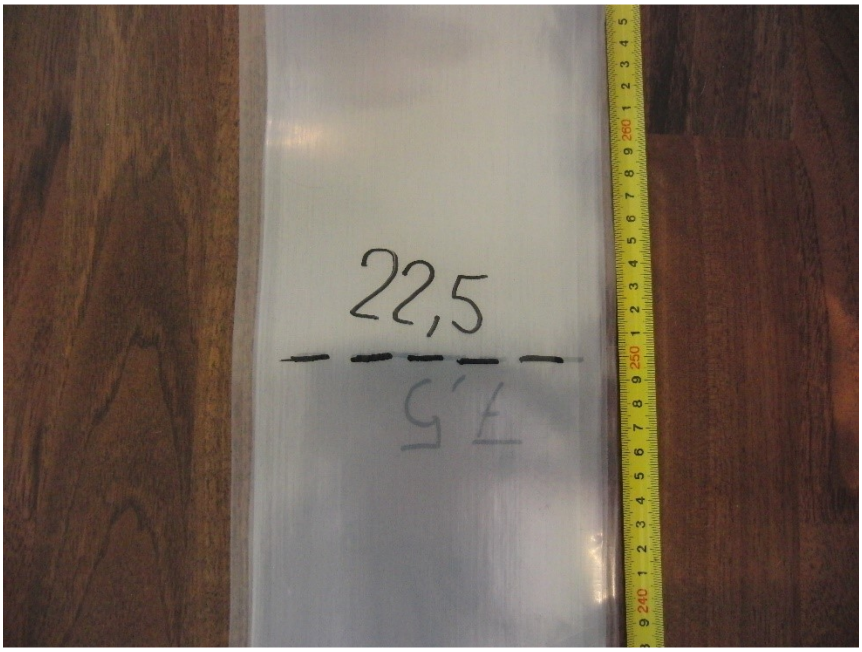

Figure 32: Section of 30 meter unfolded plastic hose

To reduce this effect three markers on 7,5 m, 15 m and 22,5 m were drawn onto the plastic hose, separating it to four 7,5 m long parts for each protection container element (Figure 32). As a result, the experimenter responsible for the folding of the hose knew exactly which part of the plastic hose belonged to which container. The protection container four was therefore not folded tenser than the other ones. Nevertheless, like mentioned in the folding experiments of the development prototype (Chapter 3.3.2.2.2, Page 23) the area between the unfolding device and the first meters of the plastic hose was very lax folded (Figure 33, blue) within the prototype. This prevented bigger bulks of plastic hose reaching the unfolding device and damaging the hose (Figure 33, red). The remnant of the plastic hose from protection container one, which was unavoidable because of the slack folding near the device, was allocated to the other three containers equally (Figure 33, starting at yellow).

Figure 33: First filled protection container of the production prototype

There was no difference in the completion of the connection of the unfolding device and the inner pipe between the prototype in the development and production stage (Section 4.2, page 23).

Comparable with the development stage, the connection of the protection containers was done similarly. The edges of the protection container were wrapped with cello tape to prevent any damage on the plastic hose while building the prototype. Furthermore, the container elements were taped with 3 layers of Duct Tape, leaving a gap of 1 cm between the elements to enable them to move slightly against each other. This created a more flexible prototype, which can maneuver in the borehole.

Attention had to be given to the connection between protection container and inner pipe. This connection was designed to fulfill two purposes. On the one hand it was the only connection between the container and the whole prototype including the charging hose. The protection container was a reusable part and therefore should be regained after the filling process. All forces, like friction of the borehole wall, stones sliding around the prototype and clamping in borehole joints, which could act on the prototype were received by the protection container. Hence this connection had to be reliable to protect the plastic hose inside and to prevent a decomposing of the prototype.

On the other hand, the risk of plugging the prototype between the borehole and plunging stones was present. Therefore, the Duct Tape should form a cylindrical link between inner pipe and container to facilitate the sliding of rocks to the side of the prototype (Figure 34).

Figure 34: Cylindrical connection between inner pipe and protection container formed by Duct Tape

Figure 35 describes the structure of the prototype. The green rectangle depicts the open plastic hose, in which a primer can be inserted before the prototype is lowered inside the borehole. The red rectangle shows the zone with the unfolding device and the area of the first protection container, in which nearly no plastic hose is folded. The light blue area indicates the area with lax folded plastic hose. The yellow rectangles are pointing out the maximum folded plastic hose zones. Purple areas depict the connection between containers linked with Duct Tape and a 1 cm gap for flexibility. The salmon color shows the connection area between inner pipe and protection container. Dark blue is the inner pipe poking out of the protection container. In this area the prototype is connected with the charging hose. The length of each protection container is 40 cm, the length of the open plastic hose (green zone) is 15 cm and the length of the inner pipe from the start of the pipe to the connection point of inner pipe and protection container is 10 cm.

Figure 35: Completed prototype for the first field test

3.7 First prototype field test

The goal of the first prototype field test on the Styrian Erzberg was to test the connection between the prototype and the charging hose of the matrix pumping unit. Furthermore, the unfolding process of the plastic hose caused by the emulsion of the pumping unit was tested. The behavior of the prototype inside the borehole was analyzed, if it was possible to lower the prototype inside the hole to the deepest part and raise it again without plugging. And how time consuming the utilization of the prototype was compared to the normal usage of emulsions. The test should also had depicted,

- if there was a difference between the blasting result applying the prototype compared with a normal blast,
- if the detonation velocity of the emulsion changed within the plastic hose,
- if the stability of the quarry face changed,
- if the grain size distribution of the blasted material had changed.

Additionally, the test should have displayed, weather the blast, supported by the plastic hose, may decrease the environmental impact of the operation or not. Was the implementation of the prototype reducing the vibration amplitude and frequency, the fly rock risk and the risk of undetonated boreholes or did it have no impact on the results.

To accomplish these goals, the Styrian Erzberg prepared a blasting plant consisting of one row of 20 boreholes. The holes had a diameter of 90 mm, a length between 25 and 30 meters and a burden of 4 meters. A prototype with a protection container length of 163 mm, filled with a plastic hose with a length of 30 m and a diameter of 90 mm, was developed to fulfill the default of the drilled boreholes.

To obtain an opportunity to compare blasts with and without the prototype, the first field test would blast 5 boreholes with the prototype together with 5 normal blasted boreholes. The remaining boreholes would be used for a second test to optimize the prototype and to refine the results of the project.

3.7.1 Surveying methods to analyze the blasting plant

Data Trap, BlastMetriX, GNSS surveyor, high speed camera, borehole camera, Pulsar probe, geophones, inclinometer and photos were used to describe the blasting plant and the blasting results.

3.7.1.1 BlastMetriX

BlastMetriX uses two displaced pictures to generate a 3D model of the rock, which has to be loosened by the blast. Combined with the curve data gained by the Pulsar probe the blasting plant can be simulated via computer and the blast can be optimized, concerning explosive consumption, the reduction of fly rock and prevention of remnant rock toes at the bottom area of the wall.

To accomplish the model four orientation markers (Figure 36, red, blue marker not visible) have to be placed to cover the blasting plant and the standpoints have to be surveyed via the GNSS system to upgrade the results to a global level. The markers have a reflective area on the side focused to the camera and are oriented with spherical levels. A Nikon camera is used to produce two displaced high-resolution pictures (Figure 36, purple). The displacement of the pictures is accomplished with five steps of the photographer to the left or right side. (3GSM GmbH 2017, p.3-21)

Figure 36: Making photos for the BlastMetriX system

3.7.1.2 GNSS surveyor

The GNSS surveyor measures a global point in x, y, and z coordinates using at least five satellites. Satellites use E5/L5 and E1/L1 frequency bands to communicate with the GNSS surveyor (Capuano V. 2017, p.333). To create correct results 500 measurements for every point were made and compared with correction data sourced by the national surveying institute.

The GNSS measurements are necessary to transfer the local data, gained by Pulsar probe, BlastMetriX, geophones and Data Trap, to a global level to enable an interaction between the informations.

Figure 37 describes the measuring set up. Red depicts the GNSS surveyor, which is in connection with at least 5 satellites. The operating computer receives the data from the GNSS surveyor and the correction data from the national surveying institute via internet and reworks them to a correct result. The length of the pole is clearly defined with 1,8 meters and oriented with a spherical level (green).

Figure 37: GNSS surveying

3.7.1.3 Pulsar probe

The pulsar probe is a measurement devise, capable to monitor its location in local 3D-space. It can depict the inclination and the geographical direction of the probe with preceded input options at the operating computer. Because the Pulsar probe measures points not a curve, it is declined to the lowest part of the borehole. Afterwards it is lifted in one-meter-steps with every point measured to create an approximation to the real curve of the borehole.

Figure 38 shows the measuring with the pulsar probe. Red depicts the operating computer, measuring the inclination, direction and position of every point. Blue shows the Pulsar probe at the launching point. In green is the connection hose with markers on every meter starting at the probe. Purple depicts the borehole labels to enable the connection of GNSS with Pulsar measurements.

Figure 38: Deployment of the Pulsar probe

To transfer the measured curve, with its inclination, geographical direction and length, into a national surveying system the launching point of the probe at the top of a borehole is measured via a GNSS surveyor. A clearly defined curve within 3D space is created.

The measurements depicted, that the borehole length of the blasting plant was between 29,2 and 25,7 meters. The deviation of the targeted drilling direction was minimal and the risk of explosive clustering due to converging boreholes was minimal.

3.7.1.4 Borehole camera

The borehole camera can be used to create anticipations about the borehole conditions. This was important for the project, because the gap length inside the borehole had to be measured to determine the impact of the unit on the filling process and the emulsion consumption. Furthermore, the risk of prototype plugging was existing, therefore the borehole was scanned for rocks, which could loosen at the filling process. Water would represent a problem for the prototype, so boreholes with a high water surface inside could be avoided and filled normally.

The inspection of the holes showed, that the first 3 to 4 meters of every hole had bad conditions and afterwards the rock was solid. Boreholes filled up to 12 meters with water existed and should be avoided by the prototype. In every hole was water to some extend and therefore the unit would be tested in water filled borehole conditions. The boreholes with the lowest level of water were chosen for the unit deployment.

Figure 39: Borehole camera recordings

Figure 39 shows the camera set-up with the borehole camera (red) connected to a hose (green), which is able to transport the camera data. The camera monitor (blue) shows live footage of the borehole conditions and the computer (purple) records the inspection.

3.7.1.5 Data Trap

MREL Data Trap is used to measure the explosion velocity inside a borehole. A conductive wire is lowered together with the bottom primer into the lowest part of the borehole and the hole is filled with the prototype or the normal way. Before the blast is conducted the Data Trap wire is connected to an electric circuit created by the Data Trap operating computer. The electrical resistance of the wire is constantly monitored by the computer. At the moment the bottom primer detonates and the detonation front moves from the bottom area to the top the wire gets destroyed by the blast. The shortening of the wire results in a decrease of electrical resistance and this decrease is converted by the computer to the velocity of the detonation front. (MREL 2017)

The Data Trap system should be used in a normally filled borehole and one filled with the prototype to compare the velocity deviations. Furthermore, it was possible to trigger the high-speed camera recordings with the Data Trap system.

3.7.2 Prototype test preparation

To achieve comparable results, boreholes blasted normally and with the prototype were required. The matrix mixing unit started obtaining consistent matrix compounds after the charging of one to two holes. The holes tend to have a higher explosive density between 0.9 to 1 $g*cm^{-3}$ in the first holes and a lower density of 0.8 to 0.9 $g*cm^{-3}$ afterwards. Both emulsion densities were perfectly fine to convert within a blast, but to gain constant conditions in the prototypes the mixing unit was used to fill the first boreholes normally. Afterwards, once the constant matrix density was reached, it should have filled the holes with the help of the prototype.

Figure 40: Matrix mixing unit preparations

The differentiation between the densities of the first two boreholes to the following once originates from the chemical gassing process. Acetic acid and ammonium hydroxide react with each other within the matrix and create micro gas bubbles. These bubbles increase the specific surface area of the emulsion and therefore increase the ability of the emulsion to react. This sensible ratio of reagents can deviate at the start of the mixing process, resulting in higher densities, because the chemical gassing works not perfectly until the system is warmed up. To ensure the flow of the reagents the pathways had to be controlled before every blast, since a plugging of the inflows could result in a lack of the chemical gassing process and a failure of detonation within the borehole (Figure 40, left). Furthermore, the components necessary to operate the mixing unit had to be refilled. Emulsion (Figure 40, right), provided by Austin Powder GmbH, was the explosive for the blast. The emulsion had a filling temperature of 18°C. Acetic acid and ammonium hydroxide were the chemical gassing reagents and water had to be used to sluice the matrix pumping unit during work discontinuities and after the working process.

To monitor the gassing process within the emulsion several cup tests had to be conducted. (Figure 41) A cup with known weight and volume was filled with emulsion sampled from the charging hose. This emulsion included both reagents and therefore the gassing process started at the second the emulsion reached the cup. The emulsion poking out of the cup was removed and the weight of the cup was measured. Since the gassing process increased the volume of the emulsion, due to the created gas bubbles, the emulsion expanded and poked out of the cup again. After a specific time, this overburden could be removed again and the cup was weighted once more. This working step was performed repeatedly over two hours and the degradation of weight was recorded. As the weight and volume of the cup was known, a direct conclusion about the density of the emulsion and a progression of the density was made.

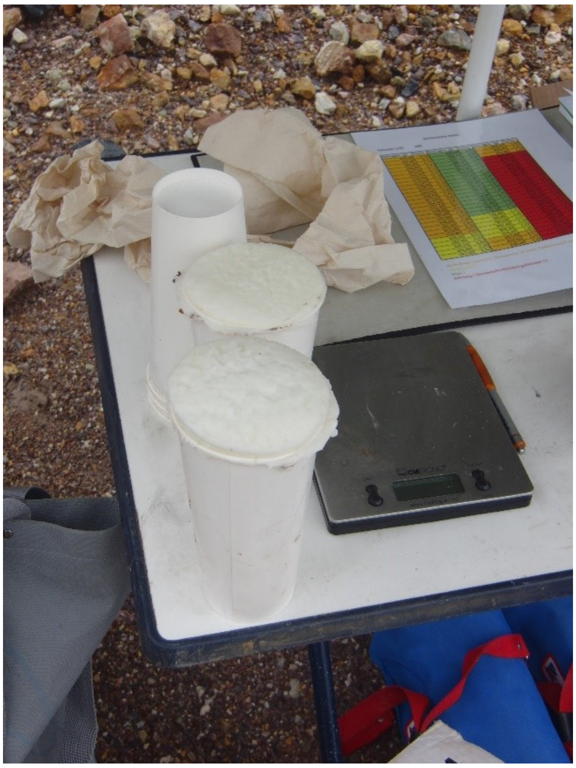

Figure 41: Photo of the working place of the cup test

While performing the filling process with the mixing unit the normal way, especially after consideration of the rather bad borehole conditions within the first three to four meters of the borehole the decision was made to reinforce the Duct Tape connections of the prototype furthermore. The link between the protection containers was extended with two layers of new Duct Tape on each side of the linking one, enfolding the Duct Tape on the one side and the protection container on the other. This procedure led to a doubling of the connective area between protection container and Duct Tape, and as a result to a reinforcement of the linkage between the containers (Figure 42, green). Furthermore, the contact of inner pipe and protection container was enhanced (Figure 42, red). The Duct Tape stripes proceed only alongside the inner pipe, connecting it with the container. This array of bands seemed to be susceptible of losing strings due to friction with the borehole wall. Therefore, two 90° displaced bands of Duct Tape were added to the linkage to improve the cohesion of the system.

Figure 42: Five prototypes ready for the testing process

3.7.3 Test implementation

The first goal of the test series was to validate the connection between prototype and charging hose. The inner diameter of the charging hose was 19,6 mm and the inner diameter of the inner pipe was 19 mm. Due to the nearly same diameter of the two hoses it was not possible to pull on of them over the other one. The same diameter of the two hoses was essential to guarantee a constant matrix flow and to avoid a bottleneck, in which the matrix would be forced through. A bottleneck would had increased the pressure within the matrix pumping unit, because more force had to be applied to move the matrix within the prototype. Such pressure should be avoided to ensure no damage within the matrix pumping unit and to alter the chemical reaction of the matrix.

Furthermore, a connection via form fit should be evaded, because the link between prototype and charging hose was the predetermined breaking point of the system. The risk of plugging the prototype within the borehole was present, hence there must be a possibility to salvage the expensive charging hose. With a form fit connection this would not been possible and therefore such a link was unfavorable.

To ensure a conjunction via tight fit a one-inch tube was used (Figure 43, blue). The tube was pulled on the inner pipe (Figure 43, purple) as well as the charging hose (Figure 43, yellow) and fixed with a clamp on each side. The tube enabled the matrix to stream from the charging hose (Figure 43, red) to the inner pipe. The clamps created a tight fit connection, linking the prototype to the tube and therefore to the charging hose. With this kind of linkage, the savage of the charging hose would had been possible. Since powerful traction force exerted on the charging hose would had detached the tight fit conjunction and only the prototype would be lost.

Figure 43: Test setup for the connection test between prototype and charging hose

At the start of the test the tube connection worked fine (Figure 44, 1). The pressure indicator on the matrix pumping unit depicted the normal working pressure of 8 bar. Matrix streamed out of the inner pipe into the not closed plastic hose and the system seemed to work fine. After several seconds though, the pressure inside the pumping unit grew, indicating an operating pressure of 18 to 20 bar (Figure 44, 2). Among this pressure conditions the connection between tube and plastic hose failed and the prototype separates from the charging hose (Figure 44, 3-4).

Figure 44: Picture sequence of the first connection test

The first consideration why the tube connection was failing, was that the clamps are twisted together too slightly and therefore were not able to withstand the pressure building up in the system. As a result, more clamps were deployed and screwed vigorous, making the tight fit linkage stronger. On the other hand, the deployment of more clamps limited the savage of the charging hose in case of prototype plugging inside the borehole.

Several tests adding clamps and closing the plastic hose in the front were conducted, leading to the final insightful experiment. The prototype, with a closed plastic hose in the front, was forced with three tense screwed clamps inside the one-inch tube and on the other side the charging hose was connected with four clamps in the tube. This linkage was too reliable to be considered a predetermined breaking point (Figure 45, 1 yellow and blue). The plastic hose was filled with matrix from previous tests, but this did not affect the outcome of the experiment. The matrix pumping unit was started and a perfect unfolding process was noticed. The unfolding stops and the pressure increases to 14 bar (Figure 45, 3), but after several seconds the mechanism resumes and the pressure decreased again. Without prominent warning, like pressure increase or a stop of unfolding, the connection within the charging hose failed (Figure 45, 5).

It had to be noticed, that the tube linkages were reliable, but the charging hose failed. The static mixer, which was responsible to mingle the acidic acid inside the matrix, was separated from the rest of the charging hose. The static mixer was linked with a crew thread inside the rigid plastic of the charging hose, generating a semi form fit connection.

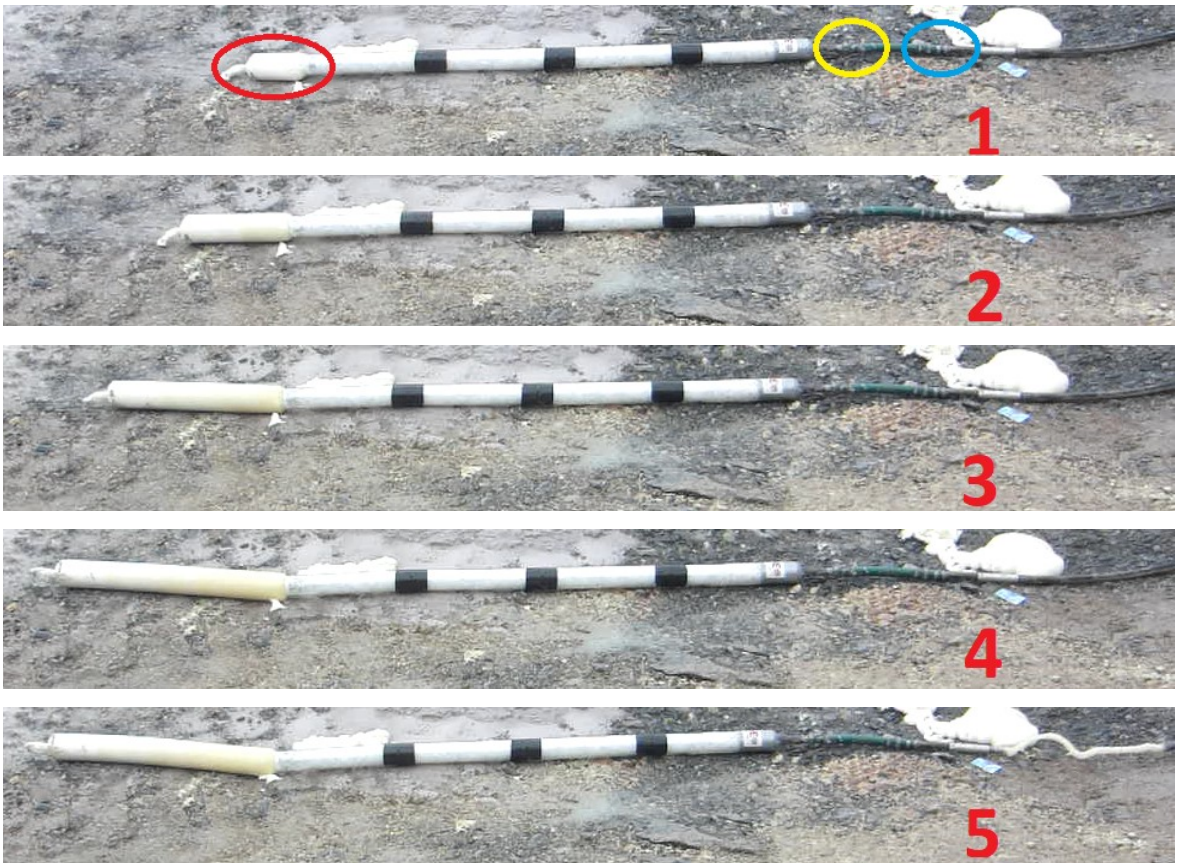

Figure 45: Picture sequence of the last connection test

The test of the tube supported connection was unsuccessful and the linkage between the prototype and the charging hose had to be reconsidered. The reason why the system failed and the pressure increased to uncontrollable magnitude was the friction between the matrix and the inner pipe, while the matrix streamed through the prototype. During the matrix movement through the charging hose the acidic acid embraced the explosive and acted as a lubricant within the hose. At the end of the charging hose the static mixer mingled the acid inside the matrix, starting the chemical gassing process. Afterwards while the matrix was moving through the inner pipe no lubricant was available anymore and the friction within the 190 mm long pipe caused a pressure increase of up to 20 bar, leading to a failure of the predetermined breaking point or even charging hose.

To prepare a tight fit connection was no possibility, because the charging hose linkages failed once the bond between prototype and charging hose became too strong. Furthermore, the high pressures would harm the pumping unit and therefore the design of the prototype had to be changed.

The new approach was, to conduct the charging hose through the prototype, letting the hose end at the unfolding area of the plastic hose. With this design the movement of matrix through the inner pipe, without lubricant, would be bypassed and the only possible pressure increase would emerge from the unfolding process of the plastic hose. The inner pipe had to have a lager diameter to be able to include the charging hose and therefore less space was available to store the plastic hose within the prototype.

While the connection test of the prototype was not successful, more tests could be executed at the quarry site. One of the most imminent risks was the plugging of the unit within a borehole. To test whether plugging occurs or not, a prototype was fixated at a rigid plastic hose used for high pressured air transportation (Figure 46). The prototype was lowered inside the borehole and the sound of stones falling down the hole because of the movement of the prototype was noticeable. After reaching the bottom of the borehole, the prototype was raised again. While raising no significant traction force was required and it was possible to salvage the prototype without problems.

Figure 46: Prototype connected via one-inch tube with a rigid plastic hose, used for high pressured air transportation

As a result, it could be claimed, that the prototype was capable of moving within the borehole hassle-free even if small stones were falling on top of the prototype.

To test the behavior of the prototype with water filled boreholes, the same test set-up used for the plugging test (Figure 46) was lowered inside a 27,6 m long hole, which was filled with water starting at 13,5 m. The movement of the prototype until the 13,5 m mark was once again hassle-free. Reaching the water surface, the motion stops and the prototype did not immerse inside the water-mud blend. The density of the plastic produced prototype and the air captured inside the folded plastic hose area, prevented the system from sinking. Furthermore, the diameter of the prototype was 70 mm and the borehole had a 90 mm one, which did not leave much space for the water-mud slurry to bypass the prototype. To reinforce the stagnant sinking process, a propulsive power was exerted by the experimenter via the rigid plastic hose. The experimenter, having a weight of roughly 80 kg, stemmed with all his strength against the plastic hose and was able to sink the prototype 1,5 m inside the mud-slurry. The rigid plastic hose was not stiff and therefor a lot of introduced propulsive power converted to deflection of the hose, not reaching the prototype at all. Further it was noticed, that the prototype was not moving towards the 13,5-meter mark of the borehole again, which would be expected due to the low density of the system. The prototype plugged inside the water-mud bend and normal traction force was not capable to lift it again. A strong traction force unlocked the predetermined breaking point of the one-inch tube, like it was planned for the charging hose, and the rigid plastic hose was salvaged. The prototype was lost and the borehole cannot be used for the blasting anymore.

3.7.4 Conclusion of the test series

The connection via one-inch hose was not applicable for the prototype. A new linkage, leading the charging hose through the inner pipe to the unfolding area, was planned and would be implemented for the next test series.

The unfolding device worked perfectly. A slight traction force was capable to unfold the plastic hose. No matrix penetrates the internal space of the prototype, in which the plastic hose was stored. Therefore, the matrix only interacted with the unfolded plastic hose and could not intervene with the unfolding process inside the prototype. No bulks of plastic hose reached the unfolding device; hence no plugging of plastic hose was possible. The plastic hose departed from the unfolding device in a single skein undamaged by the device or protection container.

The prototype was capable to move inside a borehole hassle-free, even if small stones were falling on top of the prototype. Therefore, the cylindrical connection from inner pipe and protection container will be retained.

The predetermined breakage point on the one-inch tube worked, and it was possible to salvage the charging hose or rigid plastic hose if plugging of the prototype occured.

The prototype with its low density was not suited for the deployment in boreholes filled with a water-mud slurry. The prototype tent to adhere inside the blend and could not be moved anymore. Therefore, the borehole must be pumped out before the prototype can be used.

3.8 Improvement of the unit for the second field test.

3.8.1 Limitation factors and final dimensioning

Limitation factors:

- Borehole length at the Erzberg site is between 25 and 30 m, which is longer than the borehole length of 15 to 20 m mentioned in the definition of tasks.
- Borehole diameter is 90 mm. The boreholes are in bad conditions in the first 5 meters but afterwards the holes are in good shape. Because of heavy rain 1/3 of the remaining boreholes collapsed and have to be opend.
- 10 boreholes should be blasted. Of those 4 with the LWC unit. The fifth unit includes only one container and is designed for the connection test between unit and charging hose.
- Because of heavy rain all open boreholes are filled to at least 2/3 with water. This water must be pumped out before deployment of the LWC unit.
- Temperature at the Erzberg side is above 14°C.

Final dimensioning:

- Protection container diameter is 70/65 mm and the length is 40 cm. 4 elements are lined up with 1 cm gaps between them closed by Duct Tape. Protection container length together is 163 cm
- Inner pipe diameter is 32/31 mm and the length is 190 cm. With this diameter increase the charging hose is able to slide through the inner pipe.
- Stored Plastic hose has a diameter of 90 mm and a length of 30 m. Because the hose is folded even stronger the LWC unit lost most of the flexibility.
- The unfolding device has an outer diameter of 62,5 mm made out of PLA.
- Charging hose will be guided through the inner pipe leading to the envelopment area of the unit. It will be fixated with one clamp in the envelopment area and Duct Tape on the other side of the prototype.
- Predetermined breakage point clamp, which holds the charging hose in the envelopment area. If it is not screwed strong it can easily slip off.

3.8.2 Change in inner pipe dimension

The new idea of connecting prototype with charging hose was to insert the hose into the inner pipe. This would reduce the friction between inner pipe and emulsion, because the emulsion remained in the charging hose lubricated by the reagent. To accomplish this goal, the inner pipe diameter had to be increased to an extent, that the charging hose fit into the inner pipe. The space inside the protection container was limited, hence tests were conducted to depict the repercussion on the prototype by the inner pipe increase.

Figure 47: Components used for the inner pipe diameter tests

Two new diameters for the inner pipe were tested. The inner pipe with an outer diameter of 32 mm would result in a connection, in which the charging hose beardly fit in the pipe. The 45 mm pipe would had left some space to move for the charging hose. The plastic hose had marks at the length of 5 m, 6 m and 7,5 m to depict the change in prototype length while changing the diameter of the inner pipe. If only 5 m of plastic hose were fitting inside the protection container (Figure 47, both 70/65 mm diameter) 6 elements were required to store it. 6 m would had led to a prototype with 5 container elements and 7,5 m would had indicated that the prototype length would had remained the same.

To help the experimenter while folding a device was constructed, having a 120° curved surface with an outer radius of 32 mm and an inner radius of 23 mm. This device was produced via a 3D plotter and composed out of PLA material. The plastic part was fixated on a 30 cm long stick to enable the experimenter to stuff every winding of folded plastic hose in the deepest area of the container. To store the hose with this technique was very time consuming, because every winding had to be stuffed separately and the experimenter had to change the grip between hose and device several times while storing one winding.

The charging hoses were filled 10 times with plastic hose using the device and the results were confronted. Using the 32 mm diameter inner pipe nearly 7,5 m of hose could be stored, while 6 m of plastic hose could be stored using the 45 mm one (Figure 48).

Figure 48: Comparison of storage possibilities using a 32 mm diameter inner pipe (top) and a 45 mm inner pipe (bottom)

Only 12 cm of plastic hose remained outside the container using the 32 mm inner pipe. Because the containers were not connected directly, but a gap of 1 cm was between every element, the storage possibilities for the remaining 12 cm of hose existed too. Even if the first container near the unfolding device was packed lightly it was possible to store 30 m of plastic hose within 4 container elements using the 32 mm inner pipe.

The usage of the 45 mm inner pipe would had led to 5 elements and a protection container length of 204 cm with an inner pipe length of 230 cm. This was an unpractical length for transportation and utilization.

Therefore, the 32 mm diameter inner pipe was used for the new prototype. The fitting of the charging hose inside the pipe was tight, hence the hose would have to be cleaned from mud and small stones before inserting it into the inner pipe.

3.8.3 Prototype production

The protection containers used for the first real site tests coud be reused for the second one. 4 prototypes were produced for the 30 m long boreholes and 1 prototype had one container element to test the new connection between charging hose and prototype.

The unfolding device had to be redesigned to fit together with the inner pipe. The dimensions of the outer diameter of the device had been satisfying and were retained for the new one. The inner diameter was changed to 31 mm to embrace the inner pipe (Figure 49) and the 2 mm diameter reduction at the bottom area of the inner diameter was keeping the inner pipe in place (Annex V).

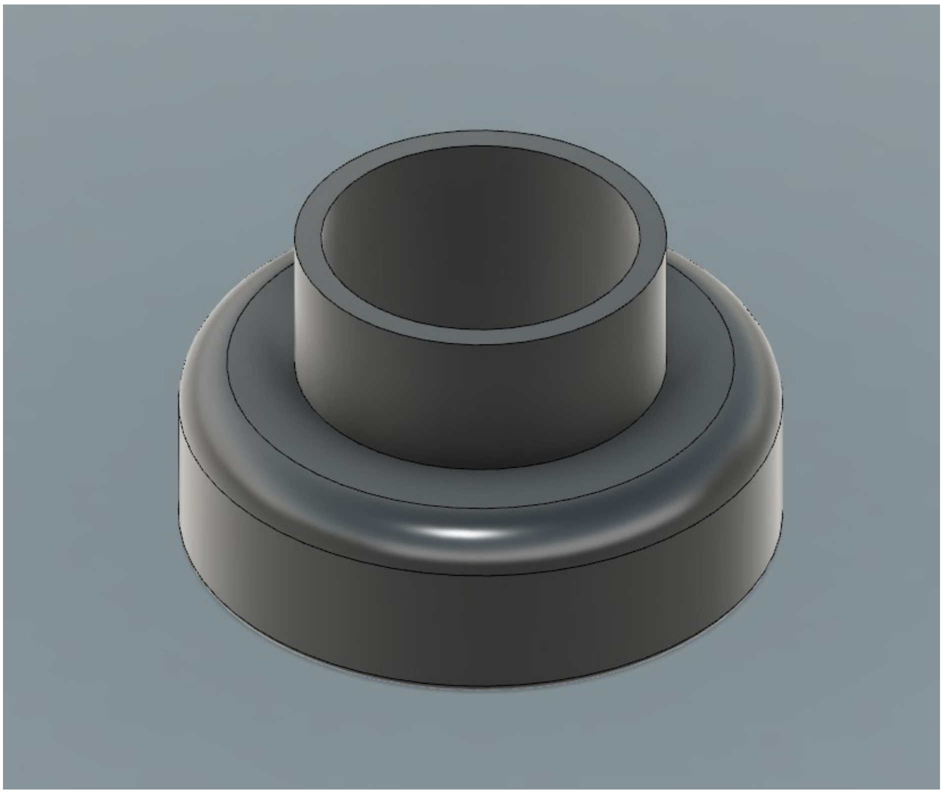

Figure 49: Computer model of the third unfolding device (Annex V)

The ABS material exposed as not more beneficial as the PLA one. Due to the redesign of the unfolding device of the unfolding tests (Chapter 3.6.2, Page 51) the manually finishing processes via abrasive paper were minimal. Because the production of ABS device was more expensive and the production time was longer, due to the difficult connection between 3D printer plate and the printed part, the decision was made to return to the PLA printed unfolding device.

The benefit of the higher temperature resistance of the ABS material was negligible at the Erzberg site in September, because temperatures are normally in the range of 18° to 15°.

Figure 50: Unfolding device made out of PLA material

The assembly of the new prototype was similar to the one used for the first field test (Chapter 3.6.2, Page 51), with slight differentiations.

While dismantling the prototype from the first test, it had been noticed that the plastic hose cleaved on the Duct Tape, used to connect the container elements. This effect had been underestimated, because the assumption was, that only parts of several windings would contact the Duct Tape dividing the adhesion forces among themselves, resulting in low adhesion forces overall. But the dismantling disproved this theory, requiring more manual force to pull the plastic hose out of the container when the windings near the connection area of two container elements started to unfold.

To limit the adhesion effect near the connection area cello tape with lower adhesive power was attached in 3 cm slices around the 1 cm gap between two container elements before the Duct Tape created the connection between these elements. Therefore, the plastic hose never contacted the Duct Tape.

To improve the transition of the plastic hose through the unfolding device out of the protection container into the borehole the first container element was abraded in the front area on the inner side to soften the sharp edge of the container. This area had never represented a problem in the previous tests, but the extended protection of the plastic hose improved the overall performance of the prototype (Figure 51, red).

Figure 51: Front side of the first protection container element

The behavior of the prototype changed with the new folding technique using the stuffing device for every winding. The package of the hose became heavily compacted. The prototype lost nearly all his slight flexibility even though having a 1 cm gap between every container element. Due to this effect the connection between the elements was increased to 7 layers of Duct Tape, because the flexibility was unneglectable and the connection strength increased furthermore.

Figure 52: 4 Prototypes for the deployment in a 30 m borehole, 1 prototype for the connection test between charging hose and prototype

Figure 52 describes the new prototype. Blue depicts plastic hose used for the envelopment zone of the primer folded back onto the first protection container to enable the blast team to fixate the charging hose at the front of the prototype. Green shows the connection area between two container elements. 3 layers of Duct Tape are directly on the 1 cm gap; 3 layers of tape are displaced by half to increase to connection area of tape to container; 1 layer of tape is directly over the gap again closing the 6 underlying Duct Tape layers. In red are 2 layers of Duct Tape each to increase the stability of the connection Protection containers to inner pipe.

3.9 Second prototype field test

The connection between the charging hose and the prototype had been tested in the first field test and found not sufficient. Therefore, this connection had to be readjusted for the second test.

Most of the goals of the first field test (Chapter 3.7, page 59) had not been tested, because they builded up on the operational capability of the prototype. The connection of charging hose to prototype had failed and as a result the required capability had not been reached.

The goal of the second field test was to reach an operational capability with a renewed charging hose connection and to fulfill the goals of the first test. Because the goals of the first test had been essential and ambitious no more goals were added for the second test.

The behavior of the prototype had been tested in the first test and the result had been satisfying, therefore this goal of the first test series had been reached and was not covered in this test series.

To conduct the second test, the remaining blasting plant at the Erzberg site was used. The boreholes with the number 11 to 20 are undamaged by the blast of the first test and can be used for the second one. Some of them collapsed and had to be opened again.

3.9.1 Test implementation

While preparing and surveying of the blasting plant with the Pulsar probe and the borehole camera, a collapse of many boreholes due to bad weather conditions in September at the Erzberg site was noticed. Only five boreholes in a row without collapsed holes between them remained. These holes were filled to two-thirds with water. The pumps used by the VA Erzberg company to drain the water out of the boreholes could be used for the prototype test plant, because the borehole diameter of 90 mm was smaller than the normally used diameter.

Ordering of a pump with a static suction lift of 30 meters would have been too time consuming, since the temperature decline in September was fast and the matrix pumping unit was not operational under 14°C.

Figure 53: Draining a water filled borehole with compressed air

At the current state of the unit development an application in water filled boreholes was not possible, like the first real site test had revealed (Chapter 3.7.3,Page 68). Therefore, the approach to remove the water was to push it out with compressed air, guided by a compressed air hose to the deepest part of the hole (Figure 53).

The attempt to drain the water failed. It was possible to drain one half of the borehole water, but the remaining half accumulated at the borehole wall, flowing downwards at the moment the compressive air inflow stopped. Furthermore, the abrupt inflow of air detached stones out of the borehole wall, resulting in a collapse. Several tries to drain the holes were made, but the only consequence was the loss of two out of five boreholes.

The in-hole prototype test was not possible under these weather and borehole conditions, therefore only the connection between prototype and charging hose was tested. The charging hose was flushed with water and afterwards filled with matrix, before the attachment to the prototype was done, hence no air was in the hose to affect the test. After the complete filling of the charging hose with matrix it was put through the inner pipe and fixed with a clamp in front of the unfolding device to prevent the sliding of the prototype from the hose (Figure 54, top). On the back end of the prototype the connection with the charging hose was accomplished with several layers of Duct Tape to prevent an upwards movement of the prototype along the charging hose under the pressure of unfolding (Figure 54, bottom). The envelopment area was closed with cable ties without a primer inside.

Figure 54: Connection of the charging hose with the prototype

After start of the matrix inflow the envelopment area got filled with matrix completely. The rinsing water, used to clean the inside of the charging hose, which remained in the envelopment area was supplanted to the inside of the prototype in the folded plastic hose area. No matrix bypassed the unfolding device and the rinsing water did not influence the unfolding of the plastic hose windings. After the envelopment area was filled completely the traction force, accomplished by the matrix inflow, unfolded the plastic hose and the envelopment area expanded. At the beginning the plastic hose windings start to unfold near the unfolding device. With continuous unfolding the unfolding migrated from the unfolding device to the subjacent windings, leaving an area with no windings between unfolding device and packed plastic hose. It occurred, that two overlying plastic hose windings reached the unfolding device, but the bypassing of them through the device worked perfectly without damaging them.

At the end of the test rinsing water got fed in the charging hose to clean it. Most of these water remained inside the envelopment area, but a fraction bypassed the unfolding device depositing in the inner side of the prototype.

Figure 55: Summary of the connection test between charging hose and prototype

The test was a success and the connection via leading the charging hose through the inner pipe to the envelopment area of the prototype could be inherited for following tests.

The filling of a plastic hose with matrix outside the borehole had benefits, because the behavior of the matrix could be studied. Instantly, after the prototype was separated from the plastic hose, a black Duct Tape was placed on the spot where the matrix filling ended and the rinsing water was removed from the plastic hose.

After only 2 to 3 minutes a clear increase in matrix volume was noticeable (Figure 56). After 40 minutes the experiment was ended because the expansion stopped. The result was an increase of approximately 25 cm for a 3 m long plastic hose filled with matrix. A lot of gas bubbles were created in the expenditure zone.

The behavior inside the plastic hose was interesting too. While in the area with an open envelopment area the matrix tent to expand along the hose direction increasing the length and creating clear gas bubbles inside the matrix, the matrix near the closed plastic hose expanded in a radial direction with a high density and a low amount of gas bubbles. This radial extension led to a deformation of the plastic hose and to a protrusion near the 1 m mark (Figure 57). This effect would had been attenuated inside the borehole, because the hose would had been in connection with the rock, which would had absorbed most of the radial stresses.

Figure 56: Strat (top) and finish (bottom) of matrix expansion inside a 3 m long plastic hose

Figure 57: Protrusion near the one-meter mark, starting from the closed part of the hose

3.9.2 Conclusion of the test series

The connection between charging hose and prototype worked perfectly, guiding the charging hose through the inner pipe in the envelopment area. The unfolding device was capable to hold the matrix in the envelopment area, but allowing water inside the inner area of the prototype. The leaked water did not influence the unfolding process inside the prototype. The unfolding of the stored plastic hose started at the unfolding device and progresses in the inside of the prototype. This left no risk of unfolding many hose layers at once, which would have led to a too small plastic hose length for the calculated borehole.

The plastic hose withstood the expansion of the emulsion, but deformations occurred if the hose was on its own not supported by surrounding rock. With an open plastic hose, the matrix was capable to start the gassing process expanding in the hose direction and creating the necessary gas bubbles for the blast. The expansion rate of matrix inside a plastic hose amounted 8,3% in length.

The prototype required dry borehole conditions, otherwise it could not be lowered to the deepest parts of the borehole.

The plastic hose filled with matrix could withstand the connection with rock surface, not bursting on the sharp edges of the rock.

4 Bibliography

3GSM GmbH: BlastMetriX 3D Bench face surveying and blast planning using 3D images, ref. num.: BMX_Info_en_v4.0 (2017)

Capuano V. et al.: High accuracy GNSS based navigation in GEO, in: Acta Astronautica 136 (2017) p.332-341

Chacon J.M. et al.: Additive manufacturing of PLA structures using fused deposition modelling: Effect of process parameters on mechanical properties and their optimal selection, in: Materials and Design 124 (2017) p.143-157

Executive Agency for Small and Medium-sized Enterprises: 730294 – SLIM -H2020-SC5-2016-2017/H2020-SC5-2016-OneStageB (2016)

Farah S. et al.: Physical and mechanical properties of PLA, and their functions in widespread applications – A comprehensive review, in: Advanced Drug Delivery Reviews 107 (2016) 367-392

Feng X. et al.: Reinforcing 3D printed acrylonitrile butadiene styrene by impregnation of methacrylate resin and cellulose nanocrystal mixture: Structural effects and homogenous properties, in: Materials and Design 138 (2018) p.62-70

Hirayama D. and Saron C.: Morphologic and mechanical properties of blends recycled acrylonitrile-butadiene-styrene and high-impact polystyrene, in: Polymer 135 (2018) p.271-278

Ivanova R. et al.: ContBlast Charging Unit Final Report (2011)

Jorda-Vilaplana A. et al.: Surface modification of polylactic acid (PLA) by air atmospheric plasma treatment, in: European Polymer Journal 58 (2014) p.23-33

Moser P. and Ouchterlony F.: A device, charging unit and method of filing a borehole with a explosive material, in: European patent office / European Patent Application / Application number: 07010995.4 (2008)

Murariu M. and Dubois P.: PLA composites: From production to properties, in: Advanced Drug Delivery Review 107 (2016) p.17-46

MREL Group of Companies Limited: Data Trap II Data/Vod Recorder Operations Manual Edition 5.4 (2017)

Research and Innovation – Participant portal: Call H2020-SC5-2016-2017, Topic H2020-SC5-2016-2017, Proposal number 730294, Proposal acronym SLIM (2016)

Song Y. et al.: Measurements of the mechanical response of unidirectional 3D-printed PLA, in: Materials and Design 123 (2017) p.154-164

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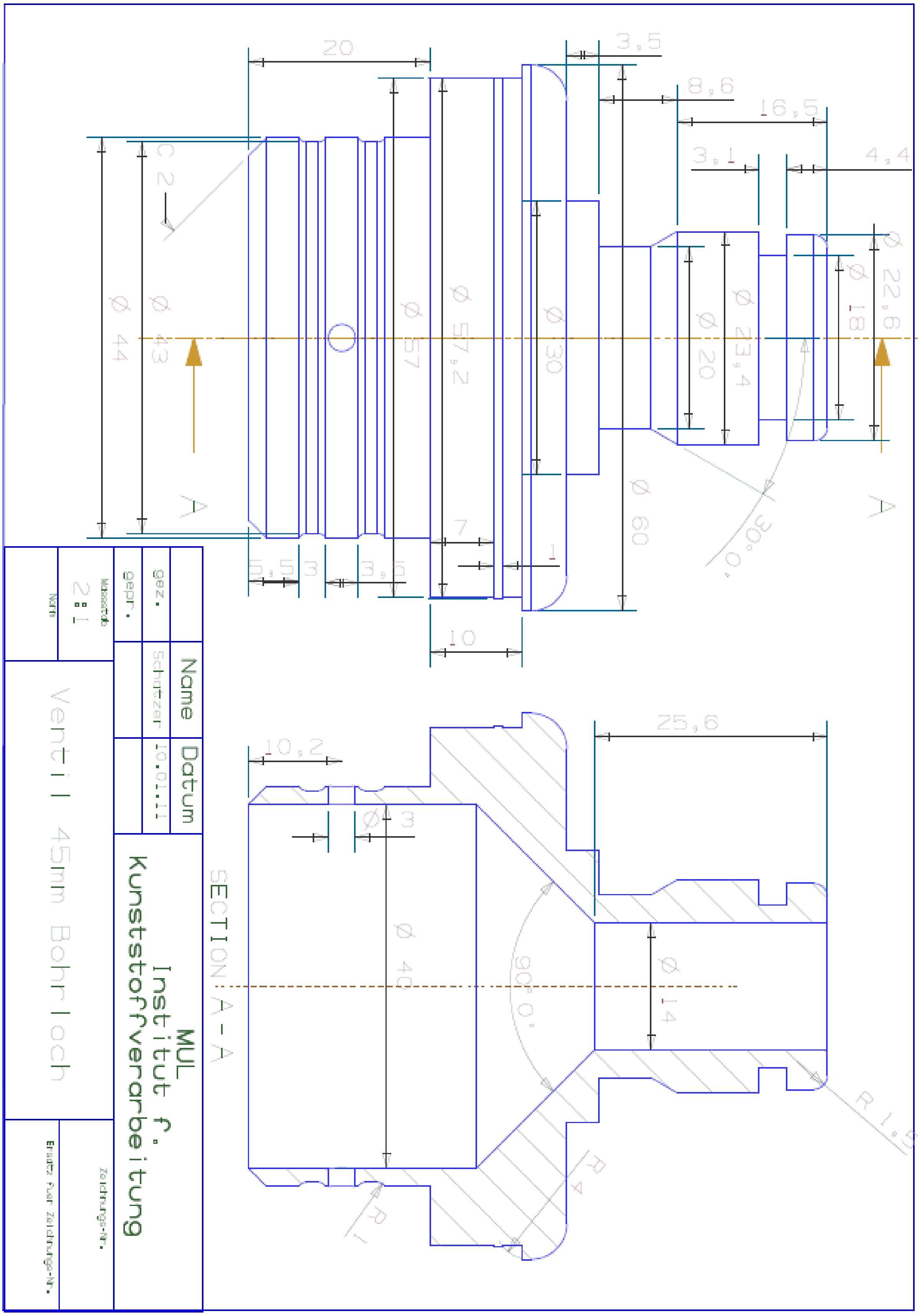
6 List of Tables

7 List of Abbreviations

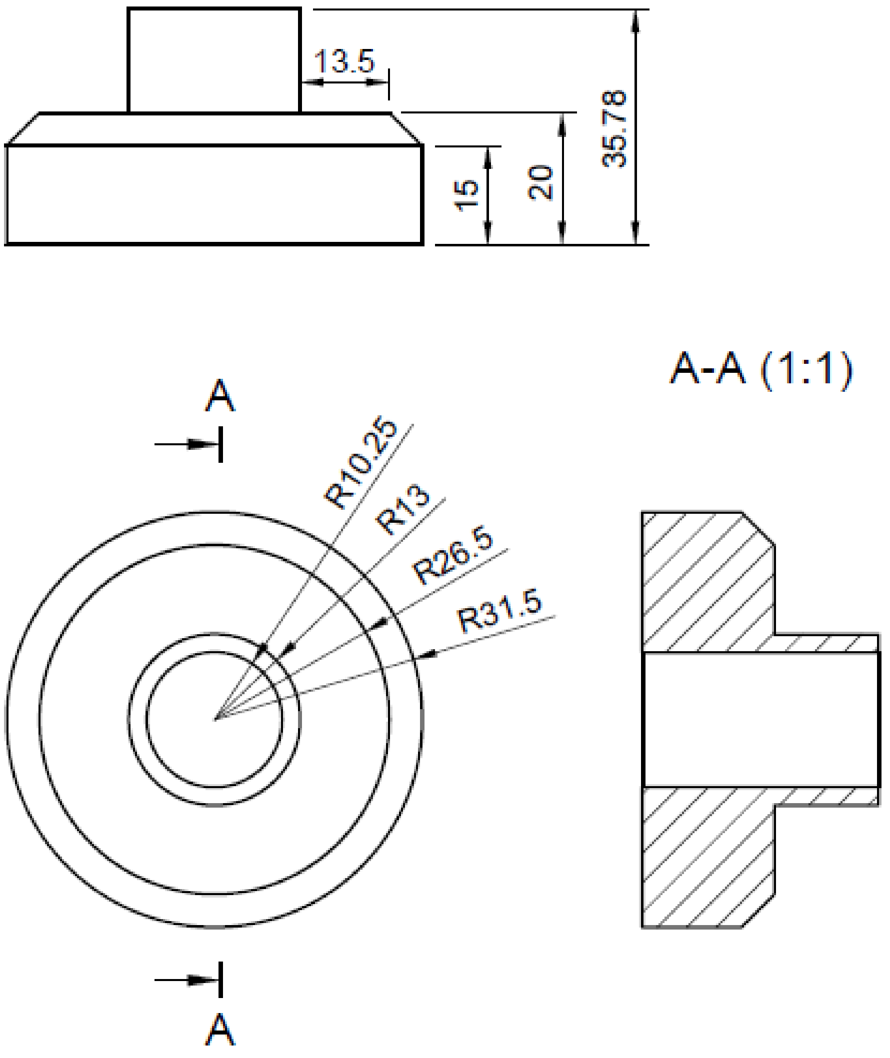
ABS	Acrylonitrile Butadiene Styrene
LWC	Lining while charging
SLIM	Sustainable Low Impact Mining
PLA	Polylactic Acid

Annex Table of Contents

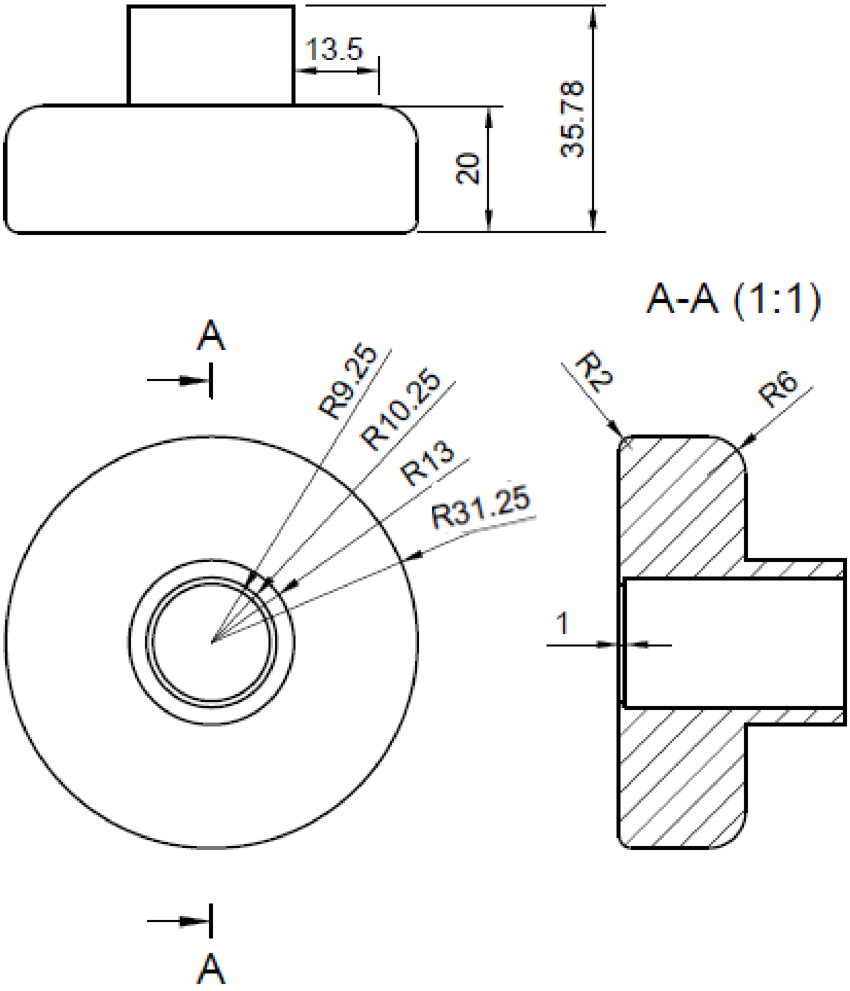
Annex



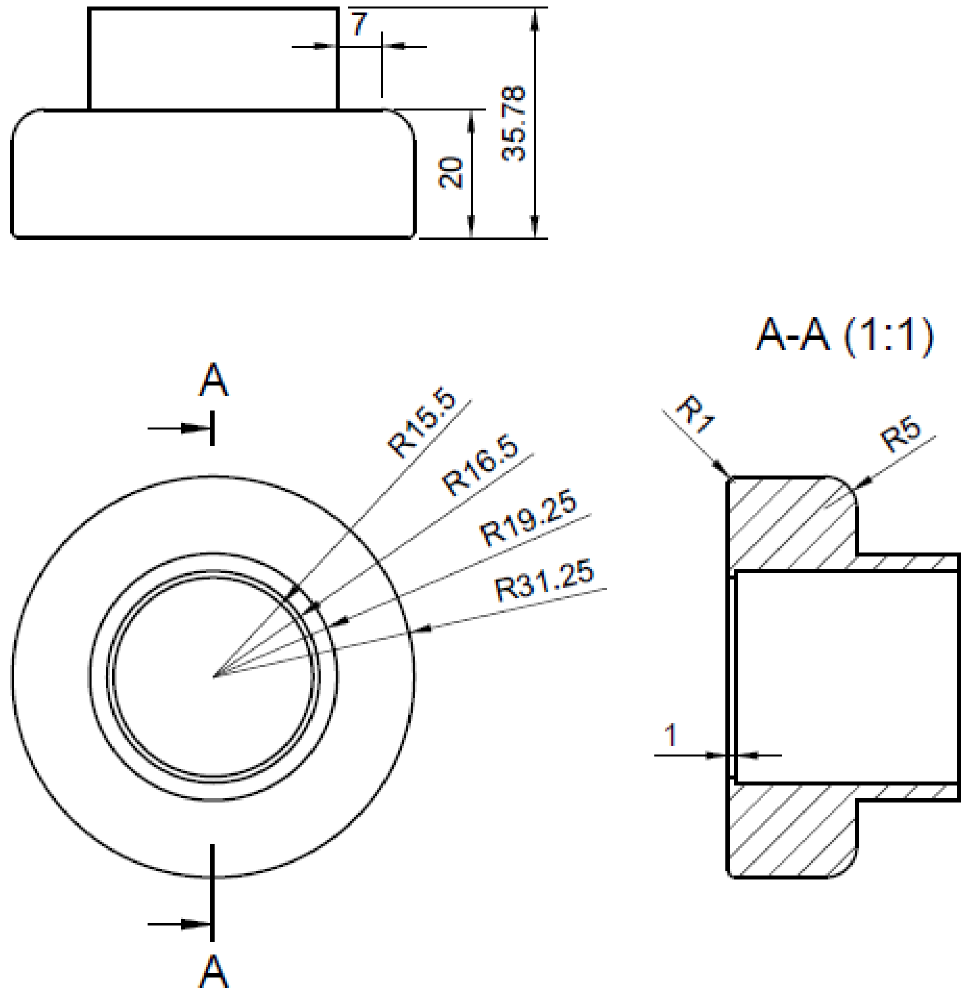
Drawing 1: Valve of the ContBlast Unit



Drawing 2: First unfolding device. Unit of dimensions in mm



Drawing 3: Second unfolding device. Unit of dimensions in mm



Drawing 4: Third unfolding device. Unit of dimensions in mm