Biogas Upgrading

Using amine absorption

Jónas Þór Þórisson

Final thesis for B.Sc. degree in
Energy- and Environmental Engineering
Faculty of Electrical and Computer Engineering
School of Engineering and Natural Sciences
University of Iceland

Keilir
Tæknifræði

HÁSKÓLI ÍSLANDS

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24 ECTS thesis submitted in partial fulfillment of a *Baccalaureus Scientiarum*
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Advisors

Egill Þórir Einarsson
Krista Hannesdóttir
Nicolas Marino Proietti

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Faculty of Electrical and Computer Engineering
School of Engineering and Natural Sciences
University of Iceland
Grænásbraut 910
235 Reykjanesbær

Phone number: 578 4000

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Útdráttur

Hreinsun á lífgasi er nauðsynlegt skref til að auðga lífgas í metan. Þetta ferli eykur orkuinnihald gassins miðað við rúmmál. Metanið er svo notað annaðhvort sem eldsneyti á bifvélar eða dælt í gas kerfi.

Markmið þessarar skýrslu er að hanna einfalda hreinsunarstöð sem tekur einnig lítið pláss með notkun á monoethanolamine (MEA). Þessu kerfi er svo ætlað að þjóna sem hagkvæmur kostur fyrir minni metanframleiðslur á Íslandi, líkt og bóndabýli eða lítil samfélög. Mikilvæg atriði í hönnuninni eru að hún sé lítil um sig, er einföld og hagkvæm.

Í þessari skýrslu mun koma fram hönnun á hreinsunarsúlu fyrir kerfið. Hönnunin verður svo staðfest með því að byggja frumútgáfu af kerfinu og það svo prófað á ruslahaugunum hjá Sorpu í Álfsnesi. Öll gögn við tilraunina verða skráð svo hægt sé að áætla færni kerfissins við að hreinsa metan og meta hvort breytinga á hönnuninni sé þörf.

Abstract

Upgrading of biogas is a necessary step to upgrade biogas to bio methane. This procedure increases the energy content of the gas per volume. Bio methane is then used as vehicle fuel or injected into a gas grid in other countries.

The main goal of this report is to design a simple and compact upgrading unit using monoethanolamine (MEA). This unit is then intended as a cost effective solution to methane production for smaller methane producers in Iceland, such as farms and smaller communities. Important aspects are, simplicity, size and cost.

This report will describe the design of an absorption column. The design will be validated by building a prototype and then tested in the methane production facility at Sorpa in Álfsnes. All test data will be documented to estimate the efficiency of the equipment and to account for necessary adjustments.

Dedication

To my wife Valgerður Lindberg and my sons,

For their unquestioned understanding, patience and support.

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Acknowledgements

This project would never have gone far without the help and funding from my instructor Nicolas Marino Proietti at ReSource international.

I would also like to take this opportunity and give my sincere regards to the two other instructors involved in this project, Egill Þórir Einarsson and Krista Hannesdóttir, for their unmatched dedication and support to their students.

And last but not least, I want to thank my wife for her patience with me through this whole process.

1 Introduction

Energy usage has been growing steadily since 1971 according to the International Energy Agency [1]. This growing demand for energy as well as the possible imminent oil depletion is a cause to start developing more suitable and preferably reusable energy sources. One of the sources that has not been fully utilized is bio-, landfill and sewage gas. This energy has been harvested in some extent all over the globe and can be a cheap and sustainable energy source. For example, biogas production has been used for a long time in rural communities and farms, especially in India and China. The first methane (CH_4) reactor was built in the 1890s by an English man named Cameron [2].

All these gases have the potential to be upgraded to bio methane. Biogas upgrading is a process where a mixture of gases are filtered, using various methods described in this text, to the point when a desired concentration of one or more gases have been achieved. Specifically biogas is usually upgraded for its CH_4 content and either used as vehicle fuel or injected into a gas grid.

Although biogas has become common in many countries it has not been fully utilized in Iceland. Even though these gases are generated naturally in various landfills, manure pits and where natural waste lies undisturbed under oxygen deprived circumstances. It should be beneficial to try to harvest as much of this energy source as possible, and not to mention the negative effect that CH_4 has as a greenhouse gas.

1.1 The problem

Iceland is a bit unique when it comes to utilization of biogas. Farms are generally small in size compared to farms in larger countries. This makes it proportionally costly to construct a CH4 reactor and upgrading equipment for an individual farm. This paper will be focused on addressing this problem by looking at decreased size and complexity and is thus likely to reduce cost in investment and operation.

A pilot scale upgrading plant that could serve as an inexpensive solution to the upgrading process of biogas is proposed. The design will focus on upgrading biogas utilizing amine absorption with monoethanolamine (MEA). It is less costly than many other methods, requires no sophisticated control instruments to run and returns CO_2 for further use if needed [3].

Absorption of biogas with MEA is a two stage process. The first stage is the actual CO_2 absorption with MEA and the second where CO_2 is stripped from the liquid. This paper will focus on the absorption process.

2 Background

Upgrading biogas to bio- methane has become a widely known technique. Methane gas is upgraded from landfill, sewage, and natural or bio gas [4] [5]. Methane reactors operate by turning natural waste, often livestock excrements to bio methane. Today many methane reactors are operational. The gas created by these reactors is then upgraded using a variety of techniques. So far, most methane upgrading plants are in Sweden and Germany but other mentionable countries include Switzerland, USA and the Netherlands amongst others [5]. The upgraded gas is then utilized either as vehicle fuel or more commonly for gas grid systems in various countries.

2.1 Biogas production

Biogas is produced naturally with the breakdown of biological material such as vegetation, animal remains or excrement. This is due to a symbiotic relationship between bacteria under oxygen deprived circumstances. All the bacteria in the process serve a specific purpose and thrive in accordance to that. The main stages in the process are called hydrolysis, acidogenesis and methanogenesis, the basic process is illustrated in figure 2-1 [4].

Figure 2-1 - Simple illustration of methane process

The first stage, hydrolysis, is the result of a facultative bacteria. These bacteria can use oxygen in their digestion process but can also turn to alternative methods if there is no oxygen present [4]. They start the process by using oxygen from the tank and in the slurry to break down complex molecules. When all free oxygen is depleted in the system they revert to oxygen in the water to continue their breakdown. Thus the name hydrolysis [4].

Second stage of the process, or as mentioned by David Fulford [4] in his works the second half of the first stage, is acydogenesis. In this stage the bacteria in the slurry start forming volatile acids such as acetic acid. If in this part of the process any air gets to the slurry, the process can go no further and no CH_4 gets produced [4].

The third and last stage of the process, is methanogenesis. This process is where methanogen bacteria start breaking down the fatty acids into smaller molecules, mainly H_2O, CO_2 and CH_4 [4].

This natural process is used for our benefits today in methane reactors, sewage plants and landfills. The biogas produced by these plants vary a little with the feed used but all have in common a high CH_4 content as seen in table 2-1.

Table 2-1 - Composition of different gases.

	Unit	Landfill	Biogas	Sewage Plant	Natural Gas	Source
Methane (CH4)	%	35-65	60-70	-	89	[5]
		47-57	55-58	57-65	-	[6]
Carbon Dioxide (CO2)	%	30-40	30-40	-	0,67	[5]
		37-41	37-38	33-39	-	[6]
Hydrogen Sulphide (H2S)	ppm	0-100	0-4000	-	2,9	[5]
		36-115	35-169	<24-62	-	[6]
Ammonia	ppm	ca. 5	ca. 100	-	0	[5]
		-	-	1	-	[6]
Nitrogen (N2)	%	ca. 0.2	5-40	1	0,28	[5]
		<1-17	<1-2	<8-13	-	[6]
Oxigen	%	0-5	0	-	0	[5]
		<1	<1	<1	1	[6]

2.2 Current status in Iceland

Currently there are only records of two places in Iceland that produce methane [7] [8]. The only publicly available source is from SORPA. They produce their gas from landfills on Álfsnes in Reykjavík and is upgraded using water scrubbing. In the year 2012 the production reached two million Nm^3 which according to Sorpa is around 60% of their current capacity [7].

The second methane producer currently known in Iceland is at the farm Hraungerði [8].

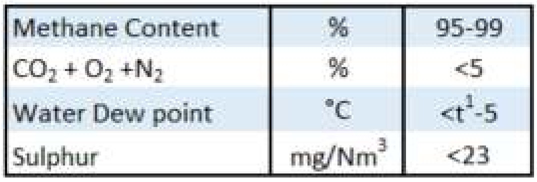
2.3 Prospects for Icelandic methane production

At the moment the biogas production in Iceland can be considered at a minimum. As stated in the previous section there is only one known farm that produces biogas, which means that all over the country there are potentially unused resources for methane production. Other sources that could be promising are landfills in various communities that hold some prospects. Sewage treatment in Iceland does not utilize any methane production to the writer’s knowledge and animal excrements are mostly used straight as fertilizer. All this has a potential to produce CH_4 gas.

3 Biogas cleaning

In order to utilize biogas as vehicle fuel or for injection into a gas power grid it has to meet standards set in each country or region. These standards vary between countries. No legislation is active in Iceland for quality of biogas, likely because methane usage is just in its early stages. If and when any legislations are implemented in Iceland they are likely to be similar to the Swedish standards, the highlights of the Swedish standard can be seen in see table 3-1.

Table 3-1 - Data from the Swedish standard for CH_4 upgrading [5]



Methane Content	%	95-99
$CO_2 + O_2 + N_2$	%	<5
Water Dew point	°C	$<t^1-5$
Sulphur	mg/Nm^3	<23

[1] *Ambient temperature*

According to the Swedish standard the CH_4 content needs to be no less than 95%. Too reach this purity the raw biogas needs to be cleaned of contaminants such as particles, hydrogen sulphide (H_2S), water (H_2O) and carbon dioxide (CO_2). Other contaminants can include ammonia, nitrogen and oxygen, although nitrogen is more common in landfill gases from oxygen that seeps in to the system through the soil [5].

The biggest reasons for upgrading biogas is to increase its energy content and to protect machinery from corrosion. Untreated H_2S can cause significant corrosion in the upgrading machinery as well as any vehicle it is intended for [5].

3.1 Water

During the digestion process the biogas becomes saturated with water vapors. These water vapors can condensate inside different parts of the upgrading system causing corrosion on metal surfaces. Water is easily removed from the gas. Methods for doing so are mainly pressure, cooling and absorption. By increasing the pressure of the biogas the dew point of the water vapors is lowered causing the water to condensate and fall, making it easy to remove. Lowering the temperature also causes the water vapors to condensate. The absorption technique works by making the biogas run through a chemical such as SiO_2 or activated carbon. The water is absorbed by these chemicals and the chemicals can then be renewed by heating [5].

3.2 Hydrogen sulphide

Although H_2S composition in biogas is usually very low it can cause problems in various stages in both the upgrading system and in any engine or system it is intended for. When H_2S contacts water sulfuric acid is generated causing corrosion. There are countless ways to remove hydrogen sulphide from gas stream. The simplest one is probably adsorption on activated carbon, but others include precipitation and chemical absorption. Precipitation is accomplished by adding Fe ions into the digester slurry creating insoluble iron sulfate that is flushed with the digester slurry [5].

4 Upgrading technologies

There are a few different upgrading methods available for CH_4 production. Many of them work on the unique properties CH_4 has. Solubility of CH_4 is comparatively low and it remains in gaseous form under high pressure. The boiling point for CH_4 is -161.5°C compared to -57°C for CO_2 and solubility is only 0.022 g/L at 25°C compared to carbon dioxide with 1.501 g/L solubility in water at 25°C [9]. This makes absorption ideal for removing many unwanted gases from the biogas stream.

4.1 Pressure Swing Absorption

In Pressure swing absorption (PSA) the ability CH_4 has to stay in liquid state under pressure is utilized. The gas stream is fed through a series of columns containing absorbing material such as activated carbon. The number of columns vary between systems. Each column is subjected to high pressure causing carbon dioxide to be absorbed. When each column has been saturated with carbon dioxide the system switches to the next column while the saturated column is de-saturated. In the de-saturation process the pressure is dropped in stages. In the first stage the gasified carbon dioxide is fed back into the biogas stream in order to reduce CH_4 loss. Later stages the CO_2 is usually let into the atmosphere depending on CH_4 content [10].

4.2 Absorption

There are at least three different types of absorption techniques available. All of them work on the principle that CH_4 is quite insoluble in water as described above. They all use a liquid medium as an absorbing agent. The choice depends on the size of the system and availability of water and energy.

4.2.1 Water scrubbing

Water scrubbing is widely used method for upgrading biogas. This method is based on the significant difference in solubility of CH_4 and CO_2 in water. Gas flow is fed through the bottom of an absorption column and a counter flow of pressurized water is fed through the top. The column is filled with packing material like stainless ratchet rings or plastic filling material. Under pressure the carbon dioxide will dissolve into the water stream and highly concentrated CH_4 will carry on to the top of the column where it is removed. The saturated water is then carried on to a flash tank where the pressure is dropped and carbon dioxide is removed from the water [5]. The used water can be recycled to some extent but according to Nicolas Proietti [11], a former specialist at Sorpa, reuse of water has been troublesome.

4.2.2 Amine scrubbing

Amine scrubbing works like water scrubbing except for the addition of amine solution in the water. Carbon dioxide reacts with the amine which increases the solubility compared to water [5]. The most frequently used amines are mono-ethanolamine (MEA) and di-ethanolamine (DEA), and the former is the subject of this paper. Other amines have also been tried such as methyl-di-ethanolamine (MDEA), tri-ethanolamine (TEA) and mixtures of these and various amines [12] [13].

Biogas is fed into the bottom of the absorption column and a counter current of amine liquid is fed into the column at the top, see figure 4-1.

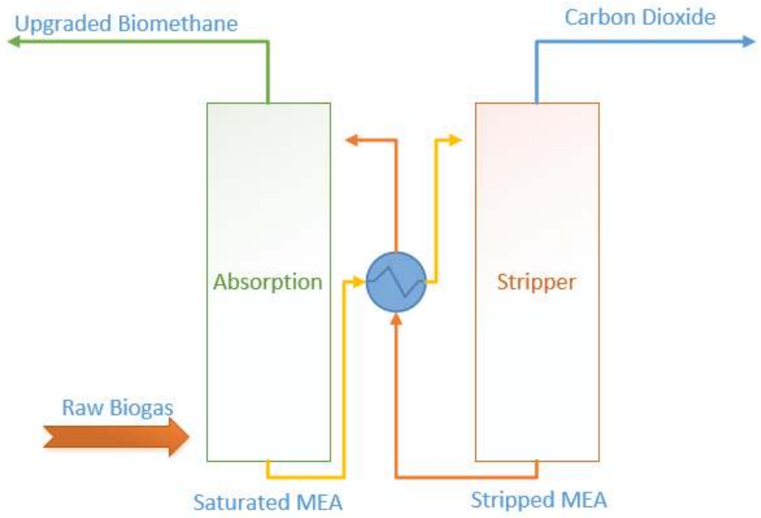


Figure 4-1 - Simple process diagram of amine scrubbing process.

After the liquid has reached the bottom of the column it has become saturated with CO_2 and needs to be replaced or regenerated. Regeneration occurs in a separate column, referred to as the stripping column. The stripping column is similar to the absorption column and is filled with packing material, often stainless steel ratchet rings due to heat. There the amine liquid is fed to the top of the column through a spray nozzle, steam is generated at the bottom. As the steam heats up the amine it carries with it CO_2 and exits at the top of the column. The steam is then cooled down in a flash tank where the CO_2 separates from the steam and is fed out of the system. Water from the steam can then be reused [5].

With chemical scrubbing CH_4 purity of up to 99% can be reached with low CH_4 slip and the system is simple in operation. The main drawbacks are that the initial investment costs can be substantial and chemicals that are used can be hazardous to personnel and environment [3].

4.2.3 Organic physical scrubbing

Organic physical scrubbing works just like water and amine scrubbing, only difference is the absorbance agent used. Commonly polyethylene glycol solution is used as absorbing agent. The major benefits of this method over regular water scrubbing is that less liquid flow is needed since CO_2 and H_2S is more soluble in polyethylene glycol than in water [10]. This also reduces the required size of the system. Same method is then used for regeneration as in amine scrubbing, the absorbing agent is heated to release the CO_2 [1].

4.3 Membranes

In membrane upgrading the principle is to lead the gas stream through a selective filter. When the gas enters the membrane, usually hollow fibers in tubes. Carbon dioxide, water and ammonia will almost completely pass through the membrane and oxygen and hydrogen sulphide will also do so to some extent. This causes clean CH_4 along with some nitrogen to pass through [5].

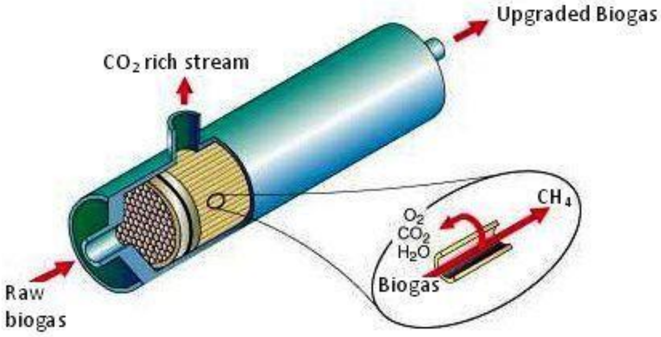


Figure 4-2 - Explanation of membrane workings [38]

CH_4 purity of 92% can be reached with one stage system but above 96% with two or three steps. Information on the economic value of membrane separation varies between sources. One important benefit of a membrane system is that it is easy to operate [3].

4.4 Cryogenic

Cryogenic upgrading uses the property CH_4 has to stay in gaseous state at very low temperatures. As stated before, CH_4 has a boiling point of -161.5°C while CO_2 has a boiling point of -78.5°C. This property makes it possible to remove individual gases by cooling the gas stream. This is usually done in two stages, where water, hydrogen sulphide and other various contaminants are removed in the first stage at around -25°C and CO_2 is then removed in a second stage at around -59°C. It is important to note that a rather high pressure is required for this since the CH_4 content affects the characteristics of the gases. Under these conditions the unwanted gases condensate either in liquid or solid state and can easily be removed [5].

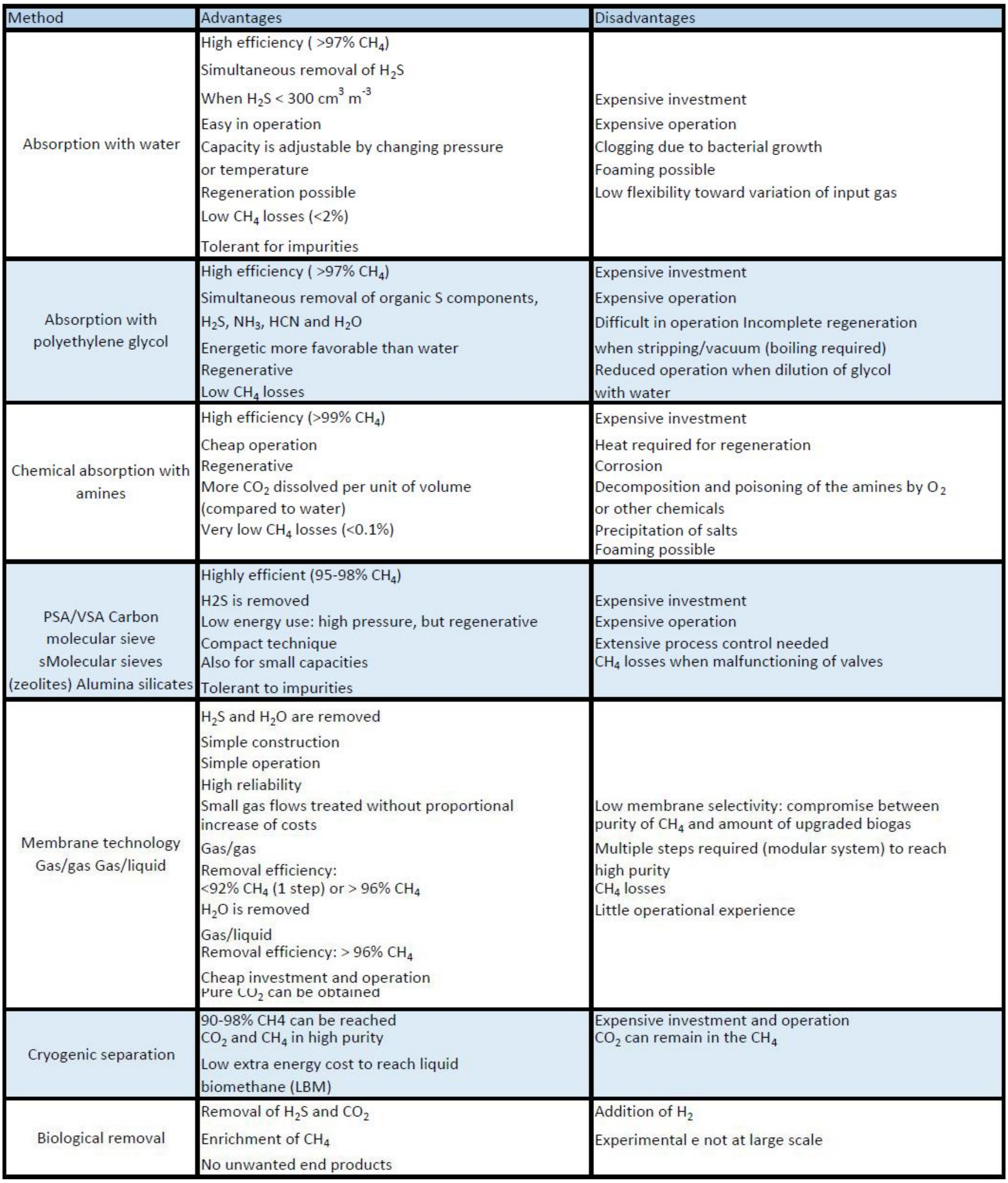
4.5 Summary

All of the upgrading techniques mentioned here have the ability to upgrade biogas above 95% CH_4 content. When choosing the best upgrading technique for any given situation careful consideration should be made on the following.

- The amount of raw gas stream.
- Composition of the raw gas in regards to CO_2, H_2S and CH_4
- Upgrading requirements, CH_4 purity.
- Environmental issues regarding disposal of hazardous byproducts.
- Cost

In table 4-1, extracted from the works of E. Ryckebosch [3], a clear comparison is made on the different techniques.

Table 4-1 - Comparison of different upgrading techniques from [3]



Method	Advantages	Disadvantages
Absorption with water	High efficiency (>97% CH_4) Simultaneous removal of H_2S When $H_2S < 300$ cm^3 m^{-3} Easy in operation Capacity is adjustable by changing pressure or temperature Regeneration possible Low CH_4 losses (<2%) Tolerant for impurities	Expensive investment Expensive operation Clogging due to bacterial growth Foaming possible Low flexibility toward variation of input gas
Absorption with polyethylene glycol	High efficiency (>97% CH_4) Simultaneous removal of organic S components, H_2S, NH_3, HCN and H_2O Energetic more favorable than water Regenerative Low CH_4 losses	Expensive investment Expensive operation Difficult in operation Incomplete regeneration when stripping/vacuum (boiling required) Reduced operation when dilution of glycol with water
Chemical absorption with amines	High efficiency (>99% CH_4) Cheap operation Regenerative More CO_2 dissolved per unit of volume (compared to water) Very low CH_4 losses (<0.1%)	Expensive investment Heat required for regeneration Corrosion Decomposition and poisoning of the amines by O_2 or other chemicals Precipitation of salts Foaming possible
PSA/VSA Carbon molecular sieve sMolecular sieves (zeolites) Alumina silicates	Highly efficient (95-98% CH_4) H2S is removed Low energy use: high pressure, but regenerative Compact technique Also for small capacities Tolerant to impurities	Expensive investment Expensive operation Extensive process control needed CH_4 losses when malfunctioning of valves
Membrane technology Gas/gas Gas/liquid	H_2S and H_2O are removed Simple construction Simple operation High reliability Small gas flows treated without proportional increase of costs Gas/gas Removal efficiency: <92% CH_4 (1 step) or > 96% CH_4 H_2O is removed Gas/liquid Removal efficiency: > 96% CH_4 Cheap investment and operation Pure CO_2 can be obtained	Low membrane selectivity: compromise between purity of CH_4 and amount of upgraded biogas Multiple steps required (modular system) to reach high purity CH_4 losses Little operational experience
Cryogenic separation	90-98% CH4 can be reached CO_2 and CH_4 in high purity Low extra energy cost to reach liquid biomethane (LBM)	Expensive investment and operation CO_2 can remain in the CH_4
Biological removal	Removal of H_2S and CO_2 Enrichment of CH_4 No unwanted end products	Addition of H_2 Experimental e not at large scale

4.6 Upgrading for small scale project

Chemical absorption was selected as the subject of this study. This decision was taken on basis of the following: a) the high purity of CH_4 that is expected, b) regenerative process and c) low operational cost of the system seen in table 4-1. Other benefits of this type of system are that the system operates under no significant pressure and only a simple process control is required. Dissadvantages of this system are, as listed in table 4-1, mainly corrosion caused by the amines and the amount of heat required to strip the amines of CO_2 [3].

5 Design of an upgrading system.

In the design of an absorption column for biogas scrubbing several factors have to be considered.

1. Diameter
   The columns have to be able to handle raw gas stream and the concentration of contaminants. The diameter of the column has to be wide enough to prevent flooding but at the same time as small as possible to limit the amount of liquid necessary to wet all the packing material for scrubbing.
2. Height
   Height of the column depends on the necessary contact time between the gas and liquid for optimal removal of CO_2 and H_2S.
3. Packing material
   Packing material increases the surface area and thus increases contact time between the gas and the liquid.
4. Flow rate
   The liquid flow rate controls the maximum removal of CO_2. It is a function of the raw gas flow rate and the CO_2 concentration.

5.1 Design parameters

The system has some predefined parameters. It should be capable of scrubbing raw gas flow between 10 Nm^3/hour and 25 Nm^3/hour, the expected production from smaller CH_4 reactors of farms and small communities. The whole column should fit inside a 20 foot container except for the top. The CH_4 purity should be at least vehicle standard, >95% or in accordance to the Swedish standard. Building material should be selected with attention to cost. It is positive if the system can be run by personnel with minimal training such as farmers. Maintenance is expected to be done by more experienced technicians. Future upgrades might include usage of waste CO_2.

5.2 Schematic diagram

A schematic picture of the system was created. The diagram displayed here shows the whole system, with stripping column and everything related to it, whereas only the absorption section of the system will be completed in this paper, figure 5-1.

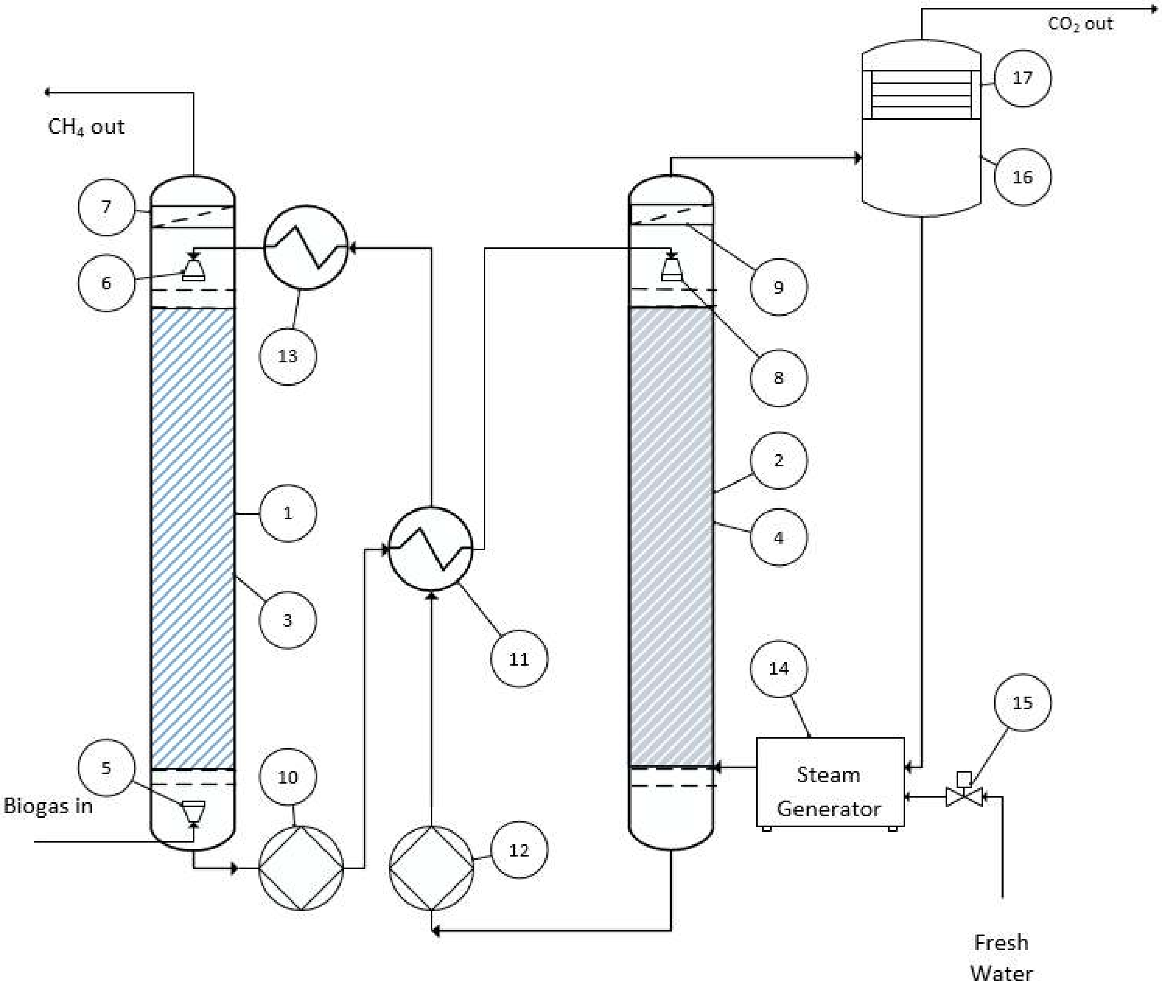


Figure 5-1 – Schematic diagram of an amine upgrading system.

The parts needed for a full system are two columns (1 and 2). Column number one is an absorption column and column two for stripping. Each column is filled with suitable packing material (3 and 4). The absorption column is usually filled with plastic pall- or ratchet rings, but the stripping column with stainless steel or any compatible heat and chemical resistant material. At the bottom of the absorption column is a diffuser (5) to separate the gas coming from the gas inlet. Spray nozzles (6 and 8) are placed at the top of each column to ensure good dispersion of MEA over the filling material. At the top of the absorption column there is a mist eliminator (7) to remove any water vapor in the CH_4 stream.

Two pumps (10 and 12) are needed. Their purpose is to pump saturated MEA from the absorption column to the stripper and regenerated MEA fluid from the bottom of the stripper to the absorption column.

It is important to maintain correct temperatur flow in the MEA liquid throughout the process. Therefore a heat exchanger (11) is placed between the columns. The use of a heat exchanger reduces energy requirement in the system by using the colder saturated MEA from the absorption column to remove heat from the hot MEA leaving the stripper.

In order to ensure good absorption the MEA needs to be cooled after the stripper. In order to do this a cooler (13) is placed before the MEA enters the absorption column.

To strip the MEA solution of CO_2 a steam generator is needed (14). The inlet of the steam is placed at the bottom at the stripping column. Into the steam generator a solenoid valve (15) supplies the steam generator with additional water when needed.

At the outlet of the stripping column a flash tank (16) is placed in order to separate the CO_2 from the steam. In the flash tank is also a condenser to both dry out the CO_2 and reuse the water from the steam.

5.3 Flow rate

In the work of J. I. Huertas it is described that the flow rate can be determined by the liquid to gas flow ratio (Q_r) [14]. According to his findings optimal Q_r ratio for this project is between 200-220, for 35% MEA with <95% CO_2 removal efficiency as seen in figure 5-2 [14].

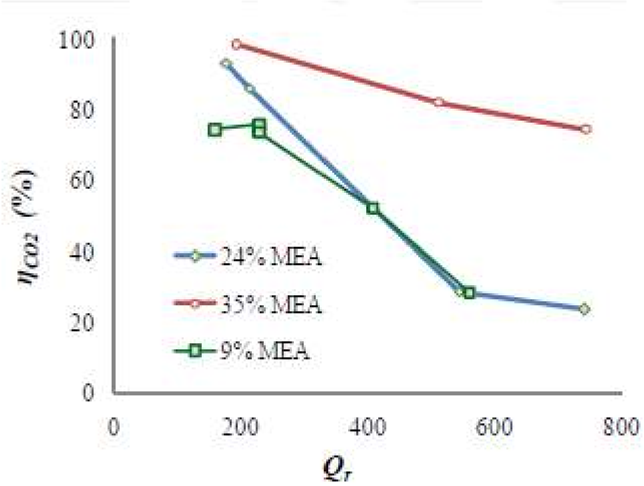


Figure 5-2 - CO_2 removal efficiency (η_{CO2}) as function of Qr [14]

According to Huertas the flow ratio for the system can be found with equation 5-1:

$$Q_r = \frac{Y_g}{X_l}$$

Equation 5-1 - For calculating Qr in terms of gas in to liquid in.

Where,
Y_g is the raw gas stream (L/min)
X_l is the liquid stream (L/min)

For the system in this paper, with 25 Nm^3/hour raw gas stream and a Qr ratio of 230, liquid flow rate is 2.0 L/min.

5.4 Packing material

Choosing the right packing material is one of the key thing that to the absorption capabilities of the system. The function of the packing material is to provide surface area inside the column. Increased surface area also increases the time gases inside the column are in contact with the liquid. On the down side, if the surface area of the packing material is too much it will also increase pressure drop along the column and thus increasing risk of flooding.

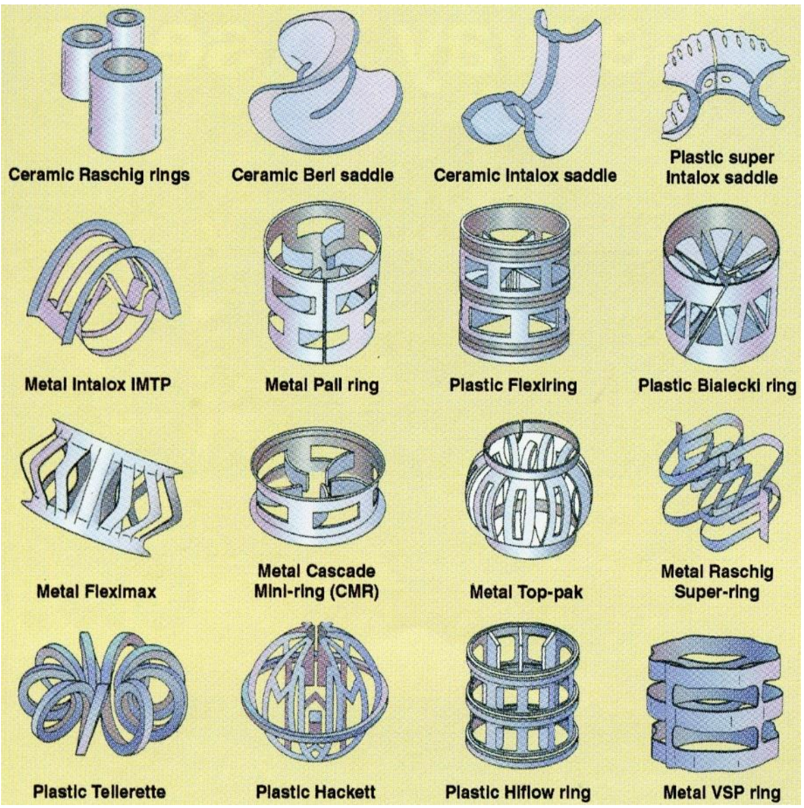


Figure 5-3 - Sample of different types of packing material [37].

Material for the packing material is dependent on the liquids inside the column, or if it needs to be chemical-, heat- or corrosion resistant. There is a large variety of packing material available on the market. In figure 5-3 there is a sample of different types of material. Common materials are polyethylene plastic, ceramics and stainless steel. All packing material have different properties. These properties are unique and are specified in datasheets provided from the manufacturer. The choice of shape is dependent on the designer's experience [15].

For this project PE plastic Pall Rings were chosen. This decision is based on the experience from Sorpa municipal waste company (Nicolas Marino Proietti, personal communication) already has with this kind of filling material for their upgrading facility. According to various sources PE plastic is a suitable choice for any material that comes in contact with MEA [16] [17]. The advised column diameter to packing size ratio is 10 [15]. This ratio needs to be validated after column diameter has been determined but smallest size available will be expected in regards to the size of the design.

There are many suppliers to choose from. In table 5-1 below, is a comparison between few suppliers of packing material. The choice has to be in regards to price, although with the table in mind Vereinigte's pall rings look promising for their big surface area and big void, and their web site supplies all necessary documentation [18].

Table 5-1 - Sample of suppliers for PE pall ring packing material.

ITEM size	Package Density (kg/m^3)	Surface Area m^2/m^3	Voidance (%)	Packing Factor	Supplier
16mm		344.2	93.1	275	[19]
16×16×1 mm	85	188	0.91	275	[20]
25 mm	90	220	90	-	[21]
15mm	80	350	91	-	[18]

5.5 Column diameter

A method for finding the pressure drop in a column can be used to find the diameter in regards to predetermined pressure drop, using a generalized pressure drop-graph, Figure 5-4, and solving for F_{LV} and choosing an appropriate K_4, both are dimensionless [22]. The recommended pressure drop for absoption column is found to be 15 to 50 (mm water/meter of packed column height) [22]. K_4 is a number descriping column and packing material properties and liquid and vapor flow rates.

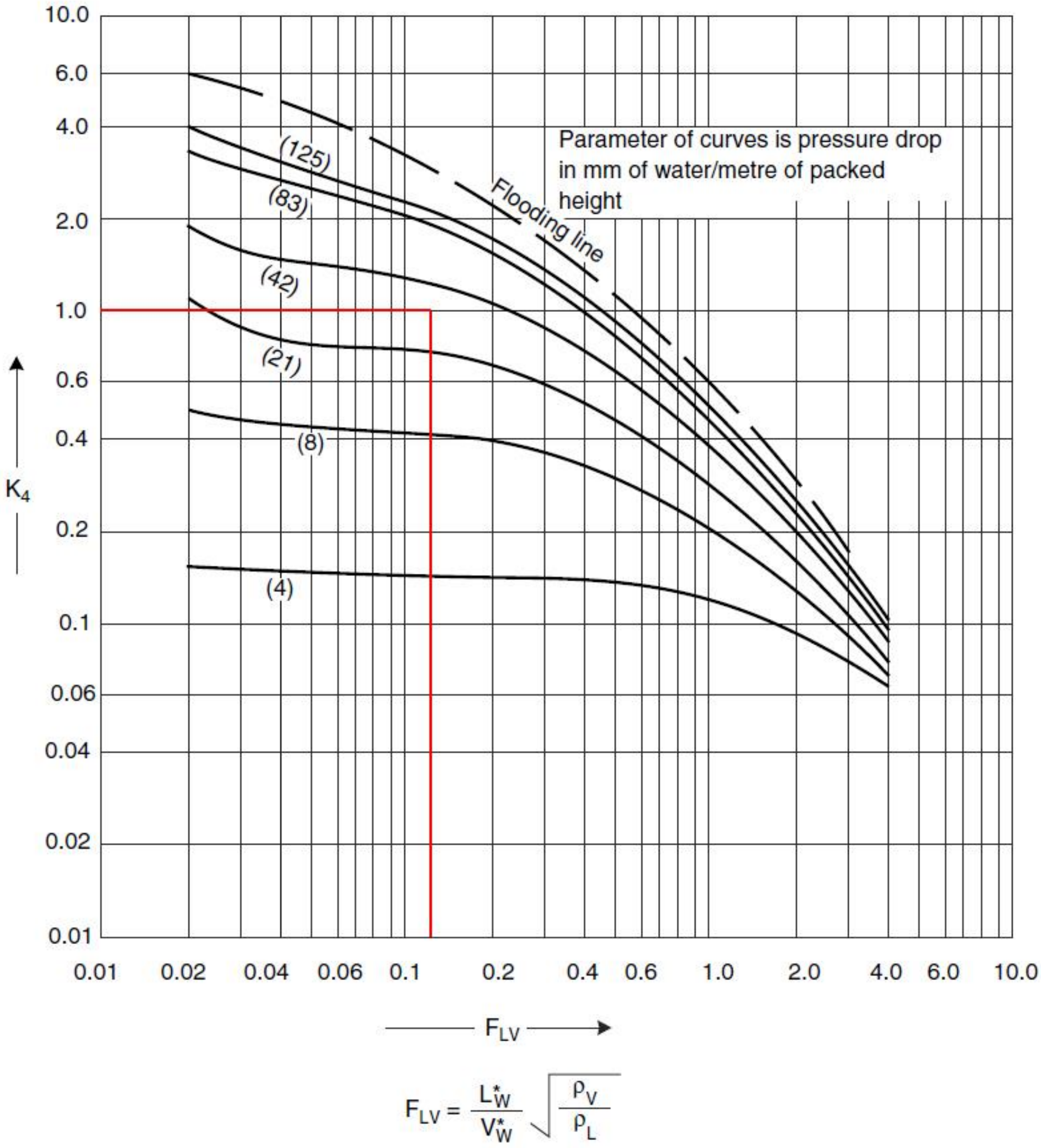


Figure 5-4 - Pressure-drop, Coulson's & Richardson's chemical engineering [22]

F_{LV} can be found using equation 5-2 [22]:

$$F_{LV} = \frac{L_{\dot{w}}}{V_{\dot{w}}} * \sqrt{\frac{\rho_V}{\rho_L}}$$

Equation 5-2 - Equation for vapor and liquid mass flow ratios

Where:

F_{LV} is the liquid to vapor mas flow ratio (unit less)

$L_{\dot{w}}$ is the liquid mass flow (kg/s)

$V_{\dot{w}}$ is the vapor mass flow (kg/s)

ρ_v and ρ_L is the liquid and vapor densities (kg/m^3)

For this project the F_{LV} ratio was found to be 0.39. List of variables are listed in table 5-2. Further calculations can be seen in appendix i.

By selecting an apropriate pressure drop for the project in this paper and thus determining K4 the diameter of the column can be found by isolating V_w from equation 5-3 [22]:

$$K_4 = \frac{13.1(V_w^*)^2 F_p(\frac{\mu_L}{\rho_L})^{0.1}}{\rho_v(\rho_L - \rho_v\ )} => V_w = \sqrt{\frac{K_4 * \rho_v(\rho_l - \rho_{v)}}{13.1 * F_p * (\frac{\mu}{\rho_l})^{0.1}}}$$

Equation 5-3 - Equation for finding K4 for pressure drop plot and isolation of V_w

Where:

K_4 is a variable for equipment properties, packing properties and liquid and vapor flow rates (unit less):

$V_{\dot{w}}$ is gas mass flow rate over the cross section of the column [kg/m^{2}s]

F_p is the packing material factor, see table 5-1.

μ_L is the liquid viscosity [Ns/m^2]

ρ_L and ρ_v are the liquid and vapor densities [Kg/m^2]

For this project the selected K_4 factor was 1. This gives a pressure drop of approximately 30 (mm water /meter packed column) which is acceptable for this type of project [22].

And since $V_{\dot{w}}$ is the gas mass flow over area then equation 4, detailed calculations can be seen in appendix i:

$$V_{\dot{w}} = \frac{V_w}{A} => A = \frac{V_w}{V_{\dot{w}}} => d = \sqrt{\frac{4}{\pi} * A}$$

Equation 4 - For finding diameter from V_w.

Where:

V_W is the gas flow (kg/s)

$V_{\dot{w}}$ is the gas flow rate over a cross sectional area (kg/m^{2}s)

A is the area of the column (m^2)

d is the diameter of the column (mm)

Table 5-2 - Table of variables for diameter calculations, see appendix i.

Variables	Units	Value	Reference
ρ_V	[kg/m^3]	1.188	[23] [24]
ρ_L	[kg/m^3]	1.003*10^3	[25]
μ_L	[mPA*s]	2.6	[26]
F_P	[m^{-1}]	275	[18]
$V_{\dot{w}}$	[kg/m^{2}s]	0.846	
L_W	[kg/s]	0.033	
V_W	[kg/s]	0.008	
F_{LV}	-	0.139	
K_4	-	1	
d	mm	98	

From these calculations the diameter was found to be 98 mm. A good choice of material for this project would be a 104x2mm standard stainless steel pipe.

5.6 Column height

The height of the column is as explained before dependent on the contact time needed for full or acceptable absorption of CO_2. The height is usually determined by experience from similar equipment rather than mathematical conclusions [27].

One similar project was found where the gas flow was 7.6 m^3/hr. The height of the column in this project was 2.3m [14]. Therefor the size will be assumed as 2.6m even though the gas flow is greater. No other similar systems were found. To validate this size test needs to be conducted.

5.7 Thermodynamics

One concern of the design is the energy generated by exothermic reaction of the absorption process. The energy created in the process can be found in the works of Inna Kim [28]. There, experiments were made that conclude that with 30% MEA concentration at 40°C the heat of absorption, for this projects mol-CO_2/mol-amine ratio calculated with equation 5-5 and equation 5-6, is 87 kJ/mol-CO_2, this can be seen in figure 5-5 [28].

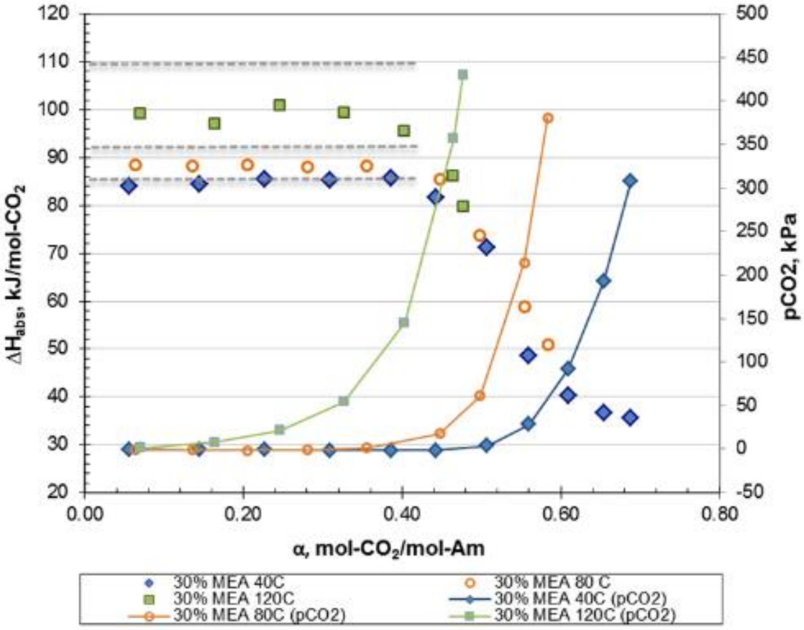


Figure 5-5 - Heat of absorption for 30% MEA [28]

With this informaiton the total heat generated by the absoption is 9.1 kJ/s when the gas flow is at 25 m^3/hour and liquid flow rate at 2 L/s. The a_r ratio described in figure 5-5 for the system in this project would be 0.68.

$$V_{CO2} = 559\,{}^{L}/_{kg\ CO2} \qquad M_{CO2} = 44{,}01\,{}^{g}/_{MOL}$$

$$n_{MOL,CO2} = \frac{G_{i\,[m^3/hour]} * 10^6 * y_{CO2}}{3600 * V_{CO2}\,[L/kg] * M_{CO2}} = [{}^{MOL}/_{sek}]$$

Equation 5-5 - For calculating CO_2 MOL.

$$\rho_{MEA} = 1016\frac{g}{L} \qquad M_{MEA} = 61.08\,{}^{g}/_{MOL}$$

$$n_{MOL,MEA} = \frac{X_{i[l/min]} * y_{MEA} * \rho_{MEA}}{60sek * M_{MEA}} = [{}^{MOL}/_{sek}]$$

Equation 5-6 - For calculating MEA MOL.

According to this the energy released in the absorbance process is 9.8 kW. With all this heat generated in the column it is necessary to account for any heat buildup that might occur. With that in mind the system was modeled in regards to heat. The operation temperature is estimated to be 30°C at the top of the tower and 50°C at the bottom. Gases working on the system are considered negligible in regards to energy transferred in and out of the system as they have very little heat capacity. CO_2 has, for example, heat capacity of 0.846kJ/kgK whereas water has 4.22kJ/kgK [29].

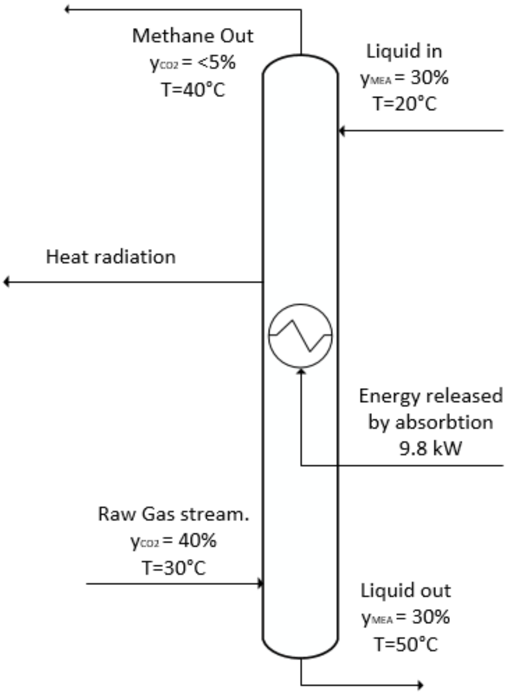


Figure 5-6 - Absorption column with heat estimates.

By building the column out of stainless steel the heat conduction from the tower is enough to keep it from heating up. According to the results from equation 5-7, where λ is the heat transfer coefficient, l is the length of the column, D is the outer diameter of the column, d is the inner diameter and t_1 and t_2 is the heat difference.

$$Q = \frac{2\pi\lambda l}{ln\frac{D}{d}}(t_1 - t_2)$$

Equation 5-7 - Heat transfer formula through a pipe [30].

For this project the parameters are as follows:

$\lambda_{\text{stainless steel}}$ = 16 W/m°C
l = 2.6m
D=104mm
d=100mm
t_1=50°C
t_2=20°C (ambient temperature)

Thus Q is approximately 270 kW.

Which means that the heat transfer from the inner to outer column can be 133.3 kW. This heat flow is dependent on a variety of factors such as air ventilation, vapor inside the column and more. The possible heat flow from the column should be more than sufficient to keep it within any desired operating temperatures.

While it is good to see the heat flow from the tank it is more practical to look at the energy removed by the water and MEA exiting the column, as the heat transfers into the liquid more readily. The energy transferred with the liquid flow can be calculated with equation 5-8.

$$E = (y_{MEA} * c_{MEA} + y_{water} * c_{water}) * X_{out} * (\Delta t) = W$$

Equation 5-8 - Energy transferred from system with liquid flow.

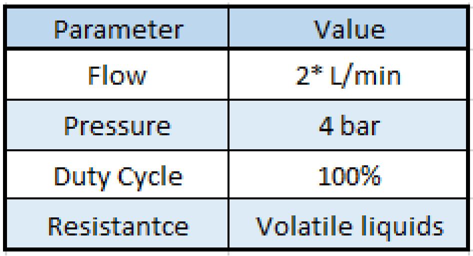
Where:
E is the total energy transferred with the liquid [W].
y_{MEA} is the MEA concentration [%].
y_{water} is the water concentration [%].
C_{mea} is the specific heat of MEA [J/kg]
C_{water} is the specific heat of water [J/kg]
X_{out}-is the liquid flow out [kg/s].
t_1 and t_2 is the temperature difference between the liquid coming in and liquid going out [°C].

The results from equation 5-8 and equation 5-7 show that the energy moved out of the system with the liquid flow is 2.26 kW and with the additional heat transfer rate of the stainless steel the system is expected to run within the maximum 50°C that is expected. To validate this the heat buildup will be monitored in testing. Calculations can be seen in appendix o.

5.8 Pumps

Having determined the size of the columns and the liquid flow rate, the pumps necessary for the project can be selected. The pumps need to withstand volatile liquids and have a 100% duty cycle, since they are predicted to operate constantly, the parameters are also listed in table 5-3.

Table 5-3 - Parameters for pump



Parameter	Value
Flow	2* L/min
Pressure	4 bar
Duty Cycle	100%
Resistantce	Volatile liquids

To this end a peristaltic pump was selected for the design. In peristaltic pumps the liquid never interacts with the machinery of the pump and can run dry without problems. They work by pressing a hose together in a circular motion causing the liquid to be pushed forward, as illustrated in figure 5-7.

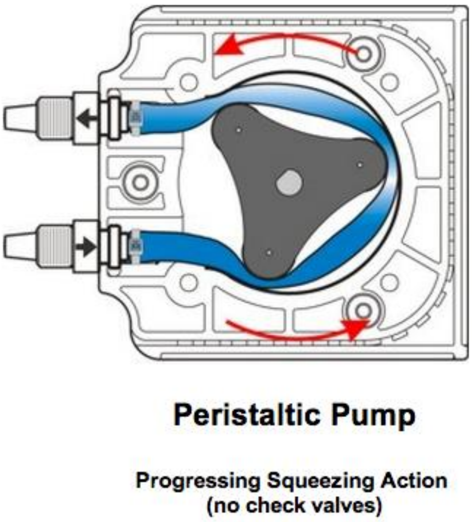


Figure 5-7 - Inner workings of peristaltic pump [36]

A pump from Verderflex was selected. They supply a variety of peristaltic pumps and different hoses for them. The selection of hoses changes the characteristics of the pump, see appendix a.

The type of pump selected is a Dura 15, seen in figure 5-8. The pump is well within its capabilities to produce 2 L/min at 4 bar pressure as seen in appendix a.

Figure 5-8 – Verderflex Dura 25 peristaltic pump [39]

For this project two pumps are needed. One for pumping MEA liquid into the absorption column and another for the striping. Control system is needed to regulate flow in and out of the column but that is outside the scope of this report.

Tubing for the pump is an important factor. Tubing available from Verderflex do not meet the required chemical resistance needed for the project so tubing from another manufacturer was chosen. The StaPure tubing from Watson-Marlow has a lifetime of 6000 hours, or approximately eight months according to data sheet in appendix b [31]. Regular maintenance is expected every six months which should be sufficient to prevent failing. Although, in the case of failure the tubing can easily be replaced by untrained personnel, although it is not recommended due to chemicals involved [32].

5.9 Design conclusions

The design process was not completed for an entire system. Emphasis was put on completing a test model of the absorption portion of the system so a test could be made to validate the current design.

For further designs the stripping column needs to be configured as the rest of the equipment is dependent on it. The heat exchanger needs to be calculated in regards to the temperature of the liquid coming from the striping column and the cooling system as well. A steam generator needs to be chosen in regards to the heat and vapor quantity needed to extract CO_2 from the MEA and finally the flash tank also is designed in regards to the steam from the steam generator.

6 Full size absorption test

To validate the design results it was decided to build a full scale absorption test. The absorption test system will be conducted according to the parameters listed in table 6-1.

Table 6-1 - List of design parameters.

Parameters	Value
Gas flow rate (Nm^3/hr)	25
Liquid Flow rate (L/min)	2
Column Diameter (cm)	16[1]
Column Height (cm)	290
Packing material	PE Pall rings
Pump Pressure (Bar)	4
MEA concentration	30%
Gas type	Landfill

[1] *The diameter size is a result of previous findings, better information in discussions in chapter 9*

These test results will determine the functionality of the design but most importantly if the column height is sufficient for full absorption.

MEA will be circulated through a stream of landfill gas. With each circulation the concentration of CO_2 will rise in the liquid. Temperature, PH and gas concentration measurements will be taken on a regular basis until the MEA has become saturated with CO_2. At that point absorption will have dropped considerably.

6.1 Test column design.

The test column will be set up as seen in figure 6-1. The main column (1) will be made out of black PE piping material.

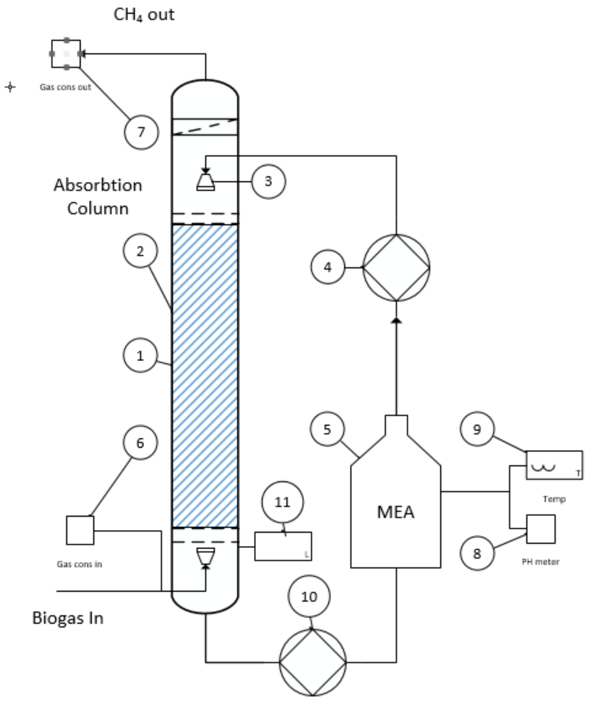


Figure 6-1 - Diagram of test system

A sieve was placed inside the column to hold the packing material (2) in place. A spray nozzle (3) is used to ensure that the MEA spreads evenly across the column.

Two pumps (4) and (10) are needed for this test. Small pumps designed for circulation of carbonated water will be used because of availability and cost. The pumps will pump the MEA from a barrel (5) placed on the ground up through the spray nozzle and controlled with a level switch at the bottom (11).

A CO_2 gas meter (6, 7) will be used at the gas input and output to monitor the absorption ratio. And in order to monitor temperature and PH values, sensors (8, 9) will placed on the MEA container.

6.1.1 Build of test equipment.

In the build of the test equipment the idea was to build a full size model of the design. First the material was chosen for the column and then part list was put together, see appendix c.

6.1.2 Frame.

The first step was building a frame that could support the column and any other equipment that was necessary for the test. The frame was built entirely out of 50x50x4mm carbon steel bars. The conclusion was to create the frame in full scale as it would be if both columns were included as well as other equipment. As seen in figure 6-2 the frame design was simple.

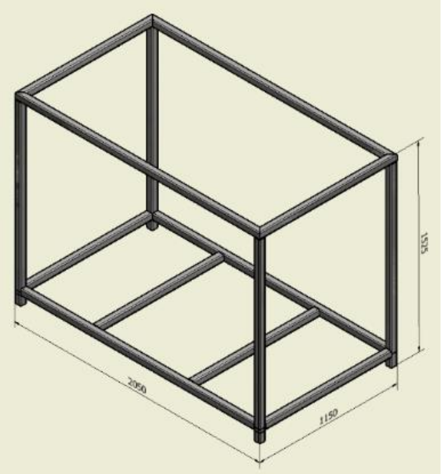


Figure 6-2 - Diagram of frame

It was set up on feet in order to prevent the steel laying on a wet floor in case of spillage and to make it possible for a forklift to get under the frame and move it. Work diagram can be seen in appendix e.

6.1.3 Fasteners.

Simple clamp fasteners were fabricated out of four 40x40x4mm corner bars with 50mm removed from the middle of one side of each. They will hold the column in its place

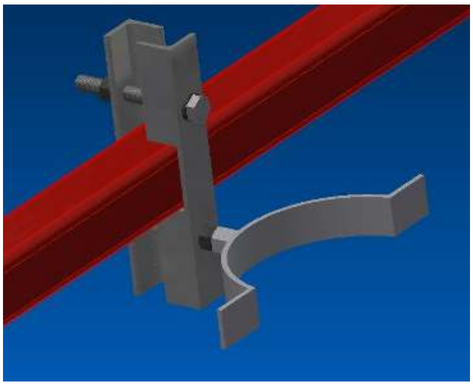


Figure 6-3 - Clamping for columns

The clamp, as seen in figure 6-3, makes it possible to adjust the column on all axes. This feature will become convenient if the system is placed on an uneven surface. A working diagram of the fasteners can be seen in appendix d.

6.1.4 Test column

The column was created from a 160mm PE plastic tube. It is wider than previous findings of 98 mm showed, reasons for this diameter difference can be found in discussions in chapter 9. The choice of this material was mostly due to cost and availability. On each end of the tube was welded a flange of same material. Two lids were then welded on two more flanges to close the column, an illustration of the test column can be seen on figure 6-5. Fittings were placed on each of the caps.

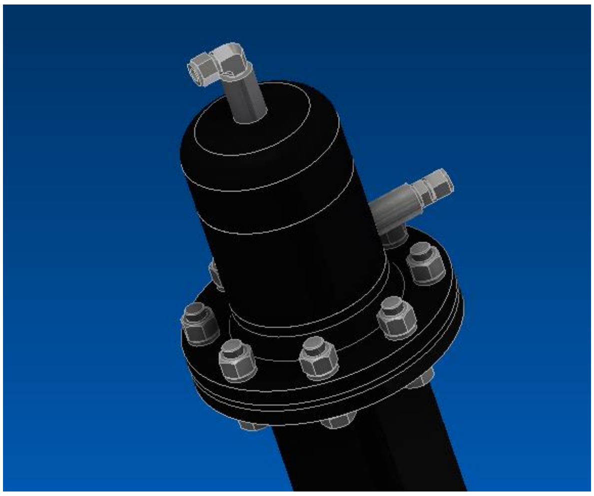


Figure 6-4 - Endcap of test column with fittings

6.1.5 Sieve

To keep the packing material from dropping to the bottom of the tower, and thus interfere with the gas flow and liquid flow out of the tower a sieve was fabricated. The inner diameter of the column is only 141,8mm and no material was available from the shelf. Therefor a 154x2x100mm Stainless steel pipe was used for this purpose. It had to be modified to fit the inside of the column. A cross support was welded to the column for the mesh plate. The plate has 4mm holes in pattern with a 35% opening ratio. Three holes were then made in the side to fit 4mm screws for support. Figure 6-5 shows the sieve assembly and work diagrams are located in appendix f, appendix g and appendix h.

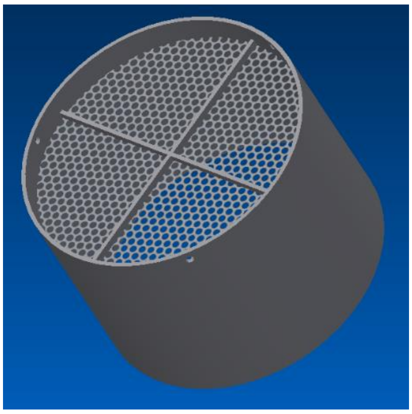


Figure 6-5 - Sieve for holding packing material

6.1.6 Pumps

The pumps acquired for this test were used circulation pumps for carbonated water. They are not peristaltic pumps as suggested in the design. They were sufficient for the test but will not be suitable for continued use. The pumps pressure were 4 Bar and were able maintain 2 L/hrs for the time needed for the tests. 3/8” plastic hoses were used with fast fittings to connect the pumps to the column. Flow control into the column was a simple manual valve and flow control out of the column is described in the next section. Calibration was made by monitoring liquid volume in a container before tests will begin.

6.1.7 Control

A simple control was required to keep the water level from rising above the gas inlet. Magnetic float sensor was placed approximately 200mm from the bottom of the column and an Arduino module was programed to activate an outlet pump until ten seconds after the float switch had reset. This way it also reduces the frequency the pump is turned on. The flow of the system can be seen in figure 6-6.

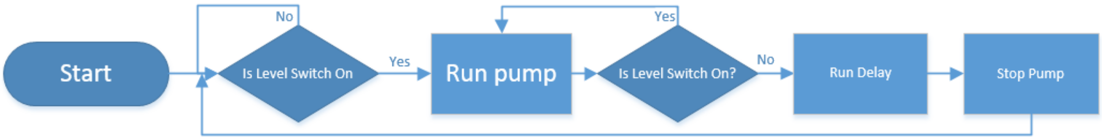


Figure 6-6 - Flow chart for the control of the test system

6.2 Test equipment

For gas measurements a gasometer designed for analyzing landfill gas was available. It is a GA5000 gasometer from GeoTech. It can measure the quantity of CH_4, CO_2, CO, O_2 and H_2S in the gas with accuracy between 0.5-3.0% depending on settings and gas. Measurements will be logged using this equipment.

Temperature and pH readings were taken straight from the MEA reservoir using an Oakion® pH 11 series pH meter.

6.3 Test procedures

First the equipment was set up as seen in figure 6-7. The equipment was set up on a small trailer for convenience. The fasteners where adjusted so the tower was vertical and pumps and control system fit into place. MEA mixture is then prepared where 30L of 99.7% MEA is mixed with 70 L of water in a barrel.

Figure 6-7 - Photo from test site of equipment

After set up a gas pump was set up with a diesel generator. Gas stream from the landfill at Álfsnes was be pumped to the bottom of the column at maximum capacity.

Measurements from the gas were taken with the GA5000 gasometer and logged. Data was taken on three minute interval to observe the absorbance efficiency. Temperature and PH temperature were be taken from the MEA reservoir on the same five minute interval and also documented.

7 Test Results

Two test had to be conducted for technical difficulties on the first one. The test were both conducted at the landfill at Sorpa in Álfsnes.

Graphs for the data were put together to give a visual description of the test. Below in Figure 7-1 are gas analysis data from test 1. The balance % series indicates nitrogen (N_2) content based on oxygen balance readings [33].

7.1 Test one

The test was set up as described in chapter 6.3. The data obtained from the test are available in appendix k. Gas flow in test 1 cannot be established for technical reasons.

Graph for the gas flow out of the absorption column were graphed in Figure 7-1.

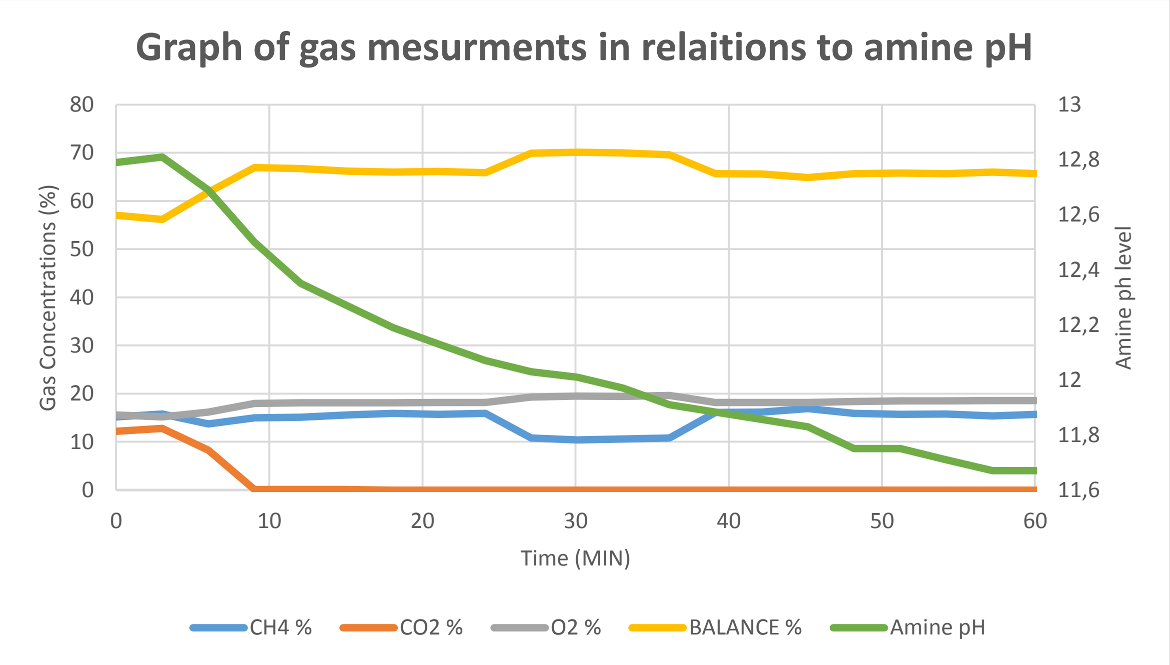


Figure 7-1 - Graph of gas measurements taken from gas analyzer from test 1.

In figure 7-2 the data from the pH and temperature readings can be seen.

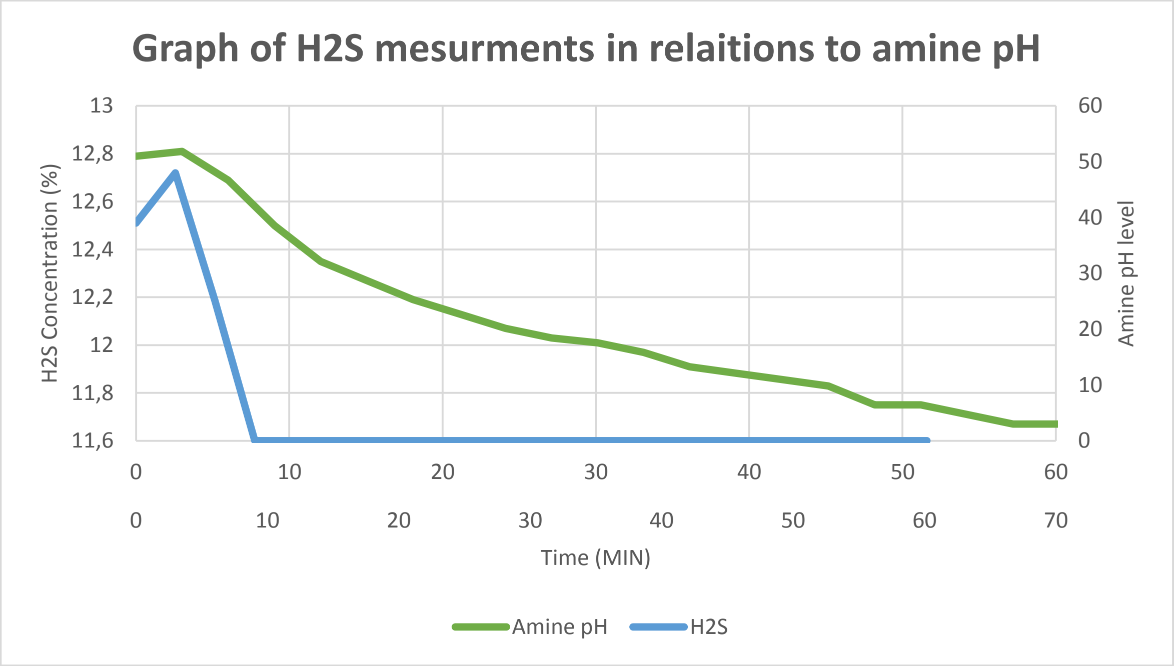


Figure 7-2 - Graph of H2S absorbance in relations to amine pH during test 1.

Because of technical difficulties data from test 1 it was decided to conduct another test. These difficulties were that the pump used to pump gas out from the landfill leaked. At first the gas content was deemed plausible since the hole in question had never been tested before. Later a severe leakage was discovered on the pump causing it to suck in atmosphere and thus distorting the data.

7.2 Second Test

The second test was continued from where test one ended so the MEA had already some concentration of CO_2 in it and thus a lower pH. The initial pH value was 12.11 as apposed 12.79 in test 1. Temperature and pH reading were monitored and noted at the same interval as the gas measurements.

First the pump had to be repaired so a viable test could be completed.

Graphs of the test results can be seen here bellow, all data is displayed in appendix j.

First the CH_4 concentration in and out of the system was plotted in comparison with the CO_2, see figure 7-3, in relations to the amine pH levels.

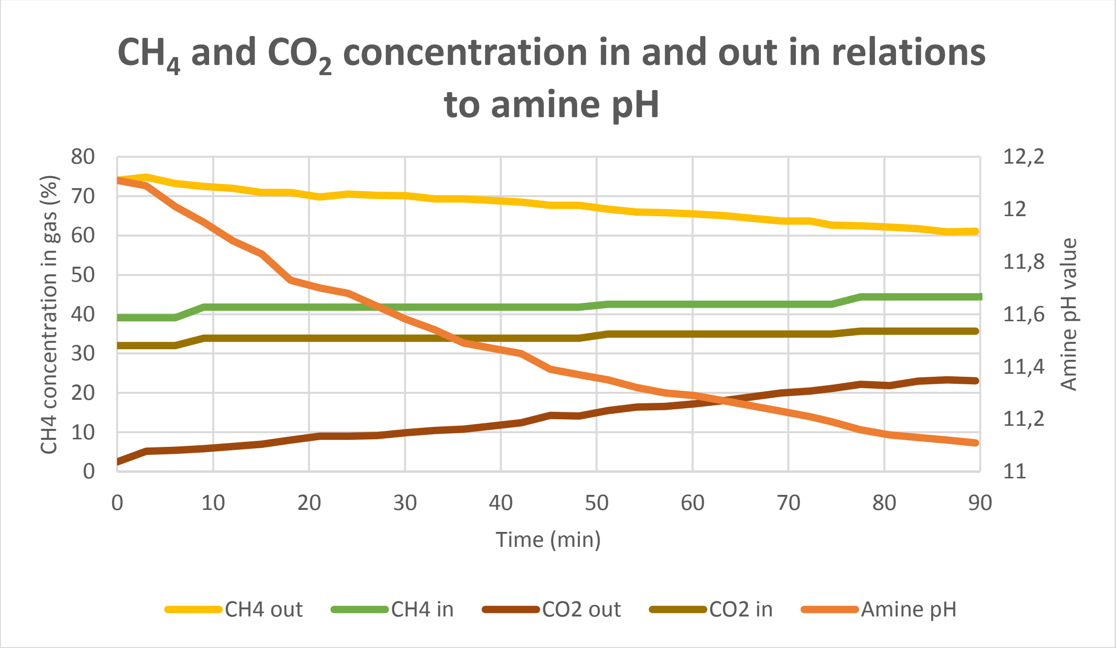


Figure 7-3 - Graph of CH_4 and CO_2 concentration in and out with amine pH..

N2 and CH4 concentration in and out were added together and plotted together in relation to the amine pH values, see figure 7-4.

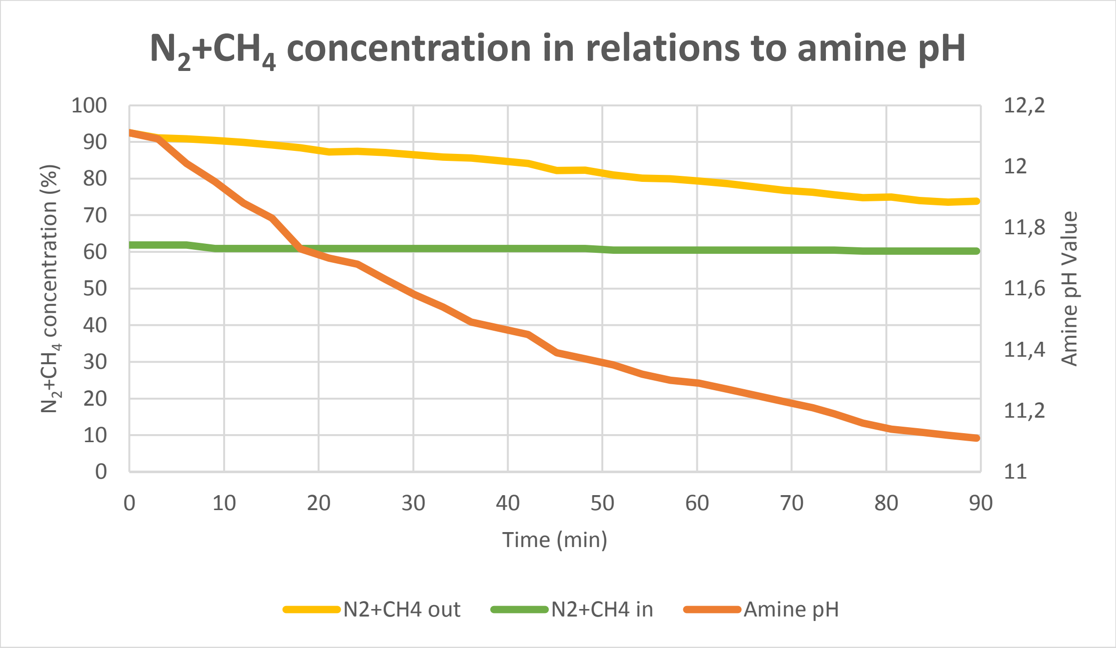


Figure 7-4 - N_2+CH_4 concentration in and out of the system in relations to amine pH.

H2S concentrations were plotted in and out of the system in relations to the amine pH value, see figure 7-5.

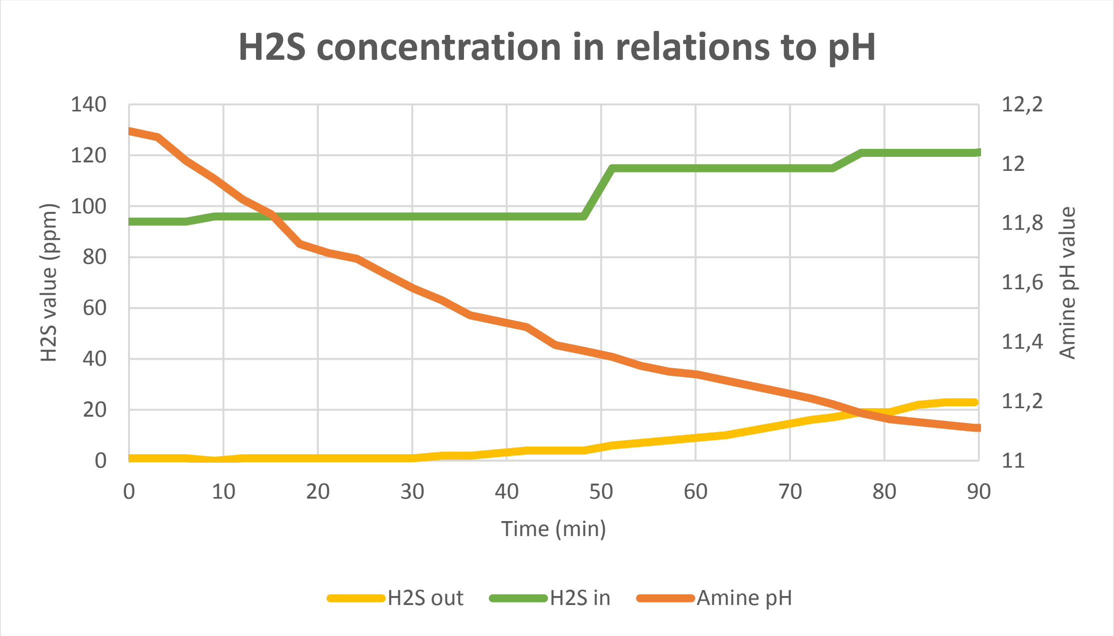


Figure 7-5 - H2S concentration in and out of the system in relations to amine pH.

Finally the total absorbance efficiency was plotted in relations to the amine pH levels, see figure 7-6.

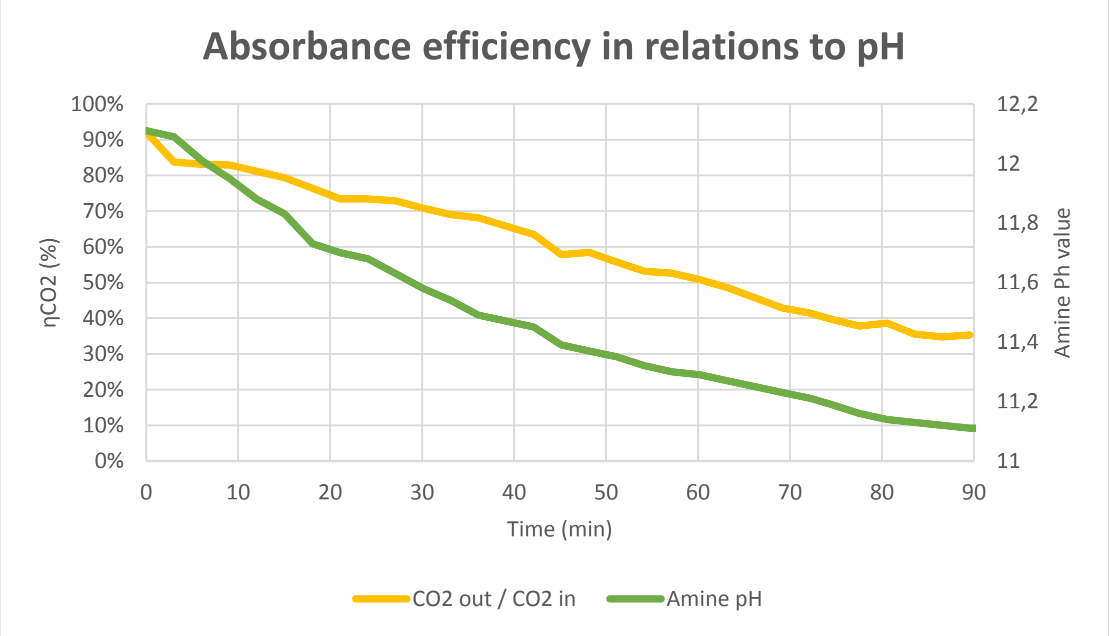


Figure 7-6 - CO2 absorbance efficiency in relations to amine pH.

8 Test Analysis

Two test were conducted with very different results. Both were conducted on the same borehole at the Landfill in Álfsnes. The second test did show some promising results.

8.1 Test 1

Because of leakage in the pump in test one this test has to be counted as inconclusive. The leakage in the pump caused atmosphere to enter the gas stream in great amount. This can be seen in figure 7-1. For landfill gas there can be some trace of O_2 and even N_2 but never in such a great quantity as in this test unless.

Data from test 1 show that CO_2 and H_2S are completely absorbed with no observable loss to CH_4. For this test, that is in no way conclusive to that the system is working as it should. But only shows that the MEA is absorbing the little quantity of CO_2 an H_2S there was in the gas stream. Since the pump for the gas extraction from the landfill was leaking, and that the test equipment itself is working properly.

8.2 Test 2

The second test worked out much better than the previous one. There was some leakage in the pump but not so that the test data was completely corrupt. The biggest problem is that the leakage interrupts with the flow of gas from the borehole thus making it complicated to determine the flow correctly. Estimation of the flow, set it only at around 150-200 L/min which is well below the max 416 L/min (25 m^3/hour) the system was designed for although the lower design flow was only at 160 m^3/hour (10 m^3/hour).

Heat measurements where intended to use to see the temperature build up in the amines because of absorption. That is also very difficult to do since the pump heated the gas stream to approximately 60°C, this temperature is only an estimate since it was measured by touch. There was buildup of heat in the MEA reservoir as can be seen in the data in appendix j but again, the affect absorption had on it is unknown, besides wind cooling is impossible to determine since no wind and ambient temperature data was acquired.

In figure 7-3 the CH_4 concentration in and out of the system was plotted. There it can be seen that the CH_4 concentration slowly falls as the CO_2 concentration rises. This happens as the absorption efficiency of the MEA is falling with the pH level.

Nitrogen (N_2) acts similarly as CH_4 in the MEA system. The solubility is very low and therefore it can be assumed that the summed up concentration of CH_4 and N_2 in figure 7-4 closely represent what can be expected if only CH_4, CO_2 and H_2S where present.

While the pH of the amine was still high, above 12, the H_2S absorbance is efficient as seen in figure 7-5. The concentration is well below the 16ppm listed in the Swedish standard and is no cause for concern.

The ratio between the CO_2 in and out falls fast with a rising pH of the amines as seen in figure 7-6. It only reaches 90% absorbance at the beginning while the MEA is at a high pH of 12.2.

9 Discussions

The first test conducted showed, as seen on graphs in chapter 7, that it was severely flawed. It turned out that a glass flow tube was broken letting in excessive amount of atmosphere. Experience was gathered with that test which made the second one a bit more conclusive.

The second test showed some promising results. The absorbance ratio of the MEA was good while the liquid was fresh but quickly fell as expected. This shows that a stripper is essential for this kind of system as 100 L of 30% MEA is not capable of absorbing much CO_2. The H_2S absorption was very good though and shows that as long as the system is designed for absorbing CO_2 it will have no problem absorbing the little H_2S that is expected in biogas.

Errors were made in the initial design calculations. The column diameter was initially too large and later turned out to need only be 98 mm, the removed design chapter can be seen in appendix n. The test column was designed with the flawed dimensions. This means that the liquid to gas ratio was also not appropriate for the size chosen for the test.

The previous method worked by comparing designs in the work of Huertas [14]. This method turned out at later stages in the design to inaccurate estimation and was therefore discarded from the formal report but can be seen in appendix n.

What helped the results in the test was probably the fact that the gas flow from the pump was only approximately ¼ of the max designed gas flow of 25 m^3/hour. It does though closely match the lower value of 10 m^3/hour, see chapter 5.1 which would mean that the results from the test are in fact promising. They show that with a stripper keeping the MEA free of CO_2 and proper adjustments of packing material and flow ratio it should work.

10 Conclusions

The design initially proposed has been completed. It will need some adjustments though if it is to work properly at 25 m^3/hour as the diameter was designed originally in excess (see ch. 9).

Tests of the equipment shows that it is only capable of upgrading the minimum design amount of 10 m^3/hour at a 90% CO_2 absorbance efficiency. Increased liquid flow should raise the efficiency to 95%.

The test conducted showed that the column is mechanically working. Modifications on the flow system should be modified to account for the increased liquid flow needed or the column tightened to fit the flow rate already established. Both the increased liquid flow and column diameter can serve as a solution. Continued work should focus on designing the stripping column. The design of it will ultimately determine whether it is more economically feasible to decrease the absorption column width or increase the liquid flow.

Time management was conducted by first making a gantt chart as seen in appendix l. It turned out that it was difficult to keep up with this schedule. In later stages of the project it was decided to break the schedule up in smaller tasks to increase oversight of the project, see appendix m.

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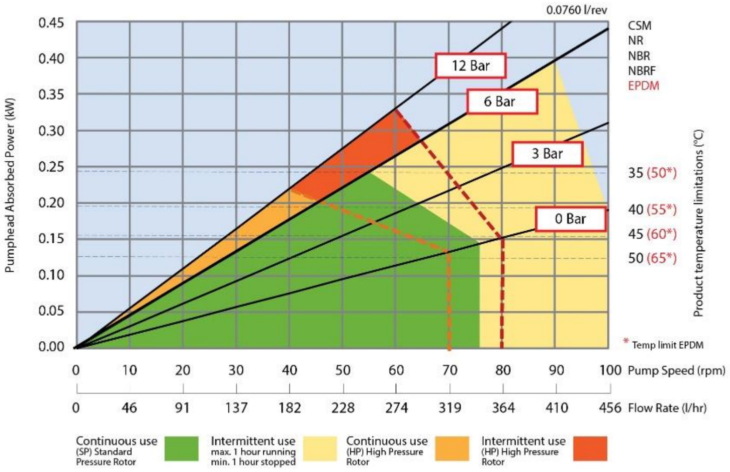
Appendix A – Data sheet for pump

Verderflex
Dura 15

Standard Pump Options for 50Hz Motor Fitted With Worm Gearbox, Suitable for Inverter Duty

Flow l/hr	Pump Speed RPM	Installed Motor Power kW	Max Turndown at 6 Bar discharge pressure
50	11	0.18	2:1
82	18	0.25	2:1
127	28	0.37	5:1
159	35	0.37	2:1
214	47	0.55	3:1
255	56	0.55	5:1
319	70	0.75	10:1



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Any application below 15 Hz may require special review

Flows are typical and were measured with water at 20°C with no suction lift or discharge pressure. Actual flows will vary according to suction conditions, discharge pressure and normal component production tolerances.

DURA PUMPS OPERATING ABOVE 6 BAR REQUIRE CONSULTATION WITH MANUFACTURER OR DISTRIBUTOR.

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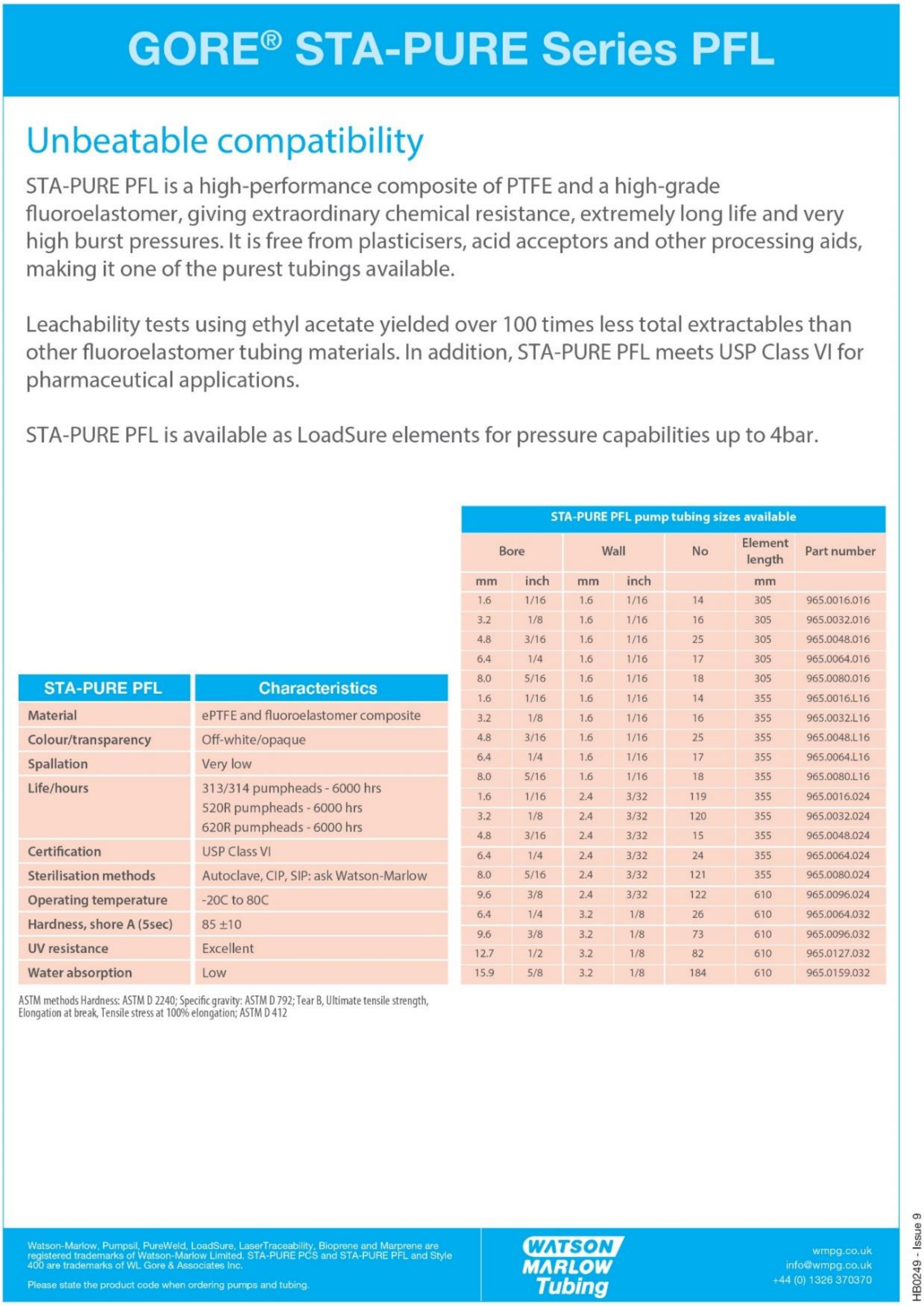
Appendix A - Data sheet for Watson Marlow 621 duplex pump properties with different hoses.

Appendix B – Data for hoses



GORE® STA-PURE Series PFL

Unbeatable compatibility

STA-PURE PFL is a high-performance composite of PTFE and a high-grade fluoroelastomer, giving extraordinary chemical resistance, extremely long life and very high burst pressures. It is free from plasticisers, acid acceptors and other processing aids, making it one of the purest tubings available.

Leachability tests using ethyl acetate yielded over 100 times less total extractables than other fluoroelastomer tubing materials. In addition, STA-PURE PFL meets USP Class VI for pharmaceutical applications.

STA-PURE PFL is available as LoadSure elements for pressure capabilities up to 4bar.

STA-PURE PFL pump tubing sizes available

Bore		Wall		No	Element length	Part number
mm	inch	mm	inch		mm	
1.6	1/16	1.6	1/16	14	305	965.0016.016
3.2	1/8	1.6	1/16	16	305	965.0032.016
4.8	3/16	1.6	1/16	25	305	965.0048.016
6.4	1/4	1.6	1/16	17	305	965.0064.016
8.0	5/16	1.6	1/16	18	305	965.0080.016
1.6	1/16	1.6	1/16	14	355	965.0016.L16
3.2	1/8	1.6	1/16	16	355	965.0032.L16
4.8	3/16	1.6	1/16	25	355	965.0048.L16
6.4	1/4	1.6	1/16	17	355	965.0064.L16
8.0	5/16	1.6	1/16	18	355	965.0080.L16
1.6	1/16	2.4	3/32	119	355	965.0016.024
3.2	1/8	2.4	3/32	120	355	965.0032.024
4.8	3/16	2.4	3/32	15	355	965.0048.024
6.4	1/4	2.4	3/32	24	355	965.0064.024
8.0	5/16	2.4	3/32	121	355	965.0080.024
9.6	3/8	2.4	3/32	122	610	965.0096.024
6.4	1/4	3.2	1/8	26	610	965.0064.032
9.6	3/8	3.2	1/8	73	610	965.0096.032
12.7	1/2	3.2	1/8	82	610	965.0127.032
15.9	5/8	3.2	1/8	184	610	965.0159.032

STA-PURE PFL	Characteristics
Material	ePTFE and fluoroelastomer composite
Colour/transparency	Off-white/opaque
Spallation	Very low
Life/hours	313/314 pumpheads - 6000 hrs 520R pumpheads - 6000 hrs 620R pumpheads - 6000 hrs
Certification	USP Class VI
Sterilisation methods	Autoclave, CIP, SIP: ask Watson-Marlow
Operating temperature	-20C to 80C
Hardness, shore A (5sec)	85 ±10
UV resistance	Excellent
Water absorption	Low

ASTM methods Hardness: ASTM D 2240; Specific gravity: ASTM D 792; Tear B, Ultimate tensile strength, Elongation at break, Tensile stress at 100% elongation; ASTM D 412

Please state the product code when ordering pumps and tubing.

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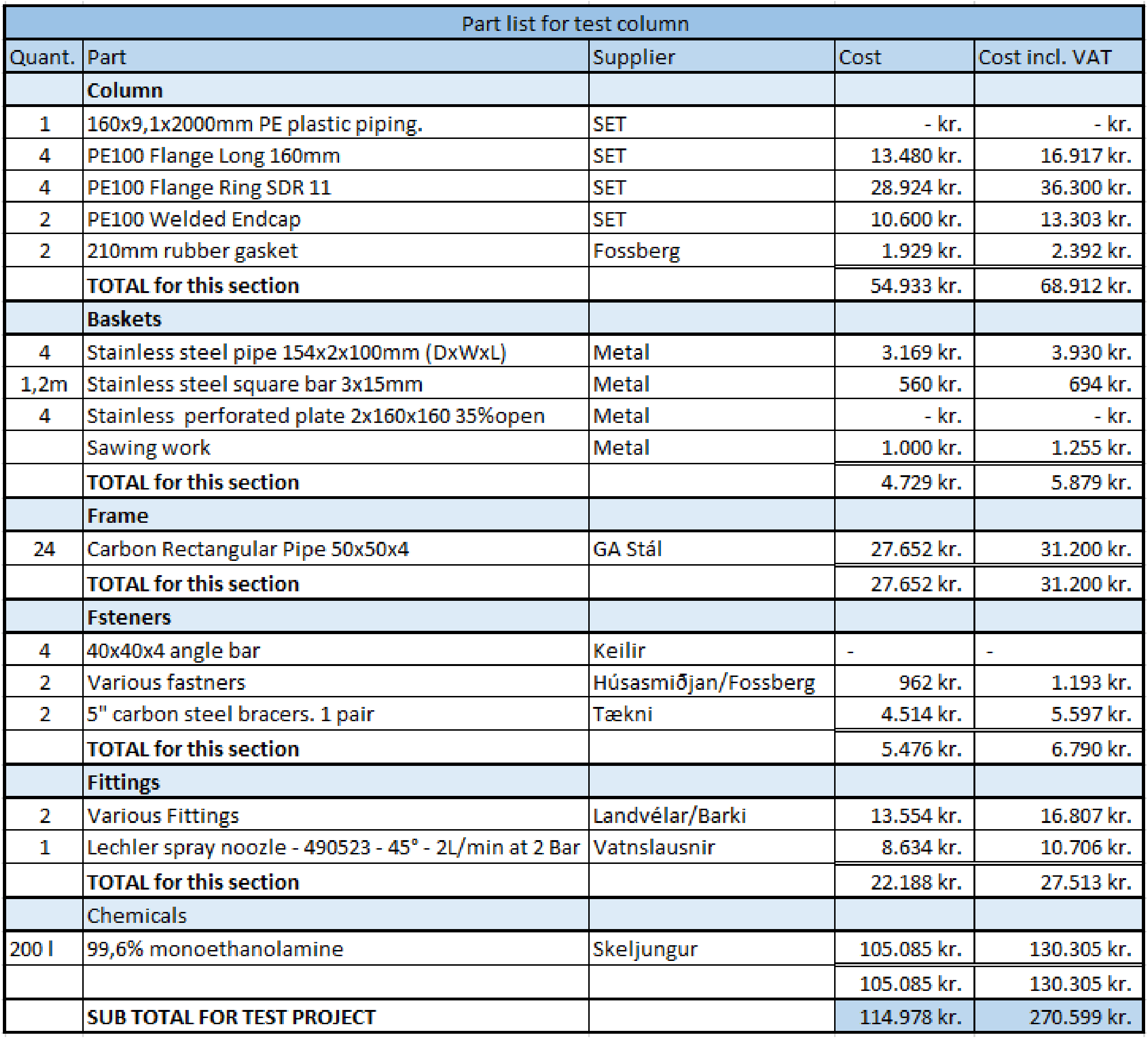
Appendix B - Tubing datasheet from Watson-Marlow.

Appendix C Part list for test equipment

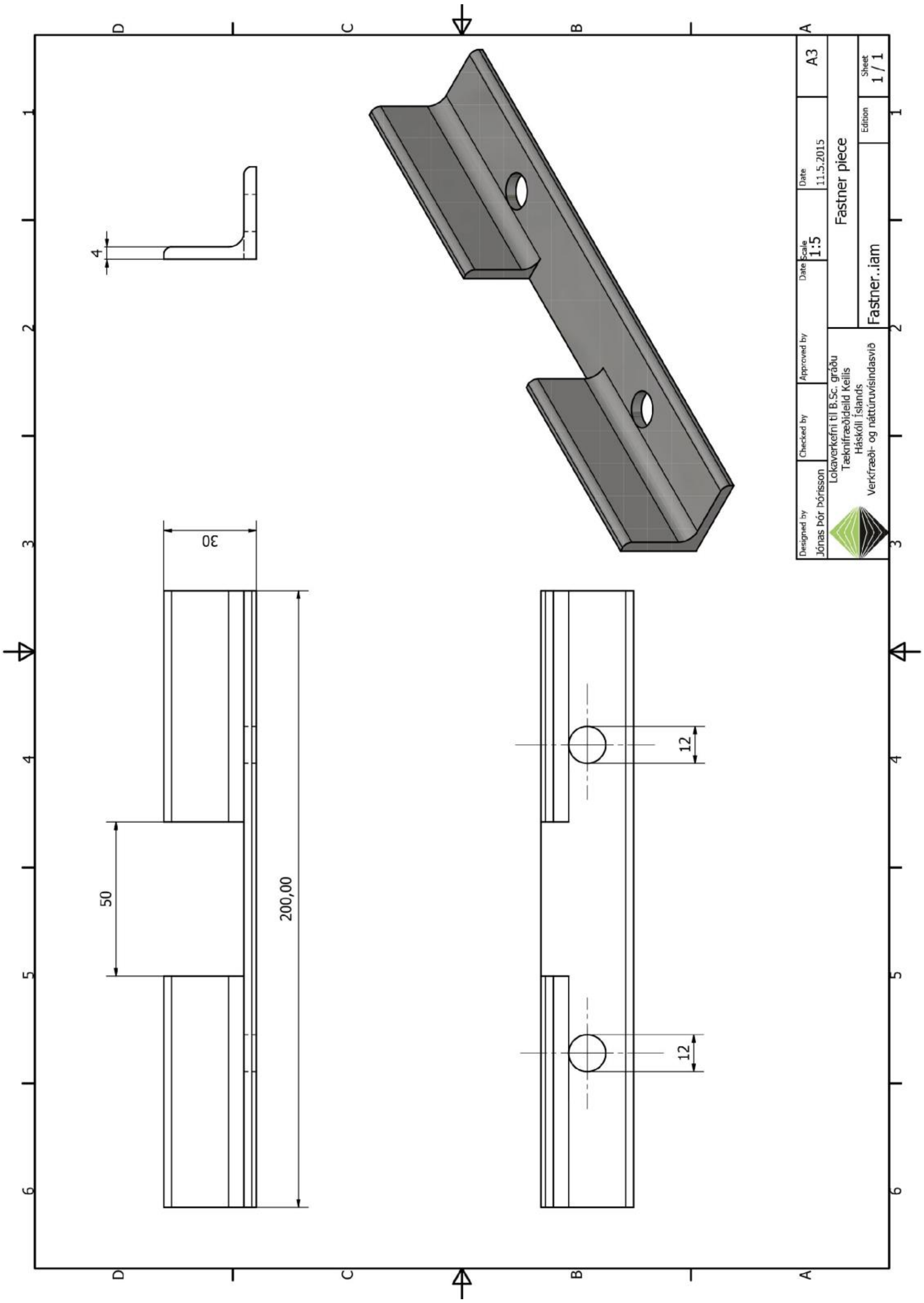


Part list for test column

Quant.	Part	Supplier	Cost	Cost incl. VAT
	Column			
1	160x9,1x2000mm PE plastic piping.	SET	- kr.	- kr.
4	PE100 Flange Long 160mm	SET	13.480 kr.	16.917 kr.
4	PE100 Flange Ring SDR 11	SET	28.924 kr.	36.300 kr.
2	PE100 Welded Endcap	SET	10.600 kr.	13.303 kr.
2	210mm rubber gasket	Fossberg	1.929 kr.	2.392 kr.
	TOTAL for this section		54.933 kr.	68.912 kr.
	Baskets			
4	Stainless steel pipe 154x2x100mm (DxWxL)	Metal	3.169 kr.	3.930 kr.
1,2m	Stainless steel square bar 3x15mm	Metal	560 kr.	694 kr.
4	Stainless perforated plate 2x160x160 35%open	Metal	- kr.	- kr.
	Sawing work	Metal	1.000 kr.	1.255 kr.
	TOTAL for this section		4.729 kr.	5.879 kr.
	Frame			
24	Carbon Rectangular Pipe 50x50x4	GA Stál	27.652 kr.	31.200 kr.
	TOTAL for this section		27.652 kr.	31.200 kr.
	Fsteners			
4	40x40x4 angle bar	Keilir	-	-
2	Various fastners	Húsasmiðjan/Fossberg	962 kr.	1.193 kr.
2	5" carbon steel bracers. 1 pair	Tækni	4.514 kr.	5.597 kr.
	TOTAL for this section		5.476 kr.	6.790 kr.
	Fittings			
2	Various Fittings	Landvélar/Barki	13.554 kr.	16.807 kr.
1	Lechler spray noozle - 490523 - 45° - 2L/min at 2 Bar	Vatnslausnir	8.634 kr.	10.706 kr.
	TOTAL for this section		22.188 kr.	27.513 kr.
	Chemicals			
200 l	99,6% monoethanolamine	Skeljungur	105.085 kr.	130.305 kr.
			105.085 kr.	130.305 kr.
	SUB TOTAL FOR TEST PROJECT		114.978 kr.	270.599 kr.

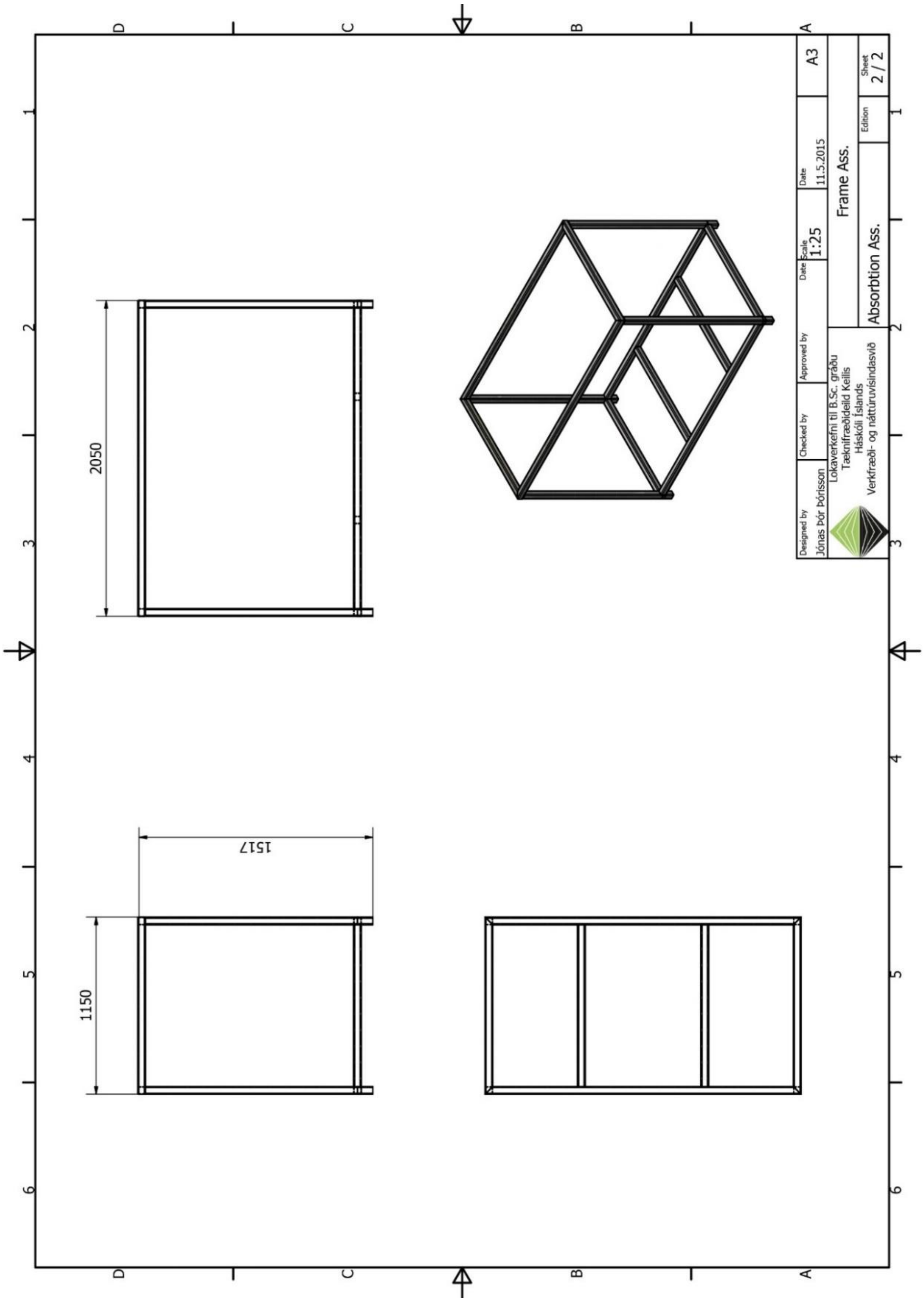
Appendix C - Part list for test build with cost.

Appendix D – Work diagram 1



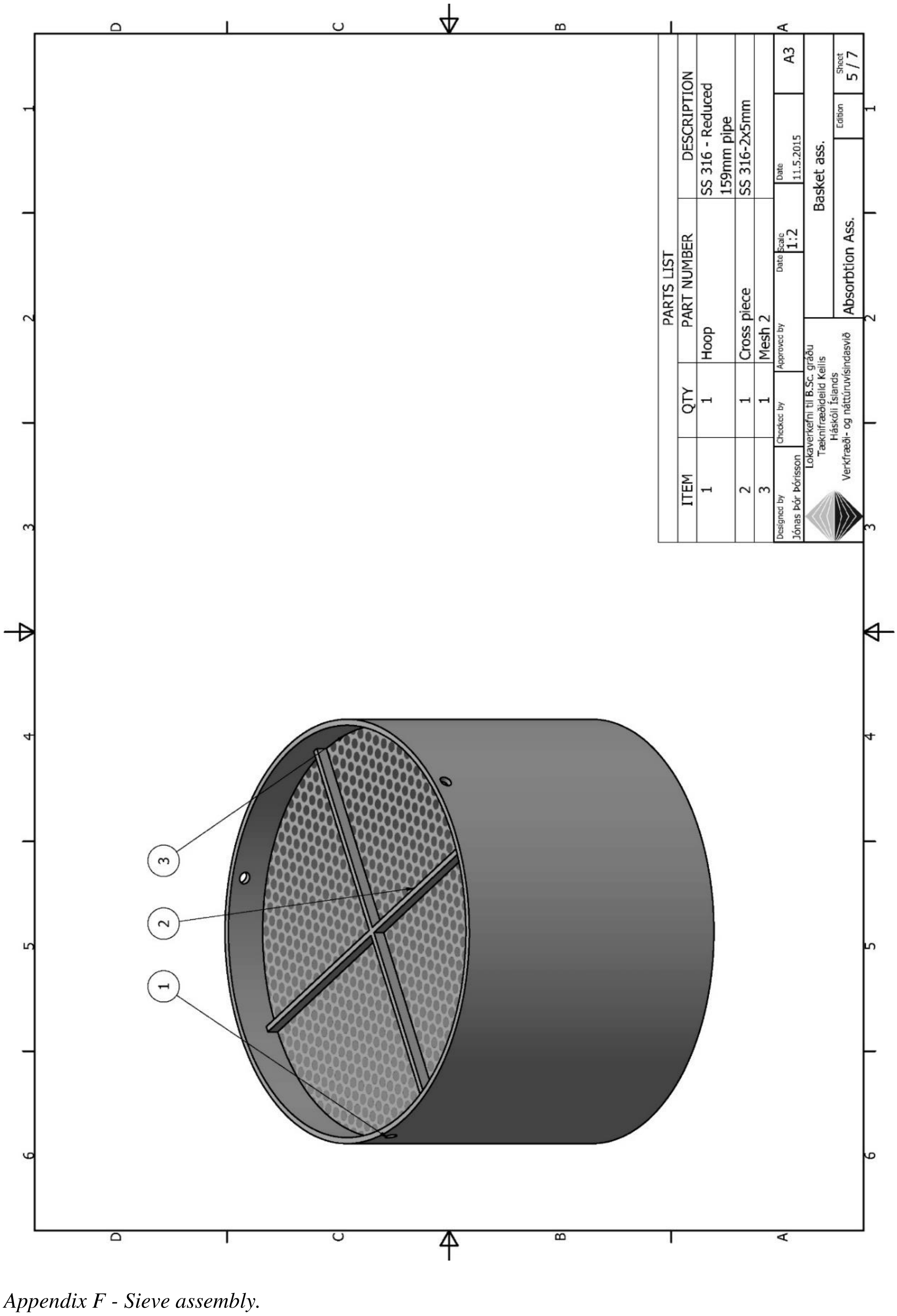
Appendix D - Work diagram of fastener piece.

Appendix E – Work diagram 2



Appendix E - Work drawing of frame ass.

Appendix F – Work diagram 3



PARTS LIST

ITEM	QTY	PART NUMBER	DESCRIPTION
1	1	Hoop	SS 316 - Reduced 159mm pipe
2	1	Cross piece	SS 316-2x5mm
3	1	Mesh 2	

Designed by	Checked by	Approved by	Date	Scale	Date	
Jónas Þór Þórisson				1:2	11.5.2015	A3

Lokaverkefni til B.Sc. gráðu
Tæknifræðideild Keilis
Háskóli Íslands
Verkfræði- og náttúruvísindasvið

Basket ass.

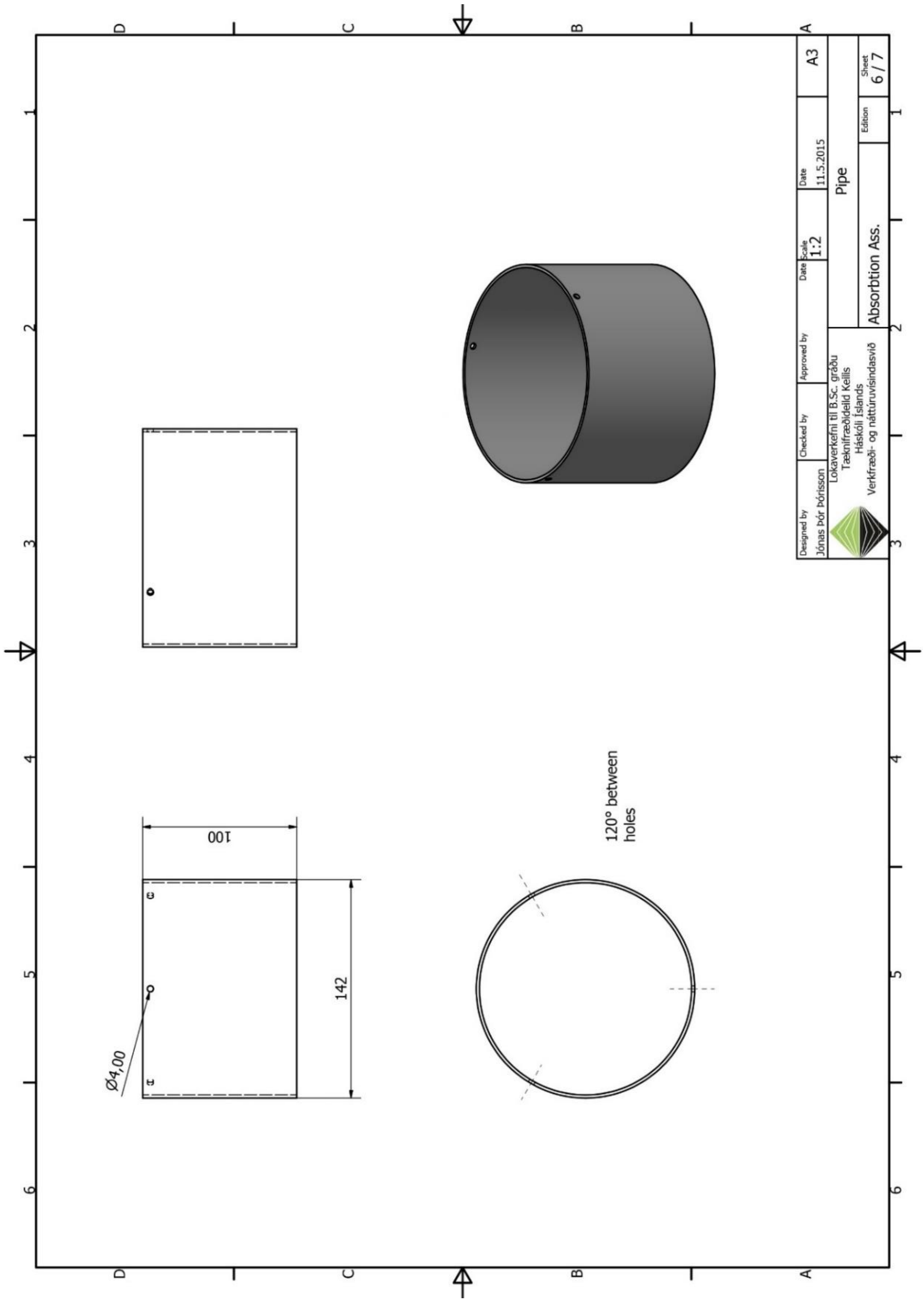
Absorbtion Ass.

Edition

Sheet 5 / 7

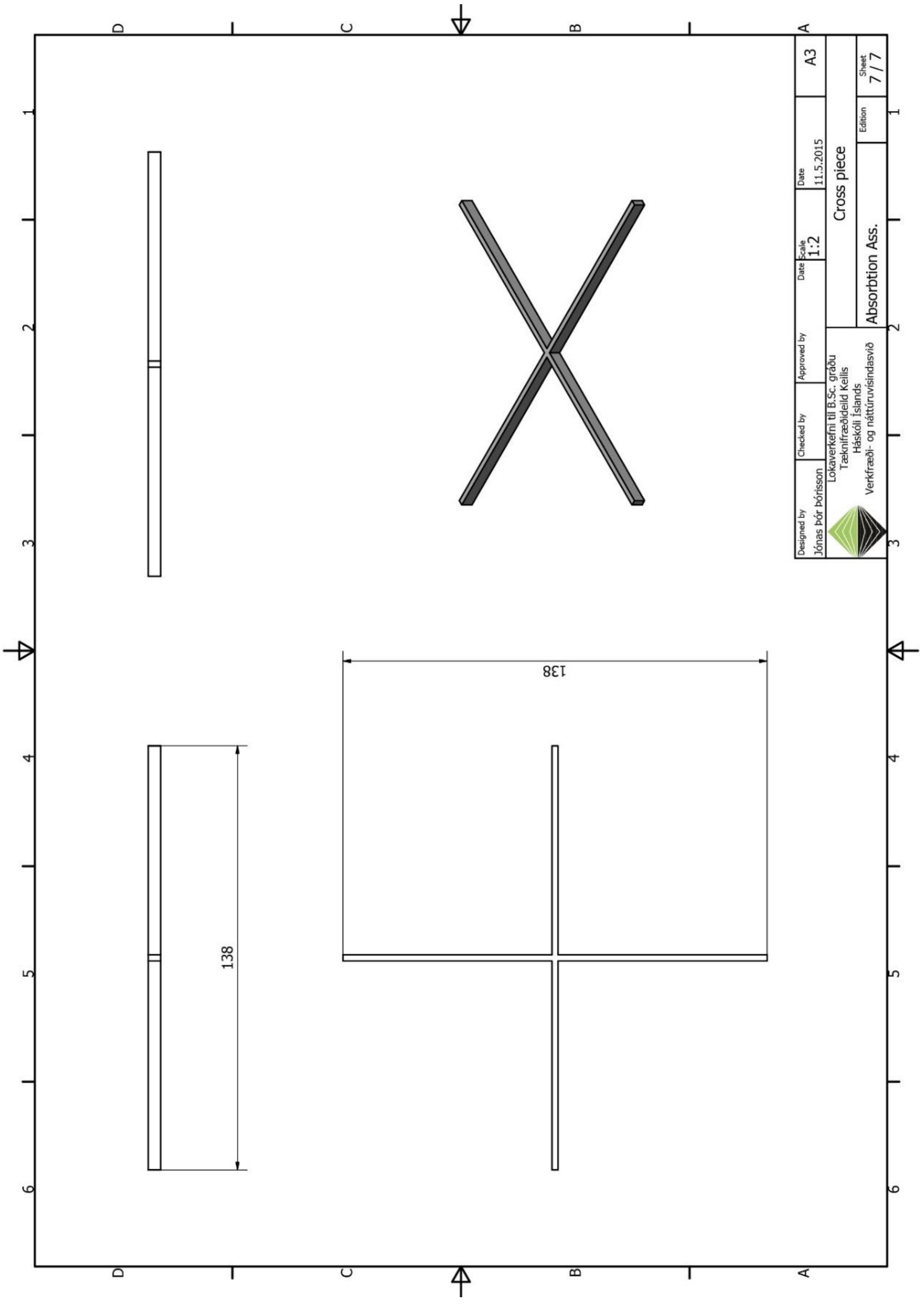
Appendix F - Sieve assembly.

Appendix G – Work diagram 4



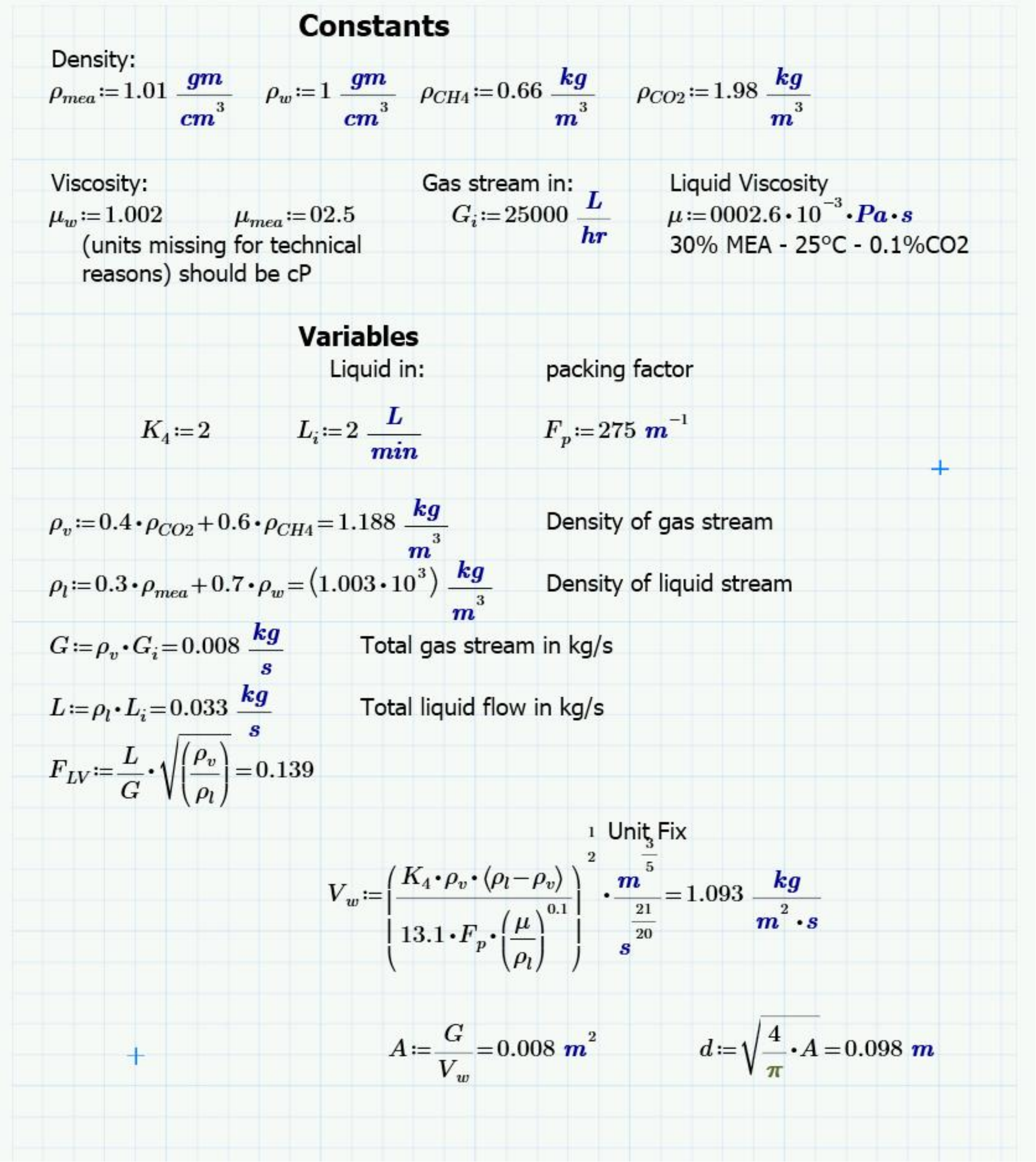
Appendix G - Pipe section for sieve.

Appendix H – Work diagram 5



Appendix H - Cross section of sieve ass.

Appendix E – Calculations of column diameter



Constants

Density:

$\rho_{mea} := 1.01 \frac{gm}{cm^3}$ $\rho_w := 1 \frac{gm}{cm^3}$ $\rho_{CH4} := 0.66 \frac{kg}{m^3}$ $\rho_{CO2} := 1.98 \frac{kg}{m^3}$

Viscosity:

$\mu_w := 1.002$ $\mu_{mea} := 02.5$

(units missing for technical reasons) should be cP

Gas stream in:

$G_i := 25000 \frac{L}{hr}$

Liquid Viscosity

$\mu := 0002.6 \cdot 10^{-3} \cdot Pa \cdot s$

30% MEA - 25°C - 0.1%CO2

Variables

Liquid in:

packing factor

$K_4 := 2$ $L_i := 2 \frac{L}{min}$ $F_p := 275\ m^{-1}$

$\rho_v := 0.4 \cdot \rho_{CO2} + 0.6 \cdot \rho_{CH4} = 1.188 \frac{kg}{m^3}$ Density of gas stream

$\rho_l := 0.3 \cdot \rho_{mea} + 0.7 \cdot \rho_w = \left(1.003 \cdot 10^3\right) \frac{kg}{m^3}$ Density of liquid stream

$G := \rho_v \cdot G_i = 0.008 \frac{kg}{s}$ Total gas stream in kg/s

$L := \rho_l \cdot L_i = 0.033 \frac{kg}{s}$ Total liquid flow in kg/s

$F_{LV} := \frac{L}{G} \cdot \sqrt{\left(\frac{\rho_v}{\rho_l}\right)} = 0.139$

Unit Fix

$$V_w := \left(\frac{K_4 \cdot \rho_v \cdot (\rho_l - \rho_v)}{13.1 \cdot F_p \cdot \left(\frac{\mu}{\rho_l}\right)^{0.1}}\right)^{\frac{1}{2}} \cdot \frac{m^{\frac{3}{5}}}{s^{\frac{21}{20}}} = 1.093 \frac{kg}{m^2 \cdot s}$$

$A := \frac{G}{V_w} = 0.008\ m^2$ $d := \sqrt{\frac{4}{\pi} \cdot A} = 0.098\ m$

Appendix I - Calculation of K_4 and F_{LV} diameter

Appendix J – Raw data from test 2

Minutes	CH4 out	CH4 in	CO2 out	CO2 in	CO2 out / CO2 in	O2 out	O2 in	BALANCE out	BALANCE in	N2+CH4 out	N2+CH4 in	Amine pH	Temp.	H2S out	H2S in
(min)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	-	°C	(ppm)	(ppm)
0	74	39,1	2,5	32	92%	5	6,1	18,5	22,8	92,5	61,9	12,11	8,5	1	94
3	74,8	39,1	5,2	32	84%	3,7	6,1	16,3	22,8	91,1	61,9	12,09	8,7	1	94
6	73,2	39,1	5,4	32	83%	3,8	6,1	17,6	22,8	90,8	61,9	12,01	9,5	1	94
9	72,5	41,8	5,8	33,9	83%	3,8	5,2	17,9	19,1	90,4	60,9	11,95	10,2	0	96
12	72	41,8	6,4	33,9	81%	3,7	5,2	17,9	19,1	89,9	60,9	11,88	10,8	1	96
15	70,9	41,8	7	33,9	79%	3,8	5,2	18,3	19,1	89,2	60,9	11,83	11,2	1	96
18	70,9	41,8	8	33,9	76%	3,6	5,2	17,5	19,1	88,4	60,9	11,73	11,8	1	96
21	69,8	41,8	9	33,9	73%	3,7	5,2	17,5	19,1	87,3	60,9	11,7	12,3	1	96
24	70,5	41,8	9	33,9	73%	3,6	5,2	16,9	19,1	87,4	60,9	11,68	12,9	1	96
27	70,2	41,8	9,2	33,9	73%	3,7	5,2	16,9	19,1	87,1	60,9	11,63	13,6	1	96
30	70,1	41,8	9,9	33,9	71%	3,6	5,2	16,4	19,1	86,5	60,9	11,58	14,1	1	96
33	69,3	41,8	10,5	33,9	69%	3,6	5,2	16,6	19,1	85,9	60,9	11,54	14,6	2	96
36	69,3	41,8	10,8	33,9	68%	3,6	5,2	16,3	19,1	85,6	60,9	11,49	15,3	2	96
42	68,5	41,8	12,4	33,9	63%	3,5	5,2	15,6	19,1	84,1	60,9	11,45	15,7	4	96
45	67,7	41,8	14,3	33,9	58%	3,5	5,2	14,5	19,1	82,2	60,9	11,39	16,3	4	96
48	67,7	41,8	14,1	33,9	58%	3,6	5,2	14,6	19,1	82,3	60,9	11,37	16,6	4	96
51	66,7	42,5	15,5	35	56%	3,5	4,5	14,3	18	81	60,5	11,35	16,8	6	115
54	66	42,5	16,4	35	53%	3,5	4,5	14,1	18	80,1	60,5	11,32	17	7	115
57	65,8	42,5	16,6	35	53%	3,5	4,5	14,1	18	79,9	60,5	11,3	17,2	8	115
60	65,5	42,5	17,2	35	51%	3,5	4,5	13,8	18	79,3	60,5	11,29	17,4	9	115

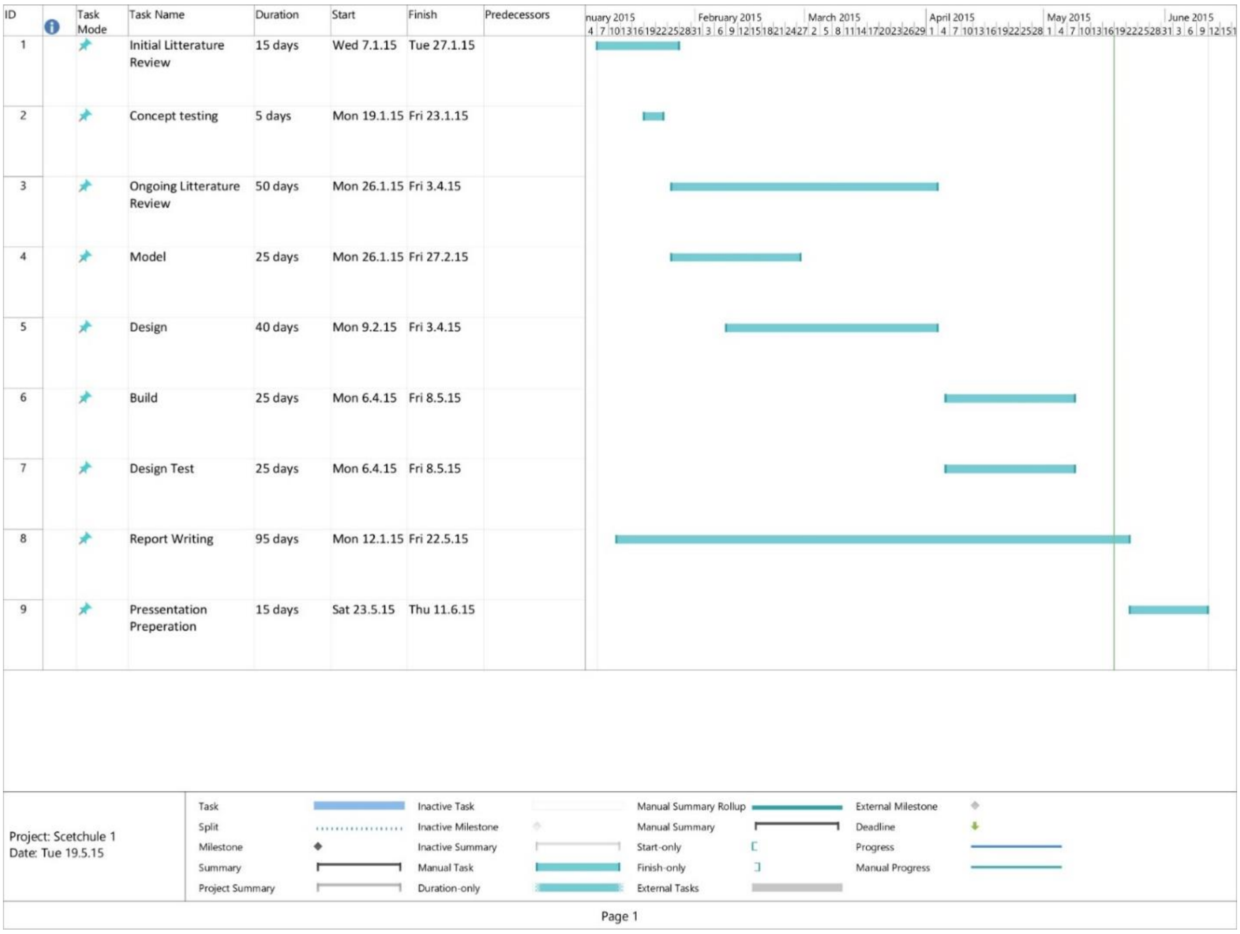
63	65,1	42,5	18	35	49%	3,4	4,5	13,5	18	78,6	60,5	11,27	17,6	10	115
69	63,7	42,5	20	35	43%	3,2	4,5	13,1	18	76,8	60,5	11,23	18,1	14	115
72	63,7	42,5	20,5	35	41%	3,2	4,5	12,6	18	76,3	60,5	11,21	18,2	16	115
75	62,6	42,5	21,1	35	40%	3,3	4,5	13	18	75,6	60,5	11,19	18,4	17	115
78	62,5	44,4	22,2	35,7	38%	3	4,1	12,3	15,8	74,8	60,2	11,16	18,6	19	121
81	62,1	44,4	21,9	35,7	39%	3,1	4,1	12,9	15,8	75	60,2	11,14	18,8	19	121
84	61,7	44,4	23	35,7	36%	3	4,1	12,3	15,8	74	60,2	11,13	18,9	22	121
87	60,9	44,4	23,3	35,7	35%	3,1	4,1	12,7	15,8	73,6	60,2	11,12	18,9	23	121
90	61,1	44,4	23,1	35,7	35%	3,1	4,1	12,7	15,8	73,8	60,2	11,11	19	23	121

Appendix K – Raw data from test 1

Δtime	DATE/TIME	CH_4	CO_2	O_2	BALANCE	H_2S	BARO	Amine pH	Amine Temp	REL.PRESSURE	Notes
min	dd.m.yyyy hh:mm	%	%	%	%	ppm	mb		°C	mb	
	Mesurements before test.										
	16.5.2015 10:58	21,3	17	13,2	48,5	29	975			-18,93	Mesurements from pump
	16.5.2015 11:53	18,7	15,5	14,3	51,5	53	975			-8,95	
	16.5.2015 11:54	18,2	15	14,4	52,4	46	975			-8,77	
	Test Mesurements										
0	16.5.2015 12:02	15,2	12,2	15,6	57	39	976	12,79	19,7	35,58	Gas pumping starts through the tower
3	16.5.2015 12:05	15,8	12,8	15,2	56,2	48	976	12,81	19,7	31,63	
6	16.5.2015 12:08	13,7	8,3	16,2	61,8	25	976	12,69	19,5	31,06	MEA flow starts
9	16.5.2015 12:11	15	0,1	18	66,9	0	977	12,50	20,3	31,41	
12	16.5.2015 12:14	15,1	0,1	18,1	66,7	0	976	12,35	21,2	31,22	
15	16.5.2015 12:17	15,6	0,1	18,1	66,2	0	977	12,27	21,4	31,01	
18	16.5.2015 12:20	15,9	0	18,1	66	0	976	12,19	21,6	30,59	
21	16.5.2015 12:23	15,7	0	18,2	66,1	0	976	12,13	21,8	30,64	
24	16.5.2015 12:26	15,9	0	18,2	65,9	0	976	12,07	21,9	30,38	
27	16.5.2015 12:29	10,8	0	19,3	69,9	0	976	12,03	22,1	22,48	
30	16.5.2015 12:32	10,4	0	19,5	70,1	0	976	12,01	22,2	20,13	
33	16.5.2015 12:35	10,6	0	19,4	70	0	976	11,97	22,2	19,49	

36	16.5.2015 12:38	10,8	0	19,6	69,6	0	976	11,91	22,4	-2,55	Water build up in test hose
39	16.5.2015 12:41	16,1	0	18,2	65,7	0	976	11,88	22,5	33,98	
42	16.5.2015 12:44	16,2	0	18,2	65,6	0	977	11,86	22,6	33,09	
45	16.5.2015 12:47	16,9	0	18,2	64,9	0	977	11,83	22,7	32,28	
48	16.5.2015 12:50	15,9	0	18,4	65,7	0	977	11,75	22,9	32,41	
51	16.5.2015 12:53	15,7	0	18,5	65,8	0	977	11,75	23,0	32,62	
54	16.5.2015 12:56	15,8	0	18,5	65,7	0	977	11,71	23,2	32,43	
57	16.5.2015 12:59	15,4	0	18,6	66	0	977	11,67	23,3	32,62	
60	16.5.2015 13:02	15,7	0	18,6	65,7	0	977	11,67	23,3	32,52	Test ends
	Post test mesurments										
	16.5.2015 13:07	13,5	10,5	16,9	59,1	0	978			-3,75	Mesurment from pump after test
	16.5.2015 13:10	56,9	44,9	0,2	0	124	979			-0,35	Mesurment from borehole after test

Appendix L – Original work schedule

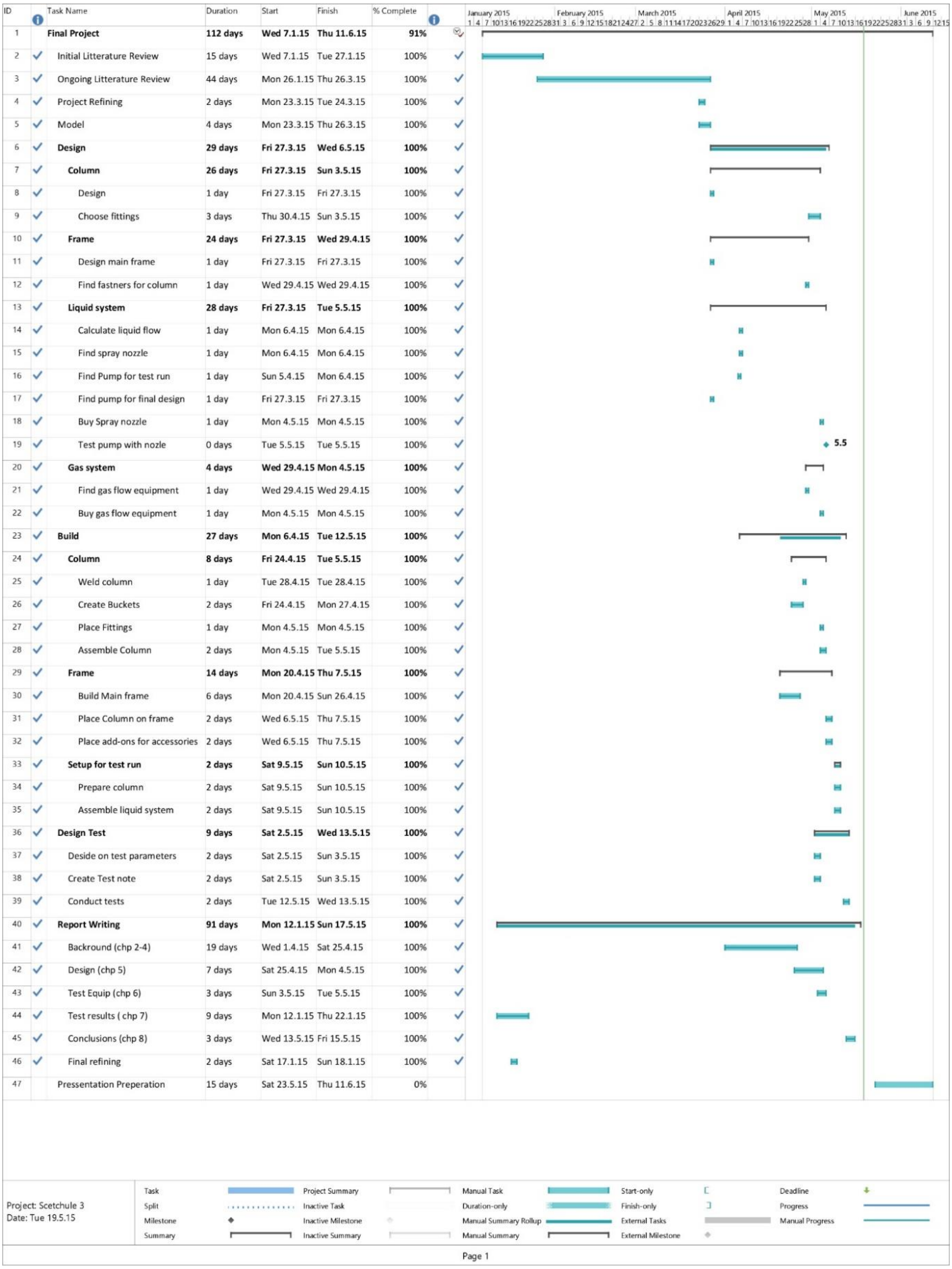


ID	ℹ	Task Mode	Task Name	Duration	Start	Finish	Predecessors
1		📌	Initial Litterature Review	15 days	Wed 7.1.15	Tue 27.1.15	
2		📌	Concept testing	5 days	Mon 19.1.15	Fri 23.1.15	
3		📌	Ongoing Litterature Review	50 days	Mon 26.1.15	Fri 3.4.15	
4		📌	Model	25 days	Mon 26.1.15	Fri 27.2.15	
5		📌	Design	40 days	Mon 9.2.15	Fri 3.4.15	
6		📌	Build	25 days	Mon 6.4.15	Fri 8.5.15	
7		📌	Design Test	25 days	Mon 6.4.15	Fri 8.5.15	
8		📌	Report Writing	95 days	Mon 12.1.15	Fri 22.5.15	
9		📌	Pressentation Preperation	15 days	Sat 23.5.15	Thu 11.6.15	

Project: Scetchule 1
Date: Tue 19.5.15

Page 1

Appendix M – Refined Work Schedule



ID		Task Name	Duration	Start	Finish	% Complete	
1		**Final Project**	**112 days**	**Wed 7.1.15**	**Thu 11.6.15**	**91%**	
2	✓	Initial Litterature Review	15 days	Wed 7.1.15	Tue 27.1.15	100%	✓
3	✓	Ongoing Litterature Review	44 days	Mon 26.1.15	Thu 26.3.15	100%	✓
4	✓	Project Refining	2 days	Mon 23.3.15	Tue 24.3.15	100%	✓
5	✓	Model	4 days	Mon 23.3.15	Thu 26.3.15	100%	✓
6	✓	**Design**	**29 days**	**Fri 27.3.15**	**Wed 6.5.15**	**100%**	✓
7	✓	**Column**	**26 days**	**Fri 27.3.15**	**Sun 3.5.15**	**100%**	✓
8	✓	Design	1 day	Fri 27.3.15	Fri 27.3.15	100%	✓
9	✓	Choose fittings	3 days	Thu 30.4.15	Sun 3.5.15	100%	✓
10	✓	**Frame**	**24 days**	**Fri 27.3.15**	**Wed 29.4.15**	**100%**	✓
11	✓	Design main frame	1 day	Fri 27.3.15	Fri 27.3.15	100%	✓
12	✓	Find fastners for column	1 day	Wed 29.4.15	Wed 29.4.15	100%	✓
13	✓	**Liquid system**	**28 days**	**Fri 27.3.15**	**Tue 5.5.15**	**100%**	✓
14	✓	Calculate liquid flow	1 day	Mon 6.4.15	Mon 6.4.15	100%	✓
15	✓	Find spray nozzle	1 day	Mon 6.4.15	Mon 6.4.15	100%	✓
16	✓	Find Pump for test run	1 day	Sun 5.4.15	Mon 6.4.15	100%	✓
17	✓	Find pump for final design	1 day	Fri 27.3.15	Fri 27.3.15	100%	✓
18	✓	Buy Spray nozzle	1 day	Mon 4.5.15	Mon 4.5.15	100%	✓
19	✓	Test pump with nozle	0 days	Tue 5.5.15	Tue 5.5.15	100%	✓
20	✓	**Gas system**	**4 days**	**Wed 29.4.15**	**Mon 4.5.15**	**100%**	✓
21	✓	Find gas flow equipment	1 day	Wed 29.4.15	Wed 29.4.15	100%	✓
22	✓	Buy gas flow equipment	1 day	Mon 4.5.15	Mon 4.5.15	100%	✓
23	✓	**Build**	**27 days**	**Mon 6.4.15**	**Tue 12.5.15**	**100%**	✓
24	✓	**Column**	**8 days**	**Fri 24.4.15**	**Tue 5.5.15**	**100%**	✓
25	✓	Weld column	1 day	Tue 28.4.15	Tue 28.4.15	100%	✓
26	✓	Create Buckets	2 days	Fri 24.4.15	Mon 27.4.15	100%	✓
27	✓	Place Fittings	1 day	Mon 4.5.15	Mon 4.5.15	100%	✓
28	✓	Assemble Column	2 days	Mon 4.5.15	Tue 5.5.15	100%	✓
29	✓	**Frame**	**14 days**	**Mon 20.4.15**	**Thu 7.5.15**	**100%**	✓
30	✓	Build Main frame	6 days	Mon 20.4.15	Sun 26.4.15	100%	✓
31	✓	Place Column on frame	2 days	Wed 6.5.15	Thu 7.5.15	100%	✓
32	✓	Place add-ons for accessories	2 days	Wed 6.5.15	Thu 7.5.15	100%	✓
33	✓	**Setup for test run**	**2 days**	**Sat 9.5.15**	**Sun 10.5.15**	**100%**	✓
34	✓	Prepare column	2 days	Sat 9.5.15	Sun 10.5.15	100%	✓
35	✓	Assemble liquid system	2 days	Sat 9.5.15	Sun 10.5.15	100%	✓
36	✓	**Design Test**	**9 days**	**Sat 2.5.15**	**Wed 13.5.15**	**100%**	✓
37	✓	Deside on test parameters	2 days	Sat 2.5.15	Sun 3.5.15	100%	✓
38	✓	Create Test note	2 days	Sat 2.5.15	Sun 3.5.15	100%	✓
39	✓	Conduct tests	2 days	Tue 12.5.15	Wed 13.5.15	100%	✓
40	✓	**Report Writing**	**91 days**	**Mon 12.1.15**	**Sun 17.5.15**	**100%**	✓
41	✓	Backround (chp 2-4)	19 days	Wed 1.4.15	Sat 25.4.15	100%	✓
42	✓	Design (chp 5)	7 days	Sat 25.4.15	Mon 4.5.15	100%	✓
43	✓	Test Equip (chp 6)	3 days	Sun 3.5.15	Tue 5.5.15	100%	✓
44	✓	Test results (chp 7)	9 days	Mon 12.1.15	Thu 22.1.15	100%	✓
45	✓	Conclusions (chp 8)	3 days	Wed 13.5.15	Fri 15.5.15	100%	✓
46	✓	Final refining	2 days	Sat 17.1.15	Sun 18.1.15	100%	✓
47		Pressentation Preperation	15 days	Sat 23.5.15	Thu 11.6.15	0%	

Project: Scetchule 3
Date: Tue 19.5.15

Appendix N – Calculations from previous version

5.4 Column diameter

As described earlier the column needs to be wide enough to prevent flooding. Flooding happens when all of the free space in the packing material is filled with fluid and the fluid gets pushed up by the gas. In the work of Huertas it can be seen that the quadratic correlation between the gas flow and liquid flow can be used to determine the diameter of the column.

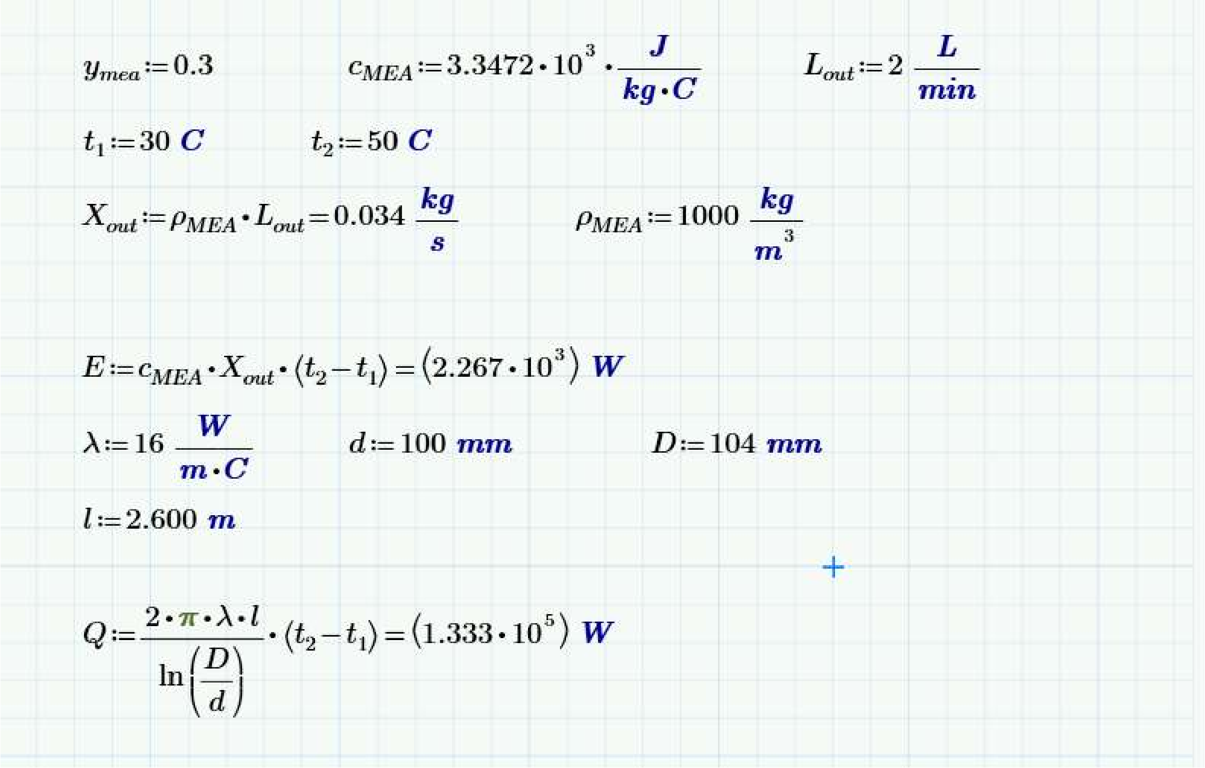
He describes two columns, first is 6.7 cm at 7.6 m^3/h and the second is 18.8 cm at 60 m^3/h. From his findings equation 1 can be created where d is the diameter of the column and Yg is the gas stream in.

$$d = \sqrt{\frac{Y_g}{7.6}} * 6.7\ cm$$

Equation 1 -. Formula for column diameter, derived from the work of Huertas. [9].

According to these findings the optimal diameter for this project at 25 Nm_3/h is 127 mm. This size should prevent flooding but a pipe of 139.7mm was chosen since it is a standard shelf pipe size. It will make slightly more MEA necessary to ensure that the filling is all wet but should be within limits for this project.

Appendix O - Calculations for temperature calculations



$y_{mea} := 0.3$ $\quad c_{MEA} := 3.3472 \cdot 10^{3} \cdot \frac{J}{kg \cdot C}$ $\quad L_{out} := 2 \frac{L}{min}$

$t_1 := 30\ C$ $\quad t_2 := 50\ C$

$X_{out} := \rho_{MEA} \cdot L_{out} = 0.034 \frac{kg}{s}$ $\quad \rho_{MEA} := 1000 \frac{kg}{m^3}$

$E := c_{MEA} \cdot X_{out} \cdot \left(t_2 - t_1\right) = \left(2.267 \cdot 10^{3}\right) W$

$\lambda := 16 \frac{W}{m \cdot C}$ $\quad d := 100\ mm$ $\quad D := 104\ mm$

$l := 2.600\ m$

$$Q := \frac{2 \cdot \pi \cdot \lambda \cdot l}{\ln\left(\frac{D}{d}\right)} \cdot \left(t_2 - t_1\right) = \left(1.333 \cdot 10^{5}\right) W$$