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Industrial Electrical Engineering and Automation

Earthing Lug Design for Alfa Laval Gasketed Plate Heat Exchanger

Evaluation of Earthing Lug Designs and a Study of the Static Electricity Phenomenon

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Abstract

In applications involving the flow of low conductivity liquids, great care must be taken to avoid static electricity build-up which could potentially lead to catastrophic discharges. As the Gasketed Plate Heat Exchanger line-up offered by Alfa Laval is used in such scenarios, the heat exchanger has to be grounded using an earthing lug to eliminate the risk of discharge. As the only requirement for such an earthing lug is that it is securely attached to the heat exchanger with a resistance low enough to ensure effective dissipation, a plethora of ways to do this is possible. But without proper understanding of how static electricity works and how it fits in with the heat exchanger, there is a significant risk that solutions chosen fail to provide a proper path to ground. For this reason, a comprehensive work on static electricity was produced and then used as a source when examining the heat exchanger.

Static electricity is essentially caused by a charge imbalance in the atoms constituting all matter. This imbalance can be caused by three mechanisms, Induction charging, Corona charging and Contact charging. In this thesis, the focus has been a special case of contact charging involving a liquid and a solid, called Flow electrification. The electrical discharges which are a consequence of charge imbalances have all been explained and the two major hazards related to it, ignition and ESD, have both been explored and examples have been given.

The source of the charge accumulation in the heat exchanger was determined to be the heat transferring plates, wedged between the frame and pressure plate. The cause is theorised to be a case of flow electrification which is a charge accumulating mechanism between a solid and a liquid.

Five designs are presently available to customers to ground the heat exchanger but all require further testing and verification to determine if they perform as expected. A circuit resistance to earth of 10 Ω or lower is usually used as an indicator of an adequate circuit and is therefore used as an evaluation parameter during testing. The results showed that the three frame plate mounted designs were ineffective as the measured resistance was well above the chosen threshold and maximum allowed resistance of 1 $M\Omega$.

After additional tests and experimentation, the epoxy paint used to coat the frame and pressure plate proved to be the reason for this as it was effectively isolating the two plates from the heat plates where the charge accumulation is believed to occur. Based on this and a selection matrix weighing factors of interest from a production and cost perspective, the two designs mounted on the support column were determined to be preferred and therefore recommended with the fastener design being the preferred one. Guidelines of how to make the three ineffective designs into viable options were also provided.

Keywords: Static electricity, conductivity, resistance, flow electrification, solid, liquid, GPHE, discharge.

Preface and Acknowledgements

This thesis marks the final step of my five years at the mechanical engineer program at LTH and was written at the division of Industrial Electrical Engineering and Automation in collaboration with Alfa Laval. I would like to begin to express my gratitude to Alfa Laval for giving me the opportunity to do my master's thesis with them, giving me a taste of how things work outside the walls of LTH.

I would like to especially express my gratitude to my supervisor at Alfa Laval, Martin Andersson, and to Kent Sallhammar who both, despite having packed schedules, always had time for me when I needed it whether it was through our regular meetings or when I needed information about something. Although lending me a GPHE was necessary for the outcome of the project, I am thankful for the freedom to do whatever I needed with it.

I would also like to express my thanks to my supervisor at LTH, Gunnar Lindstedt for the help he has provided me during these weeks and always doing so with enthusiasm. I also thank him and my examiner, Johan Björnstedt, for agreeing to take on this thesis as it is not 100% in line with the usual master's thesis projects done at the division. Special thanks also goes out to Getachew Darge at IEA for helping me with all the welding, drilling and threading needed as well as providing me with necessary equipment.

Finally I would like to thank Denis Miraljemovic and Arbias Zejnullahu for both keeping me company these many weeks but also for helping me when I had to take the heat exchanger apart and put it back together. Also, thank you Denis for risking your car when I needed help with transporting the heat exchanger to LTH. In retrospect, my plan to push the +100 Kg heat exchanger from Gunnesbo to LTH on a makeshift wagon might not have been my brightest idea (although I did make it halfway before my wagon broke down).

Acronyms and Definitions

EDL: Electrical Double Layer.
FP: Frame Plate.
GPHE: Gasketed Plate Heat Exchanger.
SC: Support Column.

Space Charge: A three - dimensional electrical charge distribution.

Charge (Q): Accumulation or deficiency of electrons in a material, giving the material a positive or negative charge. Measured in Coulombs (C)

Voltage (U): Potential difference between two points in an electric field or in other words, the work/charge unit needed to move a charged particle between the two points. Measured in Volts (V).

Breakdown Voltage: Minimum voltage necessary to make an insulator partially conductive. Measured in Volts (V).

Surface Resistance (R): Measures the ease which a charge can move through the surface of a material. Measured in Ohms (Ω). Higher resistance means it is harder for a charge to move through the surface of the material.

Conductivity (σ): The reciprocal of resistance and is often used for liquids the same way resistance is use for solids. Measured in Siemens per meters (S/m). Higher conductivity means that it is easier for a charge to move through the material.

Current (I): Charge flow through a medium per unit of time:

$$I = \frac{dQ}{dt} \tag{1}$$

Measured in Ampere (A).

Capacitance (C): A capacitors ability to store electrical charges. Measured in Farads (F). Related to Voltage and Charge in the following way:

$$Q = CV \tag{2}$$

The capacitance between two parallel plates is defined as:

$$C = \epsilon_0 \epsilon_r \frac{A}{d} \tag{3}$$

where ϵ_0 is an electrical constant $8.85 * 10^{-12}\ Fm^{-1}$, ϵ_r is the relative permittivity of the medium filling the gap between the plates in Farads, A is the common surface area between the two plates in m^2 and d the distance between the plates.

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1 Introduction

The purpose of this chapter is to present the problem at hand and to show why it is of interest for Alfa Laval. The problem will be broken down into research questions and the methodology for tackling the problem will be presented.

1.1 Background

One of Alfa Laval's primary areas of business is the development and manufacturing of heat exchangers (such as the Gasketed Plate Heat Exchanger, GPHE) for companies operating in a wide variety of industries, all which have different requirements. One of these requirements is the addition of an earthing lug to the heat exchanger with the purpose of grounding the static electricity that may be generated during normal operation and it is the design, way of attaching it and general knowledge about static electricity that is the focus of this project. Static electricity is quite common in industry [1] as a result of machines and equipment being operated, heat exchangers included. Statically charged heat exchangers is usually of no concern but there are cases where this could be a problem. If the exchanger is operating in an environment containing sensitive electric equipment or flammable substances, sudden discharge caused by the charge build-up could lead to additional equipment costs, accidents or worse. Since a part of Alfa Laval's customers who purchase heat exchangers intend to use them in hazardous environments, it is of great interest for Alfa Laval to gain more knowledge in this field in order to provide customers with a good product, at a market competitive price. As of right now, Alfa Laval has come up with a couple of suggestions which they believe to be efficient and financially doable and they believe that the flow of liquids through the exchanger is the cause of the static electricity. However, at the moment Alfa Laval is preoccupied with more pressing matters and is not able to invest the necessary time and resources which is required and even though he knowledge they have about this has served them well so far, the exact reason behind the static electricity build-up needs to be identified along with thorough testing and documentation of the existing solution suggestions.

1.2 Objective

The objective of this project is to identify and explain the cause behind the charge build-up in the heat exchangers offered by Alfa Laval but also to test, document and evaluate the existing earthing lug design suggestions so that Alfa Laval can show that the solution they choose to offer is backed by concrete data, competitive on the market, follows standards and regulations and most importantly, cost effective. In addition to this, the aim is also to contribute to Alfa Laval's knowledge portfolio in the area of static electricity. To fulfil the objective, the following research questions will be answered:

- What is static electricity and how does the physics behind it work?
- How is static electricity measured?
- Is it the liquids flowing through the heat exchanger which is the cause of the generated static electricity and in that case, how?

- How does the heat exchanger work and how does this relate to the previous point?
- Are there other similar existing solutions to draw inspirations from?
- Are the design suggestions practical and financially defendable?
- What standards and/or regulations currently exist for this type of problem?
- What parameters are of most interest for potential customers?
- Should all heat exchangers be equipped with the earthing lug or should only some where the customer specifies it?

1.3 Methodology

The project will be split into two parts, first a theoretical literature study followed by a practical testing/evaluation part. The idea is that through the initial literature study a foundation will be built which the succeeding testing/evaluation phase will build-upon and validate some of the hypothesis made during the literature study. Although the project is split into two parts, the literature study will run in parallel with the practical testing/evaluation as a way of following up on the results obtained.

1.3.1 Literature study

As stated previously, the literature study will form the base upon which the project will be built upon. The initial part will focus on answering the following questions which strongly relates back to the research questions above:

- What is static electricity and how does the physics behind it work?
- How is the static electricity in the heat exchanger generated and what parameters affect it?
- How is static electricity measured and quantified? Are those methods applicable to the problem at hand or are other methods necessary to validate the suggested solutions?

To answer these questions, information found both on the internet and literature will be consulted. To find relevant literature and information, LUBSearch (a search tool with access to all resources available through the university libraries) will he used to find relevant information in the form of literature, scientific reports, documents pertaining standard regulations for these kinds of problems and more. With more knowledge related to the three points above, the testing/evaluation of the solutions will commence while continuing the literature study in parallel on topics deemed necessary. In addition to following up on the results obtained from testing, the following research questions above will be examined:

- Are there other similar existing solutions to draw inspiration from?
- Are the suggested solutions practical and financially defendable?
- What standards and/or regulations currently exist for this kind of problem?

- What parameters are of most interest for potential customers?

For this, information obtained from the initial literature study will be used in addition to results from testing and information provided by Alfa Laval which primarily relates to customer demands, costs, manufacturing and their input in general.

1.3.2 Testing and evaluation

The test will be made on the M6 GPHE which is provided by Alfa Laval. The test are performed in the IEA division Lab 3 with equipment provided by the university. To receive help with the operations listed below, knowledgeable university staff will be consulted. The existing solution suggestions provided by Alfa Laval are:

- FP Weld (FP_1 in Fig.43 in Appendix A1)
- SC Weld (SC_3 in Fig.43 in Appendix A1)
- SC Fastener(SC_4 in Fig.43 in Appendix A1)
- FP Screw (FP_2 in Fig.43 in Appendix A1)
- FP Boss Weld (FP_4 in Fig.43 in Appendix A1)

The test will consist of measuring the resistance between the source of the static electricity in the heat exchanger and the ground connection on the earthing lug. A detailed explanation for how these tests will be performed will be given in a separate chapter. As for the evaluation of results and deciding which solution to recommend to Alfa Laval, a selection matrix incorporating the following will be used:

- Test results
- Cost of component
- Mounting
- Replaceability (damaged for instance)
- Durability

In additions to these five criteria's used in a selection matrix, one additional aspect will be considered for each design, general customer demands. This aspects is not quantifiable like the other criteria's and is of a more subjective nature. Therefore it is not a part of the selection matrix but will still be taken into account when making the final decisions.

1.4 Limitations

For practical reasons, test of the different suggestions will not be done while the heat exchanger is connected with fluids flowing through since this is impossible to replicate in the university lab environment. For this reason, the type of tests usually done when evaluating earthing lugs is not possible but the hope is that the actual test performed will be sufficient as a substitute in the sense that the conclusions drawn will still hold when implementing the final solution suggestion. The lack of a proper testing environment also means that any hypothesis presented regarding the source of the electrical charge sometimes present in the heat exchanger will be impossible to prove. What will be presented are general theories and cases deemed to be relevant enough to support any claims made regarding the cause.

1.5 Report Outline

The report is split into two parts. The first part is comprised of chapters 2, 3, 4 and 5 and will cover the theoretical concepts behind static electricity such as the physics behind it, how it manifests itself in industry and why it is a cause of concern. At the end of the theoretical part, in chapter 5, a hypothesis will be presented which hopefully will explain where and how the static electricity in the heat exchanger is generated in a factual and believable manner while also providing relevant parameters to the magnitude of the charge accumulated. The second part of the report covers the practical work of the project and is comprised of chapters 6, 7 and 8, introducing the designs to be evaluated, how to test and evaluate them and ending in a discussion based on the results from the tests and evaluation.

2 Static Electricity

2.1 Introduction

Static electricity as a phenomenon is known to most and is experienced daily in the form of clinging clothes or the occasional shock when touching a metal door handle on a dry winter day. For most people this is what static electricity is, a minor nuisance forgotten as fast as it occurred. But for industries such as the petroleum, chemical and semiconductor manufacturing, static electricity discharges has proven to be a major issue, causing damage on electrical components and explosion damage in flammable environments. Due to the nature of these industries, static build-up in some form is inevitable but with proper knowledge about the mechanisms behind static build-up and discharge, action can be taken to minimise these problems drastically. The main goal of this text is to provide the fundaments of electrical charges and how static build-up occurs.

2.2 Basics of Static Electricity

Knowledge about static electricity on the most basic level has been known to mankind for a long time. The first known noted and recorded occurrence of static electricity was in ancient Greece when the philosopher Thales of Miletus noticed that when rubbing amber against wool, what today is referred to electrostatic charge, accumulated [2]. Today, static electricity is often associated with rubbing two solid objects against each other and the most simple explanation is usually that electrons are rubbed off from one surface to the other. While it is true that this can cause a static build-up, there is more to it. But in order to fully grasp everything, a review of the basics of an atom and materials might be helpful.

The atom was for a long time regarded as the smallest building block and thought to comprise all materials known. However, discoveries made in the last two centuries proved that the atom itself is made of subatomic particles known as neutrons, protons and electrons. The core, or nucleus, consists of an equal amount of neutrons and protons (exception is Hydrogen and isotopes). Around the core, a cloud of electrons swarm, bound to the core. In Fig.1 below the Rutherford – Bohr model of a carbon atom is illustrated. The Rutherford – Bohr model is a simplified model of the actual atom structure but its simplicity while still being informative has made it popular when learning about the atom.

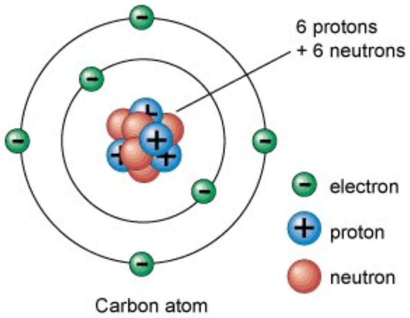


Figure 1: The Rutherford - Bohr model of a carbon atom [3]

As seen in Fig.1 above, the proton has a positive charge, the electron a negative and the neutron is uncharged. Despite this, stable atoms have no charge which is due to two things. The first is that the charge of an electron and a proton is equal in magnitude but with opposite sign. The charge of the two particles, also known as the elementary charge e, is $1,602177 * 10^{-19} C$ [4]. The second is that in addition to that the number of neutrons and protons is equal (exception is Hydrogen), so is also the number of electrons and protons for a stable atom. So as a result, the equal amount of opposite charges lead to the atom being neutral. However, if an imbalance in the number of opposite charges in the atom would occur as a result of electrons being removed or added, the atom would lose the neutral charge and whether electrons were added or removed, become positive or negative. As a result, the general consensus is that it is the electron that is the charge carrier responsible for static build-up in one way or another [5, 6, 7, 8].

Although all stable atoms share these basic principles, materials can be divided into three categories based on the surface resistivity:

- **Conductors:**
  In materials classified as conductors, the electrons are relatively free to move about within the material making them excellent at conducting a current. Typical materials are metals. Surface resistivity typically $< 10^8 \, \Omega \;\; (\Omega/Sqr)$ [7].
- **Insulators:**
  In materials classified as insulators, the electrons are bound rather tightly to the core and as a result, their movement is restricted. Typical materials are ceramics and petroleum products. Surface resistivity typically $> 10^9 \, \Omega \;\; (\Omega/Sqr)$ [7].
- **Semiconductors:**
  In materials classified as semiconductors, the electrons are freer to move than in insulators but not as free as in conductors. Surface resistivity typically found in the range of $10^6 - 10^{10} \, \Omega \;\; (\Omega/Sqr)$ [7].

Much like how volume resistance and volume resistivity are related to each other, so are surface resistance and surface resistivity. From a dimensional analysis perspective, surface resistivity is actually given in Ω but due to this being easily mixed up with surface resistance, it is commonly given in Ω/sqr [9]. The alternative unit is defined by the resistance between two electrodes on the opposite sides of a square surface [6].

2.3 The Mechanism Behind Charge Build - Up

As previously stated, the probably most common known way of creating static electricity is by rubbing two objects against each other. While it is true that this is one way of generating a charge in two materials, it will become clear that this method is actually only a special case of one out of three distinct cases that can be ascribed to charge build - up [5]:

- Induction Charging
- Corona Charging
- Contact Charging (Tribocharging)

In the cases of induction and corona charging, the charging mechanic is passive as no physical contact or relative motion between the objects is needed. Both cases also rely on the fact that a preexisting charge accumulation must be present in or close to one of the objects in order to generate a charge i the other, uncharged object. In contrast to this, contact charging, as implied by the name, requires physical contact between two materials where both can be originally uncharged, but it is not a requirement. Contact charging is for most encountered through the contact of two solid materials but it is possible to generate a charge between a solid and a liquid (and to some extent a solid and a gas).

While everything covered so far is relevant to the static electricity problem one cannot forget that the reason for all of this is to be able to provide an explanation to why Alfa Laval's heat exchangers are becoming electrically charged. For this reason, only the basics of induction and corona charging will be covered while contact charging will be given a more thorough explanation culminating in an extensive explanation behind the contact charging case involving a solid and a liquid, also called flow electrification.

2.3.1 Induction charging

It has been shown that a conductive material can become electrically charged without any involved physical contact by placing it in the vicinity of a highly charged surface [6, 7]. Imagine placing an insulator with a strong negative charge close to a conductor with no initial charge and electrically isolate them from one another, see Fig.2 below. What will happen is that the electrical field around the charged insulator will repel the electrons in the conductor surface close to the electrical field, creating oppositely charged surfaces on the conductor, see Fig.2 below. If the conductor then is grounded, the electron will flow to ground, leaving the now positively charged atoms in the conductor since they are being retained by the electrical field emanating from the insulator. If the ground connection and charged insulator then are removed, the conductor will be left with a positive charge that distributes evenly across the conductor surface since there now is a lack of electrons to balance out the protons. The example might seem a tad constructed but the fact is that this is the basic principle of how an object can become charged by being placed in the electrical field of another charged object.

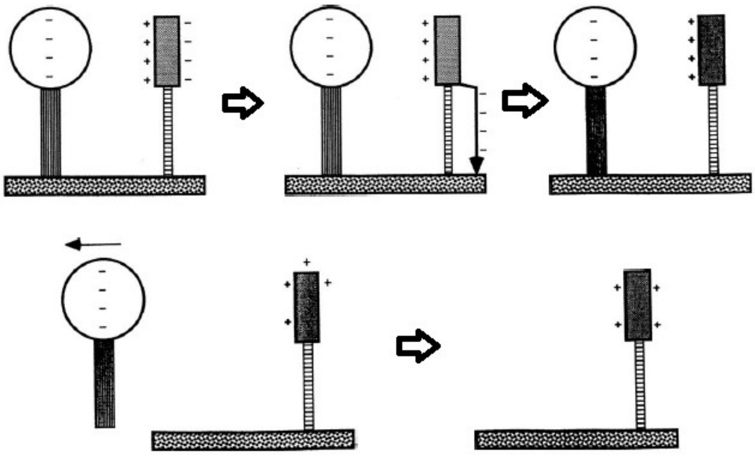


Figure 2: Induction charging. Individual figures taken from [6] and stitched together

2.3.2 Corona charging

When a corona discharge occurs as a result of a static electricity build-up, objects initially neutral nearby can become charged by capturing free ions released during the corona discharge [5]. Corona discharges will be explained later on when looking at the hazards of static electricity.

2.3.3 Contact charging

Unlike the previous two cases where the existence of an external electrical field of some kind was necessary to generate a charge in an uncharged material, contact charging occurs between two dissimilar materials at roughly the same temperature [6] and is characterised by two different materials coming into contact with each other and then separating them. It is when separating the two that lasting charges in the two may occur. As mentioned previously, there exists three cases of contact charging, each one depends on the state of the materials involved.

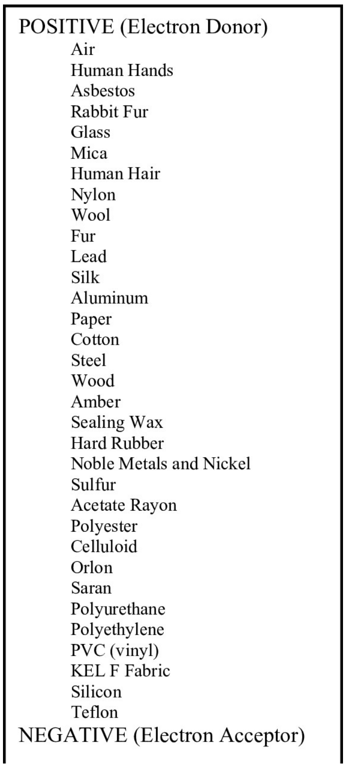
Solid - solid interface When bringing two dissimilar materials at the same temperature into rigid contact with each other to where the distance between points in the two materials are only a few nanometres apart, it has been observed that an exchange of electrons may occur [6]. The mechanisms behind the electron exchange are complex and depends on whether the two materials are both good conductors, a conductor and insulator or both insulators and the type of materials involved. But what all cases have in common is that the fundamental driving force behind it is to achieve thermodynamic equilibrium [6]. As an example, the case of two good conductors can be used, two different metals in this case.

For metals, the work function is the governing principle behind the electron transfer [5]. The work function determines the energy needed to strip an electron from the surface of a metal and different metals have different work functions. The metal with the higher work function will be on the receiving end while the metal with the lower work function will be the one losing electrons. As the electrons are migrating, a potential difference between the two materials will be created and when this potential difference equals the potential difference corresponding to the two work functions, an equilibrium will be attained and the flow will cease. If the two metals now were to be separated, the desire to balance out the charge difference would drive the migrated electrons back to the metal whence they came from [5]. Due to the low surface resistivity in metals, the electron flow would be rather unhindered and by the time that the last points of contact between the two metals was gone, the charges imbalance will be eliminated. For this reason, creating lasting charges in two good conductors after separating them is generally hard.

The reason that charges are easily generated and kept when insulators are involved is that due to the high surface resistance of insulators so the return flow of electron when separating the two materials will as a result be very weak and patch wise across the surface, resulting in two oppositely charged materials [6, 8]. The exact mechanics for when an insulator is involved is not given because due to the complexity behind it, explaining it in an understandable way is a thesis project in itself. Charge build - up between two objects of the same material type is possible but in these cases, the electron generally is not regarded as the primary charge carrier.

Instead, ions are often regarded as the charge carrier [6]. One example is a role of plastic sheet material. When unrolling the sheet one can notice that the sheet might in some cases be electrically charged.

Something easy to come across when researching contact charging is the triboelectric series [6], a list of common materials, ranking them on whether they are more inclined to donate or receive electrons. The triboelectric series is no exact science and just because a material is listed as a donor in relation to the other material it comes into contact with does not mean that it cannot act as a receiver under the right circumstances. The triboelectric series is given in Fig.3 below.



POSITIVE (Electron Donor)
- Air
- Human Hands
- Asbestos
- Rabbit Fur
- Glass
- Mica
- Human Hair
- Nylon
- Wool
- Fur
- Lead
- Silk
- Aluminum
- Paper
- Cotton
- Steel
- Wood
- Amber
- Sealing Wax
- Hard Rubber
- Noble Metals and Nickel
- Sulfur
- Acetate Rayon
- Polyester
- Celluloid
- Orlon
- Saran
- Polyurethane
- Polyethylene
- PVC (vinyl)
- KEL F Fabric
- Silicon
- Teflon

NEGATIVE (Electron Acceptor)

Figure 3: The triboelectric series [10]

As previously mentioned, friction is often attributed as the cause of charge build – up in materials. It is true that friction between two objects of different materials contribute to the overall charge accumulation but in reality, it is still a case of contact charging that is the cause of the charge build – up [6]. Friction is associated with rubbing two surfaces along each other and by doing so, a greater total surface area of contact is created, allowing more electron to migrate from one surface to the other. The freed energy with the generated heat is also considered to contribute to the electron movement.

Solid - gas interface Gas flow along a solid, a pipe wall for example, will not generate a charge in either solid nor gas due to the lack of distinct boundaries in the gas. However, solid and/or liquid particles suspended in the gas may become electrically charged according to the two other cases of contact charging but the gas itself cannot [6].

Solid - liquid interface (Flow Electrification) The basic principle of contact charging between a solid and a liquid, referred to as flow electrification from here on, is direct contact between the two mediums and an exchange of ions between the two resulting in a concentration of negative ions in one medium and positive ions in the other. Although it still in a way is the electrons that acts as the charge carriers, ions will be regarded as the charge carrier in this case.

Electrical double layer To understand how flow electrification works it is important to first familiarise oneself with the Electrical Double Layer (EDL), how it is formed and its relevance. The EDL [11, 12, 13, 14] is an electrical layer in the liquid – solid interface consisting of two parts, one found in the solid and the other one in the liquid. One part of the layer is negatively charged while the other is positively charged and it is this polarity which is the source of the flow electrification. But before delving deeper into the flow electrification phenomenon, it is important to understand how the EDL is formed. To explain this, the liquid is assumed to have a conductivity lower than 50 pS/m [7]. 50 pS/m is generally regarded as the boundary value for a liquid to be classified as a poor conductor which is required to form a permanent EDL.

A permanent EDL is the result of a physiochemical reaction which occurs when a solid comes into contact with a dielectric liquid. In general, even though the liquid is stated to be pure, it will almost always contain some trace amount of some ionic compound through additives or impurities not removed during purification [11, 12, 13] called in this case A_LB_L, where the subscript L means that it originates from the liquid. A is the positive ion while B is the negative ion. A_LB_L will exist both in the compound form and as free ions in an equilibrium state. The reaction between the two forms are given by Eq. (4) below [11, 12, 13]:

$$A_LB_L \xLeftrightarrow[k_2]{k_1} A_L^+ + B_L^- \tag{4}$$

where k_1 is the kinematic disassociation constant and k_2 is the kinematic recombination constant.

Since the compound and its free ions exist in equilibrium, the bulk of the liquid is considered to be neutral in charge. When the solid comes into initial contact with the dielectric liquid, a physiochemical reaction is initiated which can be described by two different models, the corrosion model and the adsorption model. The difference in these two models is the involved components of the physiochemical reaction and in what direction mass is transported but what they both have in common is that the solid is assumed to be isolated from earth and that the surface is composed of either an ionic compound, for the corrosion model, or some molecule, for the adsorption model.

Corrosion model The corrosion model is based on the assumption that the solid has gone through some degree of corrosion, coating it in a patch wise layer of the ionic compound C_SD_S where the subscript S stands for solid, C is positively charged and D is negatively charged. When coming into contact with the liquid, following reaction unfolds [11, 13]:

$$C_S D_S \underset{k_3}{\overset{k_4}{\Longleftrightarrow}} C_S^+ + D_S^- \tag{5}$$

where k_3 is the kinematic disassociation constant and k_4 is the kinematic recombination constant.

Following this reaction, the negative ion B_L^- found in the liquid reacts with the positive ion C_L^+ from the solid in the following reaction [11, 12]:

$$C_S^+ + B_L^- \underset{k_5}{\overset{k_6}{\Longleftrightarrow}} C_S B_L \tag{6}$$

where k_5 is the kinematic recombination constant and k_6 is the kinematic disassociation constant. This reaction continuous until equilibrium is attained.

The complete reaction is then given by [11, 12]:

$$A_L B_L + C_S D_S \Longleftrightarrow A_L^+ + C_S B_L + D_S^- \tag{7}$$

resulting in a negative charge concentration along the solid surface and a positive charge concentration along the liquid in the liquid – solid interface.

Adsorption model The Adsorption model on the other hand assumes that the solid material is covered in preferential adsorption sites comprised of the molecule C_S. What happens is that the negatively charged ions, B_L^-, adsorb to these sites in the following reaction [12]:

$$C_S + B_L^- \underset{k_7}{\overset{k_8}{\Longleftrightarrow}} C_S B_L^- \tag{8}$$

where k_7 is the kinematic recombination constant and k_8 is the kinematic disassociation constant.

Whichever model that is applicable to the situation at hand, both lead to the formation of an EDL along liquid - solid interface. In the two cases presented above, both models result in an excess of positive ions in the liquid and excess of negative ions in the solid, creating a positive current at the interface. However, the opposite is just as likely to occur. The polarity of the interface depends on what type of liquid and solid that is involved in the physiochemical reactions given above. Another point worth mentioning is that although the existence of a permanent EDL requires a liquid with poor conductivity, the physiochemical reactions described occur for all liquids, regardless of the conductivity of the liquid [6]. The difference is that in liquids with very good conductivity, the ion imbalance is eliminated almost instantly due to high charge carrier mobility. An illustration of the EDL based on the Stern model is given in Fig.4 below.

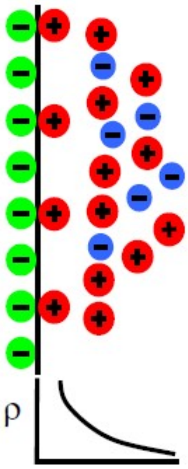


Figure 4: Stern model of the EDL in the liquid - solid interface [15]

The Stern Model is one of several models developed throughout the years and is generally considered to be the most realistic one when it comes to describing the EDL [15]. As seen in Fig.4, the liquid side of the EDL is actually comprised of two layers, the Compact Layer and the Diffuse Layer. The Compact Layer is the one closest to the solid surface where the model states that the ions "adhere" to the surface, making this layer to compact to be affected to the liquid flow. The Diffuse Layer is found further away from the solid surface and it is the convection of this layer as a result of the liquid flow which is the cause of the streaming current generated which is an indication of the magnitude of the charge accumulation.

The diffuse layer thickness δ_0 (also called the Debye length) plays an important role in the space charge density and subsequently the streaming current which will be explained later on. The Debye length is given by [16]:

$$\delta_0 = \sqrt{\frac{\epsilon D_0}{\sigma}} \tag{9}$$

where ϵ is the liquids dielectric constant, D_0 the mean diffusion coefficient and σ the bulk conductivity.

Space charge density and streaming current As a result of the EDL formation along the liquid - solid interface, a detectable space charge distribution is formed on the two sides of the interface, a positive on in the liquid and a negative one in the solid [11]. The space charge density ρ_w decreases as the distance from the interface boundary increases with $\rho_w = \rho_{wd}$ at the boundary where ρ_{wd} is the maximum value of the space charge. In addition to varying with distance, the space charge density also depends on the cross section geometry of the flow path. In lay mans terms, the space charge density is a measurement of ion concentration on the two sides of the EDL and as will become evident further on is an important parameter when determining the rate of charge generation, in this case determined through the streaming current. Theoretical expressions exist to determine the streaming current and an important part of these is knowing the wall current generated.

The wall current is a very small current generated at the liquid – solid interface during the physiochemical process and a generally accepted expression for the wall current generated is given by [14]:

$$i_w = K(\rho_{wd} - \rho_w) \tag{10}$$

where K is an effective rate constant related to the physiochemical reactions given by:

$$K = \frac{k_5 n_{N0}}{2(n_{N0} - n_{ND})} \frac{V}{A} \tag{11}$$

where k_5 is the kinematic recombination constant from Eq. (6), n_{n0} the concentration of negative ions at the beginning of contact between liquid and solid, n_{ND} is the concentration of negative ions in a fully formed EDL, V the liquid volume in contact with the solid and A the area of contact between the two mediums. Obviously this is something difficult to calculate theoretically since it would require that the involved concentrations in Eq. (11) to be known. Therefore, K is usually determined experimentally [16]. What the streaming current actually is and why Eq. (10) and (11) are relevant will be explained in chapter 5.

3 Discharge Mechanisms

3.1 Introduction

The problem with charge accumulation is often not that it exits but that it can lead to sudden and seemingly random discharges. As seen in the previous chapter, there are a number of ways for an object to accumulate an electrical charge so the fact that static electricity is encountered daily for most is understandable. However, so far this text has only covered how the charges are acquired and the physics behind, not why and how they might lead to sudden discharges and how something that only lightly stings can result in an explosion under the right circumstances. The following segment will cover the different discharge mechanisms and the conditions necessary for them to occur. Following this in the next chapter, the hazards of unchecked discharges will be shown.

There are five distinct types electrical discharge [5, 6, 7, 17]:

- Spark Discharge
- Brush Discharge
- Cone Discharge
- Propagating Brush Discharge
- Corona Discharge

Although listed as five distinct types of discharge, the underlying physics governing the discharge is the same. All but one are a part of a larger group called gas discharges where the charge imbalance in to objects is alleviated through some gas filling the gap between the two objects. In both everyday situations and industrial scenarios where there is a risk ignition, air or an air mixture is usually the gas through which the discharge occurs.

3.2 Gas Discharge Mechanism

Gas discharge is based on the existence of a small amount of free electrons in a gas [5], air in this case. When applying an electrical field to these electrons, caused by two oppositely charged objects at different potentials, the electrons will start to accelerate towards the material with the positive potential. As the electrons start to accelerate, they at some point will collide with an air molecule. If enough kinetic energy is accumulated during the acceleration of the electron, electrons in the molecule will be “knocked” off when colliding with the free electron, creating more free electrons that will be influenced by the electrical field. As more and more electrons are separated from air molecules, a sea of free electrons and positive ions is created. This sea is known as plasma, the fourth state a material can exist in (the other three are solid, liquid and gas) [5]. Plasma is conductive by nature so by filling the gap between the two charged materials with it, a path which the surface bound electrons can use to eliminate the potential difference between the two objects is presented. The sudden and rapid flow of electrons between two objects is what is known as a discharge. When plasma is created, breakdown of the initially insulating gas is said to have occurred.

For air, breakdown is the result when the breakdown voltage 3 V/mm, also known as electrical field strength, or more is reached between the two objects [5]. For the discharge type that is not a gas discharge type, breakdown and the events above leading up to it still occurs but through another medium.

3.3 Spark Discharge

Spark discharges are small, instantaneous discharges between two conductors at different electrical potentials [7]. The discharge mechanism is a gas discharge type discharge, as described in the preceding section. When bringing two conductors at different electrical potentials in close vicinity to each other, an electrical field is formed between them [6]. As the distance between them decreases, the capacitance increases in accordance with Eq. (3) above while the electrical field increases as a result of the decreased distance. When the increased potential in the field causes the field strength to reach 3 V/mm, gas breakdown occurs and a discharge is witnessed. The resulting discharge is often a single blue spark, starting and ending in a single point and a crackling sound. The crackling sound is a result of the rapid air expansion due to the increase in temperature [5]. Due to the high mobility of electron in the surface of a conductor, the spark is feed with electrons from surrounding areas in an attempt to maintain a constant local electrical potential in the surface [5]. As a result, spark discharges are often a single time occurrence because the electron imbalance in at least the discharge source is eliminated through the spark but it is common for both involved to balance out. The energy released in the discharge is often of interest for reasons explained later on and for spark discharges, the exact amount of released energy is calculable using Eq. (12) below [5].

$$E = \frac{CU^2}{2} \tag{12}$$

where E is the released energy, C the capacitance between the object at the point of discharge and U the electrical potential in the field. Worth nothing is that the same charge might not necessarily always give rise to a high enough voltage in order for breakdown to occur [17]. If the effective surface of the capacitive couple is large enough, the capacitance might become too large for a spark to occur when comparing the same charge to a case with a smaller effective surface area. A typical spark discharge is shown in Fig.5 below.

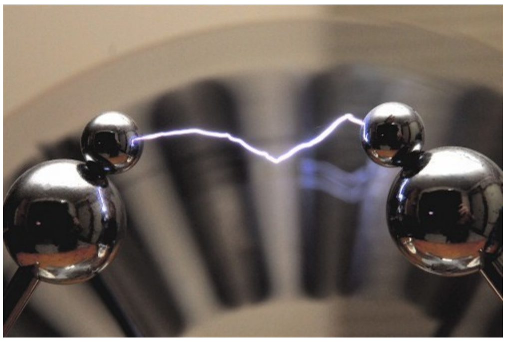


Figure 5: Spark Discharge [18]

3.4 Brush Discharge

A spark discharge is often classified as a double electrode discharge [6] since the existence of two differently charged conductors is necessary for a discharge to occur. Brush discharge on the other hand is classified as a single electrode discharge as only one charged insulator is necessary for a discharge to occur [6]. Brush discharges typically occurs between a smaller, grounded conductor, a finger for example, and a charged surface of an insulator[5, 6]. Decreased distance between the two increases the field strength until it reaches breakdown levels. Unlike a spark discharge, a brush discharge is characterised by several blue sparks [5], see Fig.6 below, originating in multiple points along the insulators surface and the reason is the high surface resistivity of insulators. Once a discharge is initiated, only the excess electrons in the closest vicinity of the discharge point are transferred as electron surface mobility is low in an insulator. So instead of all electrons flowing to a single point of discharge, multiple discharge points exist simultaneously, feeding on the electrons in the local area. This also means that a charged insulator can be discharged multiple times without the need to be recharged in-between since all electrons are not transferred. Finally, the exact energy released is extremely hard to calculate but experiments have shown that the energy released is enough to ignite several of the most common flammable substances [5, 19].

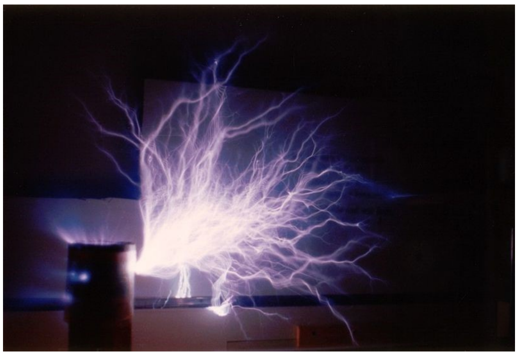


Figure 6: Brush Discharge [20]

3.5 Cone Discharge

Another type of single electrode discharge is the cone discharge which involves storing charged insulating powder in a grounded, highly conductive containment unit [5, 6]. Typically powdered substances are loaded into containment units by pouring it in, resulting in the formation of a pile at the bottom which grows as more powder is added. The problem when doing so with a powder made out of a charged insulating material is that the pile is essentially forcing particles of the same charge together through gravity. As the saying goes, opposites attract and equals repel and as the powder is being compressed by gravity [5], equal charges are being forced together, resulting in an increased electrical potential with a maximum at the centre of the pile. If the pile grows large enough for electrical field between the pile and grounded containment unit to reach the breakdown value, a discharge may occur. An example of this is loading charged grains into a grounded metal silo. As in the case with brush discharge, the exact amount of energy released during the discharge is impossible to calculate exactly but it has been established that ignition is possible [5]. A typical cone discharge is shown in Fig.7 below.

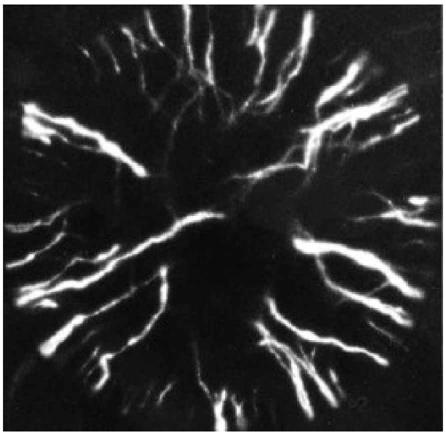


Figure 7: Cone Discharge [6]

3.6 Propagating Brush Discharge

As previously stated, one of the five discharge types was not like the other and the odd one out is the propagating brush discharge. While the other four occurred as a consequence of gas breakdown, propagating brush discharges mainly occur during breakdown of very thin, charged and insulating films (thickness <= 8mm [7]). Imagine a situation where a grounded, conductive plate is coated with a very thin, charged, dielectric film or sheet of some kind [6]. As a result of inductive charging, which is explained in the previous chapter, the surface of the plate will become oppositely charged to that of the thin film as the charged film will repel or attract electrons in the surface of the plate (depending of the polarity of the charge polarity in the film). Two oppositely charged surfaces in close vicinity or contact with each other will form a capacitor whose capacitance will be determined by the thickness of the film. As the film must be rather thin for a propagating brush discharge to be possible, the capacitance as a result is rather high and as a consequence, so will the electrical field also be [6].

As it stands right now, a discharge will not occur on its own without some external influence but the necessary conditions exist. The external influence usually comes in one of two ways [21]. The first is through some physical impact that perforates the film, causing the filed strength to reach the breakdown value of the film. The other is by placing two electrodes, one on each side of the "capacitor", boosting the field strength to breakdown values. Whichever way it occurs, the breakdown value of the film material is reached and a discharge occurs throughout the film surface in the local vicinity of the discharge point, see Fig.8 below. A consequence of the discharge occurring through a thin film and not a gas like air is that propagating brush discharges are, with the exception of lightning strikes [6], the strongest type of static electricity discharge, capable of reaching energy levels as high as $10J$ [6] (lightning strikes on average releases around $1000MJ$). The reason that the energy level is so high is that the breakdown value for these thin, insulating films is much higher than for air, $100 - 1000$ times higher [6], so the potential difference is much larger when discharge occurs. Just like a brush discharge, multiple propagating brush discharges can occur without the need to recharge the film as the discharge is localised to an area around the initial point of discharge[5].

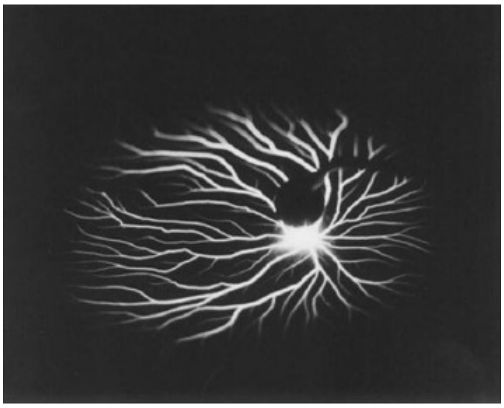


Figure 8: Propagating Brush Discharge [5]

3.7 Corona Discharge

The corona discharge is quite similar to the brush discharge with the difference that the grounded conductor is generally in the form of a small, sharp point [5]. The electrical field caused as a result of the charge imbalance is stronger around the sharp point than the rest of the conductor and is heavily localised to this point. This means that only a small potential difference is needed to reach breakdown voltage and a discharge to occur [5]. As stated in chapter 2, corona discharges can result in objects close to the discharge becoming charged and this is due to the existence of free ions in the plasma around the point of discharge which may be "absorbed" by nearby objects. Corona discharges are generally regarded as the weakest of all discharges and only poses a risk in special circumstances [5], the presence of pure hydrogen for example. A typical corona discharge is shown in Fig.9 below.

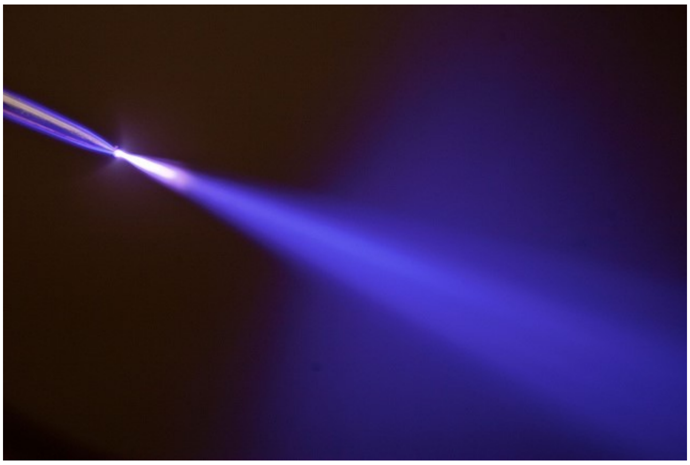


Figure 9: Corona Discharge [22]

4 Hazards of Static Electricity

4.1 Introduction

By this point, the concepts and mechanisms behind static electricity generation and discharge are hopefully clear. The goal of the preceding chapters was to provide a comprehensive yet compact "guide" of the static electricity phenomenon so that the reader will feel confident in discussing matters related to static electricity. A close look at the solid – liquid case was presented and this information will be used later when looking closely at the main problem at hand, namely the accumulated charge and how to ground it in the heat exchanger. But before doing that, the following chapter will cover the hazards of static electricity, why it is a force to be reckoned with and what requirements are necessary for these hazards to arise. Real world examples will also be presented to show that this text is not overdramatizing this problem. In short, two hazards are usually accredited to static electricity, ignitions of flammable substances and electrical component damage [5, 6, 23].

4.2 Ignition Hazard

The more severe of the two is without a doubt the ignition hazard and is a problem of great interest and importance to several industries, the petroleum and chemical for example. Reports of this issue ranges from smaller fires to full scale explosions. This problem is relevant to all who work with flammable, low conductive substances, whether it is transporting, storing or manufacturing them. Before going in to some actual reported cases, an outline of the required conditions for ignition to occur will be given. To create a fire or an explosion, three things are necessary, a source of ignition, fuel and oxygen [6]. Removing one of these three components and the risk of an explosion disappears but at the same time, just because all three exist at the same time does not necessarily mean that a fire or an explosion will occur [6]. These three components are often summarised as the fire or danger triangle, seen in Fig.10 below. What constitutes as the fuel and ignitions source varies from case to case but in the context of this text, static discharge is always the ignition source.

4.2.1 Oxygen

The common denominator for all cases of ignition is the presence of oxygen. From this point and forward, it is assumed that ignition occurs at normal atmospheric conditions where the oxygen content is around 21% [6]. There is not much to say here apart from the fact that oxygen is a necessary part. One thing though is that by adding inert gases to the air around the fuel, ignition risk can be lowered.

4.2.2 Fuel

The fuel component of the danger triangle could be any number of different chemicals and materials and going through each specific one would be impossible. However, a more generalised approach can be taken by looking at the state of the fuel, i.e if it is in a solid, liquid or gaseous state.

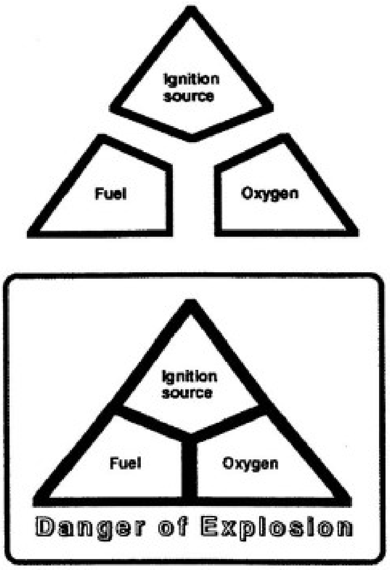


Figure 10: The danger triangle [6]

Liquid and gas To be exact, ignition does not occur in the actual liquid but in the vapours amassed at the surface which when ignited is then fuelled by the liquid [6]. Whether ignition of a combustible liquid is even possible is determined by its flash point which is formally defined as the temperature where enough liquid evaporates to create a fuel – air mixture which can be ignited [24]. Then whether this mixture in itself can be ignited is defined by the Minimum Ignition Energy but more about this later on. As an example, kerosene has a flash point of around 38 degrees Celsius [24] so igniting a barrel full of kerosene at 10 degrees Celsius would be very unlikely since there would not be enough kerosene vapour to a combustible mixture. So the end result is the same whether the fuel is originally in liquid or gaseous form, only difference is that for fuels normally kept in gaseous form, the flash point is of no relevance.

Solid Solid in this case refers to dust or powder particles in some form and not a large solid chunk of material. The principle is the same as for liquids and gases, a mixture of the fuel and air is the source of ignition. Unlike for liquids and gases, the distribution of the solid particles in the mixture is in-homogeneous due to the influence of gravity [5], meaning that the concentration of particles per cubic millimetre as an example can vary in a cubic meter of fuel – air mixture where as in the previous case, the fuel vapours is more evenly distributed throughout the mixture. The result of this is that the overall ignition risk is often lower for a mixture containing solid particles [6], reflected by a higher MIE value.

4.2.3 Ignition source

When discussing the different discharge types and the mechanism behind them, the energy released through the discharge was mentioned and in the case of spark discharges, an expression to calculate the exact energy released was given. The importance of this energy was never explained but will be here. The magnitude of this energy is of great interest since it will determine whether a discharge carries enough energy to ignite a fuel – air mixture where the fuel could be in gas or dust form.

Whether the released energy could possibly ignite the mixture is determined by the fuels Minimum Ignition Energy (MIE) [5]. The MIE is a “perfect condition” parameter stating the energy necessary to ignite the mixture when the ratio of air to fuel is optimal. Air is not the only gas that can form a mixture with the fuel but it is the most common test oxidant. Any deviation from this perfect mixture will increase the energy needed to ignite meaning that if it is possible to guarantee that a discharge will not reach the MIE, ignition will not occur. The MIE for some common materials is given in Table.1 below.

Table 1: MIE for some common gases, vapours and dusts [5].

Gas, vapour or dust	**Minimum ignition energy (mJ)**
Hydrogen	0.016
Methane	0.21
Propane	0.25
Methanol	0.14
MEK	0.53
Acetone	1.15
Sulphur	< 1
Aluminium	10
Sugar	30
Wheat	40

4.2.4 Real cases of ignition hazards

With the necessary basics to understand how a discharge can result in ignition covered, three real cases of static discharge ignition will be given together with some facts from a study done on accidents in Japan during the period 1960 – 2010 where static electricity is determined to be the cause.

Fire caused due to electrostatic charge in the filtration process of a medicine intermediate On the 15th of March, 1985, a fire caused roughly 337 000 SEK worth of material and property damage at a chemical factory in Japan [25]. The cause was determined to be a filtering operation of a pharmaceutical intermediate containing the flammable substance n – hexane. After filtering of a solution, solid particles caught in the filter was to be transported from the filter to a drier for further processing. During the transferring procedure, a fire started. Investigations determined that the ignition source was a spark discharge caused by a charge build-up in the filtering cloth through a metallic part of the filter. The fuel was a small amount of liquid n – hexane present in the filter residue which reached the flash point, evaporating enough to create an ignitable fuel – air mixture. Everything was done at ambient conditions providing the final part of the danger triangle presented above, oxygen.

Explosion and fire at a chemical tanker during cargo handling caused due to static electricity from an insulated gauge On the 17th of December, 1985, an explosion occurred during the loading of benzene to a cargo ship in Japan, resulting in two casualties and extensive damage to the ship [26].

While pumping benzene onto the cargo ship, a level gauge was placed in the tank being filled to monitor the fuel level. A Teflon ring was attached to this gauge to reduce noise disturbances in the measurements which effectively isolated the level gauge form the hull of the ship, leading to the generating of a charge. A spark discharge occurred providing the ignition source to the danger triangle. The liquid benzene being loaded had evaporated in the cargo tank, creating flammable fumes and thus becoming the fuel part. Oxygen was present resulting in all necessary components for ignition to occur of the vapour.

Explosion of a toluene tank due to static electricity on sampling On the 26th of January, 1976, an explosion occurred in a toluene tank while an employee was taking samples [27]. The sampling was done using an ungrounded sampling thief, connected to a cotton rope while the employee was wearing rubber gloves. When taking the first sample, the thief was submerged to the bottom of the tank and then quickly pulled up to then be emptied in a glass bottle. Due to the speed which the employee hoisted up the thief, a charge was created and since there was no grounding, no dissipation occurred. When lowering the thief down for a second sample, a spark discharge occurred when reaching the surface of the toluene, igniting the vapour mixture created. The employee was injured and damages of around 250 000 SEK occurred.

General statistics of fires and explosions in Japan caused by static electricity during the years 1960 - 2010 A study conducted in Japan of industrial accidents related to static electricity showed that most of accidents occurred as a result of charge build-up as a result of liquid flows, followed closely by contact charging between solids, see Fig.11 below [28]. Results also showed that fuel vapours stood for around 60% of all accidents and that spark discharges caused a majority of accidents, 71% of them, see Fig.11 below. An interesting result of this study was that roughly 70% of all accidents investigated was caused by insulated conductors. In addition to this, one of the key causes behind all accidents identified was a serious lack of information regarding static electricity handling procedures.

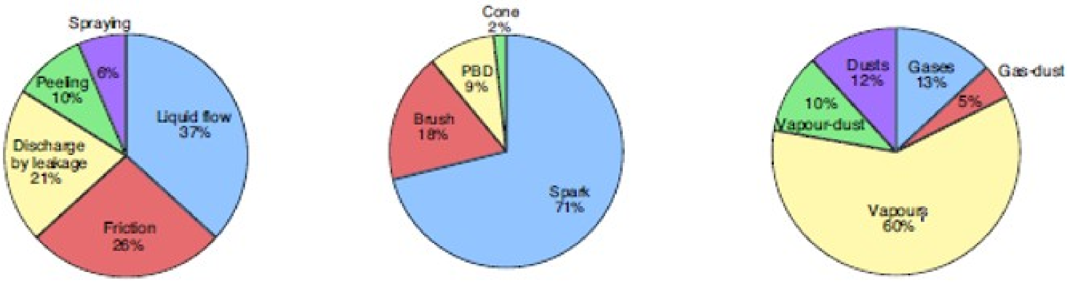


Figure 11: Results from Japanese study showing the most common source of charge build - up, type of discharge and type of flammable atmosphere [28]

Although these results comes from a study which only focused on Japan, the author states that similar results are likely to be found in other countries as the incidents investigated resembled reported incidents worldwide [28].

4.3 Electrical component damage

The second type of hazard caused by static electricity is damage done to electrical components, frequently referred to as Electro Static Discharge (ESD) damage. Although both hazards in this text are consequences of static discharge, damage done to electrical components will be referred to as ESD damage from now on to match all information available on this subject.

The ESD hazard might not seem as severe as the ignition hazard as it only effects electronics, but the resulting costs can be substantial for a manufacturer and in some rare instances, faulty electronics can lead to situations where human lives are at risk. ESD can result in two types of damage, software and hardware but the source of the damage is the same [23].

4.3.1 Software damage

Software damage usually include errors in computer operations such as loosing data bits when reading something or for an operating system to lose control, resulting in potential data loss [23].

4.3.2 Hardware damage

Hardware damage refers to actual physical damage of a component which could result in instantaneous device shutdown, device malfunction or a device showing no signs of error only to breakdown weeks later. The cause of hardware damage is usually improper handling of sensitive components [23]. As for which components are classified as sensitive, semiconductors are usually pointed out to be those at greatest risk of ESD damage [29]. The actual damage to semiconductors can be divided into two categories, catastrophic and latent damage.

Catastrophic damage Catastrophic ESD damage to sensitive components can occur in two ways, arcing and heating [29]. Arcing refers to a current pulse with a fast rise time and high absolute value going through the component, much higher than the maximum rating of the component. In the context of this text the source is an electrical discharge emanating either from a charged object to the component or from a charged component to a grounded external object. Naturally, the damage types listed below can also be the result of not abiding to the current and voltage ratings of the component and because of this it is often hard do determine if damage is caused by a discharge or improper usage. The other form is heating, which in truth is a result of arcing but damage related to heat is more visible than those caused by arcing as it usually results in molten areas in the component. Three failure mechanisms exists:

- **Oxide Punch - Through:**
  Most common form of catastrophic damage in Metal – Oxide – Semiconductors (MOS) [29]. In short, the voltage across the component during a discharge is high enough for breakdown of the gate oxide layer to occur, much like what happens when the breakdown voltage of air is reached during a discharge. The resulting damage could include material melting due to a high temperature and internal short circuits due to holes created in the oxide layer. Fig.12 below shows how this might look.

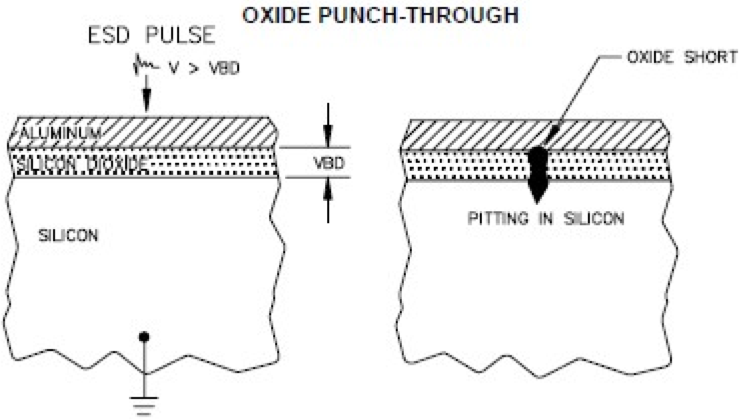


Figure 12: Oxide Punch - Through [29]

- **Junction Burnout:**
  When a sensitive device is subjected to a high current pulse and the voltage across it is large, secondary breakdown may occur, resulting in pockets with high current concentration and increase in temperature, creating hot-spots [29]. These hot-spots have a reduced impedance which in turn leads to more hot-spots forming close by [30]. An example is shown in Fig.13 below. These hot-spots allow for a high reverse leakage between the layers in the semiconductors and in severe cases, complete short circuits.

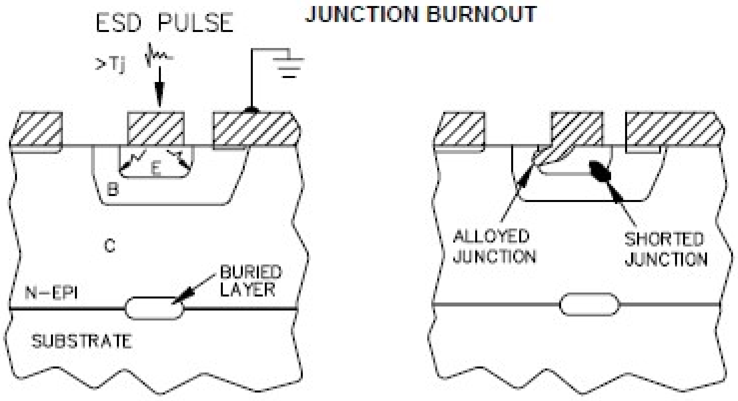


Figure 13: Junction Burnout. The black areas illustrates a hot-spot [29]

- **Metallization Burnout:**
  Like the previous case, a high current/voltage discharge leads to an increase in temperature in parts of the component due to resistive heating in the metallic parts [29]. This can result in localised molten parts, shown in Fig.14 below, and is likely to occur in conjunction with Junction Burnout since both are caused by a high current/voltage discharge.

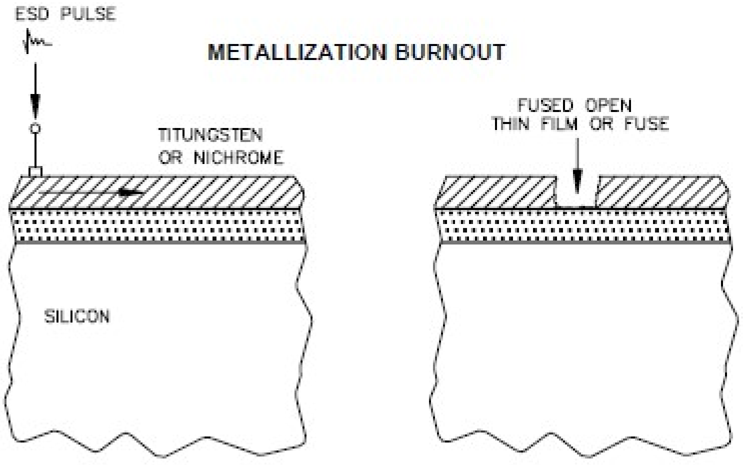


Figure 14: Metallization Burnout [29]

Latent damage Latent ESD damage to a component is much harder to detect as no visible damage occurs and testing the functionality of the component will initially not show any signs of malfunction [29] while catastrophic damage on the other hand is detectable and occurs almost instantly [23, 29]. Latent damage on the other hand might not show signs of damage until hours, days or weeks later. This is what makes latent damage so problematic since a damaged device might be shipped, causing increased costs when having to handle the inevitable breakdown later on. The three damage types described for catastrophic damage can be the underlying reason for latent damage but naturally, the degree of damage is much lower.

4.3.3 The consequences of ESD damage

Unlike previously with ignition hazards, documented cases of ESD damage is harder to come by, most likely due to the fact that the consequences of ESD hazards are in no way as severe as for ignition hazards where lives are much more likely to be at stake. When dealing with the consequences of ESD, the cost attributed to it is generally more of interest. For example, in 2003, based on production data collected from the international electronics industry sector during the period 1997 – 2001, the costs caused by ESD damage was estimated to be around 782 billion SEK per year for the sector [31]. In addition to this, inspection data from Siemens collected during their audits of production facilities in 91/92 and 94/95, costs related to ESD damage was calculated to be roughly 25 million SEK respectively 77.7 million SEK [32]. Gathering concrete data about the costs and amount of units damaged by ESD is a tricky task for the companies affected because it is not always clear is damage is caused by ESD or accidental over powering.

4.4 Detecting and Measuring Static Electricity

So far a lot has been stated concerning static electricity, how and why it is formed, the dangers of it and how these dangers might arise. But an important part, especially when evaluating the occurrence risk of some of the aforementioned hazards, is how to actually detect and measure static electricity. In everyday life, the probably most common way to static electricity is through the occasional shock when touching something but running around in a production facility, touching everything with your hand to determine if something is charged is as ridiculous as it is unsafe. No, to determine the existence and magnitude of a charge buildup, a couple devices can be used, all which will be introduced here along with a short description of what they measure.

4.4.1 Electrometer

An electrometer is a highly sensitive device, capable of detecting and measuring very low currents and voltages due to the high input impedance, around $10^{14}\ \Omega$ for modern electrometers [17, 33]. Several types of the electrometer exists but the most advanced one as of right now is the solid – state electrometer based on field – effect transistors. An electrometer can be used for static electricity related purposes but is mostly used in radiation measuring. An electrometer is shown in Fig.15 below.

Figure 15: The PASCO Basic Electrometer [33]

4.4.2 Electrostatic voltmeter

The electrostatic voltmeter is often erroneously called electrometer even though there is a clear difference between them. While the electrometer is capable of measuring very low currents and voltages, the electrostatic voltmeter typically measure voltages as high as 200 – 300 V, in some cases even as high as 3000 V [34]. Something that the older electrometers and the older electrostatic voltmeters have in common is that both were based on the electrostatic principle, opposite charges attract and equal repel. Older electrostatic voltmeters used two metallic plates where one or both were free to pivot around a point.

When applying the unknown voltage between the two plates, one or both would repel as a result of the electrostatic principle. By measuring the force in a spring connected to the deflecting plate, the unknown voltage could be calculated [17]. Nowadays, the modern electrostatic voltmeters use a probe which is placed in close vicinity to the surface of the object to be examined.

Figure 16: The Isoprobe® - model 279L Electrostatic Voltmeter [34]

Through sensors in the probe, a voltage is applied across the probe and then increased until the potential difference between the probe and surface is zero [34]. The voltage across the probe when the potential difference reached zero is then the voltage at the surface. This method has two benefits, the first is that this method does not require physical contact. When trying to detect and measure voltages which are the result of a charge buildup, direct contact measurements will not work since by making contact, some or all of the charge to be measured will be dissipated thought the device. The other benefit is that the risk of a discharge occurring when conducting the measurement is very low since the probe and surface will be at the same potential and as seen in chapter 3, a potential difference is needed for a discharge to occur. A modern electrostatic voltmeter is shown in Fig.16 above.

4.4.3 Electrostatic field meter

The electrostatic field meter is used for measuring the electrostatic field created by a charged object [17, 35]. Basically the field meter is placed at a specified distance from the object to measure. A detecting electrode, connected to ground through a resistor, see Fig.17 below, in the field meter will then sense the electrostatic field which then, due to induction charging, will induce a charge in the electrode. By periodically weakening the electrostatic field with a vibrating electrode in the field meter, a periodical variation in the charge induced will occur [35]. As the charge is periodically changing, the resulting current from the electrode to ground will act like an AC current which is converted to an AC voltage by the resistor between the electrode and ground. By analysing the AC voltage, the field strength is calculated but given in volts as the distance is constant and predefined for the device.

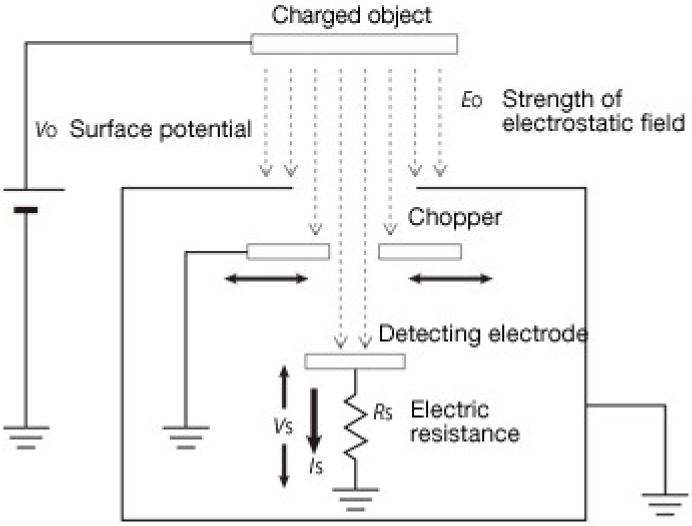


Figure 17: Principle of a Electrostatic field meter [35]

As a result of this, performing measurements on the same charged object at different distances will give different results. Another important thing to consider when using an electrostatic field meter is that the measured surface must be larger or equal to the specified area for the device [35]. The reason is the use of the detection electrode in the device, if the measured surface is smaller than the electrode, the whole electrode will not be in contact with the electrostatic field and the measurements will be wrong. An electrostatic field meter is shown in Fig.18 below.

Figure 18: The SIMCO ION FMX Electrostatic Field Meter [36]

4.4.4 Charge density meter

The charge density meter is much like the electrometer but is designed to be submerged in non – conductive liquids [17]. Measurements are made in pipes or flow channels with a constant geometry to read the charge density in the vicinity of the meter.

4.5 Controlling Static Electricity

The last matter to discuss regarding static electricity is how to handle the existence of it. As show in previous chapters and based on everyday observations most people do, static electricity can and most likely will occur in a number of places whether it is desired or not. And in most of these cases it does not matter but as seen in this chapter, there are situations where it is critical that charged objects are not given the chance to discharge and that is what this section is about, discharge prevention, ignition prevention and to what extent is it possible to prevent the charge from ever accumulating. Most of the actions described here is applicable to both type of hazards discussed in this chapter.

4.5.1 Grounding

The act of grounding a potentially charged object is as simple as it sounds. Providing the object with a permanent path to ground will eliminate the potential difference between the object and ground, effectively nullifying any charge accumulation in the object as the dissipation rate will be larger than the accumulation rate [7]. The ground path is usually in the form of a cable or wire attached to the object in some way, depending on if the connection is permanent or temporary, in one end and attached to a grounding rod which is submerged in soil in the other. In industry, fixed installations like machines, pipes and tanks are often fitted with a permanent ground connection in the form of an earthing lug [7, 17].

The way the earthing lug is attached varies with what it is attached to and a couple of possible attachment methods will be shown and tested as a part of this project. Temporary connections are usually done with clamps, making it possible to attach and remove more easily than the earthing lug [7]. In areas marked as ESD Protected Areas (EPA) grounding is also widely used. Permanent connections are often through work space mats where the sensitive components are handled while the temporary connections are often in the form of grounded wristbands worn by the person handling the sensitive component.

For ground connections the sum of resistance of the cable/wire, way of attaching it, additional components and resistance of the grounding rod is recommended to be at most 1 $M\Omega$ by several standards [7, 17, 37]. In cases where all these parts are made out of metal, a resistance of no more than 10 Ω between the source and the grounding rod is recommended but there are cases where higher is acceptable [17]. Reading of more than 10 Ω are usually indications that the earth connection is damaged, corroded or loose.

4.5.2 Bonding

Bonding is much like grounding in the sense that the goal is to eliminate the potential difference between two points. The difference is however that bonding is done between two separate objects which may hold a charge [17]. This results in a zero potential difference between the two objects but both will most likely still be at a different potential than earth. Bonding is done to eliminate the risk of discharge between to objects in close vicinity to each other. This does mean that discharges are still possible between one of the objects and some other object not bonded [7].

For this reason, bonding is often done in conjunction with grounding where one of the objects is grounded [7].
By doing this, both are grounded although one of them is only done so indirectly. The example of the wrist strap above is an example of this, the wrist strap is bonded with the mat which in turn is grounded.

4.5.3 Additives

In cases involving flow electrification, adding certain additives to the fluid may reduce the magnitude of the charge accumulation by increasing the fluid conductivity [17]. By increasing the conductivity, the mobility of ions is increased which in turn increases the recombination rate with charge carriers of opposite polarity. This is referred to as charge relaxation [7, 17] and the charge density in a liquid during relaxation is given by Eq. (13) below. It is recommended to add the additives at the beginning of the liquids flow path to minimise the potential charge accumulation but in some cases where dilution of the liquid might occur, adding the additives at the end is recommended [17].

$$Q = Q_0 e^{-t\sigma/\epsilon} \tag{13}$$

Q_0 is the initial charge density, t the time in seconds, σ the conductivity of the liquid and ϵ the dielectric permittivity of the liquid [17].

4.5.4 Flow control

While on the subject of flow electrification, some guidelines concerning the treatment of the liquid exists. First, if the liquid is filtrated for some reason along the way, the liquid must be given some resting time downstream from the filter [7, 17, 37]. The reason is that filters create turbulence which increases the charge generation. In fact, filters have been observed to increase the charge accumulation by 10 – 200 times [37]. Secondly, when transferring the liquid into a larger tank for storage through a pipe, splashing should be avoided at all cost by placing the pipe outlet as close to the bottom of the tank as possible [17]. As with filters, splashing causes turbulence which increases the charge generation. In addition to turbulence, plashing can potentially create a liquid mist which in turn is ignitable, compare this to the base of a large waterfall. Lastly, if possible, ullage in pipes and containers should be avoided. If there is no free space available, the amassing of an ignitable fuel - air mixture is not possible [37].

4.5.5 Environmental control

Another possibility is to alter the environment around an abject known to hold a charge for some reason. Four alterations are commonly used:

- **Introducing inert gases:**
  As mentioned when discussing ignition hazards, introducing inert gases to the surrounding air will lower the oxygen content to the point where ignition risk is greatly reduced. A very commonly used gas when inerting is Nitrogen.
- **Ventilation:**
  If possible, providing ample ventilation will decrease the ignition risk by removing fuel vapours [7].

- **Humidification:**
  Air humidity plays an important role for the accumulation of charge. At air humidity of above 65%, the surface resistivity of some insulators and semiconductors can drops enough for the surface charge mobility to become high enough to enable dissipation, if a ground connection is present [7]. Oppositely, at air humidity below 30%, the surface resistivity could become so high that a normally conductive object might act as an insulator. The reason for this is that the surface of the object absorbs some of the moisture in the air so at high enough humidity, enough moisture can be absorbed to lower the surface resistivity [7].

- **Ionisation:**
  The last method is ionisation. Ionisation is basically introducing both positive and negative ions into the air around a charged object. The charged ions will, due to attraction forces, be attracted to a charged object with an opposite charge and neutralise the charge on contact [7]. Ionizers are usually using small amounts of radioactive material, often Polonium – 210, which means that based on which country you are located in, the proper authority must approve, register and install the ionizer [7].

4.5.6 Control of charged personnel

The final area of control is primarily related to the personnel working in areas with sensitive components and in some rare cases ignitable substances. As most people have noticed, humans can accumulate an electrical charge when isolated from ground as the human body in the context of static electricity is generally considered to be a good conductor. For this reason certain precautions are recommended in hazardous areas. If possible, conductive shoes should be worn at all times in conjunction with conductive flooring and both should have a resistance of about $10^6 - 10^8\ \Omega$ [7]. However, in areas where there is a risk of electrocution, this is strongly recommended against as it will make the body a preferential path to ground and therefor increasing the risk that this becomes the path of least resistance. As for the clothes worn by personnel, the fabric should be conductive [7]. This only apply to the outer clothing worn, so if they wear a coat over a t – shirt, the coat is the one which should be conductive. Finally, if gloves are used, for instance in cases where sensitive electrical components are being handled, same guidelines as for shoes apply to gloves [7].

5 Static Electricity in the GPHE

5.1 Introduction

With a firm grasp of what the static electricity phenomenon is, what causes it and what the effects of it is, the final question now is: How is all of this related to the existence of an electrical charge in the heat exchanger? Well, based on previous sections, the hypothesis proposed here is that the charge accumulation in the heat exchanger is a result of the flow electrification case (liquid – solid) of contact electrification (which has been hinted to before). But before going into detail of what exactly points to this, an overview of the makeup of the heat exchanger is necessary.

5.2 The GPHE

The basic principle of the GPHE is the same as any other heat exchanger, transferring heat energy from one fluid to another. In a heat exchanger this is done by running the fluids between corrugated plates fitted with gaskets to seal the space between the plates [38], see Fig.20 below. A typical GPHE consists of several plates, assembled between the frame plate and a movable pressure plate in the back, both made out of carbon steel and coated with epoxy paint [38], see Fig.19 below. The sandwich structure formed is kept together using tightening bolts between the two covers. Between the frame plate and the support column on the opposite side, two bars are located, the carrying bar on the top and the guiding bar on the bottom. The purpose of these bars are to guide the movable cover and plates when opening the heat exchanger for inspections or to add/remove plates which in that case, the support column and pressure plate is removed to allow access. [38]. An inside view of the GPHE is given in Fig.21 below.

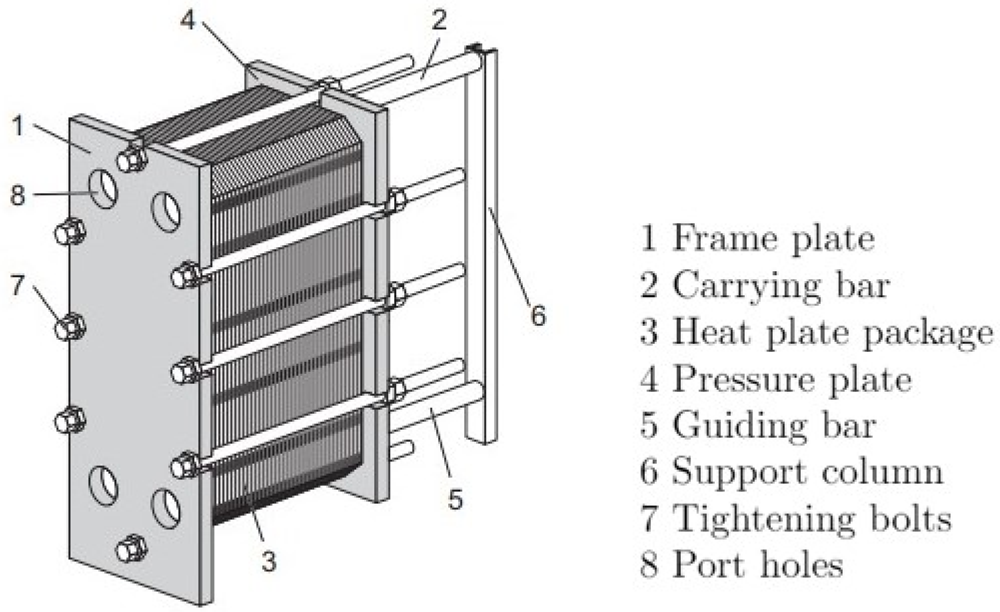


Figure 19: Heat exchanger description [39]

Figure 20: Corrugated plates with gaskets. Two adjacent plates are shown, illustrating how the gasket layout alternates between two patters to make sure that the two fluids never mix

For GPHE's of the same types as the M6, the two fluids enter the exchanger through two separate pipes, the hotter fluid goes in through the upper right while the colder goes in through the lower left [38]. Due to the gaskets found on the plates, the two fluids will never mix because each fluid only passes through every other plate pair, see Fig.22 below. This and the opposite flow directions of the two fluids results in an efficient heat transfer and thanks to the corrugation of the plates, the whole surface of the plates is utilised. After passing though the exchanger, the cooled hot fluid exits through the lower right pipe while the heated cold fluid exits through the upper left pipe.

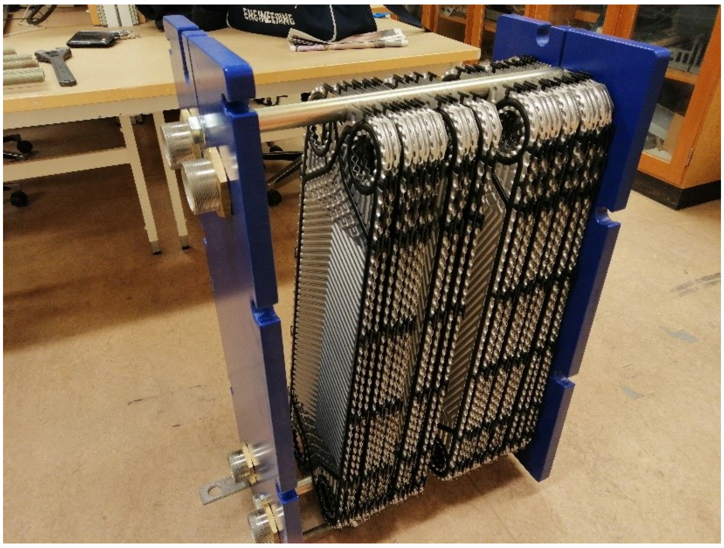


Figure 21: Inside view of the M6 GPHE

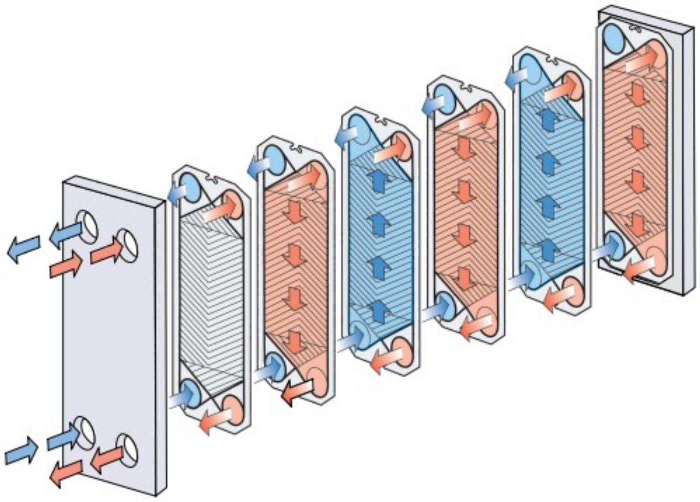


Figure 22: Fluid flow through a GPHE of the same type as the M6 [39]

5.3 Flow Electrification Applied to the GPHE

As stated in the introduction section of this chapter, the proposed hypothesis to explain the problem at hand is a case of the flow electrification phenomenon explained in chapter 2. The hypothesis is that the main source of charge separation occurs between the heat transferring plates, and one or both of the liquids flowing through, separated by these plates. The basis for this hypothesis is summarised in the following points:

- Assuming that no connection to ground exists (which is the premise of the project) the heat exchanger is effectively isolated from ground, meaning that dissipation of the charges in the solid part of the electrical double layer (EDL) interface is not possible. As shown in chapter 2, isolation from ground is a prerequisite to charge accumulation due to flow electrification.
- Not all but several of the applications of the heat exchanger involves the usage of liquids with a conductivity lower than the threshold of 50 pS/m, meaning charge recombination between the solid and liquid is extremely low or non-existing. Induce a flow in the liquid and the recombination is dampened even further.
- Due to the design of the GPHE, two bends in the flow path exists (transition from inlet to plate and plate to outlet). Agitation, sudden flow path changes and in general anything that cases turbulence have been shown to increase the charge separation [7, 17, 37]. In addition to this, the flow of the liquid is highly turbulent due to the corrugated plates [38].
- The heat exchanger itself, with exception of the epoxy paint coating, is entirely made out of different metals which are widely known to be good conductors.

To reiterate some of the concepts of flow electrification covered earlier, one or both of the liquids with a conductivity below 50 pS/m enters the heat exchanger, takes a turn and fills the space between two adjacent plates. As contact is established between the solid plate and low conducting liquid, an EDL starts to form either due to adsorption or existing corrosion. Both models could in this case be possible explanations for the EDL but the adsorption model is the more likely of the two. The plates are susceptible to corrosion but regular maintenance and control most likely means that a corroded plate will be replaced swiftly. As the EDL builds up, so does the space charge density profile along the walls, a profile dependent on the cross section geometry of the flow channel. With a fully formed EDL and stable space charge density profile, a stable streaming current is reached. The streaming current is a result of the flow of charges in the liquid, induced by the flow. Although the current in itself is not the primary point of interest, it serves as an indirect indicator of how efficient the charge build-up in the two phases is. The relation between the streaming current and charge being convected due to liquid flow is through the basic definition of current given by Eq. (1). At this point, both the heat exchanger and the liquid(s) leaving the exchanger will carry an electrical charge which can lead to disasters according to the principles in chapter 3 and 4. How these principles apply to this case will be covered in a later section.

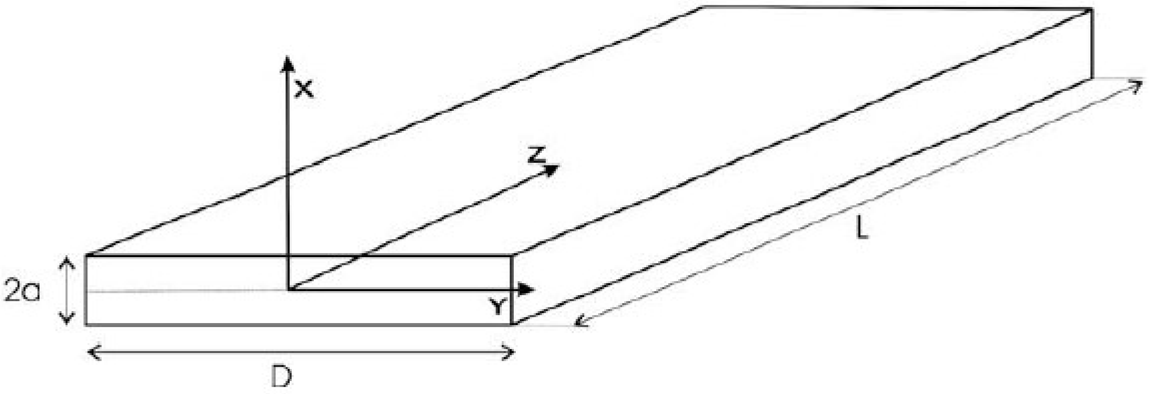


Figure 23: Rectangular flow channel cross section [11]

As previously stated, the space charge density profile along the flow channel depends on the cross section geometry. Two models are predominantly used when evaluating flow electrification in a flow channel, the circular pipe model and rectangular channel model. It is rather problematic to apply one of these directly to the heat exchanger due to the corrugation on the plates. This would be a considerable problem if the goal here was to show experimentally exactly how the charge is generated and separated in the heat exchanger but since the interest is the theory and not application, some simplifications will be made. Assuming that the space between two plates can be explained by the rectangular channel model, see Fig.23 above, while being aware of a degree of error, parameters of interest for the magnitude of the charge build-up can be identified. Assuming that the width D of the channel is much larger than the height $2a$ [16], $2a << D$, the space charge density profile as a function of the position in relation to the x and z – axis is given by [40]:

$$\rho(x,z) = \rho_w(z)\frac{\cosh\frac{x}{\delta_0}}{\cosh\frac{a}{\delta_0}} \tag{14}$$

where $\rho_w(z)$ is the space charge density along the liquid – solid interface and δ_0 is the Debye length given by Eq. (9) above.

In the presence of laminar liquid flow with a velocity profile given by [40]:

$$U(x) = \frac{3}{2}U_m(1-\frac{x^2}{a^2}) \tag{15}$$

where U_m is the mean flow velocity. Using Eq. (14) and (15), an expression for the streaming current in the liquid is obtained as [40]:

$$I_s(z) = \int_{-D/2}^{D/2}\int_{-a}^{a}\rho(x,z)U(x)dxdy = 2D\rho_w(z)\,x\,3\Big(\frac{\delta_0}{a}\Big)^2U_m(a-\delta_0\tanh{(a/\delta_0)}) \tag{16}$$

Upon close inspection of Eq. (16) one sees that all but one thing is “known”, $\rho_w(z)$, which is given by [40]:

$$\rho_w(z) = \rho_{wd}\left(1 - exp\left(-\frac{Kz}{3\left(\frac{\delta_0}{a}\right)^2 U_m\left(a-\delta_0\tanh\left(\frac{a}{\delta_0}\right)\right)}\right)\right) \tag{17}$$

The wall current i_w and physiochemical parameter K that were presented in chapter 2 are used when formulating Eq. (17) above, starting with the definition of current given by Eq. (1) [14]. The proof will not be given here but at least now it is clear why Eq. (10) and (11) are of interest. The problem now however is that one unknown (K) has been replaced by another, ρ_{wd} found in Eq. (17), the space charge density at the liquid – solid interface when the EDL is fully formed. No expression exists for ρ_{wd} without knowing what the actual streaming current at some point in time is by measuring it, creating a catch 22 scenario since the point of Eq. (16) is to be able to calculate the streaming current, not measure it. But since ρ_{wd} is a constant, only one streaming current measurement is needed to then determine ρ_{wd} which then will allow one to calculate the streaming current using Eq. (16) arbitrarily. To do this, two methods exist, the Dynamic and Static method [40].

The Dynamic method is based on a partially developed EDL during liquid flow while the Static method is based on a fully formed EDL and that the liquid initially is at rest. In this case, the Static method will be briefly outlined because it is usually preferred due to not relying on previous knowledge of the physiochemical constant K. The static method is based on using Eq. (16) above and filling the canal with the liquid and waiting a time period before introducing a flow in the liquid [40]. At liquid rest, the EDL will reach its maximum thickness. Then, when introducing the flow, a peak in the streaming current, $I_{(Streaming,peak)}$, will occur as result of convection of the fully developed EDL. As time goes, the EDL will reach a new equilibrium state which will have a diffuse layer weaker than when it is fully developed. This corresponds to the stationary value in the streaming current which is reached after a certain time. This is shown in Fig.24 below. By using the maximum streaming current in Eq. (16) above, $\rho_w(z)$ will be equal to ρ_{wd}, making it possible to calculate ρ_{wd} based on the experimental results.

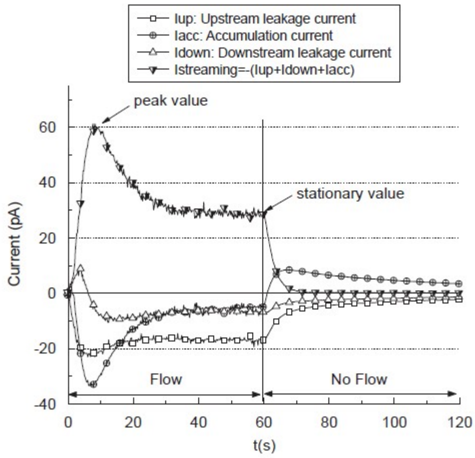


Figure 24: Streaming current development when starting at rest [40]

Although the model and equations above are useful for identifying parameter of interest, one thing must be made clear regarding one assumption made regarding Eq. (15). Eq. (15) is based on the assumption that the flow is laminar, something that is not realistic in the case of the heat exchanger due to the design of it and the corrugated plates. The flow in the heat exchanger is described by Alfa Laval as turbulent, something that is said to increase the heat transfer [38]. For turbulent flow, Reynolds number has to be taken into consideration and models do exist which handle turbulent flow. Problem is that no such model has been found that assumes a rectangular cross section, they all assume a circular pipe. As a result of this, the laminar flow model is presented. Although the expressions would look a bit different, (based on the difference between laminar and turbulent for circular pipes), the parameters of interest is unchanged with the addition of Reynolds number.

As previously stated, in addition to the rectangular model, a model for circular pipes also exist. Looking at the GPHE shown in Fig.21 above one sees that there in fact are four pipe flanges on the frame plate, meaning that the circular pipe model could also be of some interest when examining the existence of static electricity in the GPHE. One can even extend this reasoning to include the actual pipes that are connected to these four connections and wonder why this model is not presented. The answer is quite simple, it would not contribute with anything useful. With the exception of being adjusted to a circular cross section geometry, the end result usable in this case, parameters of interest, would be the same [14]. For this reason, this model has been omitted. A second reason is that while the pipe connections are a part of the GPHE, the pipes are not and the question at the center of this project is the charge accumulation in the GPHE.

So what parameters could be of interest? Looking at Eq. (16) and (17), one can see that the Debye length δ_0, mean velocity of the flow U_m, space charge density along the interface ρ_{wd} and the physiochemical constant K are of importance in the flow electrification phenomenon. Although these four parameters are of direct interest based on Eq. (16) and (17), only the velocity is directly related to controllable parameters, influencing the heat exchangers overall efficiency. However, experiments and simulations have shown that the fluid temperature T and bulk conductivity σ both play an important role by influencing ρ_{wd} and K [13, 16, 40].

5.4 Parameter Influence

With a theoretical grasp of the flow electrification phenomenon, with some assumptions and simplifications made, the time has come to see how the identified parameters of interest affects the charge accumulation. The previous section identified a couple of parameters of interest based on Eq. (9), (16) and (17). Of these, only the liquid mean flow velocity U_m is directly linked to parameters affecting the overall efficiency of a heat exchanger. However, experiments and simulations [13, 16, 40] show that the liquid temperature T and bulk conductivity σ plays an important role in the total charge generated and both can be either directly linked to the efficiency or directly controlled. Additionally, the importance of the liquid bulk conductivity is made even clearer when looking at recommended guidelines when dealing with static electricity [7, 17, 37].

5.4.1 Mean velocity U_m

The mean velocity of the fluid is strongly connected to the mass flow of a heat exchanger and thus the overall efficiency when heating or cooling something. Both the streaming current I_s and the physiochemical constant K have been shown to vary with the mean velocity. A relationship between the streaming current and velocity is also evident from Eq. (17). Experiments done [16] at the University of Poitiers, France, showed that there exists an almost linear relation between the streaming current and the mean flow velocity of the liquid. The result from one of these experiments is shown in Fig.25 below.

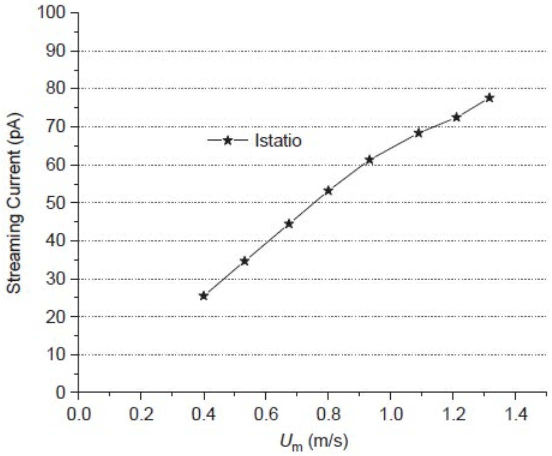


Figure 25: Results from flow electrification experiments showing the relation between streaming current and mean flow velocity [16]

The results showed that an increased velocity resulted in an increased streaming current and thus an increase in the total accumulated charge carriers. This facts is also confirmed by guidelines for handling flammable substances in environments where there is a risk for static discharge [7, 17, 37]. Generally an upper limit on the allowed flow rate is given based on the situation at hand. Both because it decreases the amount of charge generated but also that the turbulence is reduced which also contributes to the overall charge accumulation.

The experiments also showed that the physiochemical constant K does in fact vary with the velocity according to Fig.26 below. The authors suggest that a possible explanation [16] behind this relationship is found in the Corrosion model above. The classical model generally assumes that it is the concentration of negative ions found in the liquid B_L^- that controls the rate of reaction for Eq. (6) and that the concentration of C_S^+ is so large that it can be considered constant. But a possible explanation makes another assumption, instead of regarding the concentration of C_S^+ as constant, they believe that it is a function of the velocity through wall shear stress. This would mean that a higher velocity creates a higher shear stress which in turn increases the amount of C_S^+ ions that becomes available to react in Eq. (5).

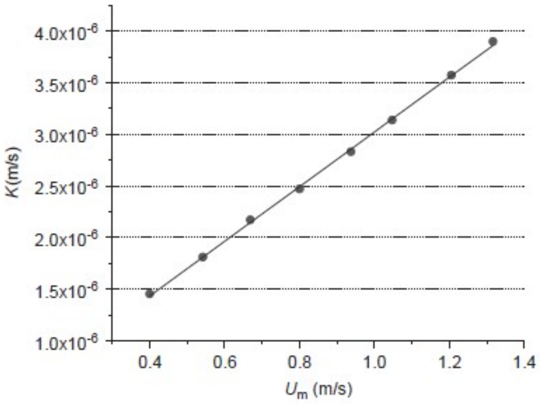


Figure 26: Physiochemical constant K versus mean flow velocity [16]

5.4.2 Fluid temperature T

For rather obvious reasons, the temperature of the fluids used is a vital part of any heat exchanger and it turns out that in addition to the efficiency of the heat transfer, the temperature also influences the streaming current peak, $I_{(Streaming,peak)}$, used for calculating ρ_{wd} but also the space charge density itself at a fully developed EDL, ρ_{wd}. Unlike the mean velocity, this relationship is not directly seen in the equations above but experiments [40] done at the University of Poitiers, France, has shown that the fluid temperature plays an important role. The results from these experiments are seen in Fig.27 and Fig.28 below.

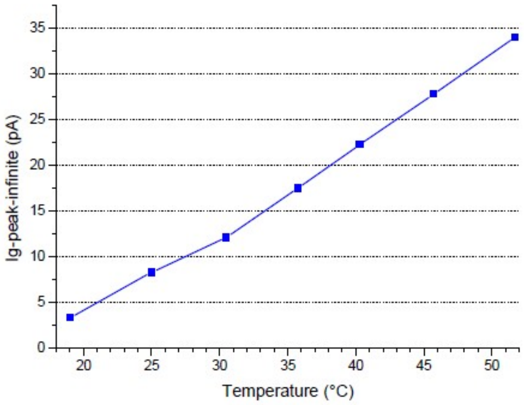


Figure 27: Peak streaming current versus liquid temperature [40]

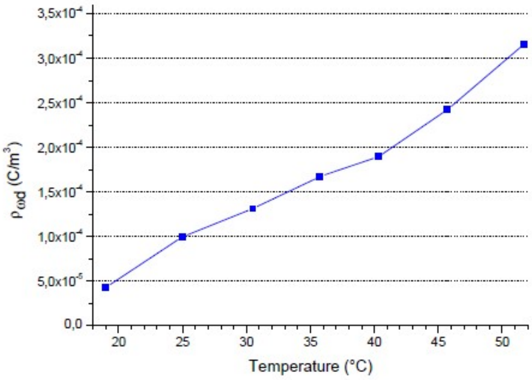


Figure 28: Space charge density at fully formed EDL versus liquid temperature [40]

5.4.3 Liquid bulk conductivity σ

Unlike the other two, the fluid conductivity might not at first seem relevant since it carries little importance for normal operations of a heat exchanger and is only indirectly related to the streaming current and space charge density through the Debye length δ_0. But the fact is that experiments [40] and simulations [13] have shown that the conductivity indeed is relevant although not as straight forward as the other parameters. Results from both the experiments and simulations show that there in fact exists a relationship between an increased space charge density and an increase in liquid conductivity. Results from experiments performed at the University of Poitiers [40] are given in Fig.29 below.

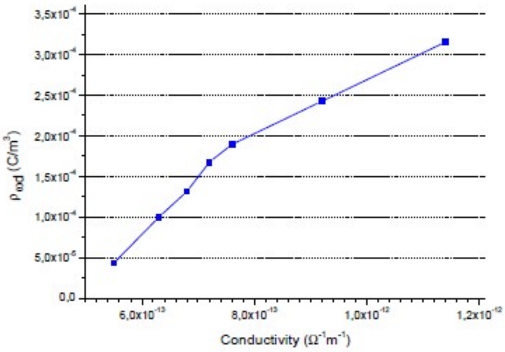


Figure 29: Space charge density versus liquid bulk conductivity [40]

As the conductivity increases, so does the space charge density, as seen by Fig.29. The increase is the result of two factors that contradict each other. As the conductivity increases, so does the amount of charges freed in the physiochemical reaction but at the same time the debye length decreases, see Eq. (9) above. A smaller debye length means a thinner diffuse layer and a lower amount of convected space charge as the layer is pulled closer to the compact layer. This can be seen in simulation results done on the EDL formation [13], presented in Fig.30 below. A greater space charge contributes to a larger streaming current as more charge carriers are convected but at the same time, a thinner diffuse layer means that less space charge is convected, clearly two contradicting facts. The proposed explanation is that increased conductivity increases the streaming current to a certain point to then start reducing it drastically [13].

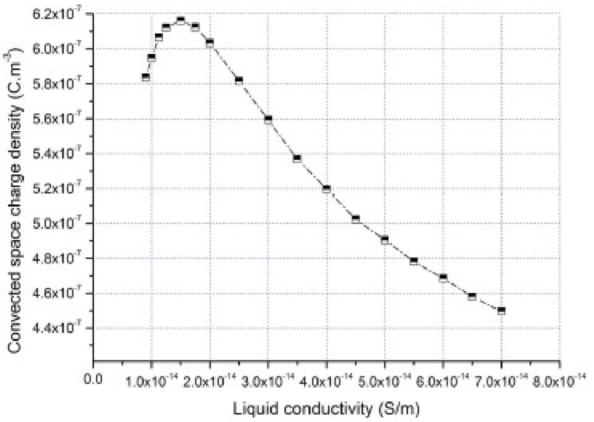


Figure 30: Simulated results of convected space density versus liquid bulk conductivity [13]

5.5 Summary and Concluding Remarks

Based on facts related to the static electricity phenomenon, the electrical charge present in the heat exchanger is theorised to be the result of contact charging between a liquid and a solid, also called flow electrification. The basis for this hypothesis is the fact that the heat exchanger is (without an earthing lug attached) isolated from ground, low conductive/insulating liquid is used in several applications, strong turbulence in the liquid is created and the entire heat exchanger, with the exception of the epoxy paint, is made out of high conducting metal. All these aspects have been proven to contribute to the overall charge accumulation in an object.

Parameters of interest have been identified by inspecting the mathematical equations governing the flow electrification phenomenon. Although the plate geometry in the heat exchanger deviates from the theoretical plate model due to being corrugated, the plate model is still the closest available model which can be used to explain the phenomenon. For this reason, assumptions have been made while also stating that the actual results from tests on the heat exchanger, if they were possible to do, would deviate from the theoretical results that the plate model would give. The problem that the model is based on laminar flow while reality is turbulent has been addressed and while it indeed is a problem, the lack of models for turbulent flow in a rectangular channel makes the presented model the closest to reality. The circular pipe model have been mentioned but no in depth explanation have been provided due to the fact that the end result, the parameters of interest, would be the same as the rectangular model provides.

Three parameters have been identified to play a significant role in how effectively the heat exchanger is charged, fluid temperature T, the mean velocity U_m and bulk conductivity σ and experimental and simulation results have been provided. Since the main purpose of a heat exchanger is to transfer heat energy from one medium to another, restrictions exists on how much the temperature and velocity of the medium involved can be tampered with. Nevertheless, there is still value in knowing how variations in these parameters influence the overall charge accumulation.

It has been shown that lowering the temperature of the liquid(s) involved would have a decreasing effect on the charge accumulation in the heat exchanger and liquid(s). This is mostly due to the fact that a lowered temperature would mean that the internal energy of the liquid will be lower and the physiochemical reactions involved would most likely be dampened as a result. But as also mentioned previously, drastic changes in the temperature would most certainly be difficult since this would lower with the efficiency of the heat exchanger. Also, the in cases where one liquid has to be cooled before further processing, the temperature is predetermined by the process preceding the heat exchanger, eliminating any chance of regulating the temperature.

The mean flow velocity of the liquid has also been shown to have an effect on the charge generation, higher velocity means larger charge build-up. There is a possibility for a somewhat greater freedom in lowering it but that would most likely require that the overall efficiency of the heat exchanger is higher than the lowest acceptable. Initially it might seem foolish to purposefully lower the efficiency of the heat exchanger but there are secondary aspects that could lead to positive results in the accumulated charge in one of the two materials. Something that has probably not been overly emphasised in this text is that grounding the heat exchanger only solve half of the problem. The actual heat exchanger itself would lose its charge since the dissipation through the ground connection would be greater than the accumulation of charge, given that the connection is adequate. This would however not dissipate the charge in the liquid going through the exchanger, the actual source of potential hazards. The physiochemical reaction between liquid and solid would still occur despite the existence of a ground connection and the liquid going through would still leave with an accumulated charge. That is why lowering the velocity at the cost of efficiency might in some cases be a reasonable course of action as the accumulated charge in the liquid would would decrease.

The last parameter, bulk conductivity, is probably the one that offer the greatest flexibility. Increasing the conductivity, as shown above, will initially increase the charge accumulation in both solid and liquid but as it passes a threshold value, the streaming current will start to decrease with an increased conductivity. This follows well with the existing recommendations on conductivity enhancing additives in low conductive liquids.

As discussed in chapter 4, ignition hazards involving liquid fuel sources are dependent on the flash-point of the liquid being handled since this will determine the likelihood of the presence of ignitable vapours. This also means that in order for ignition to occur in the heat exchanger when running a high risk liquid through it is that vapours has to be able to form and that there has to be pockets where the vapours can accumulate. Information found in a data sheet for the M6 show that maximum allowed temperature of the fluids going through it is between 180 – 250 degrees Celsius [41] which is well above the flash point for many common liquids which may produce ignitable vapours. Flash points in the interval of (– 100) – (+ 100) degrees Celsius [42] is common to find. This means that the conditions to create vapours most likely exists in some cases when the heat exchanger is used. But when the heat exchanger is operating normally it is completely filled [41] which means that there are no air pockets where the vapours can mix to create an ignitable mixture which means that the risk of sudden discharges and ignition are none.

But how about when the heat exchanger is “turned off”? Say for instance that the heat exchanger has to be opened for inspection or plate replacement. If it is opened shortly after removing any liquid inside, there is a possibility that as the liquid is pouring out, the now free volume inside allowed for fuel vapours to amass, creating a fuel – air mixture. Let’s also say that there was never enough time for this mixture to dissipate before a discharge close by occurred. In that case, the mixture could ignite, causing a fire. The question that remains then is how such a discharge could occur?

If proper procedures are followed, such as those listed in chapter 4, no discharge is possible since all potential differences between the heat exchanger and any object close to it will be zero. But imagine that the heat exchanger is grounded but that the operator who is going to perform the inspection or plate replacement has failed to follow the proper procedures. In that case it is very likely that the operator could be carrying an accumulated charge which could lead to a discharge through the operators hand or metallic tools as examples. If this is the case and a fuel air mixture is present, an accident is inevitable.

The proposed scenario might seem forced at first and realistically it is somewhat forced, but not impossible. Even though the likelihood is low for this to happen, theoretically it is a possibility and therefore it is important to be aware of it. This scenario also lines up with the findings in the Japanese study mentioned in chapter 4 where failure to follow static electricity regulations was a major factor when evaluating the cause of accident. The heat exchanger as a whole, whether it is “turned on” or off is likely a low risk apparatus. But that is generally the case in instances where flow electrification is observed, the pipe or channel that the liquid is flowing through, if it is completely filled, is not the part to be concerned about, as just recently discussed above, it is the eventual storage in conductive tanks of the liquid that is often the major issue.

Despite being confidence in the conclusions drawn and assumptions made, the fact is that all of it is highly hypothetical and without actual test to verify it, there is a risk that inaccuracies exist. While admitting this the hope is still that the facts presented are strong enough to give credence to the conclusions drawn. Several studies into the flow electrification phenomenon have been studied along with recommendations, standards and literature of how to handle the static electricity problem in industry. The heat exchanger is an extreme exception to all existing cases found where flow electrification occurs, none of them even mentioning something like this occurring in heat exchangers of any kind (most likely is due to heat exchangers being a very specific case).

6 Test Set-up

6.1 Introduction

With the theoretical part of the project completed attention turns to the practical part, evaluating the five earthing lug attachments:

- FP Weld (FP_1 in Fig.43 in Appendix A1)
- SC Weld (SC_3 in Fig.43 in Appendix A1)
- SC Fastener(SC_4 in Fig.43 in Appendix A1)
- FP Screw (FP_2 in Fig.43 in Appendix A1)
- FP Boss Weld (FP_4 in Fig.43 in Appendix A1)

Three devices used to detect and measure stored charge was detailed in section 4.4, all which could very well be used to evaluate the five solutions in any other situation. But due to the fact that the tests must be performed on the heat exchanger with no low conductive fluid flowing through it, some other method must be identified which allows for testing without liquids and gives results that are equivalent to those one might obtain through conventional testing. The proposed method of testing that will be used here is based on the basic principles of grounding described in 4.5. As stated, in cases where everything from grounding rod to charge source is metallic, the recommended maximum resistance through the system should be 10 Ω and will therefore be used as the evaluation parameter for the tests.

6.2 Resistance Measuring

Usually, resistance is measured with an ohmmeter or a multimeter which are both perfectly viable options in most cases. But when dealing with objects with a very low resistance, these two methods fall short due to the resistance of the wires between the measuring device and object. For objects with a high enough resistance this is not a problem since the wire resistance is only a couple of ohms per tens of meters of wire in most cases. In this case however, since everything is made out of metal, the resistance will most likely be quite low and therefore the wire resistance will most likely interfere with the results. For this reason, four – wire resistance measuring will be used, a method which eliminates the wire resistance interference.

Four wire resistance measurement is a rather straight forward method, four wires, a current source and a voltmeter is used to measure the resistance of an object. The set-up is illustrated in Fig.31 below.

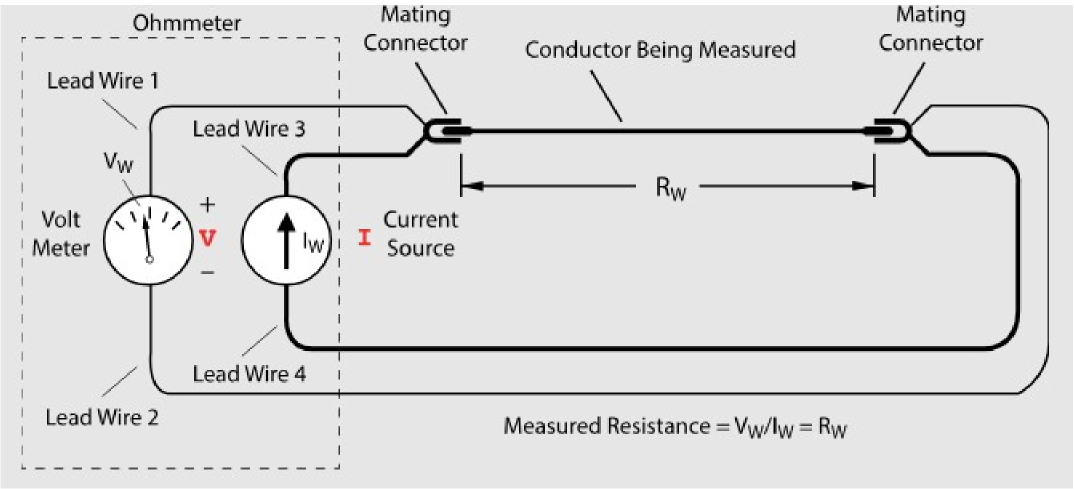


Figure 31: Four wire resistance measurement set-up [43]

Standard ohmmeters and multimeters that use two wire measurement have an internal current source which is used to create a known test current flowing through the wires and object whose resistance shall be measured. The ohmmeter then measures the voltage drop across the internal current source. Problem with this is that this voltage drop will include the resistance in the wires as well as any other type of resistance found in the circuit. With four wire measurement, as seen in Fig.31 above, the voltage drop is measured only across the object of interest, if the probes are placed close enough to the object leads. Intuitively this method might seem contradictory as the resistance in the wires from the volt meter to the probes would be included in the measurement but the current going through these wires is generally so small that the wires influence can be disregarded [43]. Knowing the applied current and being able to measure the voltage drop, the resistance R can be calculated using Ohm´s law:

$$R = \frac{U}{I} \tag{18}$$

Where U is the measured voltage drop and I the applied test current (DC). Fig.31 above depicts an ohmmeter built to perform four wire measurements so the voltage meter and current source is embedded in one compact device. No such device is available for these tests so the current source will be in the form of a stand alone current supply and the voltmeter will be a multimeter. Other than that, the set-up is still the same as in Fig.31.

6.3 Physical Set-up

When performing the test detailed above, the “object” of interest is the GPHE + earthing lug attachment + ground wire. One power supply connection will be applied at one of the plates in the GPHE since this is believed to be where the charge accumulation occurs while the other connection will be at the end of the ground wire. A known DC current will be applied and the voltage drop across these two points will be measured, resulting in a total resistance for the circuit.

Ideally the second power supply connection should be the actual grounding rod embedded in soil but practical aspects makes this very hard to do, especially in the lab environment available. Grounding rods are usually a couple of meters long and embedded fully in soil. In addition to this, the wire used will be of the same type, same thickness and same length between all tests. One could think it would be easier to exclude the wire but it is necessary to capture as much of the real situation when possible, even though the grounding rod resistance is neglected.

To ensure that the results are not specific for a certain current level, each design will be tested with an increased test current applied, starting at almost no current and going up to 5 A. The idea is to then take the data and see if the calculated resistance behaves linearly in this interval. If that is the case, there should be a linear behaviour for the lower currents which are associated with the charge build-up and whichever design proves the best through these test should still be the best in the real scenario.

6.4 Designs

A drawing showing the placement of the five designs is given in Appendix A along with individual drawings of all five designs. Fig.32 and Fig.33 shows the actual components attached to the real GPHE. Starting from the top of the GPHE in Fig.32, the FP screw comes first, then the FP boss and lastly the FP weld. In the same way, starting from the top in Fig.33, the SC fastener is the one on the top while the SC weld is at the bottom.

Figure 32: The three designs related to the frame plate. The black cable connected to the FP boss is the "simulated" ground cable which in reality is connected to a ground embedded rod.

Figure 33: The two designs related to the SC

Below in Table.2, the material of some of the parts in the GPHE is listed along with the volume resistivity of the material [44].

Table 2: Material list

Part	**Material**	**resistivity**
FP/SC weld	Carbon Steel	0.20 - 0.25 $\mu\Omega m$
FP boss	Carbon Steel	0.20 - 0.25 $\mu\Omega m$
FP screw	Stainless Steel	0.64 - 1.07 $\mu\Omega m$
SC fastener	Carbon Steel	0.20 - 0.25 $\mu\Omega m$
Frame/Pressure plate	Carbon Steel	0.20 - 0.25 $\mu\Omega m$
Support column	Carbon Steel	0.20 - 0.25 $\mu\Omega m$
Guiding bar and carrying bar between FP and SC	Carbon Steel	0.20 - 0.25 $\mu\Omega m$

7 Results and Design Selection

7.1 Introduction

With the test completed, the next step is to use the gathered data to compare the five designs against each other in order to in a systematical way determine which one is the best. As stated in Chapter 1, in addition to the results from the tests, a couple of other factors will be used as selection criteria's in a selection matrix. The aim of this chapter is to present the results from the tests and the resulting resistances calculated. The concept of the selection matrix will also be presented and the criteria's chosen will be presented in detail along with a justification of why they are deemed relevant.

7.2 Results

The results are presented in Table.3 - 10 below. For the three cases with the frame plate mounted designs, two tables are presented for each of the three designs where one for each is blank with the exception of the measured voltage. This is deliberately done to illustrate an early hypothesis based on preliminary tests and information about the GPHE which has now been confirmed with the proper tests. The attentive reader might remember that two parts of the GPHE is covered in a blue epoxy paint. The thing about epoxy paint is that it is a thermoplastic polymer paint and as most might be aware of, polymers by default are poor conductors and is actually frequently used as an insulator in electrical applications[45]. As a result, no path exists to close the circuit for the three designs mounted on the frame plate which is the reason for why a voltage is measured but no current is being outputted by the current source.

However, due to paint being scraped of in some areas a closed circuit for the three designs is possible and the three non - empty tables present a situation where this is possible, why this is the cases will be explained further on. For the three frame mounted designs when the paint is scraped and the two support column mounted designs, the calculated resistance deviates a bit between the test points. To determine whether there is an approximately linear relationship between the supplied current and measured voltage, the two are plotted against each other along with a plot showing the linear regression between the two. These plots are given in Fig.34 - 38 below.

7.2.1 FP weld

As seen in Table 4 below, the calculated resistance to earth through the FP weld design, with paint scraped, fluctuates in the interval $0.132 - 0.208\ \Omega$. Furthermore, the left plot in Fig.34 below shows that the relationship between supplied current and measured voltage can be fitted rather well, as seen by $r = 0.989$, to a linear function with a slope of $0.128\,\Omega$.

Table 3: FP Weld result with no scraped paint.

Supplied Current (A)	**Measured Voltage** (V)	**Resistance** (Ω)
-	0.411	$>> 10\,\Omega$

Table 4: FP Weld result with scraped paint.

Supplied Current (A)	**Measured Voltage** (V)	**Resistance** (Ω)
0.0	0.0	-
0.5	0.104	0.208
1.0	0.183	0.183
1.5	0.261	0.174
2.0	0.309	0.154
2.5	0.359	0.144
3.0	0.442	0.147
3.5	0.521	0.149
4.0	0.558	0.140
4.5	0.601	0.135
5.0	0.658	0.132

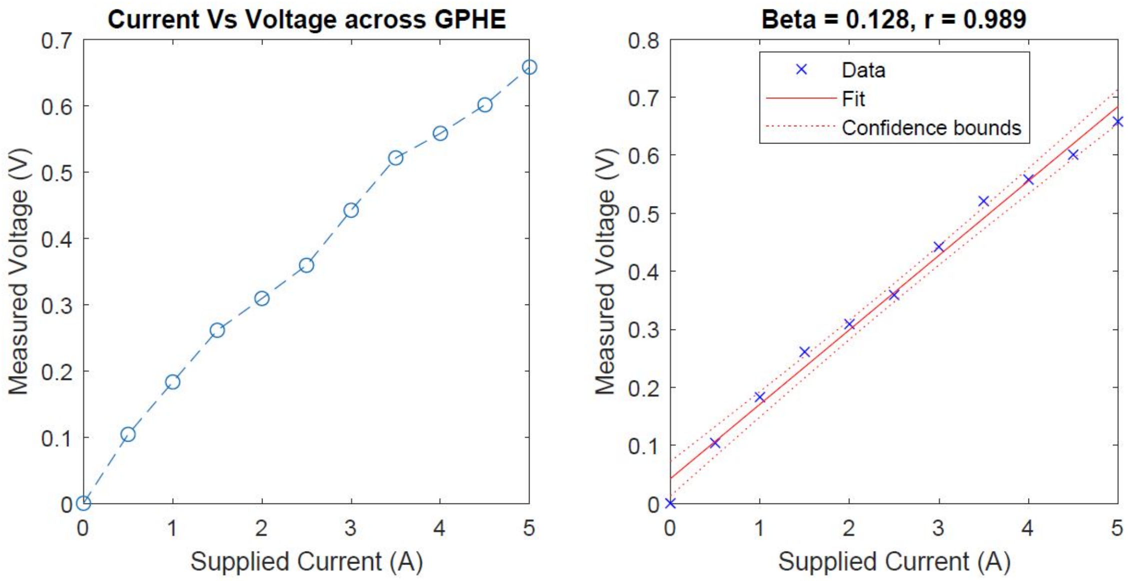


Figure 34: Plot of values from Table.4 (left) and related linear regression plot (right).

7.2.2 FP boss weld

As seen in Table.6 below, the calculated resistance to earth through the FP boss weld design, with paint scraped, fluctuates in the interval $0.138 - 0.184\ \Omega$. Furthermore, the left plot in Fig.35 below shows that the relationship between supplied current and measured voltage can be fitted rather well, as seen by $r = 0.992$, to a linear function with a slope of $0.137\ \Omega$.

Table 5: FP Boss Weld result with no scraped paint.

Supplied Current (A)	**Measured Voltage** (V)	**Resistance** (Ω)
-	0.408	$>> 10\ \Omega$

Table 6: FP Boss Weld result with scraped paint.

Supplied Current (A)	**Measured Voltage** (V)	**Resistance** (Ω)
0.0	0.0	-
0.5	0.092	0.184
1.0	0.168	0.168
1.5	0.231	0.154
2.0	0.305	0.153
2.5	0.368	0.147
3.0	0.462	0.154
3.5	0.532	0.152
4.0	0.593	0.148
4.5	0.628	0.140
5.0	0.672	0.138

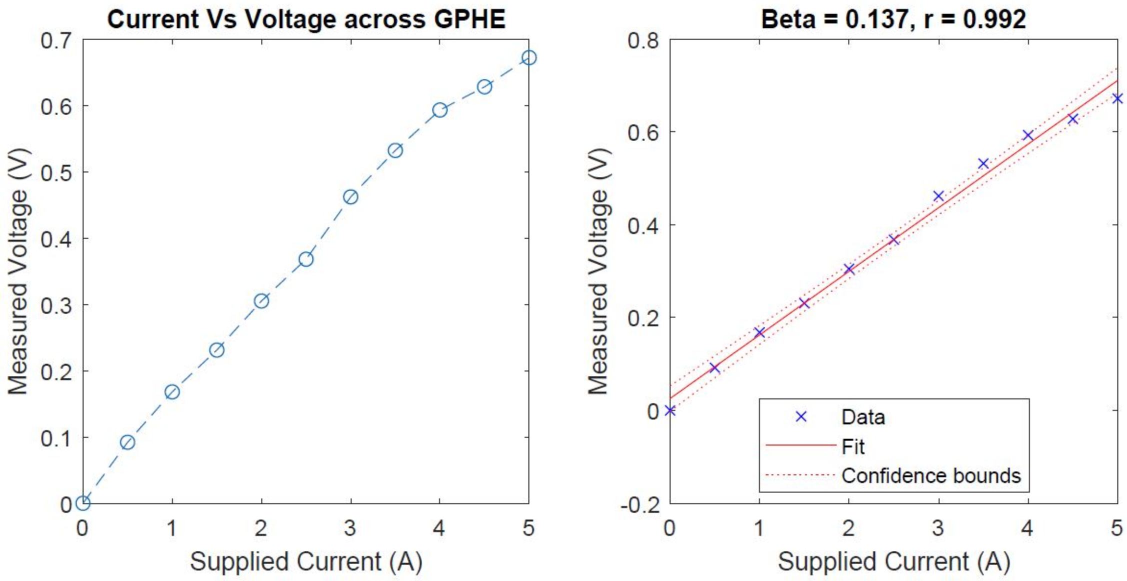


Figure 35: Plot of values from Table.6 (left) and related linear regression plot (right).

7.2.3 FP screw

As seen in Table.8 below, the calculated resistance to earth through the FP screw design, with paint scraped, fluctuates in the interval $0.142 - 0.162\ \Omega$. Furthermore, the left plot in Fig.36 below shows that the relationship between supplied current and measured voltage can be fitted rather well, as seen by $r = 0.989$, to a linear function with a slope of $0.147\ \Omega$.

Table 7: FP Screw result with no scraped paint.

Supplied Current (A)	**Measured Voltage** (V)	**Resistance** (Ω)
-	0.406	$>> 10\ \Omega$

Table 8: FP Screw result with scraped pain.

Supplied Current (A)	**Measured Voltage** (V)	**Resistance** (Ω)
0.0	0.0	-
0.5	0.071	0.142
1.0	0.149	0.149
1.5	0.227	0.151
2.0	0.303	0.152
2.5	0.373	0.149
3.0	0.485	0.162
3.5	0.556	0.159
4.0	0.627	0.157
4.5	0.663	0.147
5.0	0.690	0.138

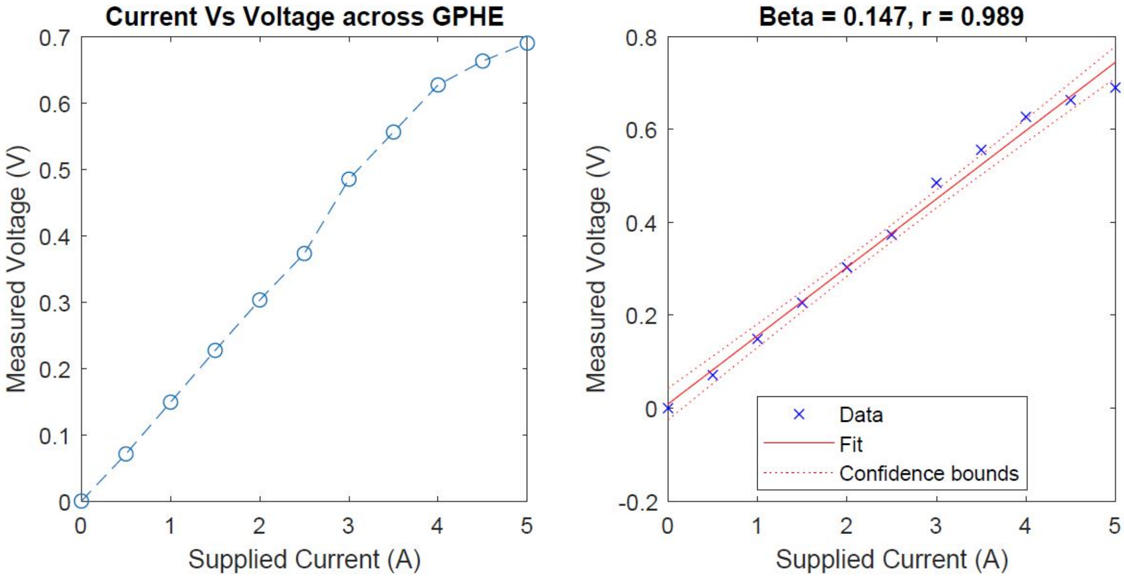


Figure 36: Plot of values from Table.8 (left) and related linear regression plot (right).

7.2.4 SC weld

As seen in Table.9 below, the calculated resistance to earth through the SC weld design fluctuates in the interval $0.132 - 0.142\ \Omega$. Furthermore, the left plot in Fig.37 below shows that the relationship between supplied current and measured voltage can be fitted rather well, as seen by $r = 0.998$, to a linear function with a slope of $0.136\ \Omega$.

Table 9: SC Weld result.

Supplied Current (A)	**Measured Voltage** (V)	**Resistance** (Ω)
0.0	0.0	-
0.5	0.071	0.142
1.0	0.139	0.139
1.5	0.212	0.141
2.0	0.279	0.140
2.5	0.351	0.140
3.0	0.428	0.143
3.5	0.487	0.139
4.0	0.552	0.138
4.5	0.626	0.139
5.0	0.659	0.132

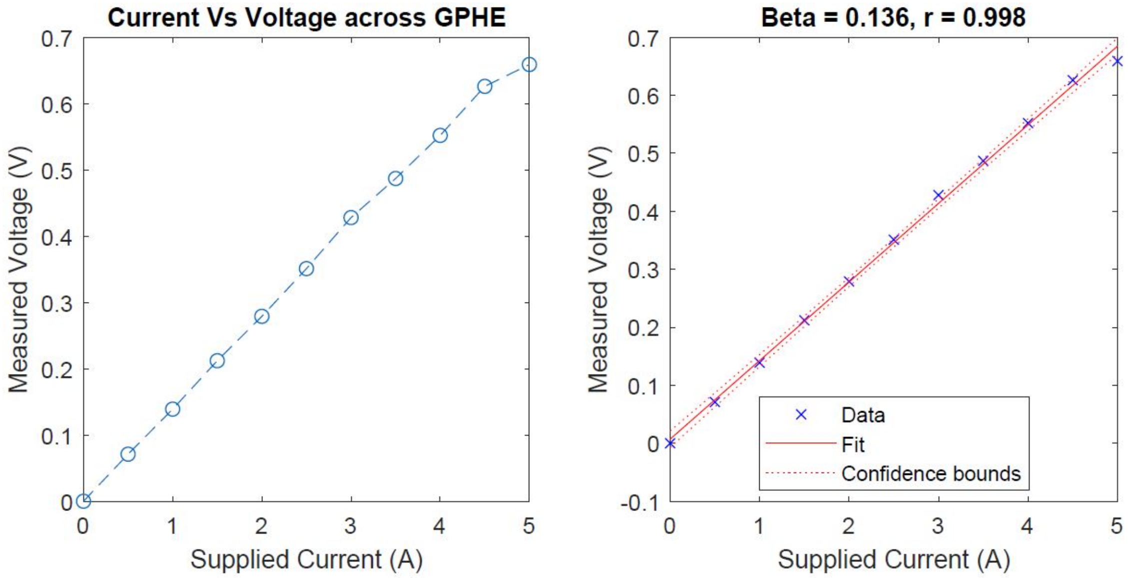


Figure 37: Plot of values from Table.9 (left) and related linear regression plot (right).

7.2.5 SC fastener

As seen in Table.10 below, the calculated resistance to earth through the SC fastener design fluctuates in the interval $0.138 - 0.154\ \Omega$. Furthermore, the left plot in Fig.38 below shows that the relationship between supplied current and measured voltage can be fitted rather well, as seen by $r = 0.995$, to a linear function with a slope of $0.139\,\Omega$.

Table 10: SC Fastener result.

Supplied Current (A)	**Measured Voltage** (V)	**Resistance** (Ω)
0.0	0.0	-
0.5	0.075	0.150
1.0	0.140	0.140
1.5	0.226	0.151
2.0	0.309	0.154
2.5	0.384	0.154
3.0	0.460	0.153
3.5	0.510	0.146
4.0	0.553	0.138
4.5	0.623	0.138
5.0	0.698	0.140

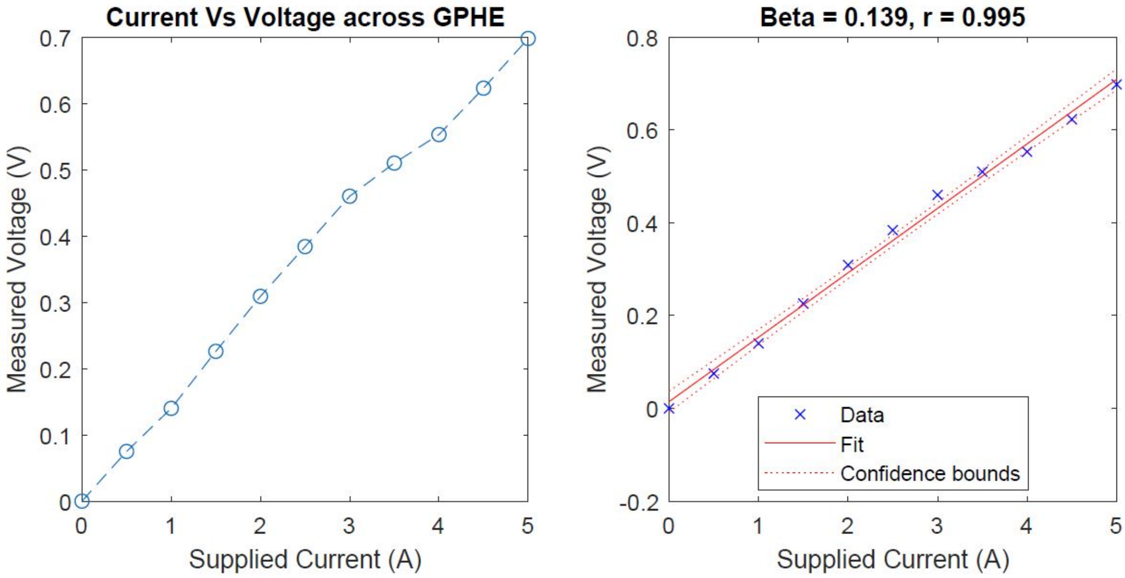


Figure 38: Plot of values from Table.10 (left) and related linear regression plot (right).

7.2.6 Result comparison

As evident from Table.11 below, all designs fall well below the threshold resistance of the recommended 10 Ω [7, 17, 37]. However, with no paint scraped, the three frame plate mounted designs fail, having a resistance far above the threshold used. The ranking based on this case is given in parentheses in Table.11.

Table 11: Results from linear regression fitting of values found in Table.4,6,8,9 and 10. Rank within parentheses reflects the actual rank when no paint is scraped off.

Design Suggestion	Resistance (Ω)	Rank
FP weld	0.128	1 (5)
FP boss weld	0.137	3 (5)
FP screw	0.148	5 (5)
SC weld	0.136	2 (1)
SC fastener	0.138	4 (1)

To illustrate the case no paint scraped off, Fig.39 below shows the measured voltage between the two test points and the supplied current for one of the three frame plate mounted designs:

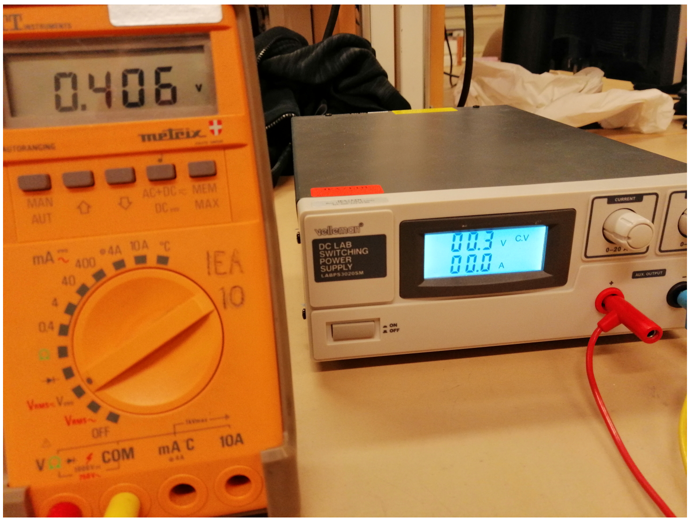


Figure 39: No (or extremely small) current is supplied but a voltage difference is measured.

As the display of the current source is limited to one decimal, the actual current provided was confirmed through testing.

7.3 The Selection Matrix

A selection matrix is a part of the Pugh concept selection developed by Stuart Pugh in the 1980s [46]. A selection matrix is used to compare a number of possible concepts with each other, based on a number of selection criterion's relevant to the problem the concepts are intended to solve. In early stages of concept screening, a concept is often rated with a + or – based on how well it performs based on a criterion. In later stages where a finer differentiation of the concepts in the selection matrix is necessary, a scoring system is implemented and all criterion's are given a weight, reflecting the importance a criterion has for the overall performance of the final product. Since test results will be used as one of the criterion's, the scoring method will be used here to better reflect the performance of the five designs.
The criteria's used in the selection matrix are given again below along with a short explanation for why it was chosen, what weight it is given and a short motivation for the chosen weight.

- **Durability:**
  The components physical durability as well as resistance to environmental influence, primarily corrosion. Is the component placed in such a place that makes it easier to damage by mistake through blunt trauma? This criterion depends heavily on the type of environment that the customer uses the heat exchanger in but general conclusions can be drawn. For instance, does the component protrude, making it easier for something to hit it by accident, or is it attached in a way that this risk is minimal. Given a weight of 5% as even though it is important for the design to be resilient to corrosion and physical damage, the reality is that the risk of actually being struck often and hard enough to reduce performance is rather low.

- **Mounting:**
  Time and effort necessary to invest when attaching the component to the heat exchanger. Interesting when evaluating whether all heat exchangers produced should be fitted with an earthing lug connection point or if it should be custom ordered as today, the default GPHE does not include this. In addition to this, compliance with regulations concerning operations on pressurised vessels will be taken into account. Certain operations performed on the surface of a pressurised vessel, in this case the frame plate, must be inspected before the unit can be put into operation [47]. This criteria also takes retrofitting into consideration i.e. if a customer some time after receiving the heat exchanger wishes to add an earthing lug although the original order did not specify one. Given a weight if 25% as this in the long run will have a substantial effect on the cost and time to produce a custom order. Is also a strongly recommended trait for grounding systems [37].

- **Replaceability:**
  In cases where the component has to be replaced due to damage or poor performance, how time consuming and how much effort must be used to remove it. Is it possible to remove it without causing cosmetic damage or worse to the heat exchanger? For this criteria the pressure vessel aspect mentioned in the previous criteria must be taken into consideration.

Given a weight of 20% as in the event that the component becomes so damaged or corroded tot he point that the performance is reduced, the time, cost and effort it takes to replace it is of interest from a profiting perspective. As with previous criteria, strongly recommended trait [37].

- **Component Cost:**
  Cost to manufacture/order the component which will then be attached to the heat exchanger plus costs related to attaching it. Just like the ease of attachment criteria, the cost is of interest when deciding whether all heat exchangers should be fitted with the component by default or if it should be custom ordered. Given a weight of 30% as the cost of components is one of the most important aspects for any one interested in making a profit. Giving this, replaceability and mounting such high weights is also a reflection of aspects of interest brought up by Alfa Laval throughout the project.

- **Test Result:**
  Self-explanatory, there is no reason to ever consider using one of the design suggestions if the measured resistance is well above 10 Ω. If all are below this value, it comes down to which one results in the lowest resistance. Given a weight of 20% as functionality is an important factor when evaluating different designs.

The selection matrix with the criteria's used and their weighs is shown in Table.12 below. Usually, one concept is chosen as the reference and all the other are then compared to the reference [46]. In this case, the FP Weld is chose as the reference. This means that this design is given a 3 on all criteria's. The rating scale ranges from 1 – 5.

Table 12: Selection Matrix with scoring based on the case with scraped paint

		Design									
		FP Weld		**FP Boss Weld**		**FP Screw**		**SC Weld**		**SC Fastener**	
Selection Criteria	Weight	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score
Durability	*5%*	3	0.15	4	0.2	3	0.15	3	0.15	4	0.20
Mounting	*25%*	3	0.75	3	0.75	2	0.5	4	1	5	1.25
Replaceability	*20%*	3	0.6	2	0.4	5	1	4	0.8	5	1
Component Cost	*30%*	3	0.9	3	0.9	4	1.2	3	0.9	5	1.5
Test Result	*20%*	3	0.6	3	0.6	3	0.6	5	1	5	1
Total Score		3		2.85		3.45		3.85		4.95	
Grade		D		E		C		B		A	

Based on the rating given to a design for each of the five criteria's, a total score is calculated by multiplying each rating with the corresponding weight for that criterion and then adding all the weighted scores together to make the total score. Based on the total score, a grade of A – E can be assigned to each design. In addition to the criteria's used in Table.12 above, the designs compliance with general customer demands will be taken into consideration when drawing a conclusion of the results in Table.12 above. In general, a majority of customers prefer an earthing lug attachment that is welded onto the heat exchanger, often on the frame plate (Meeting C Svensson 2019 – 03 – 25). In many cases it is because it fits well with the layout of the facility where the heat exchanger will be placed and thus it simplifies the ground wire management. The selection matrix will be based the 100% paint coverage case.

8 Discussion and Concluding Remarks

8.1 Discussion

Looking a the selection matrix presented in Table.12, two things stand out. The first is that the actual physical location on the GPHE plays an important role in the measured resistance and thus, the ability to effectively provide a dissipation path to ground for accumulated charge carriers. The second thing which relates back to the first is that the consequences of a bad location choice is not properly represented. One thing stressed in the previous chapter is that for the three frame plate mounted designs, two cases existed depending on whether the paint in one specific area had been scraped or not. If all criterion's but the test result are omitted, this repeated issue with the paint becomes the single factor determining whether the design suggestion is acceptable or not.

8.1.1 The epoxy paint

The set-up detailed in chapter 6 and which the practical part of this project builds upon is chosen so that the test circumstances imitate the proposed hypothesis of chapter 5. The idea is that the charge carriers accumulated in the heat exchanger through flow electrification would redistribute themselves throughout the heat exchanger to create an even electrical potential. The five designs used by Alfa Laval, offered to customers all "assume" that the charge carriers in fact do redistribute themselves evenly throughout the heat exchanger, making any point on the exchanger a viable ground point. This is however not the case, a fact strongly reflected by the test results in the case of no paint being scraped. Something that might be clear upon closer investigation of the Figures Fig.21 and Fig.32 is that there are no surfaces without paint between the heat plates and the FP. Neither are there any exposed surfaces between the two bars and support column to the frame plate. As a result of this, which is shown in Table.3,5 and 7, the circuit connecting the charge source (heat plates) to the point of dissipation (ground) is broken which is why no or possibly an extremely small current is registered by the current supply source but a voltage difference between the points is registered. The resistance of the paint is high enough that it in this case the resistance is equal to a break.

While the scenario just described where the circuit is not closed is the realistic one and will be the case for all GPHEs sold to customers, a second scenario was tested where the circuit is closed. By accident, the paint in and around the holes connecting the guiding and carrying bar to the frame plate, see Fig.19, had been partially scraped through repeated assembly and disassembly of the heat exchanger. While being done on accident, this provided an opportunity to evaluate the three frame plate mounted designs and to obtain data usable in cases where the customer is adamant to have a frame plate mounted design, despite recommendations based on the results of this report. Important to stress is that the case where accidental paint scraping will allow a current to flow through the frame plate is not a realistic case for GPHEs in operation as the only area where paint scraped can cause this is the guiding and carrying bar holes, an area not influenced by adding and removing heat transferring plates. The results of the tests made on this scenario is given in Table.4,6 and 8 and show that these three are viable solutions to the problem but as evident from the selection matrix, they are are in no way worth the extra costs, time and labour to make them viable.

Reading the above arguments one might get the impression that the case of a broken circuit is fabricated as paint was accidentally scraped before performing the actual tests. This is however not the case. While 100% paint coverage had to be fabricated using two strips of fabric covered wax cloth and electrical tape, the scenario itself is 100% realistic as the GPHE will be delivered in pristine condition. The scraped paint case could have been omitted but the results were deemed useful for cases where the customer is adamant to have a frame plate based solution. Also, one can not base a recommendation on the extremely small eventuality that paint MIGHT become scraped in the proper place to make the recommendation usable. Worth pointing out that preliminary tests made shortly after receiving the heat exchanger showed that the paint was acting as an insulator, but it was not properly quantified until later.

8.1.2 Durability

With the matter of the epoxy paint out of the way, the focus now shifts to the other criterion's in the selection matrix and how well the five designs fulfil them. Starting with the criteria with the lowest weight, durability. The FP weld and SC weld share the same score as the actually component is the same, the difference is location. From a physical perspective, a welded component will be able to take a good deal of force before breaking off and in reality, the risk of physical impacts on the heat exchanger is rather low since they are usually placed in secluded areas. The same reasoning can be extended to the FP boss weld, FP screw and SC fastener and is one reason that durability is given such a low weight. But durability also includes chemical resistance, more specifically corrosion resistance. In this aspect, the FP screw has the advantage against the other five designs as the screw itself is made out of stainless steel while the other are made out of carbon steel. Stainless steel is generally more resilient against corrosion due to the higher content of chromium [48]. The screw is however at the same time slightly held back due to the way it protrudes meaning that if the heat exchanger is struck by something, the screw is more likely to at least bend due to a leverage effect. With that said, stainless steel is generally more ductile than carbon steel [48] and a bent connection point is still better than one broken in half.

8.1.3 Mounting

The next criteria is the one with the second highest weight, mounting. Looking at the result for the FP weld and SC weld, one could be surprised to the that the score differs even though it is the exact same component and the operation used is the same. In this case but also for the FP boss weld, location once again plays an important role. Due to the high internal pressure of the GPHE, it is classified as a pressurised device, which means that there are regulations that must be followed in order to be allowed to offer the GPHE on the market and as mentioned in chapter 7, this means mandatory inspections. The GPHE is a somewhat special case where only parts of it must abide to these regulations and the frame plate is one of those parts. The support column on the other hand is not subjected to these regulations. So this fact in addition to the need to scrape of some epoxy paint, are the two factors that are the cause for why the FP weld and boss weld were given a 3 while the SC weld a 4, inspection requirements and extra paint scraping labour. Clearly, the SC fastener is preferred here as it can be attached in a matter of seconds, using only a wrench.

8.1.4 Replaceability

Looking at the replaceability scores, the score pattern is basically the same as for the mounting criterion with the exception of the FP screw. The screw scored fairly low on the previous criterion due to the need to drill and thread the hole. But in the scenario that the screw is damaged, it scores very well as all that it takes is to unscrew the old one and then screwing in the new one. As for the weld based designs, the inspection requirement for the two that are attached to the frame plate still holds.

8.1.5 Component cost

There is not much that can be said regarding the cost of the components as the ranking was done by Alfa Laval and not the author of this report. One thing that can be said however is that the ranking received was absolute, meaning that all designs were not compared to the reference (which is the FP weld). Transferring this ranking to the one used in the selection matrix went fine for all but one, the SC weld. In the absolute ranking the SC weld was given a 2 while the FP weld and FP boss weld were given a 1 (like the selection matrix, a higher number is better) and due to the resolution of the ranking in the selection matrix, all three received a 3 so that the rank of the FP screw and SC fastener would be correct in relation to the other. So in reality, the overall cost for the SC weld is somewhat lower than the cost for the FP weld and FP boss weld due to the extra labour involved in scraping the paint and the inspections but is not correctly seen in the selection matrix.

8.1.6 Test results

The final criterion in the matrix which has already been discussed to an extent is the results from the tests. Putting the matter of the paint aside and assuming that all five designs are able to close the source to ground circuit, how realistic are the results and what conclusion, generally speaking, can be drawn based on attachment method and material choice? To begin with, one interesting fact is that the three designs that performed the best during testing are all attached through welding. This could mean that although all five have a low circuit resistance, welding results in a slightly lower resistance than forced contact between two surfaces which does seem realistic as welding fuses the two surfaces together. The FP screw and SC fastener both require that the screw and bolt are properly tightened to ensure good surface contact. However, with resistances as low as they are and with so small differences, there is always a chance that the deviations are due to measuring errors.

Another interesting aspect is the choice of material and how it affects the results. Out of the four components used (same component is used for the FP weld and SC weld), all but one are made out of carbon steel while the screw for the frame plate is made out of stainless steel. As seen in Table.2 above, the resistivity for carbon steel is lower than for stainless steel meaning that for two rods of same length and cross section area, the one made out of stainless steel will have a larger resistance than the one made out of carbon steel. Obviously, the components are to small for this have a significant impact on the results but it is possible that it is a contributing factor.

One final note about the test results concerns the method of testing. As described, four wire measuring was used to measure the resistance and while the method itself was appropriate to use, the execution of it contains a minor flaw. When connecting the current source and multimeter to the heat plates and the ground wire, both devices were connected in a common point through a single clamp. In hindsight, this is not optimal as this includes contact resistance between the clamp and where it is connected to the measurement. Preferably, the two devices should have been connected through individual clamps, close to each other. As a result of this, the measured resistances is most likely slightly lower than they actually are. However, the conclusions drawn still hold as the presented results all share the same offset from the actual values.

A small note to make about the linear regression models produced for the five designs is that base on the r value for each, there clearly is a linear behaviour between the supplied current and measured voltage which was to expect since resistance is a linear constant when plotting Ohm's law (for ohmic materials at least). However, there is still value in the five models as one could not be 100% sure that a linear behaviour would exist as the circuit includes several parts in the GPHE.

As for the tests themselves it is important to emphasise that the actual resistance measured when including the grounding rod will naturally be higher but as the resistances recorded in these tests are so low, the added resistance will not mean that the overall efficiency is lowered. In addition to his, the wire or cable used will also be longer than the one used for these tests but the increase in resistance will be relatively low. They will still perform as expected.

8.2 Conclusion and future considerations

A major part of this thesis has been the introduction to the phenomenon known as static electricity to then provide an extensive yet comprehensive ”guide” to the cause of it, consequences of it, how to deal with it and how it relates to the heat exchanger presented in chapter 5. As hopefully made apparent though this report, static electricity is in generally a rather simple phenomenon, previously uncharged atoms becoming either negatively or positively charged through loosing or receiving additional electrons. The three mechanisms behind this imbalance, Induction charging, Corona charging and Contact charging has been but focus has been on Contact charging, more precise the special case called Flow electrification which involves a liquid and a solid in contact.

The consequence of charge build - up in objects, static electricity discharges, has been introduced and both a general explanation behind gas discharges and different types of discharges have been detailed. While the GHPE of interest in this thesis is not prone to cause discharges, scenarios where there could be a risk has been given. The two hazards of sudden discharges, ignition and ESD, have both been thoroughly explored, looking at requirements necessary for them to occur and the consequences of them. In order to bridge the theoretical part to the practical part of the report, different methods of detecting charge accumulation and how to deal with it has been given.

The practical part of the project has dealt ways to eliminate any charge build-up in the GPHE in the form of five designs meant to provide an attachment point for an earthing lug. As there was no way to perform tests on a GPHE in operation, alternatives had to be found. For this, resistance measuring was chosen based on recommendations and guidelines from several institutes and organisations with an interest in static electricity. The results from the test showed that three of the proposed designs, are for a lack of a better word, useless, as a direct result of the blue epoxy paint covering the frame and pressure plate. This problem can be worked around but the costs and time in relation to what can be gained are are not worth it. Tests were also done where the influence of the paint was removed to obtain results that show the influence that material choice has on the resistance, as well as the method used to attach the component.

A selection matrix was produced to in a systematical way draw conclusions based not only on the test results but also four additional criterion’s. As the influence of the paint was taken into consideration, the three frame plate mounted designs should have been eliminated from the selection matrix but to explore all possibilities and to be used in further analysis, they were kept. The final selection matrix is shown in Table.12 where the SC fastener is the clear winner, shortly followed by the SC weld. Based on this, the recommendation for future heat exchangers where customer demands a way to attach an earthing lug is to recommend the SC fastener. It is simple, effective and easy to handle.

A fact that came up during a meeting at Alfa Laval is that customers have generally preferred that the GPHE was fitted with a FP weld or FP boss weld. With the results and conclusions drawn in this report, this is not recommended as it would require extra time and costs on top of the work done when scraping paint of where the component will be attached, welding and inspection. But in cases where the customer is adamant to have it welded onto the frame plate, the recommendation is to completely scrape the paint in and around the two holes where the guiding and carrying bar are connected. The aesthetics of the GPHE would be reduced but it would ensure that the circuit is closed. In addition to this, the corrosion risk would increase significantly as one function of the paint is to protect against corrosion as the plate is made out of carbon steel. Another possibility could be to use electrically conductive epoxy paint in and around the holes. But this would still mean that time and work has to be put into it, making it unnecessarily more costly in the end as the two support column mounted designs work just as well.

While it is very much up to Alfa Laval to decide whether all GPHEs should be standardised with an earthing lug connector or a custom order, based on the results and analysis in this report, the recommendation is to keep it as a custom order. The number of cases where it is needed is low and with the SC fastener as the primary design offered, adding a connection point or retrofitting an already sold heat exchanger is done in a matter of seconds.

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A Appendix

A.1 Drawings

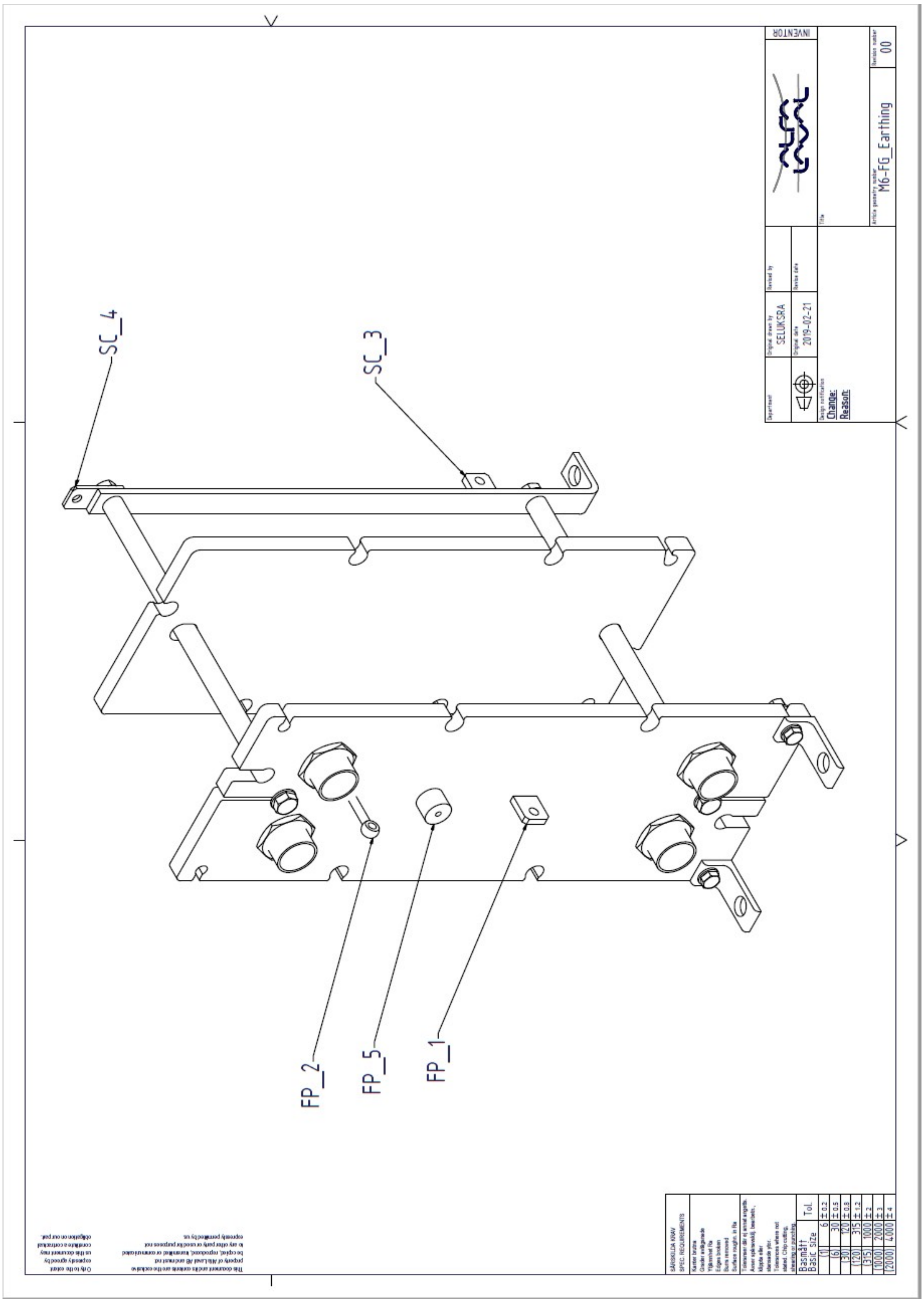

Figure 40: Placement of the five proposed component designs.

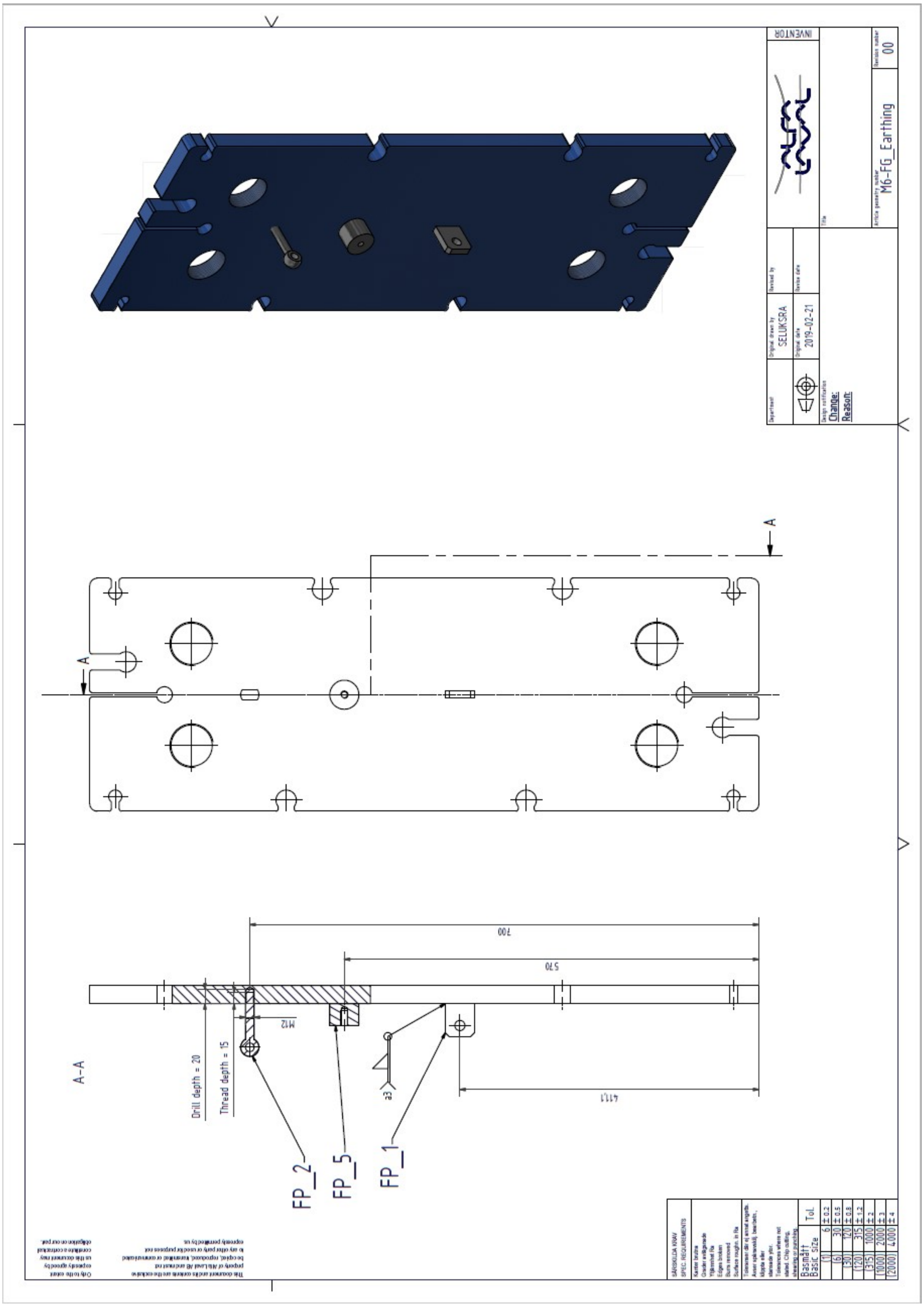

Figure 41: FP weld, boss and screw component design.

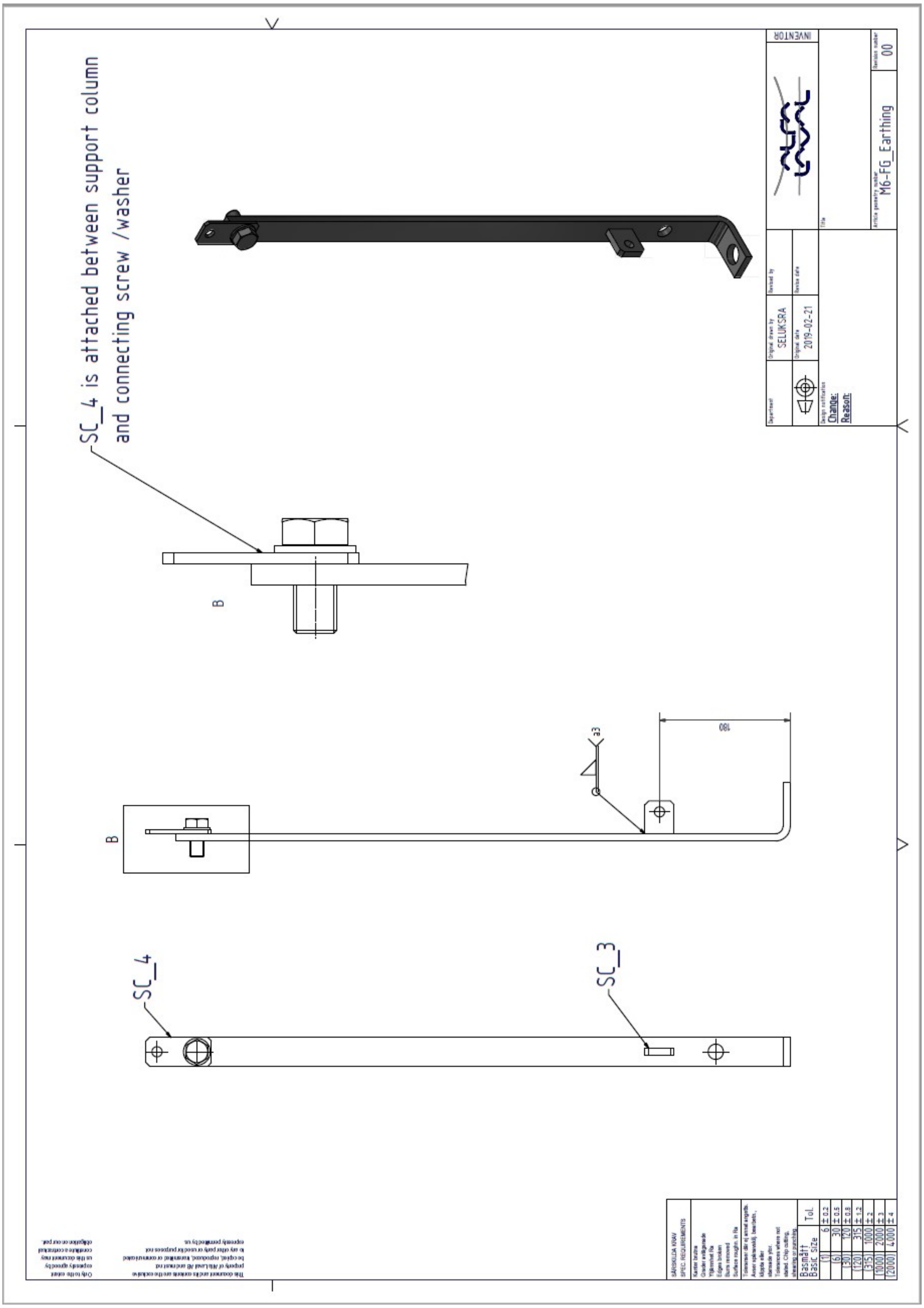

Figure 42: SC weld and fastener component design.

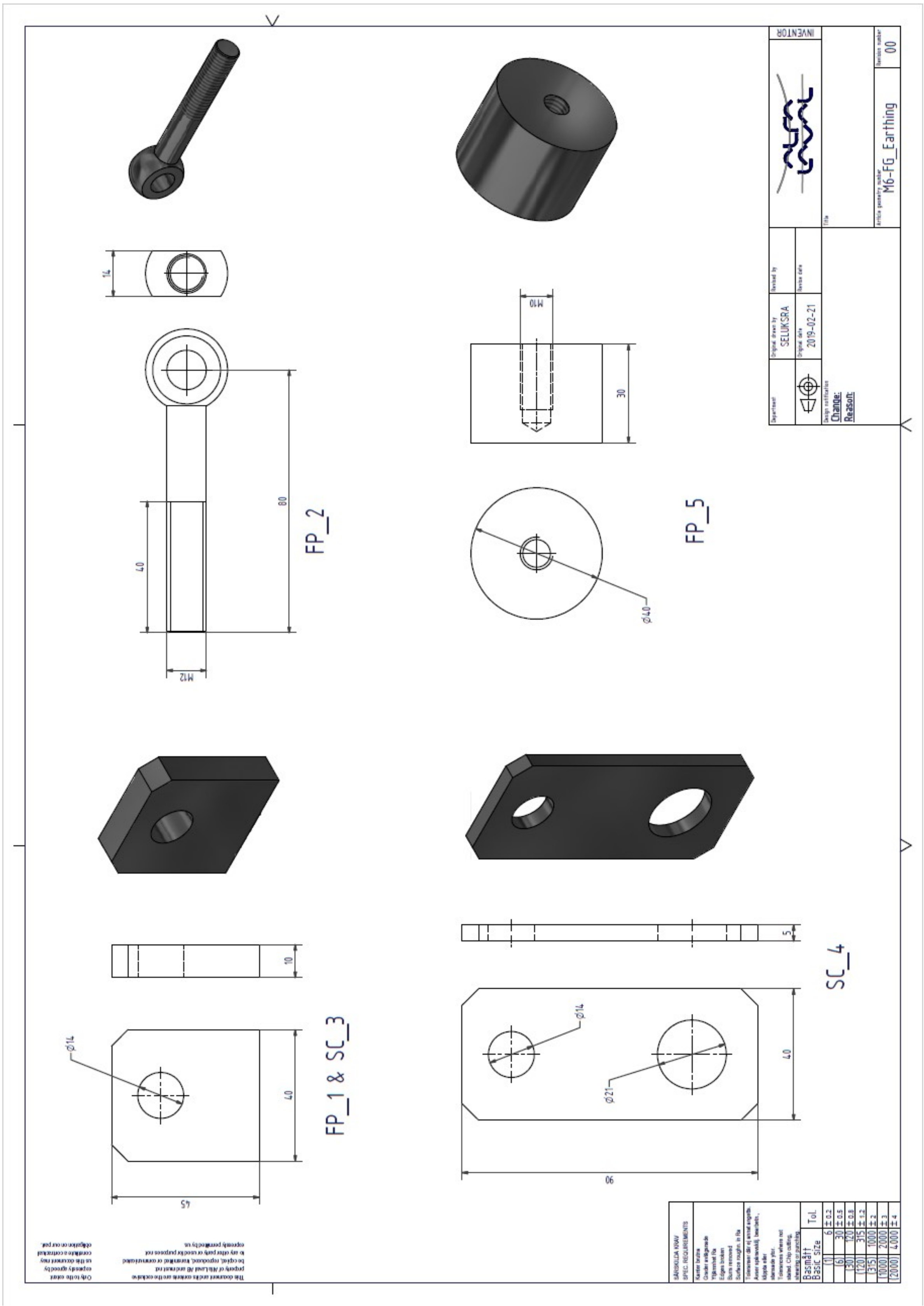

Figure 43: Component drawing. FP_1 and SC_3 are the FP weld and SC weld. FP_2 is the FP screw, FP_5 is the FP boss weld and SC_4 is the SC fastener.