Bachelor's thesis in mechanical engineering

# Design and development of a working prototype for the Green Revolution Energy Converter

Lab model V.3

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# Abstract

The emission of greenhouse gases is causing a major problem for the world by contributing to global warming. To combat this issue, a new concept called the GREC, Green Revolution Energy Converter, has been developed. The GREC is a thermal engine that utilizes a pressure difference created by moving a fluid from a heating zone to a cooling zone to convert heat into mechanical power. An electric motor actuates the rotating shutter, which is responsible for transporting the fluid inside the engine. The ultimate aim of the GREC is to generate more work from the pressure difference inside the engine than the work required to run the electric motor.

Our objective is to design and fabricate a functional rotational assembly that can be connected to sensors and an electric motor. This assembly must also be airtight while maintaining low levels of friction to ensure that the construction can serve its intended purpose. The primary goal of this project is to demonstrate the feasibility of the GREC engine and to prove that it has the potential to produce a significant pressure differential that can be used for energy production.

We planed to use Leidholm's systematic concept development to find the optimal solution within our budget and time reference. One major challenge was the potential leakage between the WGV and the outside. The leakage between the working generated volume (WGV) and the dead volume was fixed by having grooves in the RS and the leakage to the outside was fixed by using silicon and screws. Another challenge was the friction, which is minimized with good tolerances on the produced parts and to make sure that the RS is made from a stiff material that won't bend when in motion causing friction. The material choice is going to be based on the information from old reports and intelligence gained from the workshop employees.

The results were that the final design of the engine was mainly based on the previous prototypes and only small changes were made. Due to time constraints there were almost no major improvements or groundbreaking changes made to the design concept.

# Participant table

Table 1: Participant table

| **Activity** | **Andrei** | **Ida** | **Simon** | **Comment** |
|---|---|---|---|---|
| CAD and drawings | 50% | 25% | 25% | Andrei lead this part of the project as he had the most experience in CAD. |
| Abstract | 10% | 80% | 10% | Ida was responsible for the abstract. |
| Introduction | 30% | 30% | 40% | Simon did the majority of the introduction to the project. |
| Theory | 0% | 50% | 50% | Ida and Simon took over the theory as they felt more comfortable doing it. |
| Method | 70% | 20% | 10% | Andrei wrote most of the method as it is close to the CAD part of the project. |
| Results | 40% | 20% | 40% | Simon and Andrei wrote most of the results and Ida helped out. |
| Discussion | 50% | 30% | 20% | The discussion was mostly written together. |
| Conclusion | 0% | 30% | 70% | Simon was responsible for the conclusions. |
| Reference list | 70% | 15% | 15% | Andrei was responsible for coding the references and reference list. |

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# Nomenclature

$CAD$ Computer aided design

$FRP$ Fiber reinforced plastics

$GREC$ Green Revolution Energy Converter

$RS$ Rotating shutter

$WGV$ Work generating volume

# 1 Introduction

Today the world is facing big problems regarding emissions of greenhouse gases which increases the global warming of the earth. The Green Revolution Energy Converter, GREC, is a new concept of a thermal motor which resembles a sterling engine that converts heat differences to mechanical power. A benefit with the GREC is the potential of using industrial heat waste to power the engine and therefore reducing waste heat in big processes, whilst having no emissions. Previous versions of the engine have encountered problems with dead volumes, friction and leakage. These problems are the main points of the project.

## 1.1 Technology behind GREC

The GREC engine is a heat engine which is based on a Carnot cycle, where a fluid is heated so that it expands. Work can be extracted from this expansion and thus energy can be produced. A GREC engine achieves this by moving a fluid from a heating zone to a cooling zone. The fluid is moved by a revolving shutter, which is essentially a disc with a section cut out as seen in Figure 1.

The volume of this cut out section is what makes up the Work Generating Volume, WGV. The fluid is heated and cooled by conducting fins. These are put on opposite sides of the GREC so that the only heat transfer between these is from the convection of the fluid. There are insulating fins between the conductive fins to inhibit contact heat transfer. The RS is actuated using an electric motor. The goal of GREC is to extract more work from the pressure difference inside the engine than is used to run the electric motor. The energy input is only the electric motor since the heat is thought to be waste heat and therefor not included. For further understanding and visualisation of the inside of the GREC engine see the image sequence below. Figure 2

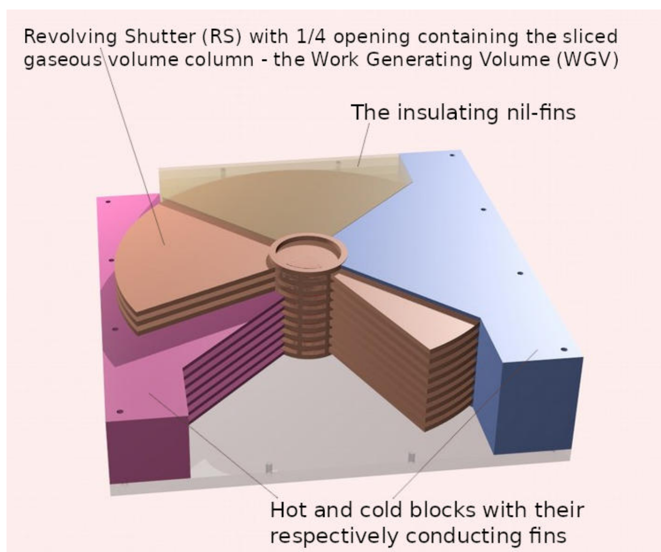
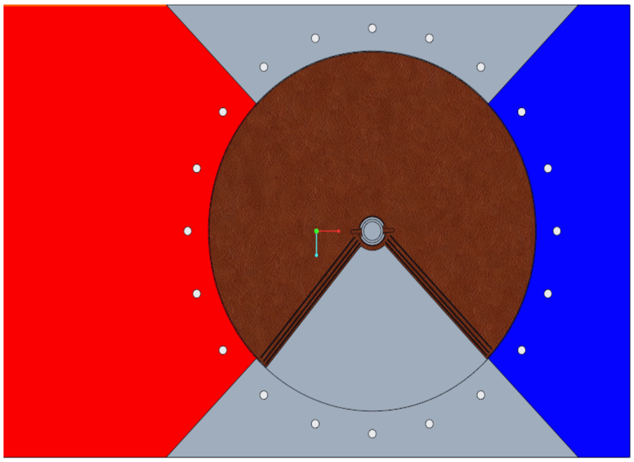
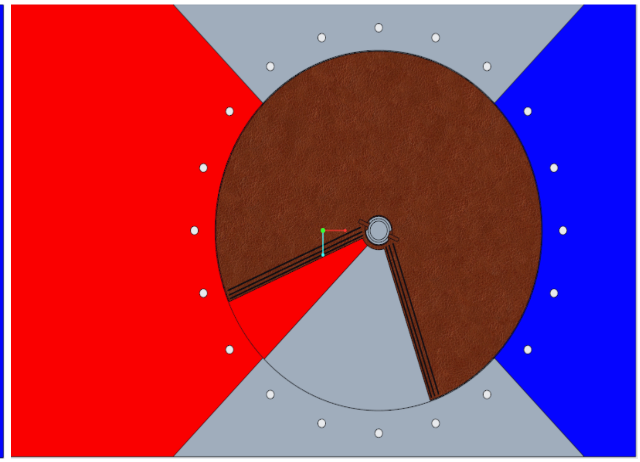



Figure 1: Visualization of an up-scaled GREC

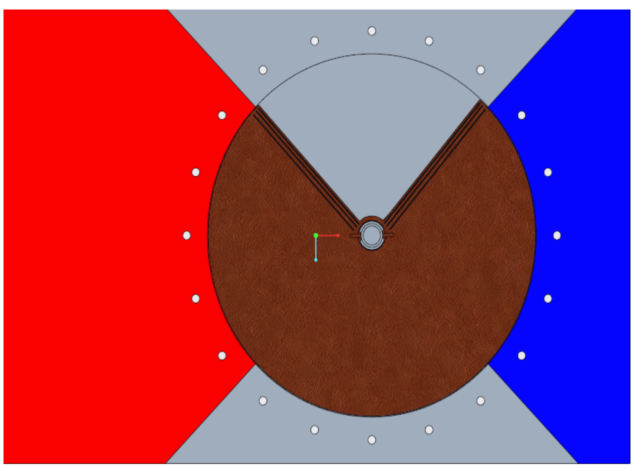
The advantage the GREC holds over a Stirling engine is that the GREC is made up of what is essentially a layer, comprised of the conducting and isolating fins and a revolving shutter. This means that unlike a Stirling engine, the GREC can be stacked to achieve a larger WGV, where a Stirling engine would have to be completely redesigned depending on its intended use.



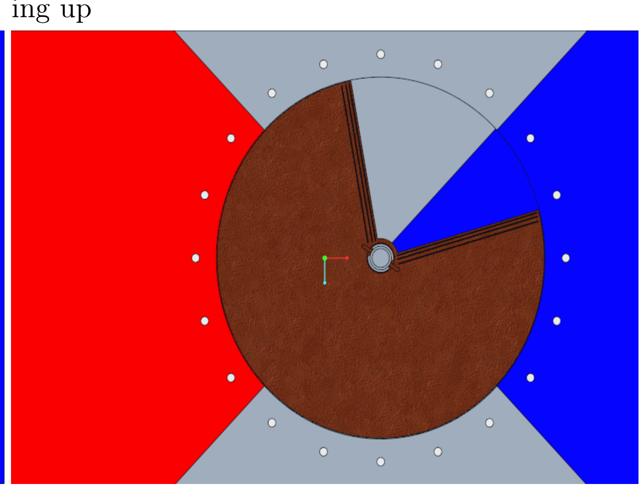
(a) The WGV has left the cold side and entered the neutral side



(b) The WGV enters the hot side and starts warming up



(c) The WGV has just left the hot side to the neutral side



(d) The WGV enters the cold side and starts cooling down

Figure 2: The rotating process of the different stages of the RS

## 1.2 Company

nilsinside AB is a company focusing on research and development of sustainable energy recovery based in Motala, Sweden and Brassac, France. Their main focus is on development of the GREC engine, an invention by their founder Nils Karlberg to which they hold multiple patents. This technology aims to reduce energy loss due to excess heat from other processes.

Technology Readiness Level (TRL) is a system which defines at what state a technology is at on a scale between 1 and 9. A lower rating indicates a more research level project while a higher rating indicates a technology that is closer to being sold to customers. At this point, the GREC has a rating between 3 and 4 and to proceed to a higher TRL the company needs to produce a working prototype and test it in a relevant environment.

Special thanks goes out to the company and especially its founder Nils Karlberg, who supported us fully with both information and energy. Throughout this project Nils has guided us in the right direction and given us all the information that we required to progress. His burning interest for the projects development was a big inspiration and motivation for us while working. Thanks to them who gave us this opportunity, we have learned a lot by developing this prototype and the knowledge gained will be very useful in our engineering journey.

## 1.3 Purpose

One of the long-term goals of the Green Revolution Energy Converter, GREC, is to reduce the use of fossil fuel by transforming heat into mechanical work and be an alternative and green energy source. The plan is to build a modular GREC design to be able to recycle more energy by being easily expandable. The results that the project should generate are a working model of the GREC motor. The model should not only work, but also preferably generate energy that should be measurable.
A working model could in the future enable the use of this motor in different industries. After this project is finished, there is hopefully a way to extract energy in a smart way from the GREC motor. It isn't necessary for the energy extracted in this project to be greater than the energy consumption of the electric motor. However, with this way of extracting energy, it hopefully opens a path for future work which can discover how to generate more energy than the motor requires to run.

## 1.4 Goals

The goal of the full project is to produce a functioning prototype of the GREC as proof of concept. This will be determined from testing of the prototype. If a pressure difference is measured, the project is considered successful. This project is executed by three different groups which all have more specific objectives in their respective fields.
This report will follow the findings and methods for the design and construction of the GREC. Our goal is to design and manufacture a working rotational assembly, with the capacity to connect sensors and an electric engine. This rotating assembly should also be airtight, to allow the construction to fulfill its purpose. This design should be simple to minimize the complexity of the assembly and manufacturing process.
Our specific goals are:

- Minimize the fluid leakage from the WGV to the rest of the dead volume.
- Produce a completely airtight engine with no pressure leakage to the outside environment.
- Producing an engine that is relatively easy to move to different locations.

## 1.5 Research Questions

- How can the WGV be sealed without compromising the friction?
- How can the geometry of the GREC be optimized in order to minimize the dead volume?
- How can the GREC in a simple manner be constructed to provide real life proof of concept?

## 1.6 Delimitations

In the original concept the engine will have a modular design and the modules with heat exchangers and shutters will be stackable. In this report, the construction and calculations will focus on only one shutter element.
The engine will be designed so that the results obtained from calculations on one module will be easily translated to a bigger engine consisting of more stacked units. The engine at this stage does not have to produce more energy than it consumes since this is only a prototype. The purpose of the engine is to act as proof of concept and to show that it could potentially produce a pressure differential substantial enough to harness for energy production.

The materials used to produce the prototype of the engine will not be optimal. A material change should be an area for future improvement and the prototype will be constructed by easily obtainable, but suitable, materials. Since this is a prototype, effort should not be put on trying to make the engine easy to mass produce. The thermodynamic group that is responsible for the choice of material, only consulting us with the specific properties for each part.

The selection of sensors and electric motors will be done by the mechatronics group and only the logistics and mounting of these will be covered in this project. The proof of concept has been completed in previous projects and there for no further mathematical calculations will be made. Previous project will therefore be treated as a reliable source.

## 1.7 Previous Work

Previous versions of the engine have encountered problems with dead volumes, friction and leakage. These problems are the main points of this project.

The previous work for the GREC engine has been studied and written in three different projects. The first project was conducted in the spring of 2022 by five students from the Department of Management and engineering. Since this project set the foundation for the rest of the research for the GREC engine this will be one of the main basis for the study. The published result is called: *Theoretical Proof Of Concept For The Green Revolution Energy Converter: Development of a mathematical model, material analysis and physical model improvements.* (Eriksson et al. 2022)

The main objectives from their study consisted of:

- Creating a proof of concept for the GREC engine
- Studying material selection for crucial parts of the engine
- Analyzing construction improvements from the initial design

Regarding the proof of concept the main results found were that a high temperature difference between the heat sources is desired. This in order to achieve the highest possible power output and efficiency. The size of the engine was also found to be of interest, larger scales showed to be more effective and efficient at different temperatures. The rotational speed of the RS was found to affect the heat transfer coefficient and therefore the temperature difference in the WGV. Higher rpm for the RS was generally found to be desired.

The material selection studies were mainly performed for three engine parts, the conducting fins, the isolation as well as the revolving shutter. Copper was found to be the best material for the conducting fins when regarding effectiveness, however aluminium was also found to be a candidate when considering price. Bakelite was the clear choice for isolation material when considering performance and price. This is because bakelite doesn't distribute the heat well in the isolating fins and is cheap. Carbon fiber ABS 10% was found to be the best material for the revolving shutter since it provides low heat transfer within the material and has a high yield limit. Polysterene is considered to be viable at low rpm and temperature since higher values for these parameters might cause the material to break. The material is also five times less expensive than the ABS 10% carbon fiber.

The project *Investigation of the internal heat transfer of GREC*, (Hagströmer et al. 2023) from a project course TMPE09 in the fall of 2022, studied how the design of the engine affects the pressure difference and work output. Furthermore the project also investigated how turbulence in the WGV affected the pressure and work. The results indicated that a slow rotation speed of the RS and a thin WGV leads to a greater pressure difference within the WGV. When the RS is rotating slowly the heat rate is increasing which results in a higher generated work output. To reach a high generated output it is concluded that a higher temperature difference between the hot and cold sides is desired. Turbulence in the WGV also increases both the generated work and pressure difference. However the scope of the project was not to decide how the turbulence is created but only how it affects the heat transfer.

A design where 1/8 instead of 1/4 of the RS was cut out was also investigated where the results showed that the heat transfer increases with this design. A main conclusion from this project is that if a high temperature difference is possible a large rotating radius is desired.

The third project conducted on the GREC engine, *Thermal Investigation of the Green Revolution Energy Converter*, (Andersson et al. 2023), cover mostly the thermal aspect of the GREC and how to heat the engine best. Since our project doesn't cover the thermal aspect of the GREC we will not base our project on the previous mentioned project.

## 1.8 Ethical reflection

The GREC engine, as all projects has some ethical considerations. Comparing to other energy sources like combustion engines, the GREC can be run on renewable sources of energy, as well as recycling energy. Simultaneously the heat source could be an ethical concern. For example, if the GREC engine is used and powered by biomass, coal or oil, the environment could be negatively impacted either by deforestation or by carbon dioxide emissions.

Furthermore the materials used for constructing multiple GREC engines, as well as the disposal of used engines can have a negative impact on the environment. Additionally, the accessibility and affordability of the technology may raise ethical concerns as it could create disparities and perpetuate socioeconomic inequalities. The impact of the GREC engine on society will depend on its implementation and usage throughout its lifespan.

## 1.9 Budget

The project's budget of 12000 SEK has been sponsored by the university to cover the costs of construction materials and electrotechnical components. As our group is only tasked with the physical construction of the project, the budget will be divided among other two groups accordingly. The allocation of resources among groups will be determined by mutual agreement, enabling each group to acquire the necessary materials to complete their respective tasks. The remaining funds will be dedicated to acquiring additional materials deemed most cost-effective for optimizing the project's positive outcome.

# 2 Theory

In the development of the GREC engine, some different fields needed to be studied. In this chapter the different fields will be explained and the theories used will be explained. Different materials were also studied for the material choice and their properties and selling points will be showcased here.

## 2.1 Material choice

The investigated materials is aluminium or more specifically EN-AW 5083 plancast, an aluminium alloy, and fiber reinforced plastic (FRP).

### Aluminium

Pure aluminum is a relatively pliable and soft metal that can be easily molded in both cold and hot conditions. While its strength is low, it can be strengthened by alloying it with various metals, similar to the strength of many structural steels. Aluminum alloys are typically categorized into two groups, those suitable for casting and those for plastic processing, such as rolling, forging, and extrusion, which can overlap. These alloys can also be further divided into hardenable and non-hardenable types, with hardenable alloys achieving high strength through precipitation hardening with copper, magnesium, silicon, and zinc, alone or in combination. (*Aluminiumlegeringar* n.d.)

Aluminum alloy 5083 is a non-heat-treatable alloy compriced of mostly magnesium but some amounts of manganese, chromium, and small amounts of other elements that contribute to its strength and corrosion resistance. It boasts a desirable combination of characteristics, including high strength, low density, and excellent machinability, allowing for easy fabrication into different shapes and forms, making it a versatile material which is allowing the design and construction of robust, lightweight structures ideal for dynamic applications. This alloy is also renowned for its remarkable seawater corrosion and stress corrosion cracking resistance, rendering it a popular choice for naval and marine structures. (*Aluminium* n.d.)

EN-AW 5083 plancast is the aluminium alloy 5083 that was manufactured through a form of die casting. The process of casting involves the pouring of molten aluminum into a mold, which is then allowed to cool and solidify. There are various casting methods available for casting aluminum, such as continuous casting, investment casting, plaster casting, sand casting, permanent mold casting, and die casting. (*Die Casting* n.d. ,*Pressgjutning* n.d.)

### Thermal expansion

When an atom absorbs thermal energy and starts vibrating, its behavior resembles that of having a larger atomic radius. As a result, the average distance between the atoms and the overall size of the material increases. This change in dimensions with temperature is known as the coefficient of thermal expansion. The EN-AW 5083 plancast alloy has a thermal expansion of $25 \times 10^{-6}/K$. (Askerland, Fulay, and Wright 2011).
The thermal expansion is calculated through:

$$\alpha = \frac{\Delta l}{l \Delta T} \tag{1}$$

Where $\alpha$ is the thermal expansion coefficient, l is the original length, ΔT is the temperature difference and Δl is the difference in length between the warm and cold temperature. (AZOM.com 2005)

### Fiber reinforced plastic

Fiber Reinforced Plastic or FRP, belongs to the category of composite plastics which utilize fibers to enhance the mechanical strength and elasticity of the plastic. These plastics are composed of a pliable polymer matrix blended with reinforcing fibers, resulting in a final product that exhibits the desired mechanical or material properties. The fibers employed in FRP include fiberglass, carbon fiber and natural fibers. (Studentlesson 2023)

Bakelite, one type of FRP is a durable and dark-colored plastic that has been utilized in numerous applications, such as electrical insulation and various consumer products, for a significant amount of time. (*Bakelite* n.d.). Bakelite is produced by the reaction of phenol and formaldehyde under heat and pressure, typically with the addition of wood flour as filler. It is favored for its excellent heat-resistant and non-conductive properties. (Nimrodplastics 2023)

Fiberglass is another type of fiber reinforced plastic that utilizes a thick, viscous resin which hardens into a brittle solid. When reinforced with glass fibers, it becomes an extremely strong and versatile material. These fibers are incredibly robust, possessing a high tensile strength. Additionally, they offer excellent resistance to moisture and chemicals, display exceptional electrical properties, are immune to biological degradation, and have a non-combustible nature, with a melting point of roughly 1500°C.(Supplies 2023).

Carbon fiber is made from organic polymers, characterized by long strings of molecules bound together by carbon atoms. The process for making carbon fibers is part chemical and part mechanical. The process of making carbon fiber is called carbonization where long strands or fibers are heated to a very high temperature in an anaerobic environment so the fibers don't burn but vibrate violently. This vibration makes all the non-carbon atoms to be expelled and only a few remaining. (Zoltek 2023). Carbon fiber is extremely stiff, strong, and light. Some other benefits with carbon fiber is high temperatur tolerance with some resins, low thermal expansion and a high chemical resistance. One disadvantage is that carbon fiber materials are significantly more expensive than traditional materials. (Dragonplate 2023)

## 2.2 Ball bearings

The main purpose of a ball bearing is to decrease the amount of rotational friction and provide support for both axial and radial loads. This is achieved by incorporating a minimum of two races that contain the balls and transfer the loads through them. Typically, one of the races remains fixed to a axis or shaft that rotates and the other is fixed to a non moving part. The rotation of one of the bearing races causes the balls to rotate as well. Since the balls are rolling instead of sliding, their coefficient of friction is considerably lower than that of two flat surfaces that slide against each other. (SKF 2023a)
Compared to other types of rolling-element bearings, ball bearings have a smaller contact area between the balls and races, which results in a lower load capacity relative to their size. However, the friction is lower in ball bearings that in cylindrical roller bearings, which is another commonly used type of bearing. (SKF 2021)

There are many types of ball bearings. Deep groove ball bearings is the most widely used type. They are very versatile and are optimized for low vibration and noise which makes them well suited for high revolution applications. They can support axial as well as radial loads. Deep groove ball bearings are easy to mount and have low maintenance relative to many other types of ball bearings. There are models that use a rubber sealing which helps to keep dirt out of the bearing to further increase its service life. (SKF 2023b)

Axial or thrust ball bearings is another type of ball bearings. They only support axial loads and should not be subjected to any radial loads and are designed as either single or double direction which means that the bearing can take a load from only one direction or from two directions along the axis. (SKF 2023c)

## 2.3 Fluid Dynamics

There are many ways to seal a system to prevent leakage. Dry gas seals is a type of seal that manipulates airflow to create a seal. It consists of a stationary part and a rotating part, usually a disk. Grooves or ramps are milled or lasered into the disk. When the disk is rotating it forces the air along the grooves. This stream of air then lifts of the ramps in the grooves and pushes on the stationary part, trying to separate the disk and the stationary part. This optimizes the film stiffness and this film creates a seal. Since dry gas seals don't have any face contact there is very little friction in the system and no friction heat is generated. (Solutions 2023)

A similar way to create a seal with a stationary part and a rotating disk is to create grooves from the outer rim to the center of the disk. When the disk is rotating, air is forced into a gap between the disk and the stationary part. As the air passes over the groove it expands due to the increase in area and becomes turbulent. When the air passes over the groove the area decreases, halting the air flow and thus creates a seal. Multiple grooves can be placed after each other to increase the effect. (Askerland, Fulay, and Wright 2011)

## 2.4 Liedholm's systematic concept development

Liedholm's systematic concept development is a framework used to guide the process of developing new concepts or ideas. Liedholm's framework places a strong emphasis on a methodical and organized method of concept development throughout the entire procedure. It promotes the production of various ideas, evaluation against defined requirements, iterative improvement, and a focus on the effective application and diffusion of the concept. The framework is divided into different stages, exploration, concept, and realization.

The exploration stage's goal and focus it to gather information, identify potential opportunities, and generating a pool of ideas that can be further developed in the subsequent stages. It involves activities such as market research, trend analysis, brainstorming, and seeking inspiration. The primary goal is to gather insights and identify potential opportunities for concept development.

The concept stage is where the initial ideas and insights from the exploration stage are further developed and refined. It involves transforming these ideas into tangible concepts that can be evaluated and potentially developed into actual products, services, or solutions. The concept stage is crucial in Liedholm's framework as it bridges the gap between initial ideas and the subsequent realization and diffusion stages. It lays the foundation for developing a well-defined and viable concept that can be translated into an actual solution or product.

The third stage, the realization stage, involves turning the selected concept into a tangible product, service, or solution. It includes activities such as designing prototypes, conducting feasibility studies, developing a business plan, and implementing the necessary processes and resources. The goal is to bring the concept to life and ensure its practicality and viability. (Liedholm 1999)

# 3 Method

In this section we will talk about the methods used and the approach used in this project for constructing the engine. The problems encountered during the project will be presented and the solutions will be explained. The technical approach to the design will also be explained.

## 3.1 Technical approach

In the beginning of the project the Liedholm's systematic concept development was used to find the optimal solution within our budget and time reference. Started off with doing a critical review of the problem and getting an understanding of the GREC engine and how it works. After that the state of art was studied, such as old versions or engines that is similar to the GREC engine, and all that leading up to the list of requirements seen below in Table 2. Leading onto the second stage, the concept stage, were the ideas how to solve the challenges were generated and refined and transformed into tangible concepts. The key activities include idea generation, concept definition, evaluation, concept selection, and concept refinement. It was in this step that our method fell away from Liedholm's systematic concept development due to the lack of time, by only finding one solution and going with it and not analysing multiple different ones.

The material choice is going to be based on the information from old reports and intelligence gained from the workshop employees or the material that is available for us to use. The chosen materials will be required to fulfill some criteria and at the same time be within our budget range. The choosing weight in this matter will be the budget as this is the most limiting factor. One of our biggest problem we'll face is the potential leakage between the WGV and the outside. Another problem we'll face is the friction, which we plan to eliminate with good tolerances on the produced parts and to make sure that the RS is made from a stiff material.

In designing the different parts we'll use CAD and inspiration from GREC V.2. We will in a systematic way design individual parts in CAD for the complete assembly. With the assembly complete digitally we can visualize potential problems and compatibility issues to further improve our design. This way the design will have an iterative process in which parts will hopefully reach their best potential in the given time frame.In combination with the iterative process of the CAD design we will also communicate continuously with the universities metal workshop for further development and knowledge in manufacturing technology.

When the design is deemed complete enough it will be sent to the metal workshop for manufacturing. Afterwards we will assemble the engine and prepare it for testing. For further information about testing, read the separate report *The heat transfer of the third GREC prototype* by Åsmo, Ross, and Jeirud 2023

The way from information and imagination to a complete product is not straight. There are several directions available and the end goal is not always clear. The process will be explained here and can be followed in Figure 3 below. The start of the project was as one would expect gathering information and determining the dimensions of the final engine. All the information gained gave us knowledge about what was done before and what problems previous groups had while working with this engine. This resulted in a list of requirements that guided us throughout the process, this list can be seen below in Table 2.

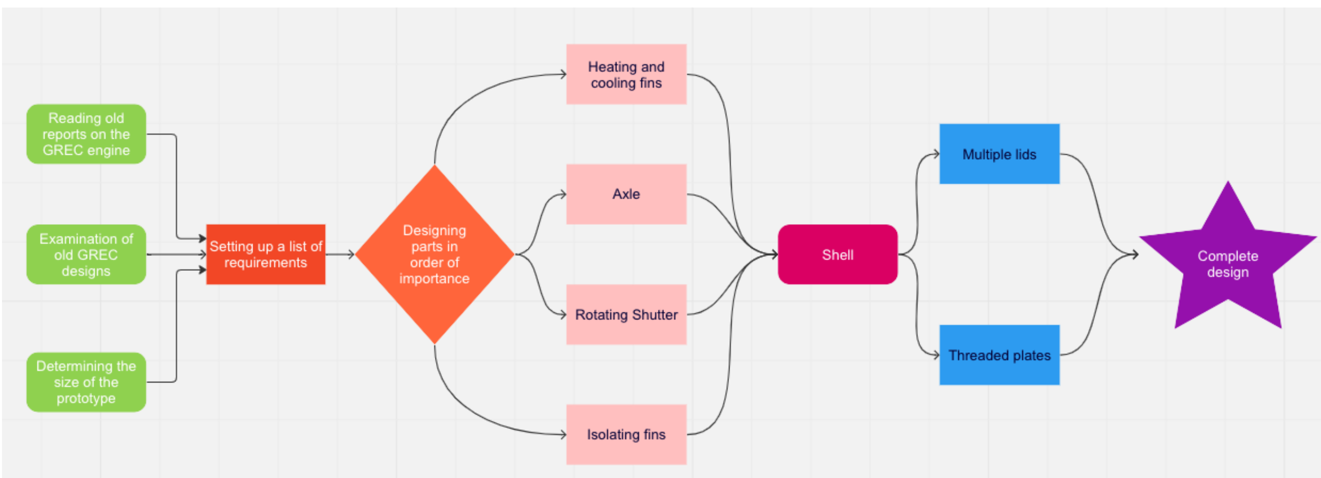



Figure 3: Flow chart of the technical approach

From the list of requirement the directorial parts of the engine could be determined. This meant that those parts could be designed and the rest of the parts would be designed afterwards. The most important parts were the axle, RS, heating/cooling fins and the isolating fins. The completion of these parts meant that the main frame of the GREC was in place. With these parts assembled, the shell could be designed and the lids could be designed following the shell. The threaded plates were an addition needed for the shell to work with the sensors. These plates would act as nuts because to make a cut out for the nuts to prevent them from rotating as the screws was tightened was not possible, This was important for the sensors to be mounted correctly. The threaded plates also made it possible to remove the sensors without the need for a engine disassembly.

Table 2: List of requierments

| **Requirement** | **Part** | **Measure** | **Difficulties** | **Goal** |
|---|---|---|---|---|
| Sealing | WGV | Tolerances,<br>Lubrication,<br>Air seals. | Available materials,<br>Available lubricants,<br>Possible tolerances from the workshop. | Optimize sealing |
| | Engine block | Silicone,<br>Sealing strip,<br>Male and female matching ends. | Can the workshop fabricate it?<br>Temperature differences cause expansion | Optimize sealing |
| Friction | RS/Engine block | Tolerances,<br>Lubrication,<br>Rollers | Finding a suitable lubricant.<br>High temperature difference during operation | Minimize friction |
| Balancing | RS | Counter weight,<br>Hollow construction,<br>Multiple materials with different properties | Hard to combine different materials with different properties<br>Needs to meed the deformation requirements | Minimize moment of inertia |
| | Axle | Acquiring good ball bearings<br>Tight tolerances on the axle-mounts | Workshops ability<br>Tight tolerances<br>Difficult to assemble | Minimize wobble of the rotating assembly |
| Material | Heating & cooling fins | Aluminum | Acquiring cast aluminum plates<br>Lead time | Minimize built-in tensions<br>Minimize shape changes |
| | Isolating fins | Isolating<br>Low deformation | Workshops ability<br>Attachment to heating & cooling flanges | Optimize structural integrity |
| | RS | Carbon fiber<br>Polyethylene<br>Glass fiber<br>FRP | Expensive<br>Difficult to manufacture<br>Lead time | Minimize plastic and elastic deformation |

## 3.2 Friction

Minimizing friction throughout the engine has been a priority from the start, as friction reduces the efficiency of the engine and limits the amount of energy that can be extracted. Several solutions were discussed and investigated to reduce friction in the WGV while simultaneously minimizing dead volume. One way to reduce the friction between the RS and the surroundings would have been to set larger tolerances, but that would have led to an unnecessarily large dead volume.

Another solution that was discussed was to lubricate with some form of oil or lubricant, but when the engine gets a temperature of around 200 degrees on one side and roughly room temperature on the other side, the lubricant would have very different properties depending on where it was placed and then potentially increase friction. What we ended up with was not using any lubricant but just using the air itself as a lubricant with careful tolerances to minimize dead volume.

## 3.3 Material for each part

The engine was produced from mainly 3 different materials, bakelite, steel and aluminum. In this chapter the choice of each material for each part will be disclosed. Included will be why each material was chosen for each purpose and why it was chosen for the specific part.

### Isolating parts

Some parts of the engine have the main purpose of isolating the hot and cold sides from each other. In the same way there are some parts that have different main purposes but still have the need to isolate. All the parts that need to fulfill the isolating criteria are:

- RS
- Isolating fins
- Shell

For all of the parts mentioned above we needed to find a material that would both be stiff enough for structural integrity and have a good isolating properties. For a simpler design we decided to use the same material both for the parts that had no rigidity requirement and the parts that had. This was done so one isolating material could be chosen for a group of parts. The RS has the requirement to be a very rigid part. The reason why it needs to be rigid is because it must neither deform during rotation due to the centripetal force nor must it bend and hit the walls as this creates increased friction which in turn degrades the efficiency of the engine.

From the old report *Investigation of the internal heat transfer of the GREC* (Hagströmer et al. 2023) we knew that bakelite was a good material for both isolation and structural integrity. Although we knew this, the material choice was not clear from the beginning. The budget was restrictive and the economic choice was not to go with bakelite but something cheaper. Because of this we looked at other plastic materials like different FRPs and some other plastics. While most of the other materials had acceptable properties the bakelite was chosen as the material of choice. Why bakelite was ultimately chosen is because it met our requirements regarding the material properties but also because it was available for us to take at no cost from the workshop, which from an economic point of view was a crystal clear choice.

#### Heating & cooling fins

The material for both the heating and cooling side fins were evaluated together because their purpose is very similar. Both sides transfer heat either to the engine or out from the engine as they are used for cooling and heating respectively. The heat transfer coefficient is an important material property as the main purpose of these fins is to transfer heat. The optimal material for the fins was previously identified in the older report *Investigation of the internal heat transfer of the GREC* (Hagströmer et al. 2023), which indicated that aluminum exhibits a high heat transfer coefficient and is also readily available at a low cost. After doing small calculations on the thermal expansion on the fins, we noticed that there will be a very small percentage difference and decided not to take that into consideration. Although we also evaluated steel as an alternative material, our findings aligned with those of the report. Additional details on this topic are available in the report by the mechanical heat groups.

**Other parts**

For the parts that didn't have high demands on the tolerances from the production, the requirements were simple. The use of a readily available material that is also very cheap. The materials chosen for these parts was steel and bakelite. These materials are good because they are rigid and at the same time easily processed. Both steel and bakelite was provided by the metal workshop free of charge, which was perfect for our strict budget.

Steel was used for the axle. Here we had the same requirements but the axle also needed to have some rigidity because it would hold up the RS. Steel was in this case also chosen because of its good material properties and ease of processing. The axle is a very intricate part which needs high manufacturing precision. This is easily achieved in our metal workshop on a steel part, their knowledge and expertise is large in production of steel parts.
The lids on both sides of the engine were made out of bakelite. They are suppose to seal the axle and act as mounting platforms for sensors and the electric engine. Since that is their main purpose, the requirements on the material are not important which makes cost the most relevant factor and thus bakelite was chosen.

## 3.4 Dimensions

The dimensions of the engine were hard to set in the first place. We had neither a maximum or a minimum size. According to *Investigation of the internal heat transfer of the GREC* (Hagströmer et al. 2023) for the best result we wanted to have a thin work generating volume and a large radius on the rotating shutter. We quickly realized that this would be hard to justify with the given budget. The material cost would be too large and there would be no funds left for the mechatronics and the mechanical heat groups.

The dimension for the rotating shutter was set to 400 millimeters in diameter and thus the rest of the engine needed to adjust accordingly. Through our material research, we discovered that casted aluminum was the optimal choice for the heating and cooling fins of our engine due to its inherent lack of tension resulting from the manufacturing process. In contrast, regular aluminum plates often contain built-in tension that can cause bending and deformation over time.
Because of time constraints and transportation cost, a local metal retailer was chosen. This retailer had only 2 sizes of casted aluminum plates in stock, leading to the dimensions being changed once again. The final dimension of the rotating shutter was a diameter of 380 millimeters.

For the engine to work well the dead volume must be as minimal as possible. This puts high demands on the tolerances of the RS and the cut outs in the fins. The thickness was set to 7.9 millimeters on the rotating shutter and the thickness for the cut outs was 3.8 millimeters resulting in a gap of 0.5 millimeters. This gives room for deviations in thickness during the production of said parts.
When determining the dimensions of the axle, no established criteria were used. The aim was to ensure that the axle was of considerable size in order to effectively support the rotating shutter while also ensuring durability and resistance to deformation during operation. A delicate balance had to be struck to avoid over-sizing the axle, which would reduce the available work generating volume. Therefore, the selection of the appropriate dimensions for the axle was a critical decision.

Later, a final deciding factor for the precise axle dimension was discovered. We needed to acquire ball bearings and these had some standard dimensions. The SKF 6005 2RSL ball bearing was chosen and the axle was dimensioned accordingly. It's final dimension became an outer diameter of 25 millimeters.
The inner dimension of the power outtake was designed with strength as a primary consideration. To prevent deformation of the axle, the walls were dimensioned to 2.5 millimeters. This results in the inner diameter of the axle being 20 millimeters.
The height of the axle is dimensioned to be the same as the total thickness of the GREC and is therefor set to 40 millimeters.

In the choosing the ball bearings we firstly had to choose a size that was compatible with the axle to make the axle and RS turn easier. With that, we had to choose the type of ball bearing and since its only one movement and one force acting axially and at the same time having no or low leakage. Those criteria led us to choose a axial ball bearing and a radial ball bearing with additional sealing to minimize the leakage. The ball bearings were placed around, on the top and the bottom of the axle.

The drawings for all the different parts can be observed closer in the appendix.

## 3.5 Design

The design process for the GREC engine was mostly based on the previous existing versions and modified to solve some of the major challenges. In this chapter you can follow how the design process went for the different parts.

**Design of RS**

While the whole GREC engine is a complicated assembly to build, by far the most complicated part in it is the RS. The RS has one main task which is moving the WGV from the hot side to the cold side and then back. While doing so the RS also need to fulfill tasks, such as allowing the pressurized gas to flow to the piston. It also need to be sealed so the gas was moved around correctly and steadily, another reason is for minimizing the dead volume in the design. Some other things to take into consideration was making sure the opening were the right size, that the RS was balanced and that it would fit on to the axle and would remain on the axle during the rotation. The whole RS is seen in Figure 4 below .

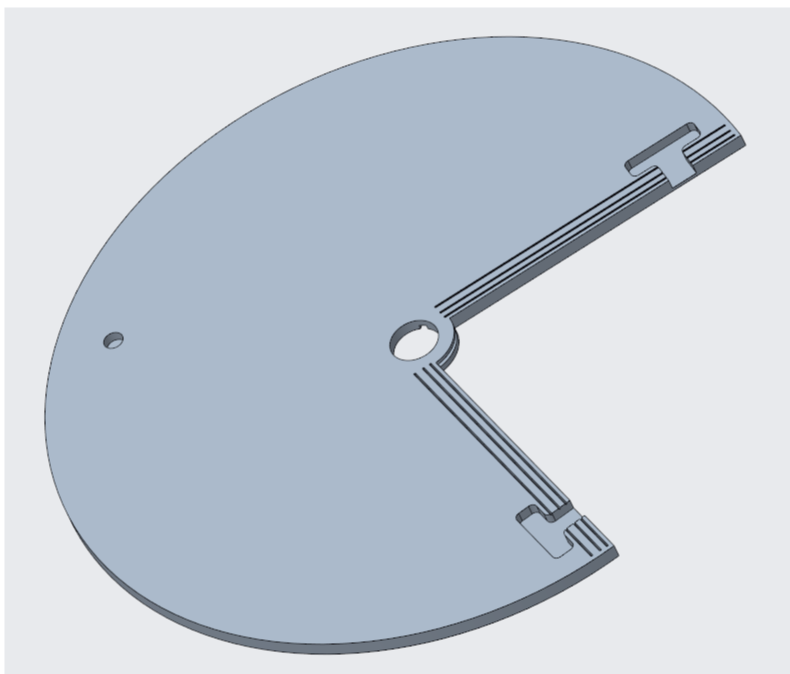


Figure 4: Overview of RS

The opening in the RS, also known as WGV, is 85 degrees, this is to be sure that the surrounding shells had bigger parts. If the opening were to be 90 degrees, same as the shells parts, there would be a possibility that the opening would be open for the warm and cold side simultaneously. This would possibly lead to a lower temperature which in turn leads to less pressure to extract.

The RS will have to be fixed to the axle to assure the RS will rotate with the axle when in motion and not move side-to-side and decrease the efficiency when hitting the sides. The rotating issue was fixed by adding a pin through the axle and in to the RS, so when the motor is spinning the axle the RS will turn. To make sure that the pin won't be overloaded we added a cut out for the rim of the engine to evenly distribute the load. To eliminate the movement sideways it was first discussed to add a socket on each side, but then we came to the conclusion that it would be much more cumbersome than necessary and then switched to using glue. The disadvantage of glue is that it cannot be disassembled, but we believe that it is not a necessary function to have.

Balancing the RS was important to ensure that when in motion it didn't wobble and possibly hit the sides which would lead to a waste of added power from the engine. Since a big part of the RS was removed to create the opening the center of mass was moved away from the middle, to compensate for this a piece of iron in a bent banana shaped design was mounted along the outer side of the RS opening, called the counter weight. The mounting included a partial cutout from the RS in the shape of a puzzle piece to hinder the counter weights ability to move, as seen in Figure 5. Another issue regarding the balancing problem is that a magnet need to be placed in the RS to be able to use the sensors that the mechatronics group (Brodin, Hollsten, and Vilhelmsson 2023) put in place. The placement was made to be opposite the WGV, to easily know where the WGV is when in action but with that an additionally weight was added. The width of the counter weight was decided through iteration to ensure the center of mass was indeed in the middle of the RS, namely where the RS mount the axle.

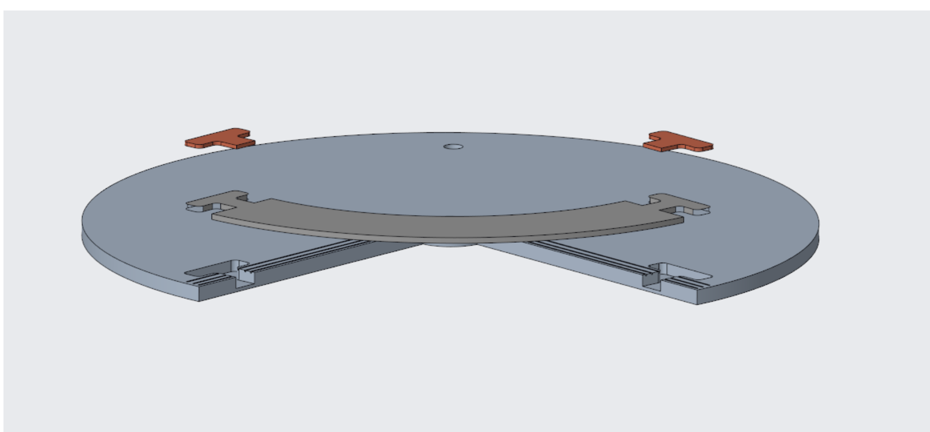


Figure 5: Exploded view of the RS and the balancing beam

To minimize the leakage between the WGV and the volume around the RS made, in consulting with Johan Hedbrant, grooves along the opening to use the air it self as both lubrication and sealing. This technique is using the difference in available area to increase the turbulent flow which in turn provides the properties requested. The three grooves is placed parallel to each other with the first groove placed 2 mm from the opening edge, the second and third groove places 3 mm respective 4 mm from each other, as you can see from figure Figure 4 .

The purpose of the GREC is to take out a pressure difference in the WGV and to be able to do that there must be an opening from the WGV to the axis to where the pressure is measured. This was done by making a slit opening of 2 mm in height and 17 mm in width. The gap goes through both the RS and the axle.

Another thing we were looking to minimize on the RS was weight, this because it would be easier for the step engine to rotate the RS and use less applied electric energy. During the designing process it was discussed multiple solutions to minimize the mass by the given material we had chosen. One of them was to make it thinner but since we had to fit certain elements, such as the grooves and pressure opening, so we made it as thin as we possibly could.
Another solution was to make the RS hollow by making it into three pieces, a top, a bottom and a edge. This would also help with the balancing problem, but we figured that the manufacturing and putting it all together would be to hard to make it worth it. This especially when the risk of possible leakage into the hollowed out volume is high and if that were to happen the dead volume would increase significantly, making the decreased mass useless.

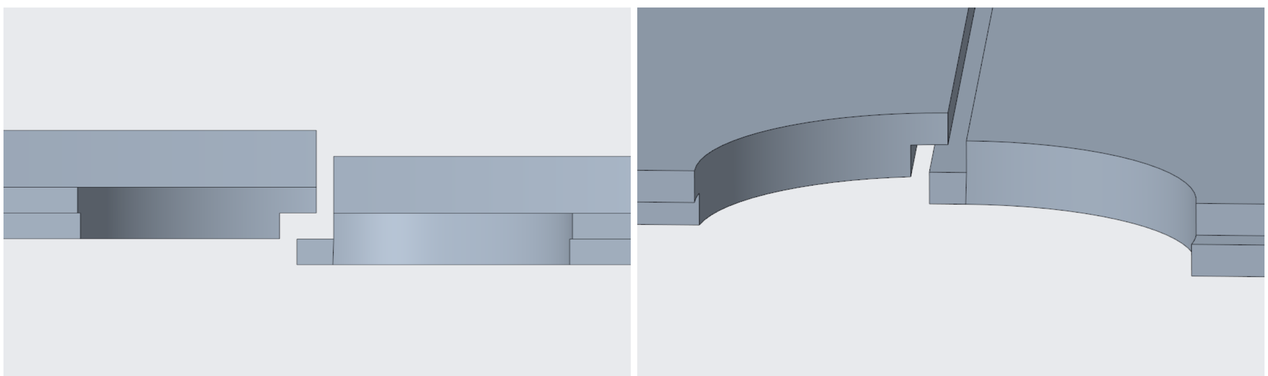
**Stiffness in the design**

During the engine design process, one problem that arose was the sagging of the fins, which posed a potential risk of friction with the rotating shutter due to a significant gap in the middle where the shutter was to be placed, leaving the fins unsupported. To mitigate this issue, various approaches were explored. Initially, we investigated using materials with high elasticity modulus to prevent the fins from sagging, but this was challenging due to budget constraints. After selecting the most suitable materials within our budget, we explored other potential solutions. Adhering the fins to the shell was initially considered, but was ultimately dismissed as an unlikely solution. The final solution involved securing the tops of the fins to the shell using screws.

**Sealing**

As pressure is the main focus of this construction, the sealing is a very important part of the construction. The design need to be completely airtight for pressure buildup to occur. For this multiple solutions were combined to hopefully achieve a working design.
For starters the cooling, heating and isolating fins we're designed for overlapping one another. This makes the gaps between the parts smaller and allows us to use force to minimize leakage.

As seen in Figure 6 below, when the screws are tightened the gap between the fins will reduce thus not allowing gases to pass. This design was achieved after multiple iterations. In the beginning the fins were meant to slot into each other, like hardwood floor. Through communication with the metal workshop we quickly understood that the slots would be to difficult to manufacture. This is why they were redesigned to assume the form of a step.



(a) Picture normal to the plane of the step

(b) The step is visualized from farther away

Figure 6: Pictures showing how the step is designed

Upon conducting a thorough evaluation of the initial engine design, it became readily apparent that a design-based approach alone would be insufficient in achieving the desired level of air-tightness within the engine. It became clear that additional measures were necessary to ensure a completely sealed engine that could meet the demanding specifications of the project. Consequently, after careful consideration, we identified the use of a silicone sealant as an essential component in our pursuit of optimal engine performance. With its outstanding sealing properties, the silicone sealant proved to be a practical and effective solution to achieving the desired level of air-tightness within the engine.

## 3.6 Assembly

Since our experience in product development was limited there were a few things that had to be altered after we received the parts from the metal and wood workshop. The first step of the assembly of GREC was to screw the fins onto the shell to make sure the fins didn't bend into the RS and hinder its rotation. The fins were designed in such a way that when they were mounted together there were no leakage and no edges interfering with the rotation of the RS as mentioned in the previous chapter of sealing. This process was repeated on both of the shells. In the second step the RS was glued onto the axle to prevent the RS from moving along the axle. The RS and axle assembly was mounted in between the shells and the fins with the ball bearings by screwing the parts together. After that the screws from shell to shell was tightened then the lids were screwed onto the shell and lastly sensors and electric engine were installed on the lids and on the shell.

The biggest problem during the assembly was to make the system completely sealed. Adding a layer of silicone to the crevices between the different plates was our primary way of dealing with air leakage but also using tight screw connections. Only relaying on the fine tolerances of the design was not enough to keep the system sealed.

# 4 Results

The results will cover the final outcome of the design, the changes that were made to the engine comparing to previous versions and the compatibility of the design.

## 4.1 Final design

The final design of the engine was mainly based on the previous prototypes and only small changes were made. Because of time constraints there were almost no major improvements or groundbreaking changes. As this stands true, there are still numerous smaller changes that were implemented for the design to be improved. The exploded view of all the parts are seen in Figure 7 and the view rotated 180° in Figure 8.

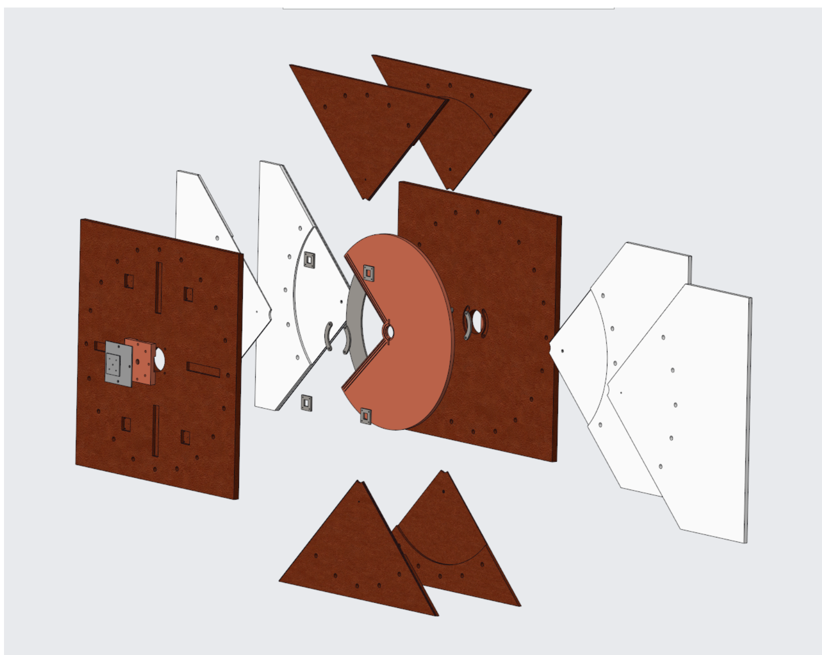


Figure 7: Exploded view of the whole GREC engine

As we started with design of the fins, the design was changed to only contain two parts instead of three per side. This was achieved by instead of having two flat sheets with a distance in between, transitioning to having two thicker sheets with on side milled down. Thus allowing the construction of the WGV and making the engine easier to seal.

The main concept behind this design choice was the less gaps there are to tighten, the tighter the design will be. Following that philosophy, as little gaps as possible were chosen in the design, and the gaps that were present got preventive sealing for minimal leakage.

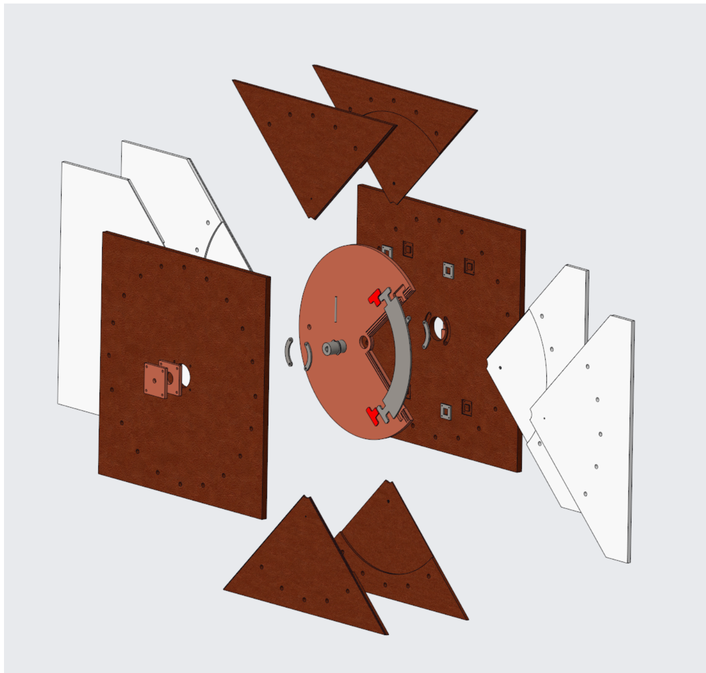


Figure 8: Exploded view of the whole GREC engine rotated 180 degrees

The previous design had lots of issues with leakage between the isolating and heating/cooling fins. This was one of the main improvements in the new design. Gaps are very difficult to seal, especially if there is no mounting pressure in the direction of the gap. That is why we implemented steps in the design of the fins, which also are positioned in the same direction as our mounting pressure. As seen in the assembly, the fins have steps that overlap each other making for an airtight construction when the engine is assembled.

## 4.2 Test results

The engine was assembled under the last phase of the project as per the assembly method showed previously. Multiple parts came with manufacturing problems and the fitment of the parts was far from perfect. With this obstacle in our way the engine assembly was hard and some measures had to be taken. The fins needed to be sanded further to lower the friction between the RS and them. A distance had to be added between the two engine halves that had the same purpose as sanding the fins. Silicone was also applied virtually everywhere for the engine to be sealed as good as possible.

Tests were done on the GREC and the results were unfortunately underwhelming. The GREC operated as intended while being heated and the rotating assembly worked, but achieved no measured pressure difference under operation.

# 5 Discussion

In this part, the final results will be talked about and discussed, ideas for future studies will be highlighted and the sources of error and improvements discussed.

## 5.1 Discussion of the Method

Our method was mostly looking at the existing parts of the previous GREC engine and see their flaws and going with the first idea. Our plan from the beginning was to use Liedholm's but as soon as we started to look into the different parts, it was clear to us that it was not possible with our limited time. If we had more time in the beginning it would be favorable to do a proper Liedholm's product development analysis and carefully use the most suitable option and not just the first one that come in to mind. One area were Liedholm would have been suitable is in the choosing of the design on the RS.
In the report Eriksson et al. 2022, they touched on the study of curving the cutout which creates the WGV. What this in turn does to the engine is that it alters the flow of gas while the engine is running. This can have both positive and negative effects but also according to Hagströmer et al. 2023 a more turbulent flow creates more efficiency in the GREC. This is because a more turbulent flow allows the air to interact more with the heating/cooling fins, for further explanation look in the report by the termodynamics group (Åsmo, Ross, and Jeirud 2023). So the optimal method for designing of the RS would be to do simulations of different shapes and see which one is providing highest pressure difference.

Another aspect of the design on GREC is that we choose the material that was available, such as the Bakelite for the RS and the isolating parts, and not the most suitable for their specific requirements.

In the constructions of GREC the most important parts are the RS and the heating, cooling and isolating fins. This because they all depend on each other and need to have good tolerances so in the producing of the parts we had to produce the RS to see its actual height and then put the measurements on the fins, this leading to even longer production time. We did not get this insight until we had a drawing review with the staff in the workshop, which was a couple of weeks into the process. Had we known that before, we would have been able to fully focus on the drawings of the RS and leave the other parts be for the moment then be able to move forward faster.

## 5.2 Discussion of the Result

In the end a working engine was achieved with the design working as intended, but there were a lot of things that we realized could be done better. For starters, we used the screws in our design both for tightening the parts and also for alignment. This could be done differently to achieve a better result. When screws are tightened they tent to shift the part under them if the part is not fixed in some way, making their job of aligning the parts very difficult. This was especially the case as the holes for the outer screws were made with very generous tolerances. The improvement that could have been implemented here is to have some kind of alignment pins in each part, mostly for the fins and shell, and holes in the other respective parts. These holes and pins could then be created with fine tolerances resulting in much higher precision while aligning the parts.

In the design phase, one of the main thought in the back of our mind was deformation. While it was hard to analyze because of time constraints, we tried our best to make the parts not bend and deform during operation and our the assembly phase. With this said, the screws holding the fins in place closest to the axle were severely undersized. They did do their job holding the fins attached to the shell, but more screw and bigger screws would have been a more optimal solution. The fins were still sagging in our assembly phase and during operation with the added bonus of the engine being very hard to assemble. While we were in the beginning afraid to have increased leakage issues with the addition of more screws and holes, we think that having them be tight enough and adding an o-ring or some silicon would solve that issue easily.

The axle was a problematic part from the start. We knew that it would be hard to manufacture for fitting the engine but we had no other choice. While not having the engine on site when designing and setting the dimensions for the axle, we could not achieve exact measurements. This later became a problem as the mounting for the engine in the axle was a bit too large and the axle started to undergo plastic deformation during operation. This was later fixed with small bits of brass sheet inserted in the mount, but taught us that the axle mount should in the future be designed with very fine tolerances.

## 5.3 Design Compatibility

As this technology is still at its early stages of development, the need to further develop this prototype was of great importance. Being able to further develop this specific prototype would speed up research drastically, as future projects will unfold. This resulted in a couple of different things that were taken into consideration during this project.

First of all we have the materials used in the design. The development of the GREC and future prototypes can very well contain expansion of the engine to have multiple WGV chambers as well as multiple RS and so on.
This will be achieved by stacking multiple fins in the assembly, making a thicker engine more materials. For this expansion to be feasible for future project groups and for keeping the cost down, materials that are easy to come by were chosen. Allowing for further development to easily find and use the same stuff as we did. This will ensure that the engine keeps the properties that are show by our project the engine has, for using the same materials should generate similar results.

The use of standard parts is pretty common in the majority of construction projects, and this one is no different. As the project rolled forward and the design of the custom parts was nearing completion, the project started needing assembly details. Screws, ball bearings and sealant were parts that needed to be tracked down and acquired. In the same way mentioned by the previous paragraph the standard parts chosen were easily acquirable and readily available to improve the projects future development.

## 5.4 Future study

Future studies of the GREC it firstly to test if there is a possible way to extract the pressure difference into mechanical energy. We made the opening through RS and axle to be able to extract the pressure difference specifically for future projects working on the GREC engine. In the work of Brodin, Hollsten, and Vilhelmsson 2023 they discuss the potentially ways of extracting the energy so a physical prototype.

When it comes to the RS, it is the most complicated part to produce because it has so many details. Simultaneously the RS is a part that strives for mass optimization. This is a combination that usually is solved with the implication of 3D printing parts. We think that 3D printing the RS could save a lot of material, make it easier to produce and at the same time introduce more structural integrity. As deformation is one big concern with the RS, it could be solved by making it lighter and and reinforced. This possibility presents itself because the forces acting on the RS are centrifugal and these decrease with mass. By making the RS hollow with organic structural beams the GREC would be more efficient and simpler to produce.

There are lots of materials with different properties in this world. The RS is a very intricate part with a lot of different tasks. This part is the one that needs to be optimized to the maximum for optimal efficiency. While the material used for our RS is pretty decent, a big change could mean a huge uplift in performance from the engine. No study was made from our side on which material is optimal for this purpose, but based from the report of

Hagströmer et al. 2023 and our intelligence it seems that FRPs are a pretty good fit. This is why we would like to endorse for a future study to take place about different FRPs or and other composite materials and how they impact the performance of the engine.

## 5.5 Sources of error

One big source of error is leakage in the design. While one of the main focuses under the design phase was sealing, leakage could still occur. The problem with leakage is that it is very hard to spot and even when we use common techniques like soapy water its very hard to spot. This comes down to the fundamentals of the engine and the small size of the prototype. The volume change and the pressure difference under load are small because of or size and that does not provide big enough bubbles to be spotted for potential leakage. If there is leakage it would also mean that out pressure testing will be obsolete, making the results very hard to evaluate.

One solution for this could be making a bigger prototype, but this would not solve the issue. As the GREC is designed for being modular, multiple modules would behave in the same way as an individual one. Therefore the solution that we would see for testing if the prototype leaks is making a bigger temperature difference. The temperature difference dictates how much pressure is generated in the engine and therefore gives more volume change, which in turn gives more tangible leakage. This could be achieved either by cooling the cold side more with for example liquid nitrogen or warming up the hot side more with more kilowatts of electricity.

As the time was very limited in this project revisions and reviews of the designs were few. There was no time for reviewing a design and letting it mature before sending it in to the workshop. This means that the designs sent were pretty rough.

## 5.6 Improvements

One major improvement that can be made for future projects is having more time to do all work and with the have time for the lead time in the workshop. We could also have started the actual work earlier, but this is something we realized now in hindsight as the arrangement was such that we would do planning in the first period and actual work in the second.

With having little to none previous experience in this area, the time it took to get all our designs and drawing complete and sent to the workers in the workshop was much longer than expected. So our time planning, even with a buffer, wasn't enough especially when some parts needed to be produced to take the actual measurements to finalize the remaining drawing since they depended on tight tolerances.

The time, combined with the small group size made it difficult for us to produce a good engine. The project group for this particular project was good and the group division was not. Because of the restrictions in how the bachelor thesis groups are divided, the project group was split into 3 groups of 3 people. In hindsight a better split would have been if the construction group had more people and other groups less. That would also make the report more comprehensive as more details about the project would be disclosed in one report.
To optimize the fluid dynamics inside the GREC-engine a Computational Fluid Dynamics (CFD) analysis is useful tool. This would have helped with the design to find the best geometry of the RS and the inside of the engine. The reason a CFD-analysis was not done was simply the lack of time due to the strict time frame.
A Finite element method (FEM) analysis is used to optimise the geometry of a part from a strength stand point. Areas where the stress of a part is high can be identified an measures can be taken to prevent catastrophic failure while the engine is running. If more time was available a FEM analysis would help with material and design optimization.

# 6 Conclusions

In conclusions of this whole project and look back to our purpose and goals is that we created a complete rotating engine and by that creating a opportunity to further investigate and develop the GREC engine. The project was very educational and giving a good insight into how a product is manufactured and produced. There are of course some improvements that can be done to improve the engines function or some of the further work as mentioned previously. The answers to our research questions are as following.

- How can the WGV be sealed without compromising the friction?

  Friction has been one of the biggest difficulties to find a good solution to. Since the system is so sensitive to friction that even lubricants in form of oil where to give the system to much frictional resistance, other methods had to be found. After discussing and analysing different ways of sealing the system we came to the conclusion that manipulating and using airflow to seal the system was the best method to implement in our engine. By milling the three grooves in the RS the air itself is used as both as sealing for the WGV and lubrication between the RS and the surroundings.

- How can the geometry of the GREC be optimized in order to minimize the dead volume?

  While our design for the engine is optimized, the final product is not. During the design process, many changes were made and decisions were taken for the dead volume to be minimized. This lead to the final design having almost no dead volume other than the one needed for it to function as intended. The only dead volume is were the sensors are placed, in the axle for the pressure to flow to the energy output and last but not least in the 0.25 millimeter gap between the RS and the fins. All the dead volumes previously mentioned were minimized as much as possible with regard to some limiting factors. This did not really transfer well from CAD to reality as the manufacturing tolerances on the parts were not optimal. This can be related to the method for mounting different parts is not fully developed and should be revolutionized.

- How can the GREC in a simple manner be constructed to provide real life proof of concept?

  During the design process, much focus was put into making the parts simple to manufacture since production was a limiting factor. The ability to assemble and disassemble the engine was also given much thought, so if necessarily the parts can easily be replaced or serviced if needed. The engine that we have now built is a simple prototype and has the potential to be further developed and then be able to prove the practical proof of concept, so I consider our approach to be a possible solution.

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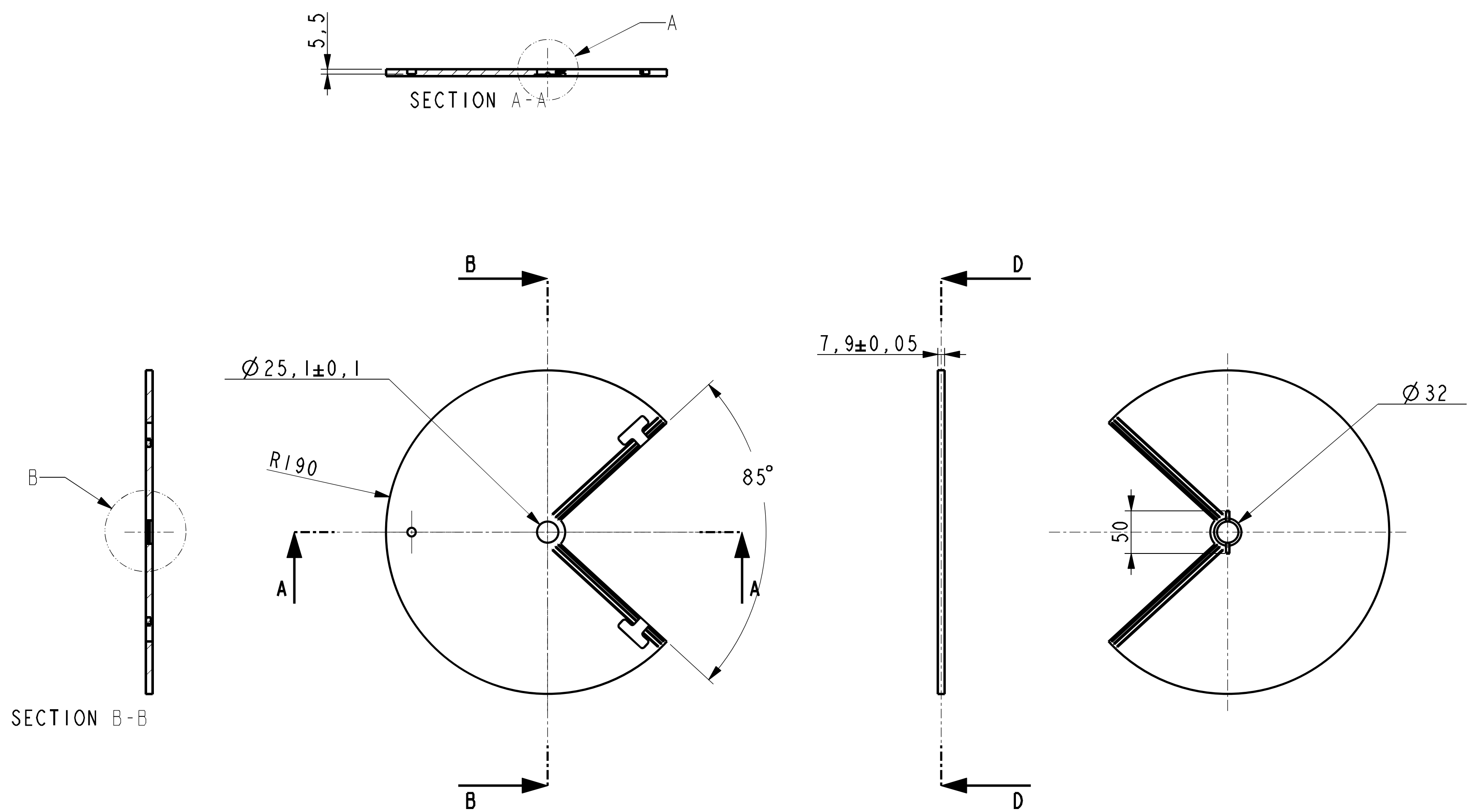
# Appendix

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| Checked by: Johan Åsmo | General Tolerance: ISO2768-mK | | General surf. roughness: Ra 3,2 | Projection method | Scale: 1:5 |
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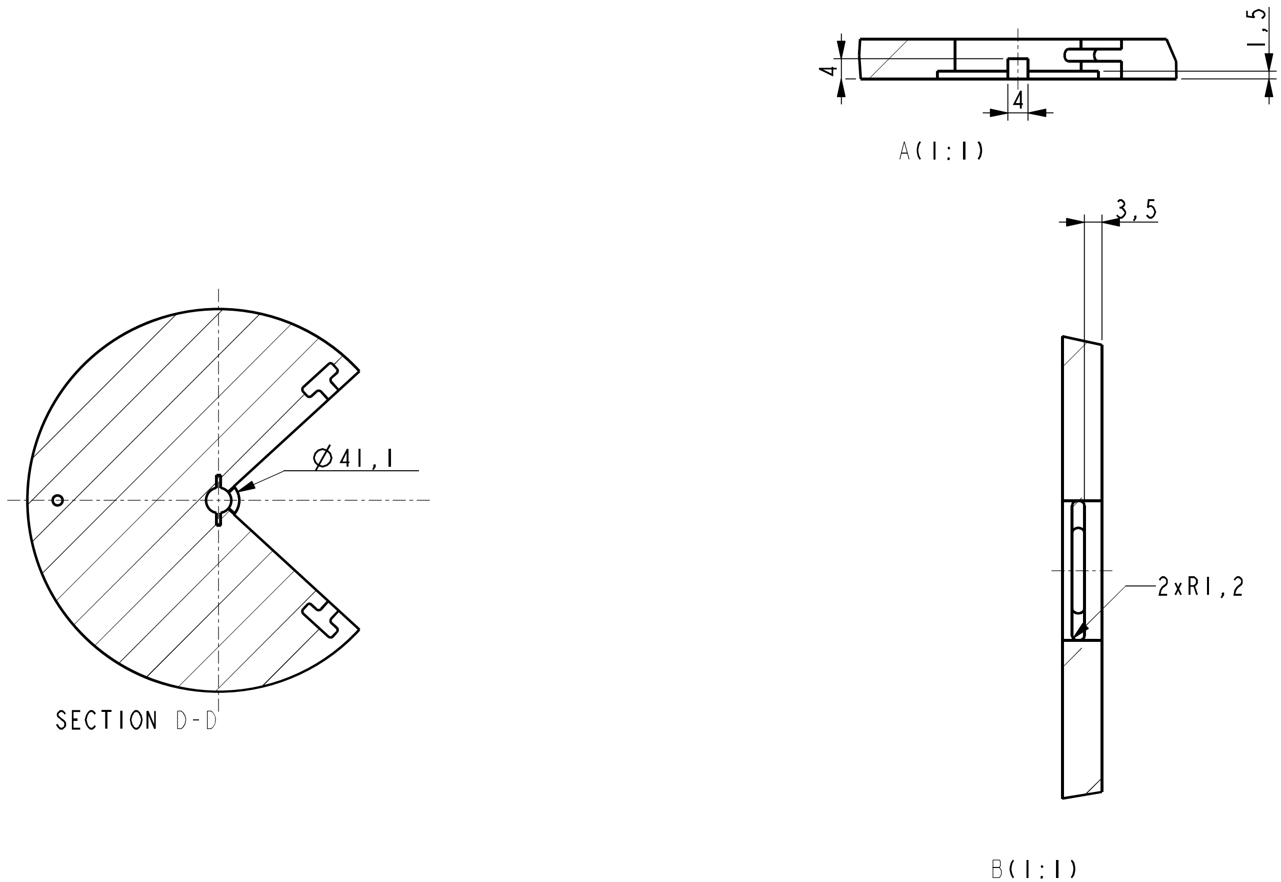


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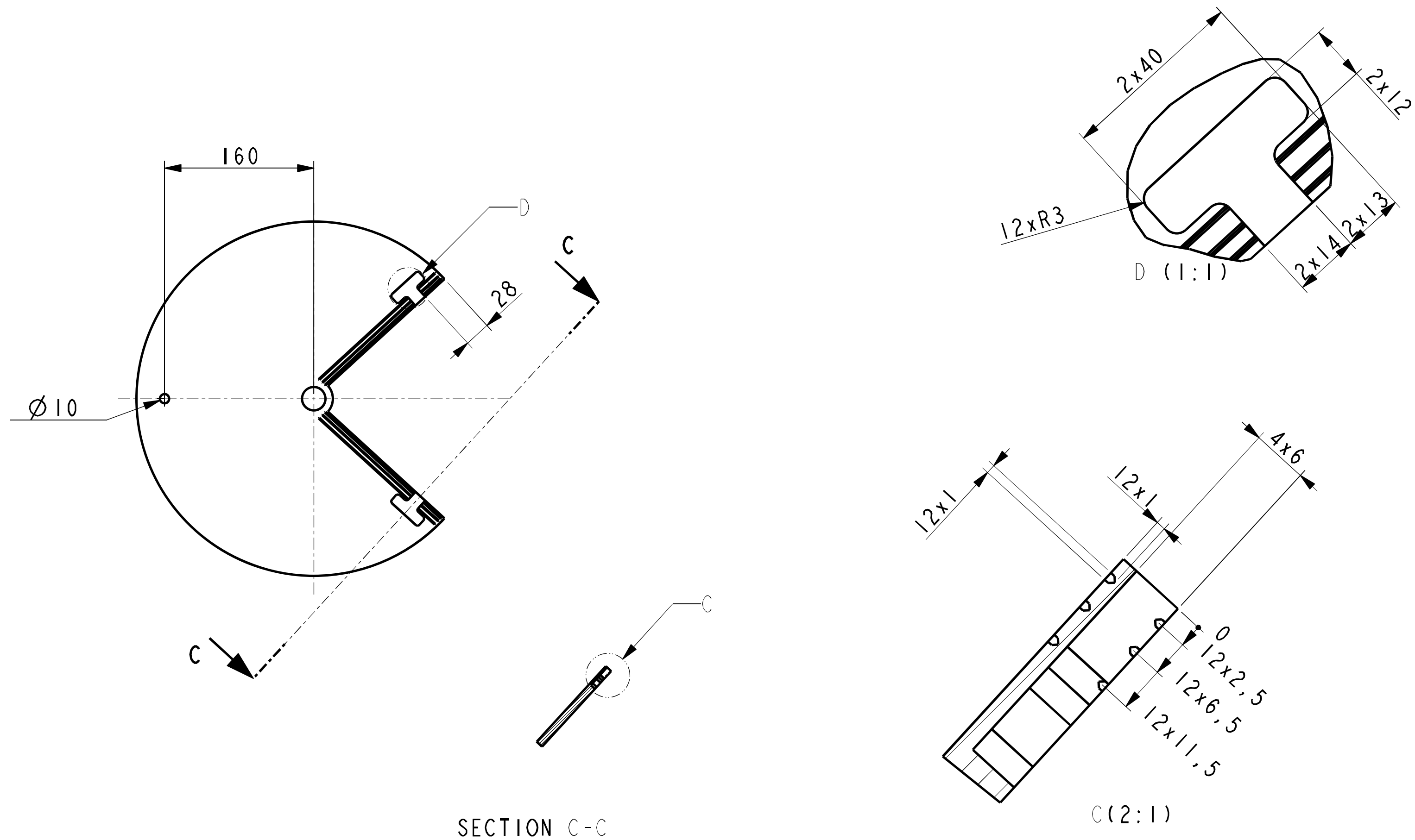


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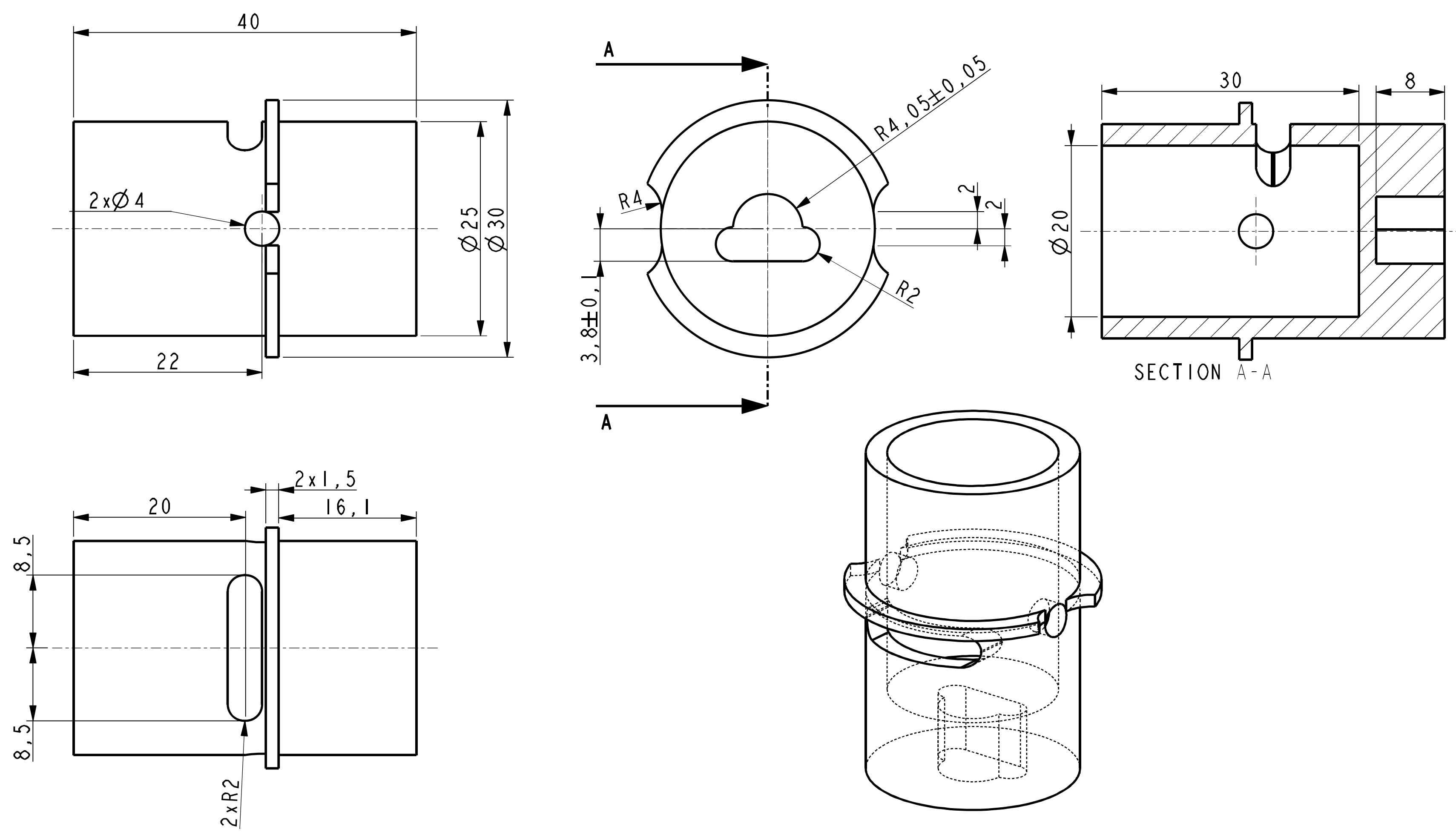


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| Checked by: Vidar Jeirud | General Tolerance: ISO2768-mK | General surf. roughness: Ra 3,2 | Projection method | Scale: 2:1 |
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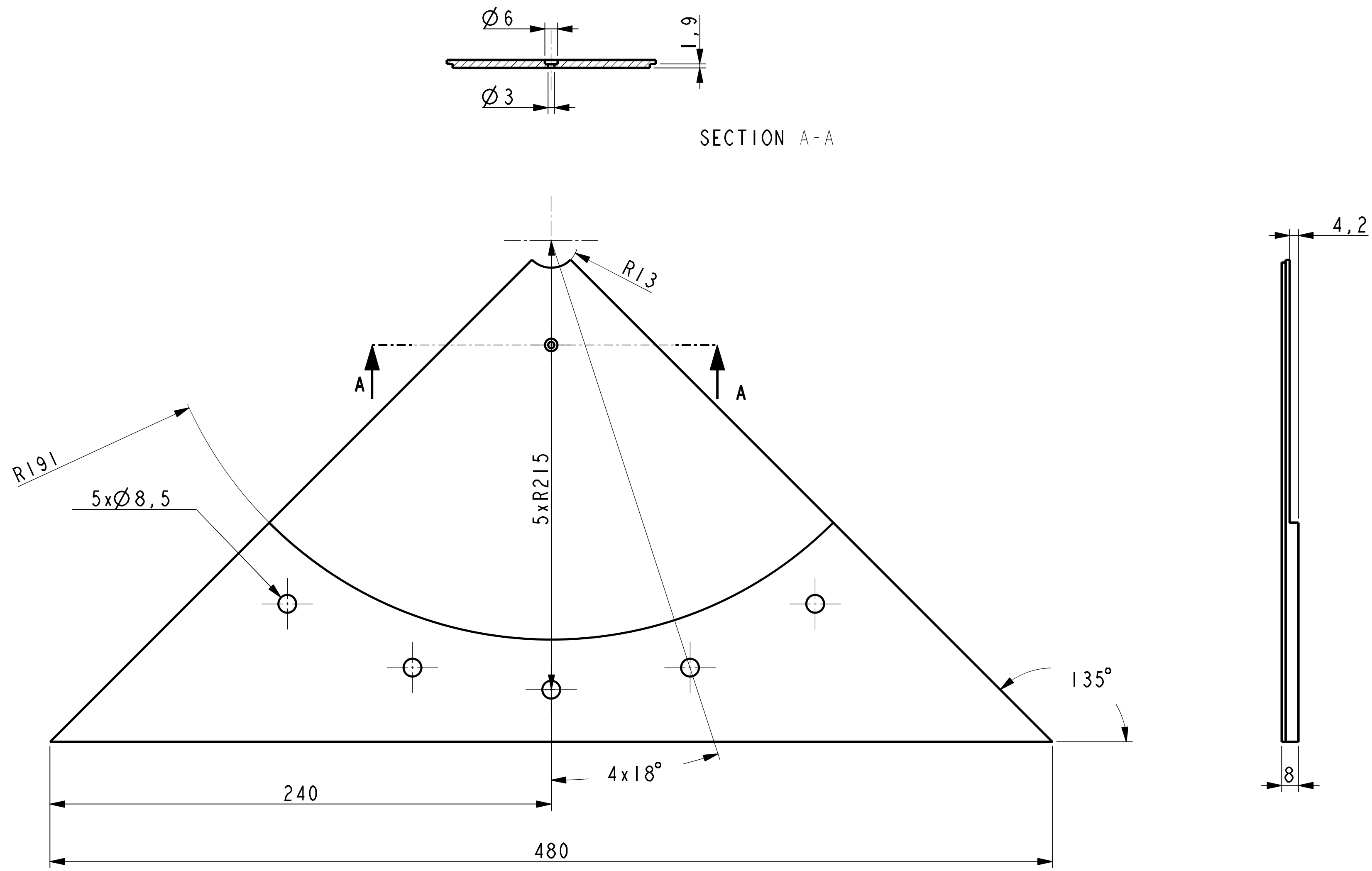


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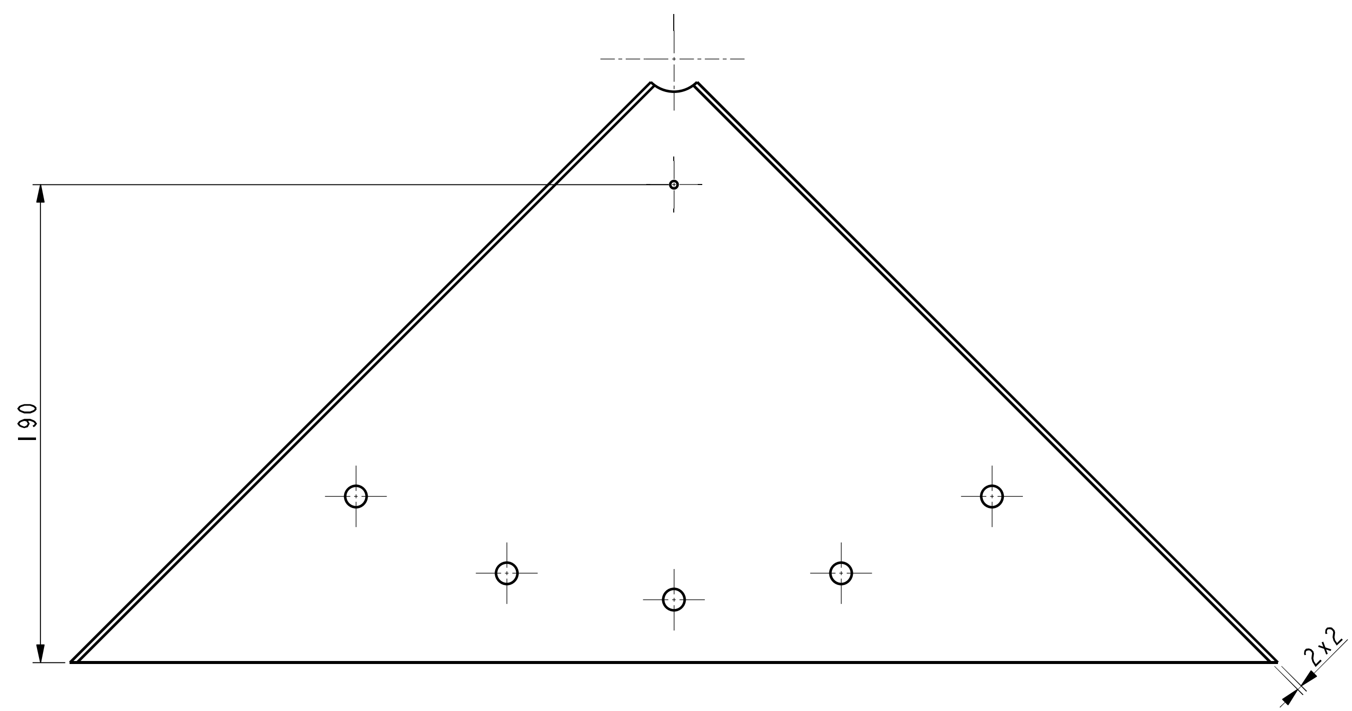


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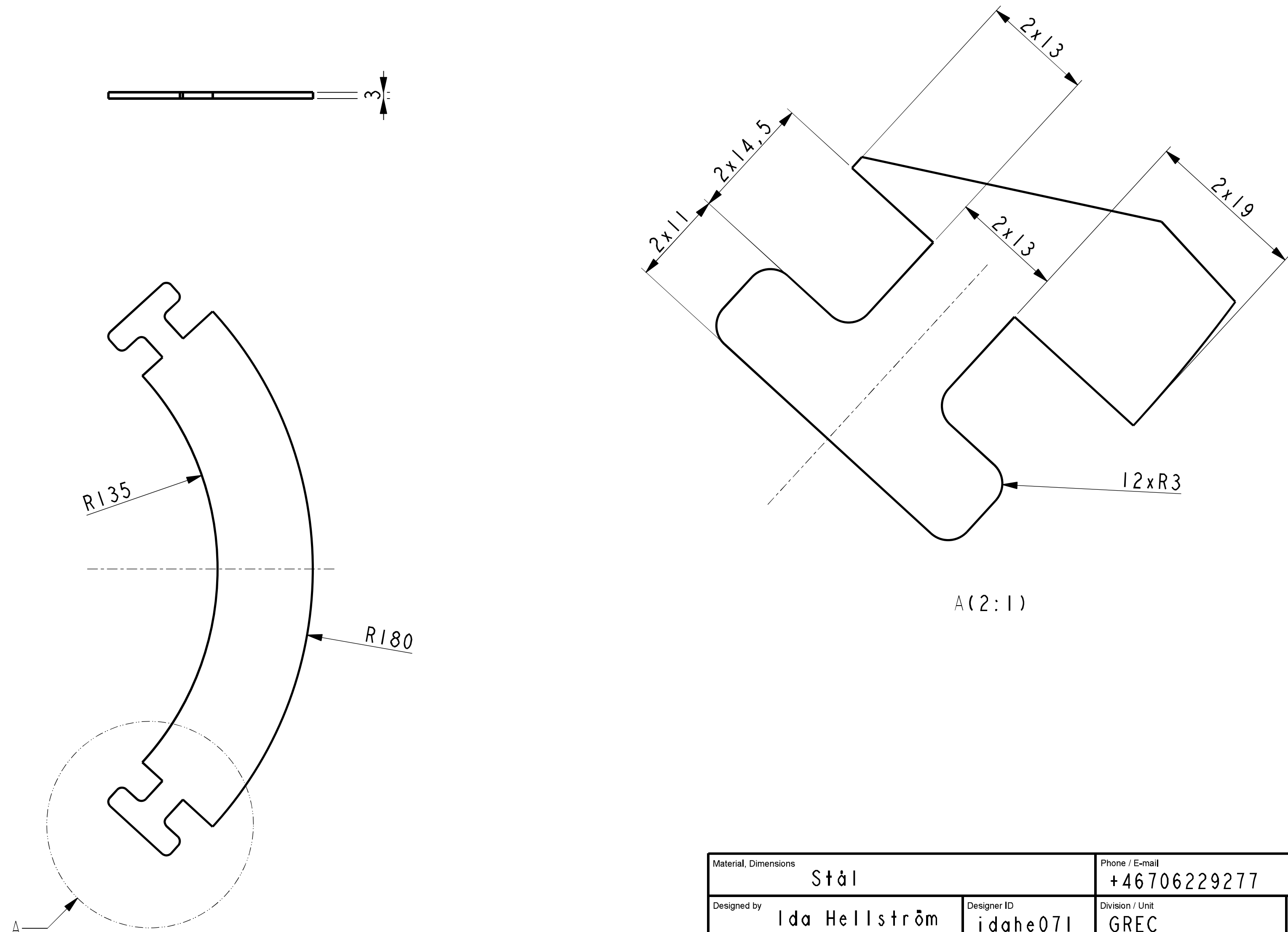


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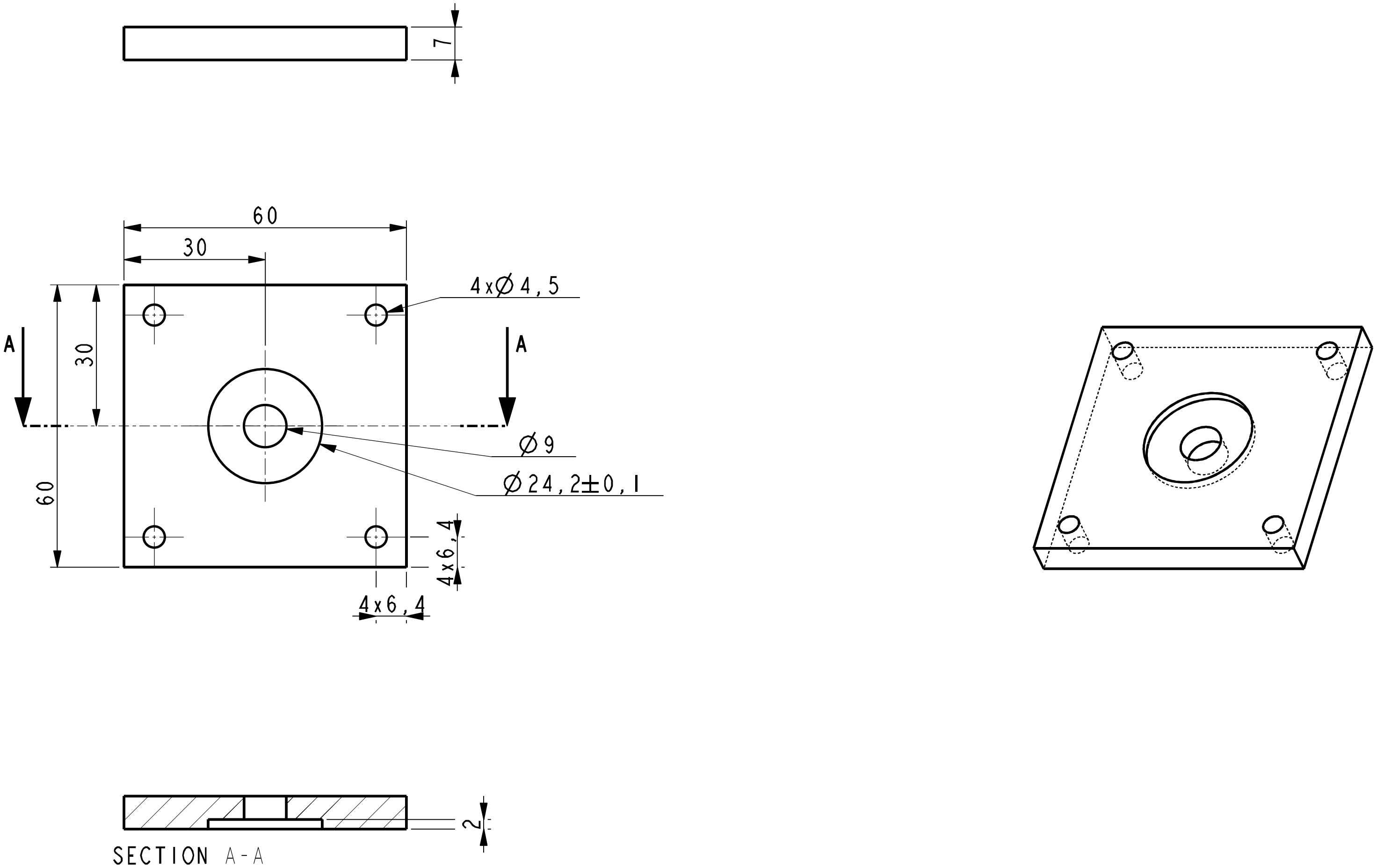


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| Designed by: Vidar Jeirud | Designer ID: vidje880 | Division / Unit: GREC | | Date: 2023-04-13 | |
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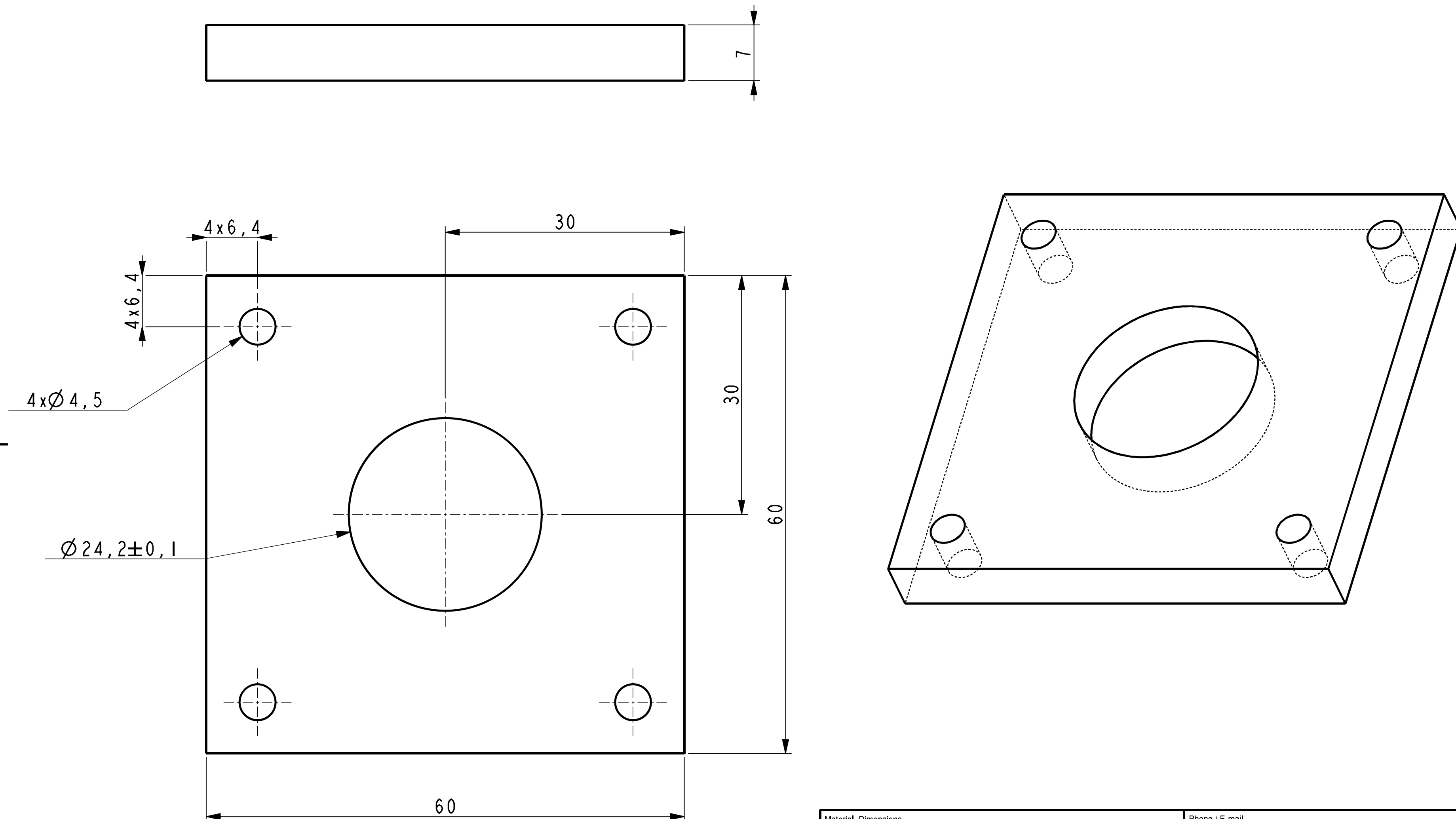


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| Designed by: Vidar Jeirud | Designer ID: vidje880 | Division / Unit: GREC | Date: 2023-04-13 | |
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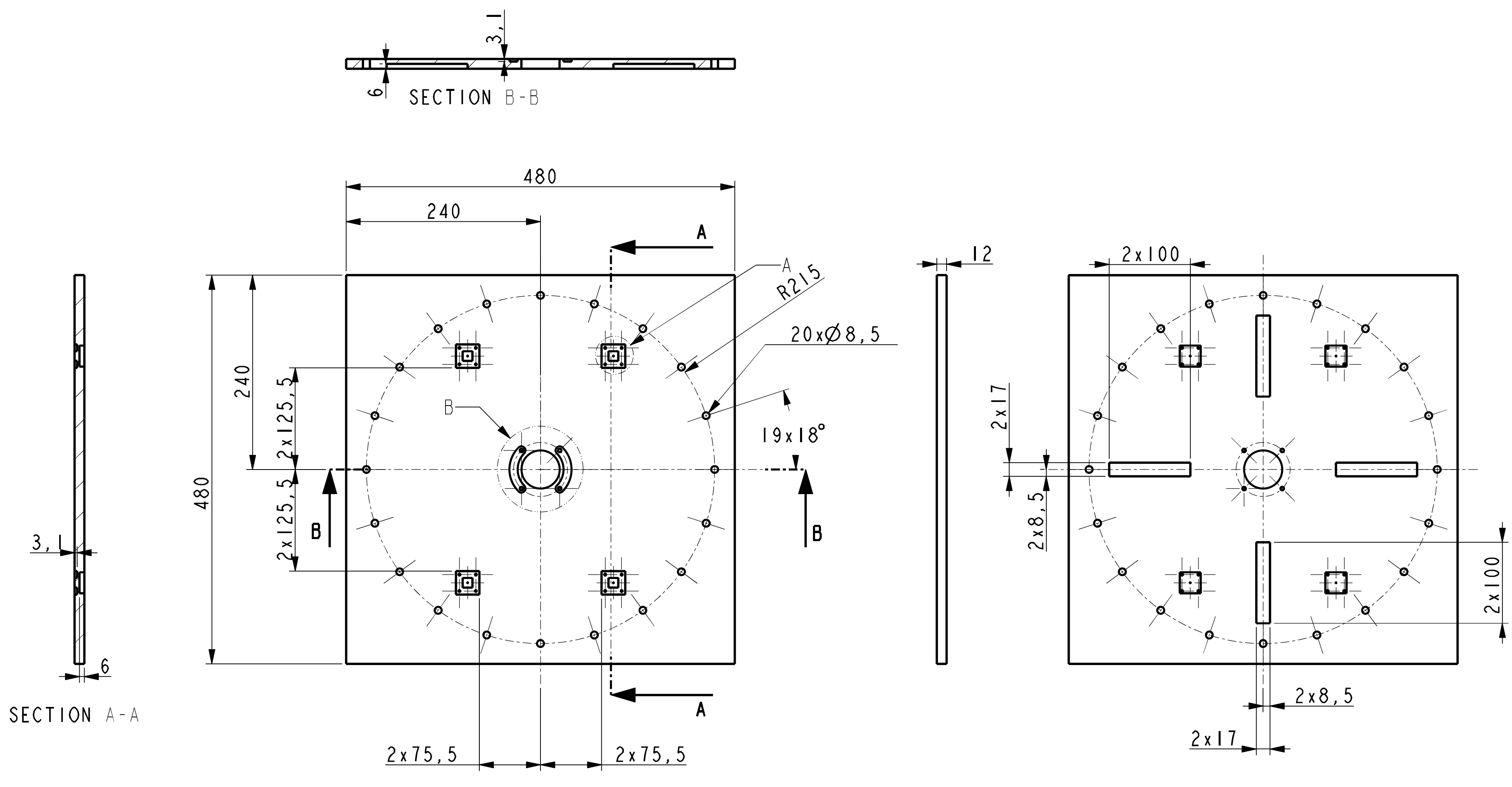


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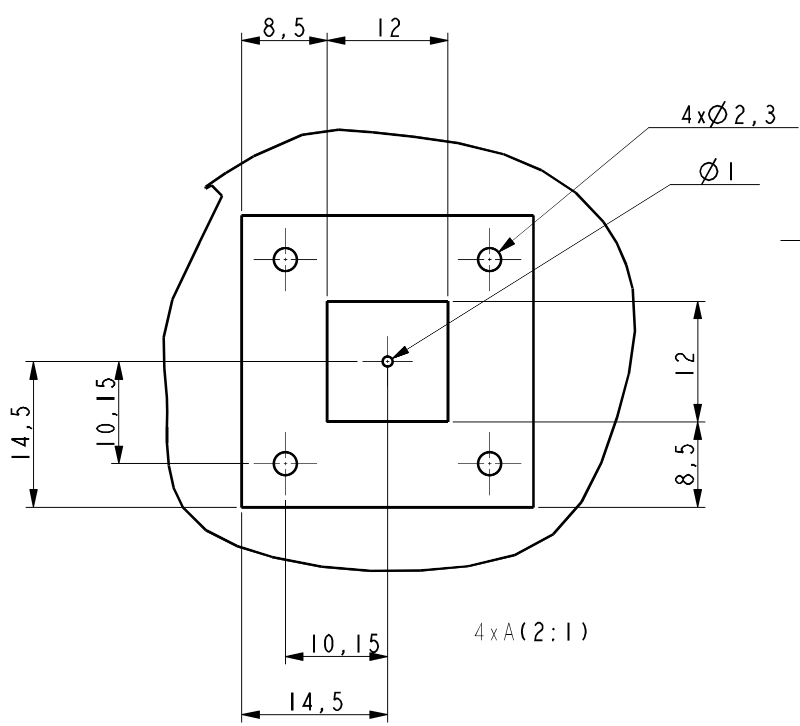


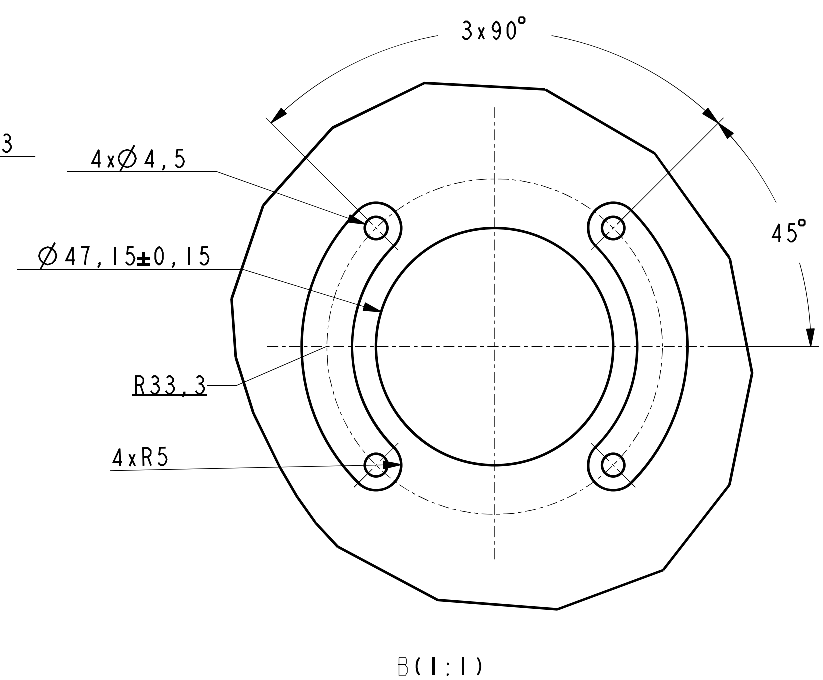


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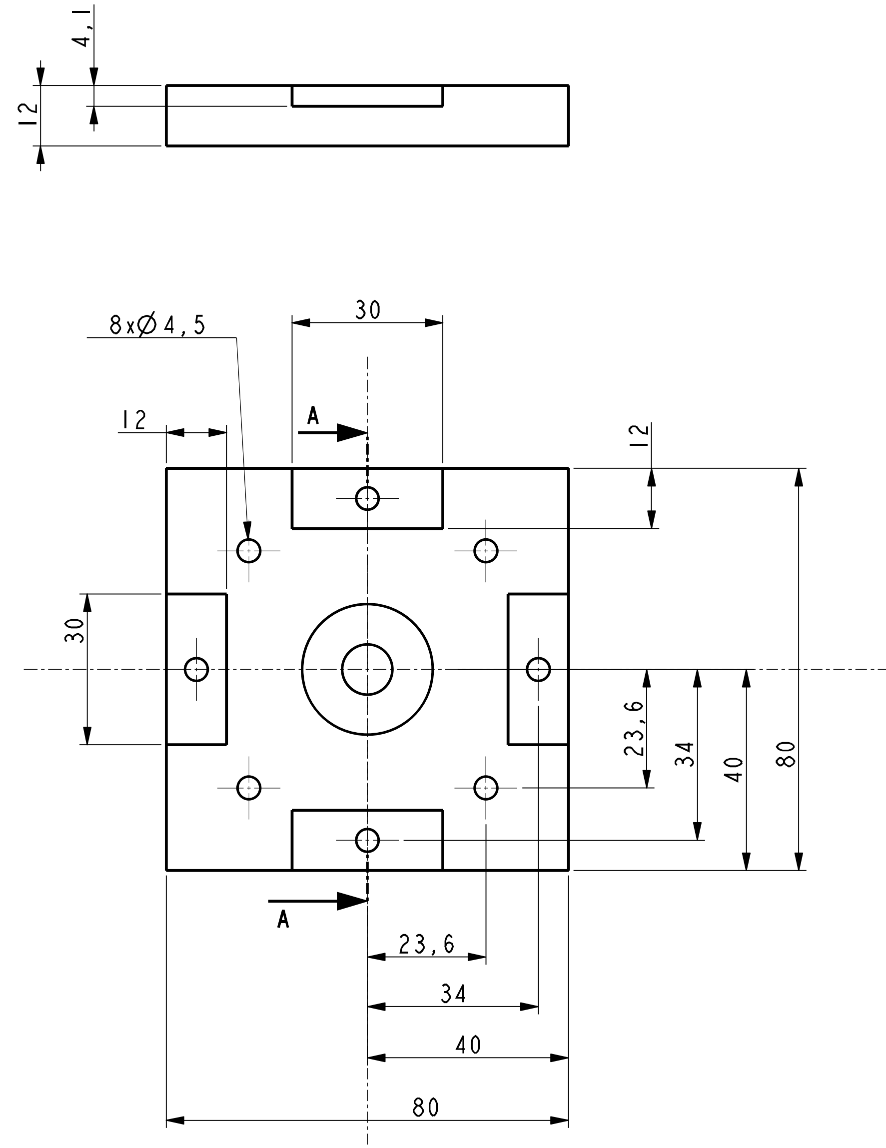


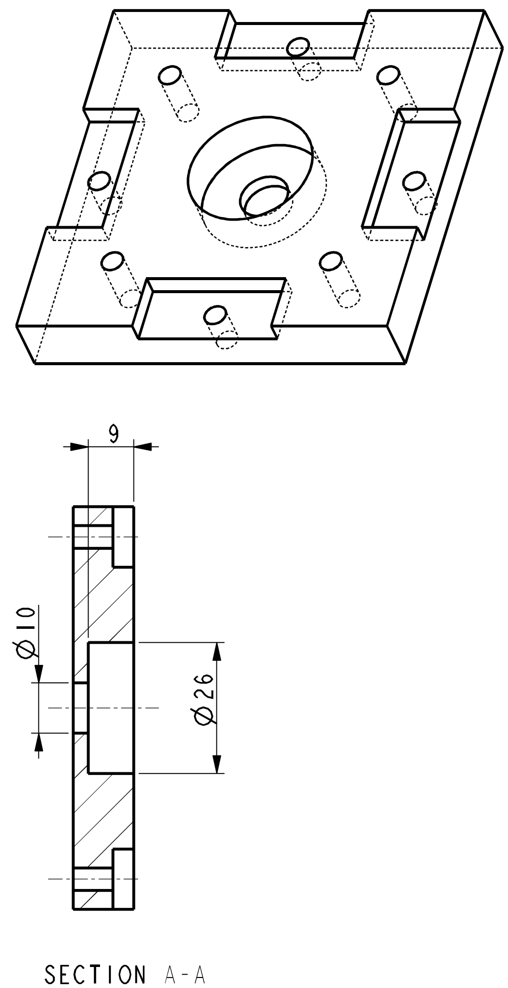


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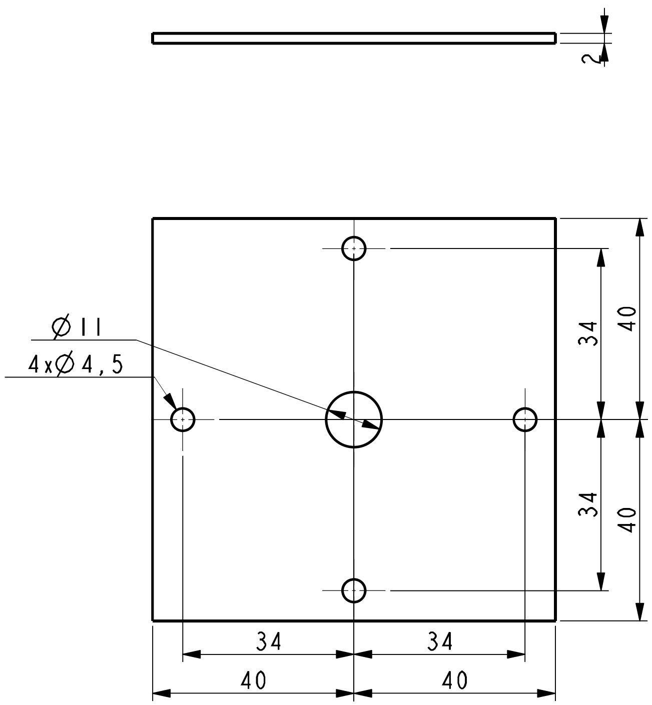


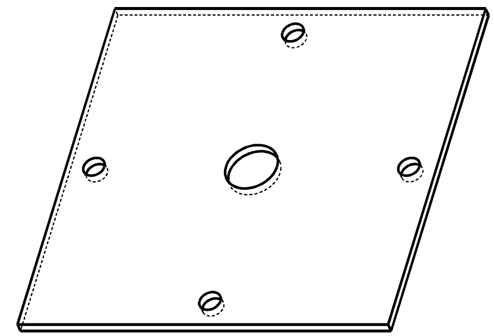

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| Designed by: Andrei Toader | Designer ID: andto616 | Division / Unit: GREC | | Date: 2023-04-13 | |
| Checked by: Ida Hellström | General Tolerance: ISO2768-mK | General surf. roughness: Ra 3,2 | | Projection method | Scale: 1:1 |
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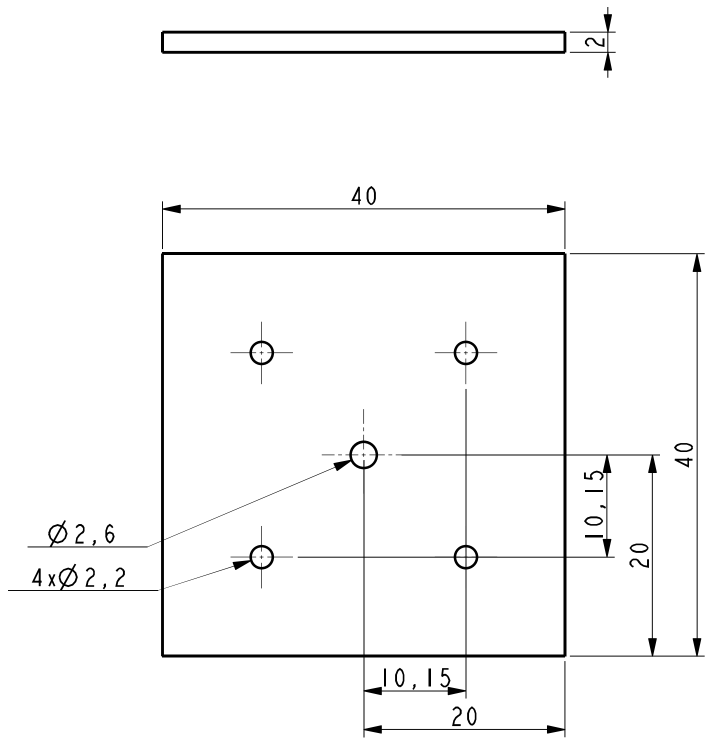


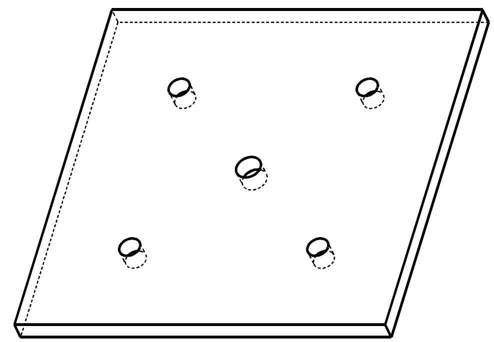

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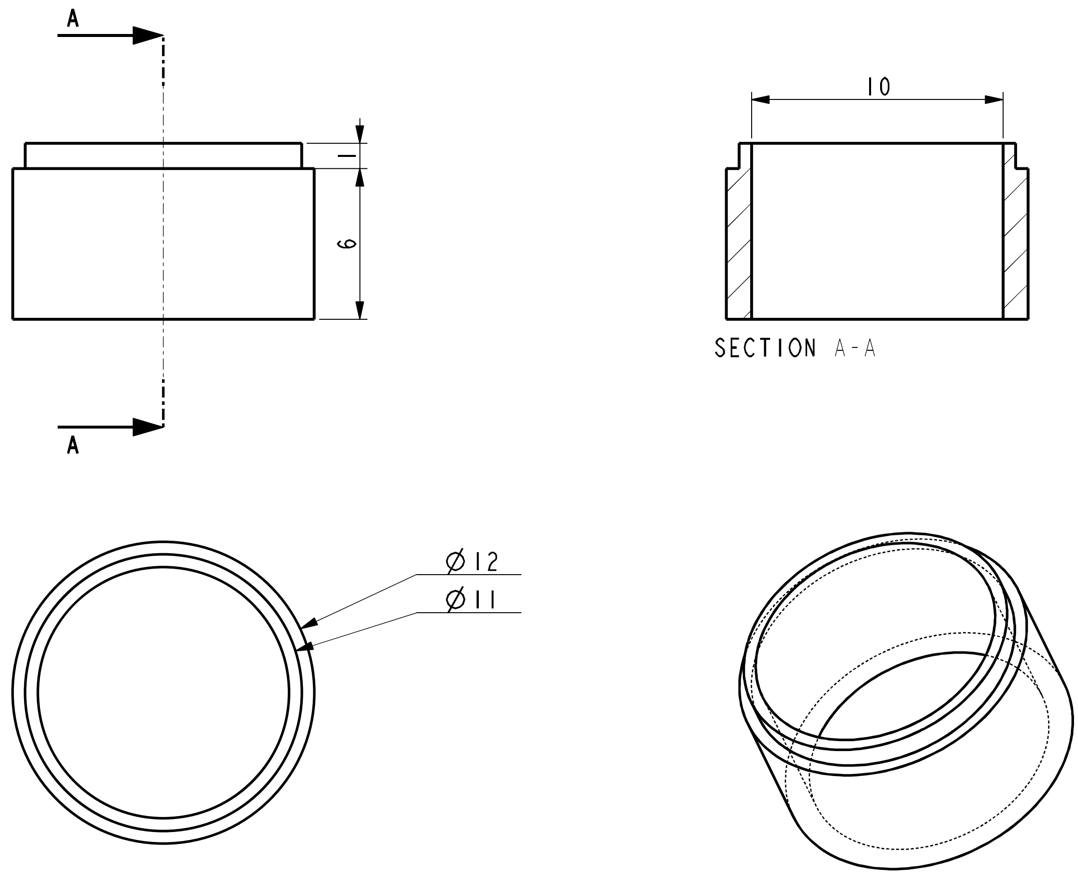


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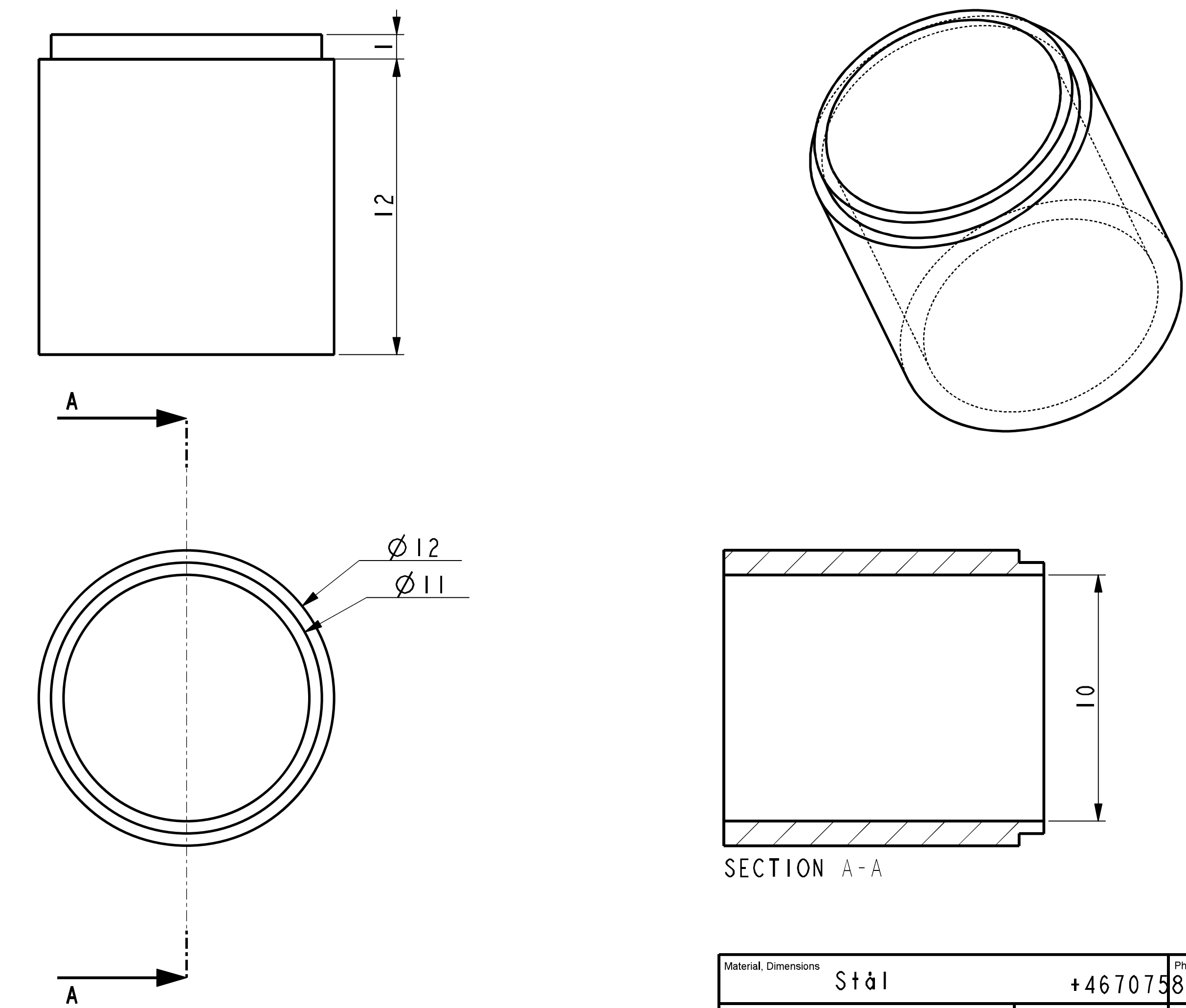


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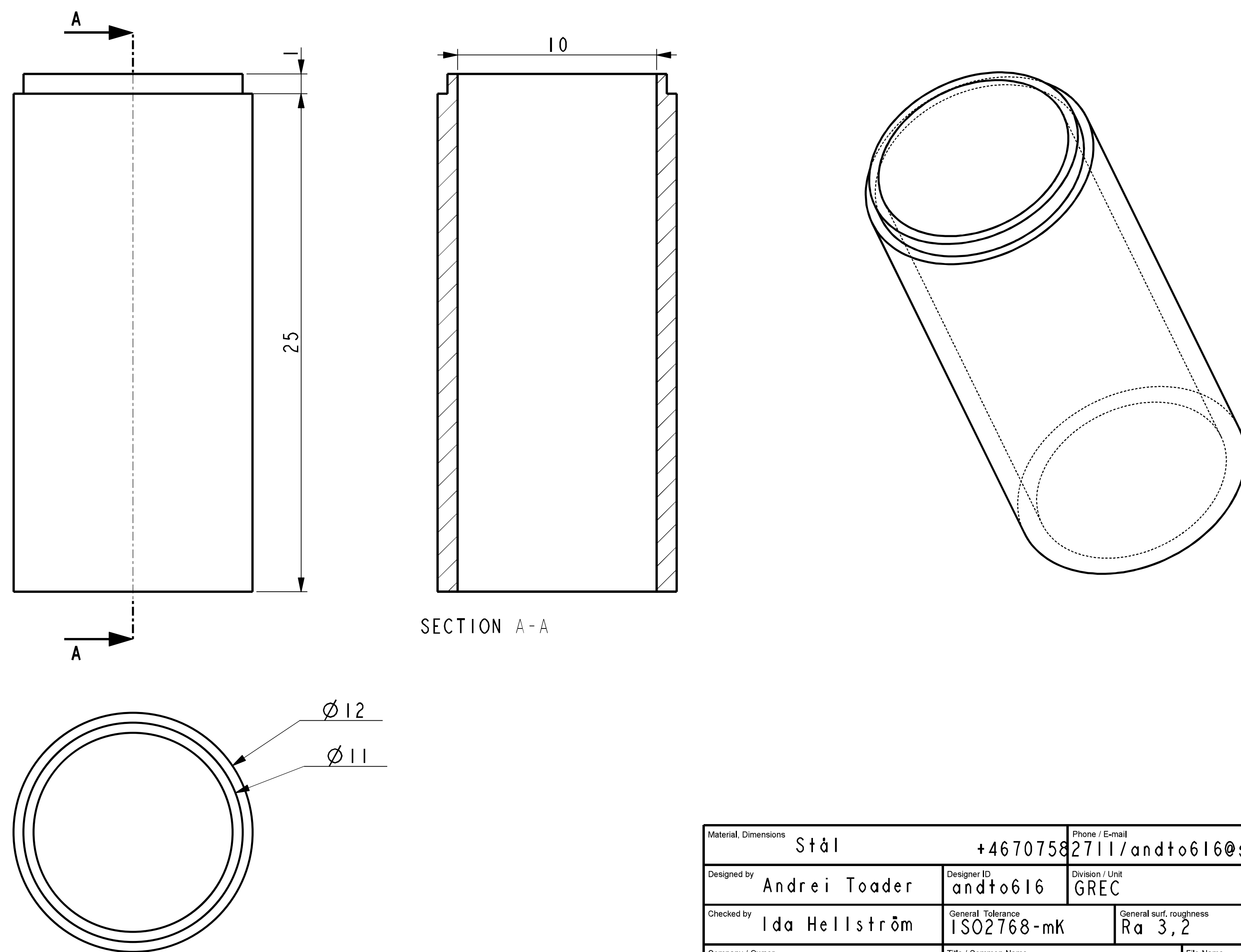


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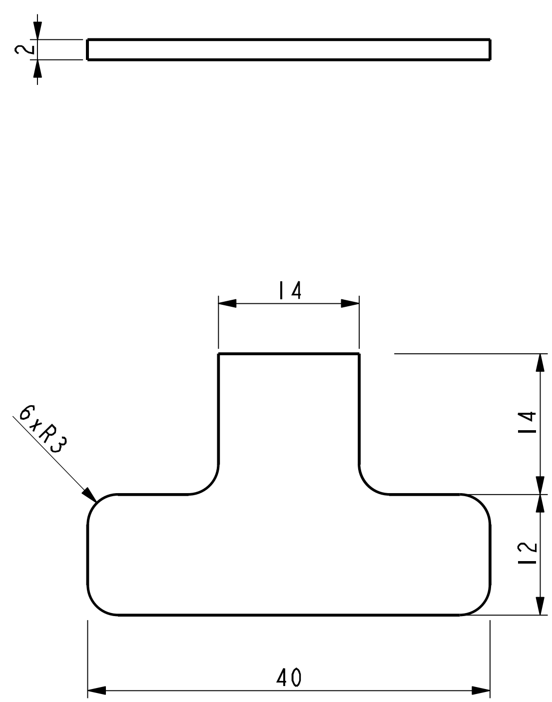


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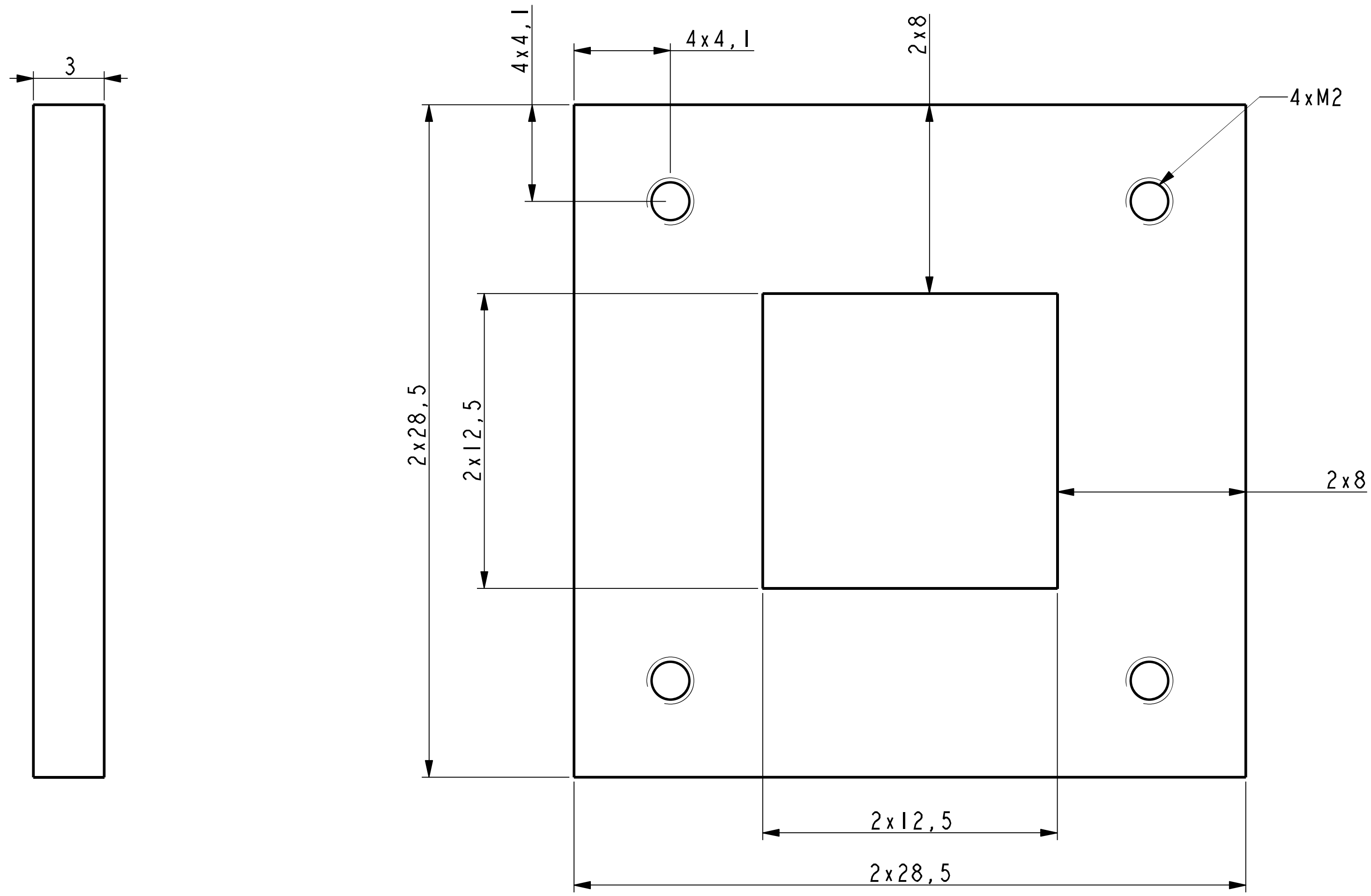


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| Checked by: Andrei Toader | General Tolerance: ISO2768-mK | General surf. roughness: Ra 3,2 | | Projection method | Scale: 5:1 |
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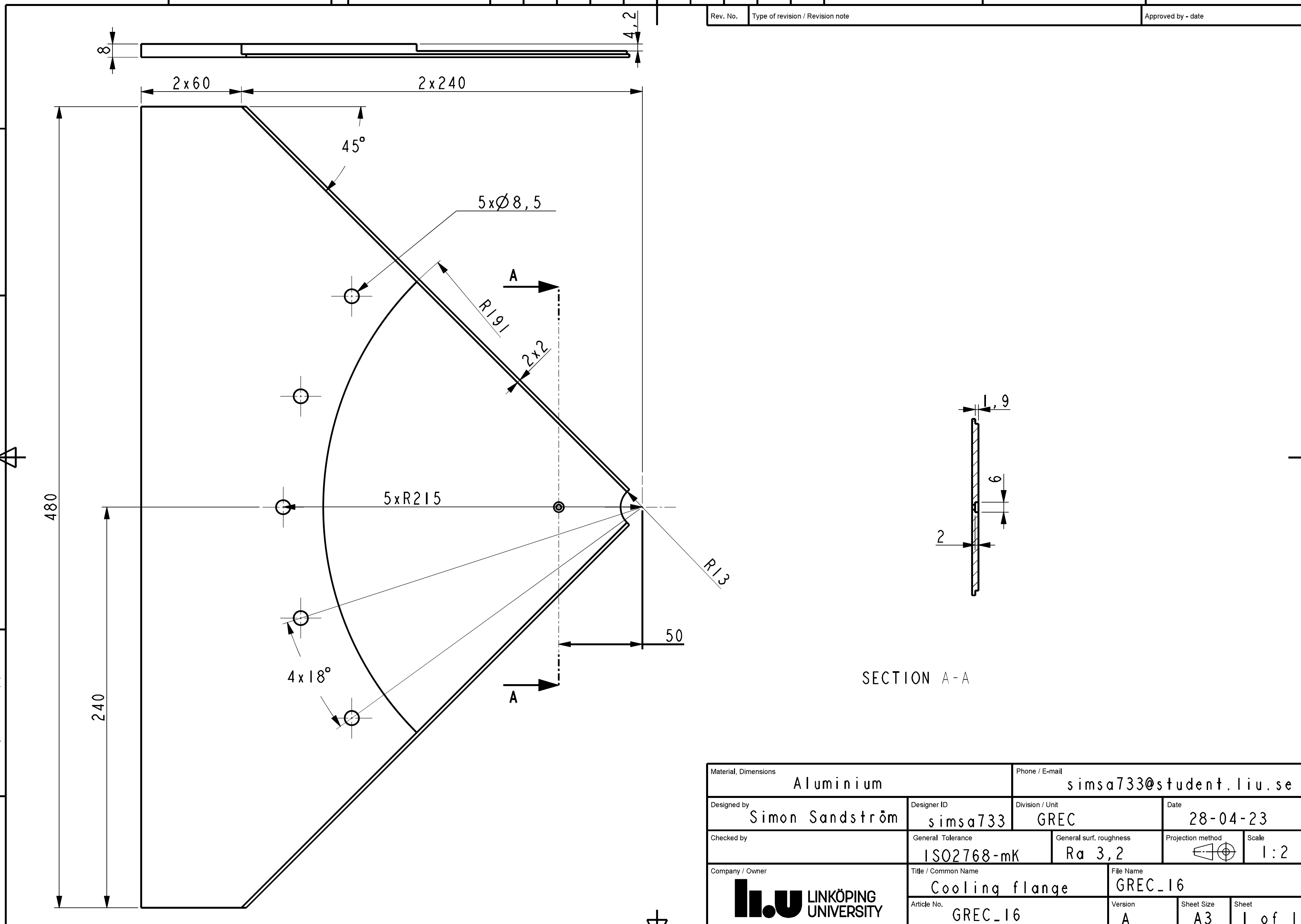

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simsa733@student.liu.se
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Designer ID
simsa733
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Checked by
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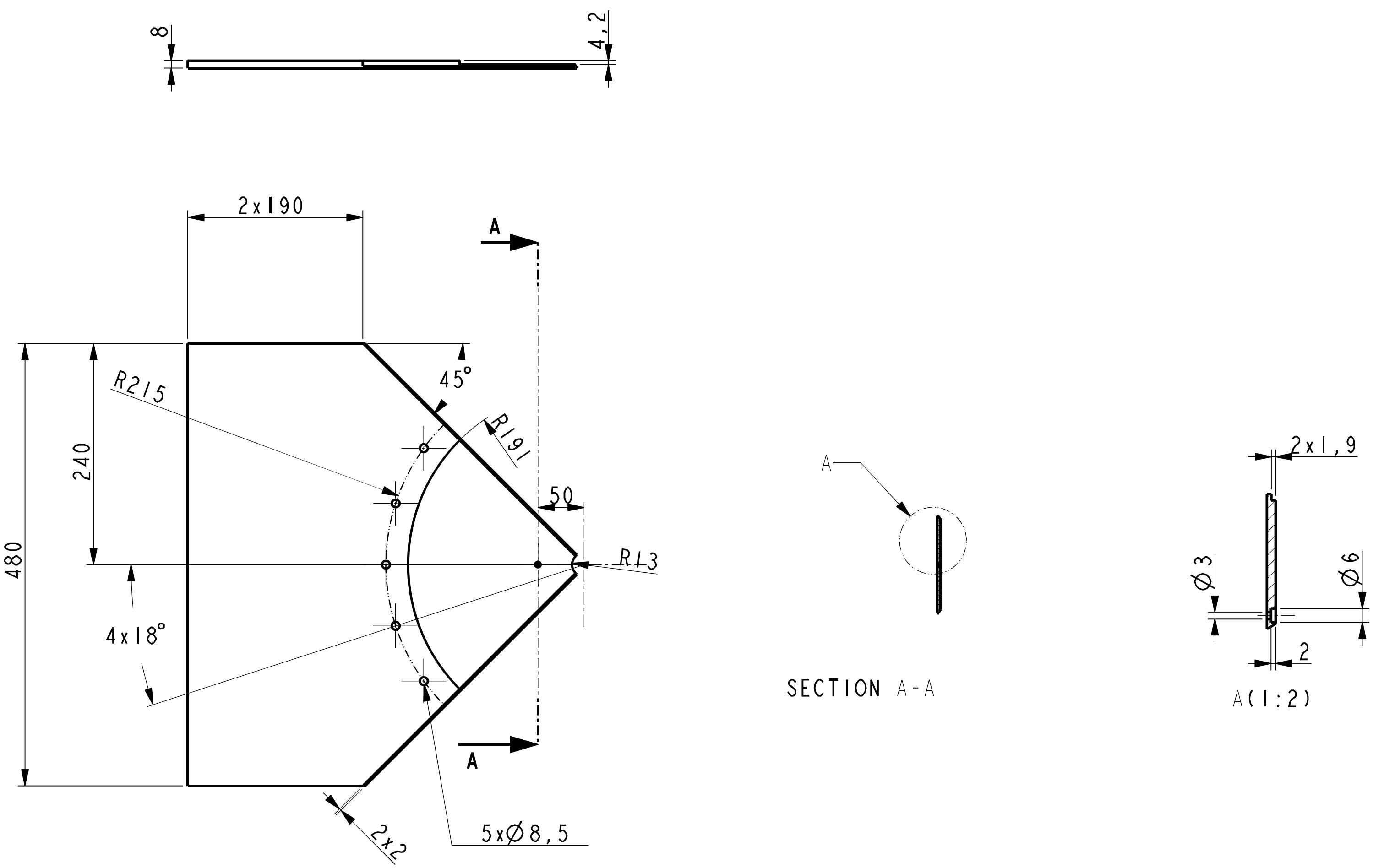


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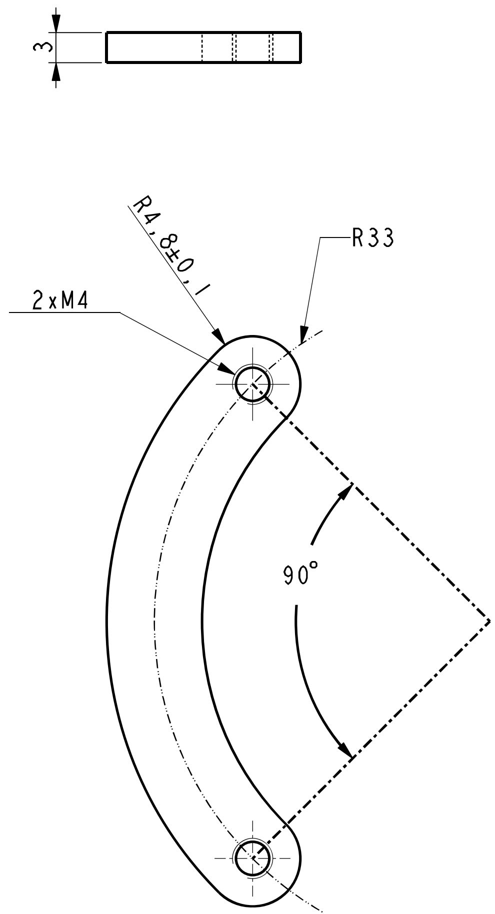
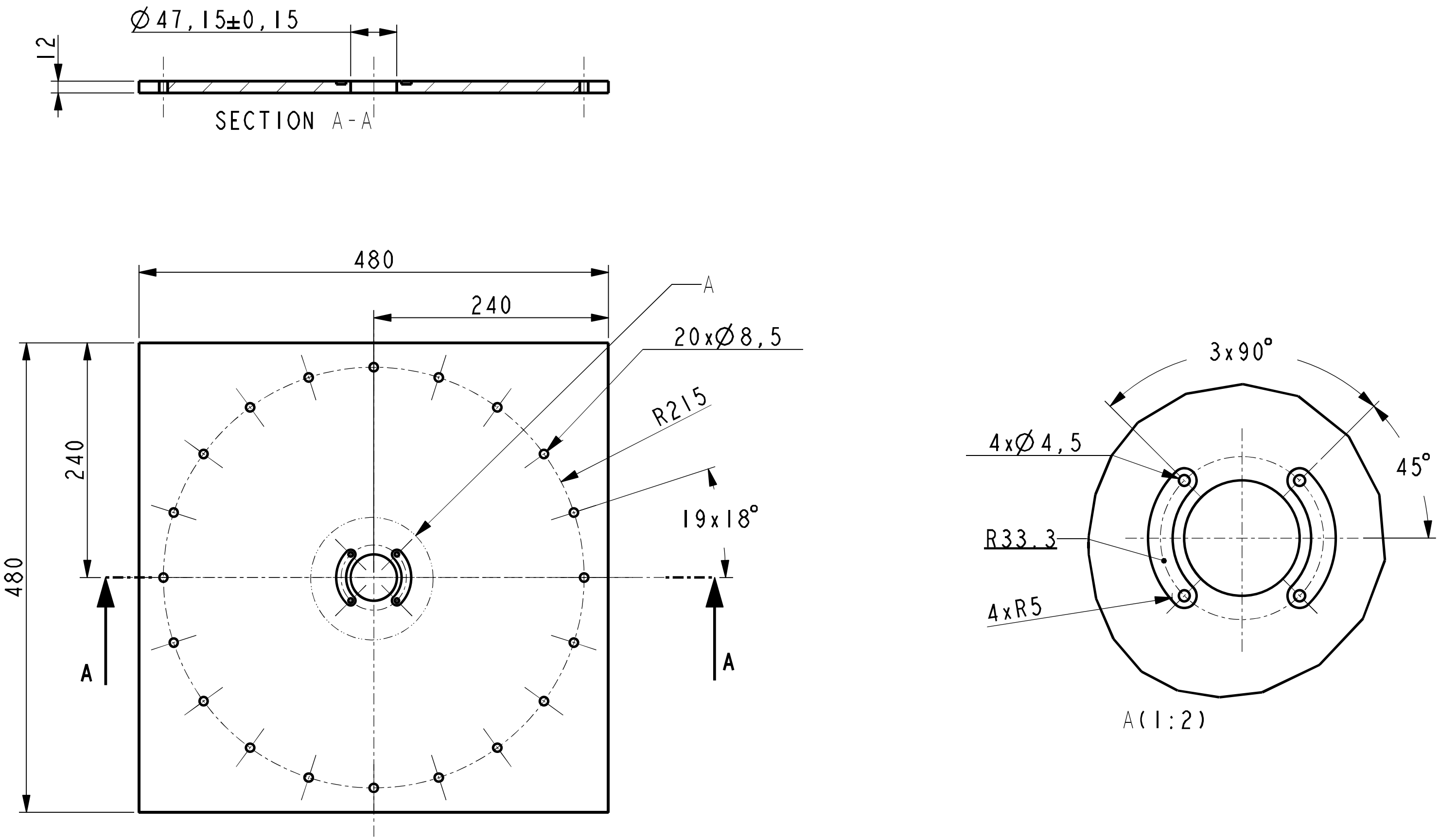
| Checked by: Simon Sandström | General Tolerance: ISO2768-mK | General surf. roughness: Ra 3,2 | Projection method | Scale: 1:5 |
| Company / Owner: LINKÖPING UNIVERSITY | Title / Common Name: Heating flange | File Name: GREC_17 | | |
| | Article No.: Grec_17 | Version: A | Sheet Size: A3 | Sheet: 1 of 1 |




| Rev. No. | Type of revision / Revision note | Approved by - date |
| --- | --- | --- |

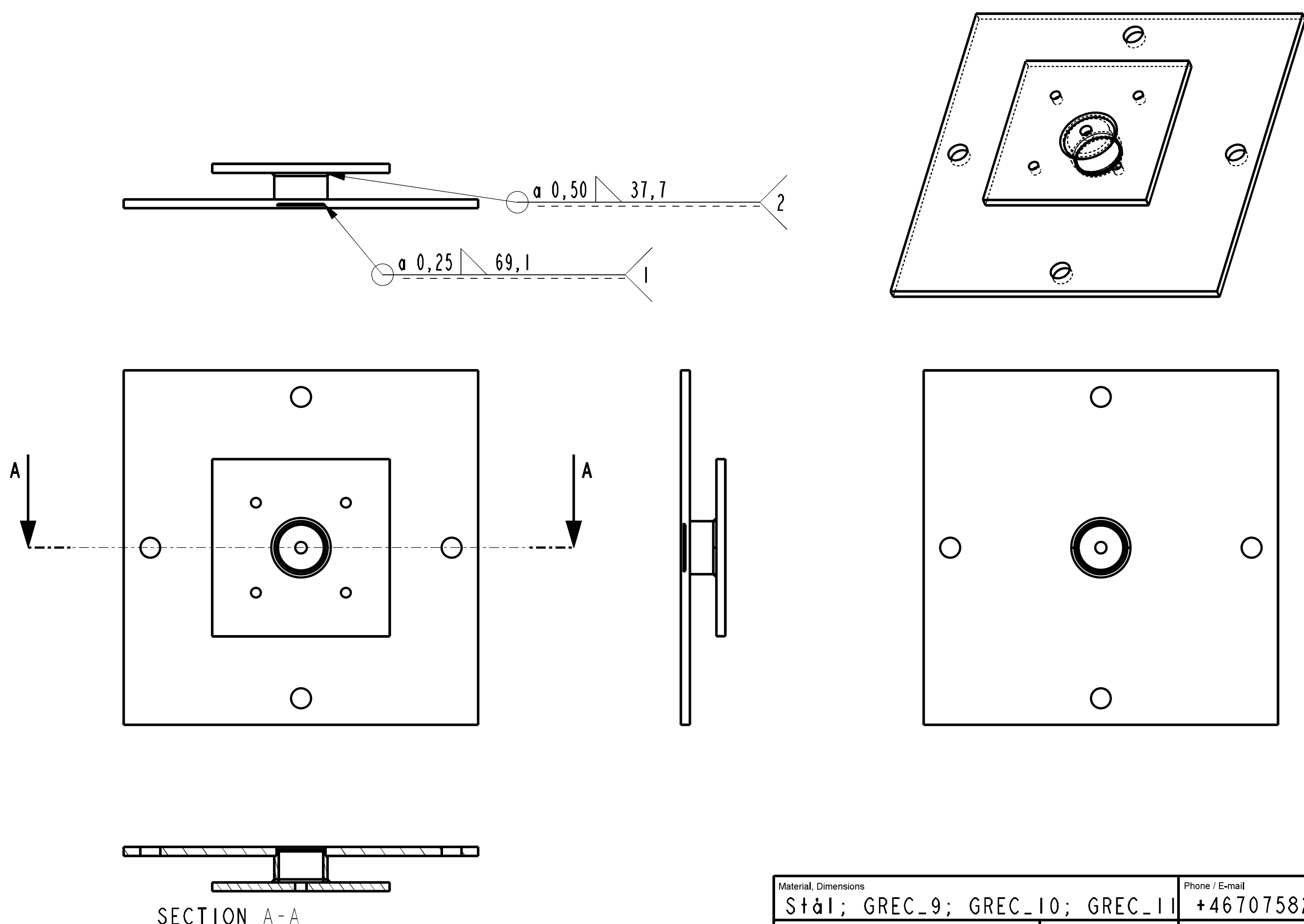
| | | | | |
| --- | --- | --- | --- | --- |
| Material, Dimensions: Steel | | Phone / E-mail: simsa733@student.liu.se | | |
| Designed by: Simon Sandström | Designer ID: simsa733 | Division / Unit: GREC | Date: 2023-04-14 | |
| Checked by: Vidar Jeirud | General Tolerance: ISO2768-mK | General surf. roughness: Ra 3,2 | Projection method | Scale: 2:1 |
| Company / Owner: LINKÖPING UNIVERSITY | Title / Common Name: Mutter Motorfäste | File Name: GREC_18 | | |
| | Article No.: GREC_18 | Version: A | Sheet Size: A3 | Sheet: 1 of 1 |





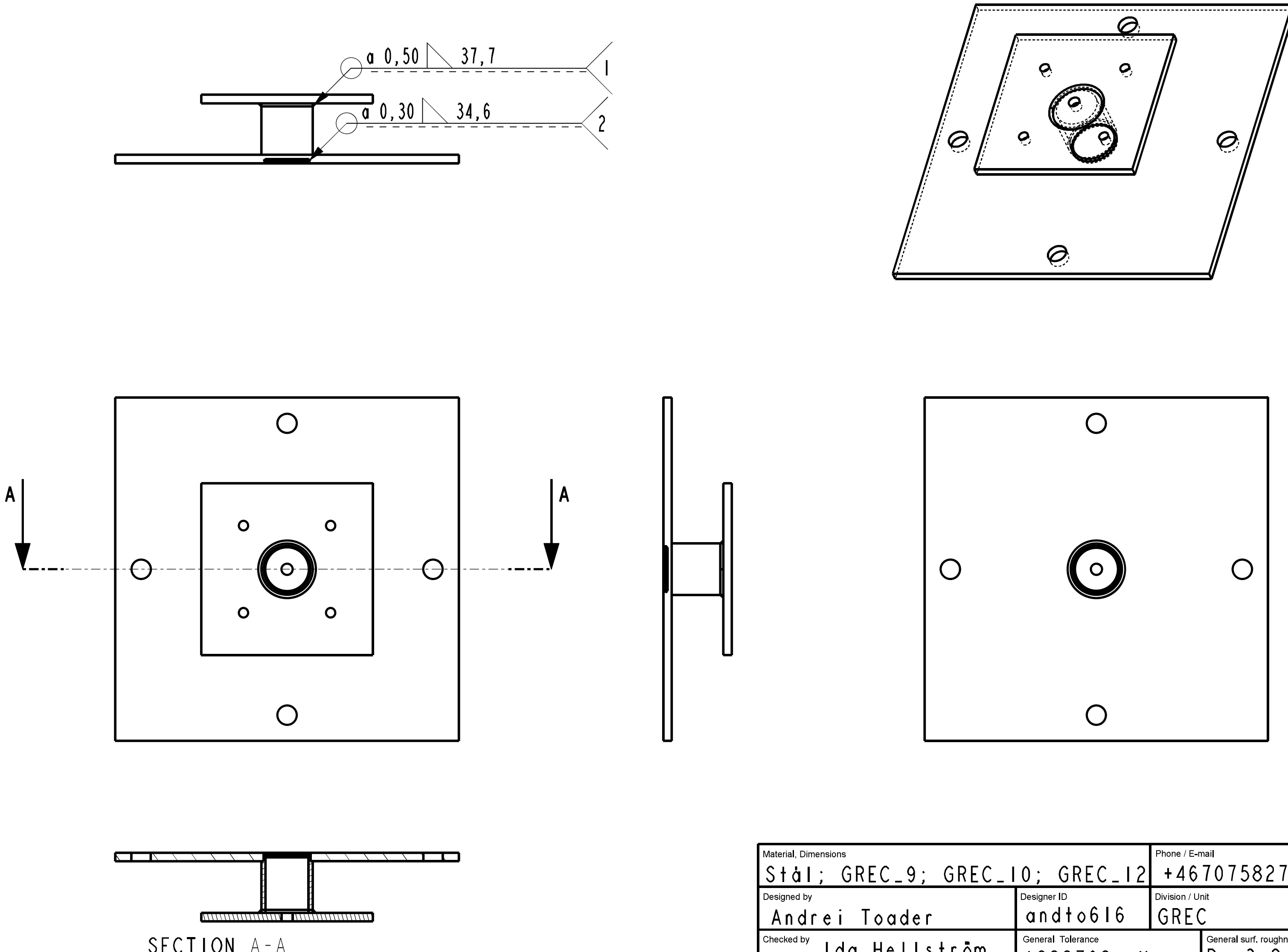

| Rev. No. | Type of revision / Revision note | Approved by - date |
|---|---|---|

| | | | | |
|---|---|---|---|---|
| Material, Dimensions: Bakelit | | Phone / E-mail: +46706229277 | | |
| Designed by: Ida Hellström | Designer ID: idahe071 | Division / Unit: GREC | | Date: 23-04-14 |
| Checked by: Vidar Jeirud | General Tolerance: ISO2768-mK | General surf. roughness: Ra 3,2 | Projection method | Scale: 1:5 |
| Company / Owner: LINKÖPING UNIVERSITY | Title / Common Name: Shell motor | File Name: GREC_19 | | |
| | Article No.: Grec_19 | Version: A | Sheet Size: A3 | Sheet: 1 of 1 |




| Material, Dimensions | Phone / E-mail | | |
|---|---|---|---|
| Stål; GREC_9; GREC_10; GREC_11 | +46707582711 | | |
| Designed by: Andrei Toader | Designer ID: andto616 | Division / Unit: GREC | Date: 2023-04-14 |
| Checked by: Ida Hellström | General Tolerance: ISO2768-mK | General surf. roughness: Ra 3,2 | Projection method / Scale: 1:1 |
| Company / Owner: LINKÖPING UNIVERSITY | Title / Common Name: Lock_komplett_6mm | File Name: GREC_20 | |
| | Article No.: GREC_20 | Version: A | Sheet Size: A3 / Sheet: 1 of 1 |

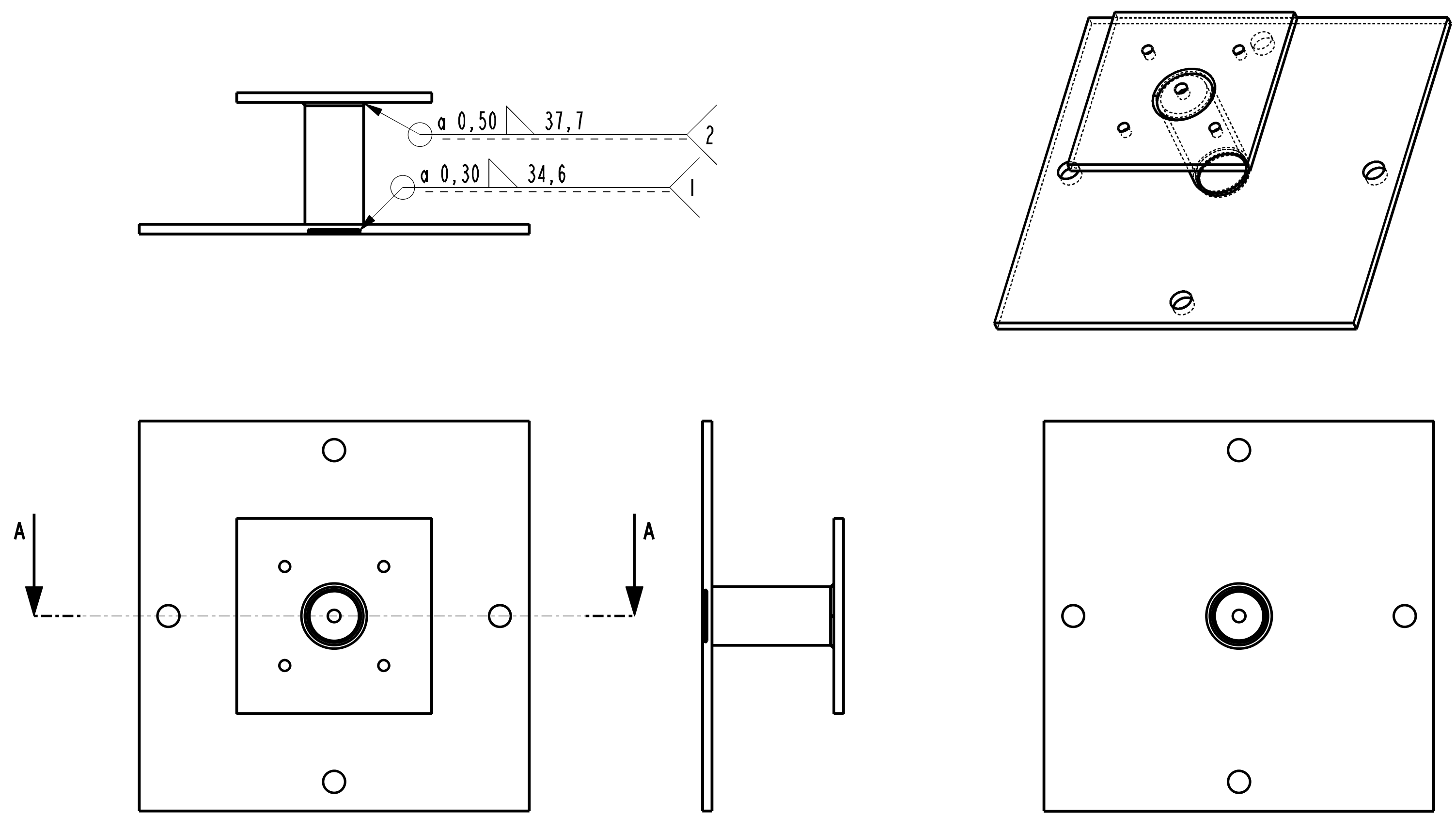
| Rev. No. | Type of revision / Revision note | Approved by - date |
|---|---|---|

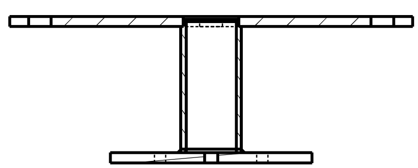



| Rev. No. | Type of revision / Revision note | Approved by - date |
|---|---|---|
| | | |

| | | | | |
|---|---|---|---|---|
| Material, Dimensions: Stål; GREC_9; GREC_10; GREC_12 | | Phone / E-mail: +46707582711 | | |
| Designed by: Andrei Toader | Designer ID: andto616 | Division / Unit: GREC | | Date: 2023-04-14 |
| Checked by: Ida Hellström | General Tolerance: ISO2768-mK | General surf. roughness: Ra 3,2 | Projection method | Scale: 1:1 |
| Company / Owner: LINKÖPING UNIVERSITY | Title / Common Name: Lock_komplett_12mm | | File Name: GREC_21 | |
| | Article No.: GREC_21 | Version: A | Sheet Size: A3 | Sheet: 1 of 1 |

| Rev. No. | Type of revision / Revision note | Approved by - date |
|---|---|---|



SECTION A-A

| Material, Dimensions | | | Phone / E-mail | |
|---|---|---|---|---|
| Stål; GREC_9; GREC_10; GREC_13 | | | +46707582711 | |
| Designed by: Andrei Toader | Designer ID: andto616 | Division / Unit: GREC | | Date: 2023-04-14 |
| Checked by: Ida Hellström | General Tolerance: ISO2768-mK | General surf. roughness: Ra 3,2 | Projection method | Scale: 1:1 |
| Company / Owner: LINKÖPING UNIVERSITY | Title / Common Name: Lock_komplett_12mm | | File Name: GREC_22 | |
| | Article No.: GREC_22 | Version: A | Sheet Size: A3 | Sheet: 1 of 1 |