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Design and development of a low-temperature reactor system for biorefining waste oil

Hans Olav Pedersen
Machine, Process and Product Development (MPP)

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by

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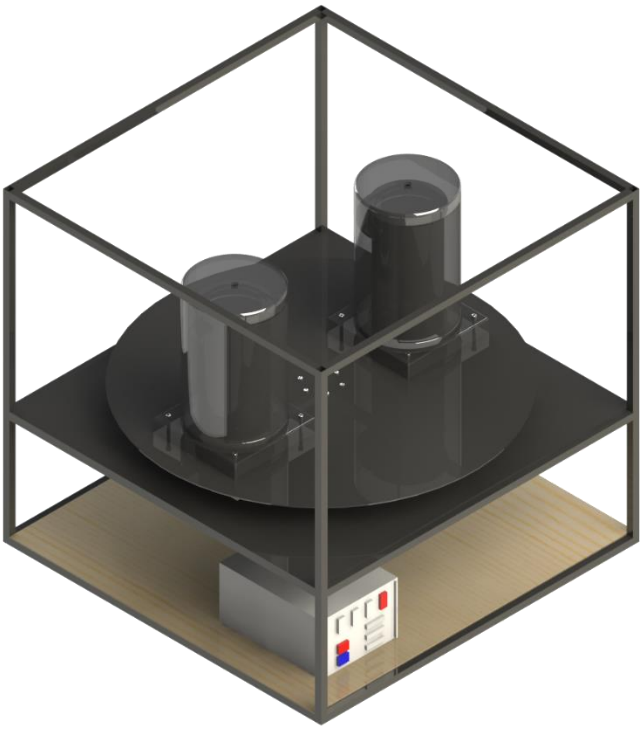

Master's thesis

Machine, process- and product development

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Norwegian University of Life Sciences

Preface

This report is the outcome of a project completed by Hans Olav Pedersen, as part of the master's degree program for Machine, process- and product development at the Faculty of Science and Technology (RealTek) at Norwegian University of Life Sciences (NMBU). The project is initiated by Associate Professor Geir Terjesen and senior engineer Kristian Omberg. It amounts to 30 credits and is completed in the 2017 spring semester.

The background for this thesis is the ongoing projects at NMBU, regarding the field of biorefining and biofuels. Senior engineer Kristian Omberg introduced me to the area of bioenergy and the task which purpose were a technological development for reactors and reactor systems for biorefineries.

The thesis can be divided into three main parts: Research and planning, theoretical review and conceptualizing. The first part; research and planning, involves report and project definitions and approaches. The second part; theoretical review, contains fundamental theory in the field of study, including biorefining, biofuels, chemical reactors and catalysts used for biofuels. The third and last part; conceptualizing, consists of the concept development, where a technological alternative to a reactor system for small-scale biorefineries is presented.

The report can be used for an introduction to biorefining, chemical reactors, catalysts and includes technical alternatives for a reactor and a reactor system. The reader should have engineering knowledge for a full benefit of this report.

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Hans Olav Pedersen

Ås, May 15th 2017

Norwegian University of Life Sciences

Acknowledgements

A special thanks to Geir Terjesen, Associate Professor at NMBU, for good advice and guidance as supervisor throughout the course of this project and during the master's degree program. Also, a sincere thanks to Kristian Omberg, senior engineer at NMBU, for presenting this assignment to me, and for the role as assistant supervisor during the project. Thank you to Gunnar Torp, engineer and workshop manager at NMBU, for material and manufacturing advice and Henrik Holmberg, senior engineer at NMBU, for construction drawing guidelines. Also, thank you to Lasse Erlandsen at LINAK for technical support. A final mention goes to my family, especially Nora Charlotte Hein Stamsø, thank you for being a supportive partner.

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Abstract

The background for this master's thesis is the focus on bioenergy and biofuels at NMBU. This has, among others, resulted in a prototype of a small-scale biorefinery, which uses methanol and waste cooking oil to produce biodiesel. The purpose of this thesis is to develop a reactor system that serves as a platform for reactors to operate on and a technological alternative for a periodically on-site clean of catalysts. The purpose of the catalysts wash is to extend their lifetime, in order to make the reactor system and thereby the biorefinery more sustainable.

The project started with research and literature review in the field of study. Solutions and alternatives were reviewed in an initial design within the concept specifications. Integrated Product Development and SCAMPER is used as methods for the concept development and creating technical alternatives and features. Pugh method has been used for the evaluation and selection of concept. The structure is optimized in a simple FEM structure analysis. Sketches and CAD are used to present the design in 2D and 3D drawings, and an environmental analysis and cost estimate of prototype and series production is completed. The final solution consists of a reactor system with two mounted reactors. Initially, one of them connected to the process of turning the reactants, oil and alcohol, to biodiesel product. The other reactor having its catalyst washed, changed or in other maintenance. When done, the reactor is on stand-by to switch position with the operational one. The position switch happens periodically, by a rotating platform driven and controlled by a motorized rotary stage. Before the rotation, the couplings for the tubes disconnect and when rotated 180 degrees, connects again, this time with the other reactor. Four linear actuators at each inlet and outlet of the reactors, is proposed as a coupling system for disengage and engage motion of the couplings. For further work, it is emphasized to finalize the coupling system, for the reactor system to be completely automatic. As of now the reactor system is depending on manual labor for this job. The structure consists of hollow squared profiles and two decks as housing, mountable with the rest of a biorefinery arrangement. Two types of chemical reactors are presented. Both are continuous packed bed reactors designed for 3D printing, using mainly Polypropylene (PP) as material. The principle is the same for both reactors, using capsules to pack the heterogeneous catalysts for easier reactor and catalyst handling.

Sammendrag

Bakgrunnen for denne masteroppgaven er fokus på bioenergi og biodrivstoff ved NMBU. Dette har blant annet resultert i en prototype av en små-skala bioraffineri, som bruker metanol og avfalls matolje for å produsere biodiesel. Formålet med denne oppgaven er å utvikle et reaktorsystem, som fungerer som en plattform for reaktorer og med et teknologisk alternativ for en periodisk rengjøring av katalysatorer. Formålet med katalysatorvasken er å forlenge katalysatorens levetid, for å gjøre reaktorsystemet og derved bioraffineriet mer bærekraftig.

Prosjektet startet med litteratur gjennomgang av emnet. Innenfor konseptspesifikasjonene ble løsninger og alternativer vurdert som innledende design. Integrert produktutvikling og SCAMPER ble brukt som metoder for konseptutvikling og for å skape tekniske alternativer og funksjoner. Pugh-metoden har blitt brukt til evaluering og valg av konsept. Strukturen er optimalisert i enkle FEM strukturanalyser. Skisser og CAD brukes til å presentere designet i 2D- og 3D-tegninger, og en miljøanalyse og kostnadskalkyle av prototype og serieproduksjon er fullført.

Den endelige løsningen består av et reaktorsystem med to monterte reaktorer. En av dem er koblet til prosessen med å omdanne reaktantene, olje og alkohol, til produktet biodiesel. Den andre reaktoren får sin katalysator vasket, byttet ut eller er i annet vedlikehold. Når den er ferdig, står reaktoren i standby, for å bytte posisjon med den biodiesel operative. Posisjonsbyttet skjer periodisk, ved hjelp av en roterende plattform drevet og styrt av et motorisert translasjonsbord. Før rotasjonen, kobles rørene av og når plattformen har dreid 180 grader, kobles på de på igjen, denne gangen med den andre reaktoren. Fire lineære aktuatorer ved hvert innløp og utløp av reaktorene, er foreslått som et koblingssystem for bevegelseskontrollen av koblingene. For videre arbeid legges det vekt på å fullføre koblingssystemet, for at reaktorsystemet skal være helt automatisk. Foreløpig er reaktorsystemet avhengig av manuell arbeidskraft for denne jobben. Strukturen som holder systemet består av kvadrerte hulprofiler og to plater, monterbart med resten av et bioraffineri. To typer kjemiske reaktorer presenteres. Begge er kontinuerlige reaktorer, designet for 3D-print med hovedsakelig polypropylen (PP) som materiale. Prinsippet er likt for begge reaktorene, ved å bruke kapsler for å pakke heterogene katalysatorer, er reaktorene enklere å håndtere når katalysatorene må skiftes ut eller vedlikeholdes.

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1. Introduction

The world is being affected by fuel price hike, fossil fuel being a finite resource and the questions surrounding climatic change. Since the mid-20th century, fossil fuel has accounted for the majority of the world's energy consumption[1]. The 2016 Key World Energy Statistics report from International Energy Agency (IEA) shows that the total primary energy supply by fuel consists of approximately 81.1 % fossil fuel (oil, natural gas and coal), and fossil fuel has virtually all carbon dioxide emissions[2]. Intergovernmental Panel on Climate Change's (IPCC) report from 2014 states that the recent climate changes have had widespread impacts on human and natural systems[3]. Further, the report says that the increased greenhouse gas (GHG) emissions have led to atmospheric concentrations of carbon dioxide among others. These emissions, together with other anthropogenic drivers, are extremely likely to have been the dominant cause of the observed warming.

Environmental concerns, increase in fuel price and predicted shortage of fossil fuels, have made scientists and engineers work towards creating alternative ways to produce and consume cleaner and more sustainable energy. As an alternative and addition to fossil fuel, bioenergy emerged to the mainstream. Bioenergy, is promoted as a more sustainable source for hydrocarbons, especially for transportation fuels[4]. IEA's report on biorefining states that "*The main focus of biorefinery systems which will come into operation within the next years is on the production of transportation biofuels (i.e. biofuel driven biorefineries).*"

Biofuel, a type of bioenergy, is renewable and can have a role in providing the energy demand for transportation[5]. Either as a supplement to fossil fuel or to a possible upcoming transition to electric vehicles. There is a great debate whether biofuel is as promising as many has promoted it to be. Biofuel is not only being used clean, but also blended with fossil fuel with mixed results. This has led to false promise of cleaner fuel, and a bad reputation for some types of biofuels.

The last experienced initiative against a more sustainable future, was participating in a kick-off seminar this spring for "Bio4fuels", the Norwegian Center for Sustainable Bio-based Fuels and Energy[6]. This effort based at the Norwegian University of Life Sciences (NMBU) is an eight-year long national project with a budget of 270 million NOK. Led by SINTEF with various project- and numerous user-partners, the center aims to create a platform of knowledge in technologies, which will ensure economically and environmentally sustainable production of biofuels.

Sustainability, is the key word for beneficial biorefining of biofuel. There are several elements to consider, for a biorefinery to be sustainable. One of them having an efficient chemical process, including getting as much as possible out of the raw materials and substances used to produce the products. In research and development (R&D), this is often examined within a chemical perspective. In this thesis, to achieve the same goal, a mechanical reactor system to a small-scale biorefining process is researched for technological development.

1.1 Background

In 2013, a project called "UMBio" was initiated at NMBU. Its purpose was to develop a method of producing biodiesel from waste. From "UMBio" a new project emerged, which resulted in a master's thesis from 2015; "A small-scale biodiesel production refinery based on a heterogeneous technology"[7]. The thesis would later proceed as an interdisciplinary project called "Bio Max", with the intent of building a small-scale biorefinery. The purpose of the refinery was to be used as a scientific demonstrator in education and research at the University.

During R&D of the small-scale biorefinery, more knowledge within the area of study, led to ideas regarding catalyst performance. In some chemical processes the catalytic reaction is crucial, and in time the catalysts must be changed or reactivated. These actions resulted in ideas to streamline the catalyst handling. One idea was to adapt the method of changing a capsule in a capsule coffee machine, to changing the catalysts in a biorefinery. A capsule with catalysts would serve as the coffee capsule, and be packed in "cartridges", which would make them easy to change and easy to reuse, hopefully resulting in a more sustainable biorefinery.

Now that additive manufacturing, also known as 3D printing, is more available, a solution is to use this method to design and produce chemical reactors. 3D designed and printed chemical reactors, has shown promising results. IFPEN, a French energy company, printed world's first chemical reactor in 2016, and experienced cut costs and time in development, and by rapid prototyping, allowing the creation of a more complex structure for the chemical reactor[8].

While the “Bio Max” prototype progressed, more suggestions to streamline the catalyst and reactor performance came to mind. During consultations with assistant supervisor and with the scientific interest in heterogeneous catalysts, the idea to periodically clean the catalysts to increase efficiency and extend the catalyst life time was presented. The goal was to come up with a way to achieve this, something which would lead to the assignment for this thesis.

1.2 Assignment description

The thesis aims to develop a technological alternative to a reactor system for small-scale (decentralized) biorefineries. The reactor system’s function is a platform for reactors to operate on and for the handling of catalysts packed in capsules inside the reactor. The system should have a way to periodically clean the catalyst material. The purpose of cleaning the catalyst is to optimize biodiesel production and increase catalyst activation time, in order to create a more cost-effective method of using heterogeneous catalyst.

1.3 Issue

How to develop a small-scale biorefinery reactor system with a more cost-effective method of using heterogeneous catalyst?

1.4 Objectives

The project is divided into a main and part objectives.

1.4.1 Main objective

The main objective is to develop a reactor system that serves as a platform for reactors to operate on and with the periodically on-site cleaning of catalysts packed in capsules, inside the chemical reactors.

1.4.2 Part objectives

The main objective is divided into six part objectives:

I. To complete a literature review
II. To define issues, objectives and limitations for the thesis
III. To complete a conceptual design of a reactor system
IV. To complete CAD of the conceptual design
V. To complete cost- and environmental analysis of a reactor system
VI. To finalize and submit the report

1.5 Limitations

- The thesis will not delve into chemical processes in the reactor system. The aspects of chemical evaluation are limited, since the task given by the assistant supervisor is the product development of a reactor system, not evaluating which chemical substances to use for a more efficient process. This thesis is thus based on the presumption that the wash of the catalysts will prolong the activation time. If the altered reactor system will be more cost-effective than a regular one, requires a test and comparison of the two options. This comparison will not be concluded because of limited time.
- The task has multiple technical solutions, but in order to finish within the given time the project will evaluate some of the more promising alternatives.
- The reactor system is built without given specifications for arrangements with other components in the biorefinery, but is designed in an open and simple way to easy fit and position with the rest of an eventual forthcoming refinery.
- The capsule designed reactors are in an early developing phase or a POC, and need further optimization and tests to achieve the preferred end-result.
- The coupling system for the reactors is limited to a proposal for a favorable method in the initial design and need further development to conclude with a final design.
- The control motion system for the reactor system is not programmed

2. Method

This chapter is an overview of terminology and symbols, the thesis' methodological approach and which measures have been applied to assure quality for the developed system and the report.

2.1 Terminology and symbols

The subchapter provides an overview of the special terms and abbreviations (Table 2-1) and symbols (Table 2-2) used in the report.

Table 2-1. Special terms and abbreviations used in the report

Term and/or abbreviations	**Definition**
Anthropogenic	Caused or produced by humans.
CAD	Computer-aided design is the use of computer software to create, modify and analyze a design.
Chemisorption	A kind of adsorption which involves a chemical reaction between the surface and the adsorbate.
DIY	Do it yourself is a term when something is made by a person(s) instead of being manufactured by a company.
Enzyme	Enzyme is a protein made from amino acids.
EoL	End of Life is a term used to describe the end or the final stage of a products' lifecycle.
Esterification	A chemical process used in biodiesel production to remove free fatty acids (FFA).

Table 2-1 Special terms and abbreviations used in the report cont.

Term and/or abbreviations	**Definition**
EXW	Ex Works is an international trade term meaning buyer is responsible for all costs and risks from seller's place of business.
FAME	Fatty Acid Methyl Esters is the chemical substance formed when fatty acids react with methanol.
FEM	Finite element method is a numeric problem solving method. The method is used by dividing a larger problem into smaller "finite" elements to handle the calculations, and then add the elements again for an equation of the entire problem.
FFA	Free Fatty Acids is a chemical substance formed when waste vegetable oil reacts with methanol.
Filaments	Here: String material used in 3D printing.
Gasification	A chemical reaction converting organic or fossil fuel materials into carbon monoxide, hydrogen and carbon dioxide.
GHG	Greenhouse gas emissions (GHG) is the increase of gases in our atmosphere which affects the greenhouse effect.
Heterogeneous catalysts	Phase of the catalysts differs from the reactants.

Table 2-1 Special terms and abbreviations used in the report cont.

Term and/or abbreviations	Definition
Homogenous catalysts	Phase of the catalysts is the same as the reactants.
Integrated Product Development	Integrated Product Development or IPD is an approach method for handling product development projects.
Phase	A phase is a state of matter, usually; solid, liquid, gas and plasma.
Plexiglas	Trademarked acrylic glass (Poly(methyl methacrylate) (PMMA).
POC	Proof of Concept is the realization of a concept to demonstrate its practicability.
Pugh method	A determination method used as a decision-matrix
Pyrolysis	A chemical reaction using heat. Pyro = heat. Lysis = break down.
R&D	Research and development
SCAMPER	SCAMPER is a thinking process that gives a structured way to develop new ideas.
Transesterification	Chemical reaction used to produce biodiesel for fatty acids and methanol.
WCO	Waste cooking oil
WVO	Waste vegetable oil

Table 2-2. Symbols and units used in the report

Symbol	Definition	Unit
m_{deck}	Mass of deck	kg
$m_{platform}$	Mass of platform	kg
a	Side length of outlet hole in deck	mm
b	Side length of outlet hole in deck	mm
l	Length	mm
h	Height	mm
t	Thickness of deck, platform, steel plates	mm
F	Reactor load on platform	N
F_y	Force in y-axis	N
R_A	Reaction force in A (wheel support with reactor)	N
R_B	Reaction force in B (center support with reactor)	N
R_C	Reaction force in C (wheel support without reactor)	N
R_D	Reaction force in D (wheel support without reactor)	N
$\sum \boldsymbol{F}$	Sum of all forces	N
M	Moment	$\frac{N}{mm^2}$

Table 2-2 Symbols and units used in the report

Symbol	Definition	Unit
$\sum \boldsymbol{M}$	Sum of all moments	$\frac{N}{mm^2}$
r	Radius	mm
d	Diameter for outlet holes in platform	mm
D	Diameter for (rotating) platform	mm
$q_{steelplate}$	Weight of steel plate per square area	$\frac{kg}{mm^2}$
A	Area	mm^2
A_{plate}	Area of plate	mm^2
A_{hole}	Area of hole in plate	mm^2
$A_{platform}$	Area of platform	mm^2
$A_{deckplate}$	Area of deck plate	mm^2
$A_{deckhole}$	Area of hole in deck	mm^2
A_{deck}	Area of deck	mm^2

2.2 Methodology

Work Breakdown Structure (WBS)[9] is used to divide the projects larger tasks into smaller and more defined activities. This method makes it easier to plan and organize the project activity and to keep track of the progress.

2.2.1 Planning

The main objective is systemized into part objectives, and then organized into the project schedule, marked consecutively as milestones (Appendix A:).

The project schedule used is a Gantt chart[10]. In the chart, the activities appear as horizontal bars along a time-axis. The timeline in the project schedule is divided into weeks. Plan schedule is from week 1 to project presentation in week 24.

The Gantt chart consists of:

- What the different activities are
- The estimated time for each activity
- The actual time spent for each activity
- Where activities overlap
- The start- and end time for the entire project
- Milestones (Part objectives)

2.2.2 Integrated Product Development (IPD)

Integrated Product Development (IPD) is a method to streamline production, provide lower lead time and increase learning outcome in product development projects, by including more areas during the development process[11]. The methodology tries to integrate modern computer tools, in addition to the procedures and practices to organize the various development processes[12]. This provides a greater extent in development, when including issues that are important in today’s society. In this thesis, economic and environmental aspects are taken into consideration, in addition to the methodology for the product development processes.

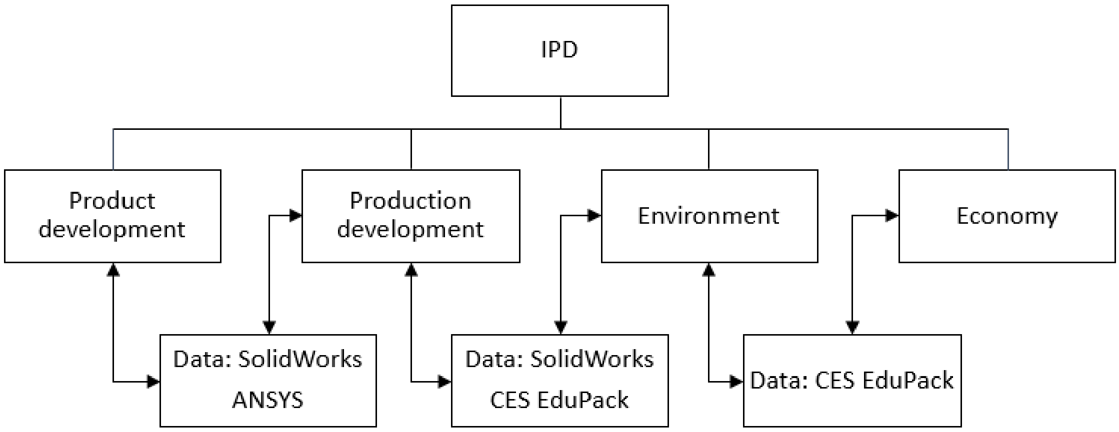


Figure 2-1. Integrated Product Development (IPD). Overview of the project's various disciplines for the development of the reactor system

Figure 2-1 illustrates how data from the various processes overlap. The computer tools that are used for the different IPD areas are described in the relevant processes in the report.

2.2.3 SCAMPER

The acronym SCAMPER (Figure 2-2) is a thinking process that gives a structured way to develop new ideas. The seven letters of SCAMPER each stand for thoughts to have in mind, while brainstorming concept ideas and alternatives.

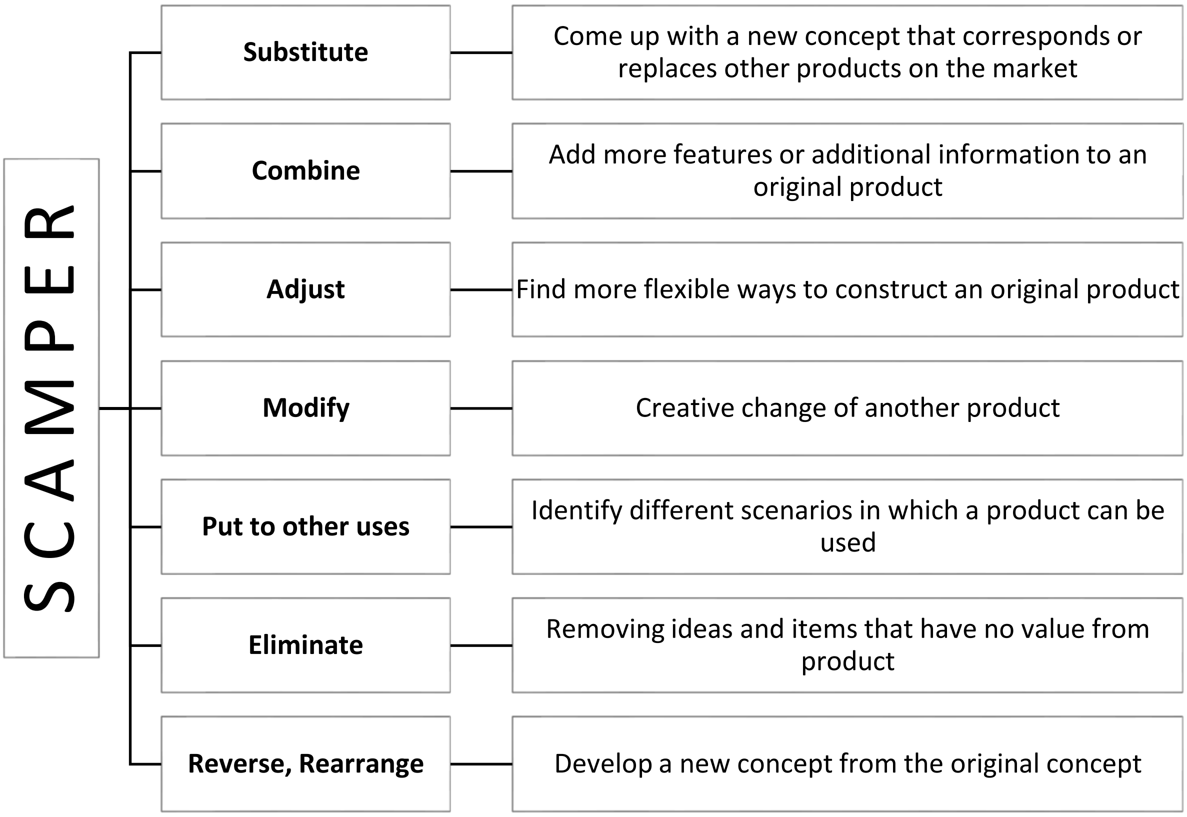


Figure 2-2. SCAMPER explained

SCAMPER is used in chapter 4, to conceive concept solutions by coming up with technological and mechanical alternatives for a similar existing reactor system.

2.2.4 Pugh method

Pugh method is a determination method, used in chapter 4 as a decision-matrix, where three concepts are ranked qualitatively. The matrix' purpose is to indicate which concept solution is the better choice, based on the weighing of the ranked properties. Disadvantages using this method is the natural subjectivity of the rating of properties for the concepts. This could be a pitfall, if the sole basis of deciding the final solution is the results from the matrix. This is considered when using the method, by consulting with the assistant supervisor/client.

2.3 Quality assurance

2.3.1 Report

The report has been proofread multiple times. Table numbering, figures numbering, formula numbering and page numbers are checked numerous times. The template from the supervisor is used for organizing report structure (with some adaptations). Calculations are controlled and a verification is done for the terminology and symbols lists. References are organized with the reference management software and Microsoft Word add-on EndNote[1]. References are examined so that they match with the relevant assertion and that the correct information about the references are given. Specialist literature is found in books, journal articles, reports, web pages, other thesis' and unpublished works from lecturers. Personal communication with experts on relevant subjects are also used as reference.

2.3.2 Product

The concept requirements and specifications are discussed and interpreted in consultations with the assistant supervisor/client at regular meetings. Dialogue with external and internal field experts has been conducted to find suitable parts and components. There is also conducted consultations to find suitable material and price estimates for machining and for manufacture, weldment etc. with the workers at the industrial workshop at RealTek.

[1] EndNote (Version: X7.7.1)

3. Theoretical background

To have a basic understanding of the field of study and to understand the purpose of the developed reactor system, the following chapter will include a review of fundamental theory within biorefining, biofuels, chemical reactors and catalysts.

3.1 Biorefinery

In IEA Bioenergy Task 42 report, a biorefinery is described as a concept, a process, a plant, or one or more facilities which provides the "*sustainable processing of biomass into a spectrum of marketable products (food, feed, materials, chemicals) and energy (fuels, power, heat)"*[13]. This means that a biorefinery uses a wide range of technologies to separate biomass resources, into their building blocks (carbohydrates, proteins, fats etc.), and converting them into beneficial products, energy and chemicals[14].

3.1.1 Biomass, conversion and product outcome

Biomass is renewable and biological materials, collected from natural surroundings or specifically grown for the purpose[15, 16]. Examples of biomass feedstock is sugar/starch crops (e.g. sugar cane/corn), oil crops (e.g. rapeseed, soybean), leno cellulosic (e.g. forestry & agriculture waste) and industrial and societal waste (e.g. sawdust, manure, sludge, food waste)[15].

The conversion technologies used to convert biomass feedstock to products, can for instance be thermal processes (e.g. pyrolysis, gasification), chemical processes (e.g. catalysts) or biotransformation (e.g. fermentation enzymatic catalysis)[17].

The product outcome of the biorefinery can be split into product groups in two categories; energy and products[13]. Energy is heat, power, fuels (e.g. biodiesel) and chemicals, while products is materials, food and feed[18].

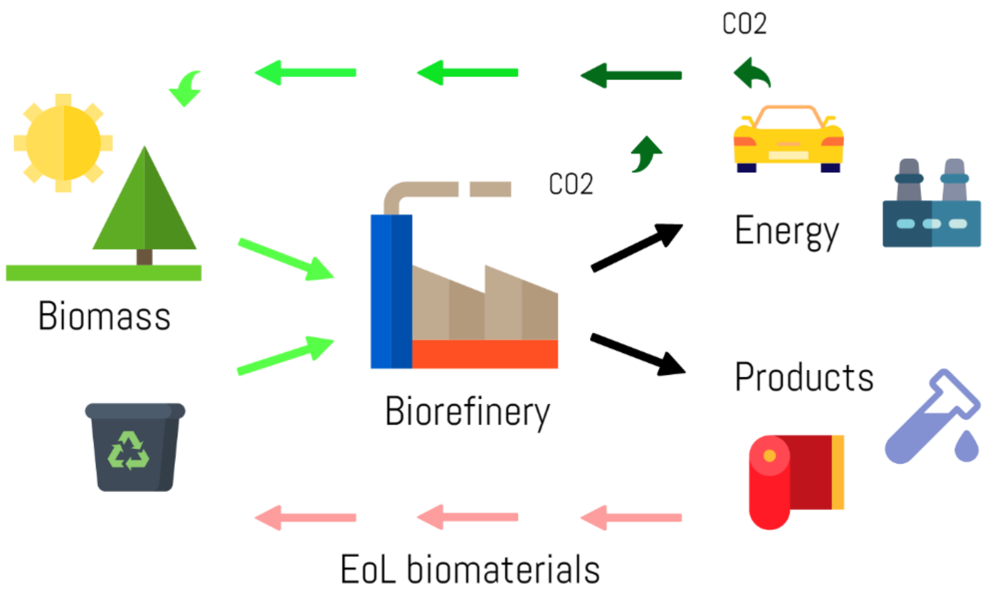


Figure 3-1. The cycle of biorefining from biomass to energy and products

Figure 3-1 illustrates the sustainability of a biorefinery cycle. Biomass goes through the biorefinery process, where it is converted into energy and products. CO_2 from the biomass conversion and by emissions from energy and products, goes back to feed the biomass. Biomaterials at their end of life, get recycled and reused.

In this thesis, the small-scale biorefinery uses waste vegetable oil (WVO) as biomass feedstock. The conversion technology is a chemical process with catalytic material and the product outcome is biodiesel, one of the most common biofuels.

3.2 Biofuels

The decrease of fossil fuel supplies and the growing demand of energy and products, has led to more research within alternative sources for fuel. Biofuels are a renewable energy and a solution to reducing GHG emissions and an alternative to fossil fuels. Biofuel technologies are evolving rapidly, and can be used for various purposes, but the main use has been in the transportation sector[19].

3.2.1 The generations of biofuels

Biofuels are mainly distinguished between two types; first generation biofuels and second generation biofuels, also called conventional and advanced biofuels. The difference between these generations of biofuels is not necessarily the product outcome, but in what biomass they derived from, and the technologies used to convert the biomass[19]. In the late, third generation biofuels have also entered the mainstream[19] and according to D. Tomes the author of the book “Biofuels”[20] a fourth generation biofuels are also progressing.

First generation biofuels are produced from food crops[21]. In a world with hunger and rising food prices, using the same biomass’ which are supplying the food market, has resulted in the “food versus fuel” dilemma[22]. This dilemma indicates and further heightens the importance of the research in possibilities for exploiting waste as biomass feedstock, either on an industrial level or in communities. Waste (waste cooking oil, animal fats, and other waste grease and sludge) is one of these options, being a cheap feedstock and with a large amount available all over the world[14].

Second generation biofuels are an advancement of the first generation, by using non-food crops such as wood, organic waste and specifically grown biomass crops[19, 21]. The only time second-generation biofuels use food crop as biomass, is as waste, when they have already completed their purpose as food.

Third generation biofuels are looking to use specifically engineered sustainable and resource efficient energy crops. Studies have reported oil from algae as future feedstock for producing biofuels[23]. The chemical composition and an extremely fast growth rate has marked algae as a feedstock that can help meet the worlds energy demand[24]. Further R&D is still required before algae fuel can be used on a commercial scale[23].

Fourth generation biofuels are not only looking to use optimized feedstock to produce sustainable energy as third generation biofuels, but also to capture and store CO2[21]. The carbon-rich biomass is then used to produce fuels. By utilizing technologies to capture and use the carbon, not only before, but during and after the biomass conversion, the resulting fuels are not only renewable, but also carbon-negative[21].

Biodiesel started out as a first generation biofuel, but with is now, due to R&D, preferred and generally used as second generation. Together with bioethanol, it is one of the most common biofuels.

3.2.2 Biodiesel

Biodiesel is considered a clean burning alternative fuel produced by renewable resources. The fuel is a liquid produced mainly by the chemical reaction transesterification[25]. This means the process when fatty acids (vegetable oil or animal fat) reacts with alcohol (typically methanol or ethanol) (1).

$$fatty\ acids + alcohol => biodiesel + glycerol \quad (1)$$

The most common alcohol used to produce biodiesel is with methanol, which results in Fatty Acid Methyl Esters (FAME) and the harmless byproduct glycerin (often used in soaps and cosmetics). When using feedstocks as waste vegetable oil, the reaction could form free fatty acids (FFA), which has to be removed or converted to biodiesel by another chemical reaction called esterification[25].

Qualities

Biodiesel can be used on diesel engines with little or no modifications[26] and has therefore been looked upon as a supplement to the transport sector. Figure 3-2 shows the “biodiesel cycle” from feedstock to product.

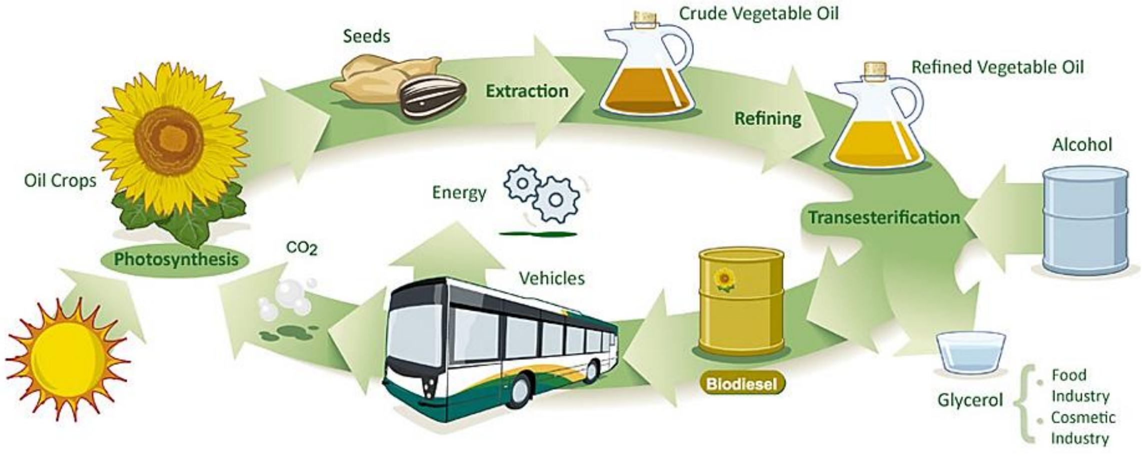


Figure 3-2. An illustration of the biodiesel cycle from oil crops as biomass feedstock and the conversion from oil to biodiesel used in transport[27]

Biodiesel can be used neat (B-100) or mixed with petroleum diesel (referred to as diesel in this report). The use of biodiesel compared to diesel has an overall decrease in gas emissions, but the diesel/biodiesel blend percentage is a big factor on how much cleaner it is (Figure 3-3). The most familiar blend is 20 % biodiesel (B-20)[16].

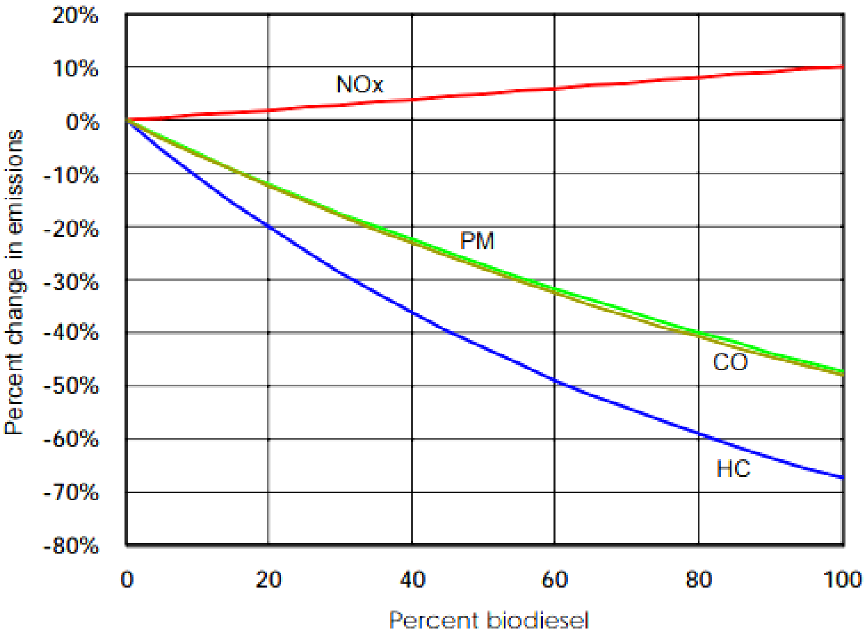


Figure 3-3. Average emission impacts of biodiesel for heavy-duty highway engines[28]

Figure 3-3 shows the average emission impacts of biodiesel for heavy-duty highway engines, with the percent change in emissions on the y-axis and percent biodiesel on the x-axis. The increase of biodiesel in the fuel blend, decreases Particle Matter (PM), Carbon Monoxide (CO), Hydrocarbon (HC) emissions, but increases Nitrogen Oxides (NO_x) emissions.

Studies show that the use of biodiesel leads to reduced engine power relative to diesel[5]. The heating value (the amount of heat released during combustion) is lower in biodiesel, and a key factor for the difference in power[5].

Another disadvantage of biodiesel is being less resistant to cold than diesel[29]. Therefore, in cold climates, it can be a challenge with high blend of biodiesel because it tends to gel (freeze) faster than diesel. The temperature at which biodiesel freezes depends on the type of feedstock it is made of[30].

Feedstock

The first step of biodiesel production is to have feedstock available. An estimate has shown that the cost of feedstock amounts to 75-95 % of the biodiesel production[14]. The production is achieved with various types. Which kind of feedstock depends on geographical position and climate[25]. For example, rapeseed oils and sunflower in Europe, palm oil in tropical countries, soybean in the United States and canola oil in Canada[31]. Also, wherever there is a fast food restaurant, there is waste cooking oil (WCO), which can be used to produce biodiesel. However, as mentioned, there must be made changes in the process procedure due to the presence of water or FFA in WCO.

To manage the technological conversion from biomass feedstock to biodiesel, the biorefinery consists of different types of components. One of the components is the reactor, which is one of the most important parts for a chemical conversion.

3.3 Chemical reactor

A chemical reactor is a vessel designed to contain and control a chemical reaction[32]. A chemical reaction is a process wherein one or more chemical substances react and convert[33]. The substance(s) involved in the chemical reaction is called reactants. The chemical conversion of the reactants, results in one or more products. In this thesis, the chemical reactor is where the biomass feedstock converts into biofuel. The reactor is considered the heart of a chemical process[33].

The design of a reactor depends on numerous aspects, one being the operating conditions – including chemical reactions, chemical energetics, and the equations of thermodynamics[33]. The features which the reactor is designed upon, leads to what type to use.

Two common chemical reactors are[32]:

- Batch reactor (Figure 3-4)
- Continuous reactor (Figure 3-5)

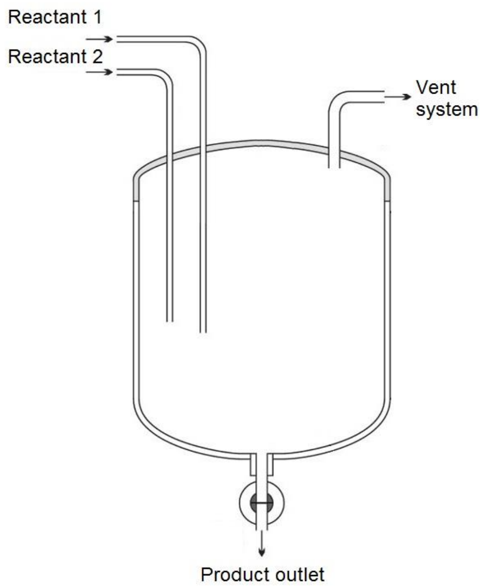


Figure 3-4. Example of a batch reactor. Illustration is edited from source[34]

A batch reactor (Figure 3-4) is most common used in small-scale operations, especially for home use. The vessel tank is filled with reactants, mixed together, sometimes heated for the reaction to take place, then cooled, and after a period of time drained out for further process[34]. A challenge with the batch reactor is that the amount of product produced is linked to the volume of the tank. To increase product, it is also necessary to increase the tank size[35].

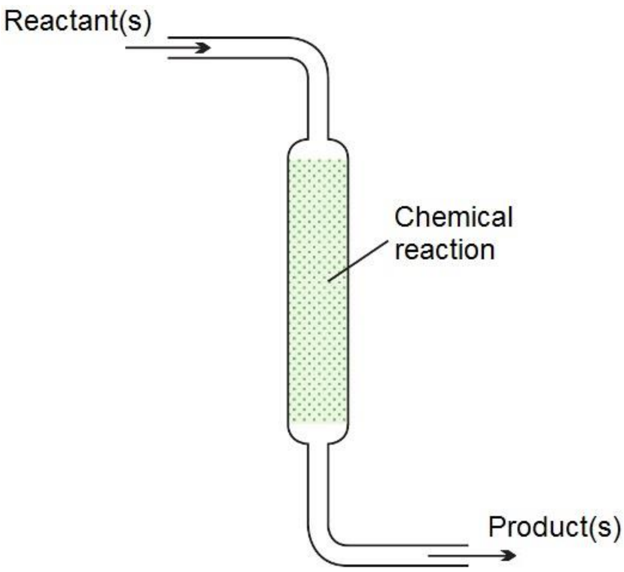


Figure 3-5. Example of a continuous reactor. Illustration edited from source[34]

With a continuous reactor (Figure 3-5), there is no need to increase the vessel to increase production. Here, the reactants are fed continuously at one point into a vessel, where the reaction takes place, and the product(s) are withdrawn at another point[34].

Typical types of continues reactors are:

- Continuous stirred tank reactor (CSTR)
- Tubular reactor (TR)
- Fluid bed reactor (FBR)
- Packed (or Fixed) bed reactor (PBR)

The most common of the continuous reactors is the CSTR. Here, one or more reactants are introduced in the vessel, where a mechanical agitator (impeller) is equipped. The agitator stirs the reactants together and the products are withdrawn. The tubular reactor consists of numerous (often heated) tubular pipes, where the reactants flow through and converts to products. A fluid bed reactor is used with catalysts sitting on a distributor plate, where the reactants pass through and mixes with the catalysts. At another point the products come out. In a packed or fixed bed reactor, either the reactants or the catalysts are solid. Usually the reactants as fluid (liquid or gas), are introduced into the vessel and will flow through or next to the solid catalysts and out at another point as products (Figure 3-6).

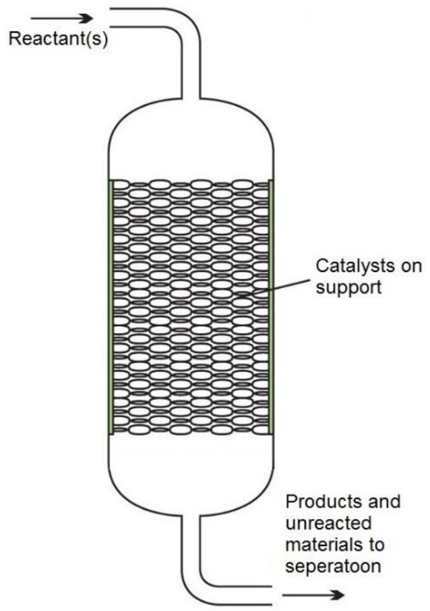


Figure 3-6. Example of a packed bed reactor. Illustration edited from source[34]

Which kind of operation and which phases that are present, determines the choice of reactor. Within the two categories, especially continuous reactors, there are different types and various combinations.

As it appears, reactors and catalysts are regularly mentioned together. The reactors used the reactor system is packed bed reactors, where the catalysts are packed in capsules. With the chemical reactor explained, next subchapter will clarify what part the catalysts have in a chemical process.

3.4 Catalyst

Scientists have done thorough research in the field of catalysts for biofuel production and how they can make the process greener and more efficient. The catalyst has a fundamental role in almost every biofuel production. The following subchapter explains what a catalyst is, commonly used catalysts in a biodiesel production and about heterogeneous catalyst deactivation and handling in biorefineries.

3.4.1 What is a catalyst?

A catalyst is a substance that affects the rate of a chemical reaction[36]. Normally increasing the rate of a reaction, to lower activation energy. The catalyst can only change the speed, not the equilibrium. This makes a shorter reaction time for the process and therefore a greater production capacity[37].

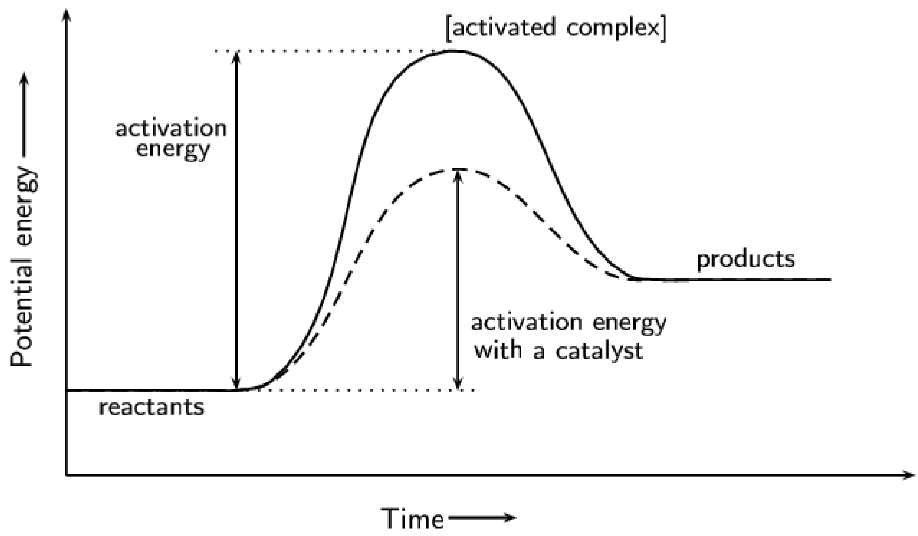


Figure 3-7. A graph illustrating the activation energy in a process with and without a catalyst[38]

Figure 3-7 shows a graph that illustrates the different activation energy required from reactants to convert into products, with and without catalyst involved in the reaction process. This exemplifies the lower activation energy, which is cost-efficient for biorefineries.

3.4.2 Catalysts in biodiesel production

The choice of catalyst is crucial, because it determines the quality of the feedstock, the reaction conditions and the final purification step[14]. As mentioned the catalyst will increase the speed, but which type will also affect the state of the final product. There may be more than one catalyst in a process, especially in larger plants, where there can be several types of catalysts which form and clean the feed to the primary catalyst[39].

Equation (2) shows the reaction of biodiesel production equation (1) including catalyst.

$$fatty\ acids + alcohol \xrightarrow{catalyst} biodiesel + glycerol \qquad (2)$$

The important role the catalysts can have in biofuel production, has led to a comprehensive development of different types of catalysts. The various types of catalyst in biodiesel production are shown in Figure 3-8, and can be classified into three types; homogeneous catalyst, heterogeneous catalysts and catalyst free[40]. Homogeneous catalysts are in the same phase as the reactants and products. Unlike the homogeneous catalysts, the heterogeneous catalyst is in a different phase. As mentioned when explaining the packed bed reactor (Chapter 3.3), most often the heterogeneous catalyst is a solid and the reactants and products are fluid[36].

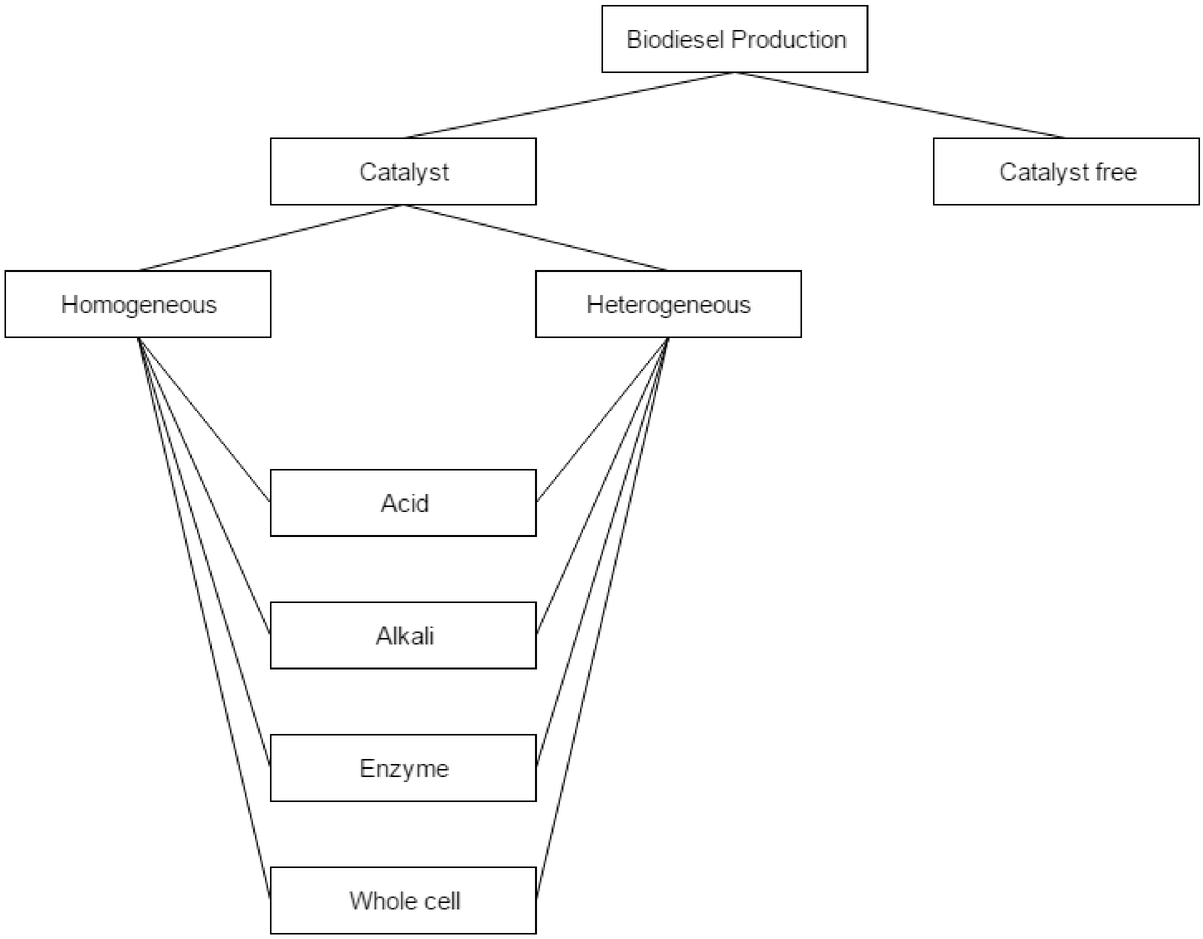


Figure 3-8. Classification of catalyst used for biodiesel production[40]

Within homogeneous, the alkaline (base) catalyst is most commonly used, providing nearly 4000 times faster reaction rate than the acid catalyst[31]. Homogeneous is the most notable catalyst used in biodiesel production, but the heterogeneous catalyst is on the increase[31]. It is now often preferred with heterogeneous catalysts in the industry, because of easier separation from the products and the major advantage of being reusable[41, 42]. Heterogeneous catalysts are on the other hand less specific and allows side reactions[43].

Further development of catalysts has resulted in biocatalyst, enzyme. Enzyme catalysts has the potential of converting FFAs into biodiesel and therefore the ability to use low quality feedstock as biomass[31, 44]. As an alternative to conventional enzymes for production of biodiesel, enzyme based catalysts can be used immobilized[45]. Immobilization means the confinement of an enzyme to a solid support or a carrier matrix[40]. This means the enzyme can be used heterogeneous, and therefore the potential of being reused. The high cost of enzyme has prompted research in the use of bacteria, yeasts and fungi that will serve as whole-cell biocatalysts, based on their immobilization ability and the display of proteins of interest on their cell surface[46].

When using a homogeneous technology in biofuel production the catalyst will be withdrawn with the product to a purification step. The catalyst must be separated from the products, a process which can be very expensive. Heterogeneous catalysts will remain in the reactor while the product is withdrawn. The heterogeneous catalysts can be reused, or changed. It is here the advantage of using the packed capsules, because when emptying the reactor, to pull out a capsule is easier then draining the whole reactor for catalysts.

3.4.3 Deactivation and handling of heterogeneous catalyst

The activity of heterogeneous catalysts will decrease over time and the rate of loss of catalytic activity is called deactivation[47]. According to journal article “Heterogeneous Catalyst Deactivation and Regeneration: A Review” there are six mechanisms of heterogeneous catalyst deactivation; (1) poisoning, (2) fouling, (3) sintering, (4) vapor formation, (5) vapor-solid and solid-solid reactions and (6) crushing. Table 3-1 from the same report, explains the different mechanisms by type and by brief definition.

Table 3-1. Mechanisms of heterogeneous catalyst deactivation[47]

Mechanism	Type	Brief definition/description
Poisoning	Chemical	Strong chemisorption of species on catalytic sites which block sites for catalytic reaction
Fouling	Mechanical	Physical deposition of species from fluid phase onto the catalytic surface and in catalyst pores
Thermal degradation and sintering	Thermal Thermal/chemical	Thermally induced loss of catalytic surface area, support area, and active phase-support reactions
Vapor formation	Chemical	Reaction of gas with catalyst phase to produce volatile compound
Vapor–solid and solid–solid reactions	Chemical	Reaction of vapor, support, or promoter with catalytic phase to produce inactive phase
Attrition/crushing	Mechanical	Loss of catalytic material due to abrasion; loss of internal surface area due to mechanical-induced crushing of the catalyst particle

As seen in the Table 3-1, the mechanisms of deactivation can be classified by the six mechanisms or by type (chemical, mechanical and thermal). The mechanisms mentioned are a general list. The type of process determines which mechanisms will act and in what proportions. For larger plants when catalysts are deactivated, generally you need to stop the unit, isolate from other processes and cool and inert the reactor[48]. After that the catalyst can be unloaded. The process is therefore ordinary shut down, except if the refinery has two lines of reactors (depending on the process)[48]. Catalyst replacement and process shutdown cost industry substantial sums every year[47].

Heterogeneous catalyst replacement methods depend on what type and which scale the refinery is. For small-scale refineries, its usually used manual labor for example by flushing them out or digging them out with safety equipment on. This task can be made a lot easier if only handling extracted capsules filled with catalysts, instead of the whole reactor.

There are various methods used on spent catalyst[49]; One of them is the disposal as landfill. Spent catalyst is regarded as hazardous and has environmental friendly requirements when disposed of. It is also possible to recover metals and other components from spent catalyst. This happens either by leaching the catalysts with acid or base, or heat treatment to separate metals. If only possible to partially recover the catalysts, the remaining portion must be treated or disposed of by other methods. Another option is to utilize the spent catalyst to produce other products. If possible, the preferred method is to clean, rejuvenate and/or regenerate the deactivated catalysts for reuses[47, 49]. These methods will extend the length of catalyst service and therefore minimize the environmental problem occurring with spent catalysts.

The idea of periodically washing the catalysts in the reactor, will increase the activation time by reducing the relevant mechanisms of deactivation affecting the heterogeneous catalysts.

4. Concept descriptions

This chapter includes specifications for reactor and reactor system and discussion of concept solution. The choice of temporary solution is used as basis to develop alternatives for the reactor system in the initial design.

4.1 Specifications

The specifications are divided in two categories:

1. The process: Use of "capsules" filled with heterogeneous catalytic material (thermochemical or biological) in a biorefining system for easy and periodically clean of the catalytic material.
2. The design: The reactor system is to be dimensioned for a small-scale biorefinery

Further explanation and details is presented in each subchapter.

4.1.1 Process specification

Table 4-1 shows the case given in consultation with assistant supervisor[50]: The biorefinery process is to use waste vegetable oil and methanol in a continuous reactor with immobilized enzyme to produce biodiesel. The max temperature of both process and de-oil/on-site wash is 60 °C and max pressure is 3 bars. Clean methanol is used as fluid to periodically clean the catalytic material. Further in the report, the two processes are distinguished between *process* for biodiesel production and *de-oil/on-site wash* for the process of cleaning the catalytic material.

Table 4-1. Process and on-site wash specification of the low temperature reactor system

Process	
Mode of operation	Continuous reactor
Reactants	Waste vegetable oil Methanol
Catalyst	Immobilized enzyme
Product	Biodiesel
Temperature	max 60 °C
Pressure	max 3 bar
De-oil/On-site wash	
Fluid	Methanol
Temperature	max 60 °C
Pressure	max 3 bar

4.1.2 Design specification

Table 4-2 shows approximate values for the reactor and reactor system. The dimensions are used as guidelines in the initial- and final design.

Table 4-2. Approximate reactor and reactor system dimensions

Reactor				Reactor system		
Measure	Minimum	Maximum		Minimum	Maximum	Unit
Depth	150	350		1100	1500	mm
Width	150	350		1100	1500	mm
Height	450	500		1200	1500	mm
Volume	10	15		1452	3375	l
Weight	15	25		-	-	kg

There are no external components to take into consideration when building the reactor system[50].

4.2 Concept discussion

The idea of the concept is to have two packed bed reactors. One being connected and operational, while the other reactor is being handled. Periodically, the reactors switch roles. The reactors consist of capsule(s) packed with heterogeneous catalysts. When a reactor is handled, it means washing of catalyst by de-oiling with clean methanol, complete change of catalysts by removing capsule(s) or other maintenance of the reactor. It’s assumed that it is not necessary with more than two reactors in the system. There are no requirements of around the clock use, and with two reactors it should be enough time to treat one of them, before they switch operation.

A similar existing solution of this concept, is to have two reactors in parallel[48], as illustrated in Figure 4-1. In this case, it would mean a system composed of reactors which has two inlets and two outlets each. The one pair of inlet and outlet on the reactor is for the process and other pair of inlet and outlet is for the wash. Valves regulate which tubes is open where, and thereby which reactor is producing biodiesel.

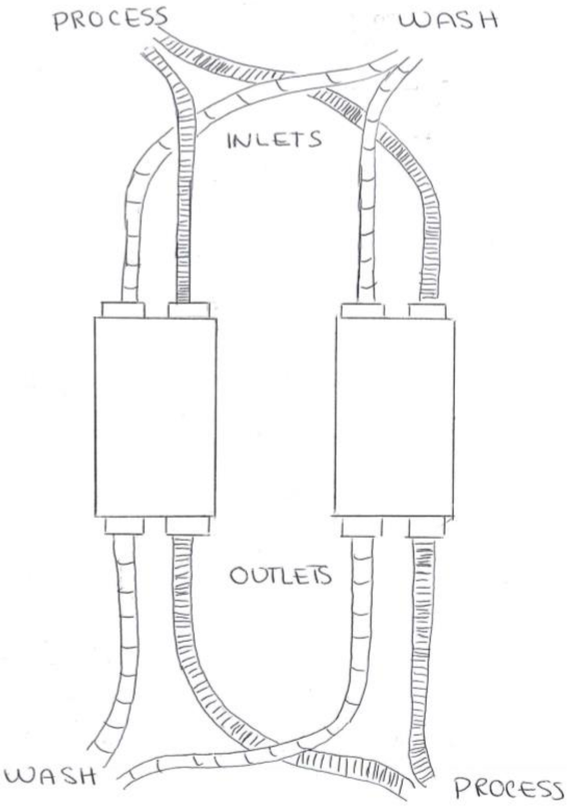


Figure 4-1. Sketch of parallel reactor system with valves regulating which reactor has an open flow to the process and for the wash.

To have the reactor system built this way with two lines of reactors, one reactor can always be active while the other reactor is connected for wash or disconnected for maintenance or change of catalyst. The system has few mechanical parts. The issue is more inlets and outlets for the reactors and more tubes which causes more difficult maintenance[50]. Less inlets/outlets can make a smaller reactor and easier uniform distribution of reactants to catalysts. There may also be more components in the way, when there is need of change of catalysts.

4.2.1 Solutions

S.C.A.M.P.E.R is used to evaluate the mentioned parallel reactor system in Figure 4-1 and come up with a new solution. Substituting the already existing system and adding technological and mechanical alternatives instead of the process engineered solution, resulted in these two main concepts:

A. Static reactors with mobile tubes
B. Mobile reactors with semi-static tubes

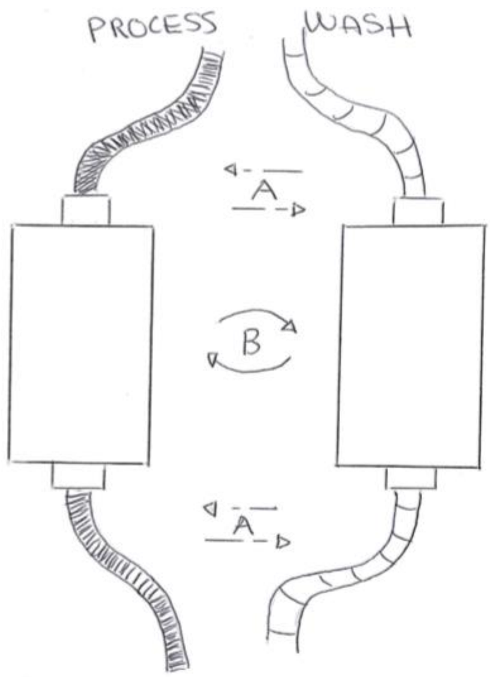


Figure 4-2. Sketch of simplified reactor system illustrating concept A and B.

The ideas are mainly having the reactors switch places or the coupling with tubes switch places - depending on which reactor is operational and which reactor is to be washed. Each solution can have various operating methods. These two options are practically the same as the parallel reactor system, but with these options other functions can be added and the capsuled design reactors may be more suitable.

Concept A: Static reactors with mobile tubes

Concept A is composed of two reactors with one inlet and outlet each. Periodically or when a sensor notices the operational reactor’s catalysts need handling, the valves on both the operational and the standby reactor will close, disconnect and exchange, so that the process tubes will attach to the reactor on standby, and the wash tubes will attach on the former operational one (Figure 4-2).

Concept B: Mobile reactors with semi-static tubes

Concept B is composed of two reactors with one inlet and outlet each. Periodically or when a sensor notices the operational reactor’s catalysts need handling, the valves on both the operational and the standby reactor will close, disconnect and a system will move the reactors until they have changed position (Figure 4-2). The valves will then reconnect to the other reactor.

4.2.2 Decision

A set of properties included to elaborate the weighing (rate) of the concept, is used in the Pugh decision-matrix (Explained in chapter 2.1).

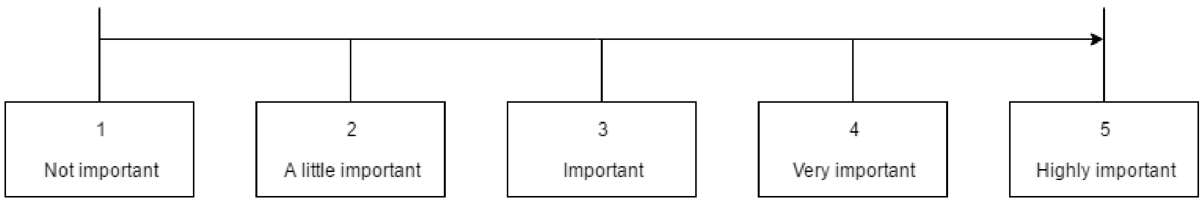


Figure 4-3. Rating definition

The rating of the properties is from 1 to 5 (Illustrated in Figure 4-3).

The properties are listed in Table 4-3, where a property description, rating and a reasoning for the rating is presented:

Table 4-3. Ranking of concept properties for the Pugh decision-matrix

Properties	Description	Rate	Reason
User-friendly	Practical and automatic	5	Highly important for the reactor system to be convenient and usable
Innovative	Original and advanced	5	Highly important as a part of the assignment is to develop a new method for a more cost-efficient reactor system
Production	Few and simple parts to produce	3	Important to lower the fixed cost
Assemble	Easy to install with refinery	2	A little important since there are no other refineries to install with yet, but it must be kept in mind when designing
Design	Here: Aesthetics	1	Not important as the biorefinery will be used at decentralized areas where practicality is the most important
Cost	Low costs	4	Very important if the reactor system should be profitable
Size	Low weight and small dimensions	3	Important for easy transport and save of space
Maintenance	Easy to maintain	3	Important for prolong lifetime
Lifetime	Durability	4	Very important to be long-term profitable
Green	Environmental aspect	5	Highly important that the reactor system is an environmental friendly solution

The existing concept (marked as X in Table 4-4), which the ideas of concept A and B derives from, is included for comparison. Concept X, A and B, are given a score with a scale from - to +. If the product is perceived as neutral, it will score 0. The weighing is then multiplied with the related rating of the properties and summed together to a final score for conclusion.

Table 4-4. Pugh matrix for selection of concept solution

Properties	Description	Rate (1-5)	Concept X	Concept A	Concept B
User-friendly	Practical and automatic	5	+	0	+
Innovative	Original and advanced	5	-	+	+
Production	Few and simple parts to produce	3	+	-	0
Assemble	Easy to install with refinery	2	+	-	+
Design	Here: Aesthetics	1	0	0	0
Cost	Low costs	4	+	-	-
Size	Low weight and small dimensions	3	+	0	0
Maintenance	Easy to maintain	3	-	0	+
Lifetime	Durability	4	-	0	0
Green	Environmental aspect	5	0	0	0
	Total +		5	1	4
	Total -		3	3	1
	Total score		2	-2	3
	Total weighted +		17	5	15
	Total weighted -		-12	-9	-4
	Total weighted score		**5**	**- 4**	**11**

Concept A requires a lot of space, and a lot of complexity because of more moving couplings to be engaged and disengaged to the reactors. This will also result in a more advanced electronic control system to synch the tubes with the reactor. Concept B scores highest in the weighing in the Pugh's matrix with 11 points, contra Concept A's -4 points. As explained in method description chapter 2.1, subjectivity can influence the rating of properties and result of matrix. When discussing the two solutions with assistant supervisor, Concept B is still preferred, and with these terms it will be further developed.

4.2.3 Concept

An illustration in form of a hierarchy diagram, illustrates the primary, secondary and tertiary functions of Concept B (Figure 4-4). The primary function for the reactor system is to be a platform for the reactors. The secondary function is being a platform for reactors to operate by having an active (biodiesel operational) reactor and an inactive reactor for catalyst handling (wash or change) or maintenance. When catalyst handling is done, the reactor is on stand-by until the switch of reactors takes place. Reactor switch is the tertiary function. This means disconnecting the tubes from reactors, switching places, and then connecting reactors with the other tubes.

The reactors are mounted on a platform, which rotates and makes the reactors switch. The operational and the stand-by reactor must be disconnected from its tubes and connected when rotate is complete. This will happen periodically by time limit decided by user or optionally notified by a sensor when in need of handling or maintenance.

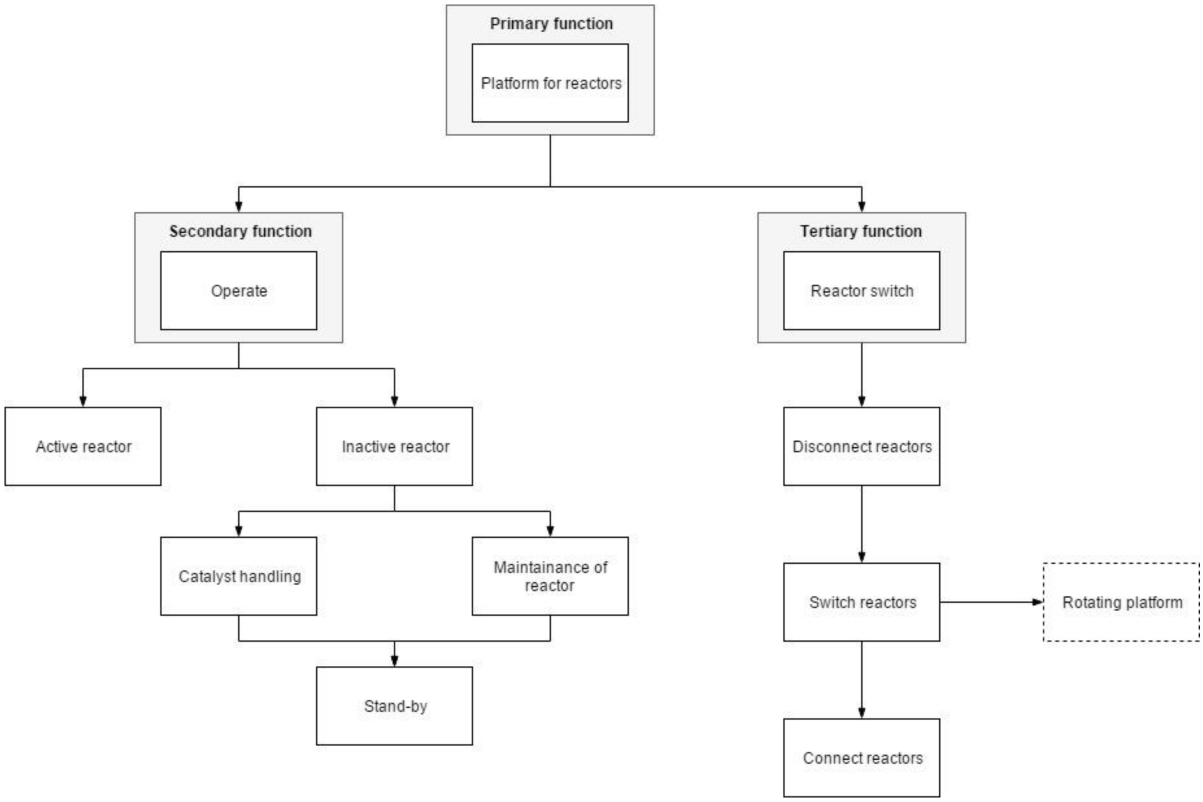


Figure 4-4. Reactor system's functional analysis hierarchy

The focus of the reactor system development will be the reactor switch. Both primary and secondary function can be carried out and completed by constructing this “rotating platform”. By assessing the problem, the main challenges for this concept to have in mind while developing is;

- Coupling system to the reactor(s) and the construction of attachment rigs for coupling systems
- The importance of precise rotation of the platform
- Reactor outlet to not interfere with the rotating platform

5. Initial design

As the main solution for the concept is chosen, next step of the process is to come up with alternatives for the reactor system. To simplify the system, it is separated into the subsystems and structures listed under:

- Reactor(s)
- Housing
- Rotating platform
- Coupling system

The reactor system will have two reactors mounted on top of a rotating platform. A drive system will rotate the reactors periodically. When the reactors are to rotate, a coupling system will close and disengage from the inlet and outlet, and engage again when the reactors have rotated 180 degrees. The reactor switch is complex and the most critical part of the reactor system wash. A motion control system is of great dependence, making all the parts interact precisely. There are no requirements for the turn speed of the rotating platform.

Gunnar Torp, engineer and responsible of the industrial workshop at RealTek, was consulted for the choice of materials and profiles for the structure and rotating platform and welding of framework[51].

5.1 Reactor(s)

The two reactors used in the reactor system are packed bed reactors for heterogeneous catalysts.

5.1.1 Draft

The reactor shown in Figure 5-1 are based on the reactors from the “Bio Max” project. The current capsule design for catalysts are in an early developing stage.

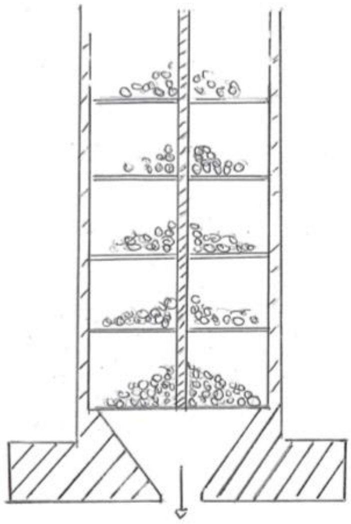


Figure 5-1. Section view sketch of reactor with six capsules

This reactor alternative has multiple capsules packed with catalysts, stacked on top of each other (Figure 5-1). The capsules are either perforated at the bottom or hold a perforated plate to keep the solid catalysts in place, but let the reactants channel through. A steel rod goes through the center of the capsules and has a plate attached at the bottom. When the catalysts need to change/regenerate, the lid is opened and the rod is used to drag the capsules up from the reactor. Another possibility for the change and maintenance of catalysts is to have an opening on the side of the reactor. When the catalysts need to change and/or regenerated, the hatch on the side opens and the capsule(s) gets taken out of the opening and replaced (Figure 5-2). For the handling in this design it may be advantageous to have one large capsule instead of multiple smaller ones.

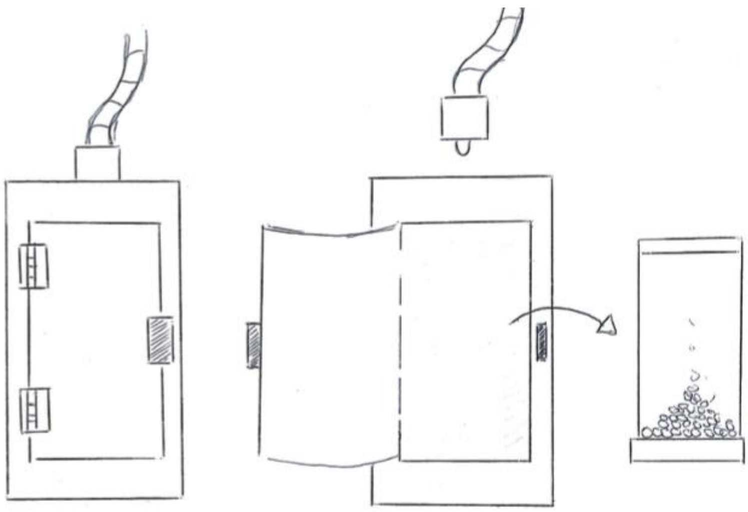


Figure 5-2. Alternative reactor design – "hatch reactor"

Further in the report the reactor based on the “Bio Max” reactor is referred to as six-capsuled reactor. Modifications to fit in with the reactor system must be made, but the general idea of having six capsuled stacked on top of each other is the same. The alternative design with the one capsule, is referred to as the hatch reactor.

Since the arrangement that rotates the platform is under the reactors, it could be beneficial for the rest of the design to have the outlets on the side (Figure 5-3). This would create an easier access to the attachment of the coupling, valves and tubes. The outlet would not interfere with the rotating platform, and therefore the rotating platform would also be easier to design.

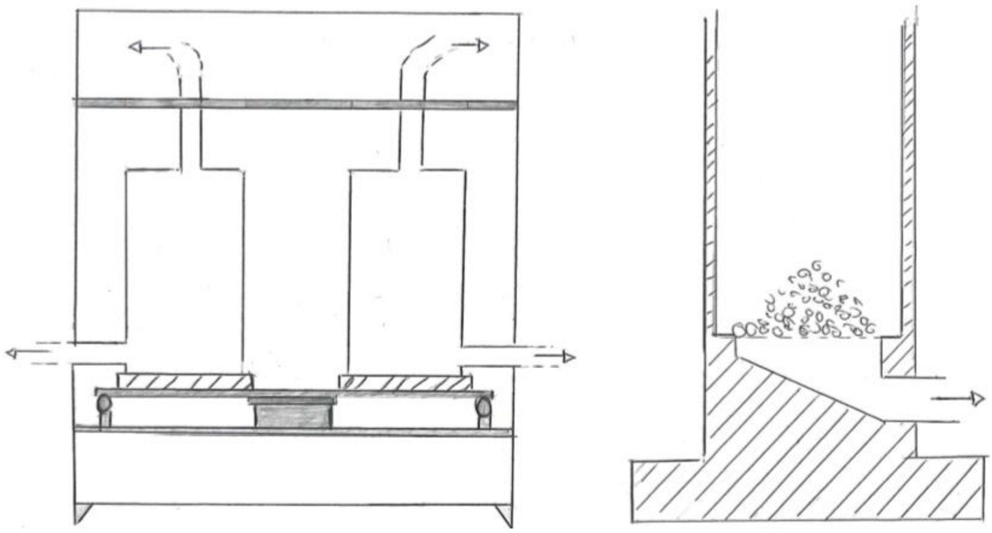


Figure 5-3. Sketch of reactor system with horizontal outlet, and detailed section view of reactor

It is important that the coupling system under the reactor has enough space for its arrangement, but because of the pressure drop in the process[50], the outlet will be placed on the bottom of the reactor (Figure 5-4). Having the outlet on the bottom means that both the inlet and outlet will have a vertical motion for the coupling engage/disengage. This is advantages for the design and development of the coupling system.

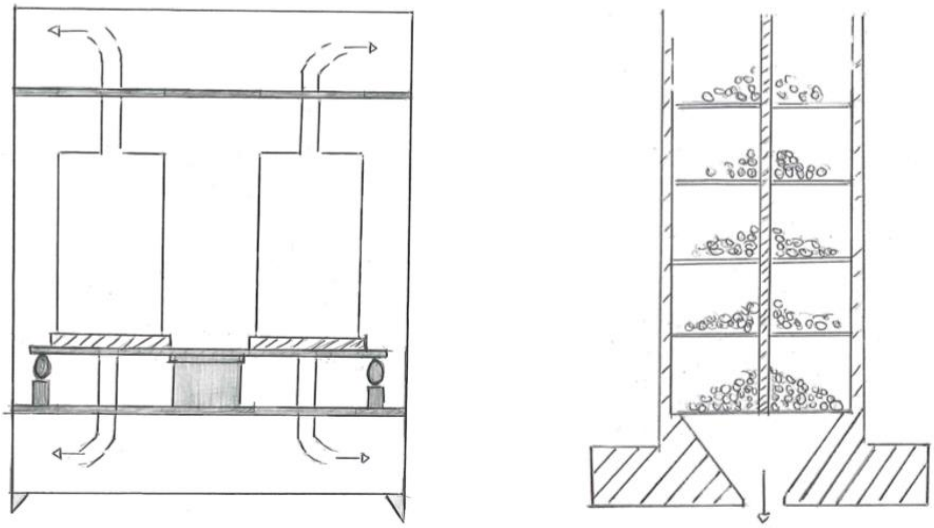


Figure 5-4. Sketch of reactor system with vertical outlet, and detailed section view of reactor

5.1.2 Materials

The material used for the "Bio Max" reactor prototype was Plexiglas. The team had bad experience with using this polymer for reactor parts. Since Plexiglas (Polymethyl methacrylate Acrylic, PMMA) is not recommended, it is done a comparison with three other materials assuming the reactors will still be built with polymer material. Because of the advancement in 3D printing, the reactors can also be designed in metals[52]. This manufacturing method of chemical reactors can be used for design of detailed inside structures of the capsule reactors. Since the reactors in this thesis is a low-temperature reactor system the quick analysis is done with polymer parts. These three promising polymers are Polypropylene (PP), Polycarbonate (PC) and Polymides (Nylon, PA).

Material properties are found in CES EduPack[2] in database level 1. The four materials are compared in a chart (Figure 5-5) with price (NOK/kg) as X-axis and maximum service temperature (ºC) as Y-axis. The red line indicates the 60 ºC maximum temperature from process specifications in chapter 4.1. PP (Green), PC (Blue) and Nylon/PA (Red) are above the red line, except Plexiglas (Grey), meaning it will change its properties because of applied

[2] CES EduPack 2016 (Version: 16.1.22.0)

heat over its maximum service temperature (Something the "Bio Max" team already experienced[53]).

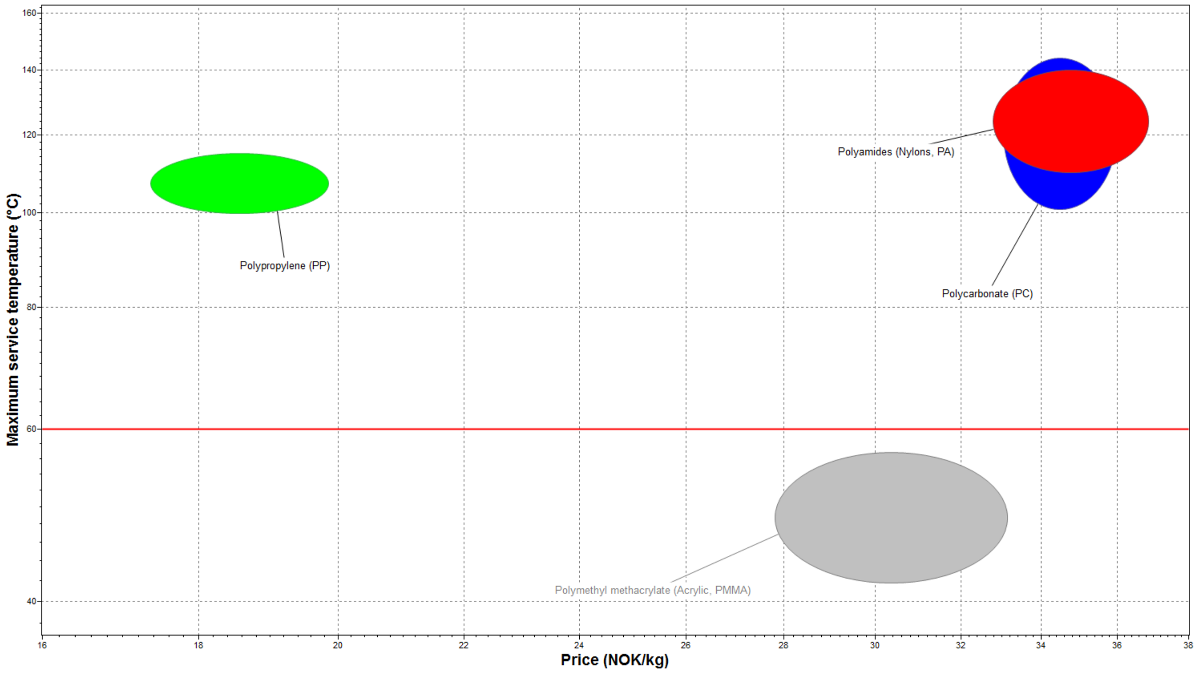


Figure 5-5. PP, PC, PA and PMMA compared in price (NOK/kg) and maximum service temperature (ºC)

All three materials display mechanical- and thermal properties which are required for the reactor, but the chemical properties must be tested to be sure that the material chosen is resistant to the substances in this reactor system process. They have all the ability to be translucent, some even transparent, which is favorable. When it comes to the price, PP costing about 17-20 NOK/kg, is cheaper than PC and PA, both costing about 32-37 NOK/kg. As the reactors are very expensive, cutting costs where you can, is important. The manufacture of the reactors is often where the highest cost comes. The materials can also be molded or extruded as to 3D printed.

5.2 Housing

The housing is the structure of the reactor system. It is viable to have an easy access to the components and that the reactor system functions have space to operate. The housing should be inexpensive and rigid. The framework will consist of two levels (Figure 5-6). Upper level is for the deck foundation to hold the rotating platform with the mounted reactors. The lower level is for holding other components and equipment.

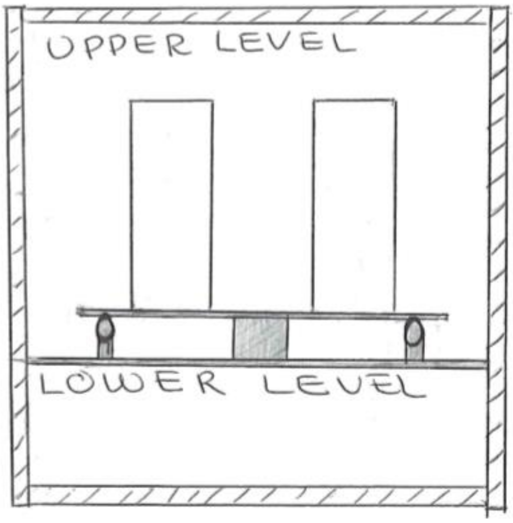


Figure 5-6. Sketch of housing arrangement

Since the rest of the biorefinery for the reactor system is not yet finished, the housing is built in a way that it can easily be integrated with the rest of a refinery.

5.3 Rotating platform

The rotating platform is a subsystem that will periodically rotate 180 degrees, switching the two reactors between process and wash of catalysts. The rotating platform consists of a circular platform for the reactors, and a drive system, which provides the rotating energy to the reactor platform. Literature from car turntables and other turntable projects, has been reviewed to construct the rotating platform.

There are basically two main options for how to design the rotating platform. Which option is used, will have a large impact on how the rest the of the reactor system is constructed. These options are:

1) Buying off-the-shelf motorized rotary stage, as a single solution.

2) Designing own rotation mechanism using motor, possible gear and transfer

Option (1) can cost more, but in return the drive system is specifically made for the job of rotating objects. Buying off-the-shelf, results in quality components giving long-term performance and good rotating accuracy. Rotary stages are made robust, and therefore the rotational platform may need less or no supports, resulting in fewer parts. Also, these solutions often come with matching control motion systems.

Option (2) is not guaranteed to cost less, but possibly cheaper, depending on the cost of the different components and hardware. The components used can also be easier manufactured by engineering them yourself or gathering the parts needed, having an available workshop. This option can therefore be favored for a DIY biorefinery. The disadvantage is the needed coupling arrangement to complete the reactor system. The rotation and reactor switch needs to be in sync with the coupling-connect and disconnect, and therefore requires a precisely synchronized control. A possibility is to have a DYI rotating platform, while the rest of the components, here: coupling system, is bought finished manufactured.

5.3.1 Drive system

The drive system is one of the most significant component of the reactor system. Without the drive system, there will be no force to rotate the platform. It is important that the position of the drive system does not obstruct the coupling system by the reactor outlets. Since the coupling system must be perfectly aligned when the platform has rotated, it is crucial that the drive system has a precise angular accuracy. If it not rotates precisely 180 degrees, either the coupling parts or the reactor inlet/outlet risks damage.

As mentioned, there are two main options.

Option (1) is buying off-the-shelf rotary stage, and attaching them under the center of the platform. The rotary stage is motorized and is made to precisely rotate light to heavy objects. There are various suppliers of this type of option.

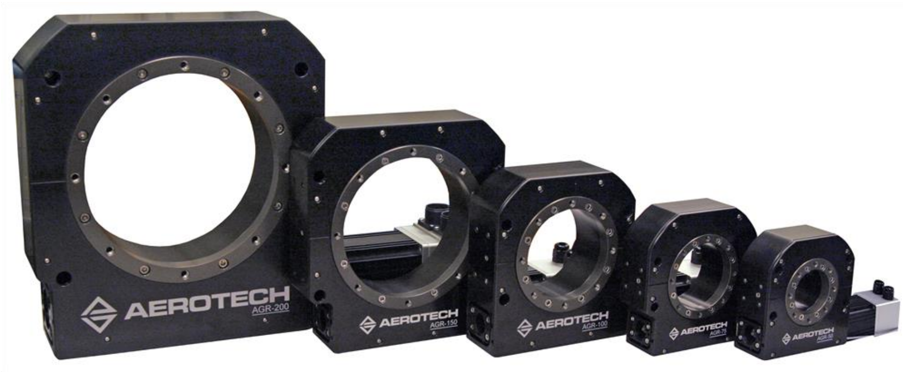


Figure 5-7. Aerotech Mechanical-Bearing Gear-Drive Rotary Stage

Figure 5-7 shows different sizes of rotary stages which can be used to different loads.

Option (2) is the design of a drive system with the components needed to rotate the platform. This option is versatile, but can be more comprehensive. The drive system usually consists of a motor, gear and transfer. A review of some promising alternatives for the drive system follows.

Motor:

A motor is essential to power the drive system. Of combustion motor and electric motor, the focus will be on the latter. Using a combustion motor would serve if running on biofuel, making it self-sufficient, no need of external power source and be fully off-the-grid. The negative part of depending on fuel, is the need of periodically filling the motors to run. A combustion motor makes more noise, but this would not be a problem considering the reactor system has no requirements concerning sound. Since this task is not requiring large amount of power, an electrical motor will be sufficient, based on lower initial cost, continuously power supply, and an easier motion control.

A stepper motor is used when position must be precisely controlled[54]. As describes in the name, a stepper motor rotates in steps. Depending on design it can advance 90°, 45°, 18° or even as low as a fraction of a degree per step[54]. A common stepper motor can rotate 1.8° per step. This would mean 200 steps per revolution or 100 steps to rotate 180°, the wanted rotation for the reactor system.

Gearing:

Gearing can be required to gear down the power output from the motor to a usable level, before being transferred to the rotating platform. Gearing can be done either by buying a ready assembled gearbox off a components catalogue and attach it to the motor, or fabricate and design using spur or other simpler gearing components bought from various engineering catalogues. Since there are no specifications of the turning speed of the platform, depending on the motor, gearing may not be required.

Transfer:

The drive/transfer component is the system that will transfer torque and rotational energy from the motor/gear, to rotate the platform. There are many different drive components to choose from. For the rotating platform they can be divided into two categories, based on where the rotation of the platform is driven from[55]. The first category is the drive components rotating the platform by its rotational axis. The drive components reviewed in this category is a belt-, chain-, and a shaft drive (worm and bevel drive).

An example of a belt drive is shown in Figure 5-8. A motor rotates a central shaft and the belt surrounds both the shaft from the motor and the platform, making the platform rotate by friction.

Figure 5-8. Example of the use of a flat belt drive in a Philips turntable[56]

Most important types of belt drives are the flat belt and v-belt (with multiple subtypes), then toothed belt among others[57]. The main difference being the increased friction when using v-belts or other belts with a larger contact surface area. An advantage with the belt drive is that they are inexpensive, even when the distance between the shafts is large. A disadvantage is the risk of too much slack, which can result in slip and disengage[55]. Chain drive is like a belt drive, but there is no dependence on friction and therefore no need for pre-tension. A disadvantage with the chain drive is the added weight of the chain relative to a belt. There would also be need of lubrication[55, 57].

The next transfer component review is a shaft drive. A shaft drive transmits rotational energy between two intersecting axes. The difference between shaft drives is usually the gear type and arrangement. A possible design for the rotating platform is a solid bevel drive shaft from the motor to a gear system that turns the rotation 90 degrees to a driving shaft, which then rotates the platform (Figure 5-9). In this illustration, the type of gear is spiral (hypoid).

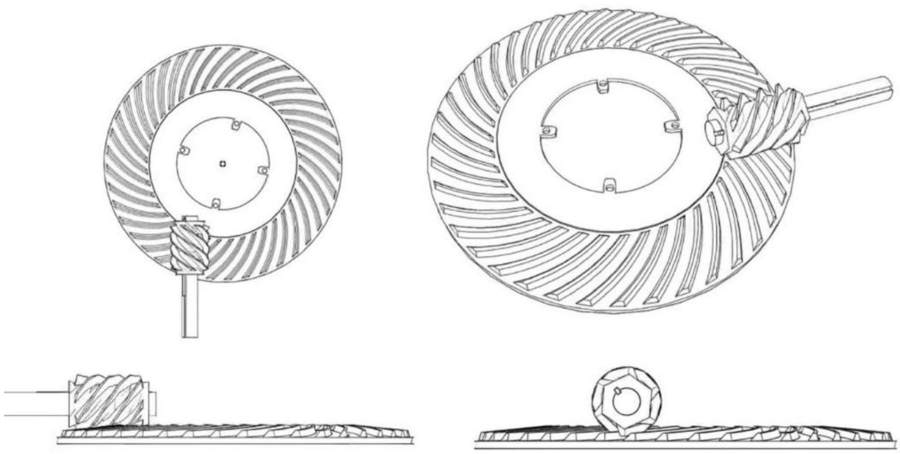


Figure 5-9. Shaft drive with a hypoid gear arrangement[58]

Another possibility to rotate the platform is using a worm drive. This type consists of a cylindrical gear shaped as a screw, which connects with the worm gear (resembling regular spur gears) (Figure 5-10).

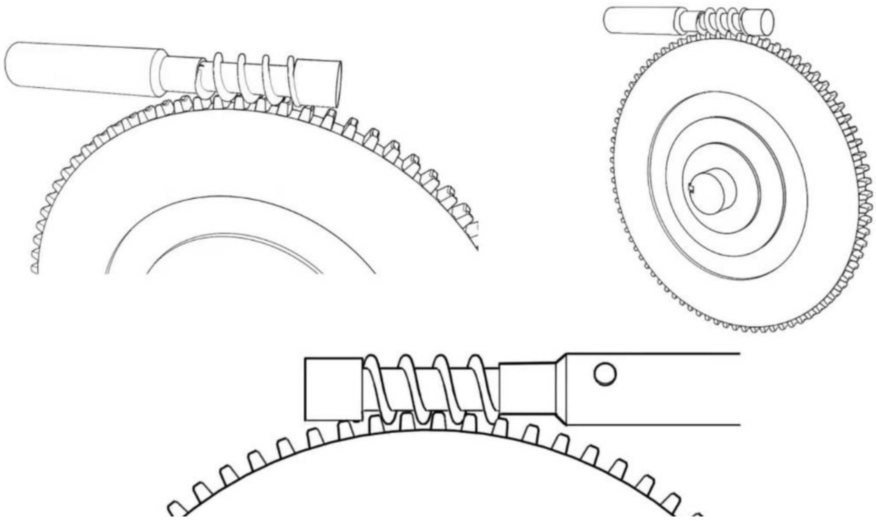


Figure 5-10. Shaft drive with a worm gear arrangement[58]

Worm drive operates silently and smoothly, but worm gear materials are often expensive[59]. For the rotating platform, it can be used as the model in Figure 5-11.

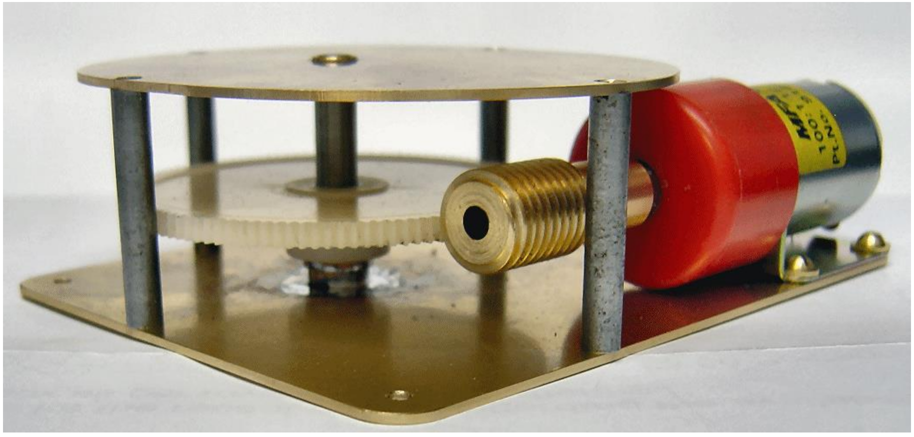


Figure 5-11. Example of the use of a worm drive on a turntable[60]

The second transfer category is to drive the platform from other places than its rotational axis. The alternative that will be looked at, is driving the platform by friction under the platform as shown in Figure 5-12. As mentioned the drive system must be placed so that it will not interfere with the reactor outlets. A drive system under the center of the platform could be too close to the outlets, and a larger diameter of the platform would be necessary to make room. To avoid this, and for an easier maintenance of the drive system, the transfer could be placed at the bottom surface on the outer edge of the platform. Another possibility is driving the platform by the edge. This would require an external horizontal force, which will not be needed by placing the drive under the platform, since then the weight of the reactors and platform can be used instead. Another reason to not set the transfer on the platform edge, is that the assistant supervisor would like to exploit the height when building the reactor system rather than width[50]. By driving the platform from underneath, it is easier to build the rest of the reactor system smaller in width.

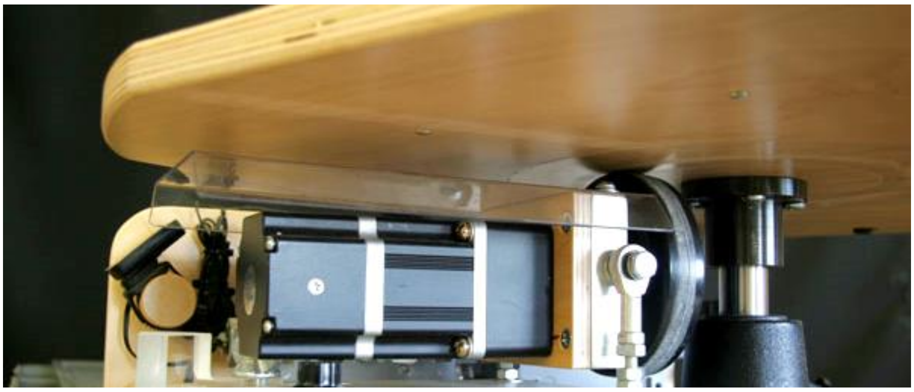


Figure 5-12. Example of the use of a drive wheel rotating the platform from underneath by friction

As seen in Figure 5-12, the drive wheel which rotates the platform, along with the motor, can be positioned other places than close to the center bearing. Choosing final drive system will depend on required torque and what's most beneficial compared to the rest of the platform arrangement. The platform requires not only a drive system to start the rotation, but also an extremely accurate stop, to align the reactors in correct positions for the tubes to connect. This must be considered when choosing a drive system.

5.3.2 Platform and supports

The platform supports the reactors and there must be room for the reactor outlets. Since the reactor outlets are at the bottom, there must be holes in the platform and space enough for the coupling, valves and tubes to exit the reactor. Initial design of platform is a circular platform with a diameter of 1200 mm, with two circular holes with a diameter of 200 mm. The platform will be having a thickness of 4 mm and be made of steel.

The supports arrangement depends on Option (1) or Option (2) as a solution.

Option (1) has, most likely, no need of supports since they rotary stage in the center is built to have a maximum load capacity larger than the maximum load of platform and reactors. If the platform would turn out to not be stable enough while rotating, a possibility is to attach wheels, surrounding the platform as explained in Option (2):

Option (2) is supported by wheels on the outer edge of the rotating platform and one center support with a roller bearing. The purpose of the wheels, other than being supports, is to minimize the negative effect on the rotational energy and stabilize the platform. The wheels could be fixed or castor wheels (Figure 5-13).

Figure 5-13. Fixed wheel (left) and castor wheel (right)[61]

The advantage of castor wheel, is that they orient themselves with the movement direction, and then they would be easier to mount. Disadvantage is that they are harder to fabricate yourself and cost more than fixed wheels (not much). Using wheels support, they should be mounted to the deck with the wheels pointing upwards. The platform bottom surface is smooth, and by doing this the wheels will not interfere with any unwanted elements laying underneath the platform. To keep the platform from moving out of its place, there is a centralized support with a bearing, bolted to the platform from underneath. When the platform is bolted, it is fixed and can only rotate with the center support (Figure 5-14).

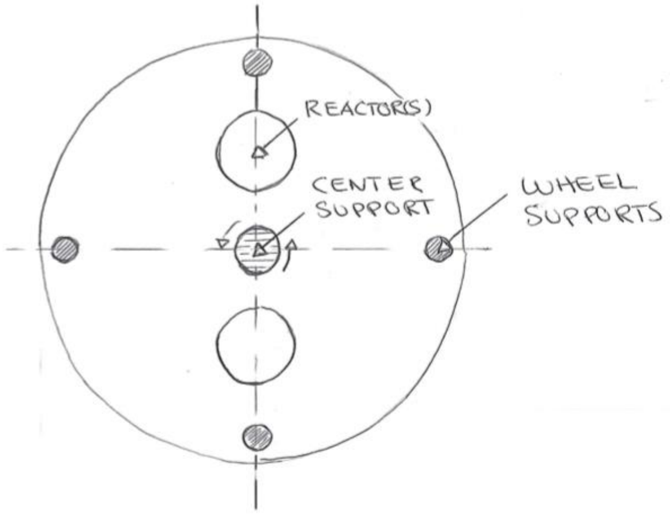


Figure 5-14. Sketch of rotating platform for Option (2) including center support, wheel (outer) supports and reactors

5.4 Coupling system

The tubes of process and wash must not only statically be connected to the reactors, but must be able to disengage when the reactors are to rotate, and engage again when they have changed position. This can be done by a subsystem, which will be programmed and in sync with the rotating platform, so that both operations will happen at the same time and in the right order. This subchapter will propose a promising solution to the motion and coupling to the reactors.

5.4.1 Motion

The motion that is required to move the tubes/valves is a linear, vertical positioning in and out of the reactor inlets and outlets. Since the reactor in wash position can have its tubes disconnected for handled etc., while the other reactor is connected and operational, it is required to have four individually motioned coupling systems.

Possible methods for the disengagement and engage operation is to use hydraulic, pneumatic, electric or other mechanical solutions. An actuator is a component that uses these technologies, to move or control a mechanism or system.

To generate motion[62]:

- pneumatic actuators use compressed air
- hydraulic actuators use liquid
- electric actuators use an external power source
- thermal actuators use a heat source

The actuator system that is categorized as the most beneficial, is an electric actuator. It can run on the same external power source as the reactor system drive components. Researching actuator options can possibly lead to a DIY solution, if necessary.

Advantages of using an electrical actuator compared to e.g. a hydraulic or pneumatic system, is the mounting, since there is no need for extra pumps and hoses. There is less space required and not no need for routine maintenance of the extra pumps and hoses to avoid oil leaks. For more information about electric linear actuators, Lasse Erlandsen from LINAK was consulted[63]. The requirements for the actuator is a stroke length of approx. 80 mm and forces needed to disengage the chosen coupling, move it linearly upwards from the reactor and then with enough force, engage the coupling again when the reactor has switched placed. After given descriptions and specifications of the reactor system, L. Erlandsen recommended LA14 or LA25 linear actuator from LINAK catalogue[64].

Figure 5-15. Electric linear actuator LA14[64]

Figure 5-16. Electric linear actuator LA25[64]

The LA14 actuator has a maximum trust of 750 N and a stroke length between 19 – 300 mm. The LA25 actuator has a trust from 600 N – 2500 N and a stroke length between 20 – 300 mm. Both run on 12 or 24 V DC permanent magnetic motor. It has the possibilities to give end stop signals, when it’s fully lowered or fully raised (outer and inner position). These are the only positions that are important to know. In this case, you must use the whole stroke length, to get the signals. Another option is to use a valve control card, to operate the stroke length using voltage and current. The actuator can put the hardest possible pressure on the valve/gasket, then stop at this current limit. Then the control card can use the registered current limit to set which position is fully inn and fully out. Using this type of control unit, it is possible to achieve a fine adjustment of the actuators required force, stroke length and get signals in the applied inner and outer position. The motions of an actuator can be programmed to be in sync with the rotating platform.

A challenge with these actuators is the brackets to fix the actuators and to attach the coupling to the actuator. The attachment must withstand the force that the actuators push down on the coupling, and the force that pulls them back. Figure 5-17 shows an example of the coupling system arrangement with actuator, tube, coupling, and reactor inlet.

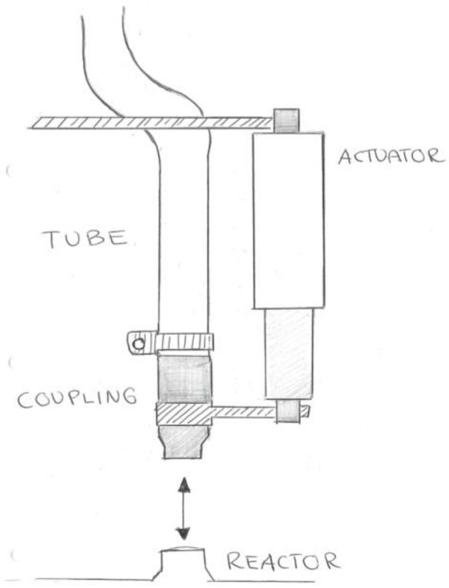


Figure 5-17. Sketch of coupling system motion for engage and disengage

The actuators can either be designed to push the coupling to the reactor or pull the coupling to the reactor. The latter option has advantage of making the actuator as compact as possible when the coupling is engaged, which it will be for the most of the time, and therefore making the actuator parts less exposed. The disadvantage is making room for the actuator.

5.4.2 Coupling

The actuator's task is to transfer mechanical force to produce the movement needed to open/close a valve. To connect the tubes to the reactor there is need of a coupling that will automatically close when the actuators disengage, to avoid leaks. One type of coupling that can do this is quick (release) coupling (Figure 5-18). They can be expensive, as already experienced when bought as an alternative to the "Bio Max" prototype and/or other projects at the University. Since the tubes are flexible, the valves can be attached to the actuators by a bracket, and therefore be motion controlled. The problem with the quick release coupling is that they are often built to withstand very high pressures, and therefore need a lot of force to connect and disconnect from each other. This requires a firm grip around the half of the coupling, while the other half is fixed to the reactor. Since the process pressure is no more than maximum 6 bar and 60 ºC, it is possible to find a low pressure quick release coupling which does not require too much force to operate.

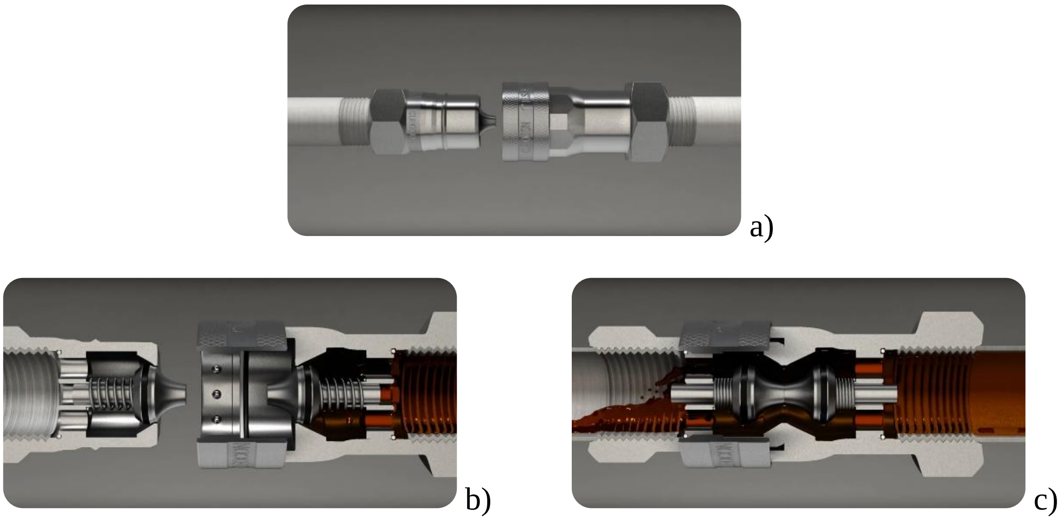


Figure 5-18. Quick release coupling[65]

As shown in Figure 5-18 (a/b) the quick release coupling is fully sealed when not in contact with its other part. When the two parts connect (Figure 5-18 c), the coupling has a spring pushed backwards on both ends, and opens the valve so that the liquid flows through. The tubes used in the "Bio Max" prototype is nitrile, which is flexible enough for movement, withstands biodiesel and moderate temperatures and pressures.

6. Structure analysis

This chapter includes a structural analysis of the initial design of the reactor system. Calculations of supports for Option (2) and structural stress of both options is completed.

6.1 Support reaction forces

A motorized rotary stage mounted in the center, as Option (1), does not only have the role of the drive system, but also the center bearing and support. The rotary stage is rigid and strong enough to hold the whole platform. However, this does not apply for Option (2). In this option, the rotating platform consists of five supports. Four of the supports are the wheels symmetrically placed under and around the platform. The last support a bearing at the center. The purpose of calculating the supports is to know the loads that the supports must withstand. The drive system in this solution, is not counted as a support.

To calculate the support reaction forces, the platform is simplified by dividing it in four parts, one part for each wheel-support (Figure 6-1). The symmetry of the divided platform gives two pairs of similar divided parts. The white pair is section A-A with the reactors, the striped pair is section B-B without the reactor. These sections will be viewed upon as beams, when calculating the support reaction forces. All four of the wheel supports are dimensioned to be the same size and therefore the maximum reaction support will be used. This is section A-A, being the one with the reactors and therefore giving the maximum support reaction force.

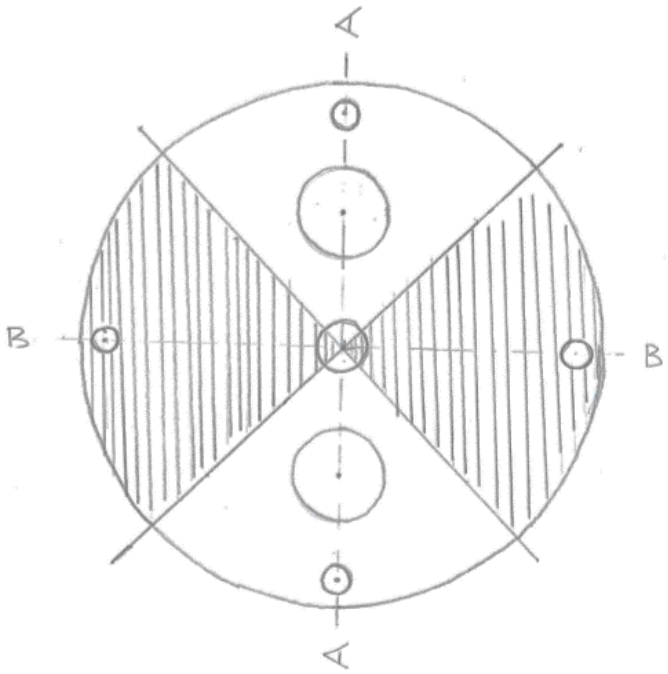


Figure 6-1. Illustration of rotating platform with supports viewed from below. The platform is divided in four parts of two pairs (white and striped). White is section A and striped is section B.

Being symmetrical, ½ of section A-A is simplified as a beam with two supports; the center support and the outer edge wheel support. To find a more correct estimate of the center force, a calculation of both situations will be made, and then added together for a total reaction force for the center support.

The section beam will be modeled with a variable distributed load, to add the weight of the platform itself in the calculations. For a steel plate with 4 mm thickness the weight is 32 kg/m^2[66]. Since the diameter of the platform is 1200 mm, the weight of the whole plate is approximately the same as a 1 m^2 square plate. The ¼ platform part is simplified as a triangle, and the load will be modeled as variable distributed force from q_{min} = 0 kg/m at the center to q_{max} = 8 kg/m (¼ section) at the edge.

$$q_{steelplate} = 32\frac{\text{kg}}{m^2}\times\frac{1}{4}m = 8\frac{kg}{m} = 0.0785\ \frac{N}{mm}$$

The beams are modeled in SkyCiv[3], an online engineering program. The sheer force diagram (SFD) and bending moment diagram (BMD) including calculations for both situations can be found in (Appendix C: SkyCiv – Report).

Section A-A: Wheel support reaction (with reactor):

The weight of the reactor is modeled as a point load positioned 260 mm from the outer edge as F = 245.25 N, the maximum load for a reactor given in the design specification at page 30.

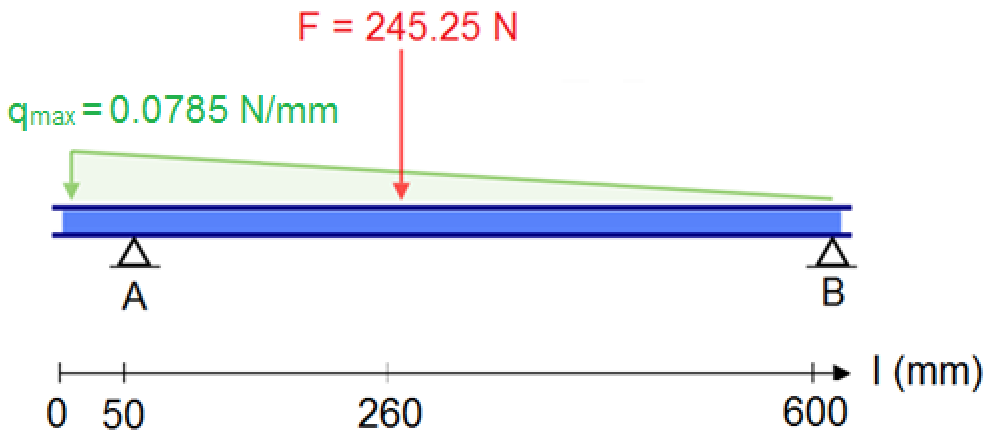


Figure 6-2. Section with reactor, center support and outer supports

To calculate the reaction forces the beam is considered in static equilibrium, the sum of all forces to be zero. The support reaction in the wheel support (A) was calculated by moment equation (3), summing the moments around the center support (B). Then using equilibrium equation again by summing all vertical forces (4) to calculate reaction force in B.

$$\sum M = 0 \tag{3}$$

$$\sum F = 0 \tag{4}$$

[3] SkyCiv Engineering (Student version 2017)

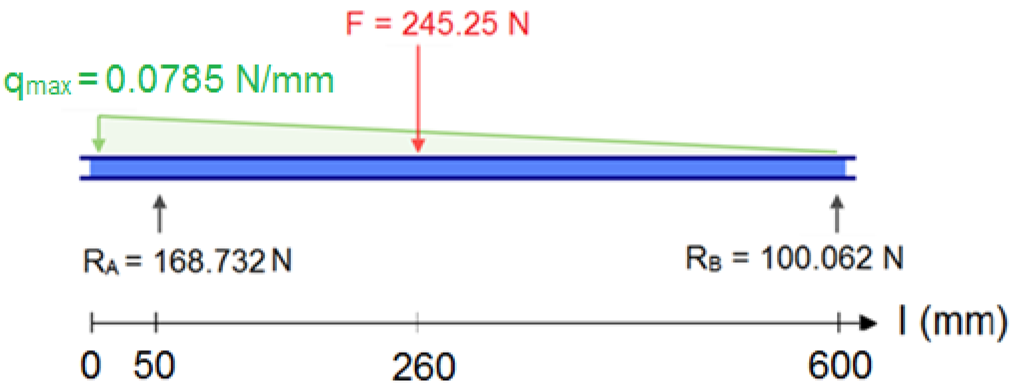


Figure 6-3. Free Body Diagram of platform section with reactor

The results of the reaction force at the outer support (R_A) is 169.8 N and the reaction force at the central support (R_B) is 100.0 N.

Section B-B: Wheel support reaction (without reactor):

The same calculation is done for the two others supports except this time the point load from the reactor will be excluded.

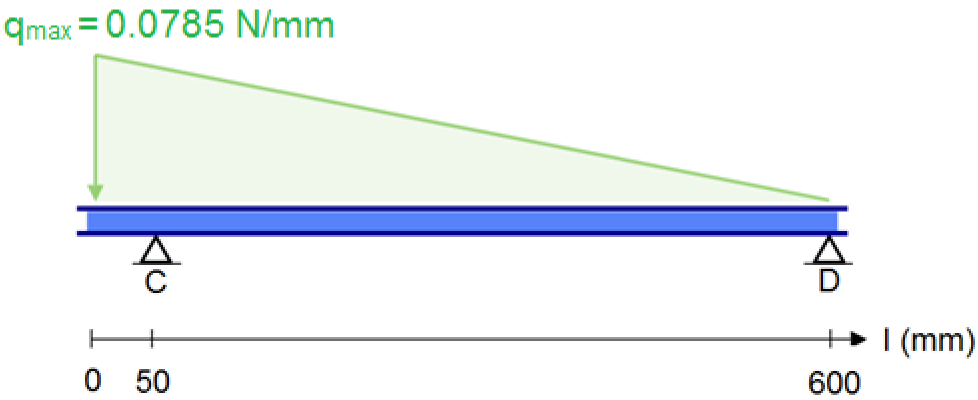


Figure 6-4. Section with reactor, center support and outer supports

The results of the reaction force at the outer support (R_C) is 17.2 N and the reaction force at the central support (R_D) is 6,4 N.

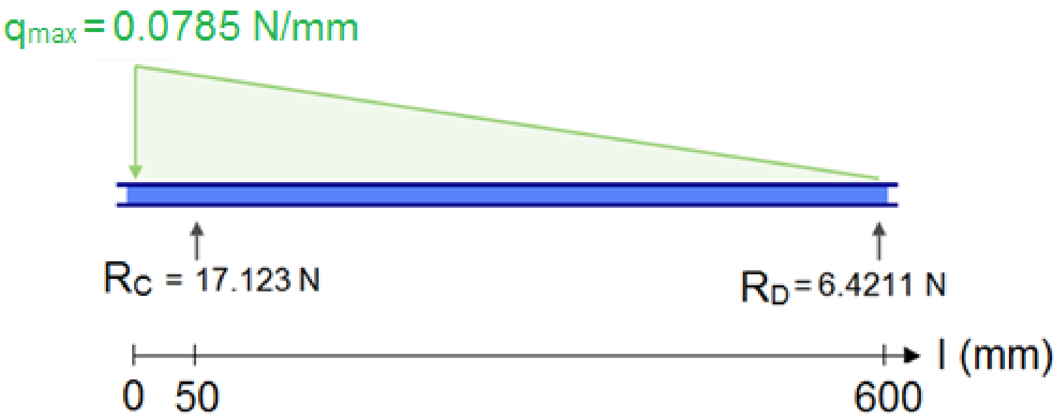


Figure 6-5. Free Body Diagram of platform section without reactor

Since the platform and load was divided in four parts, the total reaction force of the center support is calculated by adding the reaction forces from both situations. Adding center support reaction force with and without reactor, times two, adds all four parts weight on the center. This gives total reaction force at center:

$$R_{center} = (R_B + R_D) \times 2 = (100.062 \text{ N} + 6{,}411 \text{ N}) \times 2 = 212.946 \text{ N}$$

Total reaction force at the center support (R_{center}) of 213 N.

Result:

The calculations of the reaction forces for the supports leads to;

- Four outer supports, each with a reaction force of 169 N ≈ 17 kg each.
- One center support, with a reaction force of 213 N ≈ 22 kg.

This means using a rotating platform with Option (2) arrangement, the supports must at least withstand these loads.

6.2 Structure stress

The FEA analysis program ANSYS Workbench[4] is used to make a static structural analysis of the reactor platform, the deck which holds the rotating platform, and the housing. In these three elements, the largest loads will occur. The models have been imported as IGES files from SolidWorks to ANSYS Workbench. The mesh of the models was limited by the ANSYS version size limit (nodes). The mesh details of each models are described in the subchapters. Each model has total deformation and equivalent stress (Von Mises) analyzed. The rest of the analysis report is attached as a disk (Appendix D: ANSYS)

The conversion between 1 kg and 1 N is done by gravity acceleration of 9.81 N m/s^2. Weight figures extracted from SolidWorks models may vary from calculated figures, because of material properties differences from the catalogue and SolidWorks.

The section constants and material is chosen when consulted with Gunnar Torp[51], and the final solution is therefore tested for an eventual optimization of the structure. Weight figures is taken from steel supplier Tibnor's stock catalog 2015[66].

6.2.1 Platform

A static structural analysis of the platform is done, to see the impact of both the reactors' weights. The platform is a 1200 mm diameter circular plate in structural steel, with 4 mm thickness.

Figure 6-6 shows the deck upside down, as seen with the reactors' loads as forces pointing upwards. The blue ellipse areas represent the contact area of the wheels and the center support/motor, which are modeled as fixed supports. The center support is 200 mm in diameter. The wheels modelled with 80 mm in width, representing an approx. wheel size.

The two circular holes and opening for the reactor outlets has a 200 mm diameter.

[4] ANSYS Workbench Products 17.2 (Version: 17.02.53287)

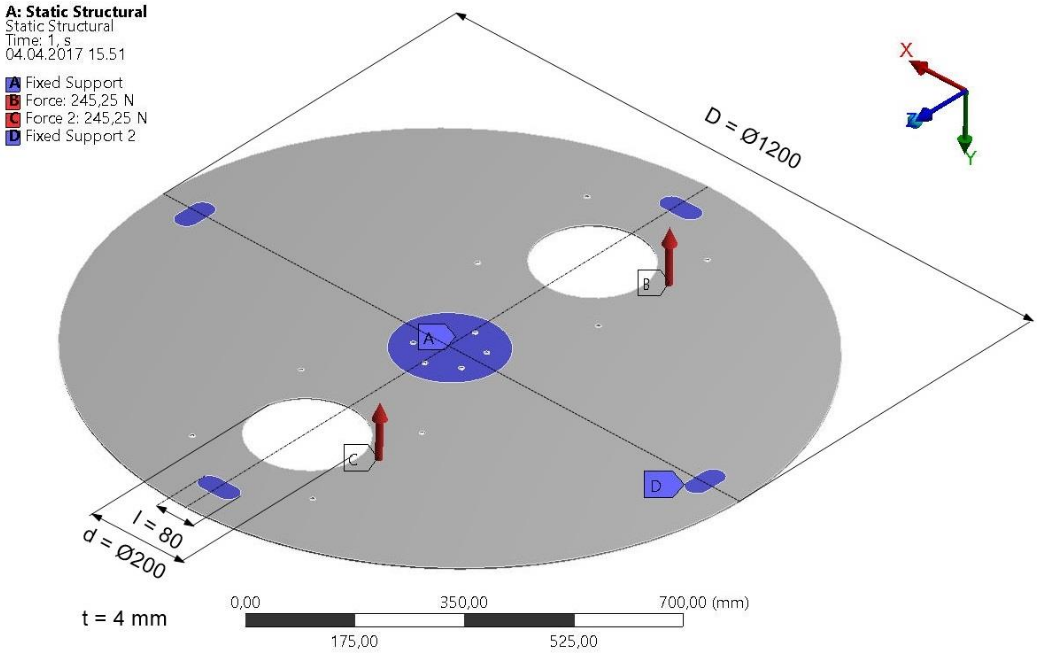


Figure 6-6. Static structural analysis – Platform (upside down) shown with wheels and center bearing as fixed supports marked in blue

A 4 mm steel plate of structural steel weighs 32 kg/m² [66].

$$q_{steelplate} = 32\frac{kg}{m^2} = 3.2\times10^{-5}\frac{kg}{mm^2}$$

Reactor is set with maximum weight (25 kg), which is equivalent to 245.25 N. The red areas are the reactor weight set as forces on the platform (Figure 6-7).

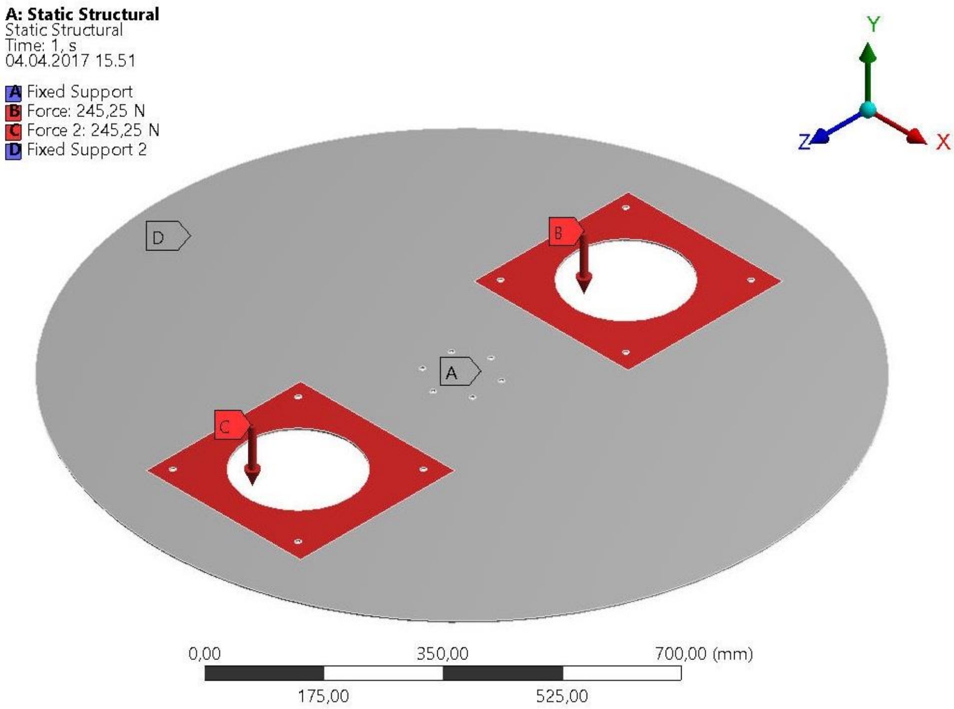


Figure 6-7. Static structural analysis - Platform shown with reactor weight as force marked in red

The analysis is done with and without the wheel supports to see if using only a rotate stage as center support will be sufficient in a static structural analysis. The platform is meshed with a refinement of 1 and mesh size of 90 mm around the holes and the center support. The rest of the platform has a default mesh size.

With wheel supports:

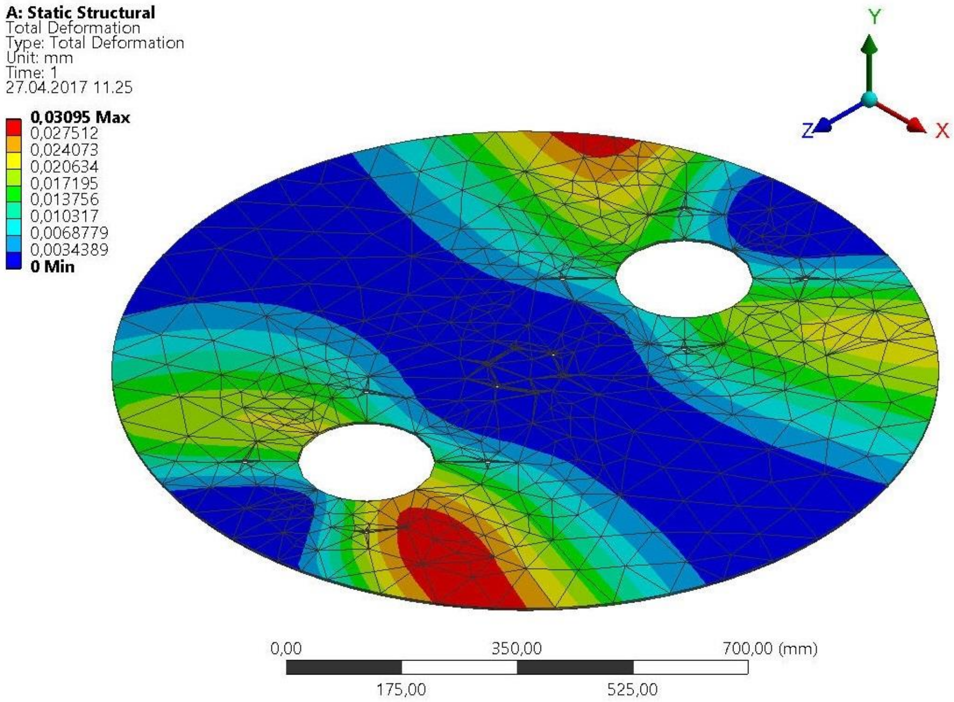


Figure 6-8. Static structural analysis - Total deformation plot of platform with wheel supports and maximum weight of reactors

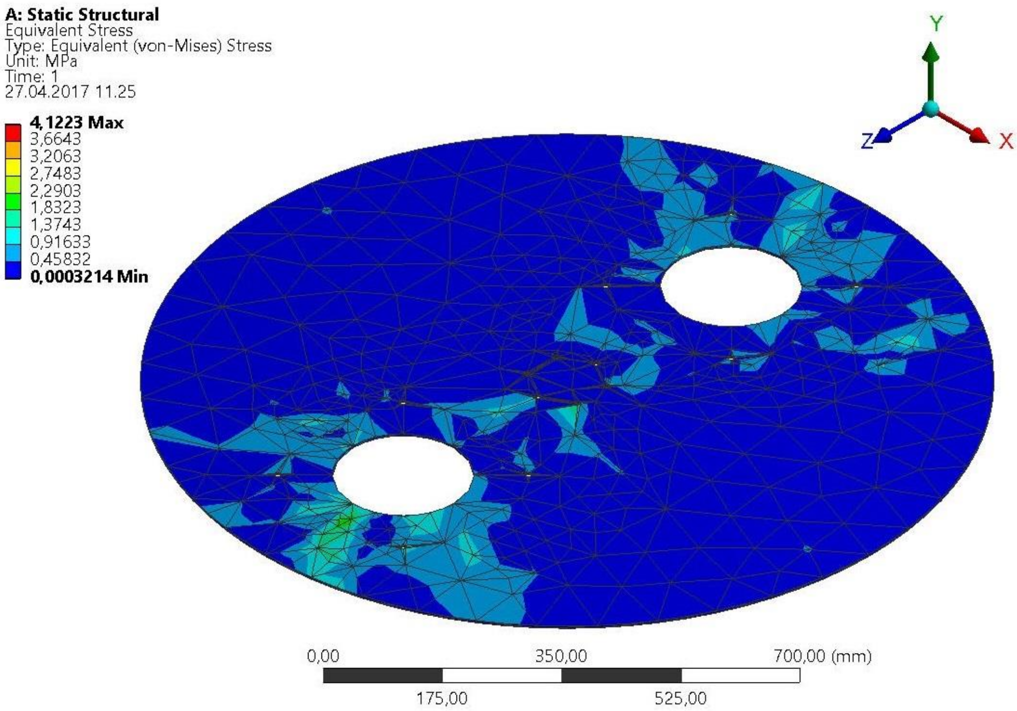


Figure 6-9. Static structural analysis - Equivalent (Von Mises) stress plot of platform with wheel supports and maximum weight of reactors

Without wheel supports:

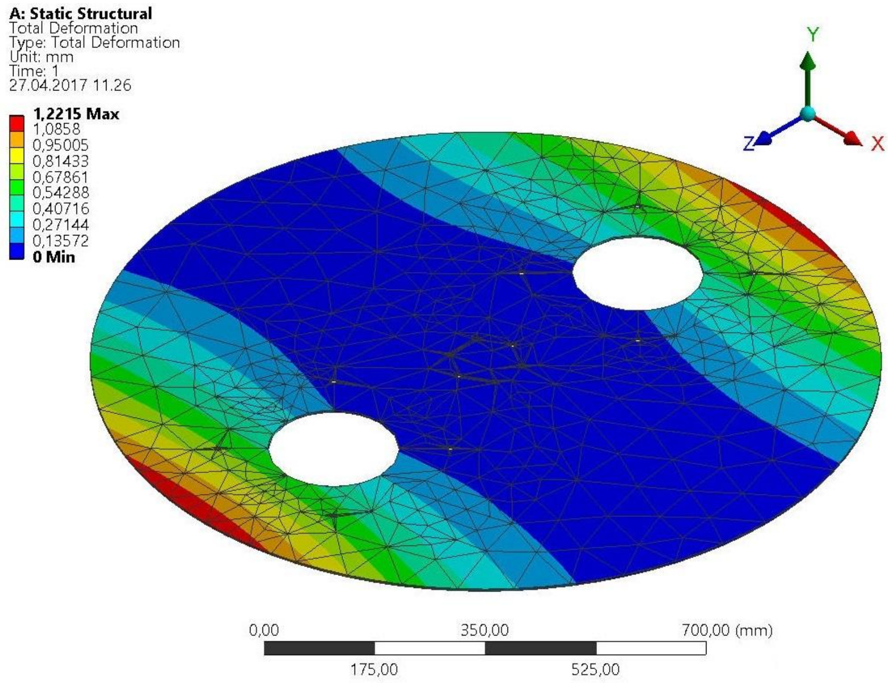


Figure 6-10. Static structural analysis - Total deformation plot of platform without wheel supports and maximum weight of reactors

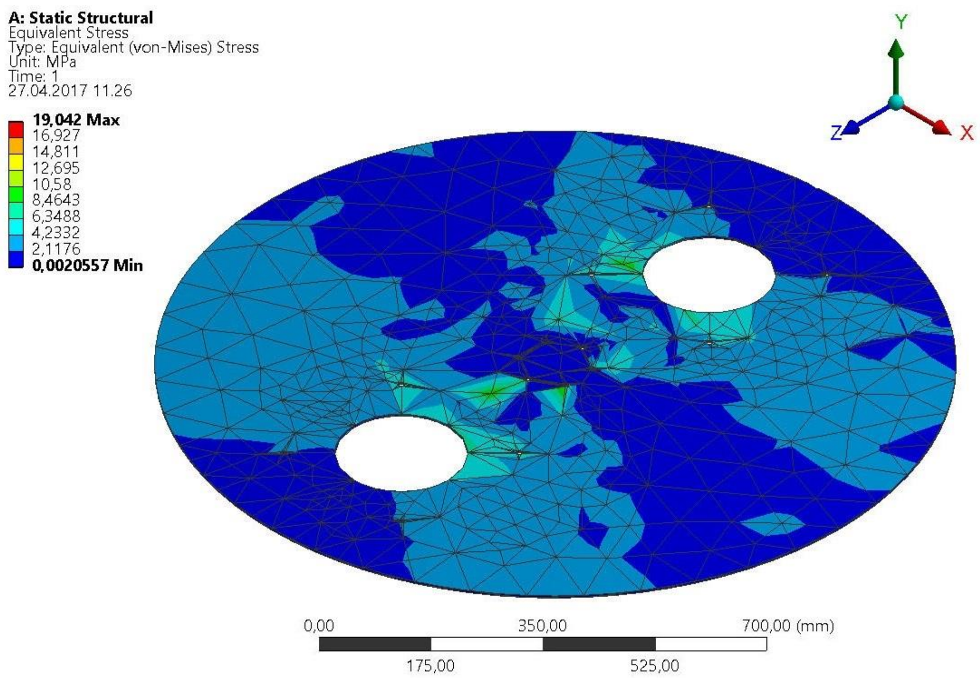


Figure 6-11. Static structural analysis - Equivalent (Von Mises) stress plot of platform with wheel supports and maximum weight of reactors

With wheel supports the maximum deformation of the platform is 0.03 mm (Figure 6-8) and max stress is 4.1 MPa (Figure 6-9).

Without wheel supports the maximum deformation of the platform is 1.2 mm (Figure 6-10) and max stress is 19 MPa (Figure 6-11)

This means the platform will hold the maximum weight without the wheel supports, and using only a rotary stage will be enough for the maximum static load. The thickness could be considered 3 mm instead, making the platform lighter. The wheel supports can possibly be beneficial for stabilizing the rotation.

6.2.2 Deck

The same analysis is done with the deck, holding the reactors and the rotating platform (platform and drive system). The deck plate is 1200x1200x4 mm made of structural steel with two openings for the reactor outlets, as the platform. The hole openings are 300x300 mm.

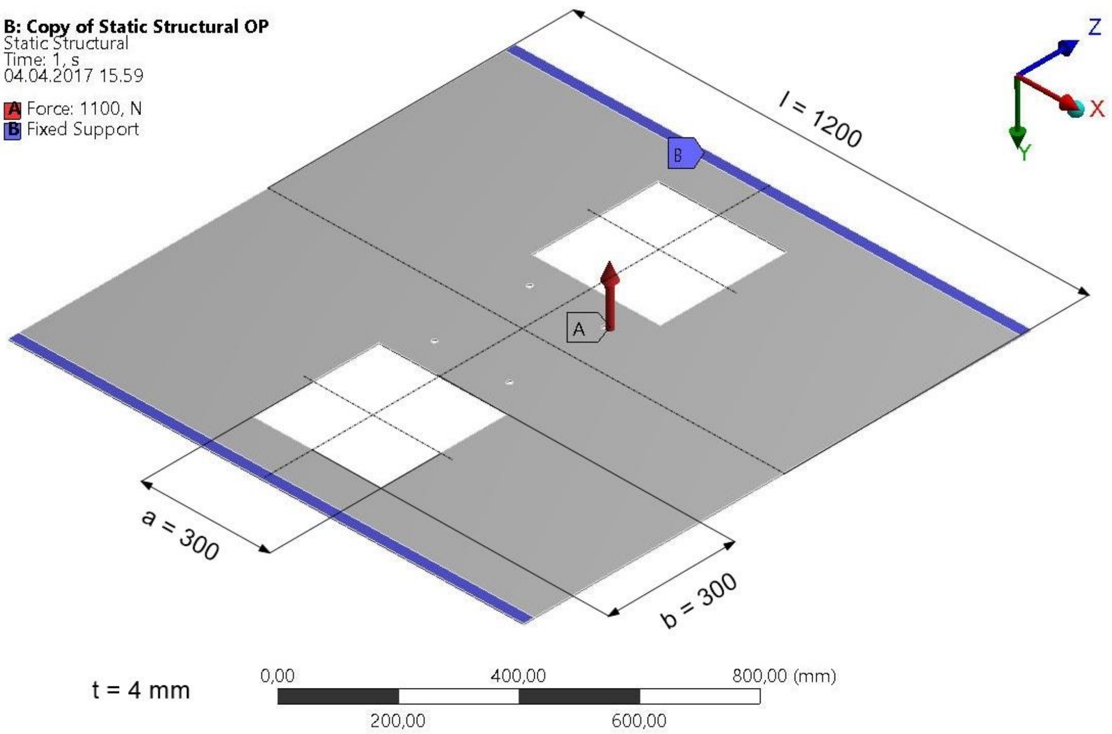


Figure 6-12. Static structural analysis - Platform shown with sides as fixed supports marked in blue.

The support for the deck is the framework of the housing. The blue is the contact area on the deck from the housing, which is 25x1200 mm (Figure 6-12).

To find the platform mass, the circular holes is subtracted from the rotating platform (see Figure 6-6 for reference):

$$A = \frac{\pi}{4} d^2 \tag{5}$$

$$A_{plate} = \frac{\pi}{4} D^2 = \frac{\pi}{4} 1200^2 = 36{\times}10^4 \pi\ mm^2$$

$$A_{hole} = \frac{\pi}{4} d^2 = \frac{\pi}{4} 200^2 = \pi 100^2$$

$$A_{platform} = A_{plate} - A_{hole} = 36{\times}10^4\pi - (2 \times 100^2\pi) = 34{\times}10^4\ mm^2$$

$$m_{platform} = A_{platform} \times q_{steelplate} = 34{\times}10^4\pi\ mm^2 \times 3.2{\times}10^{-5} \frac{kg}{mm^2} = 34.18\ kg$$

SolidWorks figures as a comparison is 36.2 kg.

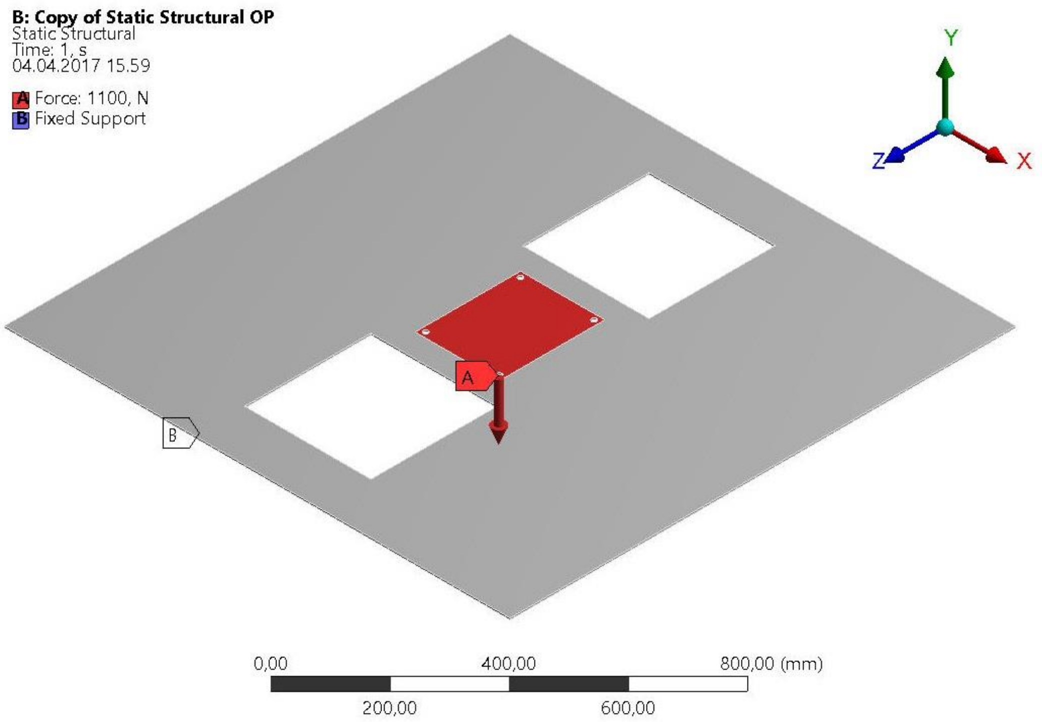


Figure 6-13. Static structural analysis - Platform shown with total weight of rotating platform, reactors and drive system as force marked in red

Total force in this scenario is the platform, reactors and drive system. Total weight of reactors and rotating platform is (2 x 25 kg) + 34.18 kg = 84.2 kg. The suitable rotating stages for the reactor system usually weighs between 10 – 15 kg[67]. With its control system and other components, the drive system in total is chosen arbitrary to weigh around 25 kg. This means a total weight of 109.2 kg, approx. 1100 N on the center of the deck as shown in Figure 6-13. The whole deck is meshed with a refinement of 2 and mesh size of 100 mm.

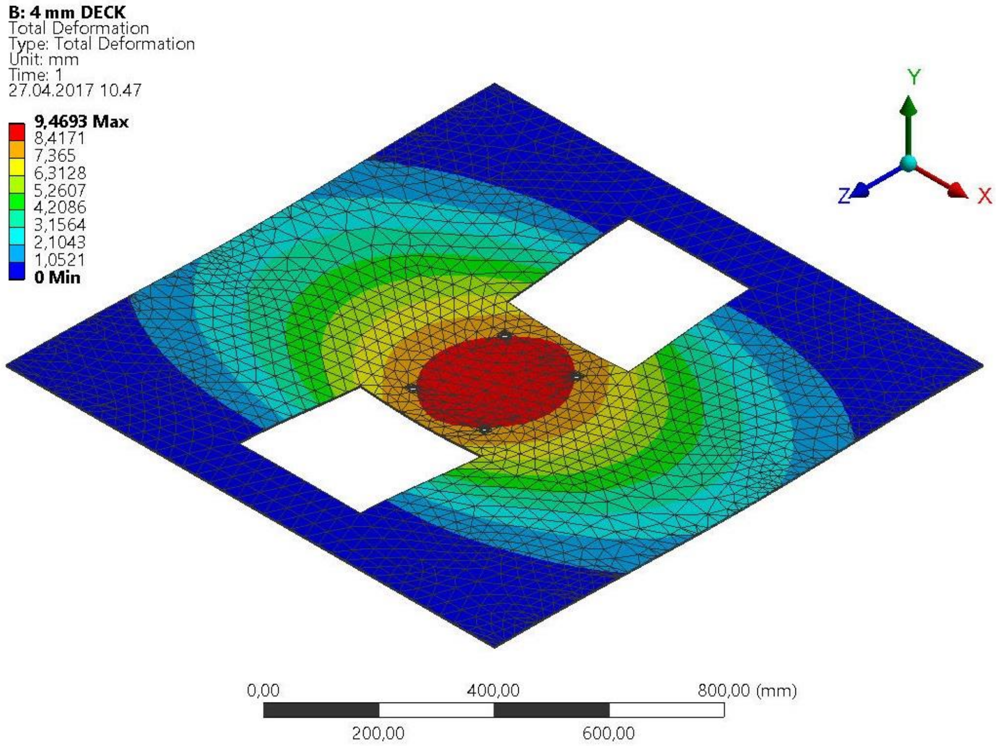


Figure 6-14. Static structural analysis - Total deformation plot of 4 mm deck

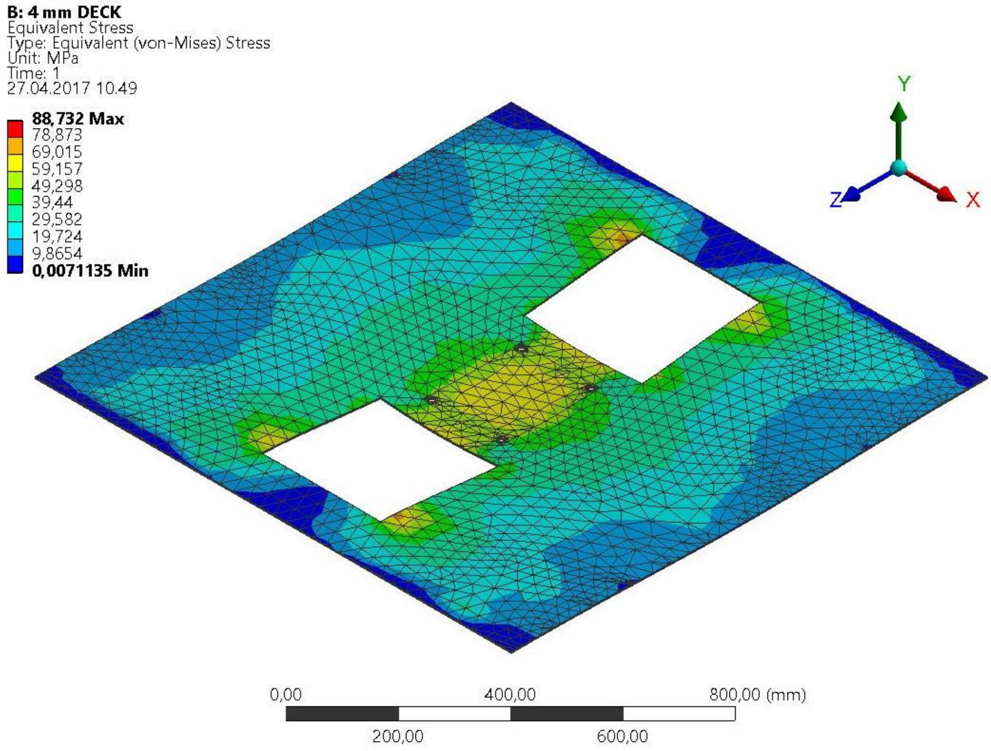


Figure 6-15. Static structural analysis - Equivalent (Von Mises) stress plot of 4 mm deck

Maximum total deformation is at the center of the deck and is 9.5 mm (Figure 6-14). The maximum equivalent stress is 88.7 MPa (Figure 6-15). The platform and deck seems to hold its weight with a good margin. The construction can be optimized by using 3 mm thickness steel plates for deck as well.

Next analysis is the housing framework for the reactor system.

6.2.3 Housing

The framework of the housing is made of 25x25x2 mm square hollow tubes of steel (S235JR) with a weight of 1.42 kg per meter[66]. The frame is built to hold the deck, which holds the rotating platform and reactors. The final design of the housing depends on the chosen coupling system and the placement.

Figure 6-16 shows where the load stresses the framework. The framework is without any added support or attachments for the coupling system, and the structural analysis is only for the reactors, rotating system and deck.

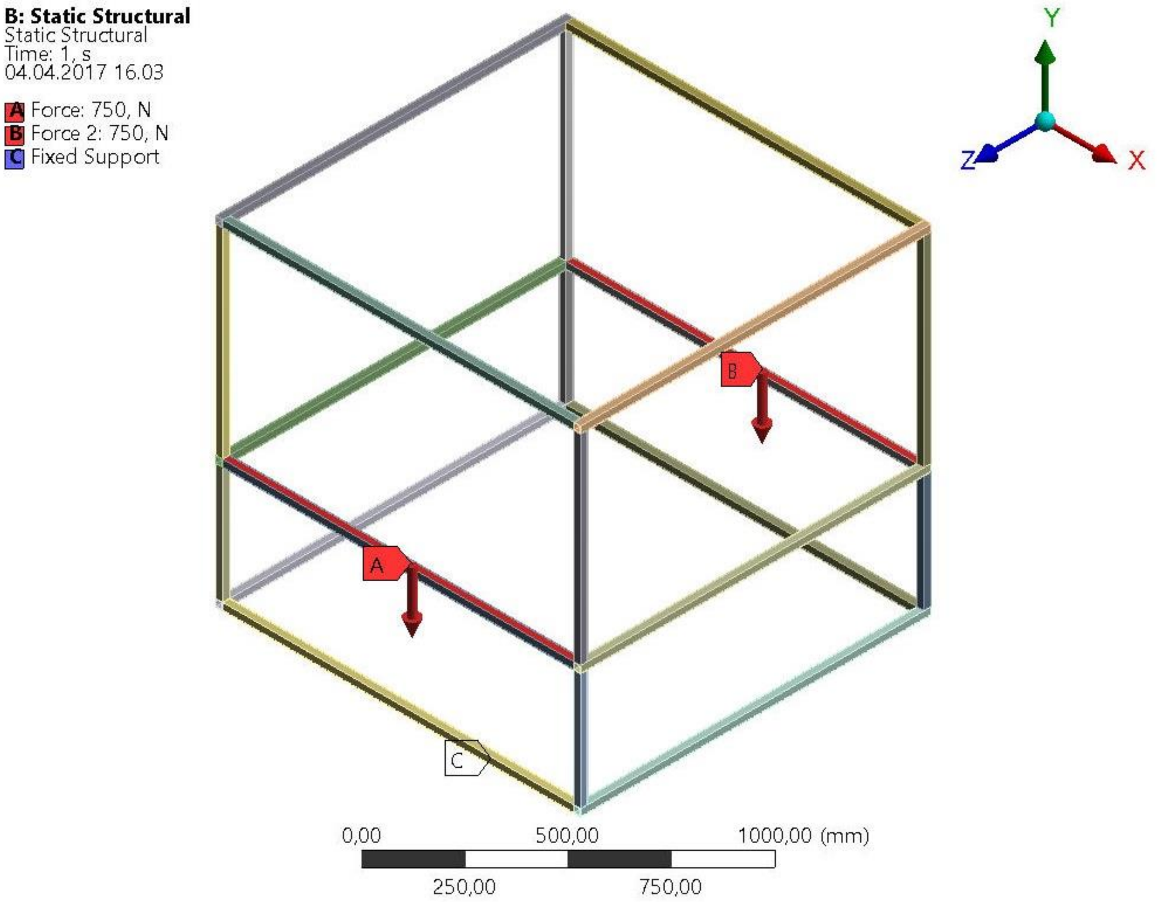


Figure 6-16. Static structural analysis – Housing framework shown with total load as force marked in red

To find the total load on the frames, the square holes is subtracted from the deck and added to the weight of the reactors and rotating platform:

$$A = a \times b \quad (6)$$

$A_{deckplate} = a \times b = 1200 \times 1200 = 144 \times 10^4\ mm^2$

$A_{deckhole} = 300x300 = 9 \times 10^4\ mm^2$

$A_{deck} = A_{deckplate} - A_{deckhole} = 144 \times 10^4 - 9 \times 10^4 = 135 \times 10^4\ mm^2$

$m_{deck} = A_{deck} \times q_{steelplate} = 135 \times 10^4 \pi\ mm^2 \times 3.2 \times 10^{-5} \frac{kg}{mm^2} = 43.2\ kg$

SolidWorks figures as a comparison is 39.3 kg.

$Total\ weight = 43.2 + 109.2 = 152.4\ kg$

Total weight on housing is 152.4 kg, approx. 1500 N. This means 750 N on each side of the framework as shown in Figure 6-16. The housing is meshed with a refinement of 1 and mesh size of 90 mm on the profiles which has the loads on them. The rest of the framework has a default mesh.

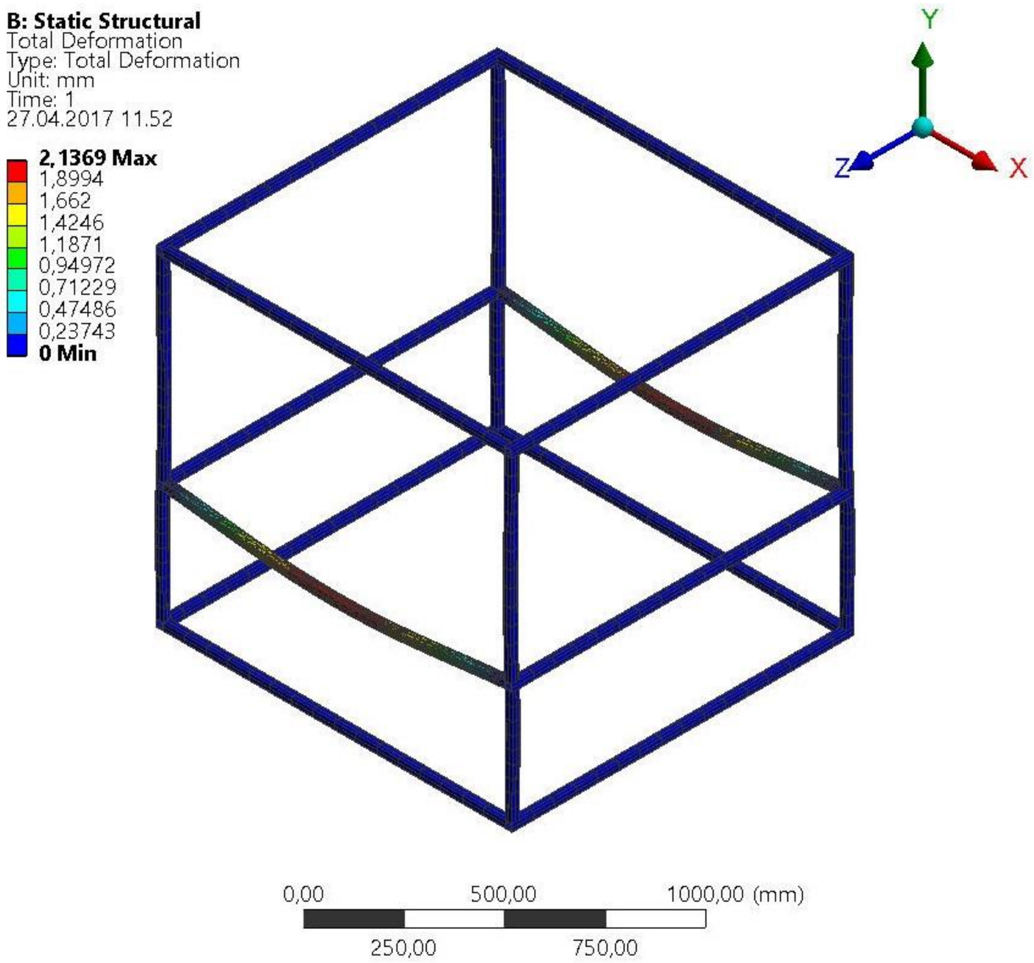


Figure 6-17. Static structural analysis - Total deformation plot on framework from deck and reactor system load

The maximum deformation on the frames is approx. 2.1 mm on the steel frame. The rest of the structure has little or no impact.

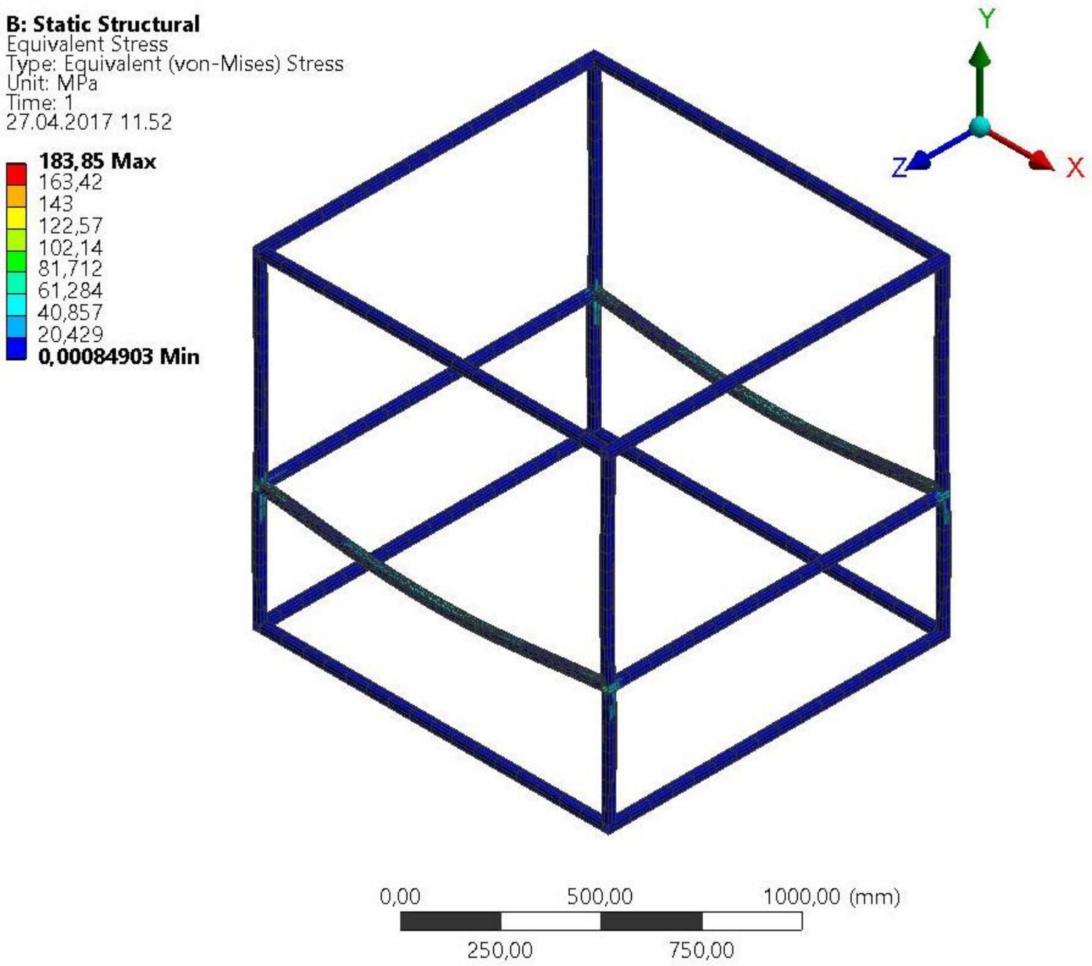


Figure 6-18. Static structural analysis – Von Mises stress plot on framework from deck and reactor system load

The equivalent stress is a lot higher than the platform and deck. Here the maximum stress is at 184 MPa. The housing profiles over the deck support can be smaller, but this depends on the rest of the biorefinery structure and which coupling system is chosen.

6.2.4 Adjustments

Since the largest load is on the deck, the same analysis as the 4 mm deck is done with 3 mm instead, to see if the deck and platform can be scaled down.

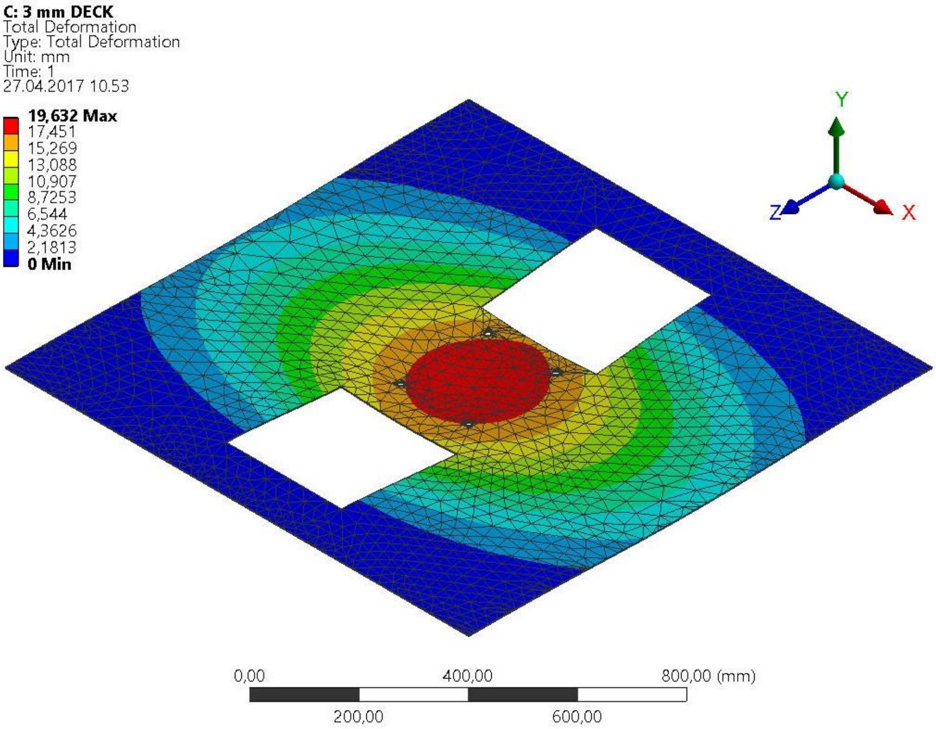


Figure 6-19. Static structural analysis - Total deformation plot of 3 mm deck

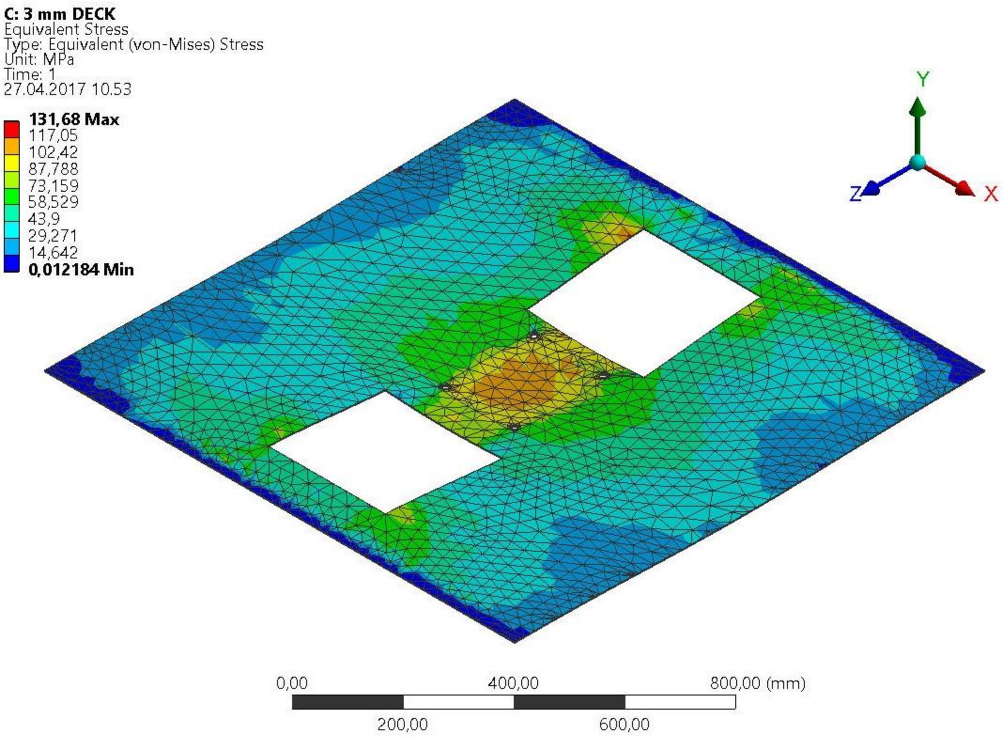


Figure 6-20. Static structural analysis - Equivalent (Von Mises) stress plot of 3 mm deck

Maximum total deformation is at the center of the deck and is now 19.6 mm (Figure 6-19) and the maximum equivalent stress is 131.7 MPa (Figure 6-20). With the platform scaled down to 3 mm also, the load on the deck will decrease. With 3 mm thickness SolidWorks figures shows the mass of the deck weighs 29.5 kg and platform weighs 27.4 kg, resulting in lower material costs. Still since the load of the coupling and its other components is not present the platform will stay 4 mm thick, but the deck can be scaled down to 3 mm thickness.

To reduce fixed cost of the reactor system the material should remain steel, instead of more expensive material as for example aluminum alloys. A possibility for a DYI decentralized system, is to use other material for the platform and/or deck, for example plywood. The criteria is that it holds and is stable when rotating.

The structure is statically indeterminate when the platform rotates. This means the only part which holds the structure together when rotating, is the welds on the shortest vertical beam up against the upper level beams (Figure 6-21).

Figure 6-21. Framework indication of a critical point when rotating

Since the rotation is only 180 degrees (not continuous 360), and at a low speed, the rotational energy in the structure is low and the centrifugal force is inconsequential. Still the framework would be stronger by having four vertical beams from the top to bottom, and have the horizontal beams welded on these instead of splitting up in two vertical beams on each corner. This will decrease the required weld and only require 1200 mm length profiles. By doing this the structure would need a deck which is 1200x1250 mm instead. Another possibly is diagonal stiffener from the top corner of lower level to the bottom corner of lower level.

7. Final design

SolidWorks[5] is used as modeling tool to create, design and visualize the reactor system in 3D and for detailed engineering drawings in 2D.

Option (1) is preferred as final design. The main reason is that this conceptual design with its subsystems, is the most suitable as a technological development to a small-scale biorefinery with automatic de-oil of catalysts. The option has precise rotation, is robust and computer controllable for the subsystems to be synchronized.

Option (2) ca be evaluated further as a DIY solution. The drive system for this solution is favored to be a stepper motor, driving a wheel, which rotates the platform by friction. The coupling system is harder to engineer at a personal basis without more expensive parts, but further research may open possibilities for this option.

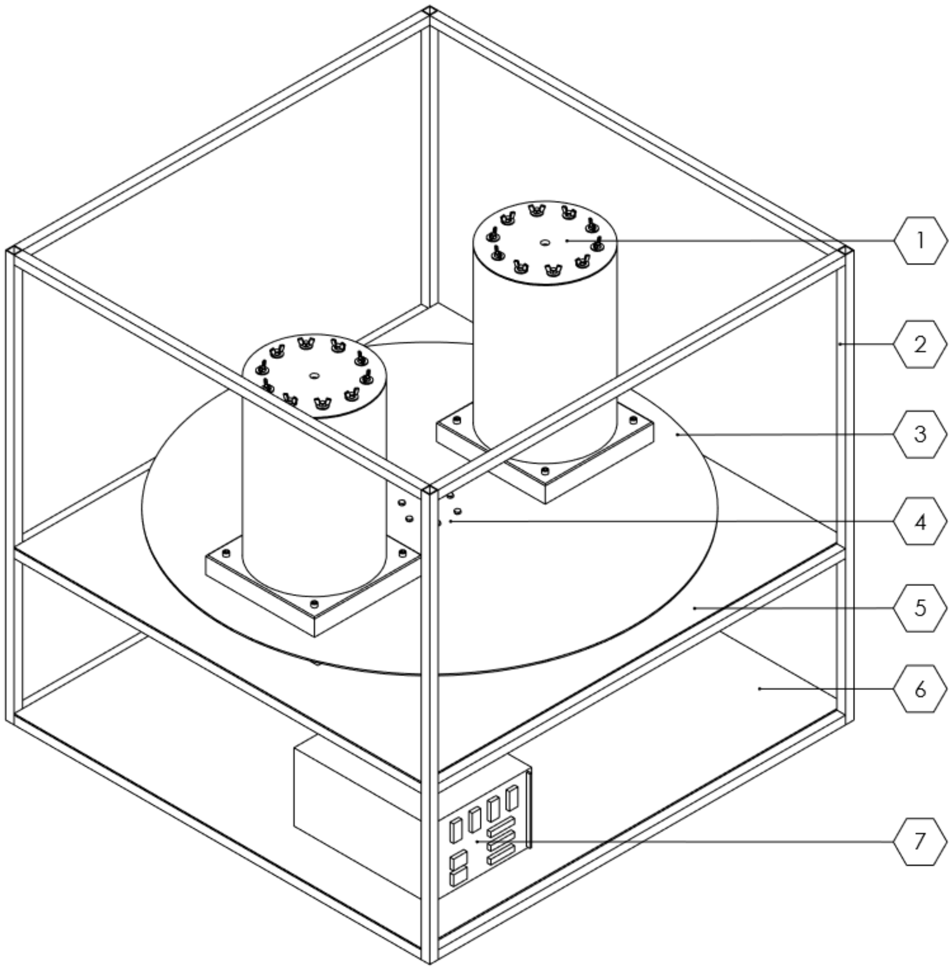
Consequently, the final design of the reactor system is divided into:

- Reactor(s)
  - Two packed bed reactors with capsules packing heterogeneous catalysts
    - Both the six-capsule reactor based on the "Bio Max", and the hatch reactor is presented, although the latter is at an early developing stage.
- Housing
  - Two deck-plates and hollow squared profiles as framework
- Rotating platform
  - A rotating platform driven and controlled by a rotary stage with control system, mounted at the center of the platform
- Coupling system
  - Four coupling subsystems at each inlet and outlet, which controls the coupling/tubes engage and disengage.

All sides are shown of the cubic reactor system in Figure 7-2, Figure 7-3, Figure 7-4 and Figure 7-5. The reactors mounted in the system are the six-capsuled alternative and the

[5] SolidWorks 2016 (Version: 24.2.0.50)

material is not transparent. The control motion component can be seen on the bottom deck at the lower level. This must be connected to the rotary stage.



⬡	Qty.	Part	⬡	Qty.	Part
1	2	Packed bed reactor	5	1	Upper deck
2	16	Hollow profile 1200x25x25x2	6	1	Lower deck
3	1	Platform	7	1	Motion control system
4	1	Rotary stage (under platform)			

Figure 7-1. Reactor system assembly with number, quantity and part name of main components

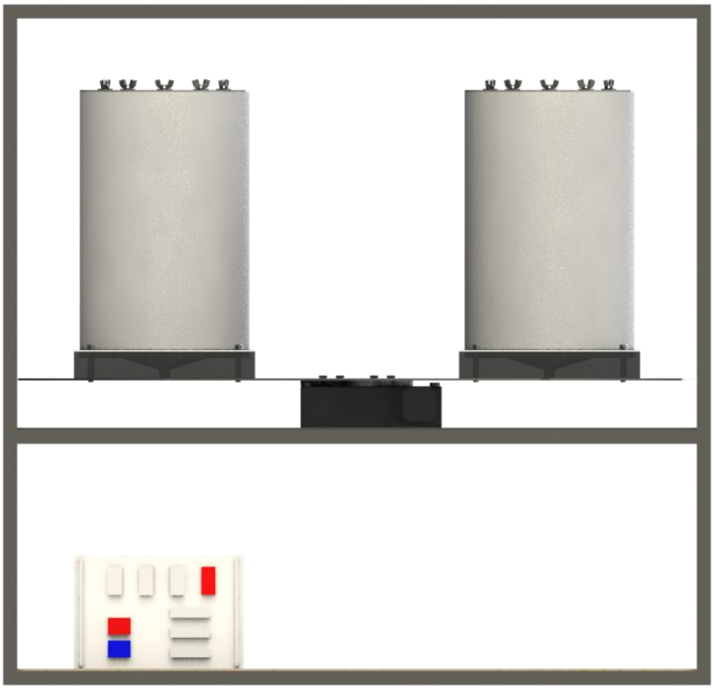


Figure 7-2. Front view of reactor system with six-capsuled reactors

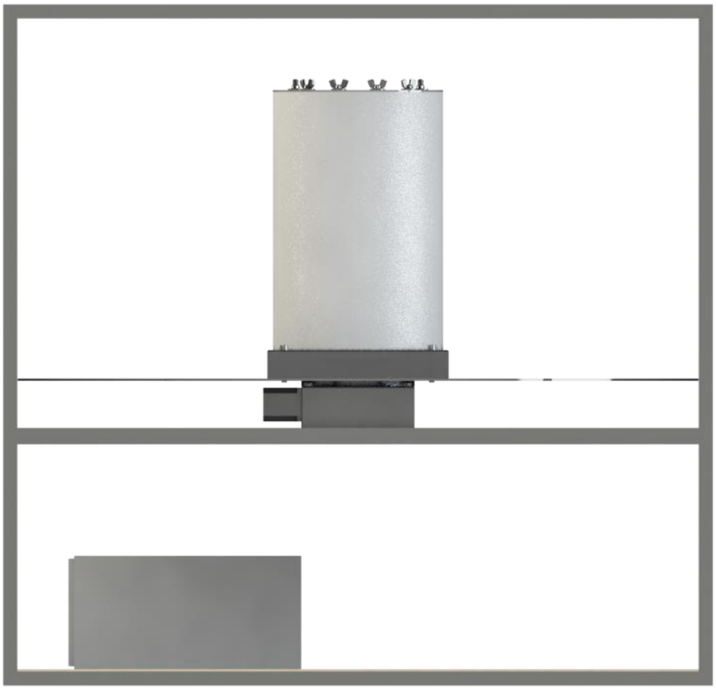


Figure 7-3. Side view of reactor system with six-capsuled reactors

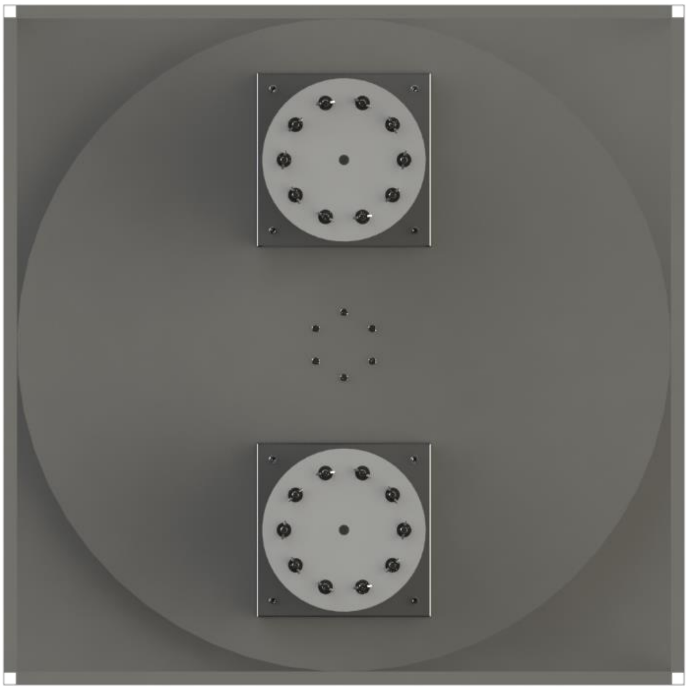
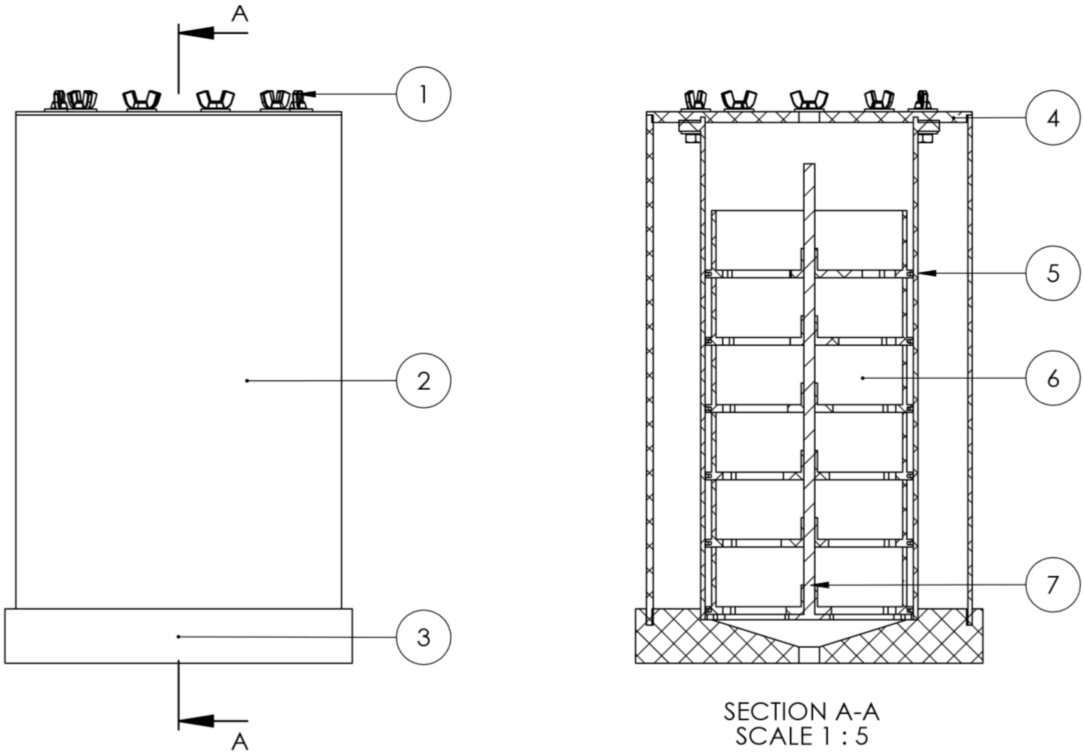


Figure 7-4. Top view of reactor system and reactor inlets

Figure 7-5. Bottom view of reactor system and reactor outlets (lower deck and control station is removed for better view)

7.1 Reactor(s)

The six-capsuled reactor and the hatch reactor are shown in 2D and 3D CAD. Although the hatch reactor is in an early developing phase, it is included to show the concept build.



○	Qty.	Part
1	10	Lid fasteners (M10 Screws)
2	1	Outer shell
3	1	Base

○	Qty.	Part
4	1	Lid
5	1	Mid shell
6	6	Capsules
7	1	Rod with plate

Figure 7-6. Six-capsule reactor assembly and section view with part number, name and quantity

Figure 7-6 shows the six-capsuled reactor assembly. The reactor has a base, which is attached to the rotating platform by screws. The base has a hole in the middle which serves as a funnel to the outlet. The outer shell is attached to the base. It serves as a protection and stabilizes the mid shell and lid. Inside the mid shell is the six capsules stacked on top of each other and a rod with a plate at the bottom. Between the capsules is a perforated plate that-holds the catalysts and lets the flow pass through. Since 3D printing has become a lot more advanced, it may be possible to print the capsule with perforated bottom, without the extra perforated plate. To empty the capsules the rod is pulled up and the plate in the end of the rod presses the capsules up. There is also seals on the outside of each capsule so that the flow does not pass other places than through the capsules with catalysts. CAD of this the six-capsuled reactor is seen in Figure 7-7.

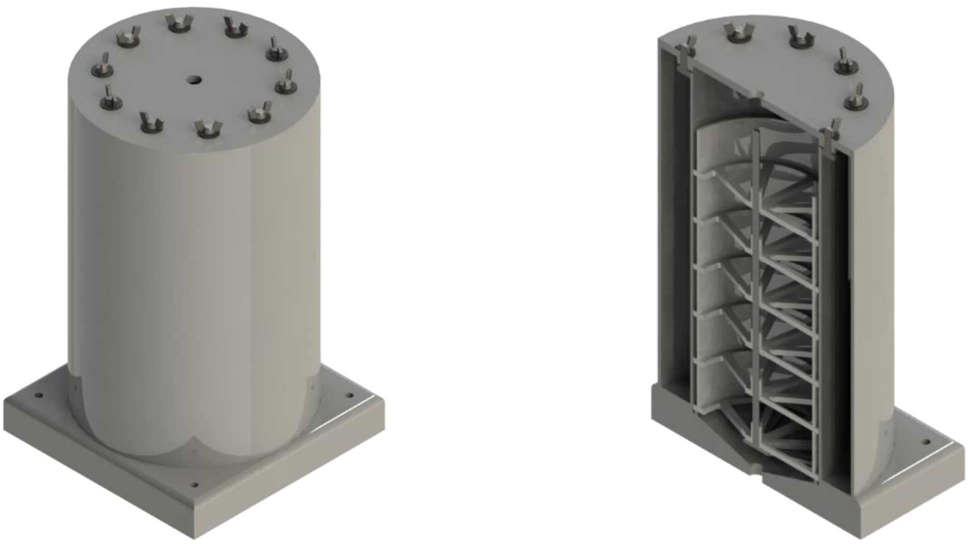
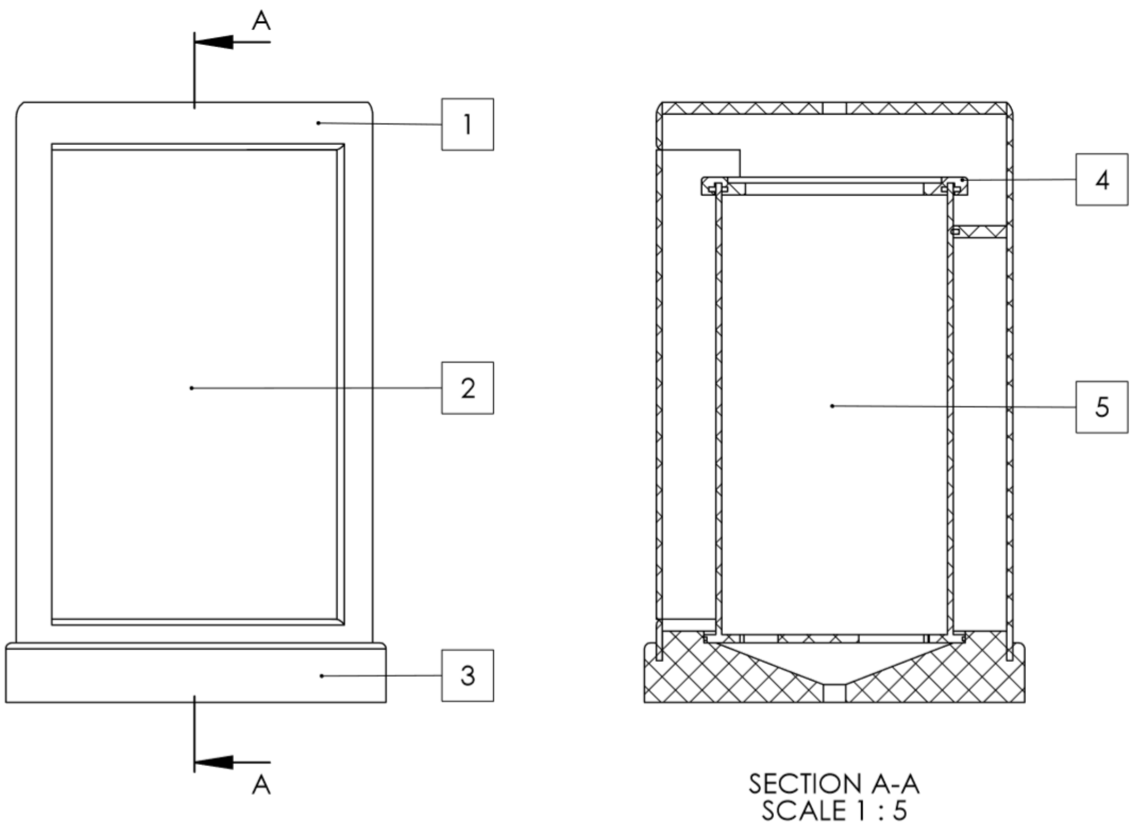


Figure 7-7. Whole and section view of six-capsuled reactor (without perforated plates between capsules)

The hatch reactor (Figure 7-8), has a similar base and mount to the reactor system as the six-capsuled reactor. The base has also a hole in the middle, which serves as a funnel to the outlet. It has only one capsule and one shell surrounding it. On the side of the shell is a hatch to open and close the reactor. The hatch reactor has one large capsule, which is easily replaceable and cleaned by opening the reactor hatch, lifting the capsule up from the base and pulling it out. Hinges and close mechanisms are not developed yet.



	Qty.	Part
1	1	Shell
2	1	Hatch
3	1	Base

	Qty.	Part
4	1	Lid
5	1	Capsule

Figure 7-8. Hatch reactor - early developing/design phase

As seen in Figure 7-9, the opened hatch reactor has a capsule placed inside. Since it is illustrated transparent it is possible to see the bottom opening and outlet through the base. Also here, it needs a perforated plate or a perforated capsule bottom, so that the packed heterogeneous catalyst is fixed and the reactants flows through and down the funnel and outlet of the reactor base.

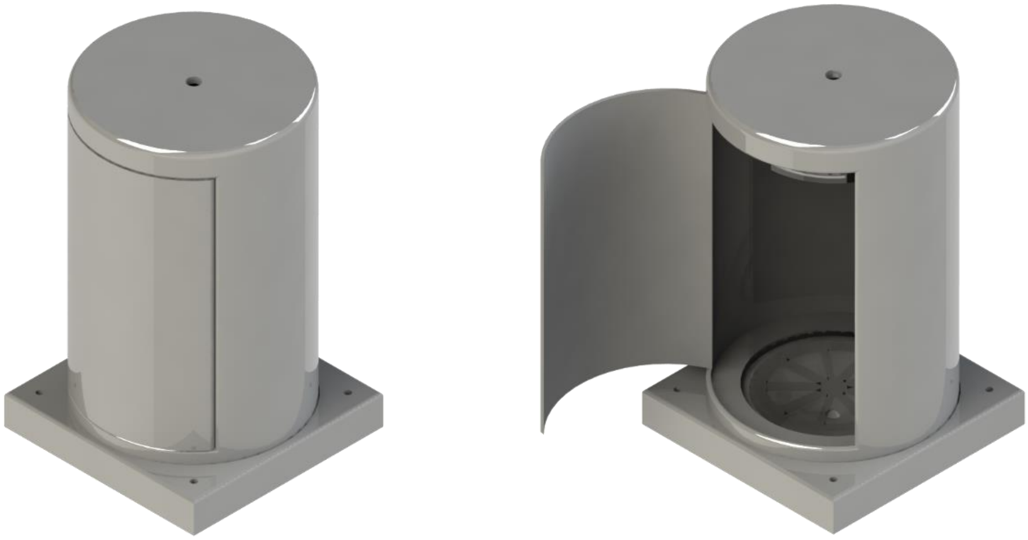


Figure 7-9. Closed and open view of hatch reactor with transparent capsule (without perforated plate at the bottom of the capsule)

Figure 7-10 illustrates how the reactor is when translucent. Used in th figure is the hatch reactor.

Figure 7-10. Example of translucent reactor

7.2 Housing

The housing consists of hollow steel profiles as framework holding two decks. The decks create a lower and upper level. The lower level is for holding of lightweight components and equipment, while the upper level holds the rotating platform (motorized rotary stage, platform) and reactors.

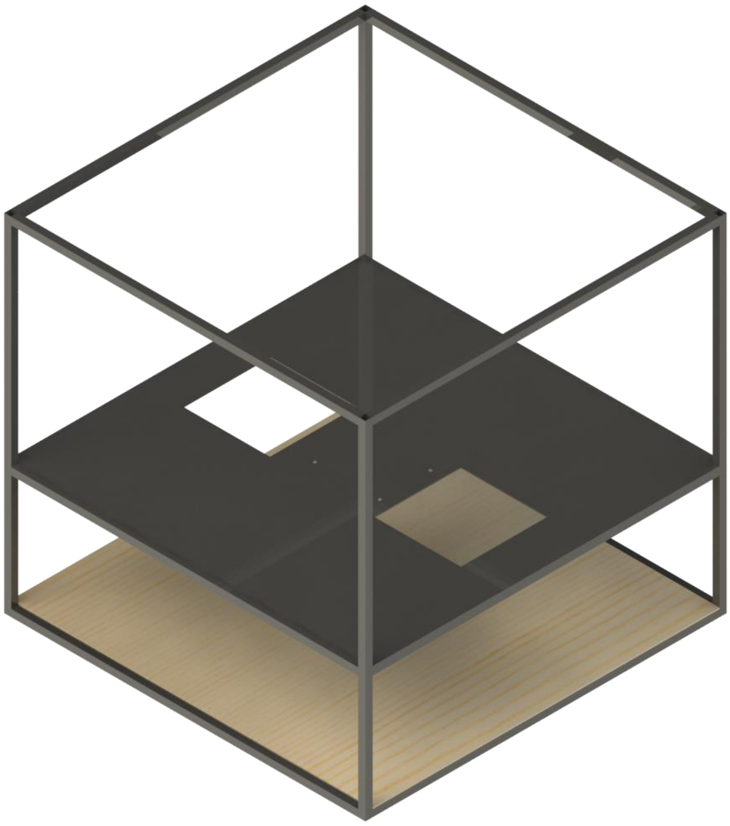


Figure 7-11. Housing - Framework with steel deck for upper level and plywood deck for lower level

7.3 Rotating platform

The rotating platform consists of a drive system and a circular platform. The drive system includes a motorized rotary stage mounted under and in the center of the platform and a motion control system by Optimal Engineering Systems, Inc. (OES)[67]. Numerous companies were consulted for rotary stage solutions, but in terms of price, quick replies and service, OES Inc. became the final choice. The rotating platform is shown in Figure 7-12, with a transparent platform to view the rotary stage beneath.

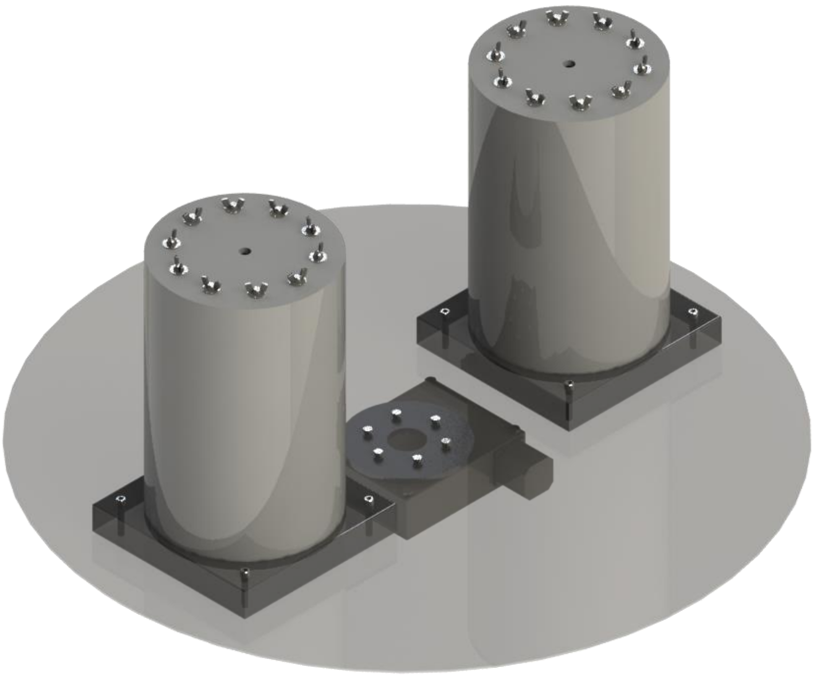


Figure 7-12. Rotating platform with reactors and 60 % transparent platform to highlight the placement of the rotary stage

The rotary stage diameter is 200 mm and the drive mechanism is a worm gear driven by a stepper motor. The base material is aluminum alloy and weighs 12 kg. Its load capacity is 100 kg and the rotary stage has a 360° range of travel with positional accuracy of 0.005°. The stepper motor draws about 40 Watts of power when it is driving the stage. The motion control system is a plug-and-play motor control with a RS-232 interface, and can be programmed by PLC, C/C++, Visual Basic or LabVIEW. All specifications are taken from their website or in personal communication with OES support[68].

7.4 Coupling system

The development of the coupling system has not been modelled in CAD for a final design. The proposed method remains an electrical linear actuator as explained in the initial design. This means one electrical linear actuator at each inlet and outlet, which controls the engage and disengage motion of the coupling. Further work is needed.

8. Enviromental analysis

Analysis of the environmental aspect is done in CES EduPack[6], "Eco Audit". The analysis sums up environmental impacts in material, manufacture, transport, use, disposal and EoL potential. Summary and detailed report from "Eco Audit" is attached as Appendix E: CES EduPack - “Eco Audit”.

The analysis is of the main mechanical components and parts in the reactor system. This means chemical substances as oil, alcohol, catalysts and other process fluids and equipment is not included. The purpose of the analysis is to see if it is possible to limit the carbon footprints, energy usage, waste and emissions and to get a preview of these impacts for the reactor system.

The reactor system (without coupling system) is divided into which type of materials they consist of. Weight figures are extracted from SolidWorks models.

- Structure is divided into housing, platform and deck, all made of steel (medium carbon steel). Housing weighs 26.9 kg and is extruded, while deck weighs 39.3 kg and platform weighs 36.2 kg and are both rough rolled.
- Drive system is divided in rotary stage, that is made of aluminum alloy and weighs 8 kg, stepper motor as power supply unit weighing 4 kg, control system as desktop computer (w/o screen), weighing 5 kg.
- Reactor is divided into steel parts 0.08 kg as casted and polymers parts as molded (no 3D print alternative). Since all materials have been decided, except the reactor polymer, the latter will be the only material which will have numerous materials to be compared. These polymers are Polypropylen (PP), Polycarbonate (PC) and Polyamides (Nylons, PA), which were introduced in chapter 5.1. The rest of the reactor system is included for an overview of their environmental impact. The density for PC and PA is approx. the same, but PP has a lower density. This means for PC and PA the parts weigh 12.1 kg, and for PP 9.2 kg.

[6] CES EduPack 2016 (Version: 16.1.22.0)

The other input in the analysis takes basis in a likely scenario for use of the reactor system:

The steel parts are set to 80 % recycled content, while the reactor polymer parts are set to 30 %. Every included material is set to be recycled at EoL, except stepper motor and control system, which is set as downcycle. Transport of components is divided into OES products, structure components and reactor parts. OES products have sea freight at 8000 km as transport type, approx. distance between USA and Norway. Structure has 14 tonne truck traveling 50 km as transport type. Reactor has light goods vehicle at 50 km as transport type. The last two reflecting the distance between Ås and local suppliers. Product life is set as 20 years with appliance in Europe. Energy used is set as electric to mechanical (electric motors) with a power rating of 40 W[68]. The example scenario of usage is 365 days a year, periodically each 3 hour. The rotate is set to take about 10 seconds.

When the reactor system is compared with different polymer reactors, the PP reactors have the least overall energy use (Figure 8-1) and CO2 footprints (Figure 8-2). The differences are in material and manufacture for both energy use and CO2 emissions. As seen is the summery chart in Figure 8-1 PP reactors have -12 % less energy usage than PA.

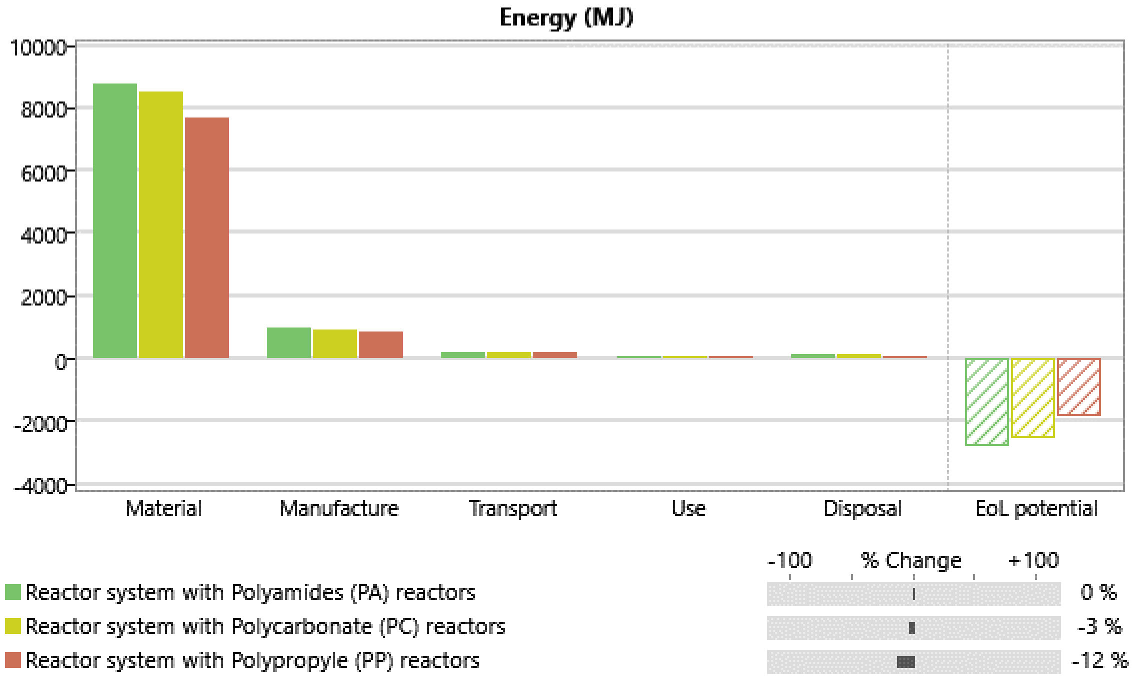


Figure 8-1. Eco Audit - Energy footprint comparison of reactor system with Polypropylene (PP), Polycarbonate (PC) or Polyamides (Nylons, PA) reactors

In the summery chart in Figure 8-2, the PP reactors have -16 % less CO2 footprint than PA.

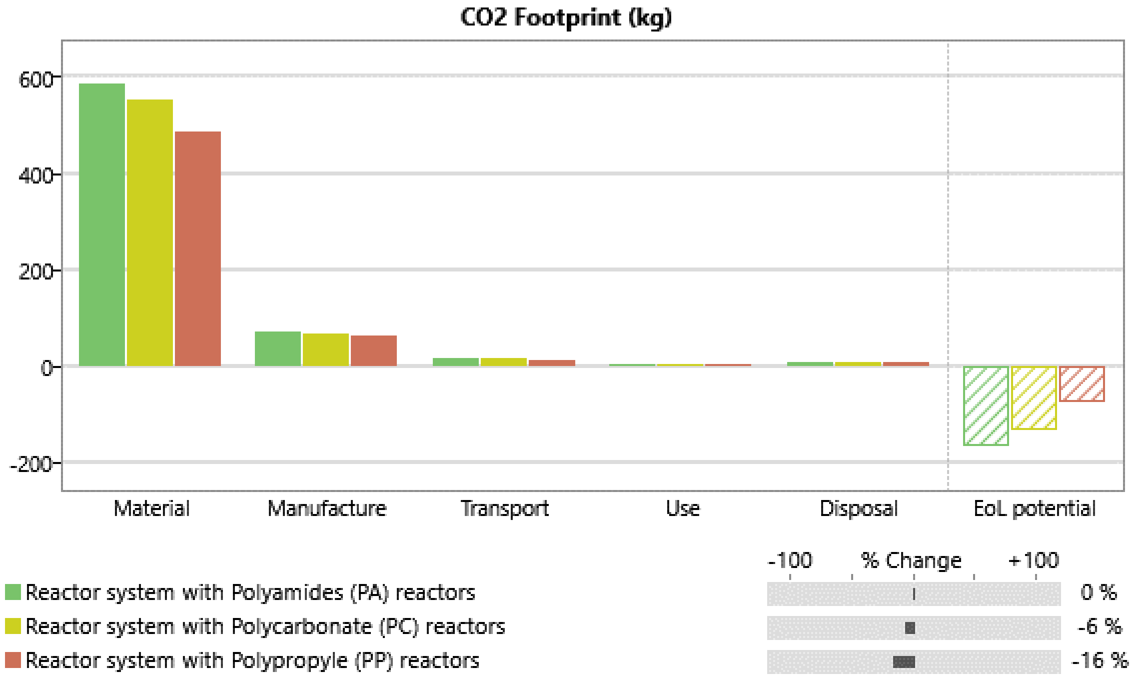


Figure 8-2. Eco Audit - CO2 footprint comparison of reactor system with Polypropylen (PP), Polycarbonate (PC) or Polyamides (Nylons, PA) reactors

In consultation with assistant supervisor about which reactor material that are 3D printable, he mentions that the PP filaments has been bought for the industrial workshop. It can therefore be tested for material properties in further work. Research also showed that the material has been used to 3D print microreactors at the University of Helsinki[69], with promising results. In conclusion, with the basis that price and environmental impact is lower than PC and PA, the reactors will be set as Polypropylen (PP) for reactor material in further development.

Figure 8-3 shows the relative energy and CO2 footprint contribution of life phase for the reactor system with PP reactors. The life phase being material, manufacture, transport, use, disposal and EoL potential. As the chart indicates it is the attaining of material which scores highest both of energy and CO2 footprints contra the rest of the factors.

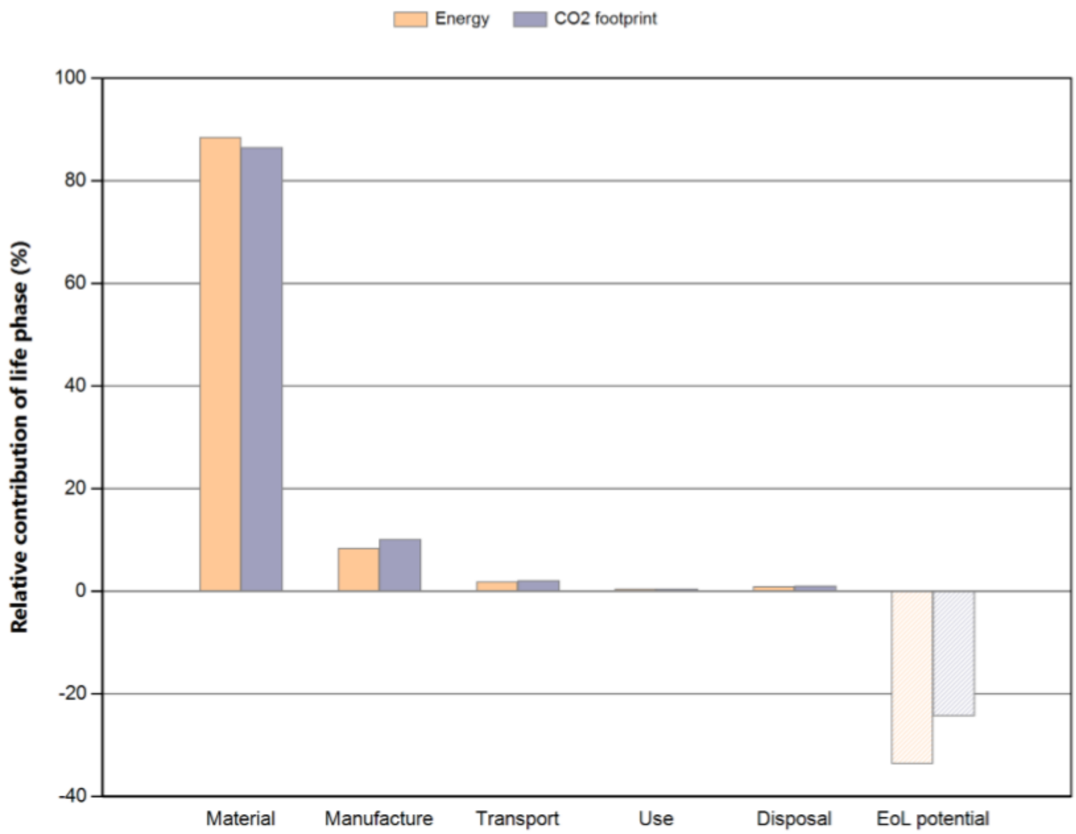


Figure 8-3. Eco Audit - Relative contribution of life phase for reactor system energy and CO2 footprint

To decrease environmental impact, it's important to select material with lowest body energy and CO2 emissions, use as little material as possible while still retaining strength and functions and use as large recycled content material as possible[70]. The last measure mentioned is set as an example by using virgin material (Table 8-1), meaning 0% recycled material compared with the original analysis where steel parts are 80% recycled and PP is 30% recycled (Table 8-2). This comparison of figures illustrates the importance of using recycled material, decreasing total energy by 2370 MJ and CO2 footprint by 125 kg.

Table 8-1. Eco Audit -Summary of energy and CO2 footprint for reactor system using all virgin material

Phase	Energy (MJ)	Energy (%)	CO2 footprint (kg)	CO2 footprint (%)
Material	9,88e+03	88,5	601	86,4
Manufacture	935	8,4	70,2	10,1
Transport	200	1,8	14,2	2,0
Use	53,8	0,5	2,94	0,4
Disposal	98,8	0,9	6,92	1,0
Total (for first life)	**1,12e+04**	**100**	**695**	**100**
End of life potential	-3,75e+03		-169	

Table 8-2. Eco Audit -Summary of energy and CO2 footprint for reactor system using recycled material

Phase	Energy (MJ)	Energy (%)	CO2 footprint (kg)	CO2 footprint (%)
Material	7,67e+03	87,0	486	85,3
Manufacture	811	9,2	60,8	10,7
Transport	192	2,2	13,6	2,4
Use	53,8	0,6	2,94	0,5
Disposal	94,8	1,1	6,63	1,2
Total (for first life)	**8,83e+03**	**100**	**570**	**100**
End of life potential	-1,84e+03		-76,7	

9. Manufacturing and production

This chapter contains detailed information about manufacture of the reactor system components and cost estimates for material and production.

9.1 Manufacturing

Technical drawing in 2D is attached as Appendix G: Technical drawings. Senior Engineer Henrik Holmberg at NMBU, has been consulted with construction drawings.

Reactor parts are described and illustrated in Table 9-1, Table 9-2 and Table 9-7

Housing components are described and illustrated Table 9-3 and Table 9-6.

Drive system components are described and illustrated in Table 9-4.

Platform is described and illustrated in Table 9-5 and Table 9-6.

9.1.1 Main components

The reactor described in this subchapter is the six-capsule reactor, since the hatch reactor is in an early developing stage, and not ready for manufacture. The six-capsule reactor also needs further development, but has shown with the "Bio Max" prototype that it can be used as a POC. The outer dimensions on both reactor alternatives are similar, including the mounting on the platform. So, in relation to the reactor system, it has no physical impact which reactor type is used of the two alternatives. The polymer reactor parts are created using 3D printing. Since the maximum dimensions for 3D printed parts is 200x200x200mm at the University, some or all the parts must be manufactured at an external supplier. A descaled rapid prototype may be a possibility at the University.

In this chapter the Polypropylene (PP) reactor parts are shown as off-white opaque, and not transparent.

Table 9-1. Six-capsuled reactor parts 3D printed in Polypropylene (PP)

○	Qty.	Description	Part
4	1	Lid with inlet and screw holes for fasteners. The valve solution determines the final inlet design. (Appendix G: Technical drawings – Drawing no. R04)	 *Figure 9-1. Lid*
5	1	Mid shell with lid attachment on top. The holes for the fasteners must have threads if outer shell is used. The mid shell is glued to the base and is pressed shut with the lid. (Appendix G: Technical drawings – Drawing no. R05)	 *Figure 9-2. Mid shell*
2	1	Outer shell fastened to the base and pressed down by the lid. (Appendix G: Technical drawings – Drawing no. R02)	 *Figure 9-3. Outer shell*

Table 9-1. Six-capsuled reactor parts 3D printed in Polypropylene (PP) cont.

◯	Qty.	Description	Part
6	6	Single capsule used for packing heterogeneous catalysts. Inside each capsule is a perforated plate (Figure 9-16) to hold the catalysts. (Appendix G: Technical drawings – Drawing no. R06)	 *Figure 9-4. Capsule*
		Figure 9-7 shows the capsules stacked on top of each other as when positioned inside the reactor.	 *Figure 9-5. Capsules*

Table 9-1. Six-capsuled reactor parts 3D printed in Polypropylene (PP) cont.

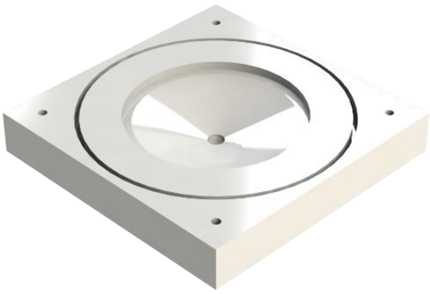
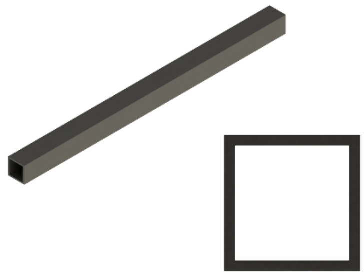
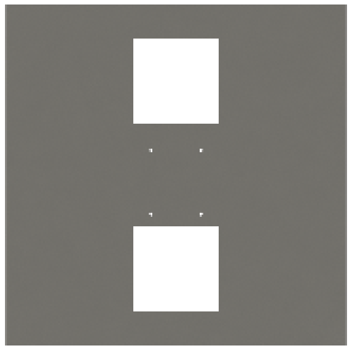
◯	Qty.	Description	Part
3	1	3D printed base for attachment to the rotating platform. The small engraved circle is for the placement of the mid shell and the large engraved circle is for placement of the outer shell. In the middle of the base is the funnel and outlet hole. (Appendix G: Technical drawings – Drawing no. R03)	 *Figure 9-6. Base*

Table 9-2. Six-capsuled reactor part stainless steel

◯	Qty.	Description	Part
7	1	Rod with plate to “fish” up the capsules when catalysts need change, or other maintenance is required. (Appendix G: Technical drawings – Drawing no. R07-1 and R07-2)	 *Figure 9-7. Rod with plate*

Table 9-3. Housing components

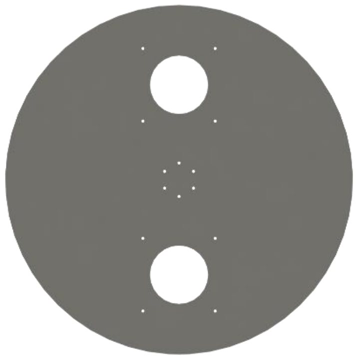
⬡	Qty.	Description	Part
4 8	16	l = 1200 mm (Appendix F: Catalogue) 25x25x2 mm hollow square structural profiles for housing framework (Appendix G: Technical drawings – Drawing no. 4)	 *Figure 9-8. Hollow square framework profiles*
5	1	1250x1200x4 mm (Appendix F: Catalogue) Hot-rolled plates support the rotating platform. Cut out holes for reactor outlets and drill holes for the fastening of the rotary stage (Appendix G: Technical drawings – Drawing no. 5)	 *Figure 9-9. Upper level deck*
6	1	1250x1200 mm Plywood or other lightweight material. Only purpose is support of lightweight components and equipment (Appendix G: Technical drawings – Drawing no. 6)	 *Figure 9-10. Lower level deck*

Drive system components is bought by OES Inc. The rotary plate (The circular shiny metal on top at Figure 9-11) is fastened to the platform and the fixed part of the component is fastened to the deck. The control system (Figure 9-12) is placed underneath on the plywood deck. The control system must be connected to the rotary stage.

Table 9-4. Drive system components

⬡	Qty.	Description	Part
4	1	Hollow Core Motorized Rotary Stage - AY110-200 by OES Inc. (Appendix F: Catalogue)	 *Figure 9-11. Hollow Core Motorized Rotary Stage [67]*
7	1	Serially Controlled Motion Control System - FIGARO Series by OES Inc. (Appendix F: Catalogue)	 *Figure 9-12. Motion Control system[67]*

Table 9-5. Platform component

	Qty.	Description	Part
3	1	Circular Ø1200x3 mm Hot-rolled plate with cut out holes for reactors outlets (Appendix F: Catalogue) 4x2 drilled holes for reactors M6x6 drilled holes for rotary stage (Appendix G: Technical drawings – Drawing no. 3)	 *Figure 9-13. Platform for mount of reactors*

9.1.2 Standard components

Table 9-6. Standard components for housing and rotating platform

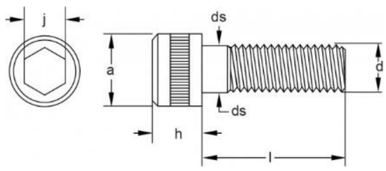
	Qty.	Description	Part
-	8	Socket Head Cap Screws (For mounting reactors to platform) d = M10.1.25 l = 55 mm h = 10 mm	 *Figure 9-14. Socket Head Cap Screws description (reactors to platform)*
-	6	Socket Head Cap Screws (For mounting rotary stage to platform) d = M10.1.25 l = 25 mm h = 10 mm	
	4	Socket Head Cap Screws (For mounting rotary stage to deck) d = M6.1.25 l = 10 mm h = 10 mm	

Table 9-7. Standard components for six-capsule reactor

○	Qty.	Description	Part
1	10 10 20	M12 Wing Nut M12 Hex head structural bolt M12 Flat washer	 *Figure 9-15. Fasteners aligned as when mounted on lid in reactor assembly*
3	6	A perforated sheet plate can be bought, cut to the right diameter, and drilled a M10 hole in the center. The perforated pattern in the plate must be smaller than the solid catalysts.	 *Figure 9-16. Perforated plate*

9.1.3 Assemble

The steel profiles (Figure 9-8) is welded together to the framework seen in Figure 9-17. Technical specifications and weldment are described in Appendix G: Technical drawings – Drawing no. 10. No detailed calculations of the weldment are done as consultations with Gunnar Torp and specialists at the workshop was made, and the framework profiles and material not advanced. The steel deck (Figure 9-9) is welded to the frame (Figure 9-17). The plywood deck (Figure 9-10) is not required to be fixed, but can be screwed or glued to the frame. **Note**: Weldment of frames must not interfere with the decks placement on top of the frame.

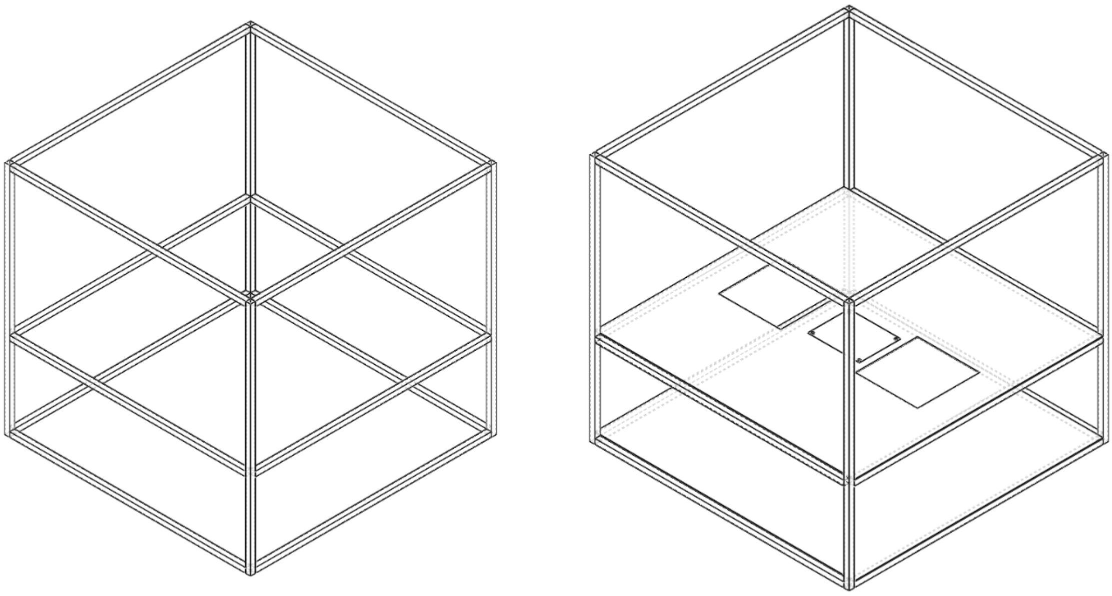


Figure 9-17. Housing assembly - Framework without and with the two deck levels

When the deck is welded to the framework, the motorized rotary stage (Figure 9-11) is fastened to it by 4 - M6 screws. The platform (Figure 9-13) is then fastened on top of the rotary stage by 6 - M10 screws (**Note**: The screw head is important to not exceed 10 mm, to not be higher than the rotary stage and interfere with the underside of the platform). Finally, the two reactors are fastened with 4 - M10 screws each (eight in total). Both the six-capsuled and the hatch reactor has same base dimensions and similar assembly with the platform.

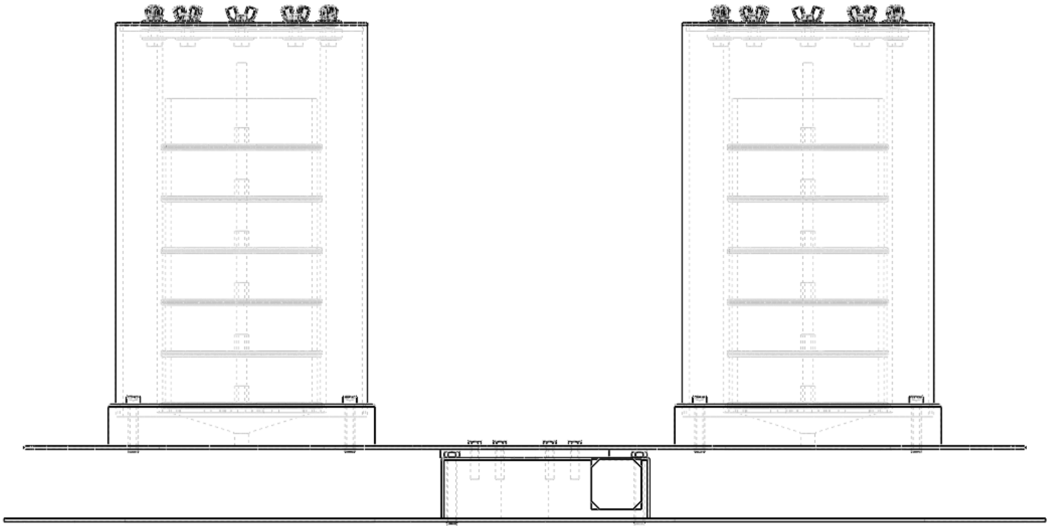


Figure 9-18. Assembly of rotating platform, deck and reactors – side view

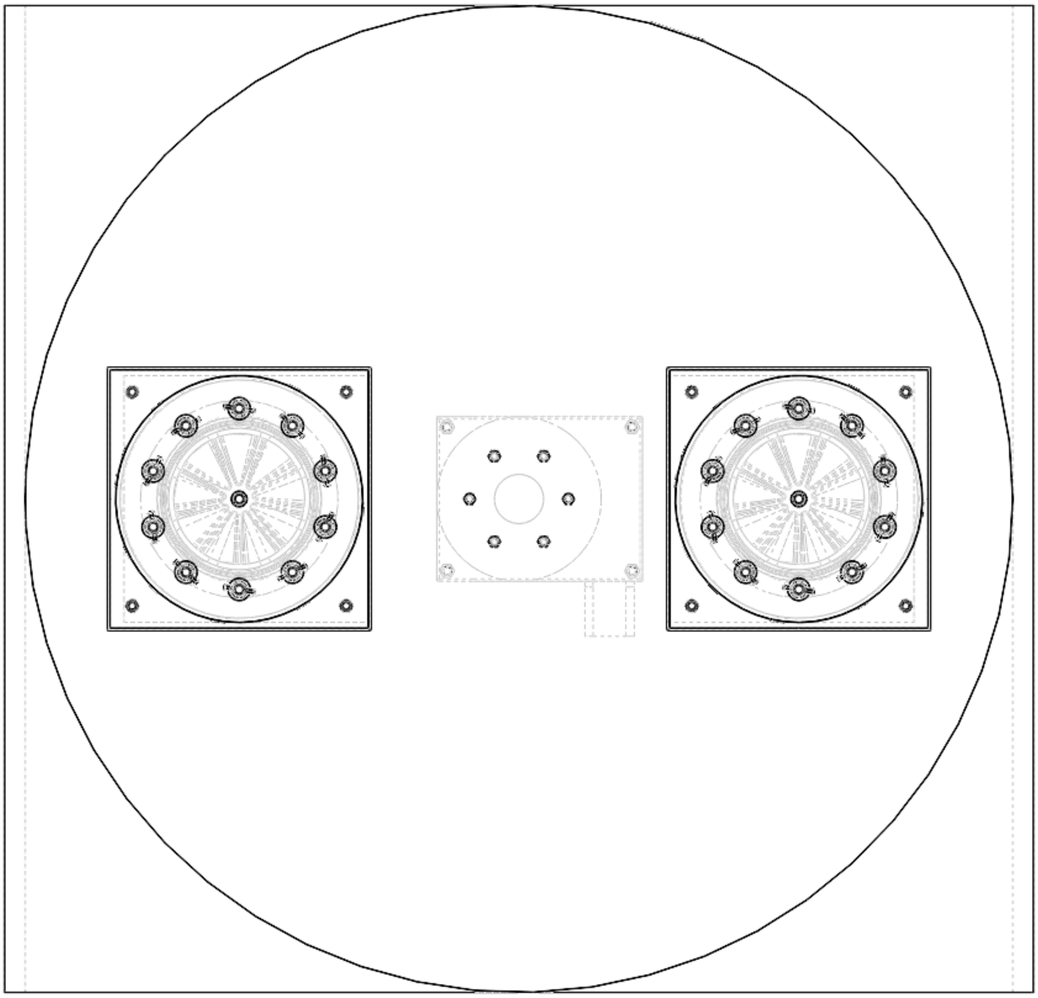


Figure 9-19. Assembly of rotating platform, deck and reactors – top view

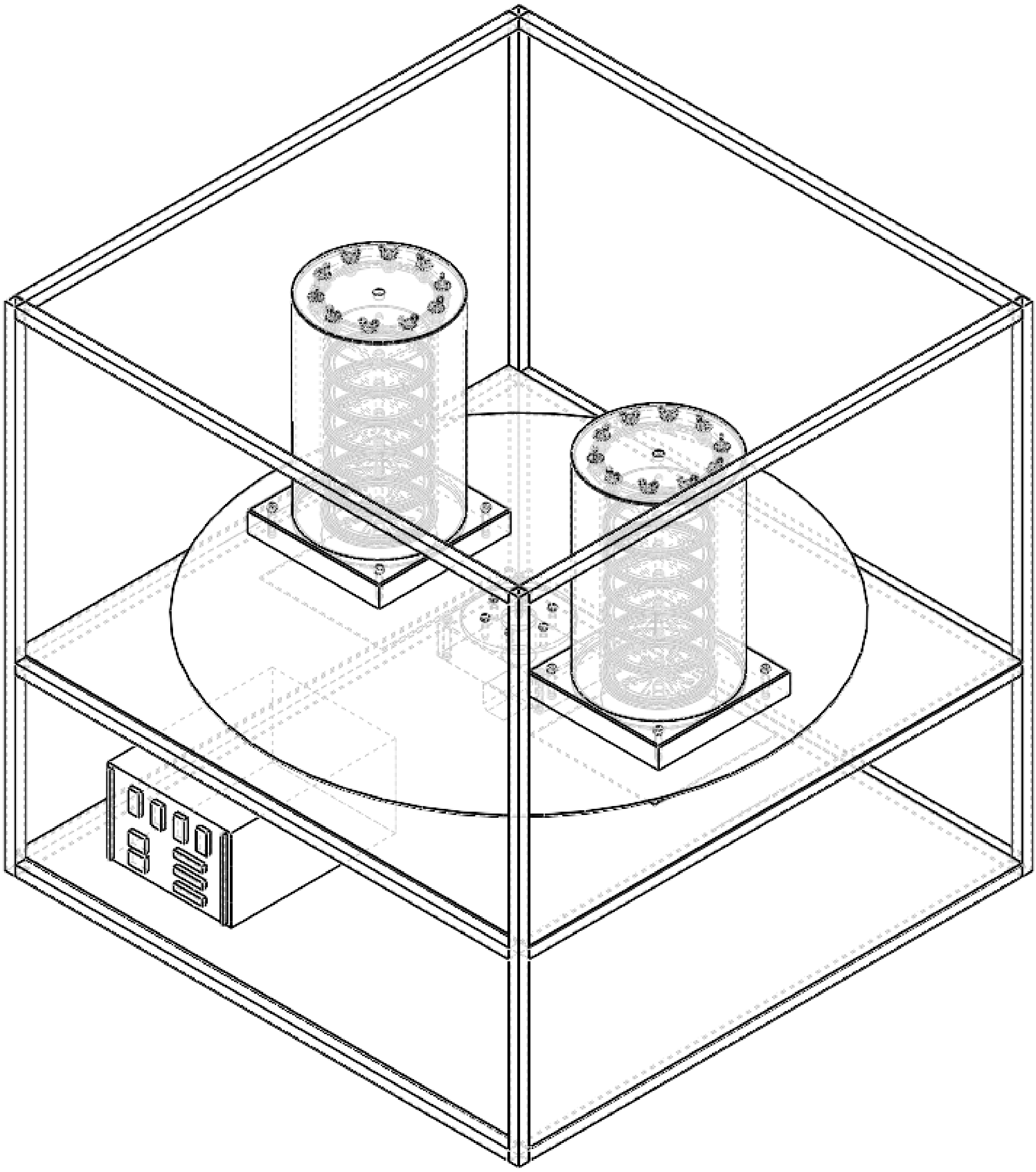


Figure 9-20. Assembly of reactor system - isometric view

Figure 9-20 shows the full assembly of the main components (except tubes, coupling etc.). The rotating platform and reactors are placed on the upper level deck and the control motion system is placed on the lower level on the plywood deck.

9.2 Material- and production costs

In this subchapter, a rough cost approximation of prototype and series production is completed. Labor hours/price and steel price was found in consultation with Gunnar Torp[71]. Table 9-8 shows a cost estimate for a prototype. The table posts are divided in concept development and prototyping which includes labor, materials and components. Cost of Plexiglas reactors are included, estimated from the price tag of the "Bio Max" project.

9.2.1 Cost estimate for prototype

The six-capsuled reactors made of Plexiglas cost 35 000 NOK each and was delivered from superprint.no including glue for the attachment of the reactor parts[53]. Since the polypropylene (PP) material is cheaper, the price for a 3D-printed reactor is chosen arbitrary at 30 000 NOK.

OES sale support offered a price for the rotary stage and control system over mail in a quotation said to be valid for 30 days. The prices are EXW out of their plant in Van Nuys, CA, USA, meaning cost will increase for shipping, import etc.

Table 9-8. Cost estimate for reactor system prototype

Post	**Hours**	**Qty.**	**Price**	**Sum [NOK]**
CONCEPT DEVELOPMENT				
Research and planning	150	-	550	82 500
Theoretical review	160	-	550	88 000
Conceptualizing	150	-	550	82 500
Report	200	-	550	110 000
Construction drawings	50	-	550	27 500
Subtotal development	710	-	550	390 500

Table 9-8. Cost estimate for reactor system prototype cont.

Post	Hours	Qty.	Price	Sum [NOK]
PROTOTYPING				
Production tools:				
-	-	-	-	-
Labor:				
Rough roll and casting	0.02	-	450	9
Manufacturing	0.5	-	450	225
Welding	4	-	600	2 400
Mounting	1	-	450	450
Materials and components:				
Reactor(s)	-	2	30 000	60 000
Rotary stage	-	1	-	21 422
Control system	-	1	-	12 836
Steel	-	102.4 kg	15 NOK/kg	1 536
Screws and small parts	-	-	100 NOK	100
Subtotal prototyping				98 978
Total cost				489 478

The cost analysis does not include the coupling system, which will increase the cost estimate for concept development, labor and material and components. Total cost of prototype is 489 478 NOK (Table 9-8).

9.2.2 Cost estimate for series production

A cost analysis for series production is completed to give an insight in what the cost estimate per unit will be if produced units increase.

Table 9-9. Cost estimates for series production

Post	Qty.	Price
Concept development	1	390 500
Production tools	-	-
Sum fixed expenses		390 500
Sum periodic expenses*	1	98 978

*Costs that vary by the number of units produced. Labor costs, materials and components are included as periodic expenses. When producing more units the cost of steel, parts and components will decrease because of discounts etc.[71]

Equation (7) shows how the price per units is calculated using the numbers from Table 9-9 with 100, 1000 and 10 000 produced units as an illustrating scenario.

$$price\ per\ unit = \frac{fixed\ expenses}{number\ of\ produced\ units} + periodic\ expenses \quad (7)$$

Table 9-10. Price per unit when producing hundred, thousand and ten thousand units

Number of units produced	10	100	1 000
Price per unit [NOK]	138 028	102 883	99 368.5

Table 9-10 shows the calculated price per unit for the number of units produced. With these numbers and without a coupling system, the price when producing more than 100 units will be about 100 000 NOK.

10. Presentation

Chapter includes a presentation of the final solution with rendered visualizations of reactor system with six-capsuled reactors and the hatch reactors. The chapter also has an improvement list for the current developed reactor system.

10.1 Visualization

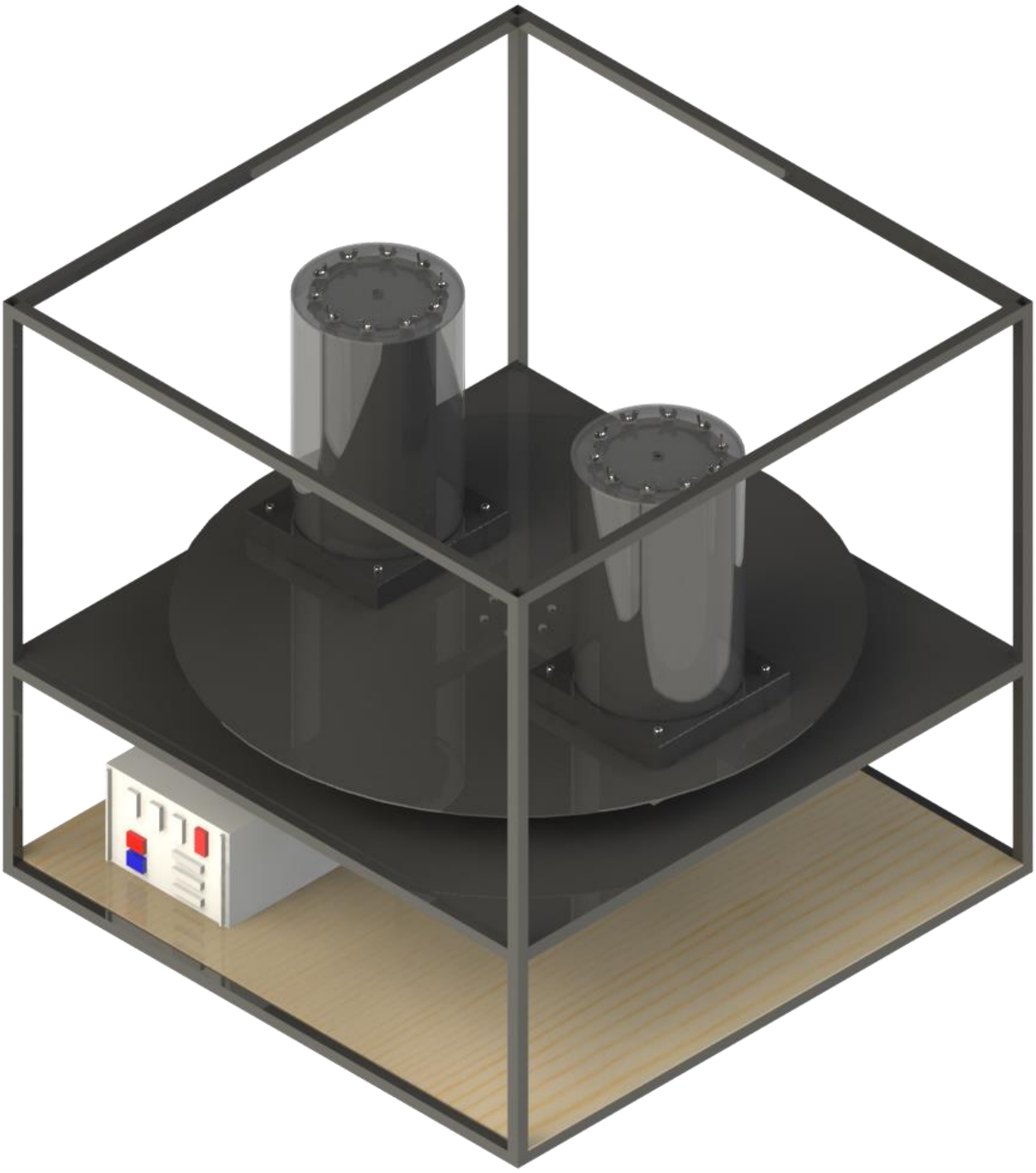


Figure 10-1. Presentation of reactor system with six-capsuled reactors

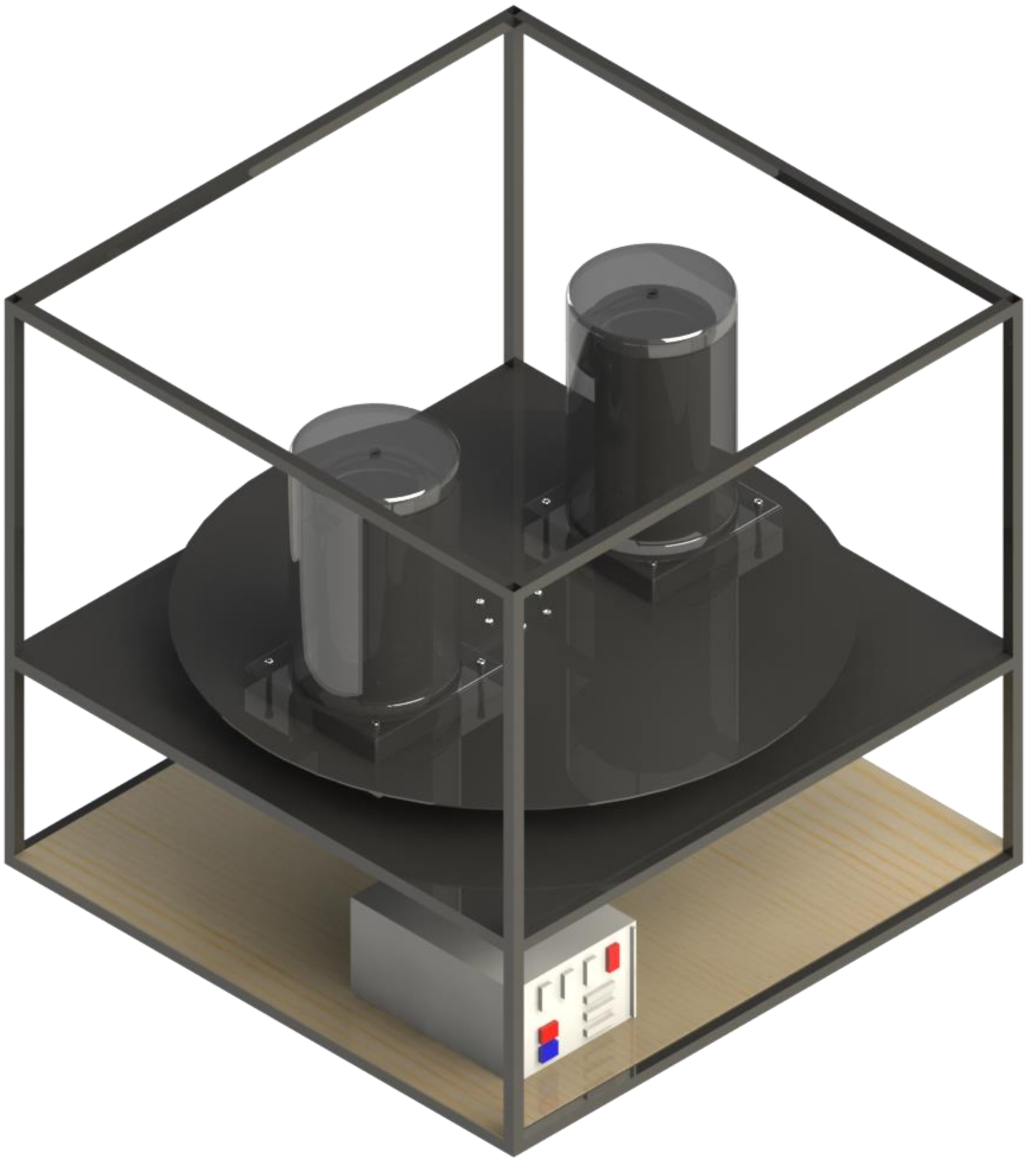


Figure 10-2. Presentation of reactor system with hatch reactors

10.2 Improvements

The improvements are based on the current reactor system design, as shown in the visualization. This means, among others, the coupling system is excluded and is described in further work.

- The reactors are in an early developing stage or a POC as the reactor system needs further optimization to achieve the preferred end-result. The “Bio Max” team suggests to make the reactors in stainless steel or glass instead of Plexiglas, because of the troubles in building with this type of material[53]. As seen in this report other polymers than Plexiglas can also be examined further for 3D printing, and the advantages that comes with this type of manufacturing method. Both reactors need to develop an inlet/outlet arrangement that comes with the coupling solution.
  - The six-capsuled reactors need another fastener option for the lid - if using the outer shell. When mounting the lid, it is not possible to get to the bottom end of the screws because of the outer shell. This can be solved by placing a thread or nut in the holes of the mid shell, so that there is no need to manually hold the screws at the bottom when fastening the lid.
  - The hatch reactor needs to develop hinges, close mechanism and seals/gaskets to keep it sealed. It could also be clever to design the hatch opening in a way to make it easier to pull the capsule out and put it back in.

11. Discussion

A low-temperature reactor system for biorefining waste oil, is researched for technological development. Many different systems and arrangements of the technical alternatives can be used to accomplish the task, but some are more promising than others. With further development, the reactor system can have a fully automatic periodically on-site clean of catalysts via two main subsystems. Discussed topics follows.

- Reactor system design
    - The structure and drive system can have multiple possibilities for a DIY solution, as reviewed in initial design. However, the coupling system to be in sync with a drive system requires more expensive components and regulator of system. The coupling system is therefore a bottleneck in this solution, but further development can result in other alternative solutions and therefore decreasing the use of manual labor as the reactor system requires now.
    - The operating environment in question is not a "shielded" place. The biorefinery could be used for example by the farmer, who is used to equipment that is rugged and rigid, or other similar rough environments. Therefore, it is no point in making the structure as light as possible or more optimized that it is. It is better to have a structure that can handle an accidental impact. The cost savings of a little less steel to the structure is small and insignificant.
- Reactor design and materials
    - The outer shell of the six-capsule reactors can provide more protection, but can be excluded in favor of less parts and easier mount of reactor-lid. In a test of the built prototype, the outer shell caused the lid to not be completely sealed, which caused a leak. Packing are of most important for the reactor to be properly sealed, and a fix was made to keep the outer shell. A citation from the "Bio Max" project report told this about the reactor development; *"There was also made a design flaw that is not shown in the drawing, namely fastening screws that was supposed to seal the entire reactor lid. This problem was later fixed by gluing nuts underneath the lid. If it were to be built new reactors and/or other vessels, they should not be built in Plexiglas.*

It looks good, but it is expensive and very difficult to build with. We have also learned that it (red. the material) is not very fond of high temperatures (over 100 ° C)."[53] The Polypropylene (PP) material, that was concluded for the reactor parts, can be interesting to further research and test if they have the needed qualities for this process.

  - The purpose of the capsule design in the reactors, is making the replacement of catalysts easier by decreasing labor. Therefore, using one capsule as the hatch reactor may be easier to handle, than many smaller as the six-capsuled reactor. The hatch reactor capsule has a height of 380 mm and 20 mm diameter, something that is still small and easy to handle. An advantage of using the six smaller capsules, is that it can be more manageable to empty and pack the catalyst.

- Cost of reactor system with wash vs. "regular" reactor system
  - The main argument for a reactor system with wash, is increasing cost-efficiency in a long-term perspective. A small-scale biorefinery with automatic catalyst handling, can seem against its purpose when a decentralized refinery is preferred cheap and simple, especially for a DIY. Comparing the reactor system to "regular" solutions (without the wash of catalysts), some of the parts and components are still the same. In a small-scale biorefinery without wash, there are no need of two reactors, except if the users wish to run them in parallel. Therefore, the price without the wash would exclude the cost of one reactor, the rotating platform (platform, drive system, control system) and the coupling system. These fixed costs must be compared to a reactor system without the wash-function. If further research shows that the advantage of slower catalysts deactivation and the increased efficiency of the process with catalyst wash, it may then be worth the start-up costs for this reactor system in a long-term perspective.

12. Conclusion

The part objectives of the project have been completed. It has been reviewed, designed and developed a solution for a reactor system platform to operate on with proposed technical components and arrangements for a fully automatic periodically on-site clean of catalysts.

The chapter contains a result overview of the project as well as recommendations and further work to finalize the reactor system.

12.1 Result

The issue surrounding this thesis was how to create a more cost-efficient biorefining of waste oil with heterogeneous catalysts. The idea was to prolong the activation time, to create a more sustainable small-scale biodiesel production, by capsuled designed reactors in a system for catalysts wash.

- Two types of chemical reactors are presented, the six-capsuled reactor and the hatch reactor. Both are continuous packed bed reactors manufactured by 3D printing, using mainly Polypropylene (PP) as material. The six-capsuled reactor is based on the "Bio Max" project and used in a prototype as a POC. It is constructed by stacking six capsules with perforated bottoms on top of each other. Two shells surround the capsules and with a lid fastened on top, the reactor is closed, with only one inlet and one outlet. The catalysts are changed by opening the top lid of the reactor and pulling them out with a rod. The other alternative presented, is a one-capsuled reactor with a hatch on the side. When catalysts deactivate, the hatch is opened, and the one (larger) capsule is pulled out for change of catalysts material or fully replaced with another capsule packed with activated heterogeneous catalysts. The principle is the same for the both reactors. The fluid reactants, waste oil and methanol, flows through the chemical reactors' capsule(s) and reacts with the fixed heterogeneous catalysts, resulting in the fluid product, biodiesel.
- The two reactors (ether two six-capsule reactors or two hatch reactors) are mounted on top of a platform. One is connected to the process of turning waste oil and methanol to biodiesel. The other is in a wash/de-oil operation, where the reactor is connected to a tube with clean methanol flowing into the reactor, washing the

catalyst material and preventing mechanisms of deactivation. Periodically, the reactors switch place. This is done by the platform they are mounted on, rotating 180 degrees, due to a motorized rotary stage, mounted under the rotating platform. Before the turn, the reactors disconnect from the tubes by an electrical linear actuator which disengages the couplings from the inlet and outlet with a vertical motion. When the rotation is done, the actuator engages the coupling motion again, and connects them to the reactor which switched place. As the reactor system is now, the periodically wash of catalyst depends on manual labor for engage and disengage of the reactor coupling. A suggestion for components to finalize the coupling system is presented, and further development must be performed to completely finalize the automatic reactor system.

The purpose of the subsystems is that one of the reactors is operational and the other reactor has a wash of catalyst, change of catalysts or other reactor maintenance. This way the reactors can change position and be washed periodically, resulting in that the catalytic material prolongs its activation time. With hollow square profile framework and square decks as housing, the system is easily mountable and further developed with the rest of a biorefinery arrangement.

12.2 Future work

To complete the reactor system and finalize the analysis' of the actual cost savings of a reactor system with a wash/de-oil of catalyst, future work must be conducted.

- The capsule designed reactors need further optimization and tests in flow simulation, design and manufacture process to cut costs of reactors and to achieve the preferred end-result. The polypropylene material of the reactor also needs a test to see if it is not affected by the chemical substances in the process.
- A test of the premise set for the catalyst washing must be done. Both to find the eventual greater pureness of the biodiesel product and the extended activation time.
- The coupling system must be finalized for a completely automatic reactor system. If an electrical linear actuator is chosen to control the engage and disengage motion, it

will need attachment to mount and operate on, both at the inlet and the outlet of the reactors.

- The housing must be finalized when all the reactor system components are developed (especially coupling system) and the rest of the biorefinery is ready for assembly
- The control motion system for the rotary stage needs to be programmed and regulated. When the coupling system is designed, it also needs to be programmed together with the rotary stage, so that the two subsystems are in sync when the automatic controlled reactor system is operational and the switch of reactor position takes place.

13. References

1. Roser, Max. (2016). *Energy Transitions: History, Requirements, Prospects*. Online: OurWorldInData.org. Available at: https://ourworldindata.org/energy-production-and-changing-energy-sources/ (accessed: 25.01.2017).
2. Agency, International Energy. (2016). Key World Energy Statistics.
3. Meyer, R.K. Pachauri and L.A. (2014). Climate Change 2014: Synthesis Report.
4. Council, World Energy. (2016). World Energy Resources 2016. London.
5. Jinlin Xuea, Tony E. Grift and Alan C. Hansena. (2011). Effect of biodiesel on engine performances and emissions. *Elsevier - Renewable and Sustainable Energy Reviews*, 15 (2).
6. Multiple. (2017). *Bio4Fuels*. Bio4Fuels Kick Off Seminar, Vitenparken, NMBU, Ås Campus.
7. Omberg, Kristian Sørby. (2015). *Small-scale biodiesel production based on a hereogenous technology*. Master Thesis.
8. Tess. (2016). *IFPEN unveils world's first 3D designed and printed chemical reactor*: 3ders.org. Available at: http://www.3ders.org/articles/20161024-ifpen-unveils-worlds-first-3d-designed-and-printed-chemical-reactor.html (accessed: 06.05.2017).
9. Engebretsen, Bjørn. (2012). *Prosjektledelse - Work Breakdown Structure*.
10. *Gantt chart*. (2017). gantt.com. Available at: http://www.gantt.com/.
11. Bøe, Jan Kåre. (2014). *Temahefte 1 og 2: Industriell økologi og prosjektplanlegging*: Institutt for Matematiske realfag og Teknologi, Ås. 34 pp. Unpublished manuscript.
12. Røsandnes, K.E. (2016). *Dolphin Sky, Del B: Utredning av systemkonsept, sikkerhet, produktsjon, markedsnisjer og økonomi*: Institutt for Matematiske realfag og Teknologi, Ås. Unpublished manuscript.
13. Ed de Jong, Hans Langeveld and René van Ree. (2009). IEA Bioenergy Task 42 Biorefinery.
14. Ashok Pandey, Christian Larroche, Steven Ricke, Claude-Gilles Dussap and Edgard Gnansounou. (2011). *Biofuels: Alternative Feedstock and Conversion Processes*. Oxford: Academic Press.
15. Energy, Office of Energy Efficiency & Renewable. *Biomass Feedstocks*. Available at: https://energy.gov/eere/bioenergy/biomass-feedstocks (accessed: 19.01.2017).
16. Morris, Neil. (2006). *Biomass Power*. London: Franklin Watts.
17. Bevan, Robert. (2013). *How Biorefineries and Green Products Will Make Their Mark*. Available at: https://www.youtube.com/watch?v=gDPI2EvrjMo&t=938s (accessed: 19.01.2017).
18. Jungmeier, Ed de Jong and Gerfried. (2015). *Industrial Biorefineries and White Biotechnology*: Elsevier.
19. Biofuel.org. *Biofuels*. Available at: http://biofuel.org.uk (accessed: 13.02.2017).

20. Tomes, Dwight. (2010). *Biofuels*. Dordrecht Springer.

21. Walker, Thomas Mullan and Alasdair. *Energy from Waste and Wood*: University of Edinburgh. Available at: http://energyfromwasteandwood.weebly.com/generations-of-biofuels.html (accessed: 23.02.2017).

22. Babcock, Bruce A. (2011). The Impact of US Biofuel Policies on Agricultural Price Levels and Volatility.

23. Michael Hannon, Javier Gimpel, Miller Tran, Beth Rasala and Stephen Mayfield. (2010). Biofuels from algae: challenges and potential. *NCBI*.

24. Muffoletto, Mary-Ann. (2014). Algae biofuel can help meet world energy demand, researchers say.

25. Gerhard Knothe, Jon Van Gerpen and Jürgen Krahl. (2005). *The Biodiesel Handbook*. Illinois: AOCS Press.

26. Klass, Donald L. (1998). *Biomass for Renewable Energy, Fuels, and Chemicals*. California: Academic press.

27. GreenerPro. *The Biodiesel Cycle*. Available at: http://www.greenerpro.com/Products.html (accessed: 18.01.2017).

28. Agency, Environmental Protection. (2002). A Comprehensive Analysis of Biodiesel Impacts on Exhaust Emissions.

29. Kegl, Breda. (2006). Biodiesel usage at low temperature. *Elsevier - Fuel*, 87 (7).

30. John Nowatzki, Dev Shrestha, Andrew Swenson and Dennis P. Wiesenborn. (2012). Biodiesel Cloud Point and Cold Weather Issues. *extension.org*.

31. I.M. Atadashi, M.K. Aroua, A.R. Abdul Aziz and N.M.N. Sulaiman. (2011). The effects of catalysts in biodiesel production: A review. *Journal of Industrial and Engineering Chemistry*.

32. 3.0, WordNet. (2003-2008). *Chemical reactor*: Farlex clipart collection. Available at: http://www.thefreedictionary.com/chemical+reactor (accessed: 22.02.2017).

33. Nanda, Dr. Sanju. (2008). Reactors and Fundamentals of Reactors Design for Chemical Reaction Haryana: Dept. of Pharmaceutical Sciences

34. Industry, The Essential Chemical. (2013). *Chemical reactors*: The University of York. Available at: http://www.essentialchemicalindustry.org/processes/chemical-reactors.html (accessed: 22.02.2017).

35. Gerpen, Drs. Brian He and Jon Van. (2015). *Reactors for Biodiesel Production*: extension.org. Available at: http://articles.extension.org/pages/26630/reactors-for-biodiesel-production (accessed: 15.02.2017).

36. Fogler, H. Scott. (2014). *Elements of Chemical Reaction Engineering*. Fourth ed. Essex: Pearson.

37. (CIEC), Centre for Industry Education Collaboration. (2013). *Catalysis in industry*: University of York. Available at: http://www.essentialchemicalindustry.org/processes/catalysis-in-industry.html (accessed: 24.01.2017).

38. Science, Everything Maths &. *Mechanism of reaction and catalysis*. Available at: https://www.everythingmaths.co.za/science/grade-12/07-rate-and-extent-of-reaction/07-rate-and-extent-of-reaction-04.cnxmlplus (accessed: 25.01.2017).

39. Törnqvist, Eric Olof. (2017). *Catalyst handling - Master thesis* (10.02.2017).

40. Jegannathan, Pogaku Ravindra and Kenthorai Raman. (2015). Production of biodiesel using lipase encapsulated in κ-carrageenan. *SpringerBriefs in Bioengineering*.

41. Sch€uth, Roberto Rinaldi and Ferdi. (2009). Design of solid catalysts for the conversion of biomass. *Royal Society of Chemistry*.

42. Arumugam Sivasamy, Kien Yoo Cheah, Paolo Fornasiero, Francis Kemausuor, Sergey Zinoviev and Stanislav Miertus. (2009). Catalytic Applications in the Production of Biodiesel from Vegetable Oils. *ChemSusChem*.

43. Sulaiman, Nur Syakirah Talha and Sarina. (2016). Overview Of Catalysts In Biodiesel Production. *ARPN Journal of Engineering and Applied Sciences*.

44. Abhishek Guldhe, Bhaskar Singh, Taurai Mutanda, Kugen Permaul and Faizal Bux. (2013). Advances in synthesis of biodiesel via enzyme catalysis: Novel and sustainable approaches. *Elsevier - Renewable and Sustainable Energy Reviews*, 41.

45. Transbiodiesel. (2016). *Immobilized Enzymes for Production of Biodiesel*: Transbiodiesel.com. Available at: http://www.transbiodiesel.com/products-and-services/products-overview.

46. H. Fukuda, S. Hama, S. Tamalampudi and H. Noda. (2008). Whole-cell biocatalysts for biodiesel fuel production. *Trends in Biotechnology*, 26 (12).

47. Bartholomew, Morris D. Argyle and Calvin H. (2015). Heterogeneous Catalyst Deactivation and Regeneration: A Review. *Catalysts*, 5.

48. Poussin, Bernard. (2017). *Catalyst handling - Master thesis* (31.01.2017).

49. Stanislaus, M. Marafi and A. (2003). Options and processes for spent catalyst handling and utilization. *Elsevier - Journal of Hazardous Materials*, 101 (2).

50. Omberg, Kristian. (2017). *Specifications* (01.02.2017).

51. Torp, Gunnar. (2017). *Initial design* (01.03.2017).

52. Seehusen, Joachim. (2017). Gjennombrudd for 3D i serieproduksjon. *Teknisk Ukeblad*.

53. Oscar Amlie, Erik Sjølund, Eivind Myrvold & Tord Reinaas. (2017). Prosjekt «Bio. Max». NMBU.

54. Wildi, Theodore. (2006). *Electrical Machines, Drives and Power Systems* 6th ed. United States: Pearson Education Inc.

55. Campbell, Collin. (2015). Motorised Rotating Platform. Seelio: The University of Edinburgh.

56. Lenert, Robert. (2014). *Odp: Philips 212 Electronic*. Available at: http://winyle.domek.org/index.php?topic=224.0. (accessed: 21.03.2017).

57. Gunnar Dahlvig, Sigmund Christensen og Gunnar Strømsnes. (2000). *Konstruksjonselementer*: Gyldendal.

58. Sharma, Sourabh. (2016). *Gear arrangements*. Available at: https://www.youtube.com/channel/UCTygEZlDMYHU7JNXLpiGYgw/search?query=gear (accessed: 22.03.2017).

59. Atta, Talha. (2015). *Advantages and Disadvantages of Different Types of Gears*: http://www.green-mechanic.com. Available at: http://www.green-mechanic.com/2014/05/advantages-and-disadvantages-of_7.html (accessed: 22.03.2017).

60. Clapperton, Brian. *Turntable Drive Unit*. Available at: http://www.abcgear.talktalk.net/html/turntable_drive_unit.html (accessed: 21.03.2017).

61. Station, Tool. (2017). *Wheels & Castors*: Tool Station. Available at: http://www.toolstation.com (accessed: 20.03.2017).

62. Rouse, Margaret. (2015). *actuator*: http://internetofthingsagenda.techtarget.com. Available at: http://internetofthingsagenda.techtarget.com/definition/actuator (accessed: 29.03.2017).

63. Erlandsen, Lasse. (2017). *Actuators*: LINAK (29.03.2017).

64. LINAK. *Products - Linear Actuator*. Available at: https://www.linak.com/products/linear-actuators.aspx?product=LA25 (accessed: 29.03.2017).

65. Hydraulic, Oleocon. (2015). *Oleocon Hydraulic Quick Coupling*. Available at: https://www.youtube.com/watch?v=lPEigK8pkL0 (accessed: 29.03.2017).

66. Tibnor. (2014). *Lagerkatalog 2015*.

67. Optimal Engineering Systems, Inc. (OES). (2017). *Motion Control Products*. Available at: http://www.oesincorp.com/index.html (accessed: 16.03.2017).

68. Hank, Joseph. (2017). *Rotating platform*: OES.

69. Helsinki.fi. (2017). *3D printing for more efficient research*: University of Helsinki. Available at: https://www.helsinki.fi/en/news/3d-printing-for-more-efficient-research (accessed: 06.05.2017).

70. Granta. (2016). *Material database in CES EduPack Eco Audit*. 16.1.22.0 ed.: Granta.

71. Torp, Gunnar. (2017). *Steel price and manufacturing* (18.04.2017).

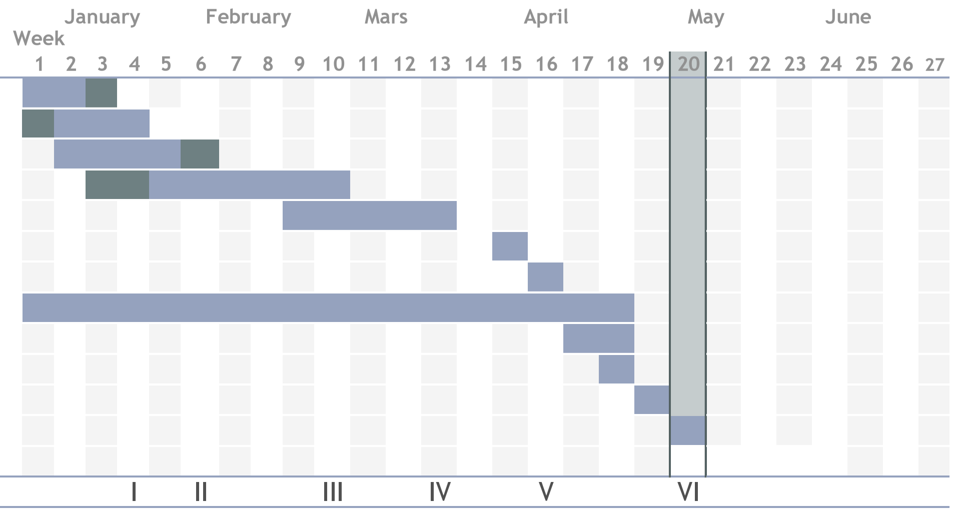
Appendix

Appendix A: Project schedule

Project schedule

Week highlight: 20 | Plan | Actual | % Complete | Actual (beyond plan)

ACTIVITY	PLAN START	PLAN DURATION	ACTUAL START	ACTUAL DURATION	PERCENT COMPLETE
Initial work	1	2	1	3	100 %
Literature review	2	4	1	4	100 %
Defining issues, objectives and limitations	2	4	2	5	100 %
Conceptual design of reactor system	5	6	3	8	100 %
CAD of concept	9	5	9	5	100 %
Enviremental analyis	14	2	15	1	100 %
Cost estimate of prototype and series production	15	2	16	1	100 %
Report writing and documentation	1	18	1	18	100 %
Finalization and editing	17	2	17	2	100 %
Deadline (May 5 - Tuesday, Week 18)	18	1	18	1	100 %
Printing (May 8 - Monday, Week 19)	19	1	19	1	100 %
Submitting of report (May 15 - Monday, Week 20)	20	1	20	1	100 %
Presentation preparations	20	5	-	-	0 %
Milestones (Part objectives)					



Appendix B: Process evaluation

The thesis has given an insight in a new subject and field of study. Creating a reactor system turned out to be a comprehensive task, because of all the technical alternatives and the multiple subsystems to be studied and developed.

Since the assignment varied a lot from start and into the thesis' period, it was hard to find which direction to take the development in and what to concentrate on. A lot of study was done, since all chemical aspects of the project was new to me, and therefore a great deal of time went to the initial literature review. Since there was an incredible amount of publications and literature within biofuels and bioenergy, a clearer objective from start would most likely decrease the amount used to browse through resources.

If done again, more focus would be on the chemical reactors and 3D printing of them. There are a lot of interesting projects surrounding this type of processing of chemical reactors, something that was discovered later in the thesis' process. A possibility would be to research what material within polymers, metals, glass' etc. would be most suitable. 3D printing in metals is an innovative way of developing chemical reactors with detailed designs. A huge initiative is the Norwegian Center for Sustainable Bio-based Fuels and Energy, explained short in the introduction. Here, there can be numerous interested partners for concept developments or funding for further development of biofuels projects at the University.

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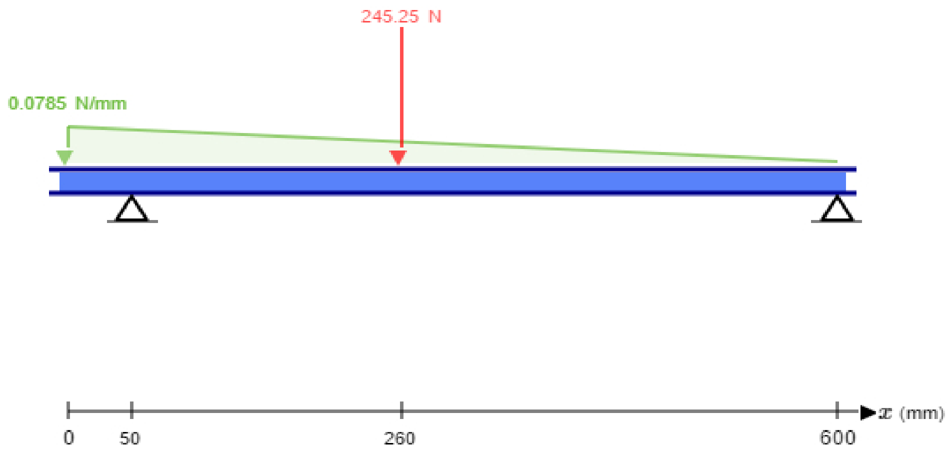
Appendix C: SkyCiv – Report

BEAM ANALYSIS REPORT

Tue May 09 2017 09:51:08 GMT+0200 (Vest-Europa (sommertid))



File Name: Rotate platform section med reactor

Software: SkyCiv Beam v2.0.3

Job Name: Empty

Designer: Empty

Included in this Report:

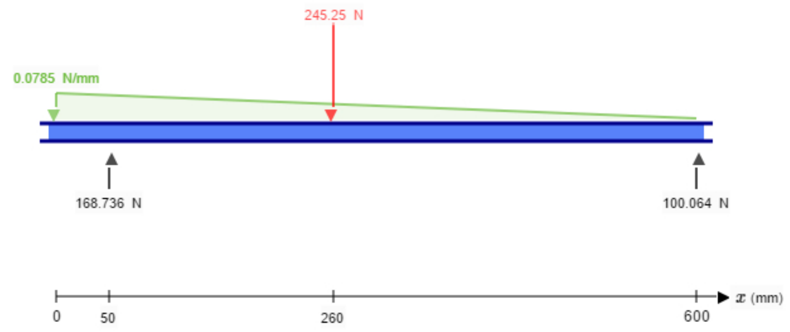
Free Body Diagram (FBD)

Shear Force Diagram (SFD)

Bending Moment Diagram (BMD)

Free Body Diagram (FBD)

Show Equivalent Loads



Start by finding the equivalent loads caused by the distributed loads (DLs).
Remember that the equivalent load of a DL has a magnitude equal to its area, acting through the area's centroid.

Equivalent load(s) of the DL from $x = 0\text{mm}$ to $x = 600\text{mm}$:

Triangular Load Magnitude: $\frac{1}{2} \times (600\text{mm} - 0\text{mm}) \times (-0.0785\text{N/mm} - 0\text{N/mm}) = -23.55\text{N}$

Triangular Load Position: $0\text{mm} + \frac{600\text{mm} - 0\text{mm}}{3} = +200\text{mm}$

Let the left support have a vertical reaction R_A and the right support have a vertical reaction R_B.
Sum of forces along the **y-axis** is equal to zero for static equilibrium:

$$+\uparrow \Sigma F_y = 0$$
$$R_A + R_B - 245.25 - 23.55 = 0$$
$$R_A + R_B - 245.25 - 23.55 = 0$$
$$R_A + R_B = +268.8\text{N} \quad \text{---- (1)}$$

Sum of moments about the **left** support is equal to zero for static equilibrium:

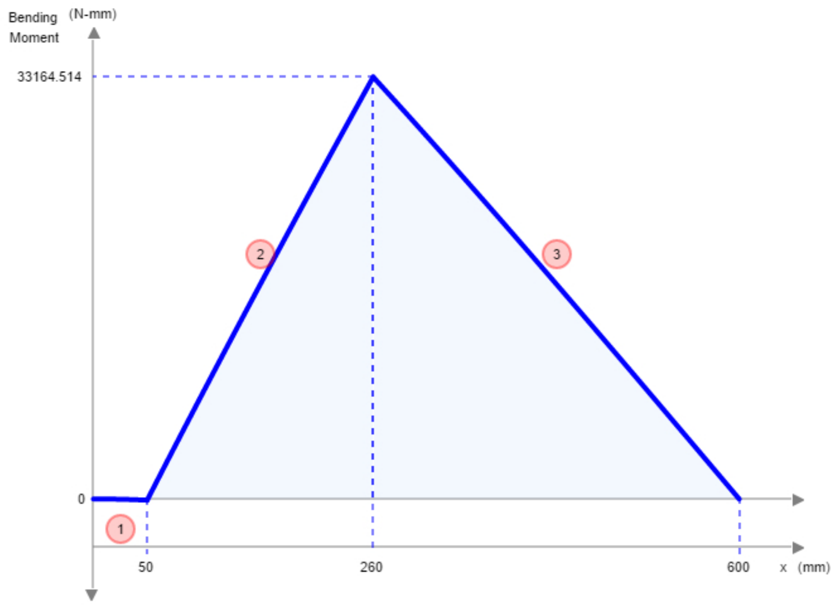
$$+\circlearrowleft \Sigma M = 0$$
$$R_B(600 - 50) + (-245.25)(260 - 50) + (-23.55)(+200 - 50) = 0$$
$$R_B(600 - 50) + (-245.25)(+210) + (-23.55)(+200 - 50) = 0$$
$$R_B = +100.064\text{N} \quad \text{---- (2)}$$

Substitute (2) into (1):

$$R_A + R_B = +268.8$$
$$R_A + 100.064 = +268.8$$
$$R_A = +168.736\text{N}$$

SkyCiv ONLINE ENGINEERING SOFTWARE

Bending Moment Diagram (BMD)



Bending Moment Equations

$M_1(x) = 0$

$M_2(x) = 0.0000218063x^3 - 0.03925x^2 + 168.736x - 8436.8$

$M_3(x) = 0.0000218063x^3 - 0.03925x^2 - 76.514x + 55328.2$

Take a cut for $0 \leq x \leq 50$:

$$+\circlearrowleft \Sigma M_x = 0$$
$$+\left[-0.039x^2 + 0x^3\right] - M_1(x) = 0$$
$$M_1(x) = -0.039x^2 + 0x^3$$
$$\therefore M_1(x) = -0.039x^2 + 0x^3 \qquad \text{for} \quad 0 \leq x \leq 50$$

Take a cut for $50 \leq x \leq 260$:

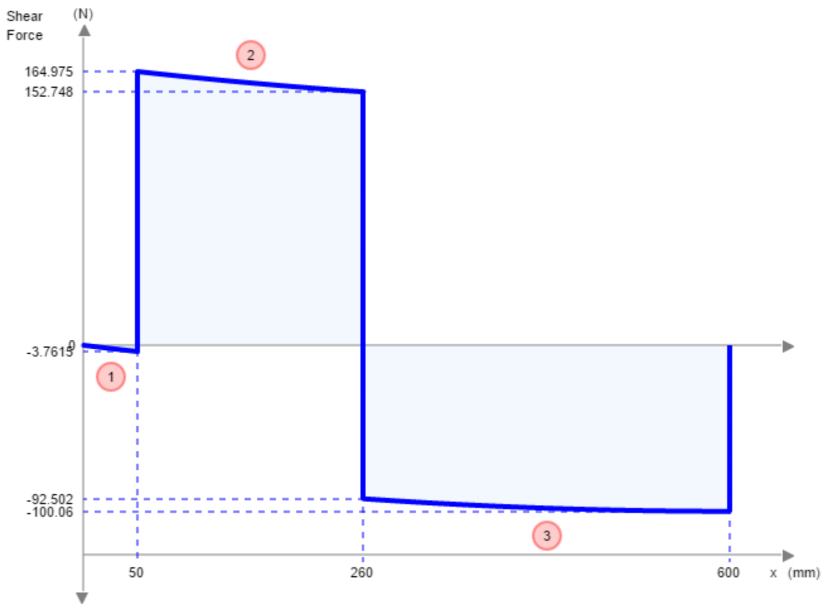
$$+\circlearrowleft \Sigma M_x = 0$$
$$+(168.736)(x-50) + \left[-0.039x^2 + 0x^3\right] - M_2(x) = 0$$
$$M_2(x) = -8436.8 + 168.736x - 0.039x^2 + 0x^3$$
$$\therefore M_2(x) = -8436.8 + 168.736x - 0.039x^2 + 0x^3 \qquad \text{for} \quad 50 \leq x \leq 260$$

Take a cut for $260 \leq x \leq 600$:

$$+\circlearrowleft \Sigma M_x = 0$$
$$+(168.736)(x-50) + (-245.25)(x-260) + \left[-0.039x^2 + 0x^3\right] - M_3(x) = 0$$
$$M_3(x) = +55328.2 - 76.514x - 0.039x^2 + 0x^3$$
$$\therefore M_3(x) = +55328.2 - 76.514x - 0.039x^2 + 0x^3 \qquad \text{for} \quad 260 \leq x \leq 600$$

SkyCiv ONLINE ENGINEERING SOFTWARE

Shear Force Diagram (SFD)



Shear Force Equations

$V_1(x) = 0$

$V_2(x) = 0.000065417x^2 - 0.0785x + 168.736$

$V_3(x) = 0.000065417x^2 - 0.0785x - 76.514$

Take a cut for $0 \leq x \leq 50$:

$$+\uparrow \Sigma F_y = 0$$
$$+\left[-0.079x + 0x^2\right] - V_1(x) = 0$$
$$V_1(x) = -0.079x + 0x^2$$
$$\therefore V_1(x) = -0.079x + 0x^2 \qquad \text{for} \quad 0 \leq x \leq 50$$

Take a cut for $50 \leq x \leq 260$:

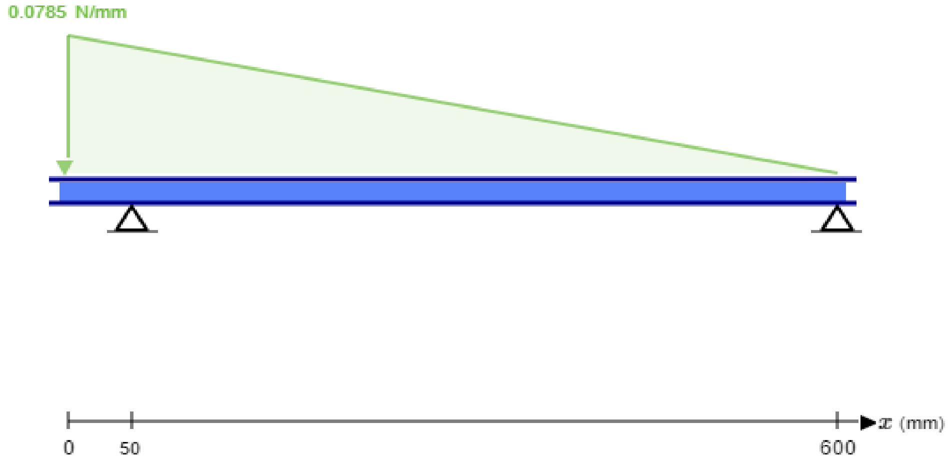
$$+\uparrow \Sigma F_y = 0$$
$$+168.736 + \left[-0.079x + 0x^2\right] - V_2(x) = 0$$
$$V_2(x) = +168.736 - 0.079x + 0x^2$$
$$\therefore V_2(x) = +168.736 - 0.079x + 0x^2 \qquad \text{for} \quad 50 \leq x \leq 260$$

Take a cut for $260 \leq x \leq 600$:

$$+\uparrow \Sigma F_y = 0$$
$$+168.736 - 245.25 + \left[-0.079x + 0x^2\right] - V_3(x) = 0$$
$$V_3(x) = -76.514 - 0.079x + 0x^2$$
$$\therefore V_3(x) = -76.514 - 0.079x + 0x^2 \qquad \text{for} \quad 260 \leq x \leq 600$$

BEAM ANALYSIS REPORT

Tue May 09 2017 09:52:45 GMT+0200 (Vest-Europa (sommertid))



File Name: Rotate platform section uten reactor

Software: SkyCiv Beam v2.0.3

Job Name: Empty

Designer: Empty

Included in this Report:

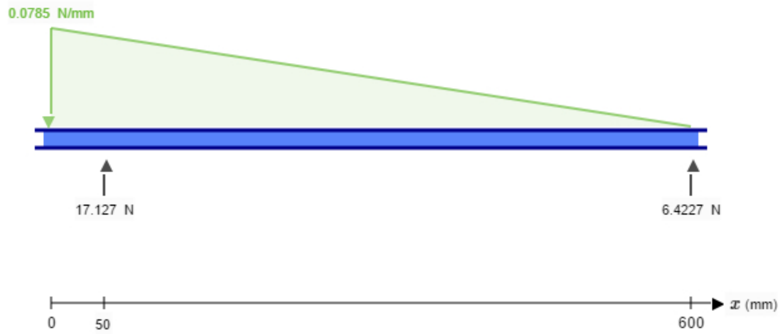
Free Body Diagram (FBD)

Shear Force Diagram (SFD)

Bending Moment Diagram (BMD)

Free Body Diagram (FBD)

Show Equivalent Loads



Start by finding the equivalent loads caused by the distributed loads (DLs).
Remember that the equivalent load of a DL has a magnitude equal to its area, acting through the area's centroid.

Equivalent load(s) of the DL from $x = 0\text{mm}$ to $x = 600\text{mm}$:

Triangular Load Magnitude: $\frac{1}{2} \times (600\text{mm} - 0\text{mm}) \times (-0.0785\text{N/mm} - 0\text{N/mm}) = -23.55\text{N}$

Triangular Load Position: $0\text{mm} + \frac{600\text{mm} - 0\text{mm}}{3} = +200\text{mm}$

Let the left support have a vertical reaction R_A and the right support have a vertical reaction R_B.
Sum of forces along the **y-axis** is equal to zero for static equilibrium:

$$+\uparrow \Sigma F_y = 0$$
$$R_A + R_B - 23.55 = 0$$
$$R_A + R_B = +23.55\text{N} \quad \text{---- (1)}$$

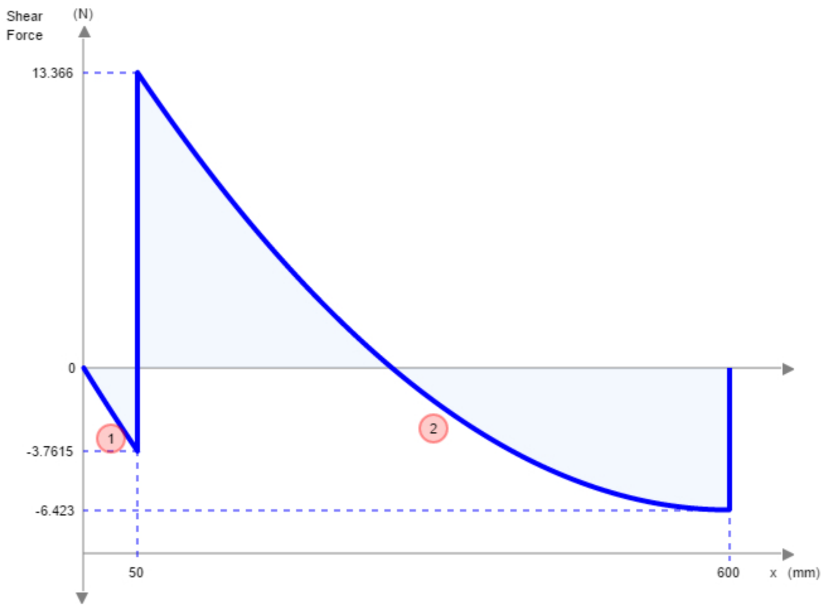
Sum of moments about the **left** support is equal to zero for static equilibrium:

$$+\circlearrowleft \Sigma M = 0$$
$$R_B(600 - 50) + (-23.55)(+200 - 50) = 0$$
$$R_B = +6.423\text{N} \quad \text{---- (2)}$$

Substitute (2) into (1):

$$R_A + R_B = +23.55$$
$$R_A + 6.423 = +23.55$$
$$R_A = +17.127\text{N}$$

Shear Force Diagram (SFD)



Take a cut for $0 \le x \le 50$:

$$+\uparrow \Sigma F_y = 0$$
$$+\left[-0.079x + 0x^2\right] - V_1(x) = 0$$
$$V_1(x) = -0.079x + 0x^2$$
$$\therefore V_1(x) = -0.079x + 0x^2 \quad \text{for} \quad 0 \le x \le 50$$

Take a cut for $50 \le x \le 600$:

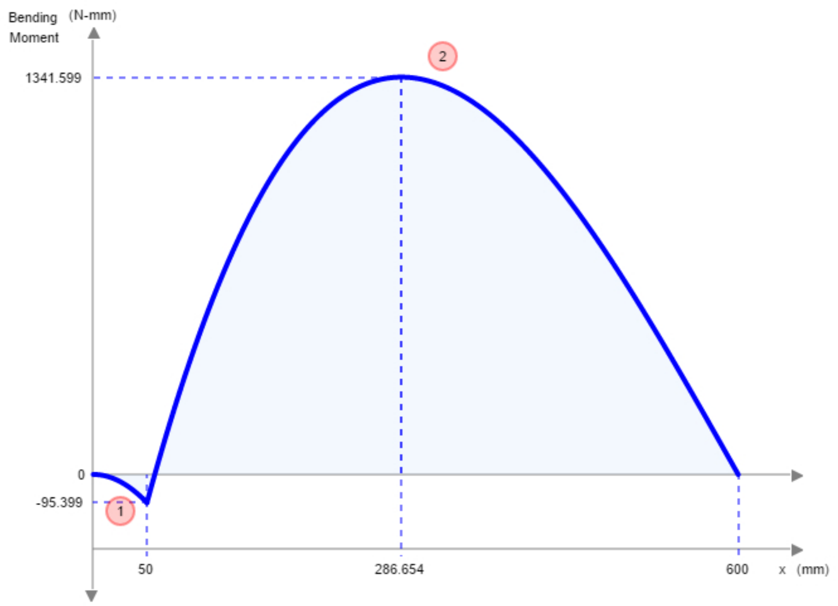
$$+\uparrow \Sigma F_y = 0$$
$$+17.127 + \left[-0.079x + 0x^2\right] - V_2(x) = 0$$
$$V_2(x) = +17.127 - 0.079x + 0x^2$$
$$\therefore V_2(x) = +17.127 - 0.079x + 0x^2 \quad \text{for} \quad 50 \le x \le 600$$

Shear Force Equations

$V_1(x) = 0.000065417x^2 - 0.0785x$

$V_2(x) = 0.000065417x^2 - 0.0785x + 17.127$

Bending Moment Diagram (BMD)



Take a cut for $0 \leq x \leq 50$:

$$
\begin{aligned}
&+ \circlearrowleft \Sigma M_x = 0 \\
&+ \left[-0.039x^2 + 0x^3\right] - M_1(x) = 0 \\
&M_1(x) = -0.039x^2 + 0x^3 \\
&\therefore M_1(x) = -0.039x^2 + 0x^3 \qquad \text{for} \quad 0 \leq x \leq 50
\end{aligned}
$$

Take a cut for $50 \leq x \leq 600$:

$$
\begin{aligned}
&+ \circlearrowleft \Sigma M_x = 0 \\
&+ (17.127)(x - 50) + \left[-0.039x^2 + 0x^3\right] - M_2(x) = 0 \\
&M_2(x) = -856.35 + 17.127x - 0.039x^2 + 0x^3 \\
&\therefore M_2(x) = -856.35 + 17.127x - 0.039x^2 + 0x^3 \qquad \text{for} \quad 50 \leq x \leq 600
\end{aligned}
$$

Bending Moment Equations

$M_1(x) = 0$

$M_2(x) = 0.0000218063x^3 - 0.03925x^2 + 17.127x - 856.35$

Norwegian University of Life Sciences

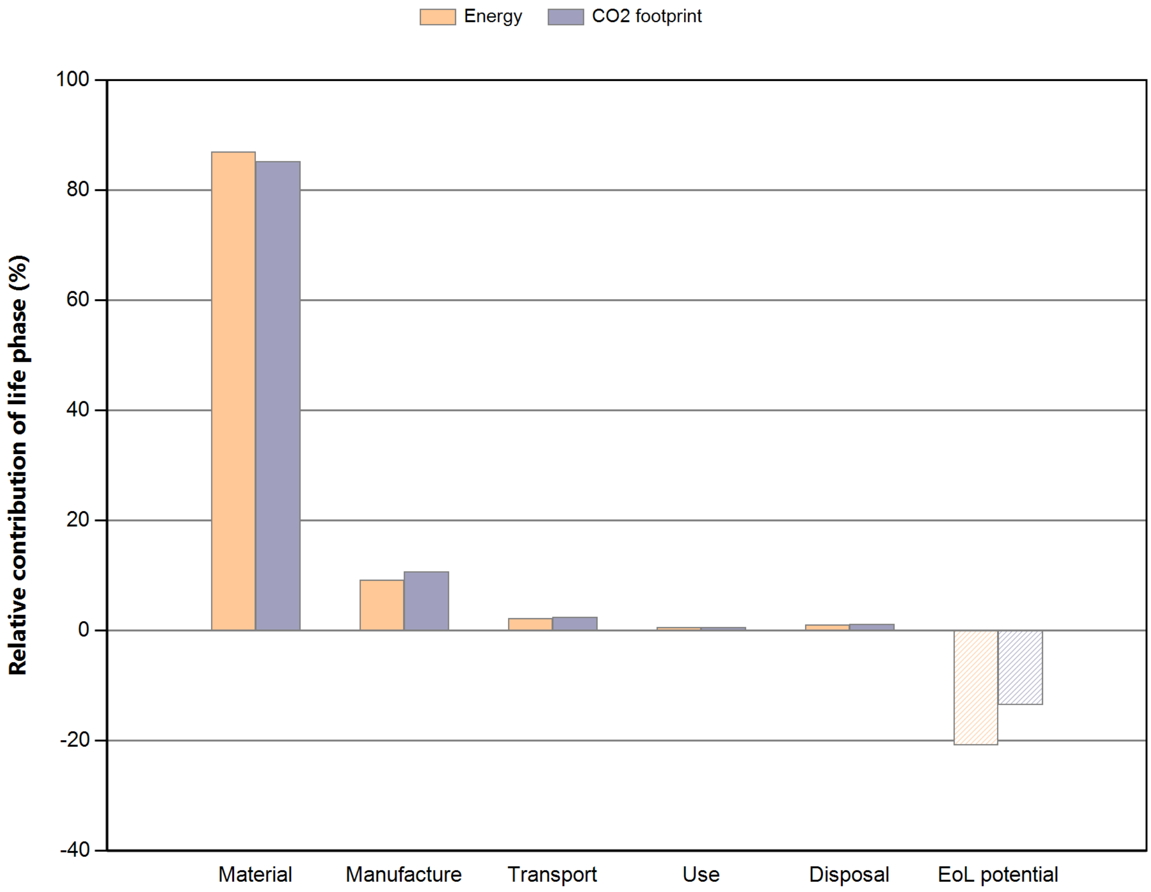
Appendix D: ANSYS Workbench (On disk)

Appendix E: CES EduPack - “Eco Audit” Report

Eco Audit Report

Product name	Reactor system with Polypropyle (PP) reactors
Country of use	Europe
Product life (years)	20

Summary:



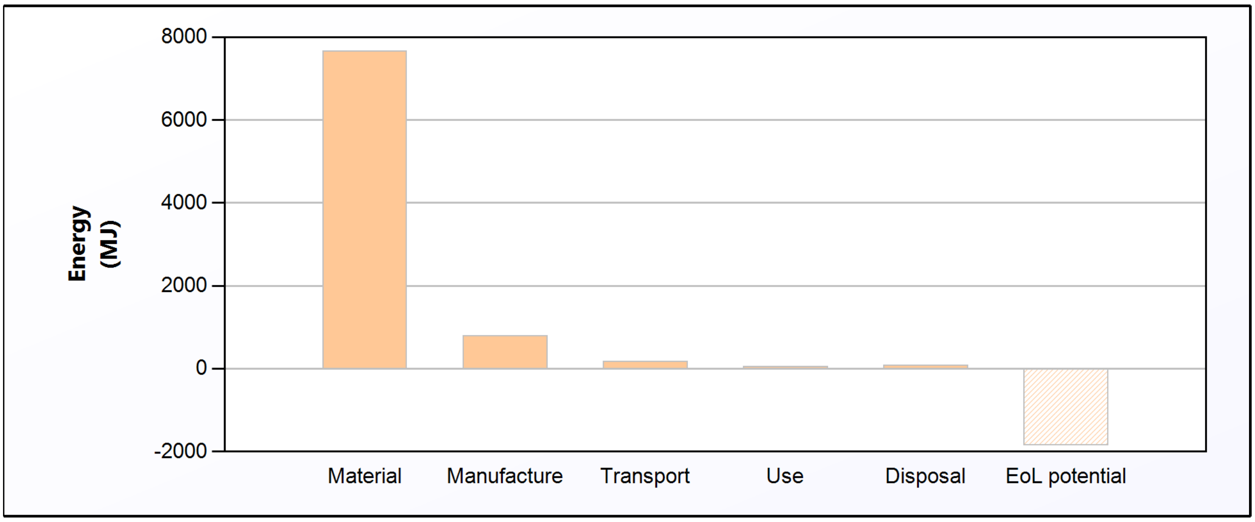
Energy details   CO2 footprint details

Phase	Energy (MJ)	Energy (%)	CO2 footprint (kg)	CO2 footprint (%)
Material	7,67e+03	87,0	486	85,3
Manufacture	811	9,2	60,8	10,7
Transport	192	2,2	13,6	2,4
Use	53,8	0,6	2,94	0,5
Disposal	94,8	1,1	6,63	1,2
Total (for first life)	**8,83e+03**	**100**	**570**	**100**
End of life potential	-1,84e+03		-76,7	

Eco Audit Report

Energy Analysis

Summary



	Energy (MJ/year)
Equivalent annual environmental burden (averaged over 20 year product life):	441

Detailed breakdown of individual life phases

Material:

Summary

Component	Material	Recycled content* (%)	Part mass (kg)	Qty.	Total mass (kg)	Energy (MJ)	%
Rotary stage	Aluminum alloys	Typical %	8	1	8	1,3e+03	17,5
Stepper motor	Power supply unit	Virgin (0%)	4	1	4	1,8e+03	23,7
Control system	Desktop computer (without screen)	Virgin (0%)	5	1	5	2,1e+03	27,0
Housing	Medium carbon steel	80,0%	27	1	27	3e+02	3,9
Deck	Medium carbon steel	80,0%	39	1	39	4,4e+02	5,7
Platform	Medium carbon steel	80,0%	36	1	36	4e+02	5,3
Reactor steel part	Stainless steel	80,0%	0,08	2	0,16	5	0,1
Reactor poly parts	Polypropylene (PP)	30,0%	9,2	2	18	1,3e+03	16,9
Total				**10**	**1,4e+02**	**7,7e+03**	**100**

*Typical: Includes 'recycle fraction in current supply'

Manufacture:

Summary

Component	Process	Amount processed	Energy (MJ)	%
Housing	Extrusion, foil rolling	27 kg	1,7e+02	20,7
Deck	Rough rolling	39 kg	1,3e+02	15,8
Platform	Rough rolling	36 kg	1,2e+02	14,6
Reactor steel part	Casting	0,16 kg	1,8	0,2
Reactor poly parts	Polymer molding	18 kg	3,9e+02	48,6
Total			**8,1e+02**	**100**

Transport:

Summary

Breakdown by transport stage

Stage name	Transport type	Distance (km)	Energy (MJ)	%
OES products	Sea freight	8e+03	1,8e+02	91,9
Structure	14 tonne truck	50	5,9	3,1
Reactor	Light goods vehicle	50	9,7	5,0
Total		**8,1e+03**	**1,9e+02**	**100**

Breakdown by components

Component	Mass (kg)	Energy (MJ)	%
Rotary stage	8	11	5,8
Stepper motor	4	5,6	2,9
Control system	5	7	3,6
Housing	27	37	19,5
Deck	39	55	28,5
Platform	36	50	26,2
Reactor steel part	0,16	0,22	0,1
Reactor poly parts	18	26	13,3
Total	**1,4e+02**	**1,9e+02**	**100**

Use:

Summary

Static mode

Energy input and output type	Electric to mechanical (electric motors)
Country of use	Europe
Power rating (W)	40
Usage (hours per day)	0,022
Usage (days per year)	3,7e+02
Product life (years)	20

Relative contribution of static and mobile modes

Mode	**Energy (MJ)**	**%**
Static	54	100,0
Mobile	0	
Total	**54**	**100**

Disposal:

Summary

Component	**End of life option**	**Energy (MJ)**	**%**
Rotary stage	Recycle	5,6	5,9
Stepper motor	Downcycle	2	2,1
Control system	Downcycle	2,5	2,6
Housing	Recycle	19	19,9
Deck	Recycle	28	29,0
Platform	Recycle	25	26,7
Reactor steel part	Recycle	0,11	0,1
Reactor poly parts	Recycle	13	13,6
Total		**95**	**100**

EoL potential:

Component	**End of life option**	**Energy (MJ)**	**%**
Rotary stage	Recycle	-1,1e+03	57,6
Stepper motor	Downcycle	0	0,0
Control system	Downcycle	0	0,0
Housing	Recycle	-1e+02	5,6
Deck	Recycle	-1,5e+02	8,2
Platform	Recycle	-1,4e+02	7,5
Reactor steel part	Recycle	-2,1	0,1
Reactor poly parts	Recycle	-3,9e+02	21,1
Total		**-1,8e+03**	**100**

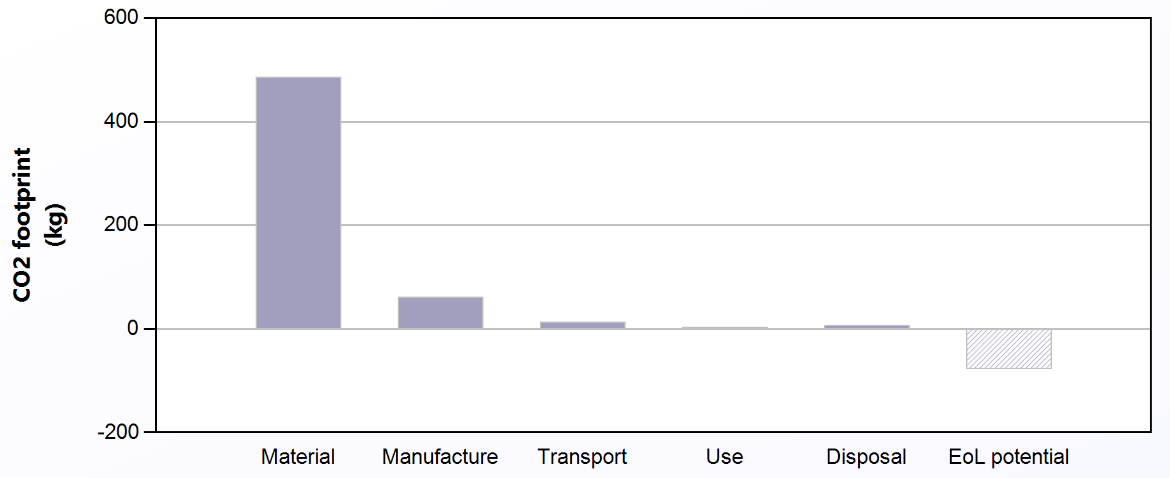
Notes:

Summary

Reactor system is without coupling subsystem. This must be further developed to complete reactor system.

CO2 Footprint Analysis

Summary



	CO2 (kg/year)
Equivalent annual environmental burden (averaged over 20 year product life):	28,5

Detailed breakdown of individual life phases

Material:

Summary

Component	Material	Recycled content* (%)	Part mass (kg)	Qty.	Total mass (kg)	CO2 footprint (kg)	%
Rotary stage	Aluminum alloys	Typical %	8	1	8	83	17,2
Stepper motor	Power supply unit	Virgin (0%)	4	1	4	1,4e+02	28,1
Control system	Desktop computer (without screen)	Virgin (0%)	5	1	5	1,2e+02	24,7
Housing	Medium carbon steel	80,0%	27	1	27	22	4,5
Deck	Medium carbon steel	80,0%	39	1	39	32	6,6
Platform	Medium carbon steel	80,0%	36	1	36	30	6,1
Reactor steel part	Stainless steel	80,0%	0,08	2	0,16	0,34	0,1
Reactor poly parts	Polypropylene (PP)	30,0%	9,2	2	18	62	12,7
Total				**10**	**1,4e+02**	**4,9e+02**	**100**

*Typical: Includes 'recycle fraction in current supply'

Manufacture:

Summary

Component	Process	Amount processed	CO2 footprint (kg)	%
Housing	Extrusion, foil rolling	27 kg	13	20,7
Deck	Rough rolling	39 kg	9,6	15,8
Platform	Rough rolling	36 kg	8,9	14,6
Reactor steel part	Casting	0,16 kg	0,14	0,2
Reactor poly parts	Polymer molding	18 kg	30	48,6
Total			**61**	**100**

Transport:

Summary

Breakdown by transport stage

Stage name	Transport type	Distance (km)	CO2 footprint (kg)	%
OES products	Sea freight	8e+03	13	91,9
Structure	14 tonne truck	50	0,42	3,1
Reactor	Light goods vehicle	50	0,69	5,0
Total		**8,1e+03**	**14**	**100**

Breakdown by components

Component	Mass (kg)	CO2 footprint (kg)	%
Rotary stage	8	0,79	5,8
Stepper motor	4	0,4	2,9
Control system	5	0,49	3,6
Housing	27	2,7	19,5
Deck	39	3,9	28,5
Platform	36	3,6	26,2
Reactor steel part	0,16	0,016	0,1
Reactor poly parts	18	1,8	13,3
Total	**1,4e+02**	**14**	**100**

Use:

Summary

Static mode

Energy input and output type	Electric to mechanical (electric motors)
Country of use	Europe
Power rating (W)	40
Usage (hours per day)	0,022
Usage (days per year)	3,7e+02
Product life (years)	20

Relative contribution of static and mobile modes

Mode	CO2 footprint (kg)	%
Static	2,9	100,0
Mobile	0	
Total	**2,9**	**100**

Disposal:

Summary

Component	End of life option	CO2 footprint (kg)	%
Rotary stage	Recycle	0,39	5,9
Stepper motor	Downcycle	0,14	2,1
Control system	Downcycle	0,18	2,6
Housing	Recycle	1,3	19,9
Deck	Recycle	1,9	29,0
Platform	Recycle	1,8	26,7
Reactor steel part	Recycle	0,0078	0,1
Reactor poly parts	Recycle	0,9	13,6
Total		**6,6**	**100**

EoL potential:

Component	End of life option	CO2 footprint (kg)	%
Rotary stage	Recycle	-61	80,0
Stepper motor	Downcycle	0	0,0
Control system	Downcycle	0	0,0
Housing	Recycle	-6,6	8,6
Deck	Recycle	-9,7	12,6
Platform	Recycle	-8,9	11,6
Reactor steel part	Recycle	-0,11	0,1
Reactor poly parts	Recycle	10	-13,1
Total		**-77**	**100**

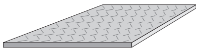
Notes:

Summary

Reactor system is without coupling subsystem. This must be further developed to complete reactor system.

Appendix F: Catalogue parts and components

Tåreplater S235JR

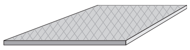


Toleranser etter EN 10051
Sertifikat 3.1 etter EN 10204

Gruppe 611

Lengde	Bredde	Tykk.	Kg/m²	Kg/stk
2500	1250	4,0	35	109
3000	1500	4,0	35	158
2000	1000	5,0	44	88
2500	1250	5,0	44	138
2000	1000	6,0	52	104
2500	1250	6,0	52	163
3000	1500	6,0	52	234

Rifleplater S235JR



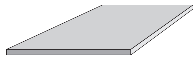
Toleranser etter EN 10051
Sertifikat 3.1 etter EN 10204

Gruppe 610

Lengde	Bredde	Tykk.	Kg/m²	Kg/stk
2500	1250	3,0	30	94
2500	1250	4,0	38	119
2500	1250	5,0	46	144
3000	1500	5,0	46	207
2000	1000	6,0	54	108
2500	1250	6,0	54	169
2000	1000	8,0	70	140

Varmvalsede plater S235JRC / NVA

Toleranser etter EN 10029, klasse B / EN 10051
Sertifikat 3.1 - 3.2 /DNV etter EN 10204.
Dimensjoner merket* lagerføres kun
i fasthetsklasse 235,
Vesentlig i knekkekvalitet - C

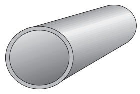


Gruppe 650/651/660 PL-235-T-B-L

Lengde	Bredde	Tykk.	Kg/m²	Kg/stk
2000	1000	3,0*	24	48
2500	1250	3,0*	24	75
3000	1500	3,0*	24	108
5000	1800	3,0*	24	216
6000	2000	3,0*	24	288
2000	1000	4,0*	32	64
2500	1250	4,0*	32	100
3000	1500	4,0*	32	144
6000	1800	4,0*	32	346
6000	2000	4,0*	32	384
2000	1000	5,0*	40	80
2500	1250	5,0*	40	125
3000	1500	5,0*	40	180
5000	1500	5,0*	40	300
6000	1500	5,0*	40	360
6000	2000	5,0	40	480
8000	2500	5,0	40	800
2000	1000	6,0*	48	96
2500	1250	6,0*	48	150
3000	1500	6,0*	48	216
6000	1500	6,0*	48	432
6000	2000	6,0	48	576
6000	2500	6,0	48	720
8000	2500	6,0	48	960
6000	2500	7,0	56	840
8000	2500	7,0	56	1120
2000	1000	8,0*	64	128
2500	1250	8,0*	64	200
3000	1500	8,0*	64	288
6000	2000	8,0	64	768
6000	2500	8,0	64	960
8000	2500	8,0	64	1280
8000	2500	9,0	72	1440

Runde Sveiste presisjonsstålrør

Toleranser og tekniske leveringsbetingelser etter EN 10305-3
*Tykkelser opp til 1,5 mm. leveres av kaldvalset bånd. E220+Cr2 - S3.
Øvrige av varmvalset, beiset og oljet bånd E220+CR2 - S2.
Overflate halvblank

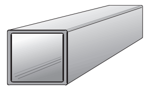


Gruppe 711

Ø	Tykkelse	Lengde i m	Kg pr m	Kg/stk
10,0	1,25*	6	0,27	1,62
12,7	1,25*	6	0,35	2,10
12,7	1,50*	6	0,41	2,46
16,0	1,25*	6	0,46	2,76
16,0	1,50*	6	0,54	3,24
16,0	2,00	6	0,69	4,14
18,0	2,00	6	0,79	4,74
19,0	1,25*	6	0,55	3,30
19,0	1,50*	6	0,65	3,90
19,0	2,00	6	0,84	5,04
20,0	1,50*	6	0,68	4,08
20,0	2,00	6	0,89	5,34
22,0	1,50*	6	0,76	4,56
22,0	2,00	6	0,99	5,94
25,0	1,25*	6	0,73	4,38
25,0	1,50*	6	0,87	5,22
25,0	2,00	6	1,13	6,78
28,0	2,00	6	1,28	7,68
30,0	2,00	6	1,38	8,28
32,0	1,50*	6	1,13	6,78
32,0	2,00	6	1,48	8,88
38,0	1,50*	6	1,35	8,10
38,0	2,00	6	1,78	10,68
40,0	1,50	6	1,40	8,41
40,0	2,00	6	1,87	11,22
44,5	1,50*	6	1,59	9,54
44,5	2,00	6	2,10	12,60
50,0	1,50*	6	1,79	10,74
50,0	2,00	6	2,37	14,22
50,8	1,50*	6	1,82	10,92
50,8	2,00	6	2,41	14,46
101,6	2,00*	6	4,91	29,46

Firkantede presisjonsstålrør

Toleranser og tekniske leveringsbetingelser etter EN 10305-5
*Tykkelser opp til 1,5 mm leveres av kaldvalset bånd. E220+Cr2 - S3.
Øvrige av varmvalset, beiset og oljet bånd E220+CR2 - S2.
Overflate halvblank



Gruppe 701

Dimensjon			Lengde i m	Kg pr m	Kg/stk
12,7	12,7	1,50	6	0,52	3,12
15,0	15,0	1,50	6	0,63	3,78
16,0	16,0	1,50	6	0,68	4,08
20,0	10,0	1,50	6	0,63	3,78
20,0	20,0	1,25	6	0,73	4,38
20,0	20,0	1,50	6	0,87	5,22
20,0	20,0	2,00	6	1,12	6,72
25,0	15,0	1,50	6	0,87	5,22
25,0	25,0	1,25	6	0,93	5,58
25,0	25,0	1,50	6	1,10	6,60
25,0	25,0	2,00	6	1,42	8,52
30,0	15,0	1,50	6	0,99	5,94
30,0	20,0	1,50	6	1,10	6,60
30,0	20,0	2,00	6	1,44	8,64
30,0	30,0	1,50	6	1,34	8,04
30,0	30,0	2,00	6	1,75	10,50
35,0	35,0	1,50	6	1,57	9,42
35,0	35,0	2,00	6	2,07	12,42
40,0	20,0	1,50	6	1,34	8,04
40,0	20,0	2,00	6	1,75	10,50
40,0	30,0	2,00	6	2,07	12,42
40,0	40,0	1,50	6	1,81	10,86
40,0	40,0	2,00	6	2,38	14,28
40,0	40,0	3,00	6	3,44	20,64
50,0	20,0	1,50	6	1,57	9,42
50,0	20,0	2,00	6	2,07	12,42
50,0	25,0	1,50	6	1,69	10,14
50,0	25,0	2,00	6	2,22	13,32
50,0	30,0	2,00	6	2,38	14,28
50,0	50,0	2,00	6	3,01	18,06
60,0	20,0	2,00	6	2,38	14,28
60,0	30,0	2,00	6	2,69	16,14
60,0	40,0	2,00	6	3,01	18,06
60,0	60,0	2,00	6	3,64	21,84
70,0	25,0	2,00	6	2,85	17,10
80,0	40,0	2,00	6	3,64	21,84

Hollow Core Motorized Rotary Stage

This hollow core motorized rotary stage is made of aluminum alloy with an elegant black anodized surface.

The drive mechanism is worm and worm gear. The worm gear ratio is 180:1.

It provides 360° of rotation.

The maximum load of this rotary table is 100 Kg.

This 100 mm diameter rotary actuator has a body weight of 12 Kg.

The resolution of 0.001° is achieved with a 10 micro-steps per step stepper motor driver. This rotation stage is also available with a servo motor and optical encoder.

The top plate mounted indicator shows the angle of rotation.

The knob mounted on the motor allows for manual adjustment. This knob may be replaced with an optical encoder for precision position verification.

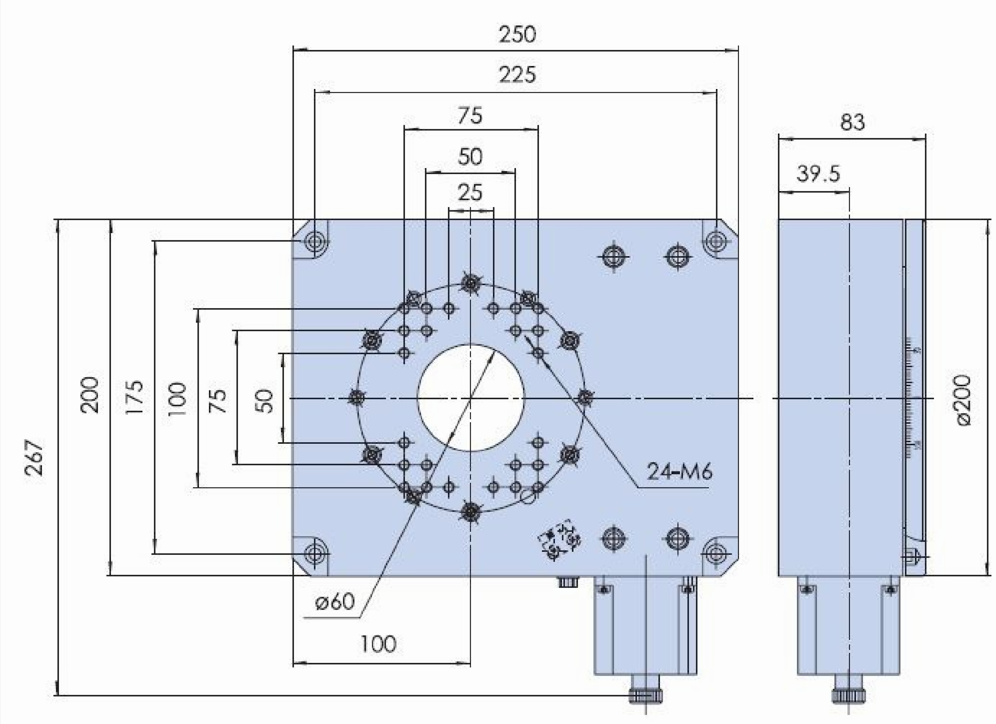
This motorized stage is capable of continuous spinning.

This stage is compatible with OES' line of **Motion Controllers.**

Specifications

Type		**AY110-200H**
Structure Description	Range of Travel	360°
	Stage Diameter	200 mm
	Transmission Ratio	180:1
	Drive Mechanism	Worm Gear
	Travel Guide	Bearing
	Stepper Motor	2 Phase Stepper Motor Phase Resistance Maximum Phase Current **9 pin DB-9 Male Connector** Pin Assignment and Description 1,2,3,4,5 — Not Connected 6 — Phase A+ 7 — Phase A- 8 — Phase B+ 9 — Phase B-
	Base Material	Aluminum Alloy
	Surface Treatment	Black Anodized
	Load Capacity	100 kg
	Weight	12 kg
Typical Accuracy	Resolution	0.001° (10 Micro-Steps per Step Driver in use)
	Repeatability	0.002°=7.2''
	Positional Accuracy	0.005°
	Surface Roundness	10 μ
	Backlash	0.002° =7.2''
	Transmission Deviation	20 μ
	Parallelism	50 μ

Mechanical Drawing



Ordering Information

Part No.	Description	Amount
AY110-200H	Hollow Core Motorized Rotary Stage	Click to Get a Quote

Related Products

	**Motion Controllers**

Sharing link:

Serially Controlled Motor Control System
Any Combination of Stepper and Servo Motors
FIGARO Series

Other Motor Controller and Driver Products

JMC Series
ANDANTE Series
ICAD Series
FIGARO Series

Features

- Plug-and-Play
- Quick and Easy to Install
- Very Compact and Easy to Use
- Low Power Consumption, High Torque Motors, High Speed Capability
- Easy Programming Language, No Compiler or Assembler Required

Software

- Easy System Setup and Evaluation
- Menu Driven
- Free Software Included

Stepper Motor Driver

- Up to 7 Amp Phase Current

ALLEGRA Series
GLORIA Series
ADAGIO Series
SONATA Series
PRESTO Series
SMDS Series

Related Products

Motorized Linear Actuators
Motorized XY Stages
Motorized Linear Lift Stages
Motorized Rotary Stages
Combined Linear-Rotary Stages
Motorized Goniometer Stages
Motorized Multi-axis Stages

- Serially Controllable, Teachable or Manual Control
- Host Controlled, PLC, C/C++, Visual Basic, LabVIEW™
- Available to Drive Stepper, DC Servo, Brushless, and Voice Coil Motors
- Optional Joystick / Trackball Interface
- Optional HOME and LIMIT switches
- Optional TTL / CMOS Inputs and Outputs
- Optional Quadrature Encoder Feedback
- Optional Gyroscope Stabilization
- Totally Integrated Solution
- Evaluation Unit Is Available upon Request

- Up to 256 Micro-steps per Step Resolution
- Size 8 to 42 Motors
- Auto Current Reduction

DC and Three Phase Brushless Motor Driver

- Up to 40 Amps Phase Current
- +18 VDC to +80 VDC

Communication Interface

- RS-232 Interface
- Optional Ethernet Interface
- Optional USB Interface

The FIGARO series of Stepper Motor control system is an easy-to-use, plug-and-play and cost effective solution for Stepper Motor control applications. It may be used as a stand-alone unit or may be commanded by an external device.

Each system includes the power supplies, the motion controller card, the micro-stepper and/or servo motor drivers.

This Motor control system supports up to 4 axes of motion.

The system may be controlled in different ways;

1) **Externally Control Operation of Motor Control System**

In this mode, the external host such as a PC, micro-controller or PLC sends a series of commands to the controller via the RS-232 serial port. The controller processes and performs the incoming commands and responds with proper messages.

2) **Operating the Motor Control System Using the Supplied Control Panel**

The supplied user friendly Control Panel software allows the user to set-up the module quickly. The operator is able to move the mechanism to different positions by pressing the corresponding buttons of the Control Panel or by using the joystick and/or trackball.

1) **Teach Mode**

The motion profile may be recorded using the "Teach Mode" capability of the software. This profile may be uploaded to the controller to repeat the same exact Stepper Motor.

2) **Profile Entry Mode**

The motion parameters are manually entered in the control panel by typing the desired values in the corresponding fields, or may be read from a text file.

The system can also be operated using an analog joystick or a trackball. The **speed of the motor is proportional** to the tilt angle of the joystick or the rotational speed of the trackball.

More Info...

Ordering Information

Part No.	Description	Amount
FIGARO-1-STPR-01	Single-axis Serially Controllable Stepper Motor Control System	Click to Get a Quote
FIGARO-2-STPR-01	Two-axis Serially Controllable Stepper Motor Control System	Click to Get a Quote
FIGARO-3-STPR-01	Three-axis Serially Controllable Stepper Motor Control System	Click to Get a Quote
FIGARO-4-STPR-01	Four-axis Serially Controllable Stepper Motor Control System	Click to Get a Quote

Power Supply:
Input Power; 115 or 230 VAC, 50 – 60 Hz

Part No.	Description	Amount
FIGARO-1-SRVO-01	Single-axis Serially Controllable DC Servo Motor Control System	Click to Get a Quote
FIGARO-2-SRVO-01	Two-axis Serially Controllable DC Servo Motor Control System	Click to Get a Quote
FIGARO-3-SRVO-01	Three-axis Serially Controllable DC Servo Motor Control System	Click to Get a Quote
FIGARO-4-SRVO-01	Four-axis Serially Controllable DC Servo Motor Control System	Click to Get a Quote

This series is suitable for DC servo motors.

Servo Motor Drivers:

Up to 40.0 Amps Phase Current

Power Supply:
Input Power; 115 or 230 VAC, 50 – 60 Hz

Part No.	Description	Amount
FIGARO-1-BLDC-01	Single-axis Serially Controllable Brushless DC Servo Motor Control System	Click to Get a Quote
FIGARO-2-BLDC-01	Two-axis Serially Controllable Brushless DC Servo Motor Control System	Click to Get a Quote
FIGARO-3-BLDC-01	Three-axis Serially Controllable Brushless DC Servo Motor Control System	Click to Get a Quote
FIGARO-4-BLDC-01	Four-axis Serially Controllable Brushless DC Servo Motor Control System	Click to Get a Quote

This series is suitable for Brushless DC servo motors.

Servo Motor Drivers:
Up to 40.0 Amps Maximum Phase Current

Power Supply:
Input Power; 115 or 230 VAC, 50 – 60 Hz

For a different configuration, please **contact us** for a prompt quotation.

Sharing link:
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Los Angeles, California, USA
Toll Free Number (888) 777-1826 in USA
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sales@oesincorp.com
Contact Us

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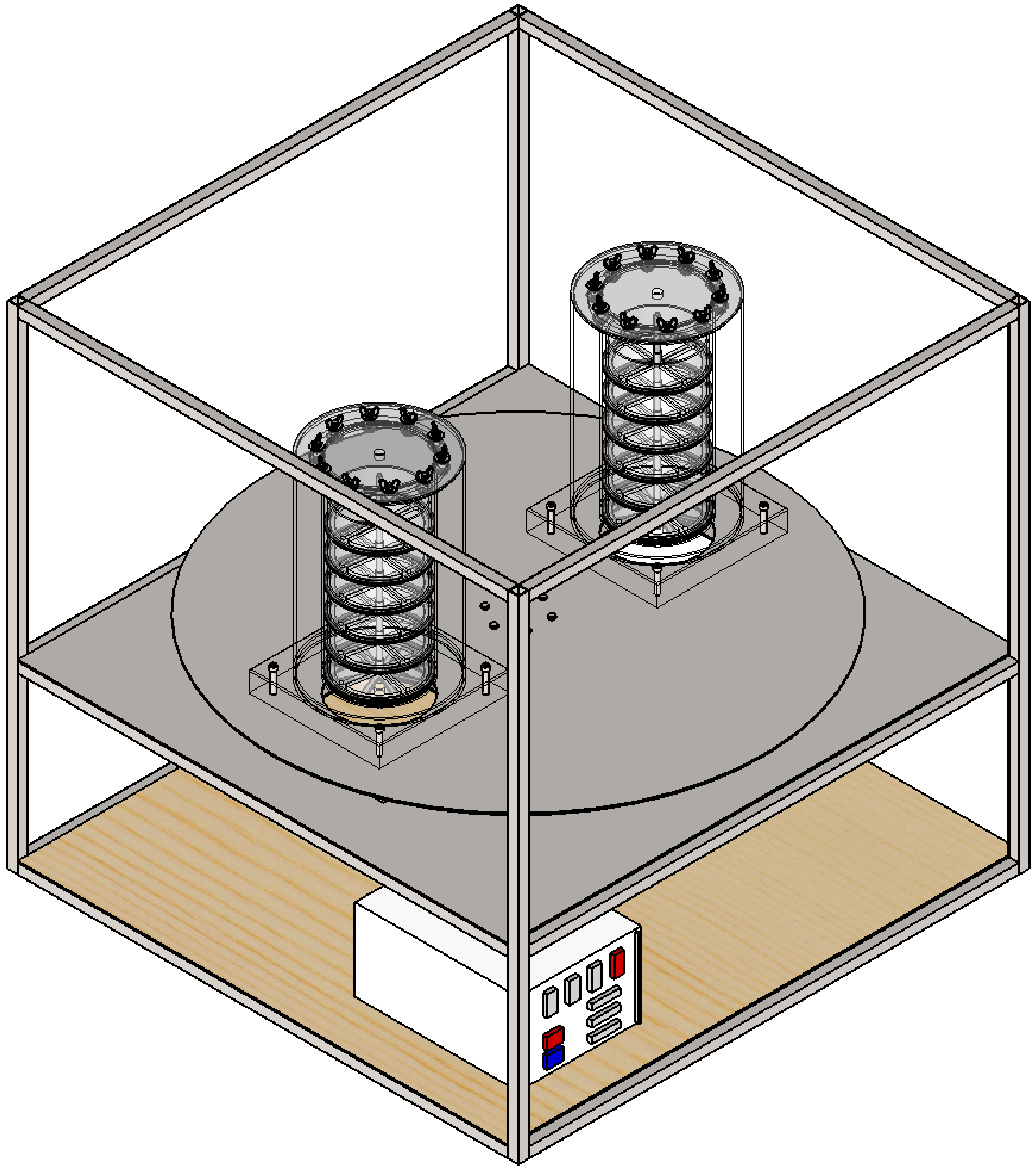
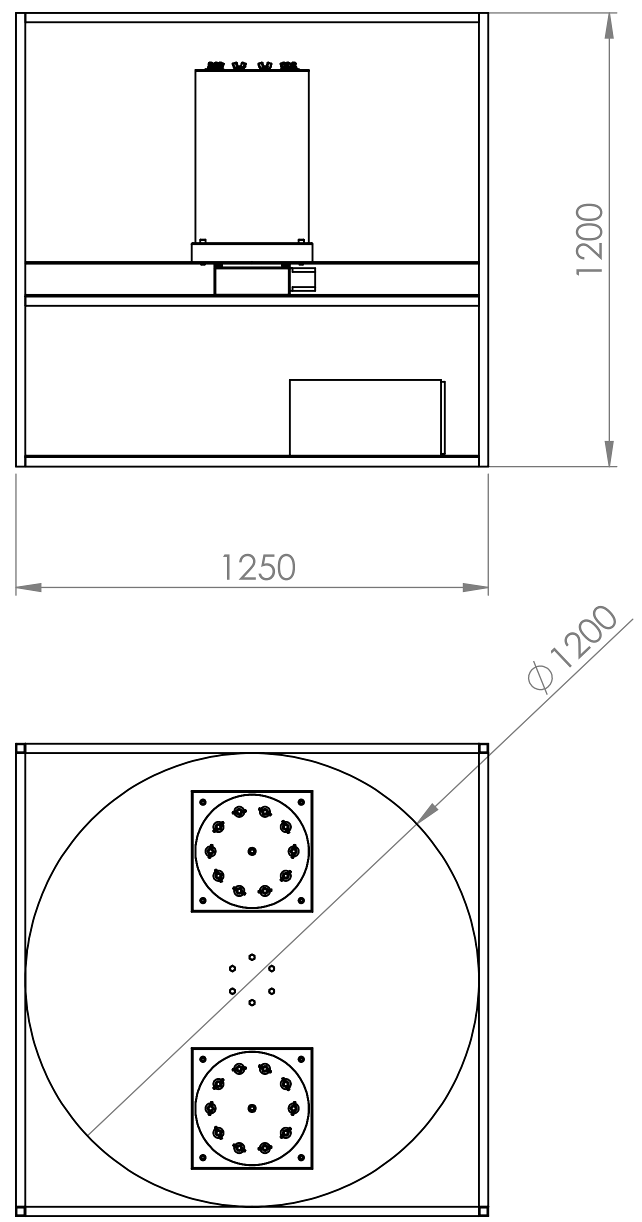
Appendix G: Technical drawings





GLOBAL DIMENSIONS OF REACTOR SYSTEM

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Master's Thesis 2017				Drawing no. 01-01

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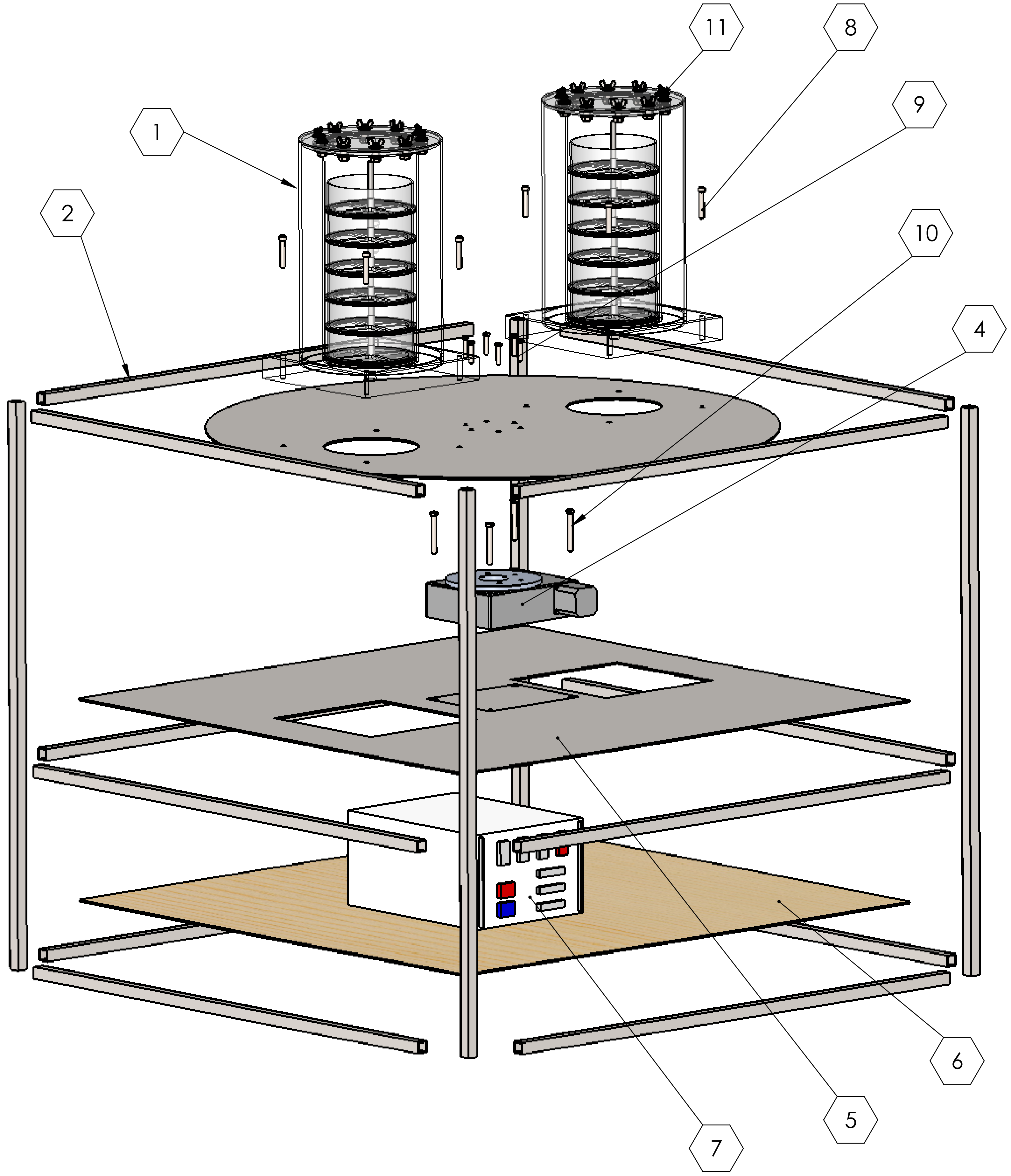

Total weight: 142.1 kg

ITEM NO.	PART NUMBER	DESCRIPTION	MATERIAL	WEIGHT	QTY.
1	A02-03 Reactor	Packed bed reactor	-	9.2	2
2	P03-02 Deck beams OP	1200x25x25x1.5 mm	S235JR	1.7 kg	16
3	P01-01 Circular platform	Platform for rotating reactors	S235JR	33.3 kg	1
4	P01-02 OES rotate stage	Motorized rotary stage (under platform)	-	15 kg	1
5	P03-01 Deck OP	Deck for support of rotating platform	S235JR	41.2 kg	1
6	P03-05 Level 1 Deck OP	Deck for lightweight equpment etc	Plywood	2 kg	1
7	P01-02 OES control system Darth Vader	Motion control system for rotary stage	-	5 kg	1
8	Socket Head Cap Screws	For mounting reactors to platform	S235JR	-	8
9	Socket Head Cap Screws	For mounting rotary stage to platform	S235JR	-	6
10	Socket Head Cap Screws	For mounting rotary stage to deck	S235JR	-	4
11	Wing nut, hex head structural bolt and (20) flat washers	For fastening lid on reactor	S235JR	-	10

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Drawing no. 01-2

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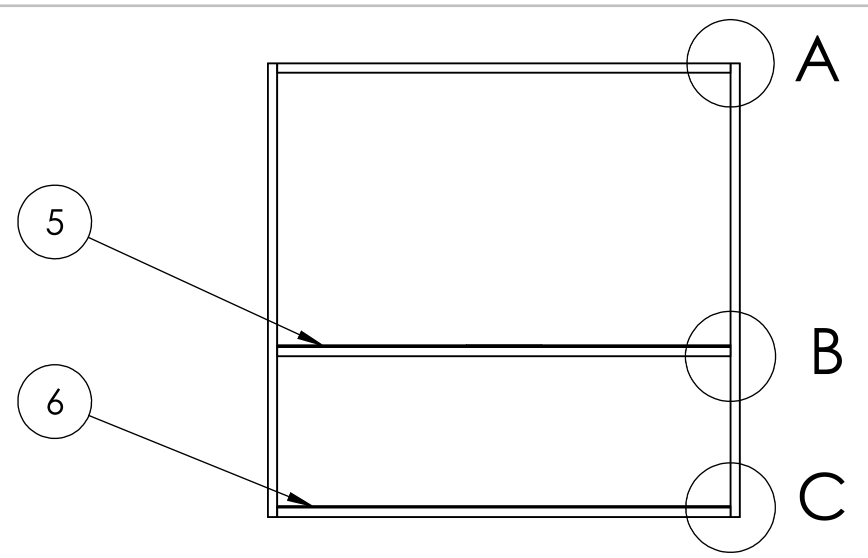
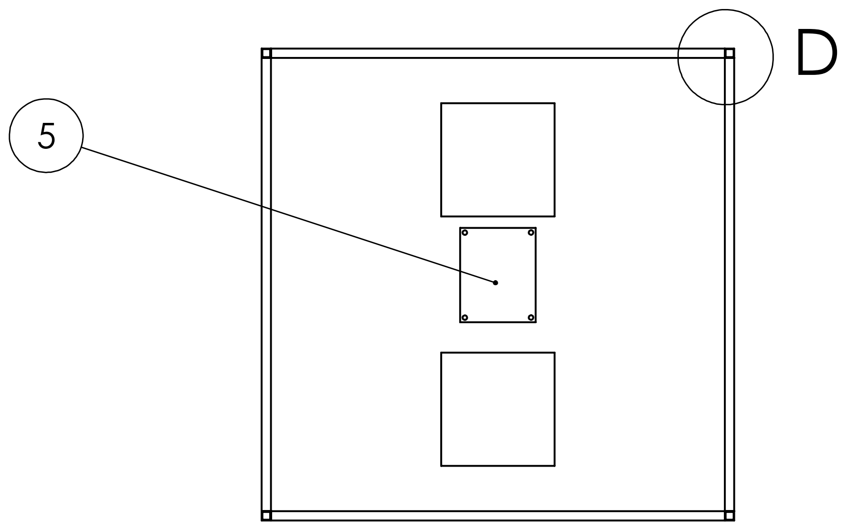
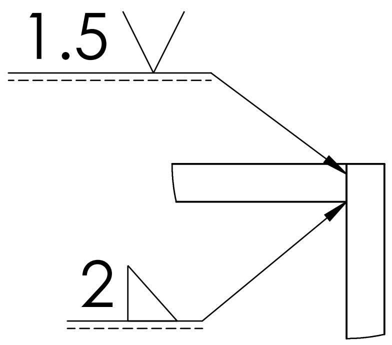


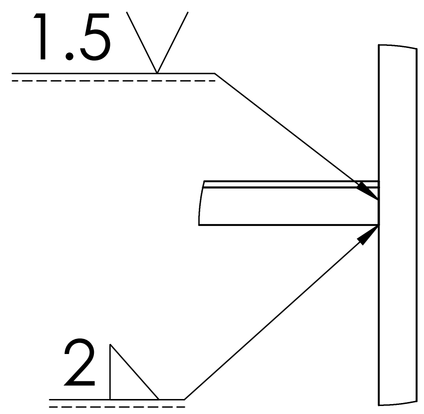




Under beam with filletweld and two sides with buttweld.

DETAIL A

SCALE 1 : 5

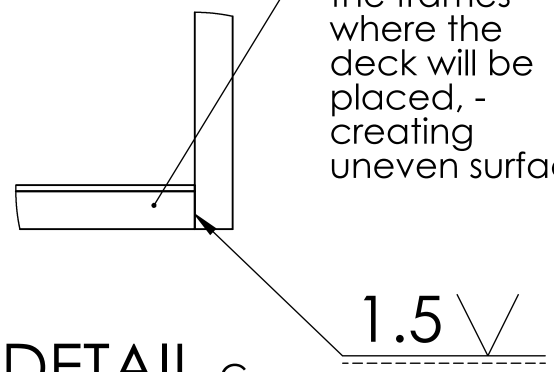


Under beam with filletweld and two sides with buttweld.

NOTE: Can not weld on top of the frames where the deck will be placed, - creating uneven surface

DETAIL B

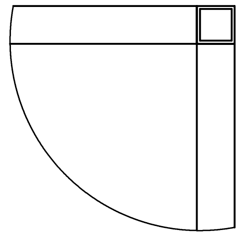
SCALE 1 : 5



NOTE: Can not weld on top of the frames where the deck will be placed, - creating uneven surface

DETAIL C

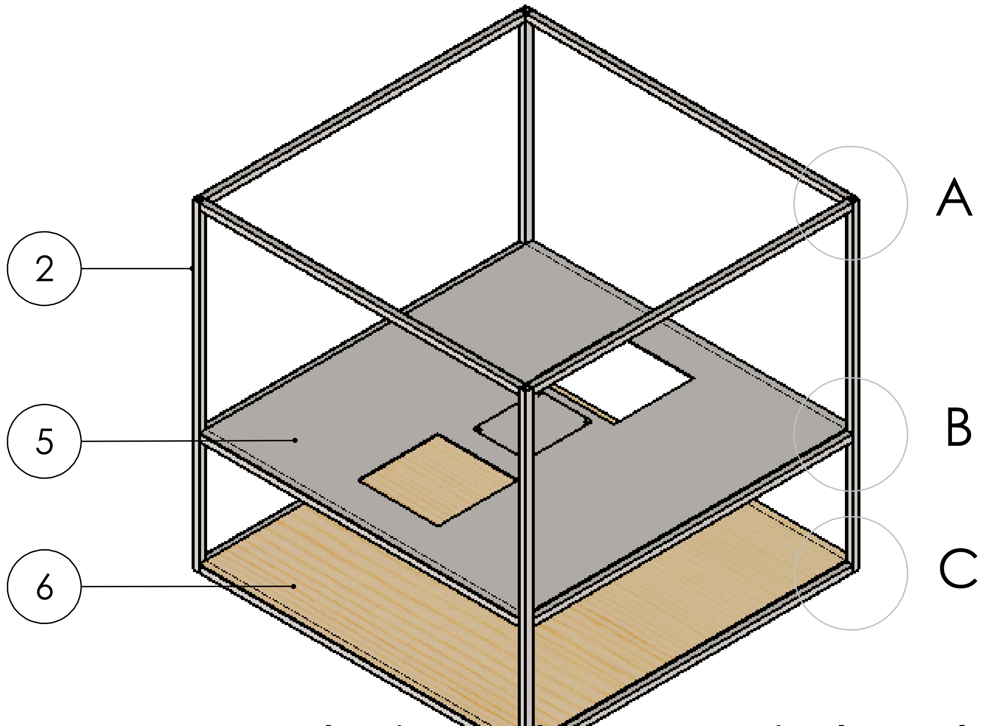
SCALE 1 : 5



Weld the two horizontal beams to the vertical beam with buttweld. Same for bottom of framwork.

DETAIL D

SCALE 1 : 5



A, B and C welds is similar on all four corners of theframework

The steel deck is welded with buttwelds on two sides to the frame and (if needed) filletweld on the other sides

TOTAL WEIGHT: 71 kg

ITEM NO.	PART NUMBER	DESCRIPTION	MATERIALS	WEIGHT	QTY.
2	P03-02 Deck beams OP	1200mm, 25x25x2 mm hollow steel profiles	S235JR	1.7 kg	12
5	P03-01 Deck OP 2	1250x1200x4 mm upper deck for rotating platform	S235JR	41.2 kg	1
6	A-02-03 Hatch reactor	Lower deck for lighweight components	Plywood	2 kg	1

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Drawing no. 01-03

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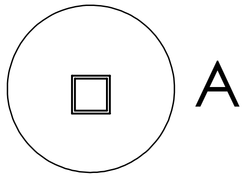
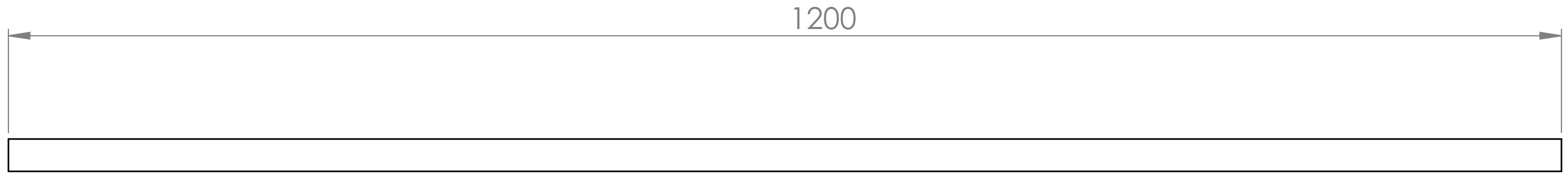
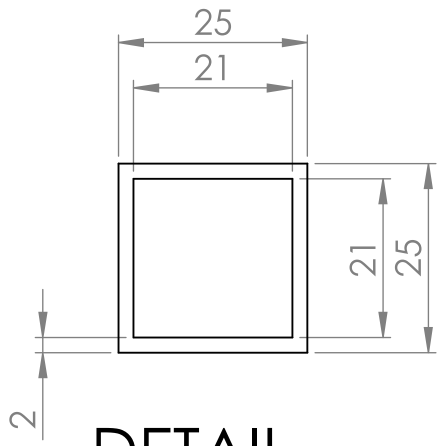
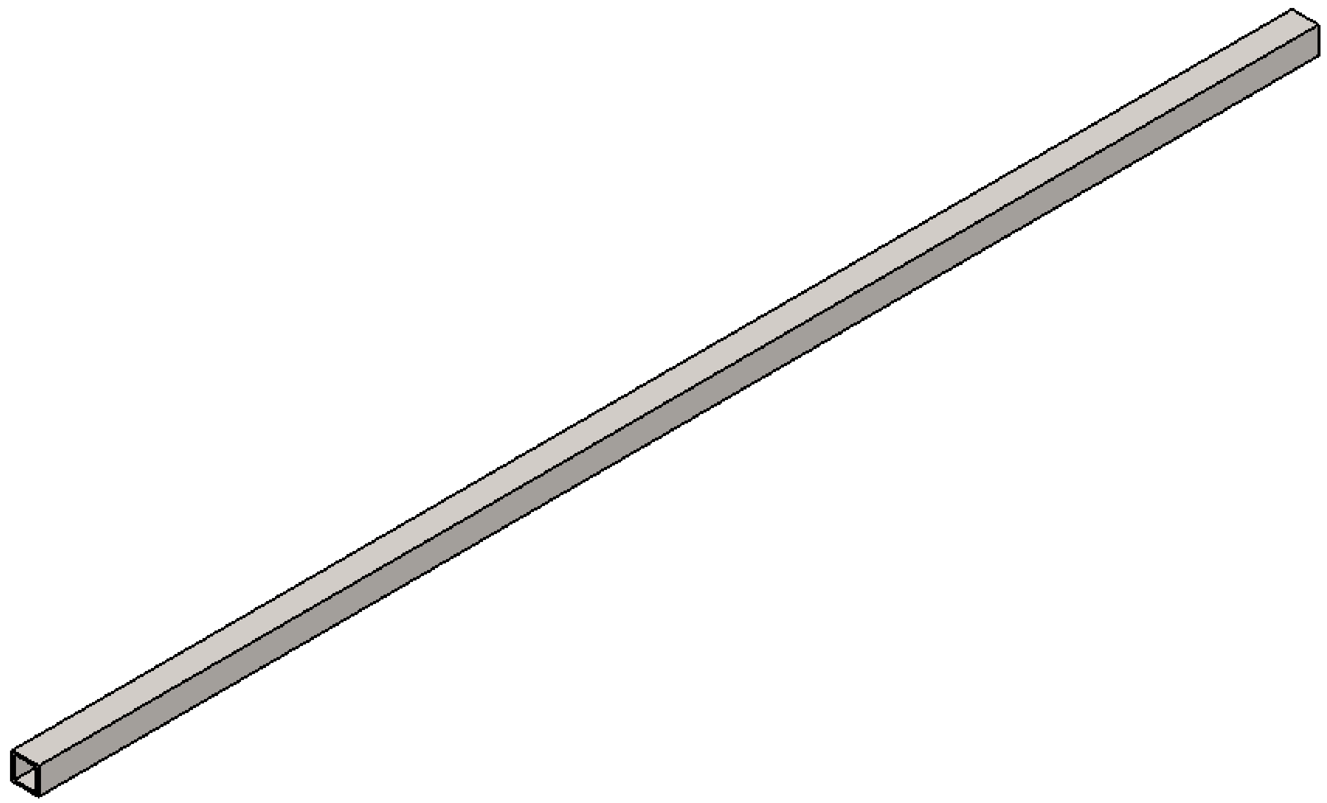






DETAIL A

SCALE 1 : 1



ITEM NO.	PART NUMBER	DESCRIPTION	MATERIAL	QTY.
2	P03-02 Deck beams OP	Hollow square profiles for the housing framework	S235JR	16

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Drawing no. 02

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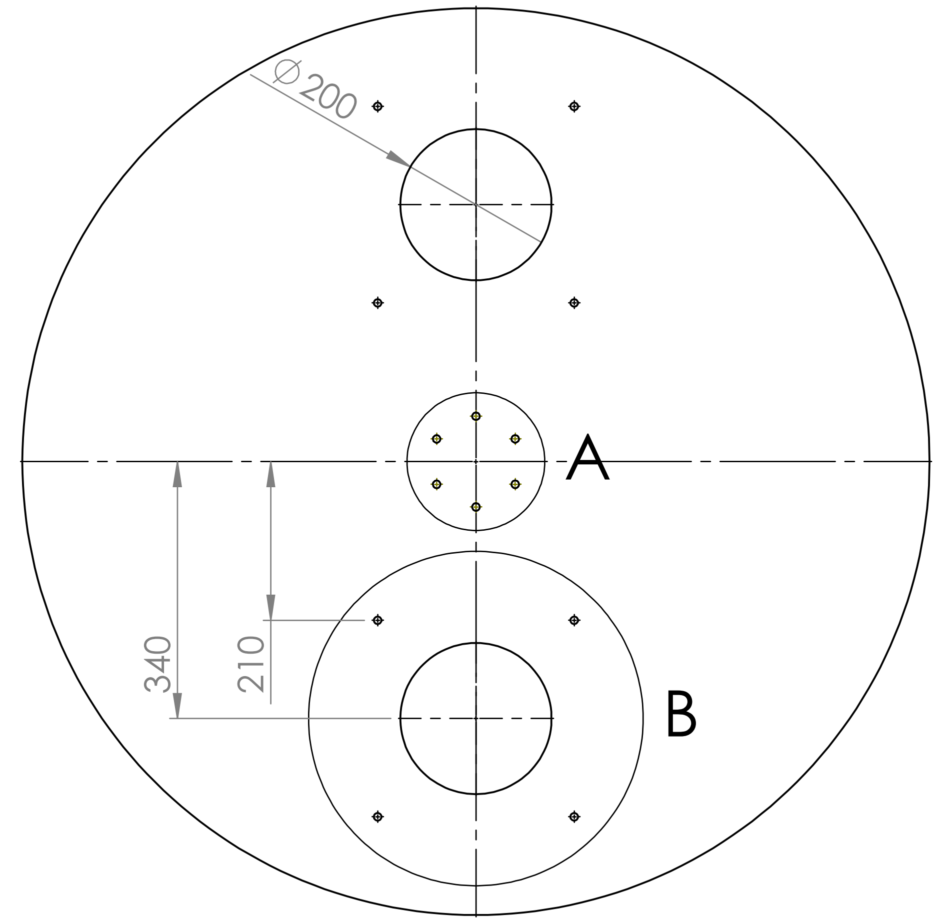
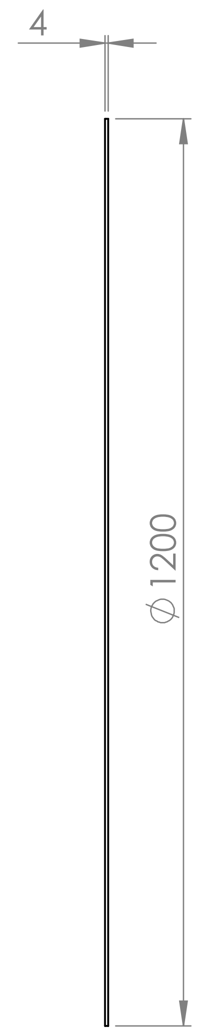
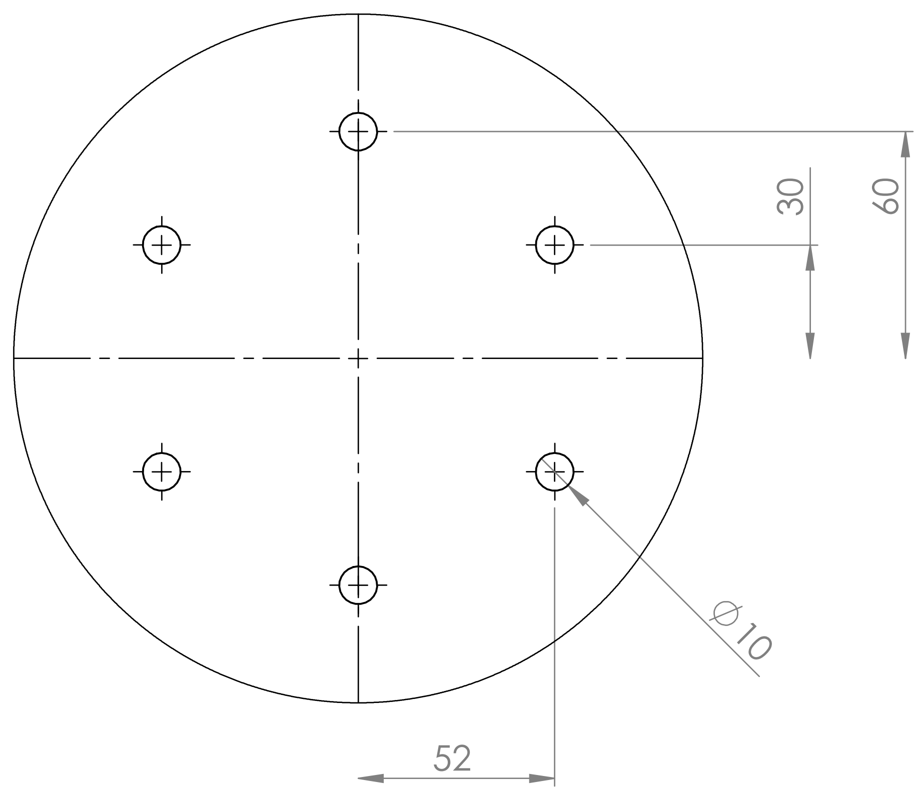


2 x Ø200 mm holes symmetric on the platform





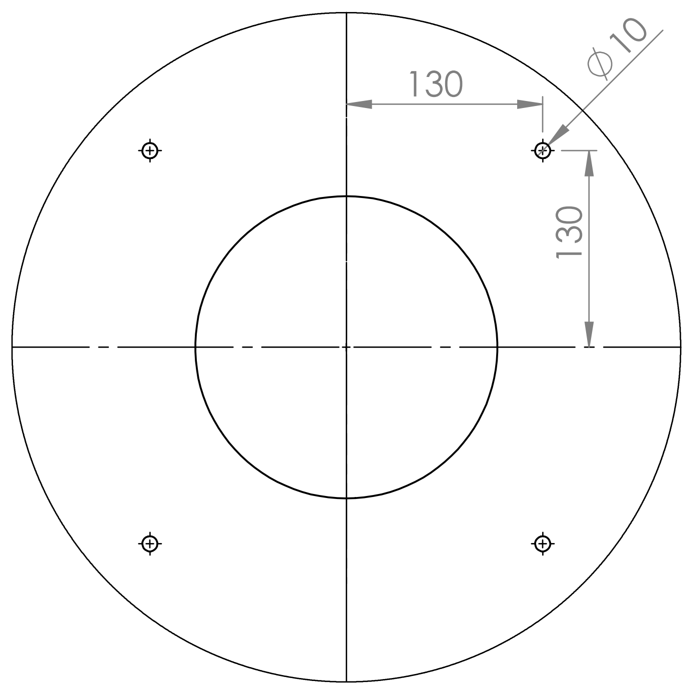
DETAIL A

SCALE 1 : 2

DETAIL B

SCALE 1 : 5

4 x M10 holes for mount of reactor. Symmetric around both Ø200mm holes



ITEM NO..	PART NUMBER	DESCRIPTION	MATERIAL	WEIGHT	QTY.
3	P01-01 Circular platform	Circular steel platform	S235JR	33.3 kg	1

Date:	Konstr./Engineer:	Projection:	Scale:
28.04.17	H.O.P		1:10

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Drawing no. 03

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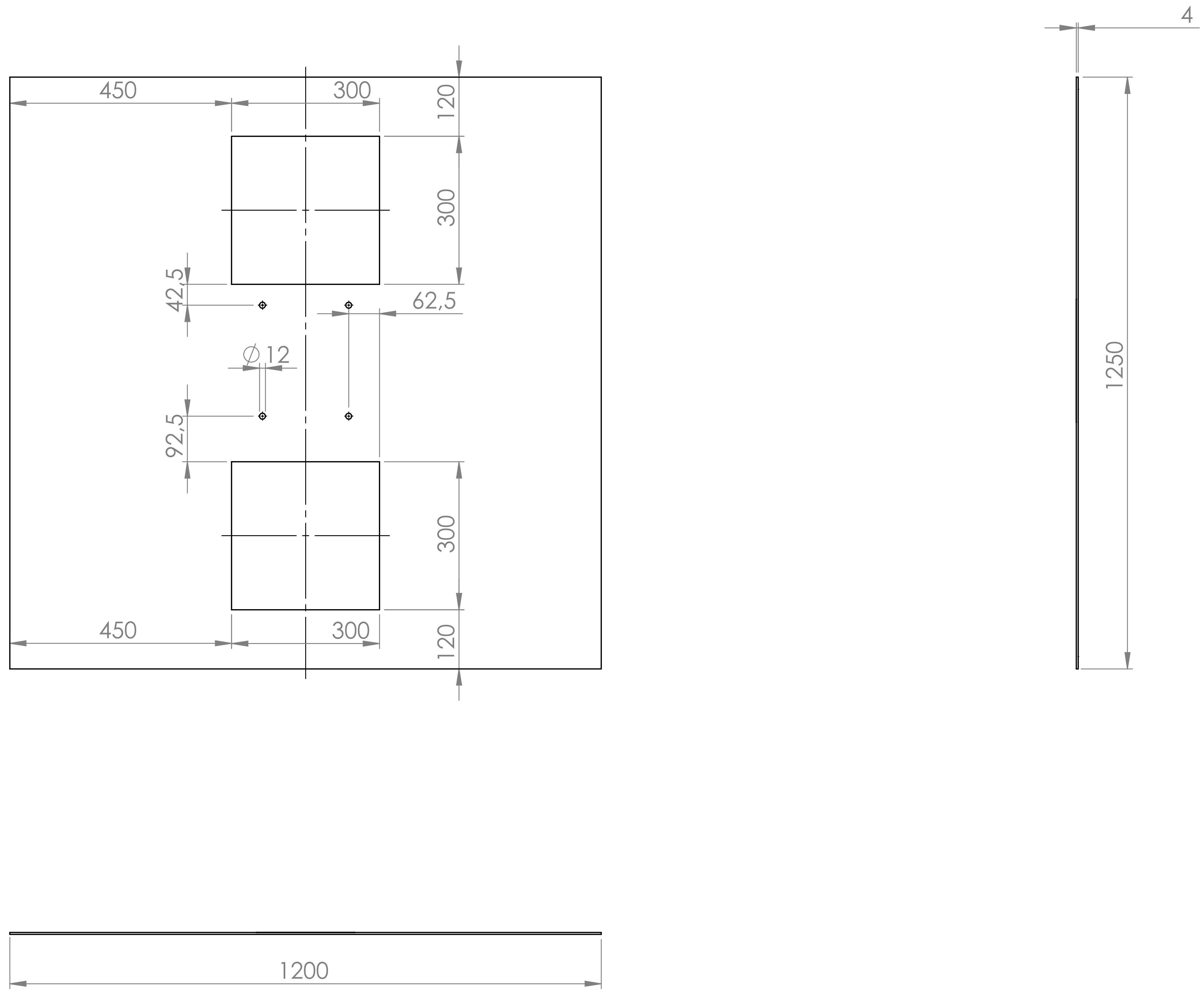
The four screw holes between the 300x300 mm are offset from the center. The deck is therefore only symmetric along one axis



ITEM NO.	PART NUMBER	DESCRIPTION	Material	WEIGHT	QTY.
5	P03-01 Deck OP	1250x1200x4 mm	S235JR	41.2 kg	1

Date:	Konstr./Engineer:	Projection:	Scale:	NMBU
28.04.17	H.O.P		1:10	

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Drawing no. 05

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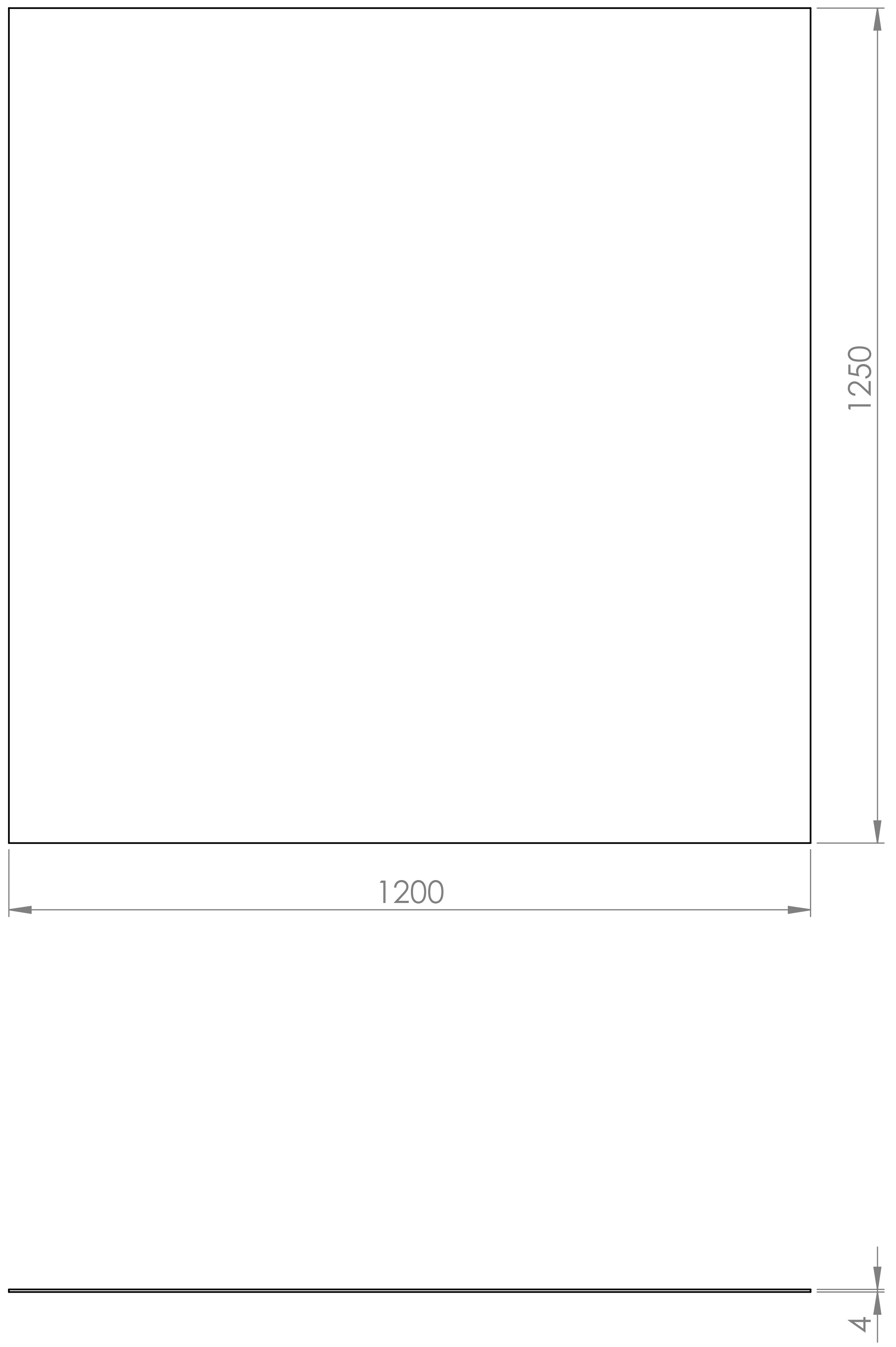

ITEM NO.	PART NUMBER	DESCRIPTION	MATERIAL	WEIGHT	QTY.
6	A-02-03 Hatch reactor	Lower deck for lighweight components	Plywood	2 kg	1

Date:	Konstr./Engineer:	Projection:	Scale:
28.04.17	H.O.P		1:10

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Drawing no. 06

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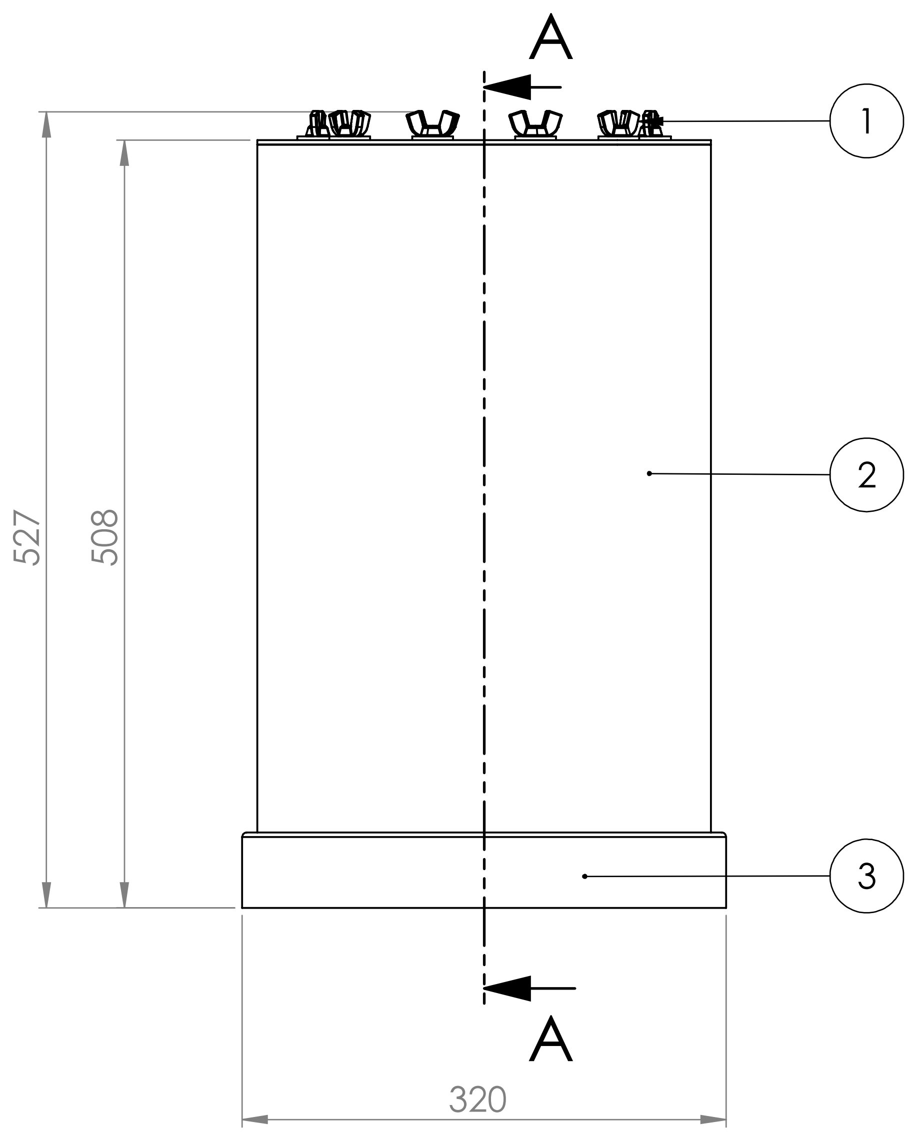

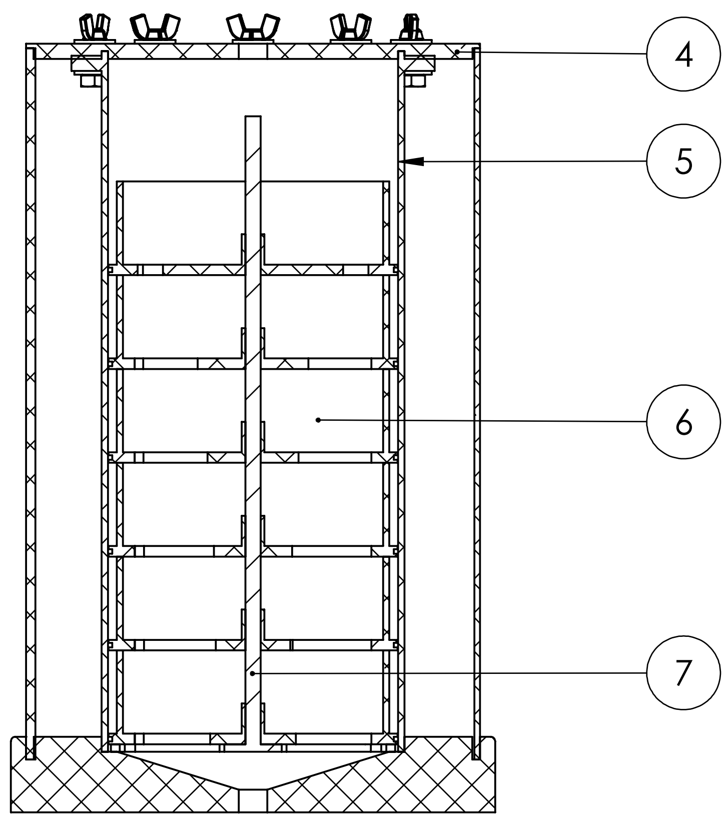

SECTION A-A
SCALE 1 : 5

TOTAL WEIGHT: 10 kg

ITEM NO.	PART NUMBER	DESCRIPTION	MATERIAL	WEIGHT	QTY.
1	M10 WING NUT	Fasteners (Screws, washer and nuts)	Stainless steel	-	10
2	P02-01 Toplid	Outer shell	Polypropylen (PP)	1.9 kg	1
3	P02-04 Base	Base	Polypropylen (PP)	4 kg	1
4	P02-02 Outer shell	Top lid	Polypropylen (PP)	0.6 kg	1
5	hex head structural bolt_din	Mid shell	Polypropylen (PP)	1.2 kg	1
6	A02-03 Capsule with seal	Capsule for catalysts	Polypropylen (PP)	0.2 kg	6
7	P02-03 Steel plate	Steel plate with rod	Stainless steel	0.62 kg	1

Dato:	Konstr./Tegnet:	Projeksjon:	Målestokk:	NMBU
04.05.17	H.O.P		1:5	

Erstatning for: | Erstastattet av:

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Tegning nr. R01

Henvisning: | Beregning:

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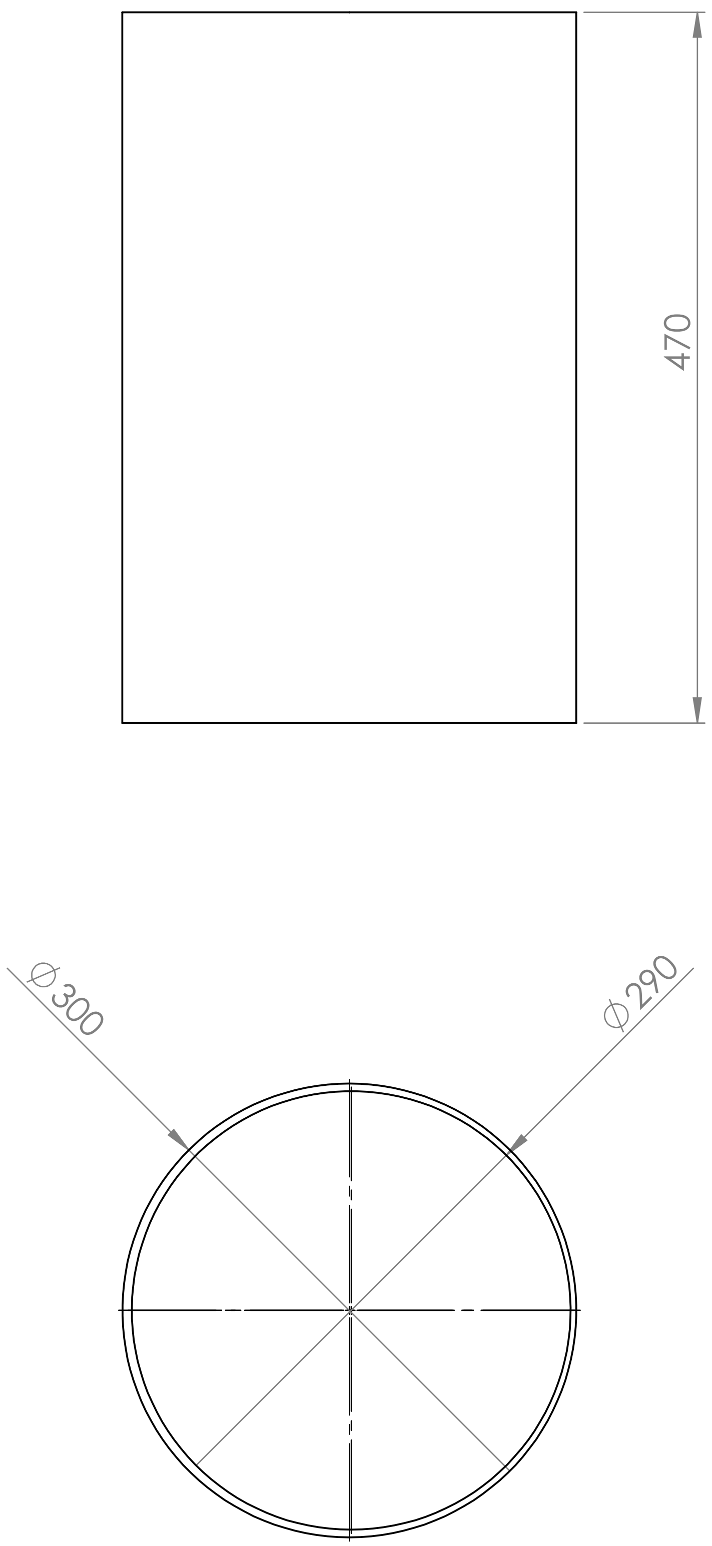

ITEM NO.	PART NUMBER	DESCRIPTION	MATERIAL	WEIGHT	QTY.
2	P02-02 Outer shell	Outer shell	Polypropylen (PP)	1.9 kg	1

Date:	Konstr./Engineer:	Projection:	Scale:	
05.05.17	H.O.P		1:5	NMBU

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Drawing no. R02

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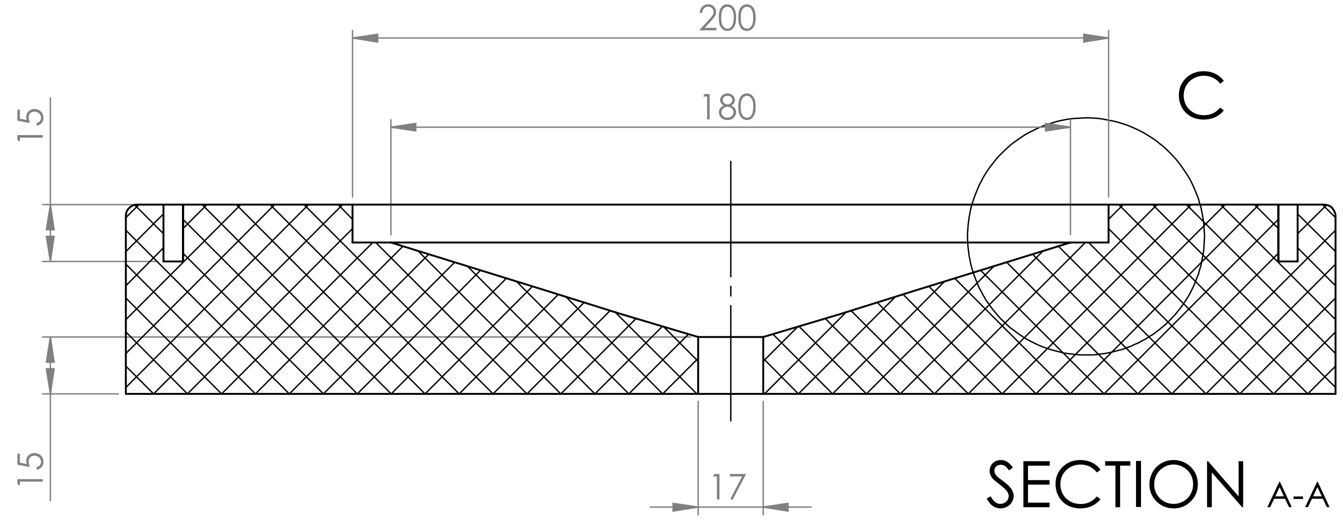
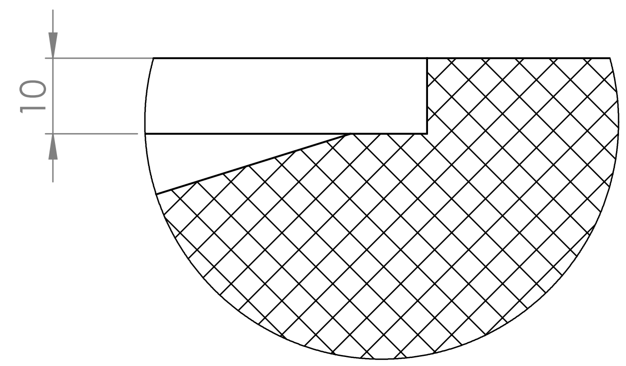
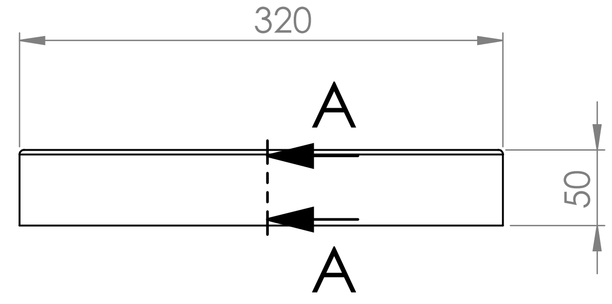
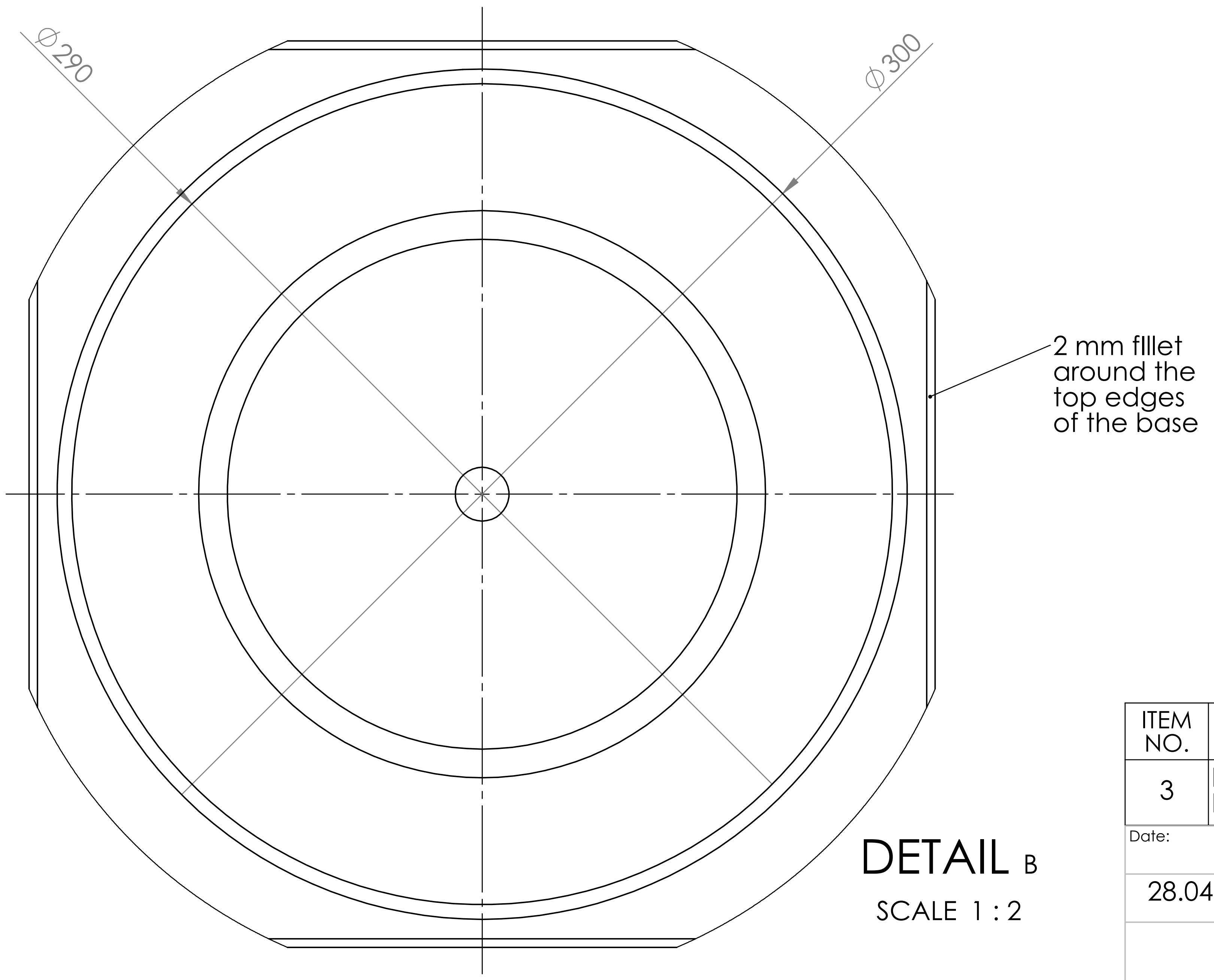


SECTION A-A
SCALE 1 : 2

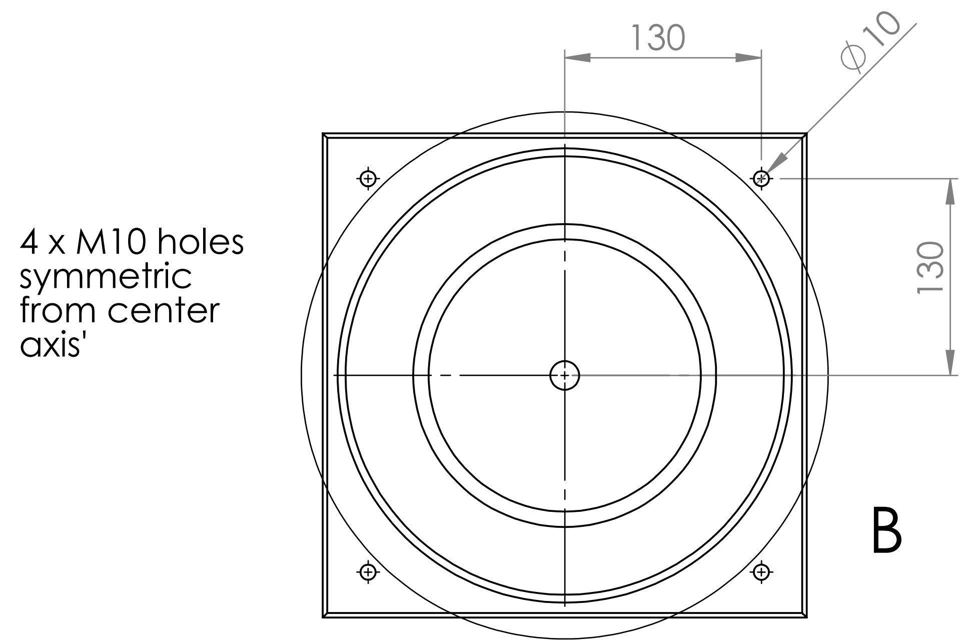


DETAIL C
SCALE 1 : 1





DETAIL B
SCALE 1 : 2



ITEM NO.	PART NUMBER	DESCRIPTION	MATERIAL	WEIGHT	QTY.
3	P02-04 Base	Base	Polypropylen (PP)	4 kg	1

Date:	Konstr./Engineer:	Projection:	Scale:	
28.04.17	H.O.P		1:5	NMBU

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Drawing no. R03

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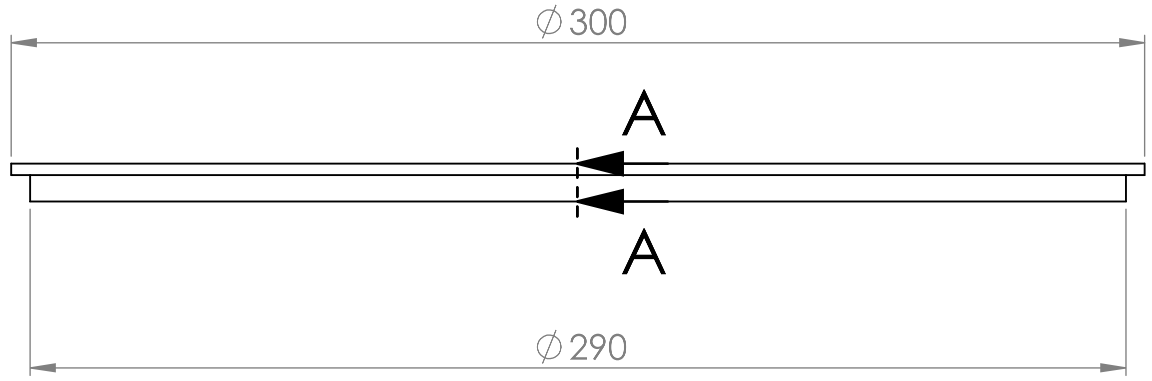
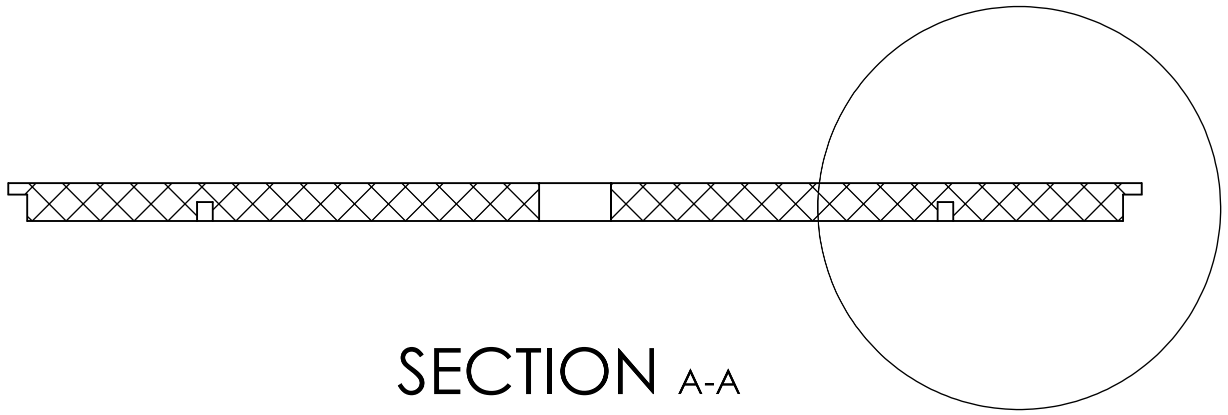
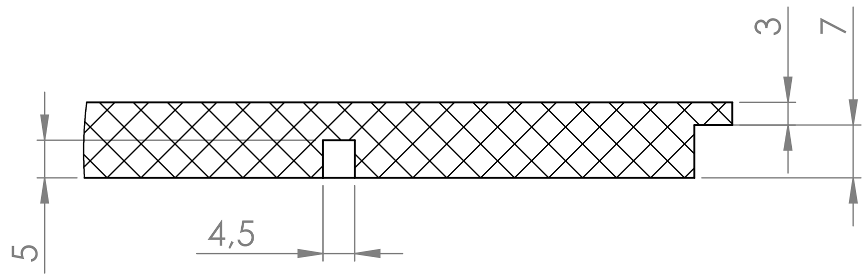
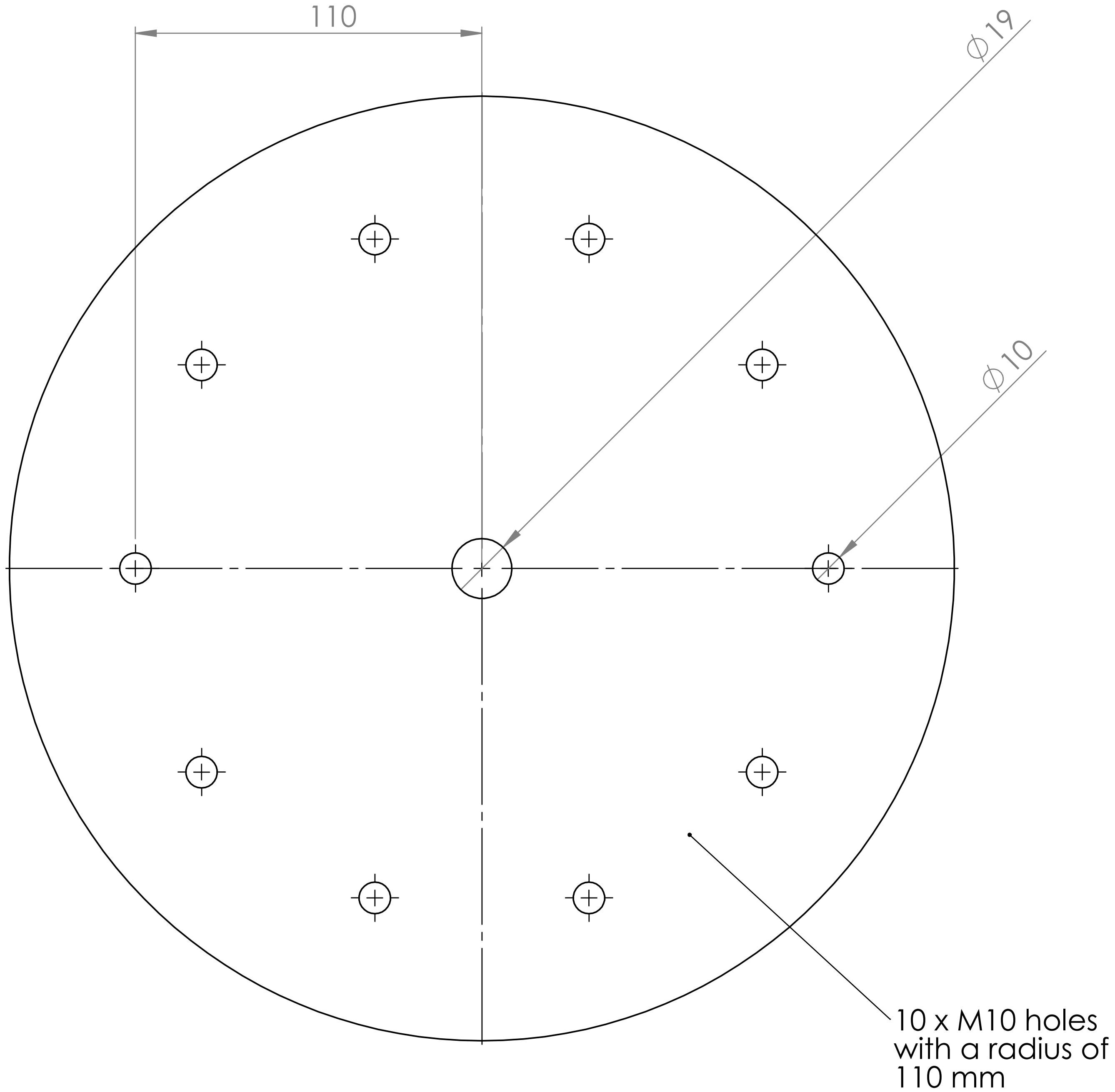




SECTION A-A
SCALE 1 : 2



DETAIL B
SCALE 1 : 1



ITEM NO.	PART NUMBER	DESCRIPTION	MATERIALS	WEIGHT	QTY.
R04	P02-01 Toplid	Top lid	Polypropylen (PP)	0.6 kg	1

Date:	Konstr./Engineer:	Projection:	Scale:	
28.04.17	H.O.P		1:10	NMBU

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Drawing no. R04

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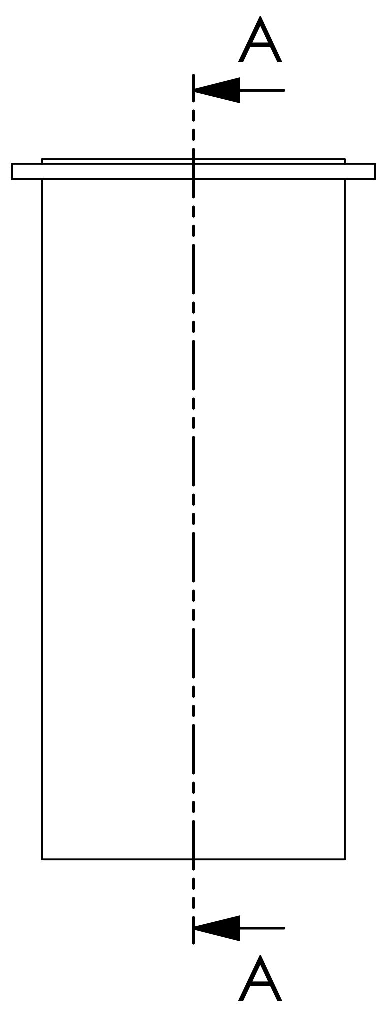
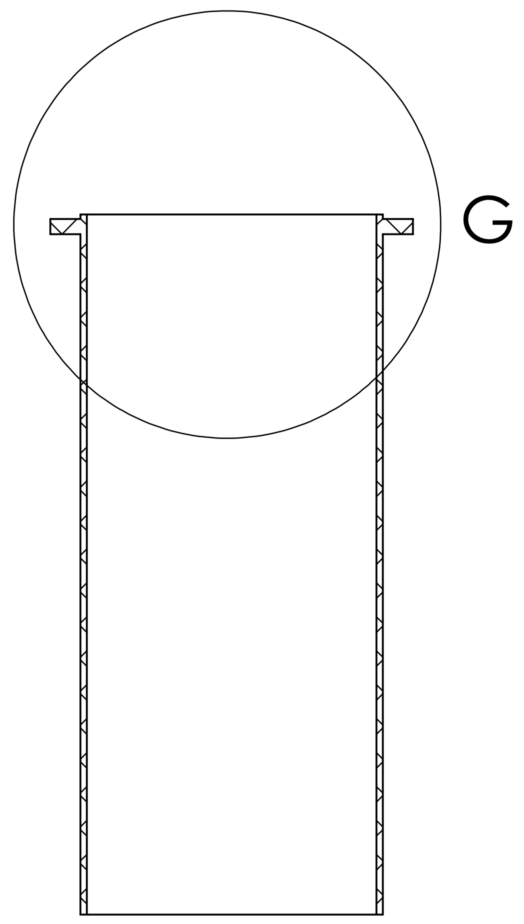
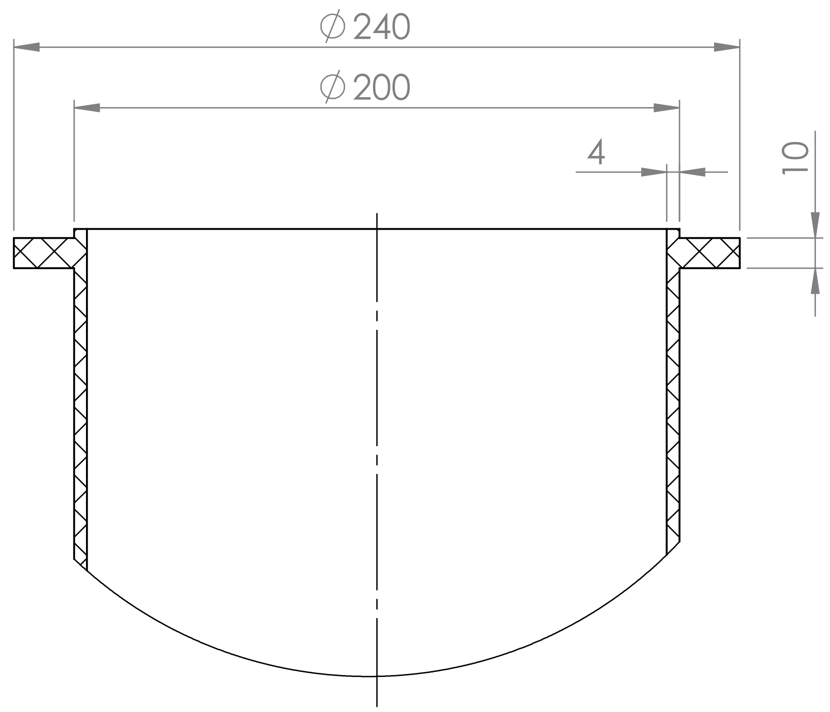
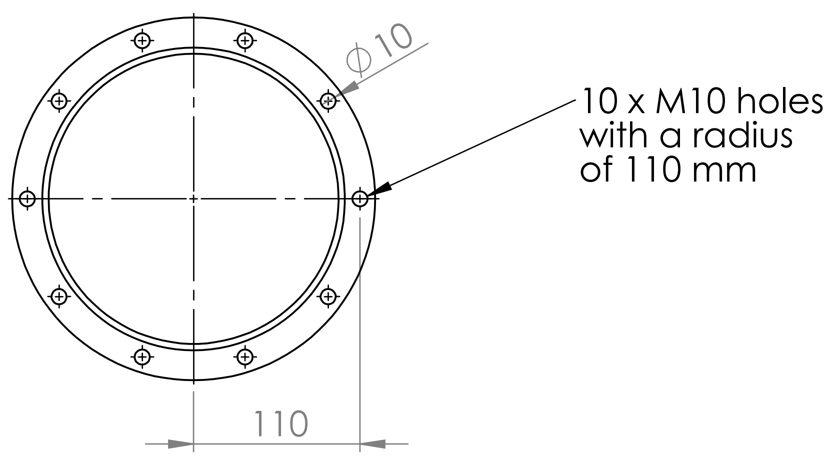




SECTION A-A



DETAIL G
SCALE 2 : 5



ITEM NO.	PART NUMBER	DESCRIPTION	MATERIAL	WEIGHT	QTY.
5	P02-03 Mid Shell	Mid shell	Polypropylen (PP)	1.2 kg	1

Dato:	Konstr./Tegnet:	Projeksjon:	Målestokk:	
28.04.17	H.O.P		1:5	NMBU

	Erstatatning for:	Erstatattet av:
Master's Thesis 2017	Tegning nr. R02	
Henvisning:	Beregning:	

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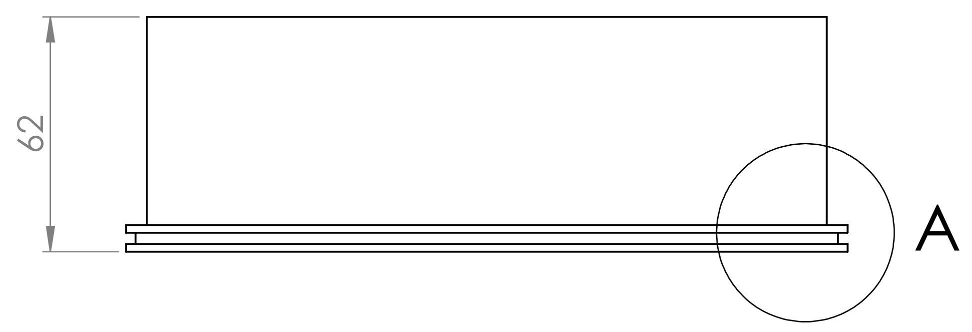
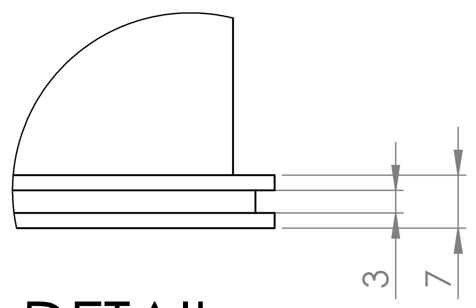
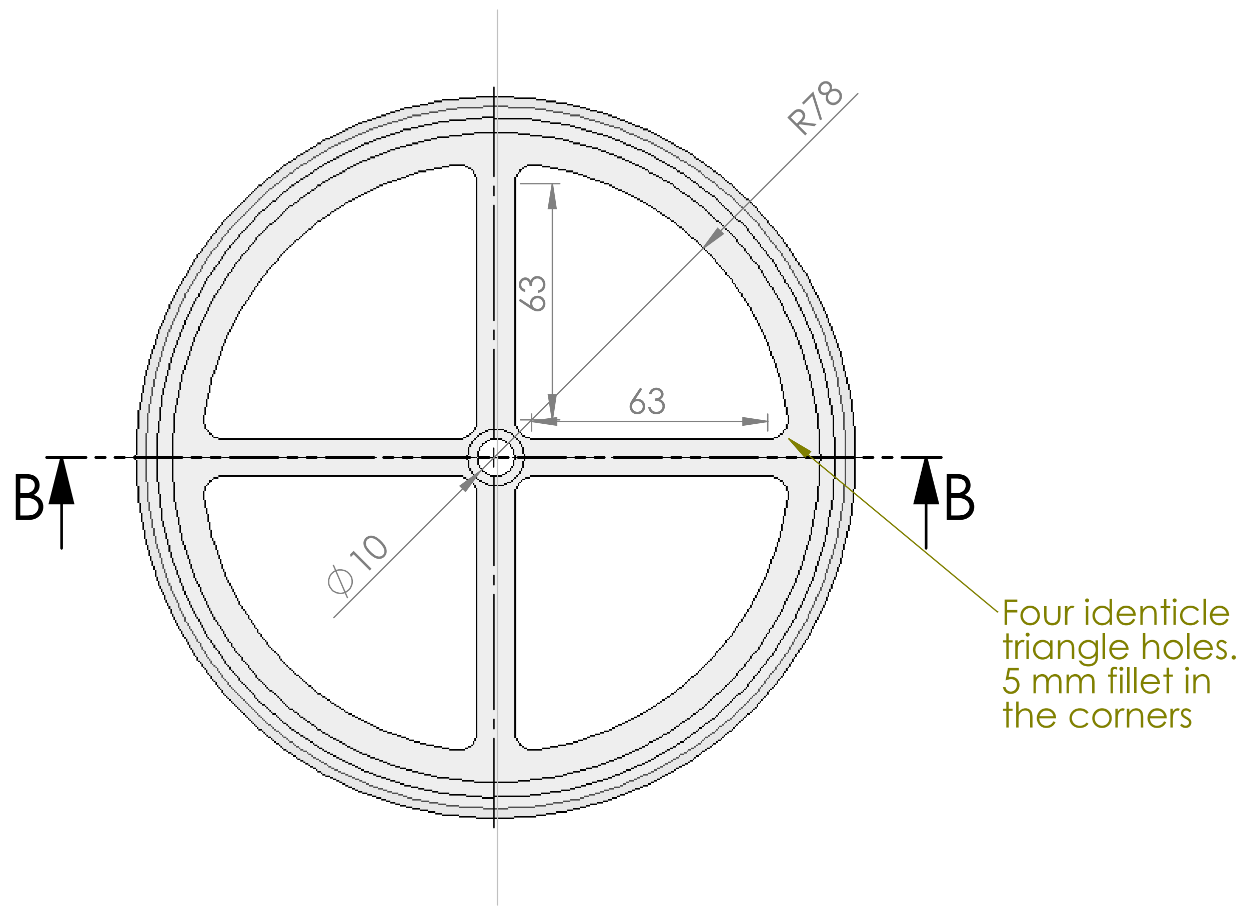
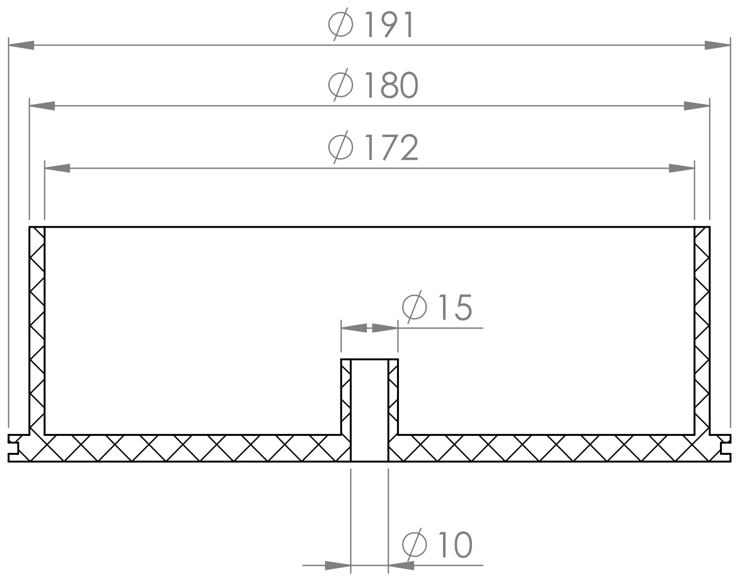




DETAIL A
SCALE 1 : 1





SECTION B-B

ITEM NO.	PART NUMBER	DESCRIPTION	MATERIAL	WEIGHT	QTY.
R06	P02-04 Capsule	Capsule for six-capsule reactor	Polypropylen (PP)	0.2 kg	6

Date:	Konstr./Engineer:	Projection:	Scale:	
28.04.17	H.O.P		1:5	NMBU

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Drawing no. R06

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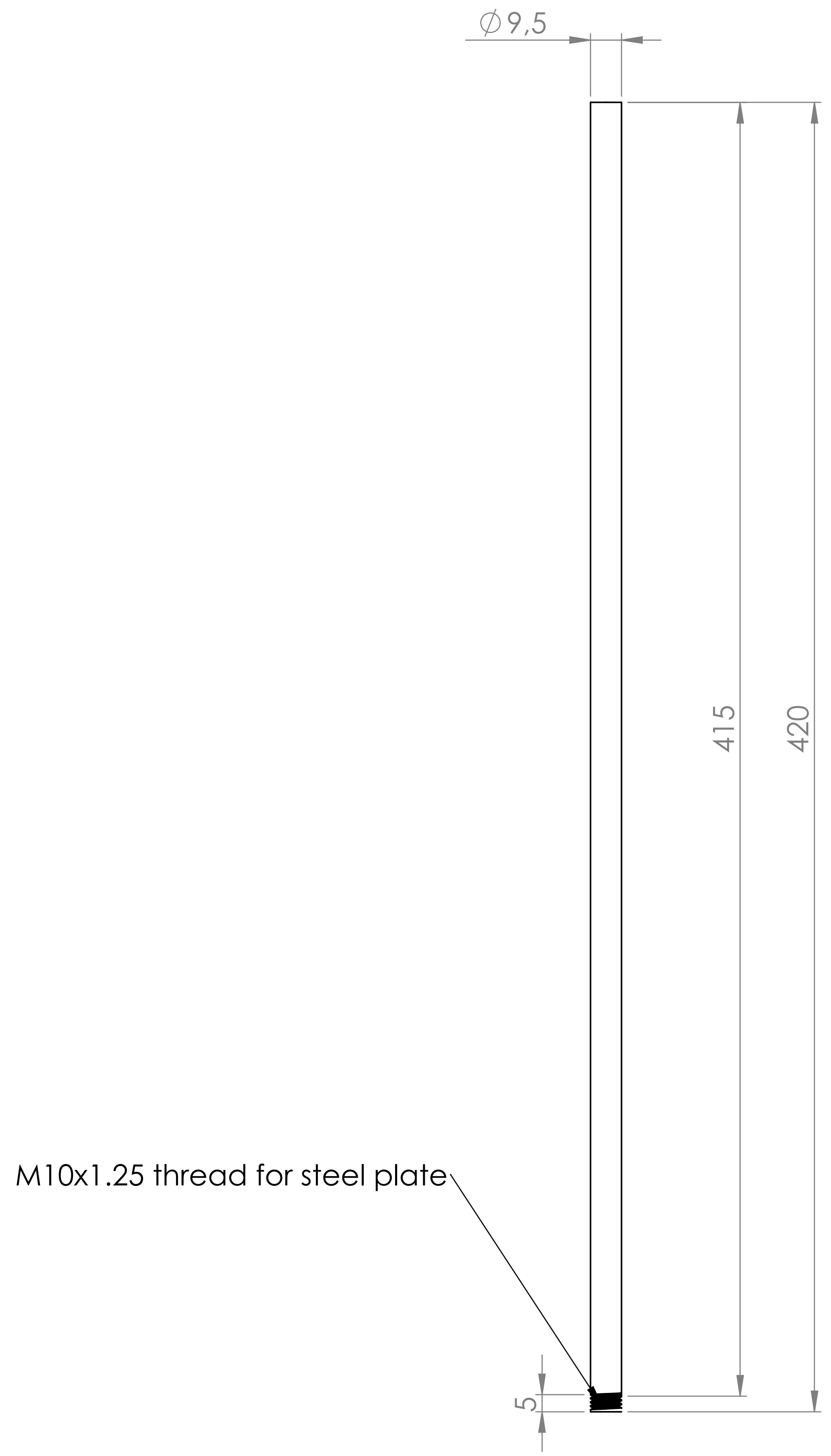

ITEM NO.	PART NUMBER	DESCRIPTION	MATERIAL	WEIGHT	QTY.
7-1	P02-03 Rod	Rod for steel plate	Stainless steel	0.24 kg	1

Date:	Konstr./Engineer:	Projection:	Scale:	NMBU
28.04.17	H.O.P		1:2	

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Drawing no. R07-1

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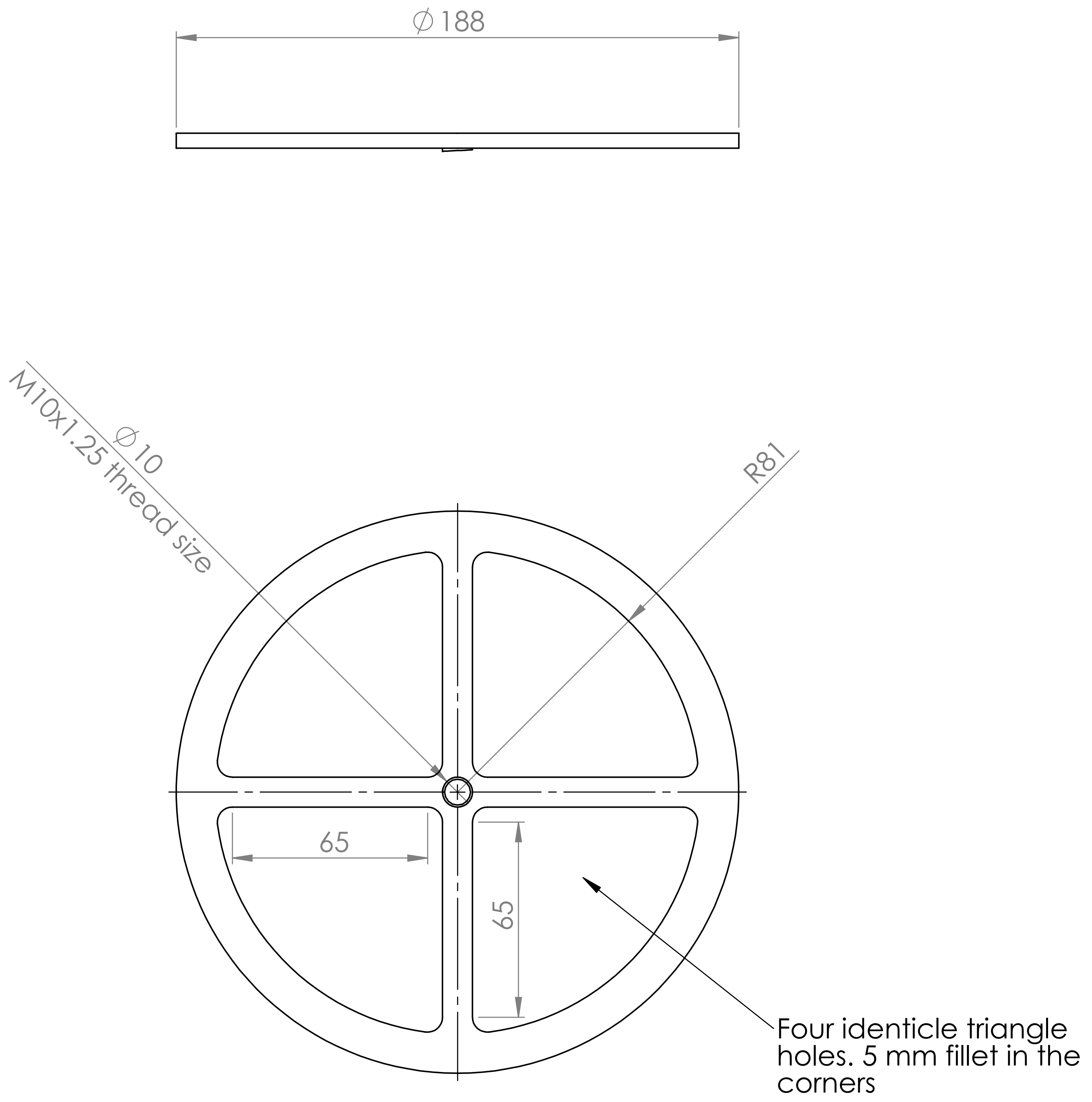

ITEM NO.	PART NUMBER	DESCRIPTION	MATERIAL	WEIGHT	QTY.
7-2	P02-03 Rodplate	Rodplate	Stainless steel	0.38 kg	1

Date:	Konstr./Engineer:	Projection:	Scale:	
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Drawing no. R07-2

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