

Development of an interface used in a scanning radar measurement system

Tailored for high-pressure and high-temperature environments

Master's thesis in Product Development

Kathiresan Singaram & Karin Westerlund

MASTER'S THESIS 2024

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CHALMERS
UNIVERSITY OF TECHNOLOGY

Department of Industrial and Materials Science
Division of Product Development
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2024

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Cover: Side view of the CAD model of the final interface design.

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Abstract

This master thesis focuses on designing and developing an interface that can be utilised in high-temperature and high-pressure environments in a scanning microwave radar measurement system. The key aspect of the project is that the interface should protect the radar from given temperature and pressure conditions while still ensuring good measurement accuracy. The project progressed using an iterative process guided by a concept development funnel, where concepts were subsequently generated, evaluated, verified and refined. The material and design were evaluated on aspects such as microwave absorption, transparency and reflectivity to ensure that the microwaves could travel as intended. There were also requirements on the strength of the interface and thermal conductivity amongst others, to ensure a durable interface and a safe environment for the radar. During this process, simple 2D sketches, CAD models, and rapid prototyping were utilised to explore possible solutions and to verify the fulfilment of specifications. Further verification was also done with the simulation tool Ansys Mechanical to test the strength and thermal performance of the interface. In conclusion, the findings and research of this study are expected to have significant implications for the design and implementation of scanning radar systems in industrial environments, paving the way for future advancements in accuracy, reliability, and safety.

Keywords: Product development, Scanning radar measurement system, Microwave radar, High-temperature, High-pressure

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Kathiresan Singaram & Karin Westerlund, Gothenburg, June 2024

List of Acronyms

Below is a list of the acronyms that have been used throughout this thesis listed in alphabetical order:

2D	two-dimensional
3D	three-dimensional
bar	unit of atmospheric pressure
°C	Celsius degrees of temperature
CAD	Computer-aided design
FMCW	frequency modulated continuous wave
FOV	field of view
GWR	guided wave radar
LCA	Life Cycle Assessment
m	meter
NCR	non-contacting radar
Pa	Pascal, SI-unit for pressure
PCB	printed circuit board
RF	radio frequency

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1

Introduction

The introduction chapter will give a comprehensive insight into the project, starting with the background, and purpose, then continuing with scope and limitations, and the problem description. Lastly, the objectives and key activities will be presented along with a report outline.

1.1 Project and company background

The background section will provide a context of the project's background as well as information about the company Emerson, and the subsidiary Rosemount Tank Radar AB, where the thesis is conducted.

1.1.1 Project Background

Today, Emerson's microwave radar is used to measure single-point levels of both solids and fluids in a magnitude of industrial facilities worldwide. The need for an accurate and reliable scanning radar system in industrial environments has been continually evolving due to more automated, high-precision processes and a wider range of contents to be measured. Currently, various technologies are used for measurements, including guided wave radar and non-contacting radars. However, single-point only measures a point on the content's surface, thus measuring any content with an uneven or irregular surface will result in a lack of accuracy when deciding fill-level. In order to improve measurement accuracy, multi-spot scanning radar is a suitable option. This would not only improve the fill-level accuracy but it could also provide a complete scan of the surface. The scan of the surface could then be used to determine, for example, where in the tank there is room to place more contents so that an even fill is obtained or decide in what stage a chemical process is in depending on if the surface is flat or covered in bubbles that create an uneven surface.

1.1.2 Company Background

Emerson Electric Co. is a well-known American multinational corporation that operates in various industries, including technology and engineering. It was founded in 1980 by John Wesley Emerson in St.Louis, Missouri, USA [1].

Originally, the company started as a manufacturer of electric motors and fans. The company operates through several business segments serving a wide range of industries, including process manufacturing, commercial and residential solutions, telecommunications [1]. Emerson is known for providing solutions that enhance efficiency, safety and sustainability in various industrial processes. The company serves customers in various industries and its products and services are used in diverse applications from manufacturing processes to energy infrastructure.

In the year 2001 Emerson acquired SAAB Marine Electronics [2], whose name was later changed to Rosemount Tank Radar as it is known today. The company portfolio includes several industry applications such as corrosion and version monitoring, liquid analysis and several types of measurement systems [3]. Some of their most well-known products are level measurement systems such as the industry-leading guide wave radar, "Rosemount 5300 Level Transmitter - Guided Wave Radar"[4], and the world's first non-contacting radar specifically for food and beverage applications, "Rosemount 1408H Level Transmitter - Non-contacting Radar" [5] both of which are single point measurement systems.

1.2 Purpose

To achieve the end goal of this project which is two new concepts for physical interfaces in a radar measuring system. The project will start with an initial literature study and the generation of conceptual ideas. This will provide a great foundation and knowledge that ensures a clear insight into the issues at hand and relevant technology.

Subsequently, the focus will shift towards the stages of design, material selection, and the development of physical prototypes. These shall be done in an iterative approach and elimination of inadequate concepts along the way. This will be done through evaluating, screening and scoring concepts.

The end result of this project should be two functional prototypes in the chosen materials that are suitable for scanning radar measurement and are transparent to microwaves so that the microwaves can travel through when doing measurements. The solutions should also be reflective at the outer edges, to keep the microwaves within the interface and guide them to and from the radar and also to block out any unwanted noise on the sides. Depending on the shape it should also be absorbent in its lower focal point to ensure accurate measurements and cancellation of undesirable reflections. Additionally, one interface should be able to withstand very high temperatures while the other one be able to withstand very high pressure. These aspects are crucial to fulfilling the demands that are derived from the designated environment in which the components will reside.

1.3 Scope and Limitations

The master thesis project will progress during the spring semester of 2024, for approximately 20 weeks and account for a total of 30 study credits. The project will be primarily conducted in Gothenburg at the Emerson office. In addition to this, the project will conduct a few parts at Emerson's office in Linköping. The resource limitations on the project are therefore the resources available at Emerson's offices and the university, as well as the time frame.

The scope of the thesis is to develop two concepts and prototypes for the physical interfaces that are to be used in a scanning radar measurement system. The project will cover the development of the interfaces and how they are to be placed and interact with other parts of the system. This includes designing, material selection and prototyping of the interfaces. However, the project does not include any software development or development of other parts of the system. Moreover, the project will neither include customer needs identification nor planning for production, which is a result of the limited time for the project.

Integrating advanced radar technology into existing industrial systems and processes may pose compatibility challenges, therefore it is of high importance to constantly verify solutions. Additionally, ensuring seamless integration with legacy systems and equipment while maintaining operational reliability could be a significant limitation.

Environmental conditions such as temperature variations, electromagnetic interference and physical obstructions may affect the performance and reliability of the radar system. Addressing these challenges and ensuring robust operation in diverse environmental conditions is crucial.

Validation of accuracy and reliability of the scanning radar measurements against data poses a significant challenge. Calibration procedures and validation protocols should be rigorously developed to ensure the integrity of measurement results.

1.4 Problem Description

The project will tackle the task of protecting the radar sensor module in a non-contacting scanning microwave radar and sealing the radar from the tank where the contents to be measured reside. The focus will consequently be on designing and implementing two interfaces that protect the module in the measurement system.

One interface should be able to operate under conditions of very high temperatures up to 400 degrees Celsius and pressures up to 345 bar (345 units of atmospheric pressure) which the module cannot handle. This is because even modules considered to be able to withstand high temperatures have an upper operating temperature limit of 150°C [6]. If the temperature exceeds this limit there can be damage to the components which can cause distorted measurements.

The other interface should be able to handle very high pressure up to 400 bar which can also affect the module negatively and lead to incorrect measurements. Very high pressure could even cause components to rupture [7] leading to no measurements at all. Accurate measurements are crucial for operational efficiency and safety and distorted measurements would be detrimental for the system and its applications.

The interfaces have to let microwaves pass otherwise the transmitters and receivers in the module will not be able to detect the microwaves and as a consequence, no measurements can be done. Therefore the interface needs to be transparent up until the edge of the interface to allow passing of microwaves. Additionally, the interfaces also need to be reflective and absorbent. This is because reflectivity will determine how the microwaves bounce off of the interface [8] and as a consequence, it will affect the refractive index and the resolution angle [9] which in turn affects the accuracy of the measurement. The reflectiveness, however, is only desired on the outer edge of the interface, this is to guide the microwaves to and from the radar and still cancel out any unwanted noise from the sides. Absorption also affects the microwaves in such a way that a material with high absorption will decrease the microwave energy thus decreasing the strength of the microwave signal [8] therefore this property is only wanted in limited amounts in certain places, which is only in the lower focal point which only exists for some geometric shapes. For such shapes, the absorbency will help in cancelling out any unwanted reflections that can occur. Consequently, the interface has to protect the module from heat and pressure respectively while still being reflective, transparent and possibly absorbent.

1.5 Objectives

To guide the project's progress a list of objectives has been outlined. They highlight the most important aspects of the project and will provide a strategic framework for the development.

The main objective is to design and develop two interface solutions that effectively protect the radar sensor module in either a high-temperature environment or a high-pressure environment while remaining transparent to microwaves. The solutions should be robust, reliable and seamlessly integrated with the radar system ensuring accurate and reliable level measurements in industrial tanks. This main objective has been divided into smaller objectives to help with clarity, measurability and motivation and they can be seen in list 1.1.

- Two physical interfaces that can be utilised in a non-contacting scanning microwave radar solution in industrial environments.
- One interface that can withstand varying and high pressure and one interface that can withstand varying high-temperature conditions.
- Two interfaces that are transparent to microwaves as well as reflective to ensure accurate measurements. Depending on the design, the interfaces should also provide absorbency in the lower focal point but not elsewhere.
- Two scalable and cost-effective solutions that align with Emerson's production processes ensuring feasibility for large-scale production across industrial facilities.
- Two high-quality interfaces that are intuitive and user-friendly for the microwave team facilitating ease of operation.
- Two interfaces that comply with relevant safety standards and regulations to guarantee a safe working environment for industries and mitigate potential risks associated with radar technology.

List 1.1: Objectives.

1.6 Key Activities

To fulfil the aims and objectives of the project, a list of key activities has been planned during the duration of the project as can be seen in 1.2. They aim to clarify important tasks and aid in planning.

- Study current interfaces in single-point measurement systems and their issues to find potential areas of improvement that can be applied to our solution.
- Generate concepts and gradually remove unsuitable ones through elimination processes.
- Design the interfaces.
- Material selection for both interfaces.

- Assess manufacturability for interfaces.
- Test prototypes.
- Seek feedback from colleagues at Emerson's, specifically from the microwave team that will be affected by the solutions.
- Define the rationale behind the proposed solutions and identify behavioural uncertainties.

List 1.2: Key Activities.

1.7 Report Outline

The report is organised into eight chapters starting with Introduction, Theoretical Background, Methodology, Target specifications, Concept Development, Final Concept, Evaluation and Discussion, Conclusion and Recommendations.

The Methodology and Theoretical Background chapter outlines the methods implemented and the fundamental general theory behind all the technology and terms used. The Methodology chapter is divided into three phases, target specifications, concept development funnel, and final concept. Each phase is explained in detail with its purpose, objectives, and applied methods. All the phases have their individual sections with detailed descriptions.

The fourth, fifth and sixth chapters present the outputs and results from target specification, concept development and final concept respectively which were the three iterations that culminated in the final solution which is presented in the last of these chapters.

The last two chapters Evaluation and Discussions and Conclusions and Recommendations are general chapters focusing on reflections on the overall project process, approach, recommendations and fulfilment of the project goals. The chapter, Evaluation and Discussion, reflects on the task, approach and results as well as presenting the ethical, social and ecological considerations of the project. The Conclusion and Recommendations chapter describes the outcome of the project's objectives and problem description, along with future recommendations.

2

Theoretical Background

This chapter will present the theory for the project. This starts with microwave radar and how microwave radar level measurements work along with existing technologies used for single-point measuring and technologies that could be used to achieve scanning measuring. This is then followed by how microwaves interact with different materials and how microwave paths can be changed. Lastly, it presents heat transfer and strength of materials that provide relevant knowledge for each application scenario.

2.1 Microwave Radar

Radar technology has been around for more than 100 years and the more in-depth development of radar technology started in the 1930s [10]. Specifically radars operating on higher frequencies, in the microwave region, came about in 1939. Microwave radar is a broad technology widely used in different applications such as traffic control, weather forecasting and navigation [11].

2.2 Microwave Radar Level Measurements

Microwave radar can be used to make level measurements, i.e. the level of substances within containers or vessels by emitting microwave signals and measuring their reflections off the substance's surface [12].

In level measurements, microwaves are utilised primarily in radar-based level measurement systems. The radar system emits microwave signals from a transmitter towards the surface of the substance being measured. Then, microwave signals are reflected towards the receiver when they interact with the surface of the contents [13]. The time it takes for the signal to travel to the surface and back to a receiver is measured and used to calculate the distance between the Radar sensor and the surface. The distance measurement is then converted into the level of the substance within the container.

Microwave-based level measurement systems provide high levels of accuracy allowing for precise monitoring of substance levels within the container [14]. The microwave radars can be used to measure levels of various substances including liquids, solids and slurries. They are applicable across a wide range of industries and can be deployed in diverse environments from chemical processing plants to food and beverage facilities [14]. It can operate effectively in many conditions including high temperatures, pressure variations and atmospheric disturbances without compromising accuracy for measurements [15]. Microwave radar system provides real-time monitoring of content levels, allowing for detection of level changes and proactive response to abnormalities.

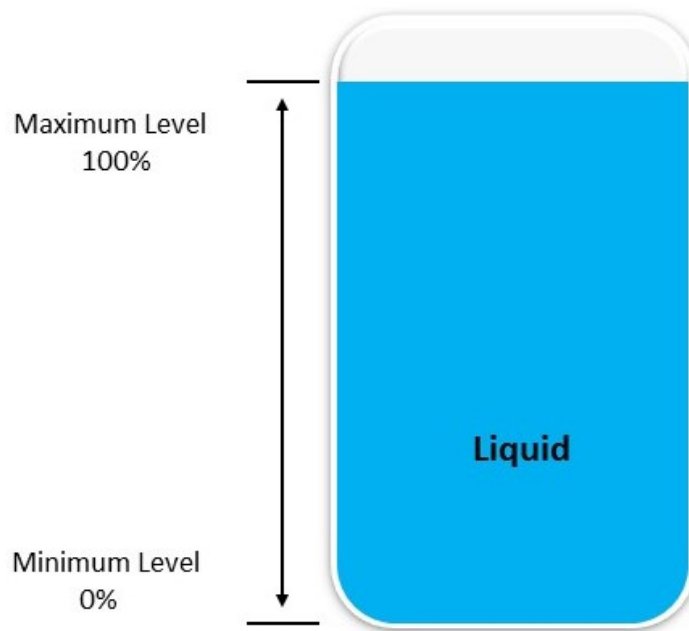


Figure 2.1: Level measurement technology

2.3 Existing Technologies

Today, there are many different technologies for microwave level measurements, both contacting and non-contacting which refers to whether the radars come into physical contact with the contents to be measured or not.

2.3.1 Guided Wave Radar

Guided wave radar (GWR) level measurement is a technology used to determine the level of contents within a container. It employs guided electronic magnetic waves to accurately measure the levels of liquids, solids, and slurry. This measurement system typically consists of a probe or a waveguide that extends into the substance being measured, along with the electronics for signal processing and level calculation [16].

The GWR emits microwaves along the length of the probe or waveguide. These waves travel down the probe and interact with the surface of the substance. Once after reaching the surface layer, the microwaves are partially reflected towards the guided wave radar transmitter. The transmitter electronics detect and measure the reflected signals. As there will be a time delay between the transmitter and the surface, using the time delay, the guided wave radar system calculates the distance from the transmitter to the surface [17]. The distance measurement is then converted into the level of contents or substances within the tank, considering factors such as probe length and calibration parameters.

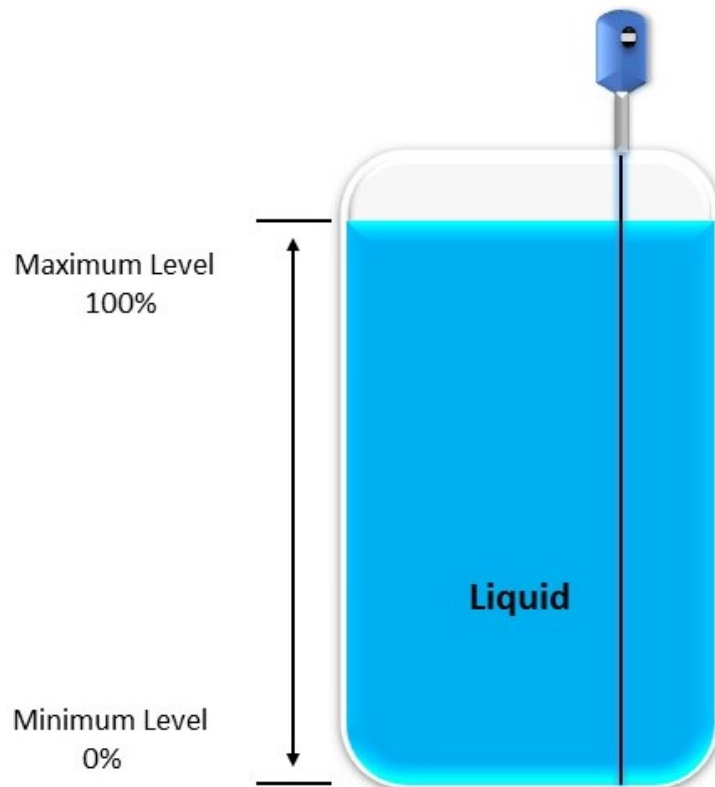


Figure 2.2: Level measurement GWR.

2.3.2 Non-contacting Radar Transmitter

Non-contacting Radar Transmitter (NCR) level transmitters are devices that measure the level of contents within the containers without physically contacting the substance itself [18]. Here, the radar uses microwaves to measure the distance from the transmitter to the substance's surface. The transmitter emits microwave signals that travel through the air and reflect off from the surface.

Generally, NCR transmitters use frequency-modulated continuous wave (FMCW) technology for level measurements [19]. This technology, particularly in Rosemount's energy-efficient FMCW radar ensures optimal performance. The level here is determined based on the time or frequency differences between sending and receiving the signal. These transmitters are suitable for liquid or solid tank levels with varying temperature and pressure requirements. They are typically mounted at the top of the container.

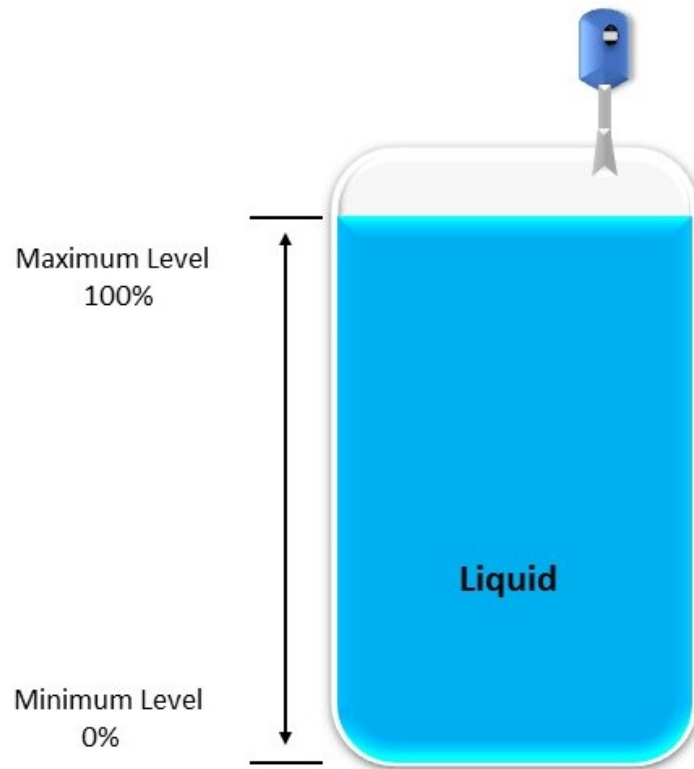


Figure 2.3: Level measurement NCR.

2.3.3 Working principle of Non-contacting Radar Transmitter

The distance in a non-contacting FMCW Radar is calculated using the principle of time of flight measurement [20].

The radar emits short electromagnetic waves, typically in the microwave frequency ranges from the antenna. This pulse will travel from the antenna to the contents being measured inside the Tank. When the microwaves touch the surface of the material being measured, a part or portion of the energy is reflected toward the antenna. The reflection happens as there is a change in the dielectric constant between air and the surface of the substance. The radar receiver detects the reflected echo signal, which has a time delay between the transmission and reception of microwaves. This time delay corresponds to the time travel of the microwaves from the transmitter to the content's surface [21].

The speed of light is a fundamental constant in physics, and the electromagnetic waves travel at approximately 3×10^8 . The time delay represents the elapsed time between transmission and reception of the microwaves.

Hence the distance to the content's surface is calculated using the formula:

$$\text{Distance} = \text{speed of light} \times \frac{\text{Time delay}}{2} \quad (2.1)$$

2. Theoretical Background

The calculated distance measurement is typically displayed on the radar transmitter to external devices. Usually, the measured distances are provided in units such as meters or millimetres depending upon the user preferences and application requirements.

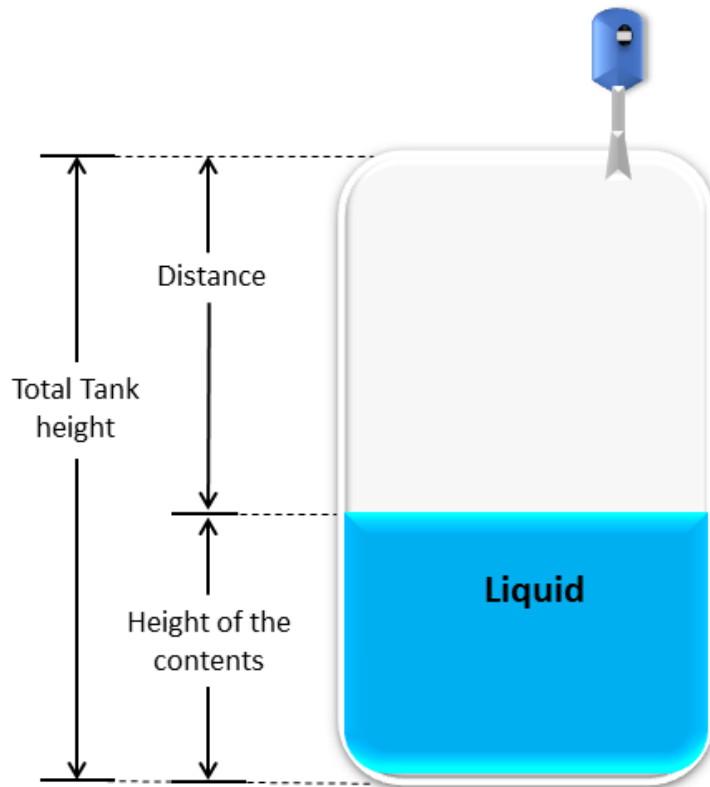


Figure 2.4: Level Calculation NCR.

The level of the contents measured is calculated based on the distance measured from the radar transmitter to the content's surface. A reference point either bottom of the tank vessel or in the empty condition is fixed. Now the level of the material in the tank is measured by subtracting the measured distance from the total height of the tank. The total height is the distance from the reference point to the top of the tank [21].

Hence the level of the contents is calculated using the formula:

Content's Level = total tank height - Distance measured.

So, accurate calculation of these distances to the content surfaces is crucial as the NCR provides real-time data for continuous level monitoring and control in various industrial applications in Tanks, vessels or any process containers.

2.4 Scanning Microwave Radar

To better determine the amount of contents filling a tank that has an uneven surface, multi-spot or scanning continuous radar is more efficient and more accurate. The microwaves are still emitted in the same way from the radar sensor module into the tank, the difference is that it also sweeps the surface [22]. The sweeping motion can be attained through several different technologies including MIMO-radar [23], a phased array [24] or simply adding a mechanical movement to a single-point measuring radar.

2.4.1 Phased Array Radar Technology

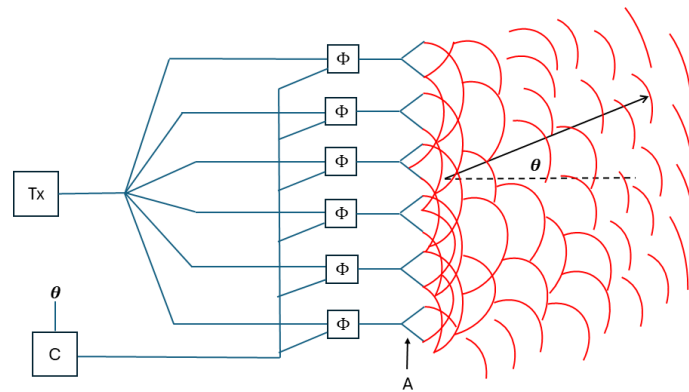


Figure 2.5: Phased array radar technology.

A phased array radar system has an array of individual antennas to create a directional beam of radio waves. These radio waves are electronically controlled in desired directions without manually moving the antenna. Phased array antennas have their own transmitter and receiver and are arranged in a regular grid pattern [25]. In order to adjust or change the directional phase of the transmitted and received signal, the radar system controls the transmitted beam directing the emitted waves at a certain angle θ relative to the antenna's axis. This process is called a phase shift where constructive interference between the signals occurs in a specific direction while destructive interference in another direction. Constructive interference adds up the amplitudes of the signal together in a desired direction where the radar is intended to be focused whereas destructive interference occurs when waves cancel out each other to reduce the unwanted signals that should be further amplified [26]. In figure 2.5 TX is the transmitter that transmits the microwaves, and the red lines are the different amplitudes of constructive and destructive interferences. Φ is the current or power input through which the phase shifter works and C denotes that the radar is being computer-controlled. A denotes the radar as an array of similar antenna elements.

2.5 Interaction between Materials and Microwaves

The interaction between the material and microwaves is the fundamental aspect of microwave engineering and has significant applications across various fields. This interaction occurs when electromagnetic waves within the microwave frequency range from 300 MHz to 300 GHz leading to a variety of phenomena and effects [27].

Factors affecting reflectivity

Reflectivity of materials refers to their ability to reflect incident electromagnetic waves instead of absorbing or transmitting them. This phenomenon is crucial in Radar systems and microwave communications. When a microwave interacts with the material's surface, a part of the wave is typically reflected back to the medium, while the remaining is either transmitted or absorbed by the material [28]. Reflectivity signifies the amount of incident energy that is reflected by the material.

Materials with high dielectric constants exhibit higher reflectivity to microwaves, as higher permittivity leads to stronger interactions between the material and the incident waves, resulting in good reflectivity [29].

Generally, materials with low-loss tangents have minimal energy dissipation and therefore reflect more microwaves. Conversely, materials with high-loss tangents absorb more energy and reduce reflectivity [29]. The loss tangent is the ratio of a material energy loss to its stored energy also called a dielectric constant.

Materials with high reflectivity

Certain materials are known for their high reflectivity of microwaves such as aluminum, copper, and Gold, they are excellent reflectors of microwaves particularly at higher frequencies [30]. The high reflectivity of those materials comes from their excellent electrical conductivity properties, which enable them to efficiently reflect electromagnetic waves.

Metalized surfaces involve coating a non-metallic substrate with metallic layers to enhance their reflectivity. Some materials that are not inherently reflective such as plastics or ceramics can still be highly reflective when coated with extra metallic layers. These metalized layers or coatings are commonly used in microwave applications, where they act as shielding layers to reflect unwanted electromagnetic waves [31].

Absorbent Materials

There are various materials that interact differently with microwaves based on their properties. These materials can be classified into three types based on how they interact with microwaves, namely transparent, opaque, and absorbent materials.

Transparent materials don't absorb microwaves and rather let them pass through easily. They usually have low energy loss when exposed to microwaves. Certain materials like alumina, magnesia, silica, and glasses. However, when these materials are heated above a certain temperature, they can absorb microwaves [32].

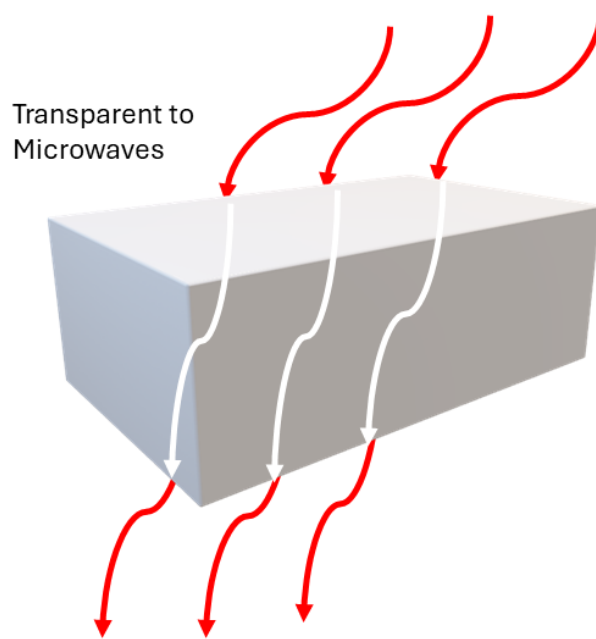


Figure 2.6: A material transparent to microwaves.

Reflective materials don't let microwaves pass through them. When microwaves touch the surface of the material, they either bounce back or get absorbed [32].

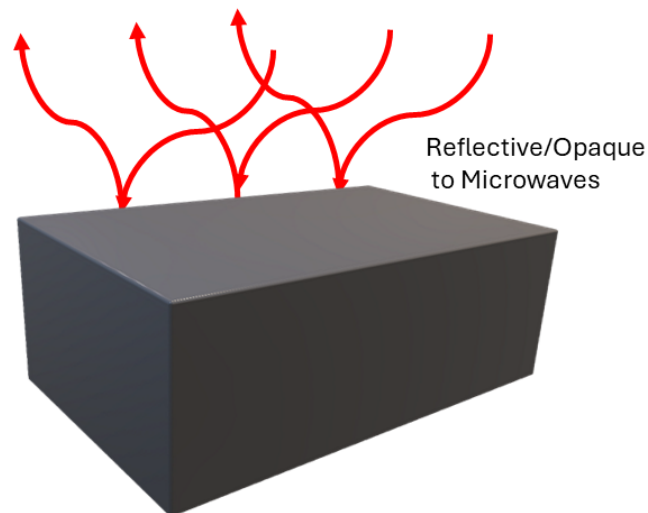


Figure 2.7: A material reflective of microwaves.

Absorbent materials absorb microwaves and convert them to heat. They have high energy loss when exposed to microwaves. The dielectric constants and loss tangents also play a major role in a material's absorbency of microwaves. Higher dielectric constants and loss tangents result in greater levels of absorbency [29].

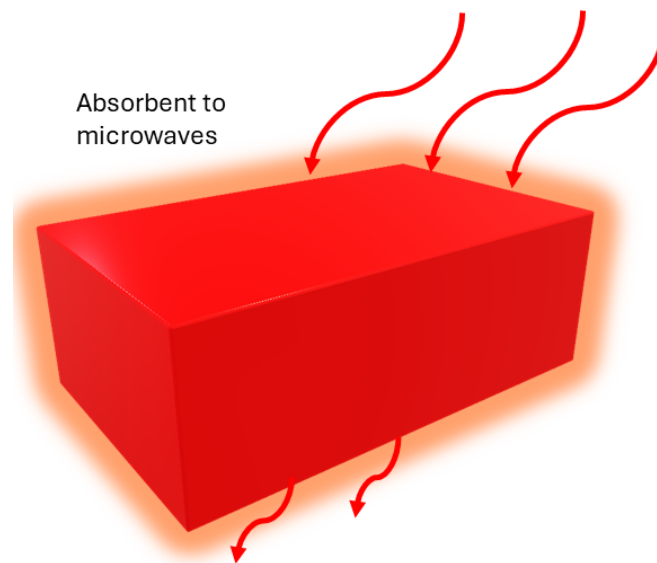


Figure 2.8: A material absorbent of microwaves.

Magnetic materials such as ferromagnetic and ferromagnetic substances exhibit significant absorption of microwaves. This absorption phenomenon is particularly seen in materials with higher magnetic properties. This phenomenon occurs because of the interaction between the oscillating electromagnetic field of microwaves and the magnetic dipole moment. This magnetic moment stays within the field and absorbs microwaves during the process [33].

Carbon-based materials such as carbon fibres, and graphite exhibit excellent microwave absorbent properties. Their complex structures and high surface enable efficient absorption of electromagnetic energy and also making suitable for microwave absorbent coatings.

2.6 Manipulation of Microwave Paths

There are several ways to affect microwaves and their path when transmitted. For example, one could utilize lenses and they will work similarly to optics and light or one could utilise different antennas or waveguides.

2.6.1 Lenses

There are lenses which can be used at radio frequencies also called microwave lenses. They are designed to control electromagnetic waves in the RF spectrum. RF lenses are similar to optical lenses in focusing and collimating EM waves.

Dielectric lenses are made using materials with high dielectric constants such as materials with polymers, plastic and ceramics. Dielectric lenses function by exploiting the properties of a particular material [34]. When the EM waves pass through a dielectric material, they experience a phase change and amplitude due to interactions

with the material's electric field. One of the main functions of dielectric lenses is to focus and direct RF waves. This is done by shaping the dielectric material that can alter the phase and amplitude of the waves passing through it [33].

There are two types of lenses that affect the microwave path such as diverging and converging lenses. Converging lenses are a bit thicker in the middle and thinner at the edges. When light passes through them, they tend to focus at a single point on the opposite or other side of the lens known as a focal point. The bending of these waves is known as refraction, purely responsible for converging light rays to a focal point. As light is one of the types of electromagnetic waves, microwaves can also work similarly to the effect of light. On the other end, Diverging lenses are thinner in the middle and thicker at the edges. whenever the parallel rays are passing through the lens, they tend to diverge outwards because the rays are bent away from each other [35].

2.6.2 Waveguides

Waveguides are specialised structures used to guide microwaves in a directed path with minimal loss of energy. They are typically made of a metal or a dielectric material. The principle of waveguide is based on total internal reflections. When a microwave passes through a waveguide reflects off from the surface due to variations in refractive index between the surrounding medium and the waveguide. They are usually designed as hollow metal tubes to confine microwaves within them [36].

2.6.3 Lens Antenna

A lens antenna is a type of antenna that uses a dielectric material to focus electromagnetic waves [37]. Lens antennas operate on the principle of refraction similar to how optical lenses work [38]. When the waves are focused towards a particular direction, the focusing allows increased antenna gain resulting in a high power density in the same direction. Focusing on the lens antenna can also affect the radiation pattern directing a larger portion of radiated energy towards the target [38].

The focusing effect of the lens antenna narrows the beam width by concentrating the radiated energy into a stronger beam [39]. This significantly enhances the antenna's ability to distinguish between signals and background noises. The beam width serves as a metric for the angular spread of the primary radiation pattern as it projects onto a spherical surface through which the reception pattern is maximum [40].

2.7 Heat Transfer

To facilitate a proper heat protection method, main aspects were considered such as heat dissipation, which is essential to maintain optimal operating temperatures. Heat sinks act as a passive cooling mechanism by absorbing and dissipating heat away from the surface [41]. Heat sinks have a large surface area, usually materials like a mixture of aluminum or copper to effectively transfer heat to the surroundings through convection and convection [42]. Natural heat dissipation allows the heat to

escape from the container vessel through passive methods of convection and radiation. This allows the heat to transfer away from the surface to the surroundings without the use of an external component or a device. Natural dissipation occurs spontaneously due to temperature differences between the surface and ambient air.

Liquid cooling systems, which has either water or cooling fluid to absorb heat from a surface and carry it away to a heat exchanger or a radiator. The coolant system usually consists of a pump to circulate the fluid in a loop around the container vessel [43].

For air cooling generated by fans, air conditioners or even natural ventilation are used to remove heat from a surface [44]. Fan-assisted cooling method blows ambient air over the components to increase convective heat transfer and also enhances cooling efficiency. Air conditioners regulate temperature and humidity to maintain optimal cooling conditions in closed containers. They can deduct heat from the air through compression and condensation processes, allowing for precise temperature control measures. Moreover, natural ventilation, is the flow of air through openings or vents to remove heat from a space.

Materials with high emissivity were considered as they can emit thermal radiation efficiently. High-emissivity materials easily radiate heat away from the surface [45]. Emissivity is a quantity that shows the material emitting thermal radiation relative to an ideal black-body radiator [46]. Materials, especially with dark or black coated on rough surfaces, can exhibit high emissivity.

Materials with high thermal conductivity can conduct heat and allow it to spread rapidly through the material. They can facilitate effective heat transfer throughout the material, resulting in uniform temperature distribution.

2.8 Strength of materials

One of the most important aspects to consider when designing a product is its structural integrity [47]. Designing a product with sound structural integrity shall ensure that the product can handle any loading conditions that the product might experience, without yielding. These loading conditions such as compression or shear will result in an internal force within the component called stress that will try to resist any deformation. This stress state can be described by a stress tensor which is a three-by-three multidimensional array with nine values [48] as can be seen in equation 2.2.

$$\begin{pmatrix} \sigma_{xx} & \sigma_{xy} & \sigma_{xz} \\ \sigma_{yx} & \sigma_{yy} & \sigma_{yz} \\ \sigma_{zx} & \sigma_{zy} & \sigma_{zz} \end{pmatrix} \quad (2.2)$$

With this stress tensor, the equivalent stress can be calculated which is very valuable as it combines all nine values into a single equivalent stress value, thus saving both time and effort. The resulting equivalent stress, also called von Mises stress, σ_v ,

represents when the material will yield. The equivalent stress can also be derived from simulations using software.

To avoid yielding, the maximum allowable stress of the material needs to be greater than the equivalent stress. This allowable stress is derived from the material yield strength divided by the safety factor [49]. The safety factor is different from application to application and there is no standard but a safety factor of four is seen as an overall good starting point.

2. Theoretical Background

3

Methodology

The project process consists of three phases as illustrated in figure 3.1. Each phase includes several methods with the aim of reaching all objectives of the project, as presented in section 1.5. The phases are inspired by the concept development process by Ulrich and Eppingerr [50], the first and final phases are the same, while the middle phase, “Concept Development Funnel”, is inspired by the stages: concept generation, concept selection and concept testing. The concept testing as presented by Ulrich and Eppinger[50] will differ from what was conducted in the project. Because of the time limit and the strictly technical task, customer feedback was not included. Instead, testing in the form of technical verification and evaluation which are suited for technical projects was conducted. The project also differs in the fact that it excludes identifying customer needs and planning downstream development, the reason for this is the limited time available therefore Emerson has conducted or will conduct these phases outside of the thesis project.

The choice of a funnel instead of the linear approach where concept generation, concept selection and concept testing are performed subsequently[50], stems from the fact that the funnel facilitates a more iterative process. This ensures more flexibility along the way and continuous improvement. The funnel itself has three stages, all of which have their own elimination process. As the concepts progress to the next stage, it becomes more and more difficult for a concept to move forward thus ensuring that any non-feasible concepts are removed.



Figure 3.1: Project progress.

Prior to the first phase, the team conducted a brief exploration of the topics of microwave radar and measurements using microwave radar. This research aimed to establish a theoretical foundation before the project advanced to the upcoming phases of development.

3.1 Phase 1: Target Specifications

Customer needs are often needs expressed subjectively by the user and/or customer and most often they can not be measured [50]. Therefore target specification is a crucial step in a project development project as it transforms these needs into measurable requirements that can be fulfilled by the product. One important thing to note in this step is that the specifications should only state what the product should achieve and not how because this phase should not generate solutions or narrow down the options, they should only describe the customer needs in measurable metrics.

Specifications should be set early in the process to serve as a guide for the development and should be chosen carefully as proper target specifications will enhance the likelihood of a successful product. However, these target specifications could be changed throughout the phases and the final specifications will not be set until the final phase which is presented in chapter 6.



Figure 3.2: Target Specifications phase.

3.1.1 Target Specifications & Competitor Benchmarking

As previously mentioned the target specifications are the customer's needs expressed in metrics that can be measured. The target specifications were created in a sub-sequential order of converting the customer needs into metrics, competitor benchmarking and lastly setting target and ideal values. In this case, the first step of converting customer needs into metrics was somewhat different as compared to many other projects as the customer needs were delivered to the team from Emerson and thus they were very technical already and included both wishes and requirements from the company. The biggest challenge with the target specification was thus making these measurable and setting suitable target values and ideal values.

Two target specifications were made, one for the high-pressure scenario and one for the high-temperature scenario despite this the execution was the same for both. The only difference between them was that a few metrics relevant to the application were different. To set appropriate values for the ideal and target values in both matrices, the team conducted a competitor benchmarking to ensure a good view of industry standards and to correctly position the product on the market [50]. The benchmarking was conducted online by looking up competitors and their portfolio and subsequently comparing their offers to Emerson's. Specific information about competitors' products was later used to set target and ideal values in the target specification. Alongside the benchmarking, the team also consulted the microwave

engineer within Emerson to validate that the values attained also applied to scanning radar and not only single-point radar.

The marginal values were the minimum needed to fulfil the metric and they represented the requirement, most of the metrics also had an ideal value which represented a wish. These ideal values also had a weighting factor on a scale of 1 to 5 based on how important they were to the project. The requirements on the other were not weighted as they must be fulfilled and thus do not have a comparative higher or lower importance when compared.

Finally, the metrics and their respective ideal and target values were inserted into the matrices along with how they can be assessed in the final stages of the project.

3.2 Phase 2: Concept Development Funnel

The Concept Development Funnel was the second phase of the project. As mentioned earlier it is inspired by the processes of concept generation, concept selection and concept testing but in a revised format that is more suitable fit the project. This framework is used to refine and evaluate ideas before they are fully developed into a product. Eventually, it can help the company or the organisation sift through various concepts, identify promising ones and allocate resources effectively.



Figure 3.3: Concept Development Funnel phase.

The funnel was an iterative process, consisting of three stages as can be seen in figure 3.4. The stages were conducted linearly and each stage will have its own subset of methods that were picked to be suited for that specific iteration.

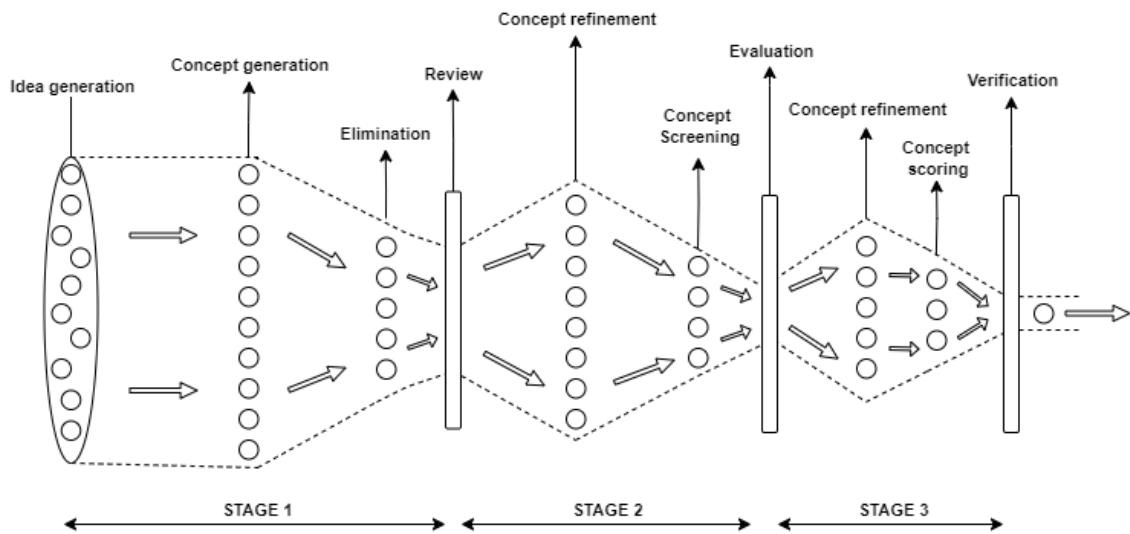


Figure 3.4: Concept Development Funnel.

3.2.1 Stage 1 - Ideation

Each stage of the funnel consisted of three processes, in the first stage these were concept generation, elimination and review. Concept generation laid the groundwork for innovation, creativity and problem-solving. At this time, the focus shifted from what to achieve to how to achieve it, without excluding solutions or narrowing down the scope. During this stage, the concept did not need to be too detailed, a simple sketch with brief explanations of working principles was enough [50]. During concept generation, it was important to have a clear understanding of the specifications that need to be met and to look both internally and externally for solutions.

The concept generation was inspired by the five-step method as suggested by Ulrich and Eppinger [50], as can be seen in figure 3.5.

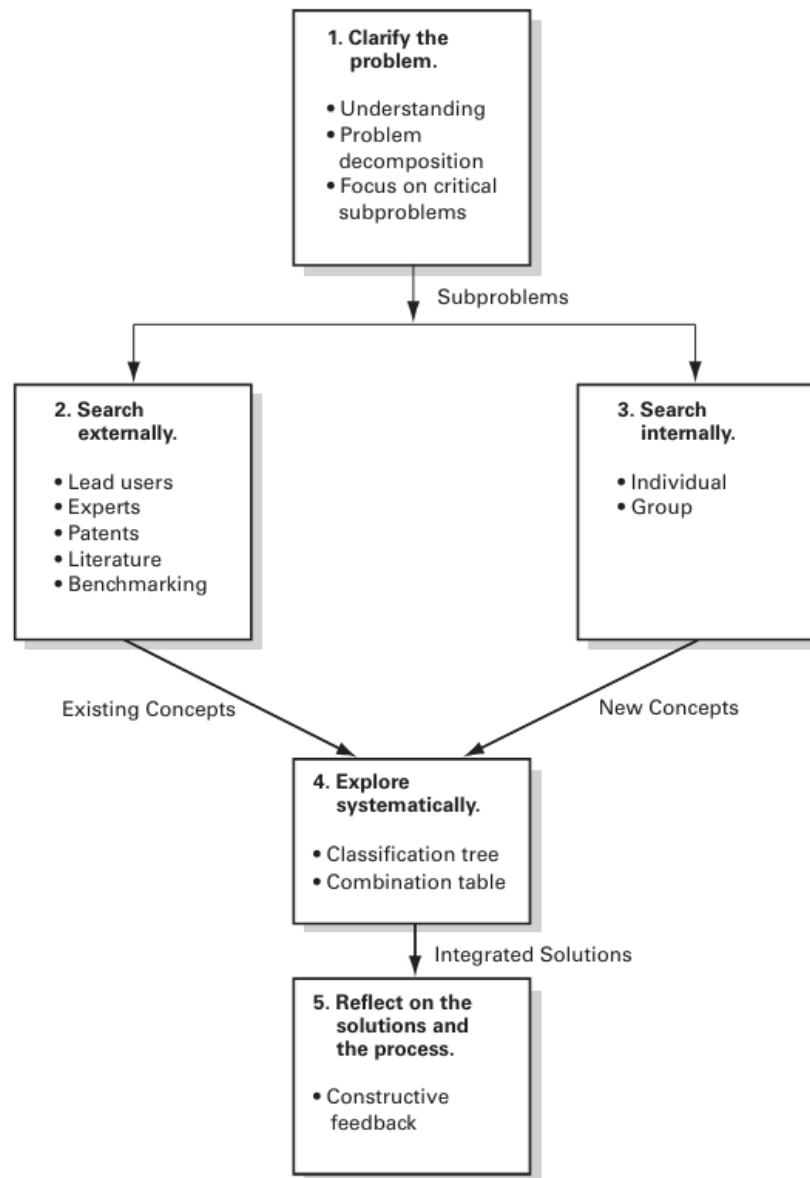


Figure 3.5: Concept Generation Method [50].

3.2.1.1 Concept Generation

The first step of clarifying the problem was already attained by the team after creating the target specification and no further division of subproblems was needed. But to attain further information on the relevant subjects before generating new concepts a substantial external search was conducted. This second step consisted of data collection which in turn utilised the methods of literature review, benchmarking of related products and a patent search.

Literature Review

A literature review is a critical analysis of a subject through different academic sources and the most efficient way to gather a lot of information from these sources

is through online searches [50]. Therefore, the literature review was conducted by searching several academic databases for journals, conference proceedings and publications on topics such as “scanning radar”, “scanning microwave radar” and “microwave radar measurements”. The information gathered was then summarized, analyzed and compared to see what information different sources agreed or disagreed upon.

Benchmarking of Related Products

Benchmarking is the study of existing products on the market with similar functionality [50]. Even though there are no microwave scanning radars in the market used specifically for tank radar measurements, there are scanning radars used for other applications and there are single-point radars used for tank measurements on the market. Scanning radars that are used for completely different purposes have a rather different functionality and therefore the benchmarking mostly focused on single-point scanning microwave radars.

Patent Search

Patents contain a lot of information such as drawings and explanations of functionality [50] and they are as a result a good source of information when exploring a subject before generating concepts. As scanning microwave radars used for tank measurements have not been launched on the market it was assumed that most companies that were working on such a product were in the development stage and possibly applying for patents. The search for patents was done through the databases Espacenet [51] and Google patents [52] searching both for companies that were found in the previous company benchmarking and search terms such as “scanning radar”, “microwave radar” and “tank radar measurements”.

Brainstorming

The third step, searching internally, was comprised of brainstorming in a group format. Brainstorming served as a creative and dynamic method to generate lots of ideas early on in the project. All the creations from brainstorming stem from knowledge the team already possessed [50]. Therefore, the brainstorming was conducted after a thorough external search. Both for the high-pressure and high-temperature brainstorming sessions mindmaps were utilized which helped to organize ideas and information in an expansive tree structure[53] and allowed the participants to build upon each other’s suggestions. Here the goal was not to make perfect ideas or detailed sketches but to generate a large amount of ideas without any judgement.

Concept Classification Tree

The penultimate step of the phase concluded of the suggested classification tree together with a morphological matrix instead of a combination table.

The concept classification tree was used as a tool for the team to divide possible solutions that could be employed into different categories and subcategories [50] as well as a good way for the team to visualise the issues at hand. This was only done for the high-temperature as there was a need to further classify and sort the large amount of ideas from the brainstorming in a structural way. The high-pressure

ideas, as compared to high-temperature, were not as many at the need for further organizing them was not needed.

Morphological Matrix

The Morphological Matrix on the other hand was used both for the high-temperature and the high-pressure ideas as it serves as a structured way to foster creativity and generate new concepts from the previously generated ideas. The Matrix comprises of various rows and columns with different solutions and characteristics of a product or a problem at hand most of which were identical for both applications besides the aspects that related to high-temperature or high-pressure. Each and every cell of the Matrix then helped to systematically explore unique combinations of attributes that may offer potential solutions. These combinations were systematically evaluated so that the most promising and viable options could be identified. This method facilitated the exploration of diverse possibilities in a methodical and orderly manner, thereby enabling the generation and assessment of innovative ideas [54]. From each matrix, the team decided to select ten concepts to continue with. This was done by studying the matrices individually, creating concepts and then meeting up together and comparing notes to finally select the most varying concepts to ensure the largest possible design space.

In the fifth step in the concept generation, after finishing the Morphological Matrix, the team spent time going through all the previous steps mainly focusing on the concepts created from the Morphological Matrix. The aim of this was to find if there were any issues or questions that needed to be figured out as well as ensuring that no viable concepts were missed. This was conducted individually by the team to minimize influencing each other before discussing what all parts found relevant.

3.2.1.2 Elimination

Following the first creative generation process was an elimination that acted as a strong filter to remove any obviously incompatible concepts.

Elimination Matrix

The elimination was done with the help of an elimination matrix which systematically eliminates concepts by judging them on the aspects of fulfilling the “main problem”, fulfilling all requirements, being compatible, having a reasonable cost, being safe and fitting into the product portfolio. Each concept then received a (+) for a pass, (-) for a fail, (!) for check requirements or (?) needs more research. Any concepts that received a fail were subsequently eliminated at this stage, ensuring that no concepts that do not align with the target requirements or otherwise are non-feasible continue to be developed.

3.2.1.3 Review

After the Elimination Matrix, the concepts that passed were reviewed both internally by the team but also externally by a microwave expert colleague at Emerson.

2D sketches

The internal review was conducted by drawing 2D sketches of all concepts as this enabled the team to visually see the concepts as a whole and not as a collective amount of subsolutions that derived from the Morphological Matrix. This was done the same for high-temperature and high-pressure concepts, taking the subsolutions from the Morphological Matrix and sketching all the subsolutions that can be viewed in a sketch.

Expert consultation

An external review, in this case, an expert consultation, served as a very important step that provided guidance and knowledge. It also gave the project an insight into the expert's experience and knowledge which aided in guiding the project and avoiding mistakes. This was, just as the internal review, conducted for both the high-pressure and high-temperature concepts. The previous resulting sketches, from the internal review, also served as a mediating tool to better present the concepts to the expert.

3.2.2 Stage 2 - Development

The second stage bears similarities to the previous stage but in contrary to stage one, there will be no new concept generation. Stage two will only include a refinement step which will facilitate smaller adjustments, improvements and combinations of the concepts. This means that there is an opportunity to temporarily increase the number of concepts before the next round of elimination of concepts.

3.2.2.1 Concept Refinement

The concept refinement was the first step in the second stage. This step served as an opportunity to use the knowledge gained from the last stage to create any new concepts or changes and combinations of the old concepts. These refinements were done for both high-temperature and high-pressure concepts and these refinements were mainly based on information gained from the expert consultation as well as Elimination Matrix. The Elimination Matrix in particular showed that some concepts were overall non-feasible but had sub-solutions that had potential and these were the changes that were implemented into new concepts or changed into old concepts.

Material Selection

At this stage, before the second elimination, materials were added. This was done by screening a material database on different properties that were deemed relevant. The database used was Granta Edupack [55] the functions of limit, chart and search were used. At this time a few materials were suggested by Emerson and these were studied along with new materials that were found relevant. All materials were evaluated on properties derived from the target specification and the ambient environment that the interface will be placed in.

3.2.2.2 Concept Screening

In the second stage, following the initial refinement and material selection, concept screening was conducted using a Pugh Matrix.

Pugh matrix

The Pugh matrix, enabled an efficient and systematic comparison of the generated concepts against each other, based on a predetermined list of criteria [56]. The list of criteria was all derived from the target specification and ensured that concepts remained on track with the project aims. This comparison against these criteria was repeated several times and each time one of the concepts was a reference concept that the others were compared to. In the first comparison, a random concept was selected to be the reference and in the following two iterations the previous top-ranked concept was the reference. For every criterion, each concept and the reference was compared and depending on if the concept was deemed better, worse or equal to the reference it received a (+), (-), or (0). This resulted in the final average ranking on which the decisions of eliminations were based. As each concept received a clear grade on all aspects the method also helped in detecting good qualities in solutions that might be non-feasible overall and this became helpful in the next stage where further refinements of concepts were conducted.

3.2.2.3 Evaluation

The last part of stage two was an evaluation of the concepts remaining and a verification that the concepts remaining after the Pugh Matrix indeed meet the specifications.

CAD models & 3D printing

The evaluation was carried out by designing CAD models and 3d printing said CAD models. This was conducted by taking the previous 2D sketches of the remaining concepts and transforming them into 3D models. These models could then be visually assessed and their dimensions verified before utilising rapid prototyping to make them into physical prototypes. These physical prototypes were also visually assessed to ensure a correct translation of the design to reality and to use as a mediating tool when seeking feedback from experts.

3.2.3 Stage 3 - Optimization

The third and final stage of phase 2 was the most thorough in its elimination and focused a lot on verification and testing solutions in different ways. However, the first activity in the stage was concept refinement, just as in stage 2.

3.2.3.1 Concept Refinement

Similar to the second stage, the third stage started with concept refinement which allowed for a new round of adjustments to any concepts that had any minor issues but still were deemed good overall and the addition of new concepts. This time,

these changes were mainly based on the information gathered from the Pugh Matrix, similar to the Elimination Matrix in the first concept screening. The changes were also based on visual reflections from the CAD-models and 3D-printed prototypes and this refinement applied to both the high-pressure and high-temperature concepts.

3.2.3.2 Concept Scoring

The third and final stage of phase 2, included a concept scoring of the concept with the use of a Kesselring Matrix.

Kesselring matrix

The last stage of concept elimination was done using the Kesselring matrix. In comparison with the Pugh matrix, the Kesselring matrix is more time-consuming but provides more precision in the assessments with the help of weighted criteria [54]. Thus, it was most suitable for the Kesselring matrix to be placed last among the methods utilized to remove inferior concepts. The Kesselring Matrix is also the most beneficial when the solutions have been developed more in detail which they had been at this stage.

Two Kesselrings were made, one for high-temperature and one for high-pressure. The criteria were once again derived from the target specifications and the respective application environment. Each Matrix evaluated all the remaining concepts along with an ideal reference concept. All criteria also had a weighting according to their importance. This weighting was decided after creating another matrix consisting of all criteria listed twice in the same order, once in the first column and once in the first row. Then each criterion was compared against each other one-versus-one and the more important criterion received a (1) and the other a (0). If they were viewed as equally important they both received a (0.5). The resulting sum for each criterion was then divided by the maximum score it could have achieved (only ones) and thus made into a percentage. These percentages were then compared and each criterion got a weighting from 1 to 6 depending on their percentage.

How well each concept fulfilled a criterion was decided by a grading scale that was created by the team for the respective criterion. Finally, each concept's total value was divided by the ideal total to see how close to perfect each concept came. Alongside this, mean, median and ranking were calculated for each concept.

3.2.3.3 Verification

The final part of stage three and the funnel was verification. This part included doing CAD models of the concepts left if they were new for this phase, verifying their dimensions and assessing their design in CAD. Then the concepts were further verified through simulations for high-pressure. However, no heat simulation was conducted at this stage as the concept for the interface that was derived from the Kesselring Matrix is not enough on its own to test if can be applied in high-temperature scenarios. Therefore, heat simulations were conducted in the third and last phase when additional aspects had been designed to conduct these simulations.

High-pressure Simulations

The simulations that were used to derive the equivalent stress needed to ensure good structural integrity in the high-pressure scenario were conducted in Ansys Mechanical [57] using their pre-existing equivalent (von Mises) stress tool. The simulations were made using the highest-ranking concept from the Kesselring Matrix for high-pressure.

Besides the equivalent stress, the total deformation was also simulated to ensure that the desired shape and structure were intact. Both simulations used fixed supports and loading conditions according to real-life applications and simulated for a total of a year to ensure that the interface could be in constant use without breaks. The simulations were repeated with different dimensions until a desired outcome.

3.3 Phase 3: Final Concept

Setting the final specification was the final phase of the project along with final adjustments to the design and material as a result of this stage verification which was conducted by the use of simulations. These changes and refinements were applied to the target specification and subsequently, these created the final specifications.



Figure 3.6: Final Specifications phase.

High-temperature Simulations

The heat transfer analysis was conducted to see the maximum and minimum temperature at the bottom of the radar chip. To determine the thermal convection heat transfer between the surface of the interface to the radar chip, heat transfer rates were analysed in Ansys Mechanical [57].

This analysis involves considering the interior surface boundary conditions and edges of the housing, interface and the radar chip. Hence, transient thermal analysis was carried out to find temperatures that can be varied over time and optimise the entire housing based on the temperature results. Thereby, the heat transfer rates between solid to solid through a stagnant air gap have been simulated continuously for a year.

High-pressure Simulations

The high-pressure simulations were in the third phase repeated as new concepts had surfaced and they needed to be verified. The simulations of the maximum equivalent (von Mises) Stress and the maximum Total Deformation were conducted exactly the same as in phase 2.

Material Selection

In the final phase, the previous material selection was refined as a result of the new information that had emerged since the prior selection. The selection was nevertheless conducted in the same way using Granta EduPack [55].

Cost Calculation

To estimate the material cost of the interface the software Granta EduPack was used [55]. Specifically, the inbuilt tool called “part cost estimator” was utilised. The tool works by inserting the following values:

- mass of the part
- length of the part
- value of scrap material (%)
- batch size
- primary process
- availability
- part complexity
- load factor
- overheat rate
- capital write-off time

The tool then estimated the material cost for the part.

4

Phase 1: Target Specifications

This chapter presents the results of the first phase of the project, which consists of the project's target specifications and the complementing competitor benchmarking that was conducted in parallel with the creation of target specifications.

4.1 Target Specification

The main result of the first phase was the target specification for high-pressure and high-temperature applications which can be seen in figure 4.1 for the high-pressure application and in figure 4.2 for the high-temperature application. Alongside the specifications, a big takeaway from the first phase is that there are no competitors that have a scanning radar for measurements within tank systems on the market yet. Therefore all values in the target specification were derived from single-point scanning radar systems or scanning radars utilised in other ways than tank measurements.

Chalmers		Target Specification for high-pressure application				
Master Thesis: Interface for Scanning Microwave Radar		scale 1-5		≈ Requirement/ Demand	≈ Desire / Wish	
	Metrics	Importance of ideal value	Units	Marginal value	Ideal value	Verification method
1.	Design					
1.1	Diameter of interface		mm	40		Measurement verification on CAD design
1.2	Thickness of interface		mm	10		Measurement verification on CAD design
1.3	Shape of interface			cylindrical		Visual verification on CAD design
1.4	Minimizing trapping points	4	excellent/good/fair/poor	good	excellent	Testing and engineering assessment
2.	Performance					
2.1	Max Field of view (FOV) Not negatively affect microwave paths (shape of lens/interface)		° (degree)	59		Calculation
2.2	Ensure ability to do non-contacting measurements		binary	pass		Assessment by microwave engineers
2.3			binary	pass		Engineering assessment
3.	Life cycle					
3.1	Carbon footprint	3	kg/kg	7	4	Calculation
4.	Safety					
4.1	Hazardous approvals		binary	pass		Testing
4.2	Hygienic approvals		binary	pass		Testing
4.3	Leakproof interface		cms (cubic meter per second)	0		Testing
5.	Cost					
5.1	Product material cost	4	SEK per unit	100	75	Calculation
6.	Material					
6.1	Ensure no condensation/steam build up		binary	pass		Testing and engineering assessment
6.2	Chemical resistance	4	excellent/good/fair/poor	good	excellent	Testing and material specifications
6.3	Absorption of microwaves in lower focal point but not elsewhere. (if there is a design that has focal points, otherwise not needed)	2	excellent/good/fair/poor	good	excellent	Testing and engineering assessment
6.4	Reflective to microwaves	4	excellent/good/fair/poor	good	excellent	Testing and engineering assessment
6.5	Transparency to microwaves	5	excellent/good/fair/poor	good	excellent	Testing and engineering assessment
7.	Operating Conditions					
7.1	Handle ambient temperature in tank (below the interface)	5	°C	84	96	Testing and simulations
7.2	Handle pressure from tank (from below)	5	bar	208	400	Testing and simulations

Figure 4.1: Target Specifications for high-pressure application.

Chalmers		Target Specification for high-temperature application				
<i>Master Thesis: Interface for Scanning Microwave Radar</i>		scale 1-5		≈ Requirement/ Demand	≈ Desire / Wish	
	<i>Metrics</i>	<i>Importance of ideal value</i>	<i>Units</i>	<i>Marginal value</i>	<i>Ideal value</i>	<i>Verification method</i>
1.	Design					
1.1	Diameter of interface		mm	40		Measurement verification on CAD design
1.2	Thickness of interface		mm	10		Measurement verification on CAD design
1.3	Shape of interface			cylindrical		Visual verification on CAD design
1.4	Minimizing trapping points	4	excellent/good/fair/poor	good	excellent	Testing and engineering assessment
2.	Performance					
2.1	Max field of view (FOV)		°	59		Calculation
2.2	Not negatively affect microwave Ensure ability to do non-contacting measurements		binary	pass		Assessment by Testing and engineering assessment
2.3			binary	pass		
3.	Life cycle					
3.1	Carbon footprint	3	kg/kg	7	4	Calculation
4.	Safety					
4.1	Hazardous approvals		binary	pass		Testing
4.2	Hygienic approvals		binary	pass		Testing
4.3	Leakproof interface		cms (cubic meter per second)	0		Testing
5.	Cost					
5.1	Product material cost	4	SEK per unit	100	75	Calculation
6.	Material					
6.1	Ensure no condensation/steam build up		binary	pass		Testing and engineering assessment
6.2	Chemical resistance	4	excellent/good/fair/poor	good	excellent	Testing and material specifications
6.3	Absorption of microwaves in lower focal point but not elsewhere. (if there is a design that has focal points, otherwise not needed)	2	excellent/good/fair/poor	good	excellent	Testing and engineering assessment
6.4	Reflective to microwaves	4	excellent/good/fair/poor	good	excellent	Testing and engineering assessment
6.5	Transparency to microwaves	5	excellent/good/fair/poor	good	excellent	Testing and engineering assessment
6.6	Operating service temperature		°C	≥ 480		Material selection
7.	Operating Conditions					
7.1	Handle ambient temperature in tank (below the interface)		°C	480	480	Testing and simulations
7.2	Ensure safe operating temperature for the radar chip (above the interface)	5	°C	85	80	Testing and simulations
7.3	Handle pressure from tank (below)	5	bar	50	208	Testing and simulations

Figure 4.2: Target Specifications for high-temperature application.

Both target specifications are divided into seven categories: design, performance, life-cycle, safety, cost, material, and operating conditions. All categories except operating conditions are the same for both, as they should work the same but be applicable in different environments.

Several of the metrics such as thickness and diameter correlate to microwave performance, as thickness affects transparency and diameter affects field of view, and thus some target specifications go very hand in hand. Others focus more on ensuring correct measurements in some way, like ensuring no trapping points as these can get filled with debris and disrupt the microwaves and the same goes for condensation and steam build-up.

The metric in the operating conditions has also taken a safety factor given by Emerson into consideration. For pressure, this safety factor is 4 and for temperature, it is 1.2. The pressure requirements were based on ASME flange standards [58] according to Emerson's standard. The high-pressure option should at least fulfil class 300 and hopefully fulfil class 600, that was respectively 52 bar for the requirements and 100 bar for the wish, and when the safety factor is considered the requirement is 208

bar and the wish is 400 bar. The temperature requirement of 400°C was given by Emerson and after adding the safety factor this gave the marginal value of 480°C. The printed circuit board on which the radar resides and that the interface should protect has a maximum service temperature of 105°C [59] and when considering the safety factor it gave the requirement of a maximum temperature of 87.5°C.

There is one metric that is a bit special even though the value is the same for both applications and that is the field of view metric. The difference is not the FOV value itself but how they have been derived for each application. Different sizes are used for different applications and when discussing application scenarios with Emerson it became clear that systems suitable for high-pressure often use smaller tanks and high-temperature utilises bigger tanks and sometimes even open tanks.

In this project, the assumed application for high-pressure was a smaller closed tank that could be used in the pharmaceuticals, chemical and beverage industries. The diameter was assumed to be 1 meter and when the tank was filled to the max there was a gap of 0.3 m up to the interface and the radar. How tall the tank was, however, does not affect the FOV so no limitations were set for the height. These measurements resulted in a FOV of 59°.

For the high-temperature application, an open tank was used for calculations of FOV and a tank diameter of 15 m. This size is more appropriate in industries such as mining or waste management that handle bigger volumes. Depending on the height of the tank, it could for example hold up to 10 standard shipping containers[60] when the height is 5 m. In this case, the distance between the maximum fill level and the interface was set to 4.5 m which gives a FOV of 59°, however, this does not include any distance that might be needed to achieve the temperature requirement of a maximum 85 ° C above the interface where the PCB is to be placed. This distance and its effect on the FOV was not calculated in phase 1 as the materials were not selected and this would affect the thermal radiation that affects the temperature above the interface.

5

Phase 2: Concept Development

This chapter presents the results of the second phase of the project, which consists of three stages. All of these contain three subtasks of either concept generation or refinement followed by some type of elimination process and review.

5.1 Stage 1 - Ideation

5.1.1 Outcomes from Concept Generation

This subsection presents the outcomes derived from the concept selection processes. It consists of idea generation results and various product development matrices, with a concluding elimination and evaluation of the results. All the steps involved during the process with several iterations using different methods and tools.

5.1.1.1 Output from Brainstorming Sessions

The brainstorming results were used to explore various solutions for sealing, design, and material properties. The mind-mapping method produced numerous ideas for all the concepts, which is considered fundamental progress for the methods that follow after the brainstorming. The final result of the sessions were two brain-drawing, one focusing on high-pressure protection as can be seen in fig 5.1 and one for high-temperature protection as can be seen in 5.2.

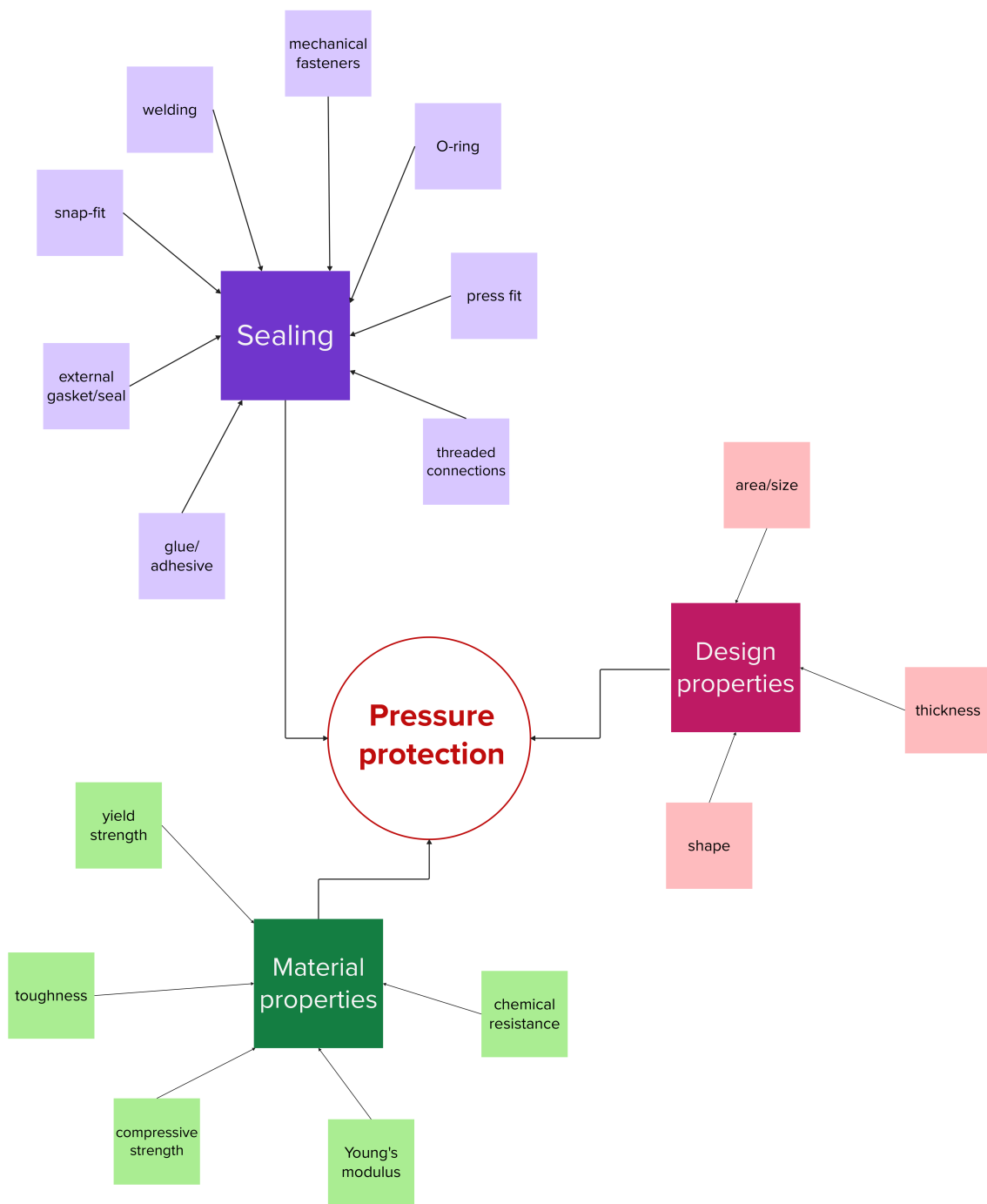


Figure 5.1: Mind map for high-pressure application.



Figure 5.2: Mind map for high-temperature application.

5.1.1.2 Concept Classification Tree Results

In this case, the concept classification tree was only used to visualize different solutions for heat protection specifically and not the whole system. This was because

the function of heat protection was especially tricky as it had solutions within solutions and brainstorming did not clearly show the relationships between different solutions.

5. Phase 2: Concept Development

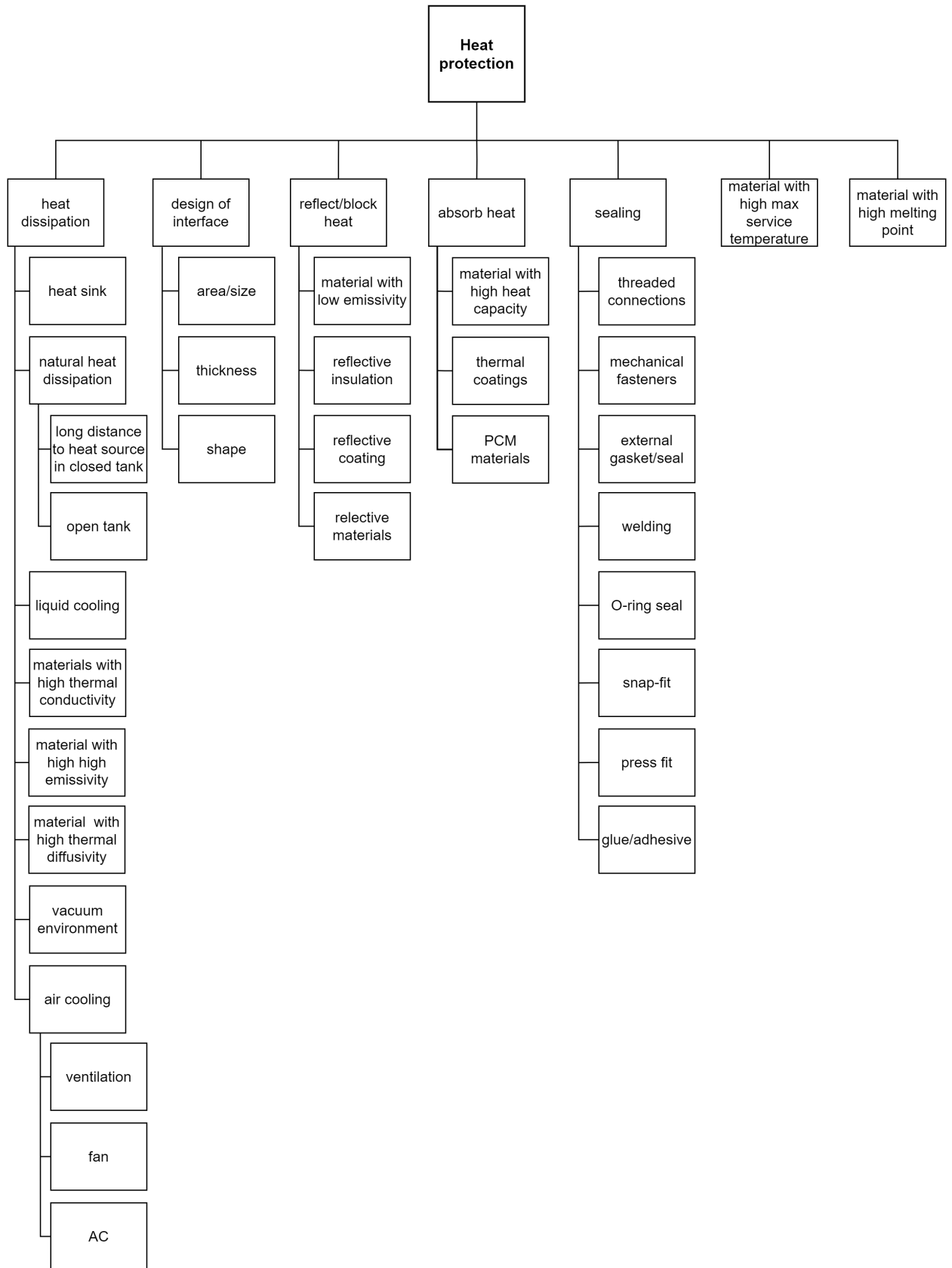


Figure 5.3: Concept Classification Tree.

5.1.1.3 Results from Data Collection

The results from the data collection, which consisted of benchmarking, patent search and literature review, were knowledge and information that was utilised, mainly in the Morphological Matrix but also other processes. It was also concluded that there are currently no level measurement systems that utilise scanning radar. This resulted in the search focusing more on scanning radar in other applications to understand the functionality and single-point measurement systems to investigate current interface solutions. The search itself did not produce any tangible output that could stand for itself but was as mentioned used to find inspiration for the solutions in the Morphological Matrix and later design phases as well as help with understanding the functionality and use cases.

5.1.1.4 Morphological Matrix Results

Firstly, the Morphological Matrix, for high-pressure can be seen in the figures 5.4 and 5.5.

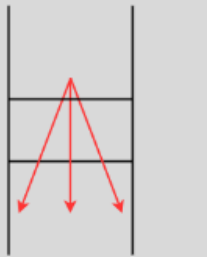
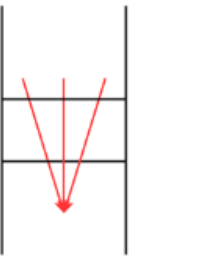


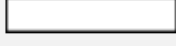

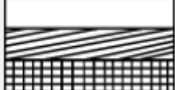
Morphology Matrix for high-pressure solution			
Sub-functions	Sub-solutions		
	1	2	3
A Protect radar chip from high pressure	material properties		
	material with high yield strength	material with high toughness	material with high compressive strength
B Manipulate microwaves	<div style="text-align: center;">  <p>diverge waves</p> </div>	<div style="text-align: center;">  <p>converge waves</p> </div>	
	lens shapes (concave, bioconvex, plano-concave, negative meniscus, etc)	probe/waveguide	lens shapes (convex, plano-convex, positive meniscus, bioconcave, etc)
C Sealing interface from contents	pressed fit	external gasket/seal	glue/adhesive
D Provide structure	one component	two components	
			
E Material diversity	1 material	2 materials	3 materials
			

Figure 5.4: High-pressure Morphological Matrix part 1.

5. Phase 2: Concept Development

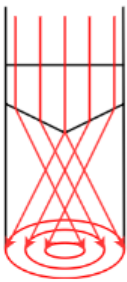
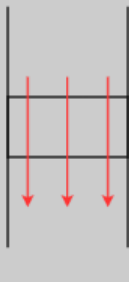
Morphology Matrix for high-pressure solution					
Sub-functions	Sub-solutions				
	4	5	6	7	8
A Protect radar chip from high pressure	material properties				
	material with high Young's modulus	material with high chemical resistance			
B Manipulate microwaves	 <p>Circular ring pattern</p> <p>Axicon lens</p>	<p>no effect</p>  <p>flat lens</p>			
	C Sealing interface from contents	welding	mechanical fasteners	O-ring seal	threaded connections
D Provide structure					
E Material diversity					

Figure 5.5: High-pressure Morphological Matrix part 2.

Secondly, the Morphological Matrix, for high-temperature can be seen in the figures 5.6, 5.7 and 5.8.




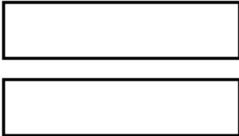



Morphology Matrix for high-temperature solution			
Sub-functions	Sub-solutions		
	1	2	3
A Protect radar chip from high temperature	dissipate heat		
	heat sink	liquid cooling	air cooling
B Manipulate microwaves	diverge waves 	converge waves 	
	lens shapes (concave, bioconvex, plano-concave, negative meniscus, etc)	probe/waveguide	lens shapes (convex, plano-convex, positive)
C Sealing interface from contents	pressed fit	external gasket/seal	glue/adhesive
D Provide structure	one component 	two components 	
E Material diversity	1 material 	2 materials 	3 materials 

Figure 5.6: High-temperature Morphological Matrix part 1.

5. Phase 2: Concept Development

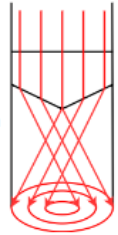
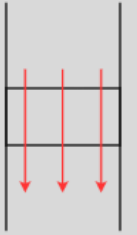
Morphology Matrix for high-temperature solution					
Sub-functions	Sub-solutions				
	4	5	6	7	8
A Protect radar chip from high temperature	dissipate heat				
	vacuum environment	"natural" heat dissipation (within tank, open tank)	material with high thermal conductivity	material with high thermal diffusivity	material with high emissivity
B Manipulate microwaves	Circular ring pattern  Axicon lens	no effect  flat lens			
C Sealing interface from contents	welding	mechanical fasteners	O-ring seal	threaded connections	snap-fit
D Provide structure					
E Material diversity					

Figure 5.7: High-temperature Morphological Matrix part 2.

Morphology Matrix for high-temperature solution							
Sub-functions	Sub-solutions						
	9	10	11	12	13	14	15
A Protect radar chip from high temperature	absorb heat			reflect heat			
	material with high heat capacity	PCM material	thermal coatings	material with low emissivity	reflective insulation	reflective materials	reflective coating
B Manipulate microwaves							
C Sealing interface from contents							
D Provide structure							
E Material diversity							

Figure 5.8: High-temperature Morphological Matrix part 3.

Both matrices show the generated sub-solutions across columns and sub-functions in the rows. The only difference between the two matrices is their respective applications just as for the target specifications and this aspect is considered in the first row for both matrices.

For the high-pressure one, the focus was to protect the radar chip from any damage from pressure, therefore material properties were taken into account i.e. material with high yield strength to ensure the interface handles pressure and mechanical loads, high toughness to resist fracture and durability, and high compressive strength to prevent deformation to maintain its structural integrity.

The first sub-function of the high-temperature matrix is to protect the radar chip from heat. The sub-solutions for the protection of heat were also categorised into three categories dissipating heat, reflecting heat, and absorbing heat as those were the common themes amongst the found solutions.

The remaining sub-functions and sub-solutions were identical for both matrices, as previously mentioned. The second sub-function focused on the effect on the microwave path, and the solutions were mainly variations of lenses that could be used. For instance, converging lenses focus the microwaves at the point while diverging lenses spread the microwaves away. There were also two other options, not affecting the microwaves at all so that the microwaves can completely pass through and an axicon lens that creates a spherical ring pattern.

The third sub-function was how to seal the tank away from the radar chip. The sealing type is important as prevents leaks and ensures a strong integrated fit for the product.

There were ten concepts made for each application, the ten concepts for high-pressure application can be seen in figure 5.9 and the ten concepts for high-temperature application can be seen in figure 5.10. However, material selection for each concept is conducted later in stage 2, 5.2.1.1, and as a consequence, all the subsolutions from subfunction A for high-pressure were selected and no subcategories within subfunction A were selected for high-temperature. These aspects were instead reviewed again during the material selection process.

	A	B	C	D	E
1	all	circular ring pattern - axicon lens	external seal	1 component	1 material
2	all	diverge waves- lens shape	O-ring	2 components	2 materials
3	all	no effect	threaded	1 component	1 material
4	all	converge waves - probe/waveguide	snap-fit	2 components	1 materials
5	all	no effect	glue	2 components	3 materials
6	all	diverge waves- lens shape	Pressed fit	1 component	1 material
7	all	circular ring pattern - axicon lens	O-ring	2 components	2 materials
8	all	converge waves - lens shape	glue/adhesive	2 components	2 materials
9	all	no effect	snap-fit	1 component	2 materials
10	all	no effect	weld	2 component	3 materials

Figure 5.9: High-pressure Concepts Derived from Morphological Matrix.

	A	B	C	D	E
1	absorb reflect dissipate	no effect	external seal	1 component	3 materials
2	dissipate reflect	no effect	weld	1 component	2 materials
3	absorb dissipate	converge waves - lens shape	mechanical fasteners	2 components	2 materials
4	reflect absorb	diverge waves- lens shape	external seal	2 components	3 material
5	reflect dissipate	circular ring pattern - axicon lens	O-ring	1 component	1 material
6	dissipate absorb	converge waves - lens shape	mechanical fasteners	1 component	2 materials
7	dissipate absorb	diverge waves- lens shape	O-ring	2 components	1 material
8	dissipate	no effect	Snap fit	1 component	1 material
9	dissipate	no effect	Glue/adhesive	2 components	2 materials
10	dissipate	circular ring pattern - axicon lens	Pressed fit	2 components	1 material

Figure 5.10: High-temperature Concepts Derived from Morphological Matrix.

5.1.2 Elimination results in Stage 1

The high-pressure Elimination Matrix started with the ten concepts derived from the Morphological Matrix. After evaluating all the concepts according to set criteria that can be seen in figure 5.11, six concepts remained and will move forward and thus a total of four concepts were eliminated. The reasons for elimination can be seen in the figure 5.11.

5. Phase 2: Concept Development

Chalmers		Elimination Matrix for high-pressure								
Master Thesis: Interface for Scanning Microwave Radar		Created: 2024-03-07			Last modified: 2024-03-19					
		+ Yes - No ? Research ! Control target spec.			+ Keep solution - Eliminate solution ? Research more information ! Control target spec.					
Concept	Elimination Criterias								Comments	Decision
	Solves main problem	Fulfill all requirements	Compatible/realizable	Reasonable cost	Safe	Fits company's portfolio	Enough information	Other		
1	+	+	+	+	+	+	+			Keep
2	+	+	+	+	+	+	+			Keep
3	+	-							Threading could create trapping points.	Eliminate
4	+	-							Probe/waveguide does not enable non-contacting measurements	Eliminate
5	+	+	+	+	+	+	+			Keep
6	+	+	-						The pressed fit would be assembled by thermal expansion or contraction to make a strong seal which means it would be affected by ambient temperature and tank temperature.	Eliminate
7	+	+	+	+	+	+	+			Keep
8	+	+	+	+	+	+	+			Keep
9	+	-							Snap-fit could have issues with leakage and very costly	Eliminate
10	+	+	+	+	+	+	+			Keep

Figure 5.11: High-pressure Elimination Matrix.

Just as the Elimination Matrix for high-pressure, the Matrix for high-temperature started with ten concepts. After reviewing them on the criteria as can be seen in figure 5.12 four concepts remained and six were eliminated. The bases of elimination for each concept can also be seen in figure 5.12.

Chalmers		Elimination Matrix for high-temperature							
Master Thesis: Interface for Scanning Microwave Radar		Created: 2024-03-07			Last modified: 2024-03-19				
		+ Yes - No ? Research ! Control target spec.			+ Keep solution - Eliminate solution ? Research more information ! Control target spec.				
Concept	Elimination Criteria							Comments	Decision
	Solves main problem	Fulfill all requirements	Compatible/realizable	Reasonable cost	Safe	Fits company's portfolio	Enough information		
1	+	+	+	+	+	+	+		Keep
2	+	+	+	+	+	+	+		Keep
3	+	-						Fasteners can create trapping points	Eliminate
4	+	+	+	+	+	+	+		Keep
5	+	-						O-ring would not be able to handle the high temperatures.	Eliminate
6	+	-						Fasteners can create trapping points	Eliminate
7	+	-						O-ring would not be able to handle the high temperatures.	Eliminate
8	+	-						Snap-fit could have issues with leakage and very costly	Eliminate
9	+	+	+	+	+	+	+		Keep
10	+	+	-					The pressed fit would be assembled by thermal expansion or contraction to make a strong seal which means it would be affected by the environment temperature in the tank.	Eliminate

Figure 5.12: High-temperature Elimination Matrix.

5.1.3 Outcomes from the first Review

After the Elimination Matrix, the current concept needed to be reviewed and assessed. This was done by first sketching all remaining concepts and consulting experts for feedback not only on interaction with microwaves but on design and functionality as well.

5.1.3.1 Resulting 2D sketches of current concepts

The remaining concepts were as mentioned made into simple digital 2D sketches. These sketches illustrated all subsolutions, that could be visualized in sketch format, for each concept as can be seen in the following sections divided into high-pressure and high-temperature.

High-pressure concepts

The six high-pressure concepts can be seen in figure 5.13 and 5.14.

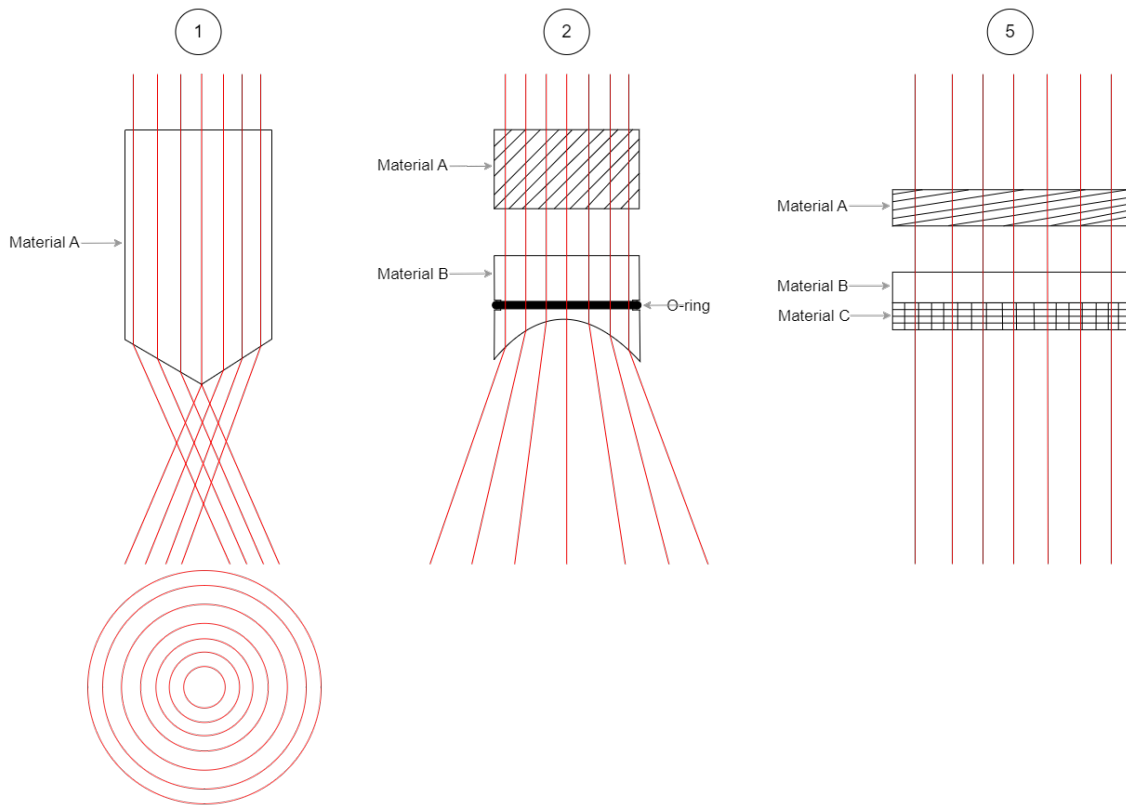


Figure 5.13: First stage high-pressure concepts part 1.

- 1 **“axicon bullet”**: The interface includes an axicon lens shape that spreads the microwaves in a circular pattern. The interface is one component made of one single material and an external seal is attached to the interface for sealing purposes.

- 2 **“shark mouth”**: The interface includes a plano-concave lens shape that diverges the microwaves. The interface is divided into two components, each with its own material and an O-ring is attached to the interface for sealing purposes.

- 5 **“sandwich”**: A flat interface without any lens shape, thus no manipulation of the microwave paths. The interface is divided into two components and a total of three materials. The interface uses glue or adhesive for sealing purposes.

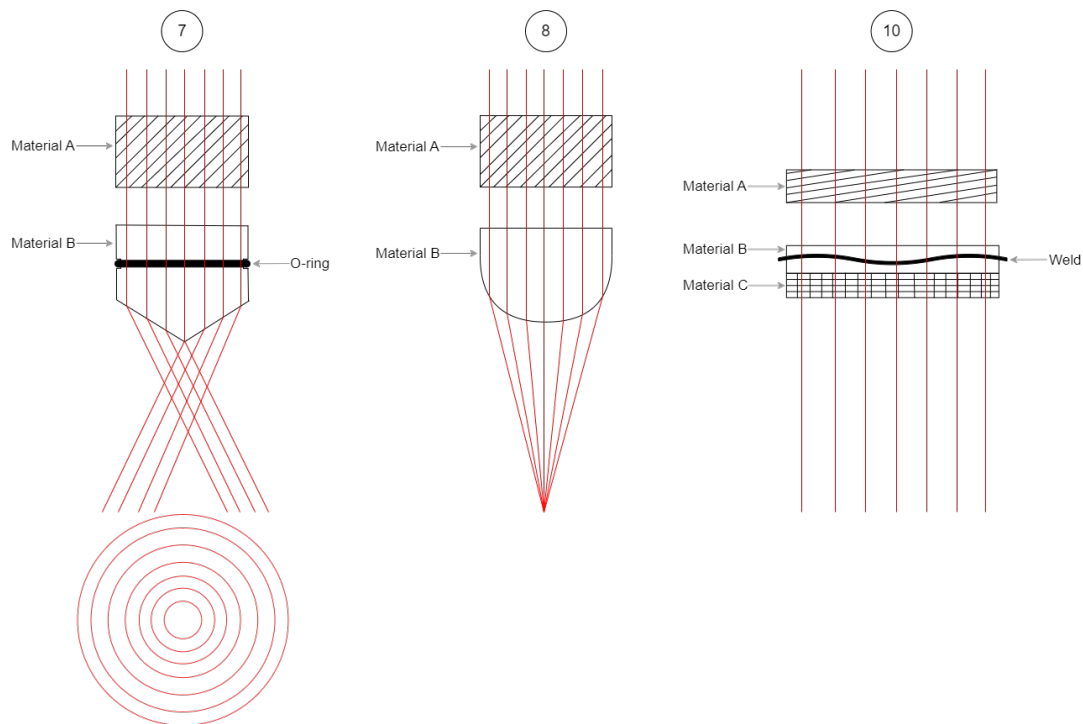


Figure 5.14: First stage high-pressure concepts part 2.

7 **“ice cream cone”**: The interface includes an axicon lens shape that spreads the microwaves in a circular pattern. The interface is divided into two components, each with its own material and an O-ring is attached to the interface for sealing purposes.

8 **“cake bowl”**: The interface includes a plano-convex lens shape that converges the microwaves into a point. The interface is divided into two components, each with its own material. The interface uses glue or adhesive for sealing purposes.

10 **“cheeseburger”**: A flat interface without any lens shape, thus no manipulation of the microwave paths. The interface is divided into two components, with a total of three materials. The interface utilizes welding for sealing purposes.

High-temperature concepts

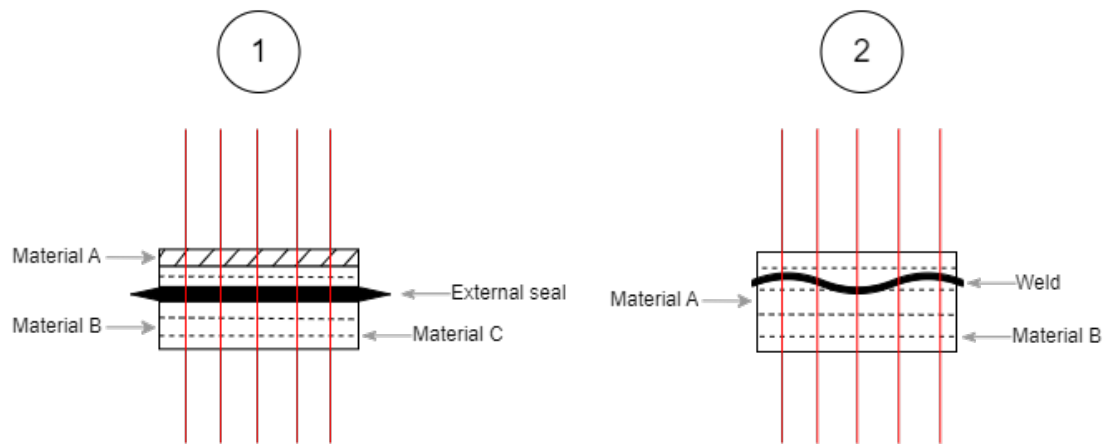


Figure 5.15: First stage high-temperature concepts part 1.

- 1 **“mailbox”**: A flat interface without any lens shape, thus no manipulation of the microwave paths. The interface is one component, made of three materials, one of which is a coating/thin layer on the outside circumference. An external seal is attached to the interface for sealing purposes.
- 2 **“wave”**: A flat interface without any lens shape, thus no manipulation of the microwave paths. The interface is one component made of two materials, one of which is a coating/thin layer on the outside circumference. The interface utilizes welding for sealing purposes.

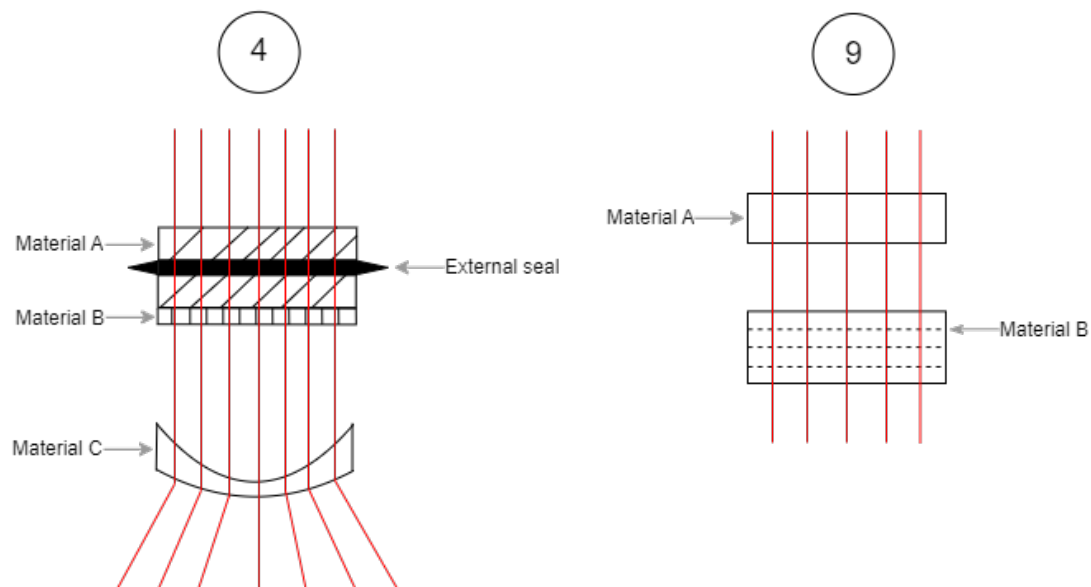


Figure 5.16: First stage high-temperature concepts part 2.

- 4 **“smiley”**: The interface includes a negative meniscus lens shape that diverges the microwaves. The interface is divided into two components with a total of three materials. An external seal is attached to the interface for sealing purposes.

- 9 **“floor 2”**: A flat interface without any lens shape, thus no manipulation of the microwave paths. The interface is divided into two components made of two materials, one of which is a coating/thin layer on the outside circumference. The interface uses glue or adhesive for sealing purposes.

5.1.3.2 Takeaways and Outcomes from Expert Consultation

The result after the expert consultation was that even more concepts were removed. Out of the six high-pressure concepts, three concepts were eliminated. These were 1: “axicon bullet”, 2: “shark mouth” and 7: “ice cream cone”. These were eliminated as diverging microwaves in any sense were not suitable for scanning radar.

Similar to the high-pressure concepts, the high-temperature concepts that diverged microwaves were removed. In this case, this was only one concept, namely, number 4: “smiley”.

Further, the idea of making an interface into a slightly conical shape was introduced by the experts. Its shape would be beneficial as it can eliminate steam and condensation build-up which can negatively affect the measurements. There was also a discussion on adding a hydrophobic layer to flat interfaces. However, adding such a coating would result in an additional step in the current production process. Hence, an inverted conical shape was suggested as a better alternative to ensure no steam build-up on the interface.

Lastly, after the consultation with the microwave expert, it was clear that a phased array would most likely be the most suitable option. The field-of-view calculations for the interface from here on out have therefore been based on this technology.

5.2 Stage 2 - Development

The second stage of the concept funnel focused on further developing the concepts at hand, not only refining them but also picking suitable materials and making CAD models and 3D printed prototypes.

5.2.1 Outputs from Concept Refinement in Stage 2

As the previous Elimination Matrix and expert consultation eliminated quite a few concepts it was deemed necessary to try to improve the current selection of concepts and the concepts in figure 5.17 were the ones added to the high-pressure selection. The concepts earlier called 8: “cake bowl”, and 10: “cheeseburger” are from here on out called 8A “cake bowl” and 10A: “cheeseburger” to make it clear that 8B and 10B were concepts inspired by them. For high-temperature, only one concept as can be seen in figure 5.18 was added, this one with a totally new number as it was not inspired by any of the former concepts but by the suggestion from the expert.

Added High-pressure Concepts

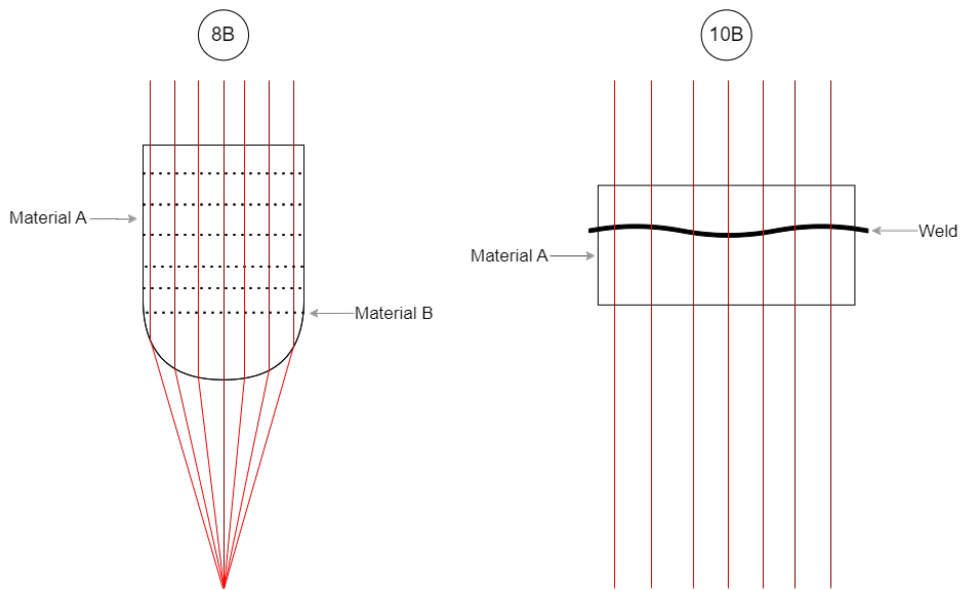


Figure 5.17: New high-pressure concepts added during second stage refinement.

8B **“drop”**: The interface includes a plano-convex lens shape that converges the microwaves into a point. The interface is one component made of two materials, one of which is a coating/thin layer on the outside circumference. The interface uses glue or adhesive for sealing purposes.

10B **“the box”**: A flat interface without any lens shape, thus no manipulation of the microwave paths. The interface is one component made of one single material. The interface utilizes welding for sealing purposes.

Added High-temperature Concepts

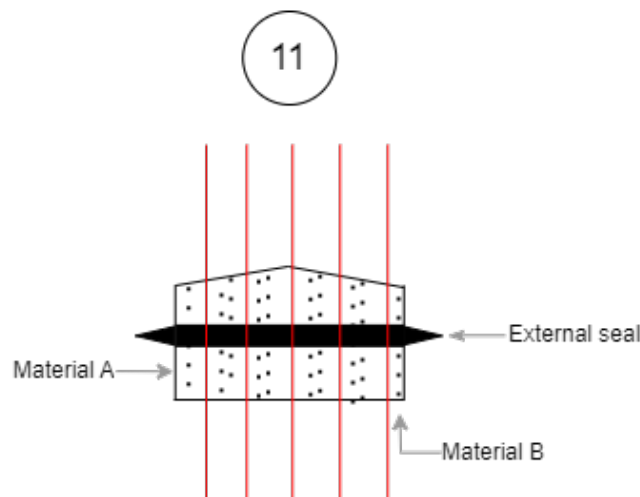


Figure 5.18: New high-temperature concepts added during second stage refinement.

11 **“inner circle”**: An interface with a slightly conical top end and a slightly inverted conical bottom end. The angle of the cone however is so small that

there is no noticeable effect on the microwave paths. The interface is one component made of two materials, one of which is an inner coating/thin layer along the inside of the circumference of the solid interface. An external seal is attached to the interface for sealing purposes.

5.2.1.1 Resulting Material Selection for Current Concepts

At this stage, before the next elimination stage, the materials for each concept were selected. Materials were evaluated on several criteria. Some were specifically for high-pressure applications, others for high-temperature and some were generic and were considered for both. The high-pressure ones focused mainly on structural integrity and the strength of the material, including the following from the Morphological Matrix 5.1.1.4:

- Yield strength
- High toughness
- Compressive strength
- Young's modulus
- Chemical resistance

The high-temperature criteria subsequently focused on the heat protection properties from the Morphological Matrix 5.1.1.4 such as:

- Thermal conductivity
- Thermal diffusivity
- Thermal emissivity
- Heat capacity
- Melting point
- Maximum service temperature

Besides these, the generic ones were mostly aspects relating to microwaves but also a few others, some of which were:

- Hydrophobic
- Microwave absorption
- Microwave reflection
- Microwave transparency
- Cost
- Carbon footprint
- Recycling

5. Phase 2: Concept Development

The material selection was conducted in Granta Edupack [55] where all these aspects were used as limits, and as axes in graphs to find suitable materials. A few examples of such are illustrated figures 5.19, 5.20, 5.21, 5.22 and 5.23.

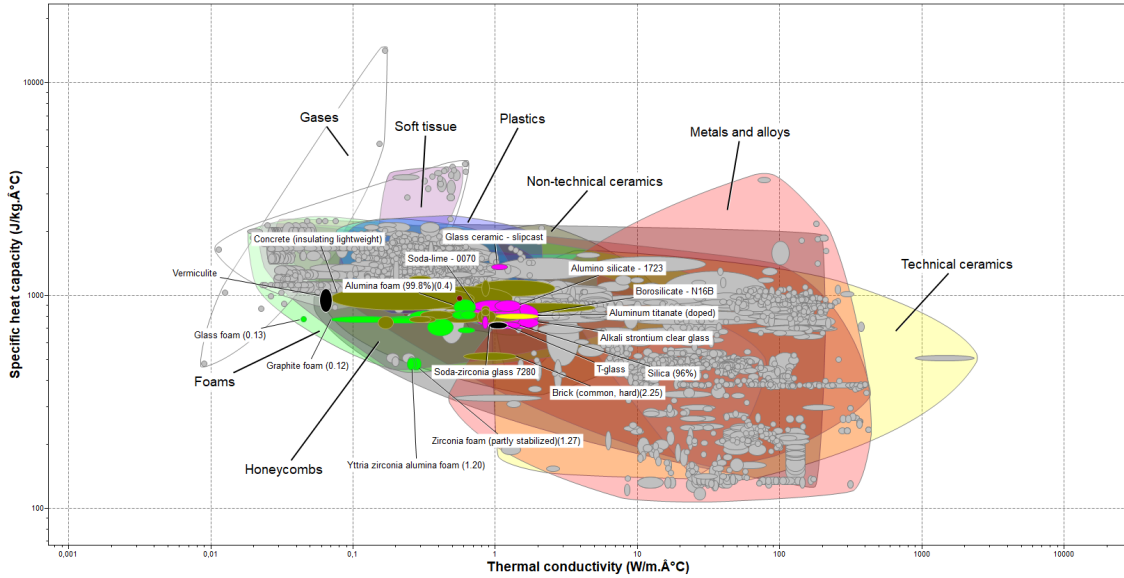


Figure 5.19: Chart depicting heat absorption of materials.

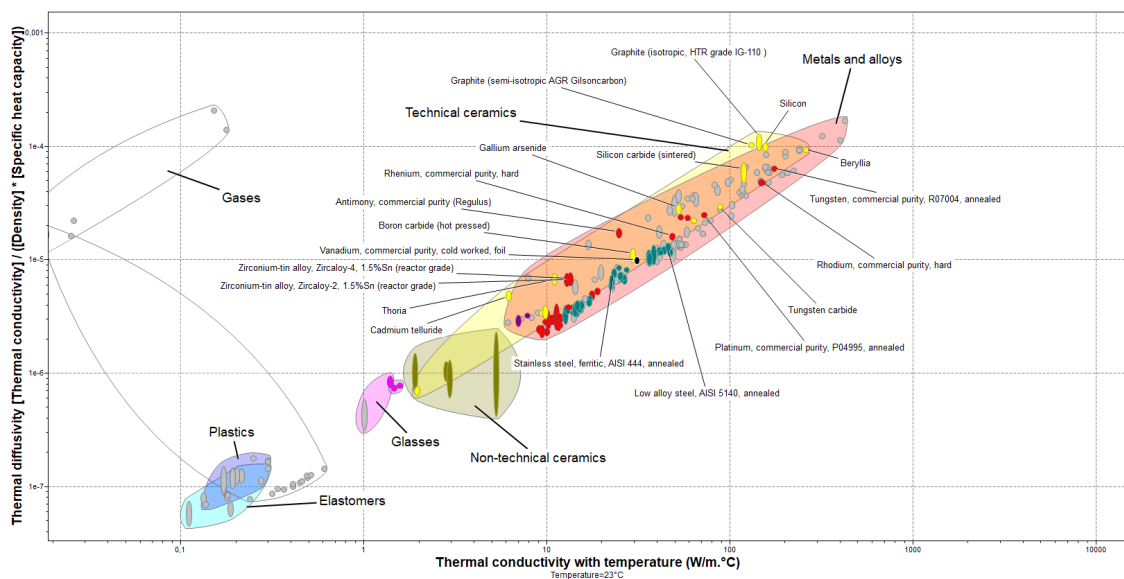


Figure 5.20: Chart illustrating heat dissipation of materials.

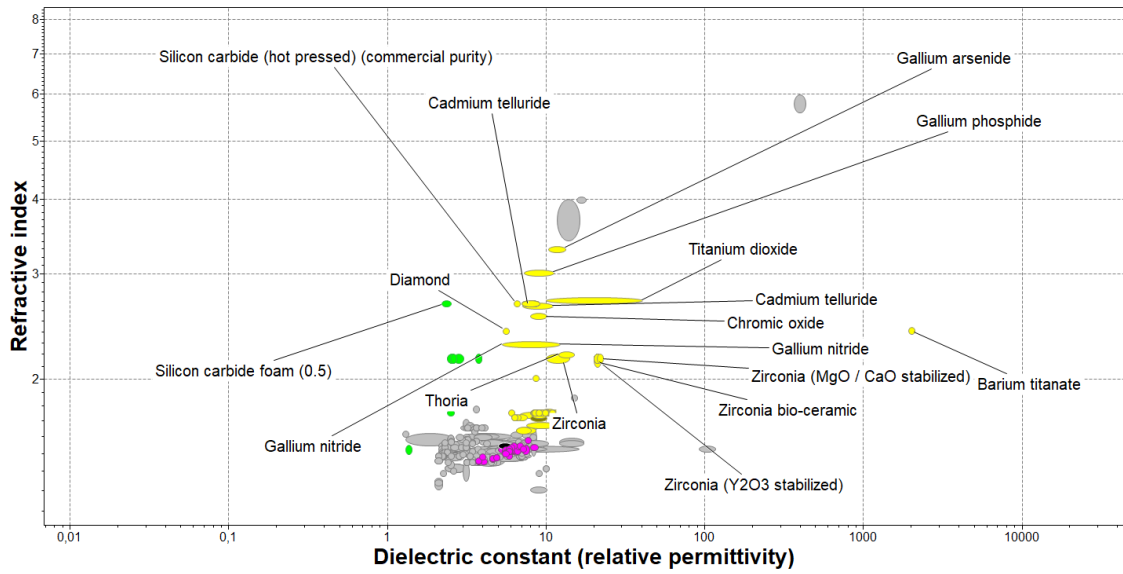


Figure 5.21: Chart representing the transparency and reflectiveness of different materials to microwaves.

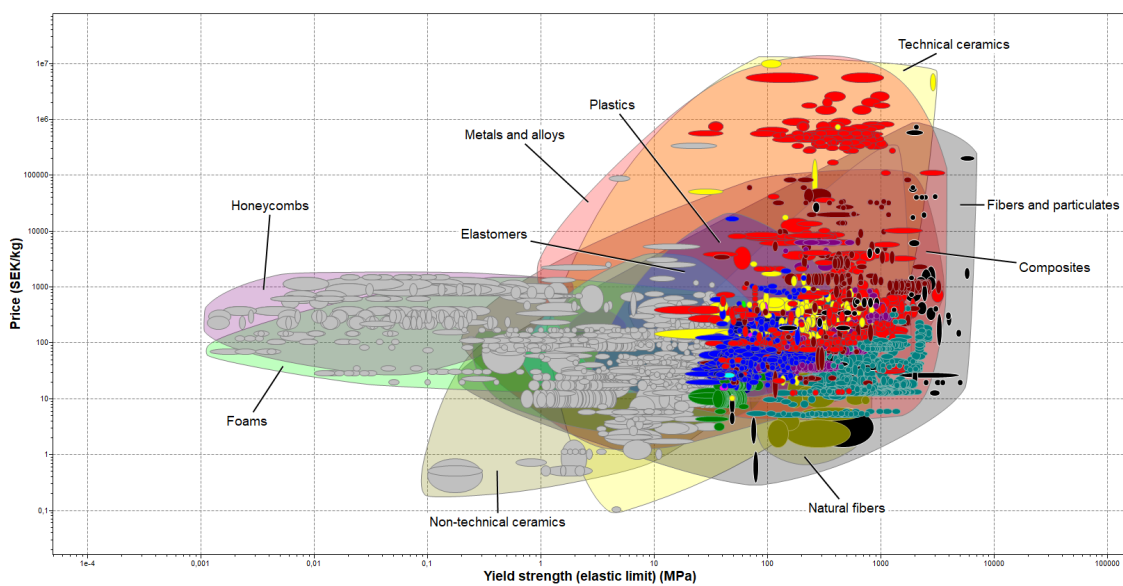


Figure 5.22: Chart visualizing cost versus maximum yield strength of materials.

5. Phase 2: Concept Development

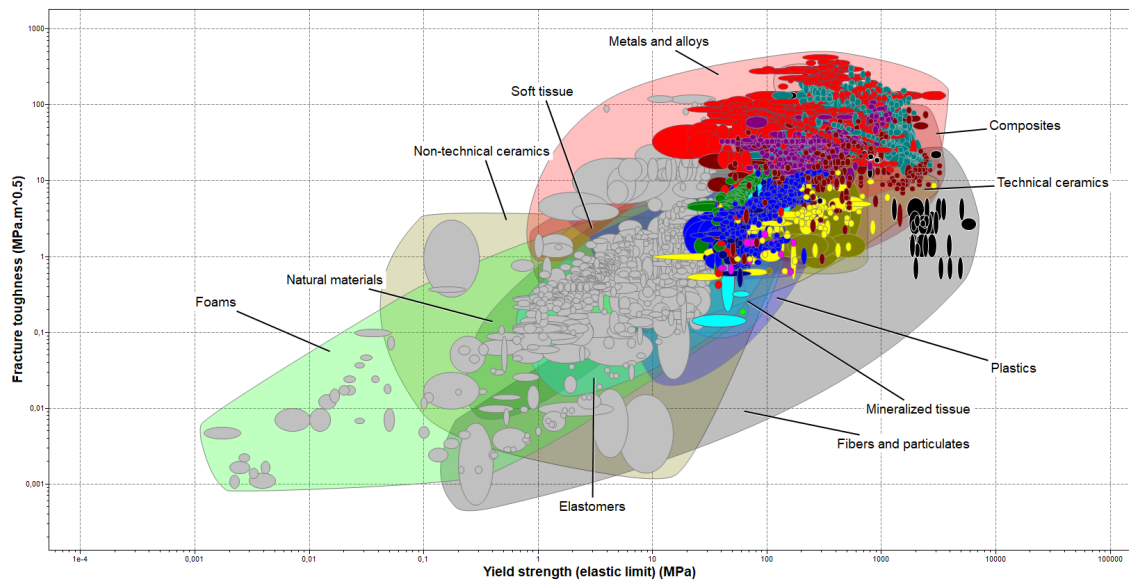


Figure 5.23: Chart visualizing fracture toughness versus maximum yield strength of materials.

Based on this search the material selection was performed. In table 5.1 the chosen materials for high-pressure concepts are listed and in table 5.2 the selected materials for high-temperature concepts are listed.

Table 5.1: Material Selection for high-pressure concepts

Concept	Material A	Material B	Material C
5 sandwich	Gold	CFRP	Silver
8A cake bowl	PEEK	Aluminium	
8B drop	Aluminium oxide	Silver	
10A cheeseburger	Aluminium oxide	PEEK	Gold
10B the box	CFRP		

Table 5.2: Material Selection for high-temperature concepts

Concept	Material A	Material B	Material C
1 mailbox	Soda zinc	Beryllia	Silica
2 wave	Aluminium oxide	Rhodium	
9 floor 2	Aluminium oxide	Silica	
11 inner circle	Aluminium oxide	Titanium nitride	

The selection of materials for each concept also enabled the Pugh Matrix to compare the concepts beyond functionality and design as it now could compare material properties as well.

5.2.2 Results of Concept Screening in Stage 2

The second elimination process of the project consisted of a Pugh Matrix which further evaluated and eliminated concepts.

5.2.2.1 Outcomes from Pugh Matrix Screening

Five concepts were inserted into the Pugh Matrix for high-pressure applications. The three left after the elimination in Stage 1 5.1.2 and the two new refinement concepts that were added in Stage 2 5.2.1. Three iterations were carried out, the first of which picked a reference concept at random and the following two using the previous top-ranking solution as a reference. The third and final of the iterations can be seen in figure 5.24 along with the rankings in figure 5.25.

Pugh Matrix for high-pressure					
Master thesis: Interface for Scanning Microwave Radar					
Criteria	Created: 2024-03-21		Last modified: 2024-03-27		
	5 sandwich	8A cake bowl	8B drop	10A cheeseburger	10B the box
Price	-	+	R	-	+
Complexity (higher complexity = less good)	-	-	E	-	+
Environmental impact(CO2 footprint)	-	+	F	-	+
Transparent	-	-	E	-	-
Absorbant	+	0	R	0	+
Reflective	+	-	E	-	-
Pressure protection	+	0	N	+	-
Durability (for chemicals and other substances)	-	-	C	-	-
			E		
Amount +	3	2		1	4
Amount -	4	3		5	3
Amount 0	0	2		1	0
Net value	-1	-1	0	-4	1
Ranking	2	2	1	3	1

Figure 5.24: Pugh Matrix for high-pressure.

	Pugh 1	Pugh 2	Pugh 3	Average ranking	Final Ranking
5	4	3	2	3	4
8A	3	2	2	2,333333333	3
8B	2	1	1	1,333333333	2
10A	3	3	3	3	4
10B	1	1	1	1	1

Figure 5.25: Rankings after after three iterations using Pugh Matrix for high-pressure.

It was clear that some concepts consistently placed at the bottom of the ranking while others placed at the top. Therefore, on the basis of the average ranking, it was decided that the concepts “cake bowl”, “drop” and “the box” would continue to be developed while the rest were eliminated.

For the high-temperature application, three concepts remained after the Elimination Matrix 5.1.2, and an additional concept was added during the refinement in Stage 2 5.2.1. Thus, a total of four concepts were included in the Pugh Matrix. Three iterations were conducted in the same way as for high-pressure and the second iteration can be seen in figure 5.26 and the resulting ranking in figure 5.27.

Pugh Matrix for high-temperature				
Master thesis: Interface for Scanning Microwave Radar				
Criteria	Created: 2024-03-21		Last modified: 2024-03-27	
	1 mailbox	2 wave	9 floor 2	11 inner circle
Price	+	-	R	-
Complexity (higher complexity= less good)	-	+	E	+
Environmental impact(CO2 footprint)	+	-	F	+
Transparent	0	-	E	-
Absorbent	0	+	R	+
Reflective	0	+	E	+
Heat protection	0	-	N	-
Durability (for chemicals and other substances)	-	-	C	+
			E	
Amount +	2	3		5
Amount -	2	5		3
Amount 0	4	0		0
Net value	0	-2	0	2
Ranking	2	3	2	1

Figure 5.26: Pugh Matrix for high-temperature.

	Pugh 1	Pugh 2	Pugh 3	Average ranking	Final Ranking
1	2	2	1	1,666666667	2
2	3	3	2	2,666666667	4
9	1	2	3	2	3
11	2	1	1	1,333333333	1

Figure 5.27: Rankings after three iterations using Pugh Matrix for high-temperature.

The decision was then made to move on with the two concepts “mailbox” and “inner circle”

5.2.3 Evaluation Outcomes in Stage 2

Similar to the previous stage, there was an evaluation and review following the elimination. This time the evaluation consisted of further developing the sketches of the concepts left into CAD models and 3D printing one high-pressure concept and one high-temperature concept each.

5.2.3.1 Resulting CAD models & 3D- printing in Stage 2

The team aimed to create a diverse set of prototype options, and ultimately selected one concept for each application scenario. For high-pressure the concept that was selected for print was “drop” and for high-temperature, it was “mailbox”. This selection was mainly made because having two vastly different prototypes was deemed the most valuable and would provide more insights as compared to printing “the box” and “inner circle” for example. Due to the team’s inability to do any rapid prototype that could have sealing functions such as welding or external gaskets, it was decided the “mailbox” should feature a groove along its circumference where the external seal would reside if it could have been added. The physical prototypes of “drop” and “mailbox” can be seen in figure 5.28 and figure 5.29 respectively.



Figure 5.28: 3D printed prototype of “drop”.



Figure 5.29: 3D printed prototype of “mailbox”.

5.3 Stage 3 - Optimization

The third and final stage of phase 3 started with another concept refinement followed by the most thorough elimination process and lastly, verification, consisting of virtual simulations.

5.3.1 Outcomes from Concept Refinement in stage 3

Similar to the last stage, there was a need to refine the current concepts and optimize them according to all the findings in stage 2, drawn from both the Pugh Matrix and the evaluation process.

The new concepts added to the ones remaining after the Pugh Matrix in stage 2 5.2.2.1 can be seen in 5.30 for high-pressure applications and in figure 5.31 for high-temperature applications.

Added High-pressure Concepts

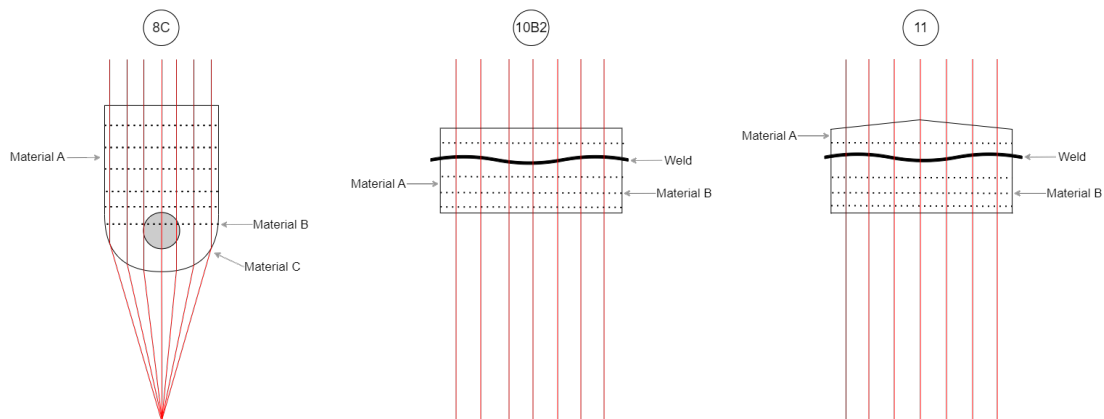


Figure 5.30: New high-pressure concepts added during third stage refinement.

8C **“cake drop”**: The interface includes a plano-convex lens shape that converges the microwaves into a point. The interface is one component made of three materials, one of which is a coating/thin layer on the outside circumference and another is a material mixed into the base material at the bottom of the interface (in the bottom focal point). The interface uses glue or adhesive for sealing purposes.

10B2 **“new box”**: A flat interface without any lens shape, thus no manipulation of the microwave paths. The interface is one component made of two materials, one of which is a coating/thin layer on the outside circumference. The interface utilises welding for sealing purposes.

11 **“conical valley”**: An interface with a slightly conical top end and a slightly inverted conical bottom end. The angle of the cone however is so small that there is no noticeable effect on the microwave paths. The interface is one component made of two materials, one of which is a coating/thin layer on the outside circumference. The interface utilises welding for sealing purposes.

The first of the new high-pressure, 8C: “cake drop” was a combination and replacement of the former 8A and 8B. The second, 10B2: “new box” was an updated version of 10B and the third 11: “conical valley” was a completely new concept for high pressure.

Added High-temperature Concepts

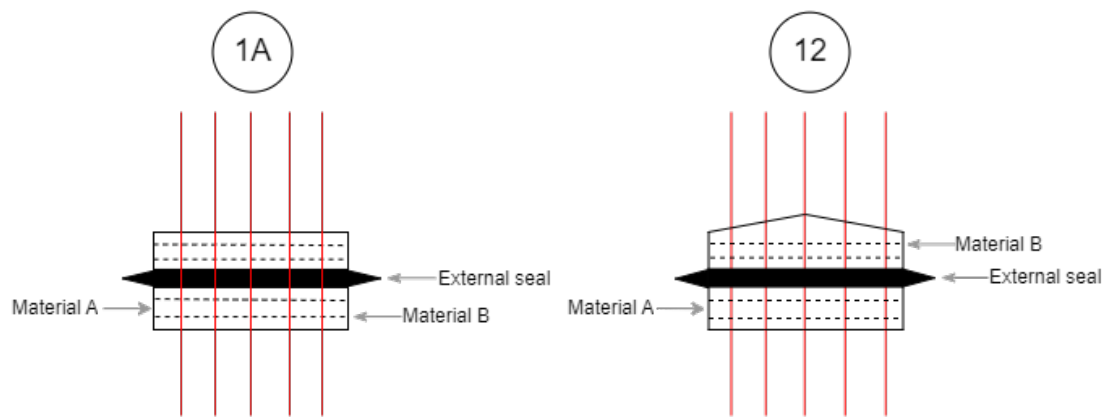


Figure 5.31: New high-temperature concepts added during third stage refinement.

- 1A **“new mailbox”**: A flat interface without any lens shape, thus no manipulation of the microwave paths. The interface is one component made of two materials, one of which is a coating/thin layer on the outside circumference. An external seal is attached to the interface for sealing purposes.
- 12 **“flat cone”**: An interface with a slightly conical top end and a slightly inverted conical bottom end. The angle of the cone however is so small that there is no noticeable effect on the microwave paths. The interface is one component made of two materials, one of which is a coating/thin layer on the outside circumference. An external seal is attached to the interface for sealing purposes

For high-temperature one of the new concepts, 1A: “new mailbox” was a refinement and replaced the former 1: “mailbox” while the second, 12: “flat cone” was a completely new concept.

Besides design and construction refinements, there were some material changes as well. These changes and the new concepts’ respective materials can be seen in table 5.3 for high-pressure and 5.4 for high-temperature. This new material selection was done considering the same requirements and aspects as in section 5.2.1.1 but with all the new knowledge that had been gained since.

Table 5.3: Material Selection for new high-pressure concepts added in refinement in stage 3.

Concept	Material A	Material B	Material C
8C cake drop	PEEK	aluminium	carbon
10B2 new box	zirconium oxide	copper	
11 conical valley	aluminium oxide	silver	

Table 5.4: Material Selection for new high-temperature concepts added in refinement in stage 3.

Concept	Material A	Material B
1A new mailbox	beryllia	soda zinc
11 inner circle	aluminium oxide	titanium nitride
12 flat cone	beryllia	titanium nitride

5.3.2 Results of Concept Scoring using the Kesselring Matrix

At this point, there were three high-pressure concepts and three high-temperature concepts remaining. The concepts for each application scenario were evaluated in a separate Kesselring Matrix. The Matrix for high-pressure concepts can be seen in figure 5.32 and in figure 5.35 for high-temperature concepts. The weighting factor for all criteria, in both matrices, was derived from a systematic comparison of each criterion as seen in figure 5.33 and 5.36. The assessment of fulfilling each criterion was based on the grading scales in figure 5.34 and 5.37.

Results of High-pressure Concept Scoring

Kesselring matrix: High-pressure									
Master thesis: Interface for Scanning Microwave Radar				Created: 2024-04-05			Last modified: 2024-04-18		
Criteria	w	Ideal		Concepts					
		v	t	8C Cake drop		10B2 new box		11 conical valley	
		v	t	v	t	v	t	v	t
Price	3	5	15	5	15	3	9	2	6
Environmental impact (CO2 footprint)	1	5	5	5	5	4	4	3	3
Transparent	6	5	30	2	12	4	24	3	18
Absorbant	5	5	25	5	25	2	10	2	10
Reflective	5	5	25	4	20	3	15	5	25
Pressure protection	6	5	30	3	18	3	18	5	30
Moisture Accumulation	2	5	10	5	10	1	2	4	8
Sealing	6	5	30	2	12	5	30	5	30
Flexible use	4	5	20	1	4	1	4	1	4
Safety	6	5	30	2	12	3	18	3	18
FOV	6	5	30	1	6	5	30	4	24
T (Total net worth)		45	205	29	118	26	125	31	146
T / Tideal		1	1	0,64	0,58	0,58	0,61	0,69	0,71
Mean		5,0	22,0	3,2	13,1	2,9	13,9	3,4	16,2
Median		5	25	3,5	12	3	12,5	3	14
Ranking		1		4		3		2	
Final decision								FINAL CONCEPT	

Figure 5.32: High-pressure Kesselring Matrix.

5. Phase 2: Concept Development

	A	B	C	D	E	F	G	H	I	J	K
A (Price)	-	0	1	1	1	1	0,5	0,5	1	1	1
B (Environmental impact)	1	-	1	1	1	1	1	1	1	1	1
C (Transparent)	0	0	-	0	0	0,5	0	0	0,5	0	0,5
D (Absorbant)	0	0	1	-	0,5	1	0	0	1	0	1
E (Reflective)	0	0	1	0,5	-	1	0	0	1	0	1
F (Pressure protection)	0	0	0,5	0	0	-	0	0	0,5	0,5	0,5
G (Moisture Accumulation)	1	0,5	1	1	1	1	-	0,5	1	1	1
H (Smoothness)	1	0,5	1	1	1	1	0,5	-	1	1	1
I (Sealing)	0	0	0,5	0	0	0,5	0	0	-	0	0,5
J (Flexible use)	0	0	1	1	1	1	0	0	1	-	1
K (Safety)	0	0	0,5	0	0	0,5	0	0	0,5	0	-
Σ	3	1	8	5,5	5,5	8	2	2	8	4,5	8,5
Σ_{rel}	0,33	0,11	0,89	0,61	0,61	0,89	0,22	0,22	0,89	0,50	0,94
Resulting weight factor	3	1	6	5	5	6	2	2	6	4	4

Figure 5.33: High-pressure Kesselring Matrix weighting table.

Price		Environmental impact		Transparent		Absorbant		Smoothness			
1	Very expensive	1	Very bad	1	Very low	1	Very low	1	Very rough		
2	Expensive	2	Bad	2	Low	2	Low	2	Rough		
3	Moderate	3	OK	3	Moderate	3	Moderate	3	Somewhat smooth		
4	Inexpensive	4	Good	4	High	4	High	4	Smooth		
5	Affordable	5	Very good	5	Very high	5	Very high	5	Very smooth		
Reflective		Pressure protection		Moisture Accumulation		Sealing		Flexible use		Safety	
1	Very low	1	Very weak	1	Very high	1	Very weak	1	Very low	1	Very bad
2	Low	2	Weak	2	High	2	Weak	2	Low	2	Bad
3	Moderate	3	Moderate	3	Moderate	3	Moderate	3	Moderate	3	OK
4	High	4	Strong	4	Low	4	Strong	4	High	4	Good
5	Very high	5	Very strong	5	Very low	5	Very strong	5	Very high	5	Very good

Figure 5.34: High-pressure Kesselring Matrix grading scale table.

The winning concept, as can be viewed in figure 5.32 was “conical valley”. It scored a fair bit above both the other concepts and some of the aspects mostly contributing to the high score as its conical shape ensured no build-up of moisture or condensation, its wide FOV and the welding it utilises for sealing purposes.

Results of High-temperature Concept Scoring

Kesseling matrix for high-temperature									
Master thesis: Interface for Scanning Microwave Radar					Created: 2024-04-05			Last modified: 2024-04-18	
Criteria				Concepts					
		Ideal		1A new mailbox		11 inner circle		12 flat cone	
	w	v	t	v	t	v	t	v	t
Price	3	5	15	4	12	2	6	2	6
Environmental impact (CO2 footprint)	1	5	5	5	5	5	5	5	5
Transparent	6	5	30	5	30	3	18	5	30
Absorbant	5	5	25	1	5	2	10	1	5
Reflective	5	5	25	2	10	4	20	4	20
Heat protection	6	5	30	5	30	3	18	5	30
Moisture Accumulation	2	5	10	1	2	4	8	4	8
Sealing	6	5	30	4	0	4	0	4	0
Flexible use	4	5	20	3	12	4	16	3	12
Safety	6	5	30	1	6	4	24	1	6
FOV	6	5	30	5	6	4	24	4	6
T (Total net worth)		50	235	32	106	37	143	36	122
T / Tideal		1	1	0,64	0,45	0,74	0,61	0,72	0,52
Mean		5,0	22,7	3,2	10,6	3,7	14,3	3,6	12,2
Median		5	25	4	6	4	16	4	6
Ranking		1		4		2		3	
Final decision						FINAL CONCEPT			

Figure 5.35: High-temperature Kesseling Matrix.

	A	B	C	D	E	F	G	H	I	J	K
A (Price)	-	0	1	1	1	1	0,5	0,5	1	1	1
B (Environmental impact)	1	-	1	1	1	1	1	1	1	1	1
C (Transparent)	0	0	-	0	0	0,5	0	0	0,5	0	0,5
D (Absorbant)	0	0	1	-	0,5	1	0	0	1	0	1
E (Reflective)	0	0	1	0,5	-	1	0	0	1	0	1
F (Heat protection)	0	0	0,5	0	0	-	0	0	0,5	0,5	0,5
G (Moisture Accumulation)	1	0,5	1	1	1	1	-	0,5	1	1	1
H (Smoothness)	1	0,5	1	1	1	1	0,5	-	1	1	1
I (Sealing)	0	0	0,5	0	0	0,5	0	0	-	0	0,5
J (Flexible use)	0	0	1	1	1	1	0	0	1	-	1
K (Safety)	0	0	0,5	0	0	0,5	0	0	0,5	0	-
Σ	3	1	8,5	5,5	5,5	8,5	2	2	8,5	4,5	8,5
Σ_{rel}	0,33	0,11	0,94	0,61	0,61	0,94	0,22	0,22	0,94	0,50	0,94
Resulting weight factor	3	1	6	5	5	6	2	2	6	4	6

Figure 5.36: High-temperature Kesseling Matrix weighting table.

5. Phase 2: Concept Development

Price		Environmental impact		Transparent		Absorbant		Smoothness			
1	Very expensive	1	Very bad	1	Very low	1	Very low	1	Very rough		
2	Expensive	2	Bad	2	Low	2	Low	2	Rough		
3	Moderate	3	OK	3	Moderate	3	Moderate	3	Somewhat smooth		
4	Inexpensive	4	Good	4	High	4	High	4	Smooth		
5	Affordable	5	Very good	5	Very high	5	Very high	5	Very smooth		
Reflective		Heat protection		Moisture Accumulation		Sealing		Flexible use		Safety	
1	Very low	1	Very weak	1	Very high	1	Very weak	1	Very low	1	Very bad
2	Low	2	Weak	2	High	2	Weak	2	Low	2	Bad
3	Moderate	3	Moderate	3	Moderate	3	Moderate	3	Moderate	3	OK
4	High	4	Strong	4	Low	4	Strong	4	High	4	Good
5	Very high	5	Very strong	5	Very low	5	Very strong	5	Very high	5	Very good

Figure 5.37: High-temperature Kesselring Matrix grading scale table.

The winning concept of the high-temperature applications was “inner circle” as figure 5.35 shows. Some of the main aspects that it scored significantly higher on as compared to the other two were safety, environmental impact and FOV. Regarding safety, both of the other concepts have beryllia as a base material and it can be toxic [61].

5.3.3 Verification Results in Stage 3

The verification in the last stage of the concept funnel aided in ensuring requirements were met, especially verifying that the structural integrity of the concept was sound.

5.3.3.1 Results from Pressure Simulations in Stage 3

The simulations were, as mentioned, done on the highest-ranking concept from the Kesselring Matrix “conical valley”, which is a slightly conical interface in aluminium oxide with the following dimensions. A diameter of 20 mm which was derived from the needed field of view as set in the target specifications and a starting thickness of 16.5 mm was picked as it was slightly greater than similar interfaces that Emerson uses for single-point measurements. The thickness was then gradually decreased until the max equivalent became higher than the max allowable stress which meant that it was too thin and the optimal thickness could be found right before that point.

The maximum allowable stress for the concept which was made in aluminium oxide was derived from its yield strength divided by the safety factor. The yield strength of aluminium oxide is 262.5 MPa and the safety factor was 4. Which gave the maximum allowable stress:

$$\text{Maximum allowable stress} = \frac{262.5}{4} = 65.625\text{MPa} \quad (5.1)$$

Both simulations of deformation and equivalent stress were done with fixed supports to the circumference of the interface as that is how it will be fastened and the pressure was applied from below as the pressure will be originating from the tank below.

Table 5.5: Pressure Simulation Results for 20 mm radius.

Thickness [mm]	Max Equivalent(von mises) Stress [MPa]	Max Total Deformation [μm]
16.5	20.316	1.1661
13.5	30.983	1.6636
11.5	43.997	2.3852
10	62.264	3.4574
9.5	68.5	4.0133

The simulations with varying thickness resulted in the values found in table 5.5 and the thickness of 10 mm was chosen as the most suitable as the equivalent stress was close to the maximum allowable stress without exceeding it. This meant that we made the interface as thin as possible as the even thinner one would have yielded as the maximum equivalent stress was higher than the maximum allowable stress as can be seen for the 9.5 mm simulation.

Equivalent (von Mises) Stress

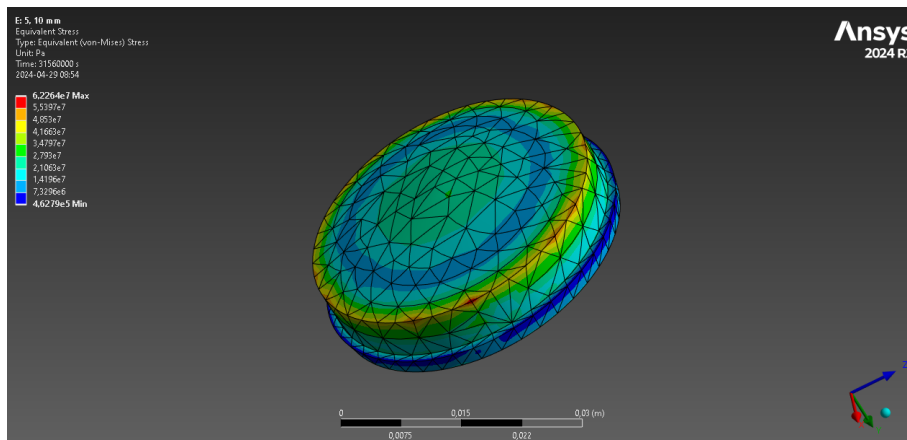


Figure 5.38: Equivalent (von Mises) stress simulation of “conical valley” with 20 mm radius.

Total Deformation

As the resulting maximum total deformation does not pass $3.4574\mu\text{m}$, which is equal to $3.4574/1000\text{ mm}$, it has no significant effect on the shape and the structural integrity of the interface.

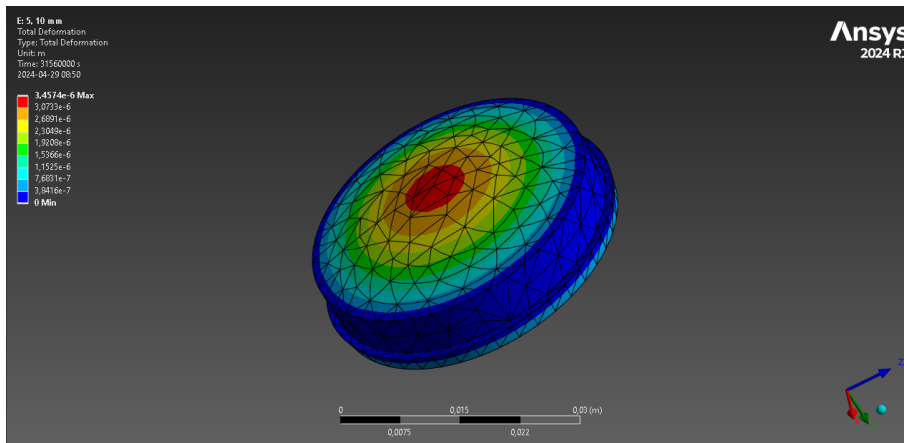


Figure 5.39: Total Deformation simulations of “conical valley” with 20 mm radius.

6

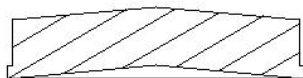
Phase 3: Final Concept

The absolute final phase of the project was the selection and creation of the final concepts. This included final CAD models and prototypes along with final target specifications and material selection.

6.1 Final Design for high-pressure and high-temperature applications

In the end, because of the many similarities between the two final concepts for each application scenario, it was decided that it would be most beneficial to combine them into one final concept. The final concept is therefore a combination of “conical valley” and “inner circle”. As both designs featured a slightly inverted conical shape at the bottom and a slightly conical shape at the top, this stayed the same, thus ensuring no condensation build-up without having to add a hydrophobic coating to the interface. They also had the same base material of aluminium oxide that therefore also stayed the same as it has already been ensured that it is suitable for both applications. The final design has a thickness of 13.5 mm and a diameter of 60 mm as this fulfils the pressure and temperature requirements, the verification for this and other details such as material selection will be presented in more detail in the upcoming sections 6.1.1.2, 6.1.1.1 and 6.2. In the figure 6.1 the final design drawing can be seen including a cross-sectional view and the figures 6.2, 6.3 and 6.4 depict the final design from the side, cross-section and front.

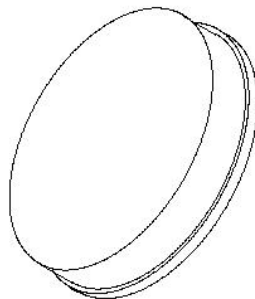
Section view A-A
Scale: 1:1



Front view
Scale: 1:1



Isometric view
Scale: 1:1



Top view
Scale: 1:1

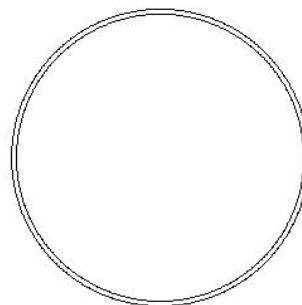


Figure 6.1: CAD drawings of final design.

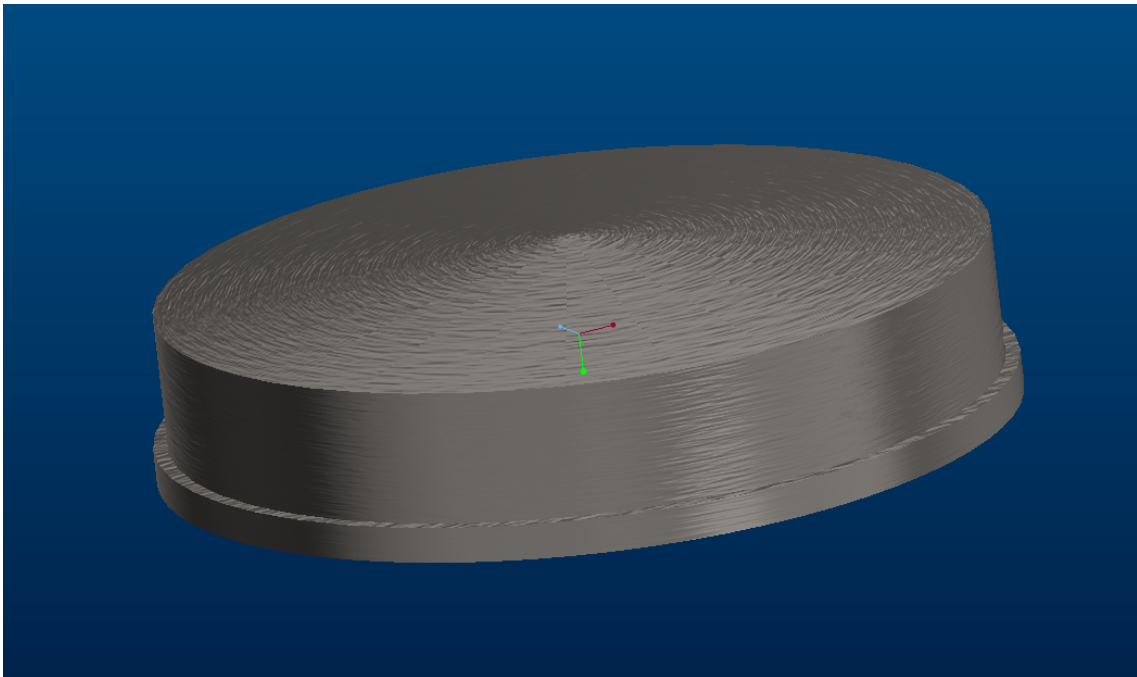


Figure 6.2: Side view of final design in CAD.

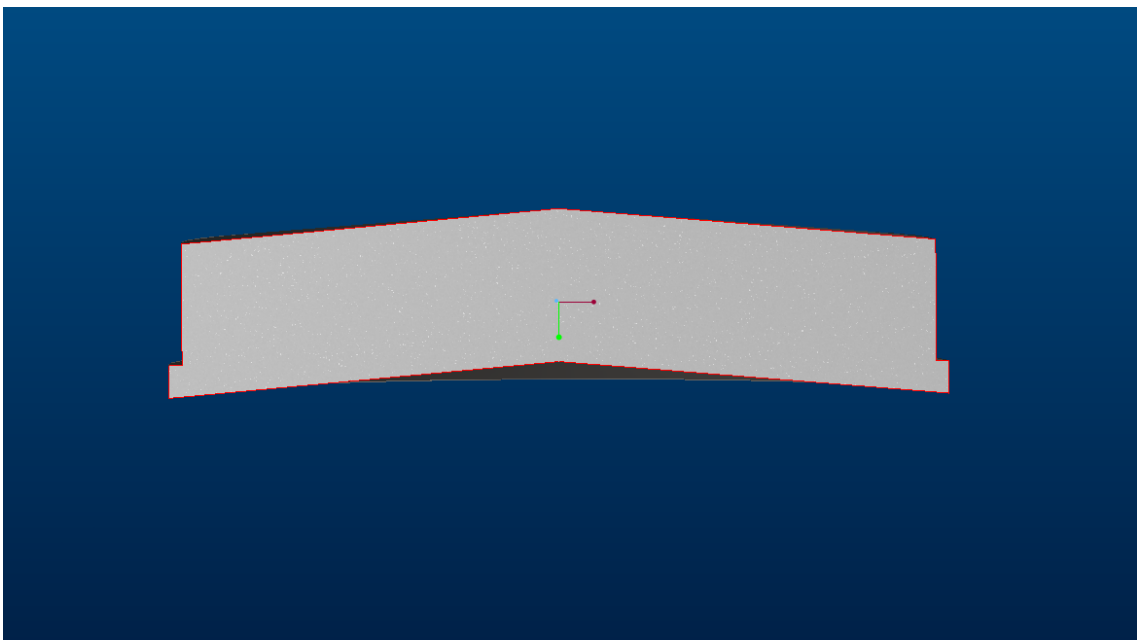


Figure 6.3: Cross-section view of final design in CAD.

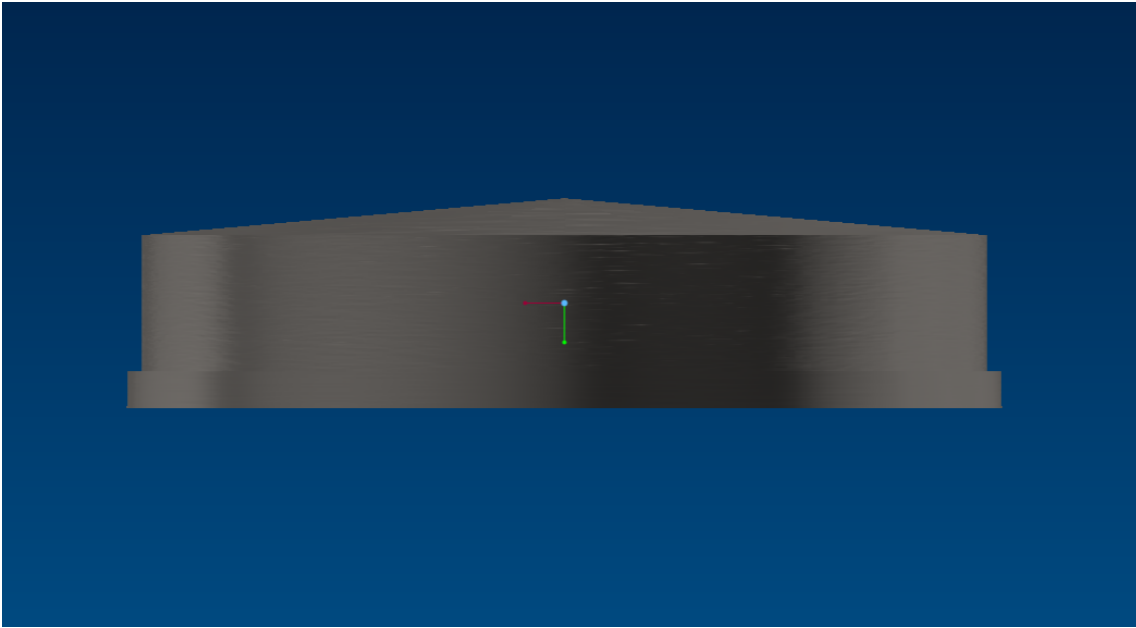


Figure 6.4: Front view of final design in CAD.

The most distinct features and key aspects of the design are as follows in the list 6.1

- Conical shape on top and inverted conical shape on bottom to eliminate condensation or steam build-up which otherwise would negatively affect measurements, seen in figure 6.3.
- A very small angle on the conical shape, of approximately 5° to avoid diverging or converging microwaves as that would negatively affect microwaves measurements, seen in figure 6.3.
- A small cutout in the circumference and an edge on the bottom of the circumference as seen in figure 6.4, this is to make room for metallization, plating and the metal band used for welding, which is further explained in 6.2. This ensures a flush fit without protrusion anywhere on the part which guarantees that no debris or particles can get trapped and disturb measurements.
- A thickness of 13.5 mm to ensure structural integrity when put under pressure.
- A radius of 30 mm to ensure an appropriate FOV.

List 6.1: List of Important Design Features

6.1.1 Creation of Housing for Heat Simulations

As previously mentioned no heat-simulations were conducted in phase 2. The reasoning for this was that there was no frame or housing that connected the radar on the PCB to the interface only the interface itself. Thus any simulations that could have been done in phase 2 would not represent reality as the frame will also transfer heat to the PCB. Subsequently, a preliminary housing was therefore designed in phase 3 to be used in the heat simulations. The housing was designed to fit into an

enclosed space and be suitable to function in an industrial environment. However, as the housing transferred heat to the PCB, the PCB needed to be moved away from the interface even when simulating with materials with very low thermal conductivity. A consequence of moving the PCB was a smaller field of view which was undesired and therefore it was decided that the diameter of the interface should be increased to try to compensate for this. Then a wider interface needs to be thicker to withstand the pressure, as this concept should now work for both high-pressure and high-temperature. This then leads to an issue of absorbency, even if a material has very low microwave absorption, more and more microwaves will be absorbed as it has to pass through more material when it is thicker. This led to a trade-off between FOV and thickness. Therefore the simulations for high-pressure and high-temperature were conducted in parallel to find dimensions that fulfilled both use cases.

The housing and its material are not the final design that will be used in future implementation as that is outside of the project scope. During this project, the current design and material act as a placeholder that ensures the feasibility of the interface. The housing used in the simulations has a thickness of 1mm, consisting of titanium alloy with a polyphenylene sulfide polymer (PPS plastic) at the top corners of the housing where the PCB is attached.

6.1.1.1 Results of Heat Simulations on Final Concept

The heat simulation included the interface and housing along with the PCB board. As mentioned, this is not the final housing that will be implemented in a future product, but a temporary design used to ensure that the interface actually can protect the radar in high-temperature applications. The simulations were done with an ambient of 480°C according to the target specifications and according to the same specification the temperature on the PCB had to be below 85°C. The heat transfer of materials was according to material specifications in Granta EduPack [55] and the gap between the interface and PCB board was filled by stagnant air as they were placed in an enclosed space. This was then simulated for 1 year to see if the temperature exceeded 85°C or not. This resulted in the distance between the PCB and the interface being 30mm. The final diameter was 60 mm which resulted in a FOV 45° instead of 59° which was set as a target specification in the beginning. The FOV could not be increased past this point because of the conflicts and subsequent trade-offs, which were explained in 6.1.1. Resulting in a maximum temperature of 64°C on the PCB.

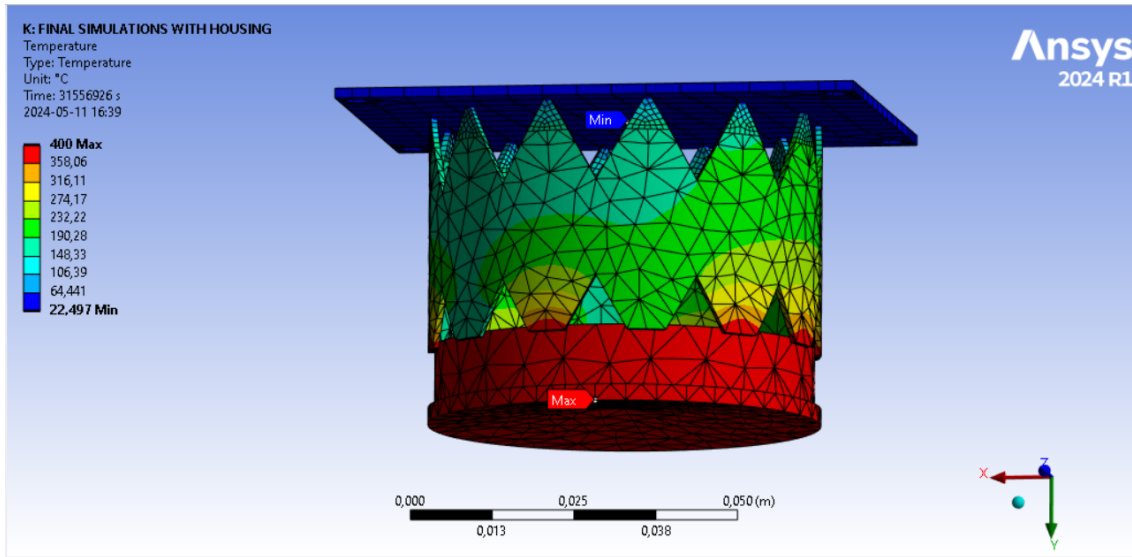


Figure 6.5: Heat simulation of final concept with housing.

6.1.1.2 Results of Pressure Simulations on Final Concept

The decision to make a common interface for high-pressure and high-temperature, resulted in a change in diameter to 30 mm as mentioned in the 6.1.1.1. Therefore the simulations from phase 2 5.3.3.1 were redone with the new diameter. This time, the starting thickness was set to 14.5 mm which was assumed to be thicker than needed based on previous simulations. Similar to the prior simulations, this thickness was then gradually decreased until it was too thin and the max equivalent stress was higher than the max allowable stress thus an optimal thickness could be found right before that happened.

Both simulations of deformation and equivalent stress were done with fixed supports to the circumference of the interface as that is how it will be fastened and the pressure was applied from below as the pressure will be originating from the tank below.

Table 6.1: Pressure Simulation Results for 30 mm radius.

Thickness [mm]	Max Equivalent(von mises) Stress [MPa]	Max Total Deformation [μm]
14.5	54.216	4.729
13.5	60.422	5.6666
13	66.899	6.2725

The simulations with varying thickness resulted in the values found in table 6.1 and the thickness of 13.5 mm was chosen as the most suitable as the maximum equivalent stress was close to the maximum allowable stress but still smaller. This meant that we made the interface as thin as possible as the thinner interface passed the point where the allowable stress was lower than the maximum equivalent stress and would yield.

Equivalent (von Mises) Stress

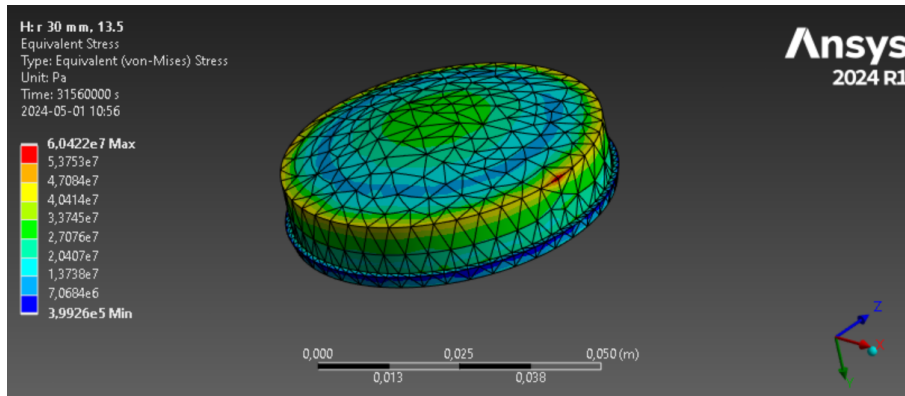


Figure 6.6: Side view of the Equivalent (von Mises) Stress of the final concept.

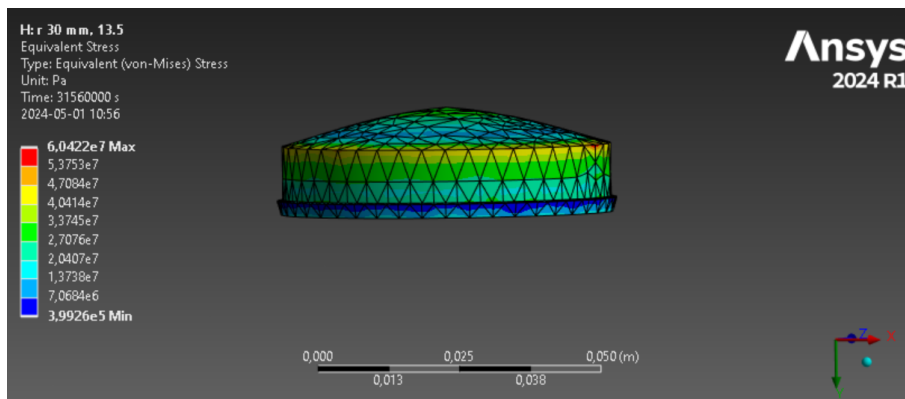


Figure 6.7: Front view of the Equivalent (von Mises) Stress of the final concept.

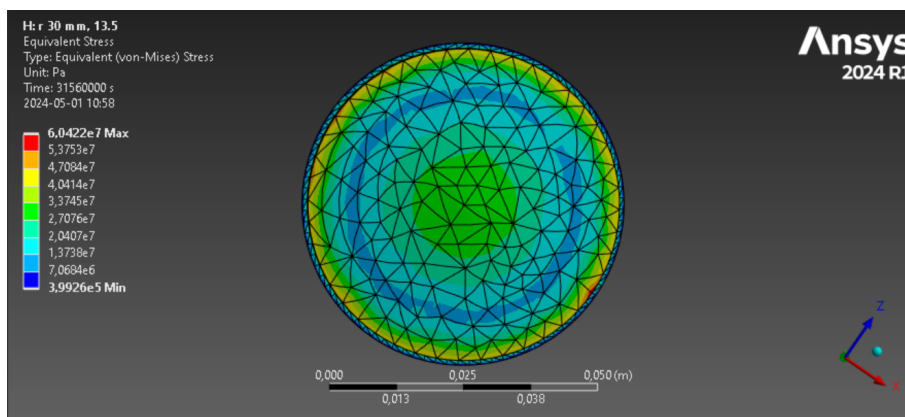


Figure 6.8: Top view of the Equivalent (von Mises) Stress of the final concept.

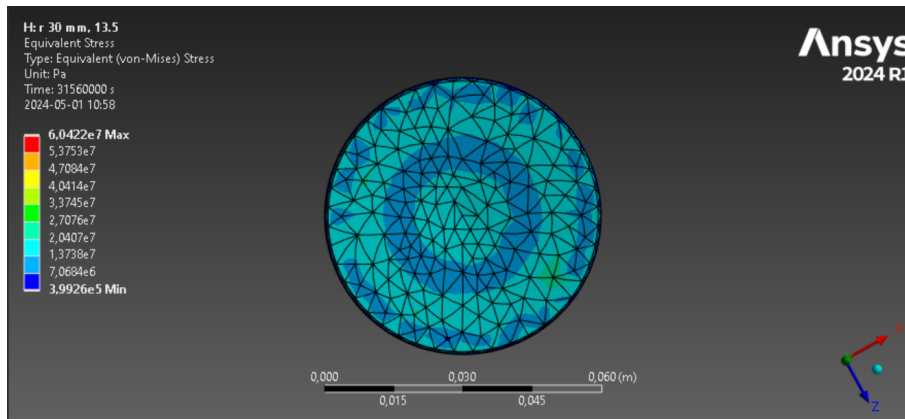


Figure 6.9: Bottom view of the Equivalent (von Mises) Stress of the final concept.

Total Deformation

As the resulting maximum total deformation does not pass $5.6666\mu\text{m}$, which is equal to $5.6666/1000$ mm, it has no significant effect on the shape and the structural integrity of the interface.

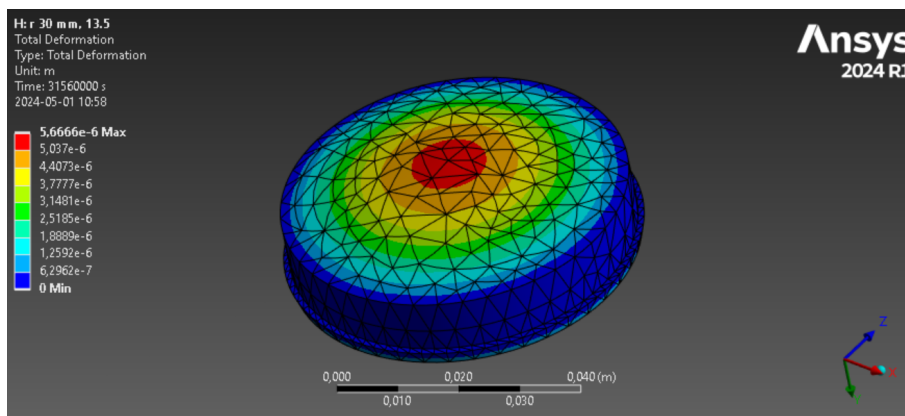


Figure 6.10: Side view of the Total Deformation of the final concept.

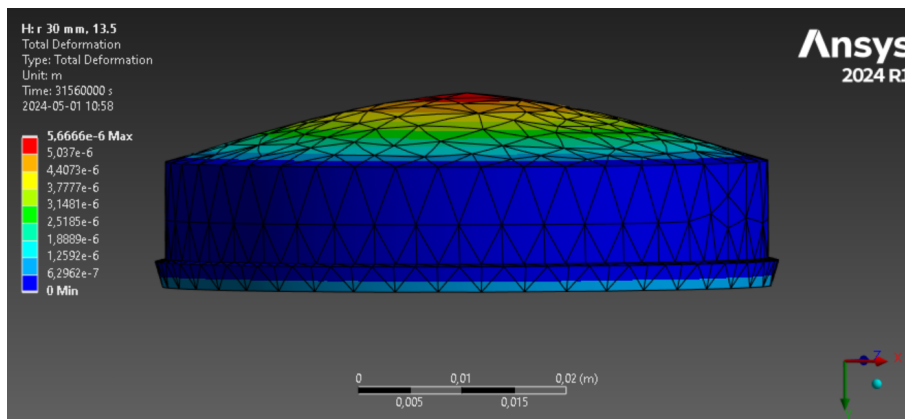


Figure 6.11: Front view of the Total Deformation of the final concept.

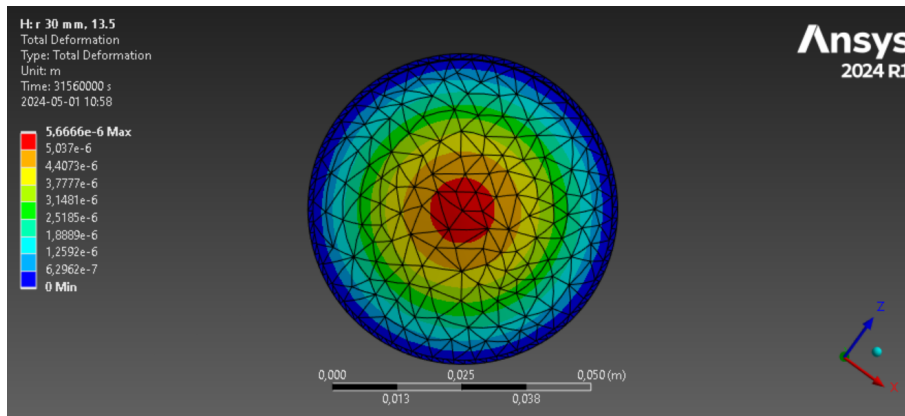


Figure 6.12: Top view of the Total Deformation of the final concept.

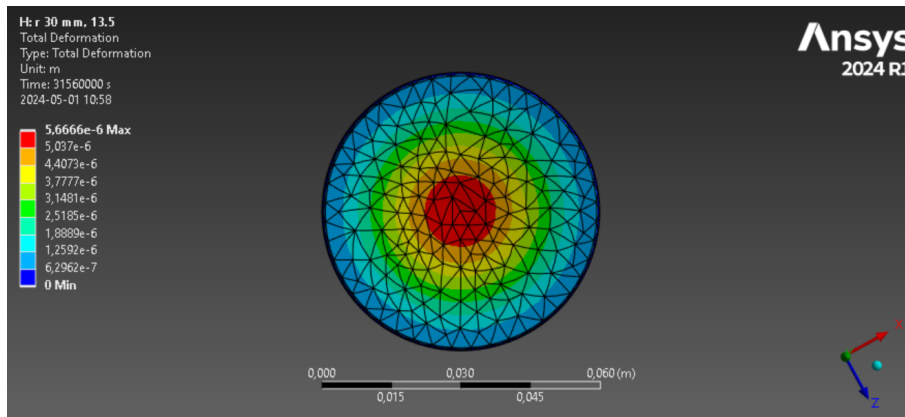


Figure 6.13: Bottom view of the Total Deformation of the final concept.

Resulting Costs for Final Concept

After the final dimensions were derived the cost per part was calculated. This was done with the tool, part cost estimator in Granta Edupack. The values used in the tool can be seen in table 6.2. These values are estimations as production planning is not included in the scope of the project. These estimations are based on industry standards in the technology sector for low-volume production and using powder hot pressing. As the process for manufacturing the interface is not included, powder hot pressing was selected as it could be a suitable option according to [55].

Table 6.2: Cost Calculation variables.

Mass [kg]	Part length [m]	Value of scrap material [%]	Batch size
0.12127423	0.0135	7	100
Primary process	Availability	Part complexity	
Powder hot pressing	Custom form	Standard	
Load factor [%]	Overhead rate [SEK/h]	Capital write-off time [years]	
75	250	8	

The resulting cost per part was 42.3 to 63.1 SEK per part. However, this only includes the base material of aluminium oxide. This is because the other materials are used in very small quantities and they were also not available in the material database. Instead, an extra margin was added on top of the cost that Granta EduPack estimated to cover the extra costs for the materials besides the base material. Subsequently, the final specification metric for material cost was set to 95 and 70 SEK per unit for marginal and target value respectively.

6.2 Outcome from Final Material Selection

As this final concept should be applicable in both high-pressure and high-temperature scenarios a few changes had to be made to the material selection. The main material aluminium oxide remained the same as both of the top-ranking concepts in the respective Kesselring Matrices consisted of aluminium thus it was already an option suited for both. The reflective material that was to be used in the high-pressure concept has a maximum service temperature below 400 ° C and subsequently cannot work in a high-temperature environment. The coating of titanium nitride on the inside of the interface could not work in a high-pressure environment either as the high-pressure environment requires a welded seal. Thus a new solution was needed. A final search in Granta EduPack [55] resulted in the selection of a gold-nickel alloy.

However, the gold-nickel alloy cannot be directly placed on the interface. First, the interface has to go through a metalisation process and a metal plating process. The selected materials for these were molybdenum manganese for metalisation and nickel-chromium for plating. The reasons for this were that the molybdenum manganese can withstand extreme temperatures, create a completely hermetic seal, is ideal for harsh environments and is compatible with aluminium oxide[62]. The nickel-chromium was selected on the basis of being a common pairing with the molybdenum manganese and it has a maximum service temperature above the needed requirements [55] as compared to regular nickel that could have otherwise been a suitable option as it shares many similarities with nickel-chromium and is cheaper. Nickel-chromium also has a high yield strength and low thermal conductivity making it ideal for both high-pressure and high-temperature environments.

When it comes to reflective materials that can withstand the temperature there are not many to choose from. In addition to having a high service temperature, it also needs to be compatible with other materials which gold-nickel is. Moreover, it is also oxidation resistant up to 815° C and has very high mechanical strength at very high temperatures [63]. Lastly, and most importantly, it is suitable for welding [63] which is a must for a high-pressure environment.

6.3 Final Specifications Results

Final specifications for both applications have been tabulated and combined with the metrics and requirements from the Initial target requirements. Since there will be a single concept at the end with diameter, thickness, and shape, these corresponding values 60mm and 13.5mm are fixed and don't have an ideal value because if they are varied it affects the entire solution. The same goes for performance criteria, where the microwave path should not fail if negatively affected by the lens shape or the interface. The inverted conical part of the interface should at least be good enough to ensure no condensation build-up. However, The interface should pass the ability to do non-contacting measurement solutions irrespective of the application scenarios. The maximum field of view of 45° was derived from the new dimensions of the interface and the placement of the PCB relative to the interface.

6. Phase 3: Final Concept

Chalmers		Final Specifications for high-temperature and high-pressure application				
<i>Master Thesis: Interface for Scanning Microwave Radar</i>		scale 1-5		≈ Requirement/ Demand	≈ Desire / Wish	
	<i>Metrics</i>	<i>Importance of ideal value</i>	<i>Units</i>	<i>Marginal value</i>	<i>Ideal value</i>	<i>Verification method</i>
1.	Design					
1.1	Diameter of interface		mm	60		Measurement verification on CAD design
1.2	Thickness of interface		mm	13.5		Measurement verification on CAD design
1.3	Shape of interface			cylindrical		Visual verification on CAD design
1.4	Minimizing trapping points	4	excellent/good/fair/poor	good	excellent	Testing and engineering assessment
2.	Performance					
2.1	Max field of view (FOV)		*	45		Calculation
2.3	Not negatively affect microwave paths (shape of lens/interface)		binary	pass		Assessment by microwave engineers
2.4	Ensure ability to do non-contacting measurements		binary	pass		Testing and engineering assessment
3.	Life cycle					
3.1	Carbon footprint	3	kg/kg	7	4	Calculation
4.	Safety					
4.1	Hazardous approvals		binary	pass		Testing
4.2	Hygienic approvals		binary	pass		Testing
4.3	Leakproof interface		cms (cubic meter per second)	0		Testing
5.	Cost					
5.1	Product material cost	4	SEK per unit	95	70	Calculation
6.	Material					
6.1	Ensure no condensation/steam build up		binary	pass		Testing and engineering assessment
6.2	Chemical resistance	4	excellent/good/fair/poor	good	excellent	Testing and material specifications
6.3	Absorption of microwaves in lower focal point but not elsewhere. (if there is a design that has focal points, otherwise not needed)	2	excellent/good/fair/poor	good	excellent	Testing and engineering assessment
6.4	Reflective to microwaves	4	excellent/good/fair/poor	good	excellent	Testing and engineering assessment
6.5	Transparency to microwaves	5	excellent/good/fair/poor	good	excellent	Testing and engineering assessment
6.6	Operating service temperature		°C	≥ 480		Material selection
7.	Operating Conditions					
7.1	Handle ambient temperature in tank (below the interface)	5	°C	420	480	Testing and simulations
7.2	Ensure safe operating temperature for the radar chip (above the interface)		°C	87.5		Testing and simulations
7.3	Handle pressure from tank (below)	5	bar	50	208	Testing and simulations

Figure 6.14: Final Specifications.

7

Evaluation and Discussion

This chapter presents the assessment of methodology and outcomes and an overall discussion of the project. It aims to provide a nuanced view of the project, discussing both challenges and successes.

7.1 Project Task

To get a grasp of microwave technology, the team had to go through a substantial initial literature study on the workings of level measurements and how microwaves benefit in non-contacting scanning propagation instead of a probe-guided wave radar. Moreover, there are no existing solutions such as scanning radar in level measurements which was still challenging to look for out-of-the-box solutions in automotive, aerospace, etc.

Although the project phase was more focused on the mechanical aspects such as material selection and design of the interface, still the microwave background was equally important for making a final product that works. For instance, even if a material was suitable in the aspect of the strength of materials (pressure) it also needed to fulfil certain criteria regarding microwaves such as transparency, thus adding the extra step of ensuring a good solution from not only a mechanical aspect but a microwave aspect as well.

7.2 Project Approach

The pre-study of the project was not based on a customer needs analysis, it could have been beneficial if an analysis was conducted based on customer and user experiences during the thesis project with interviews or workshops. Now, the results from the final requirements specification might have been biased by the team and Emerson due to the lack of personal customer feedback and opinions.

Any of the elimination stages would have benefited from a criterion on life span, as that will affect both the environmental and economic aspects when choosing a concept, and this was something considered but never added. The reason was that it was hard to determine and even compare the life spans of different concepts without any testing over longer periods. Furthermore, the specific scenarios in which the interface will be replaced will affect the life span. This does not only refer to high-temperature or high-pressure but to the contents that will be measured as they can decrease the life span of the interface. For example, there can be contents that can cause abrasion or chemical contents that can cause deterioration.

The project only utilised one source when evaluating and selecting materials. A better way could have been to use several sources. This would most likely expand the amount of materials available but also increase the validity that the information used was correct as it was verified by more than one source. However, the resources available to the project only included one material database and the time limitation made an additional manual search, without a database, too time-consuming.

7.3 Project Results

One big setback was that no final prototypes in the right material could be delivered in time, thus the planned testing in the application environment as well as for safety

and user-friendliness could not be conducted.

One of the greatest achievements of the project was that the final concept was one interface that could be used in both high-pressure and high-temperature and as a result, fewer resources will be used during production as only one production process is needed instead of two. This also results in a more attractive product for the customer as it is multi-functional.

Furthermore, the shape of the interface significantly affects the microwave paths, irrespective of the thickness of the material. The lens plays a crucial role in determining the field of view and both a diverging and covering lens is not suitable as it can reach a rather low FOV below the requirements of the interface. Hence, a flat interface or slightly conical interface was the only option left and out of these two, a conical one was prioritized because it ensured no condensation build-up on the interface that potentially could have affected the measurements.

The final FOV ended up being 45° instead of the 59° that was set in the target specification. But because of the trade-off between FOV and absorption of microwaves, explained in 6.1.1, the lesser FOV was judged to be a better option than more absorption. This is because more absorption would lead to less accuracy of the measurements and having a wide FOV but with very low accuracy was assessed to be worse than having a somewhat smaller FOV with high accuracy. Having good accuracy is important for several reasons, for example, measuring the fill level accurately can guarantee that the system will alert when the maximum fill level is reached before any overflow and possible leaks happen that could harm equipment and/or people.

7.4 Social, Ethical and Ecological Considerations of the Project

The development of an interface and a scanning radar system that can be used in high-pressure and high-temperature environments will allow for further development in other research areas that before could not be studied or analysed with current technology. Furthermore, The advancement in developing the interface fosters innovation and can create job opportunities in engineering, design and manufacturing. Moreover, the development of the interface also leads to the growth of the company and respective clients and contributes to an overall technical advancement in society.

The improvement will also increase safety and efficiency in various industrial applications and its durability in harsh environments will minimise the likelihood of any issues that can cause hazards to humans. Another aspect of safety that relates to the ethical implications of the interface is the material selection. Aluminium oxide was partly picked because it is non-toxic both during use and production which was an issue with many other suitable materials.

The material selection was also done considering their environmental impact. Aluminium oxide which makes up the majority of the interface is recyclable which

ensures that the material can be used even after it has served its time in the measurement system. Having one interface, that can be used for both high-pressure and high-temperature applications, instead of two makes a positive impact on resources as one less component has to be made.

8

Conclusion and Recommendations

This final chapter summarises the culmination of the project and presents the conclusions in regards to objectives and overall purpose providing an overview of the project and key insights. This is followed by recommendations that aim to guide any future development of the project.

8.1 Conclusions related to objectives

The conclusion of this project directly relates to how well each objective and overall purpose. These objectives that were set at the beginning of the project were based on the assumption that two interfaces would be the final result one for high-pressure and one for high-temperature. However, the actual result was one interface suitable for both scenarios.

Objective 1:

- Two physical interfaces that can be utilised in a non-contacting scanning microwave radar solution in industrial environments.

This objective is concluded to have been fulfilled as the final solution is compatible with the phased array technology that provides a scanning measurement.

Objective 2:

- One interface that can withstand varying and high pressure and one interface that can withstand varying high-temperature conditions.

Simulations and material properties point to no issue handling either high-temperature or high-pressure. This objective is therefore deemed fulfilled even though it has not been concluded by testing.

Objective 3:

- Two interfaces that are transparent to microwaves as well as reflective to ensure accurate measurements. Depending on the design, the interfaces should also provide absorbency in the lower focal point but not elsewhere.

The material selection is according to material properties and testing suitable as they provide both a transparent base material and a reflective coating and ensure accurate measurements. Moreover, because of the almost flat design, there is no lower focal point and thus no absorbent part of the interface and the objective is overall fulfilled.

Objective 4:

- Two scalable and cost-effective solutions that align with Emerson's production processes ensuring feasibility for large-scale production across industrial facilities.

The estimated price of the material per part is below the target value however this price is an estimation and is only based on the cost of the base material and industrial standard, thus this could change depending on the supplier and processing. Secondly, the result of one interface instead of two is deemed very cost-effective as it can be used in several applications. As the final solution also works in both high-pressure and high-temperature environments, it will more likely be a good option for more customers as compared to an interface that works in one of the environments. As a result, the interface will more likely be produced in larger quantities, thus most

likely lowering the price per part. Therefore this objective is concluded to have been fulfilled.

Objective 5:

- Two high-quality interfaces that are intuitive and user-friendly for the microwave team facilitating ease of operation.

Due to the long delivery time on prototypes and the limited time for the thesis, no testing by microwave engineers to assess user-friendliness was conducted. As a result, it is not possible to say that this objective has been fulfilled, as it has not been verified through testing, even though the design has been evaluated by microwave engineers.

Objective 6:

- Two interfaces that comply with relevant safety standards and regulations to guarantee a safe working environment for industries and mitigate potential risks associated with radar technology.

The interface has been designed with a safety factor considered both for high-pressure and high-temperature, thus some information points to the solution being safe. However, only simulations have been conducted and further testing on longer time periods and different contents should be conducted to guarantee a safe working environment. As a result, this objective is concluded to not have been fulfilled.

8.2 Recommendations

As the project had a limited timeframe, not all beneficial methods and processes could be conducted. Therefore there are some recommendations that could be considered during potential future work.

Firstly, some processes that were planned to be executed were not conducted because of the limited time and long delivery times on prototypes. As a consequence, the first suggestion is to make a final prototype in the correct material and test it rigorously. This should include safety testing in both high-pressure and high-temperature environments with a range of different contents to be measured as well as assessing user-friendliness.

Additional future work that would be beneficial to do is a Life Cycle Assessment. An LCA would provide a comprehensive evaluation of the environmental impacts of the interface through its whole life cycle. This would include effects from manufacturing, raw material production, distribution, use and end-of-life. This could help identify possibilities and challenges from an environmental perspective, there could for example be raw material production that produces more or less greenhouse emissions or different ways of recycling that utilise less energy.

Lastly, looking into how to integrate the interface in the measuring system and how to connect the interface to the tank itself is a crucial step that should be conducted. As of now, it is only decided that it should be fastened by welding and there are

8. Conclusion and Recommendations

endless ways to design a frame that attaches to the tank and that the interface could be welded into. During this development, it would be very important to consider how this frame affects both structural integrity and heat transfer.

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