



CHALMERS
UNIVERSITY OF TECHNOLOGY



Towards A Product Development Handbook for Ultra-Low Temperature Hardware in Quantum Computers

Investigating Stakeholder Needs, Materials, and Simulation Processes for MilliKelvin Quantum Computing Hardware

Master's thesis in Product Development

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Cover: Showing a sample holder with a protective shield and a sample holder with-
out the protective shield side-by-side made for a quantum computer designed by
SCALINQ.

Gothenburg, Sweden 2023

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Abstract

The development of the quantum computing industry has received significant attention and investment in recent years, providing an opportunity for the industry and its stakeholders to develop new solutions. The quantum bits used for computation in quantum computers are extremely sensitive to external noise and interference. Therefore, the quantum bits are placed in a cryogenic refrigerator, which uses protective shields to remove external noise such as radiation, with high levels of vacuum and ultra-low temperatures to eliminate as much interference as possible from ambient noise and thermal fluctuations. The extreme conditions place high demands on the hardware used in quantum computers, both to withstand ultra-low temperatures and to minimise interference with the quantum bits.

The project was carried out in collaboration with SCALINQ AB and the aim of the project was to investigate the current state of the art and its challenges in the development of ultra-low temperature quantum computing hardware. The aim was also to create the basis for a product development handbook, that includes the specific needs and wishes of stakeholders, different materials and simulation techniques.

Through a literature review of stakeholders, the primary stakeholders were identified as quantum hardware manufacturers, research institutions, customers and users, such as the operating researchers, as they have the most influence on the hardware used in the quantum computer. The primary stakeholders were interviewed to gather information about their needs for the hardware, and a complementary literature review was carried out to identify the needs of various stakeholders. The stakeholder needs were then translated into a comprehensive list of requirements. A materials study was also carried out to find materials with properties such as non-magnetic, high thermal conductivity and operating temperature of 10 milliKelvin. The materials study resulted in 21 materials proposed for further analysis as no material data was found at 10 milliKelvin. Finally, simulations were carried out to investigate the capability of the Ansys software to simulate temperatures in the milliKelvin range. The simulations showed promise as a development and evaluation tool, but the conclusion was that further investigation and verification by physical testing were required.

Keywords: cryogenic temperatures, hardware, materials, milliKelvin, product development, quantum computers, requirements, simulation, stakeholders, ultra-low temperature.

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List of Acronyms

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

Be	Beryllium.
C	Constraint.
DR	Dilution Refrigerator.
DS	Design Solution.
ETP	Electrolytic Tough Pitch.
FR	Functional Requirement.
K	Kelvin.
mK	milliKelvin.
MXC	Mixing chamber Flange.
OFHC	Oxygen-Free High-Conductivity.
PCB	Printed Circuit Board.
RF	Radio Frequency.
RRR	Residual Resistance Ratio.
QIP	Quantum Information Processing.

Nomenclature

Below are the nomenclature parameters and variables that have been used throughout this thesis.

Parameters & Variables

e	Electron charge.
k_B	The Boltzmann constant.
m	Mass of an electron.
n	Number density of electrons.
ρ	Electrical resistivity.
τ	Relaxation time of electrons.
T	Absolute temperature.
V	Volume of the material.
V_{atom}	Volume of an atom.
ω	Phonon frequency.
A	Cross-sectional area.
\hbar	The reduced Planck constant.
N	Total number of electrons.
C_e	Electronic heat capacity.
C_v	Specific heat of the phonons or lattice.
L_0	Lorenz number.
L_e	Mean free path of electrons.
λ_e	Free electron thermal conductivity.
λ_p	Phonon thermal conductivity.
λ_t	Total thermal conductivity.
U_e	Mean velocity of electrons.
U	Phonon velocity.

v_F	Fermi velocity of electrons.
E_F	Fermi energy.
x	Dimensionless variable.
$\lambda(T)$	Temperature dependent thermal conductivity.
L	Length.
L_p	Mean free path of the phonon.
θ_D	Debye temperature.
k	Wave number of phonons.
f	Distribution function of the particles.
\mathbf{p}	Momentum vector.
\mathbf{F}	External force acting on the particles.
Q	Heat conduction.
R	Molar gas constant.

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1

Introduction

This chapter presents the background to the thesis, including some principles of quantum mechanics, superconducting quantum bits, cryogenics, and some challenges and obstacles. This is followed by an introduction to the company SCALINQ, with whom the thesis was carried out in collaboration, and their products. Then, the problem is stated and the purpose of the thesis and the three research questions are presented. Thereafter, the delimitations of the thesis are presented. The chapter then concludes by outlining the product development phases covered.

1.1 Background

The field of quantum computing is rapidly evolving, with significant investment by companies and research institutions in the development of new hardware and software. The recent surge in the development of different physical platforms for quantum processors is due to the potential of quantum information processing (QIP) to outperform classical supercomputers in tasks such as the simulation of quantum systems and specific algorithms such as factorisation, search and optimisation [1, 2, 3, 4]. The advantage of quantum systems over classical computers is attributed to the fundamentally different ways in which information is encoded and processed [4]. The field of quantum computing is experiencing significant progress due to the combined efforts of academic and industrial research. This has resulted in tremendous momentum, with both theoretical and experimental advances driving the transformation of quantum computing from a mathematical curiosity to a rapidly advancing field of innovation [5]. Small-scale quantum computing devices that are built on different physical implementations are currently in use in laboratories and have been developing for more than a decade. These devices have demonstrated the essential properties required for the construction of systems [6]. However, the development and manufacturing of quantum computing hardware still pose major challenges, especially regarding available information, cost and time-to-market.

1.1.1 Quantum Mechanics Used in Quantum Computing

The field of physics known as quantum mechanics is the study of the behaviour of matter and energy at the atomic and subatomic levels. It was originally developed at the turn of the 20th century to explain the peculiar and sometimes illogical behaviour of particles at this scale [7]. A fundamental principle of quantum mechanics

is superposition, which states that a particle can exist in multiple states simultaneously until it is observed or measured [8]. Superposition contrasts with conventional physics, which assumes that particles have a single, well-defined state. Another key principle of quantum mechanics is entanglement, the relationship between two particles that allows their states to depend on each other even though they are separated by a distance [9]. Superposition and entanglement have been shown to be essential to many quantum computing algorithms and protocols, but these principles can be fragile and sensitive to various types of noise from both internal and external sources. Quantum computers are particularly sensitive to temperature, as heat can cause quantum states to become unstable and decohere, leading to computational errors. To mitigate the effects of decoherence, quantum computers are cooled to ultra-low temperatures. In addition to cooling the quantum computer, it is also important to minimise the amount of noise generated by the environment, as small amounts of noise can have a significant impact on the quantum states. Other types of noise include control noise caused by errors in the timing, strength or duration of the control pulses applied. Additionally, there is readout noise caused by thermal fluctuations or electrical interference, crosstalk noise caused by qubits directly or indirectly interacting with each other, and other types of environmental noise such as electromagnetic radiation. Therefore, quantum computers are often found in specialised laboratories designed to maintain a very stable and noise-free environment in which calculations can be performed in the milliKelvin range.

1.1.2 Quantum bits

In quantum computing, quantum bits or qubits are the fundamental units of information processing. They can exist in multiple states simultaneously, allowing exponentially more information to be processed in parallel than classical bits, which can exist in only one of two states: 0 or 1. There are several types of qubits currently being explored for use in quantum computing, including Superconducting qubits, Gate-defined quantum dots, Ion traps, Colour centres, and Topological qubits [10].

Superconducting qubits rely on the properties of superconducting materials that exhibit no electrical resistance when cooled to very low temperatures or ultra-low temperatures. These qubits are currently the most widely used in the development of quantum computing hardware because they are relatively easy to fabricate and scalable. One of the most developed QIP platforms is the superconducting qubits, where state-of-the-art processors based on these qubits have been scaled up to 65 completely programmable qubits on a single chip, operated at a temperature of about 20 milliKelvin [11]. An example of a typical superconducting qubit circuit can be seen in Figure 1.1.

Promising solid-state quantum computing platforms, such as superconducting circuits [12] or charges and spins in semiconductor quantum dots [13], require ultra-low temperatures to initialise systems and avoid errors due to thermal excitation during operation [14]. These temperatures are extremely cold and close to absolute zero, the temperature at which all matter has its lowest possible energy. Absolute zero is

approximately -273.15 degrees Celsius. To put this in perspective, the temperature of outer space is about 2.7 Kelvin, which is equivalent to -270.45 degrees Celsius. In other words, 10 milliKelvin are over 270 times colder than the temperature in space. The extreme temperature to which the components are exposed places high and specific demands on the material itself, the product development and manufacturing process and its durability. Therefore, a robust cryogenic infrastructure is essential for solid-state quantum processors [14].

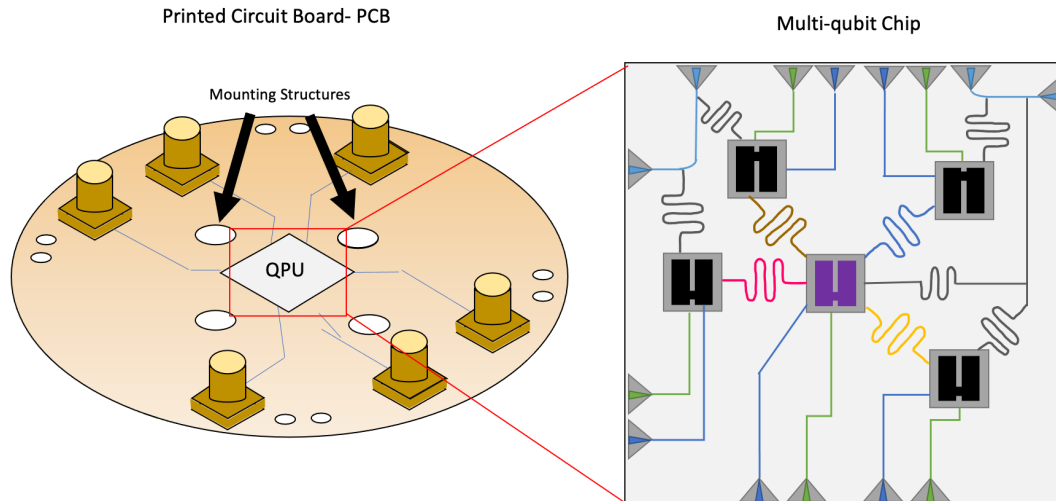


Figure 1.1: The left side of the figure shows the printed circuit board and the placement of the multi-qubit chip, which is shown to the right. The image is inspired by Gao et al. [5].

1.1.3 Cryogenics

Cryogenics is defined as the study of low-temperature phenomena but the temperature dividing refrigeration in the conventional sense and cryogenics is somewhat arbitrary [15]. The cryogenic temperature range is often defined as the temperature from 123.15 Kelvin (-150 degrees Celsius), to absolute zero (-273.15 degrees Celsius) [16]. At absolute zero the molecular motion comes as close to zero as theoretically possible to ceasing completely. At these extreme conditions, such properties of materials as strength, thermal conductivity, ductility, and electrical resistance are altered in ways of both theoretical and commercial importance [16]. Because heat is created by the random motion of molecules, materials at cryogenic temperatures are as close to a static and highly ordered state as is possible [16]. Within the cryogenics temperature range (123.15 Kelvin to absolute zero), there is a temperature interval typically referred to as *ultra-low temperatures* which are considered to include temperatures below 1 Kelvin [17]. Further, *very-low temperatures* refer to temperatures below 10 Kelvin and down to 1 Kelvin. For a clearer description of temperature ranges, see the table 1.1.

Table 1.1: The different temperature ranges of cryogenic, very-low and ultra-low temperatures.

0 Kelvin	1 Kelvin	10 Kelvin	123.15 Kelvin
Cryogenic temperature			
Very-low			
Ultra-low			

More than any other factor, including pressure, magnetic field, and electric field, temperature affects how processes perform and how materials behave [18]. There are three factors that contribute to the ultra-low temperature region's significance [18]. The first factor is that some phenomena only occur at low temperatures, such as delicate quantum mechanical effects in superconductors and semiconductors [18]. The second factor is that the specific heat of solids becomes very small below 1 Kelvin, enabling highly sensitive sensors such as bolometers. Thirdly, thermal noise is suppressed, which is important for both sensors and qubits in quantum computers [18].

The ability to understand and exploit these temperature effects has led to significant advances in civilisation [19], where ultra-low temperature techniques and refrigeration have developed rapidly for extensive application and study in quantum computing, condensed matter physics, space research instruments, astronomical observations, and ground-based experimental study of superconductivity [18, 20, 21]. There are many ways in which cryogenic temperatures are produced that are different from those used in conventional refrigeration [19]. The properties of materials and the behaviour of systems are often profoundly affected by significant temperature drops [19]. When considering the three conventional technologies for refrigeration, which include adsorption refrigeration, adiabatic demagnetisation refrigeration and dilution refrigeration, it is worth noting that dilution refrigeration stands out as the most popular option [18]. The main reasons for this are its ability to achieve ultra-low temperatures down to a few milliKelvin, the advantage of continuous cooling, which makes it ideal for applications that require sustained low temperatures, and its relatively high cooling capacity [18].

1.1.3.1 Dilution refrigerator

Dilution refrigerators achieve cooling by circulating helium and are able to provide continuous cooling down to a few milliKelvin with reasonably high cooling power without electromagnetic interference [18, 22]. The cooling method uses the properties of the helium-3 and helium-4 mixture to achieve cooling. The helium mixture is enclosed in the dilution refrigerator, which then conductively removes heat from the cryostat via copper tubes [23].

The most important components for a dilution refrigerator are its heat exchangers [24], as they determine the ultimate performance of the refrigerator [25]. The heat

exchangers, therefore, require accurate design, which is difficult due to the complicated low-temperature effects below 1 Kelvin that make conventional modelling approaches inapplicable [24]. Variable fluid properties, axial heat conduction, viscous heating and heat leakage to the environment can cause cryogenic heat exchangers to lose a significant amount of their effectiveness at low temperatures [26].

Currently, the lowest temperature reached by conventional dilution refrigerators is 1.75 milliKelvin, and the highest cooling power at 100 milliKelvin is 2 milliWatts [18]. The performance of dilution refrigerators is therefore well suited to quantum computers using superconducting circuits, as they are often operated at 20 milliKelvin [5]. However, the ability to cool is not the only necessary function of a dilution refrigerator, careful shielding and filtering must also be considered to minimise exposure to residual thermal noise and stray electromagnetic radiation [5]. The performance of a quantum system is highly dependent on the operating environment in which it is embedded, where an effective quantum environment must provide thorough isolation from the various sources of noise, both free space and transmission lines while allowing coherent transmission of control signals to implement fast quantum operations [5]. Vortices can be trapped in the thin-film superconductor and significantly reduce the coherence qualities when a device is cooled to 20 milliKelvin in the presence of a magnetic field stronger than 0.1 Gauss [27, 28, 29]. To mitigate the vortices, the sample is often housed in Cryoperm shields, which are made of high permeability nickel alloys and treated to ensure robust magnetic shielding properties [5], or in shields made of mu-metal, a nickel-iron alloy. It is also important to minimise the residual magnetic field within the shield by using only components made from non-magnetic materials [5].

Bluefors LD400

The Bluefors LD400 is a state-of-the-art dilution refrigerator developed for cryogenic research, which allows researchers to study a wide range of low-temperature phenomena. The LD400 is capable of delivering ultra-low temperatures down to 10 milliKelvin [30], making it well-suited for superconducting quantum computers. Furthermore, it can provide more than 15 microWatts of cooling at 20 milliKelvin on the experimental flange [30]. The experimental flange, also known as the Mixing Chamber Flange (MXC), of the dilution refrigerator has a diameter of 290 millimetres and is responsible for mixing the helium isotopes and cooling the system to ultra-low temperatures, which it is capable of doing in less than 24 hours [30]. Figure 1.2 shows a detailed view of the LD400's main components inside the cryostat, including the MXC flange. Figures 1.3 and 1.4 illustrate the typical layout of the LD400 dilution refrigerator, showing its main components and their respective locations. The schematic view in figure 1.4 provides a comprehensive overview of the dimensions of the system and highlights the need for significant laboratory space to accommodate it.

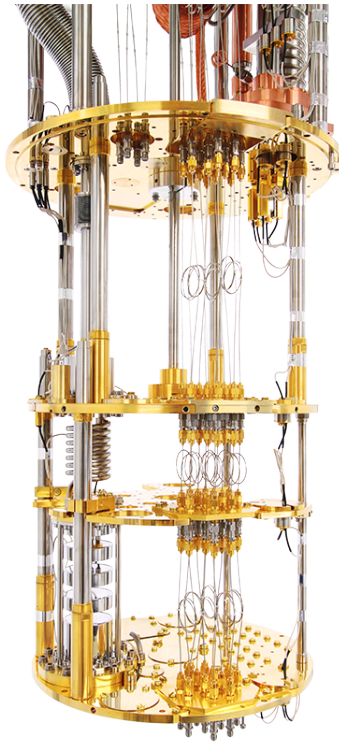


Figure 1.2: Inside view of the Bluefors LD400 dilution refrigerator. This image has been kindly provided by Bluefors and used with their permission [30].

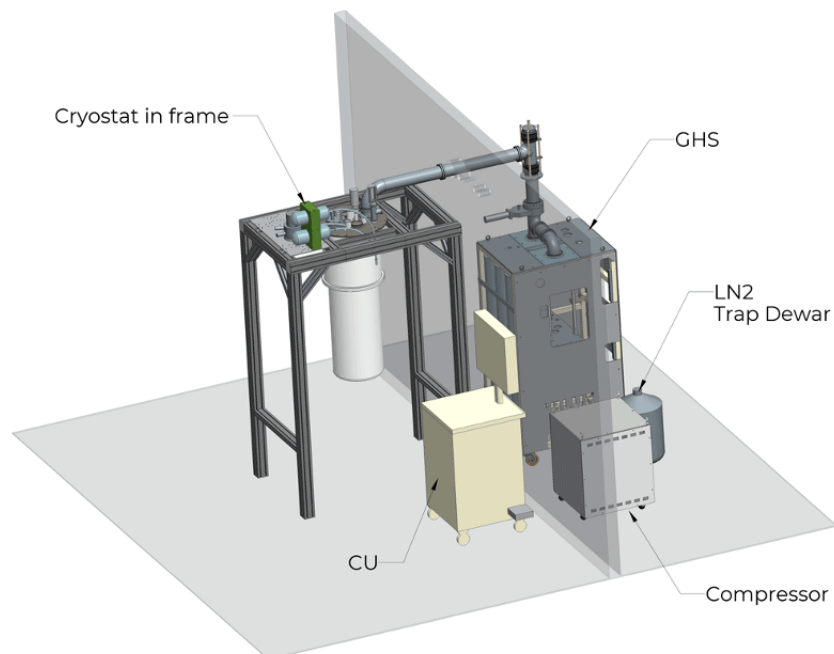


Figure 1.3: Schematic representation of the Bluefors LD400 dilution refrigerator, illustrating its typical layout and main components. This image has been kindly provided by Bluefors and used with their permission [30].

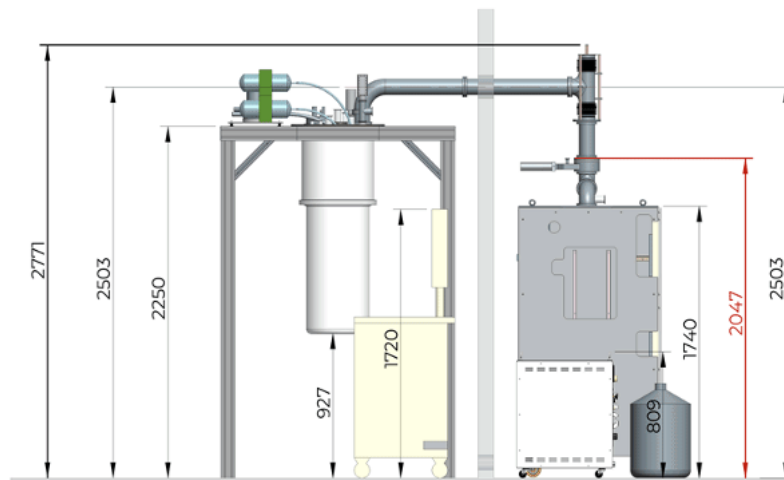


Figure 1.4: Side view of the Bluefors LD400 dilution refrigerator, showing a typical layout and highlighting important dimensions. The image has been generously provided by Bluefors and the use of this image is authorised by Bluefors [30].

The system has a variety of available shields to protect the sample from noise, whereof the standard inner shields are made from gold-plated copper [30]. Figure 1.5 shows a sectional view of the flanges, outer shield and inner shields of the LD400 dilution refrigerator. The flanges are shown in bold grey, while the outer shield is shown with a black line to distinguish it from the inner components. The inner shields, which are critical to minimising thermal radiation and achieving ultra-low temperatures, are highlighted with bold red lines for clarity. The figure shows how shields can be used, but may vary depending on the type of experiments and the shields required for those experiments.

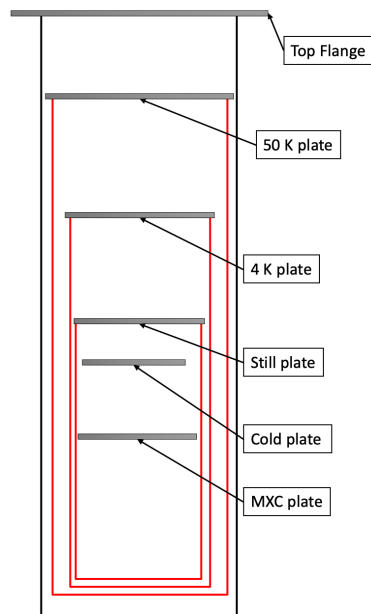


Figure 1.5: Cross-sectional view of a typical shield allocation.

1.1.4 Challenges and obstacles

While the development of quantum computers has made significant strides in recent years, there are still a number of challenges and obstacles that need to be overcome before developing useful, scalable quantum computing hardware.

The main challenge is to create a quantum computing system on a larger scale. The motivation for scaling up quantum computers is to be able to have more qubits per computer, increasing the computing power, speed and range of problems that can be solved. As mentioned in Section 1.1.2, the current state of the art has been scaled up to 65 fully programmable qubits on a chip, and in order to scale up further, the challenges of hardware development that can accommodate more qubits and cables need to be overcome. As mentioned by Xiong et al. [11], if superconducting quantum circuits follow Moore's law, the number of qubits will reach 1 million in the next 10 years. In addition, according to Van Meter et al. [6], general-purpose quantum computers capable of efficiently solving difficult problems will be physically large, comprising millions or possibly billions of qubits in distributed systems. In order to design larger quantum computers, it should be recognised that larger systems are not simply larger versions of small systems, and instead, the conceptual stack of subfields must all contribute to achieving a quantum computer of scale [6].

However, a more immediate challenge is to be able to scale up to hundreds or thousands of qubits, which will require new approaches to hardware, fabrication and control. In addition, the integration and further improvement of the quality of the qubits is an issue that needs to be considered at this stage. In the case of limited refrigerator space and cooling capacity, the miniaturisation of quantum chips and cryogenic circuits is a more rational choice [11].

To realise large-scale systems based on these technologies, it will be necessary to achieve much lower error rates on a scalable platform than have been demonstrated to date. These activities will require major advances in materials science and engineering, new fabrication and synthesis techniques, and new measurement and materials analysis techniques [10]. However, there has been relatively little research into applying the methods of materials science to improve and scale quantum hardware beyond material selection. Rather than directly measuring and addressing the limitations of the underlying material systems, most work to date has focused on developing quantum control schemes and device architectures that avoid sources of noise, loss and decoherence [10].

1.1.5 SCALINQ

SCALINQ is a company specialising in the development and production of advanced hardware for quantum computing [31]. The field of quantum computing is developing rapidly, and one of the key challenges facing the industry is the need for specialised hardware that can operate at ultra-low temperatures, close to absolute zero (Z. Saeed, personal communication, 17 January). SCALINQ is founded by researchers at Chalmers University of Technology and focuses on overcoming the challenges of increasing the number of qubits in a superconducting quantum computer.

To overcome these challenges, SCALINQ is developing novel hardware solutions that make it easier to build and improve quantum computers. The technology used is specifically designed to provide high-density solutions that enable scalable and more powerful quantum computing. SCALINQ provides its solutions to research institutes and quantum computing companies worldwide. One product that SCALINQ offers is their sample holder called LINQER, which can be seen in Figure 1.6. The LINQER is currently offered in four different versions with up to 16, 36, 52 and 80 connectors [31]. The number of connectors relates to the number of cables necessary by the customer which indirectly correlates to the number of qubits. The project is mainly based on these four versions of LINQER but an effort is put into making the methods and results fitting for a wider base of ultra-low temperature hardware for quantum computing.



Figure 1.6: SCALINQ’s sample holder LINQER, with shielding installed on the left and without on the right. The image also shows where the printed circuit board is located inside the LINQER. The image has been generously provided by SCALINQ and the use of this image is authorised by SCALINQ [31].

The sample holder plays a crucial role in quantum computing as it facilitates the connection between the external components and the superconducting qubits. The primary function of the holder is to provide a stable and secure platform to house the qubit while allowing easy access and manipulation. To achieve easy access and manipulation, the LINQER includes a printed circuit board (PCB) specifically designed to hold and connect the superconducting qubit chips. The PCB is carefully installed in the lower part of the sample holder where it is connected to the necessary cables and wiring. In addition to providing a secure housing and interconnection platform for the qubits, the sample holder has the critical function of providing an optimal operating environment for the qubits. The sample holder is able to provide the optimal environment through the use of a dilution refrigerator, where the

sample holder conductively transports heat from the PCB, superconducting chips and cables to the dilution refrigerator. By conducting the heat, the superconducting qubits are maintained at the ultra-low temperatures required for them to function properly. The sample holder, together with the PCB and chips, is carefully installed in the dilution refrigerator to ensure that the qubits are exposed to ideal operating conditions. Figure 1.7 shows how the LINQER is installed in a dilution refrigerator.



Figure 1.7: SCALINQ’s LINQER on the left and a depiction of its installation in a dilution refrigerator on the right. The image is generously provided by SCALINQ and the use of this image is authorised by SCALINQ [31].

1.2 Problem statement

SCALINQ believes there is a significant gap in the availability of consolidated information, guidelines and comprehensive data on the development of hardware for ultra-low temperature environments. Without such resources, the process of engineering and manufacturing quantum computing hardware becomes more difficult and time-consuming. However, if a comprehensive set of information, guidelines and data were available, SCALINQ could use it to establish a standardised process for developing its products. Not only would it save time and resources, but it would also increase the efficiency and consistency of their hardware development process,

ultimately leading to better products for their customers. There is therefore a need to create a comprehensive product development handbook for ultra-low-temperature hardware. The handbook should outline the specific requirements that the materials, manufacturing processes and simulations must meet, taking into account the specific needs and expectations of customers and industry stakeholders. By including such requirements, the handbook can help to ensure that the developed hardware meets stakeholders' needs and is fully optimised for its intended use. Furthermore, the handbook should provide detailed information on suitable materials and simulation techniques for the development of hardware capable of operating at ultra-low temperatures according to the requirements.

1.3 Purpose & Research questions

The purpose of the thesis is to investigate the current state of the art and its challenges in the development of ultra-low temperature quantum computing hardware. In doing so, the thesis seeks to push the current boundaries and expand the frontiers of knowledge by thoroughly investigating different materials and simulation techniques. Furthermore, the purpose of the thesis is to identify the specific needs and requirements of customers and industry stakeholders for the hardware. Ultimately, the aim is to provide SCALINQ with the information and knowledge required to create a comprehensive product development handbook for ultra-low temperature quantum computing hardware. To achieve this purpose, the following research questions have been addressed.

RQ1: *What are the current challenges and gaps in product development for ultra-low temperature hardware in quantum computing and how can they be addressed?*

RQ2: *What are the most critical factors and parameters for product development, materials, and simulation of ultra-low temperature hardware for quantum computing?*

RQ3: *What are the key requirements and wishes of customers and industry stakeholders in the field of ultra-low temperature hardware for quantum computing?*

1.4 Delimitations

Through the course of the project, a number of limitations were identified that needed to be addressed. It is important to note that these limitations do not detract from the overall conclusions of the study, but rather serve to highlight areas for further research.

First, the research was limited to a specific type of quantum computer, a superconducting quantum computer, and the results may not be applicable to other types of quantum computing systems.

Second, the scope of the study was limited to a specific dilution refrigerator, the Bluefors LD400, due to its current use by both Chalmers University of Technology and SCALINQ. Therefore, the results may not be applicable to other cooling techniques.

Third, the hardware is limited to the structural components of quantum computing hardware and does not include the electrical components, which are also a critical part of the overall system. This decision was made due to the complexity and breadth of the field of quantum computing and the need to focus on a specific area in order to provide a comprehensive and in-depth analysis.

Fourth, the research focused on the thermal and mechanical properties of the hardware at low temperatures but did not include other factors such as electrical conductivity and susceptibility to magnetic fields within the simulations. Although these factors are important in quantum computing applications, they were outside the scope of the work.

Finally, the scope of the research is limited by the availability of software and resources through Chalmers University of Technology. This limitation means that other software and resources will not be considered for the conduct of this study. This limitation may have an impact on the potential results and limitations of the research, as certain tools or techniques that could have been used to improve the results may not be available.

1.5 Product Development Phases Covered

The thesis will cover several important aspects of product development for ultra-low temperature hardware for quantum computing. First, a functional analysis of the product LINQER will be conducted to identify the functions that the product must be able to perform, which is done by breaking down the product into its individual components and identifying all necessary functions. The functional analysis could be considered as the second product development phase in sequential order covered in the thesis, as visualized in Figure 1.8 as the second vertical bar.

Thereafter, stakeholder analysis will be performed in order to identify and analyse the stakeholders of the LINQER. The analysis will intend to understand the stakeholder's needs and wishes and then translate them into requirements to ensure that the product meets the stakeholder's expectations. The stakeholder identification and analysis could be considered as a parallel process, as visualised in Figure 1.8, due to the importance of considering the voice of the stakeholders throughout the product development process. The identification of stakeholder needs and wishes was added as a vertical bar as well to point out the importance of this product development phase and visualise its sequential order in the product development process.

Opportunity identification, a key aspect of the thesis, will then be undertaken. The opportunity identification performed will intend to identify potential development

issues or opportunities that may arise during the product development process. The phase can therefore be seen as a parallel process, as visualised in Figure 1.8, due to the importance of constantly identifying potential opportunities and issues.

Furthermore, a materials study will be conducted to identify fitting materials for the product based on the stakeholder's needs and wishes. The materials study is considered to be the third, in sequential order, of the product development phase covered in the thesis as it is dependent on the stakeholder expectations and the functions that the product needs to perform.

Finally, a case study demonstrating how simulation and verification can be performed will be conducted. The phase of simulation and verification is further an important part of the product development process as it verifies if the product meets the stakeholder's expectations. The phase could be considered as a later part of the product development process and as visualised in Figure 1.8 it is the final part covered in the thesis.

It should be noted that the thesis will not cover all parts and phases of product development and the different parts of product development covered were due to SCALINQ's request for research in these areas. Additionally, knowledge in the industry regarding these parts is still limited, and the thesis aims to contribute to the development of knowledge in the field.

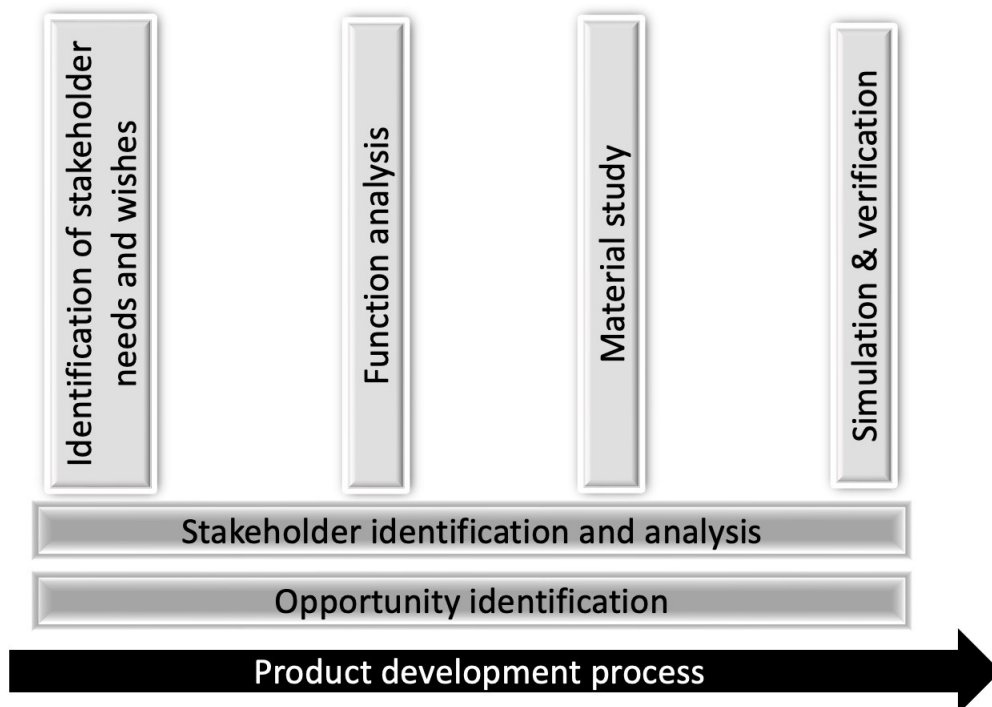


Figure 1.8: Overview of the product development process covered for the thesis.

2

Theory

The following chapter introduces some of the important theories and formulas used in the thesis. The theories and formulas are related to product development, heat transfer and thermal conductivity.

2.1 Product Development

The product development process involves a series of steps that transform inputs into outputs. Physical processes are commonly understood, but product development processes include intellectual and organisational activities [32]. Individual organisations may have their own unique development processes, and multiple processes may exist within a single organisation. Figure 2.1 shows what a generalised product development process can look like and includes a suggested sequence of product development phases from Ulrich et al. [32]. The following section explains some of the theories of product development, including the concept of opportunity identification, stakeholder needs and requirements specifications.



Figure 2.1: Typical process flow diagram for a generic product development process inspired by Ulrich et al. [32].

2.1.1 Opportunity identification

Within the planning phase of product development, as visualised as the first phase in Figure 2.1, the opportunity identification process is carried out. An opportunity in the context of product development refers to new product ideas and are assumptions of value creation in an environment of uncertainty and may take different forms [32]. Opportunities can emerge from a perceived need, through technological advances, or through the identification of a need with a potential solution [32]. The opportunities are typically stated concisely, often with descriptive titles, and may sometimes be illustrated with a product sketch [32]. Identifying and selecting a number of opportunities for further development is essential since only a small number will proceed to full product development [32]. Before formal product development is initiated, exploratory activities, such as prototyping, are often used to assess the feasibility

and potential of different opportunities. Such activities enable the evaluation of multiple alternative opportunities, where only the most promising proceed to full development [32]. Ulrich et. al [32] present a scheme that helps developers to categorise the opportunity by using the team’s current understanding of the need and the solution associated with the opportunity, as shown in Figure 2.2.

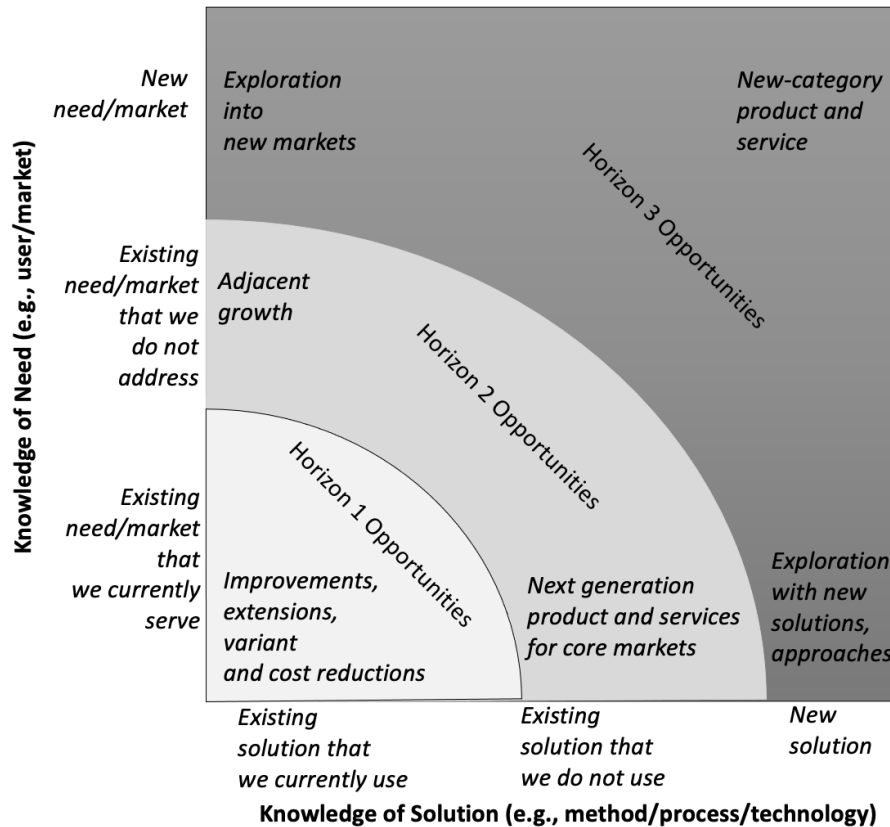


Figure 2.2: Types of opportunities where increasing horizons represent increasing levels of risk, reflecting different types of uncertainty. Figure inspired by Ulrich et al. [32] categorisation of opportunities.

Ulrich et al. [32] also provide a systematic approach to opportunity generation and screening. The structure for the opportunity identification includes six steps, which are as follows:

1. Establish a charter.
2. Generate and sense many opportunities.
3. Screen opportunities.
4. Develop promising opportunities.
5. Select exceptional opportunities.
6. Reflect on the results and the process.

2.1.2 Stakeholder Needs

The second phase of the product development process includes the concept development phase, as shown in Figure 2.1. Within this phase, Ulrich et al. [32] propose to start by identifying stakeholder needs, as shown in Figure 2.3.

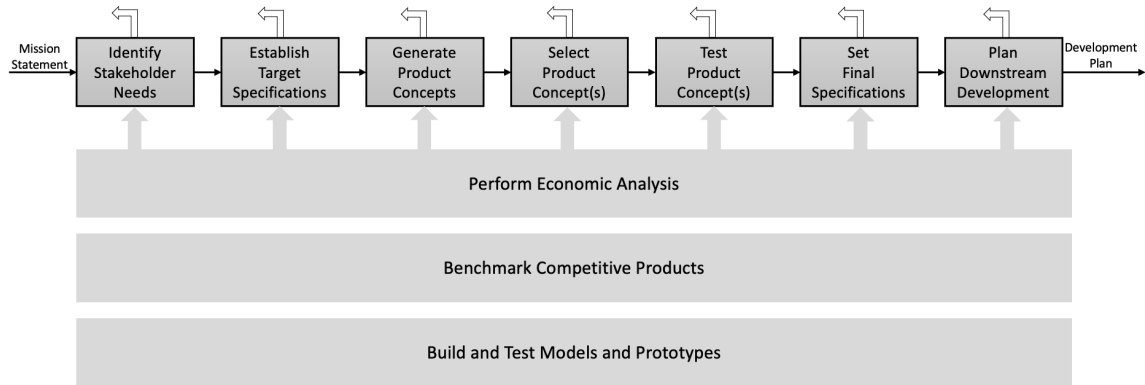


Figure 2.3: The various front-end activities involved in the concept development phase, inspired by Ulrich et al. [32].

The aim of this step is to understand the stakeholder’s needs and to communicate them effectively to the developers. The outcome of the step is a collection of thoughtfully compiled stakeholder needs statements, hierarchically organised according to their importance [32]. Emphasis should also be placed on identifying latent needs which are needs that are difficult for stakeholders to express and that are not currently addressed by existing products. The approach is based on the principle that the developers who are directly controlling the details of the product need to communicate with stakeholders and understand the environment in which the product will be used. Without this first-hand interaction, important stakeholder needs may go unrecognised, technical trade-offs may not be properly addressed, and innovative solutions to stakeholder needs may not be discovered [32].

According to Ulrich et al., the process of identifying stakeholder needs is an essential part of the product development process and is closely tied to the identification of opportunities and the creation of requirements specifications [32]. In order to carry out the essential process of identifying stakeholder needs, Ulrich et al. [32] have developed a structured approach consisting of five steps, which are as follows:

1. Gather raw data from stakeholders.
2. Interpret the raw data in terms of stakeholder needs.
3. Organise the needs into a hierarchy of primary, secondary, and (if necessary) tertiary needs.
4. Establish the relative importance of the needs.
5. Reflect on the results and the process.

2.1.3 Requirement Specification

Within the concept development phase, the second process is to establish a target specification, as shown in Figure 2.3. The term "requirements specification" refers to the precise description of what the product must do in terms of the required functionality. Other terms are often used, such as "product requirements", "engineering characteristics", "specifications", "technical specifications" and "target specification", but they all refer to the main design variables of the product [32]. Specifications are created after stakeholder needs have been identified, and each specification consists of a metric and its corresponding value, as opposed to needs, which contain only a metric or a statement [32].

Stakeholder needs are generally expressed in the "language of the stakeholder" and are helpful in understanding the stakeholder's interests [32]. However, they do not provide concrete instructions for product design and engineering. The lack of concretisation can lead to subjective interpretation and development teams therefore commonly create a set of specifications that provide precise and measurable details of the required functionality of the product. These requirement specifications do not dictate how stakeholder needs are to be met, but they do serve as a clear guideline for the team's objectives in meeting those needs [32]. Ulrich et al. further provide a four-step method for the process of creating a requirements specification, which is as follows:

1. Prepare the list of metrics.
2. Collect competitive benchmarking information.
3. Set ideal and marginally acceptable target values.
4. Reflect on the results and the process.

2.2 Heat Transfer

Heat transfer has a fundamental importance in many areas of physics and engineering, from thermodynamics and materials science to environmental engineering and industrial processes. It involves the study of how thermal energy is transferred between bodies or regions due to temperature gradients. Understanding heat transfer mechanisms is necessary for developing efficient thermal systems, predicting temperature distributions and optimising heat exchange processes. The thesis will explore the topic of heat transfer with a particular focus on conduction.

2.2.1 Heat Conduction

Conduction is the transfer of heat through solids when there is a temperature gradient and energy is transferred from an area of higher temperature to an area of lower temperature. The solution for heat conduction is based on the empirical expression known as Fourier's law, written as follows:

$$Q = -\lambda(T) \cdot A \cdot \frac{\partial T}{\partial x} \quad (2.1)$$

wherein $\lambda(T)$ is the temperature dependent thermal conductivity of the material, A is the cross-sectional area and $\frac{\partial T}{\partial x}$ is the temperature gradient across the material [33]. The equation 2.1 can be modified to include the length L of the conductor and the steady-state temperatures T_1 and T_2 and is given by:

$$Q = \frac{A}{L} \int_{T_1}^{T_2} \lambda(T) dT \quad (2.2)$$

2.3 Thermal Conductivity

To change the heat transfer of an object by conduction, the dimensions of the object could be changed, the temperature gradient could be altered or the thermal conductivity could be changed, as seen in equation 2.2. For the project, the product's dimensions had already been set and the operating temperature of the dilution refrigerator determined the temperature gradient. However, the thermal conductivity could be changed to optimise heat transfer and depends heavily on the material used. At ultra-low temperatures, accurate calculation of thermal conductivity is difficult due to the low energy of the particles involved. The following section will present the theory behind calculations of thermal conductivity at ultra-low temperatures used in the thesis and the use of the Boltzmann transport equation and the Wiedemann-Franz law.

The total thermal conductivity is given by the sum of two components. The first component is the free electron thermal conductivity and the second component is the phonon thermal conductivity and are given by:

$$\lambda_t = \lambda_e + \lambda_p \quad (2.3)$$

where λ_t is the total thermal conductivity, λ_e is the free electron thermal conductivity, and λ_p is the quantised lattice vibrational phonon thermal conductivity [34].

2.3.1 Free Electron Thermal Conductivity

Free electron thermal conductivity refers to the thermal conductivity contributed by the motion of free electrons in a material [35]. Materials with high electrical conductivity, such as metals, free electrons can transport thermal energy through random motion and collisions with other electrons, lattice vibrations and impurities, making λ_e much greater than λ_p for most pure metals [36]. The following formula can be used to calculate the free electron thermal conductivity (λ_e):

$$\lambda_e = \frac{C_e \cdot U_e \cdot L_e}{3} \quad (2.4)$$

In the equation, C_e is the electronic heat capacity, U_e is the mean velocity of the electrons and L_e is the mean free path of the electrons between collisions [34]. These

parameters are essential for understanding the behaviour of the electrons and for determining their contribution to the thermal conductivity.

The electronic specific heat of the electrons is defined as the ratio of the part of the heat taken up by the electrons to the increase in temperature of the system [37]. The electronic heat capacity, also called the electronic specific heat per unit volume, can be calculated as follows:

$$C_e = \frac{\pi^2 \cdot n \cdot k_B \cdot T}{2 \cdot E_F} \quad (2.5)$$

where n is the number density of electrons, k_B is the Boltzmann constant, T is the absolute temperature and E_F is the Fermi energy [38]. The number density (n) refers to the number of electrons per unit volume in a material and is often expressed as the electron density, which is the total number of electrons divided by the volume of the material. The number density is expressed as:

$$n = \frac{N}{V} \quad (2.6)$$

where N is the total number of electrons and V is the volume of the material [39].

At absolute zero, the electrons in a solid occupy the lowest energy state, known as the ground state. As these states are filled, the electrons occupy progressively higher energy levels until they reach a boundary known as the Fermi level. The energy associated with this highest occupied level is called the Fermi energy. The Fermi energy from the equation 2.5, can be calculated using the following formula:

$$E_F = \frac{\hbar^2}{2 \cdot m} \cdot \left(\frac{3 \cdot \pi^2 \cdot n}{V_{\text{atom}}} \right)^{\frac{2}{3}} \quad (2.7)$$

where \hbar is the reduced Planck constant, m is the mass of an electron and V_{atom} the volume of an atom [38].

The mean free path, L_e in the equation 2.4, is the average distance an electron can travel before colliding with impurities, defects or lattice vibrations [40]. It can be related to the relaxation time and the Fermi velocity by the following equation:

$$L_e = v_F \tau \quad (2.8)$$

where v_F is the Fermi velocity and τ is the relaxation time of the electrons [38]. The Fermi velocity (v_F) is the velocity of electrons near the Fermi level and determines the rate at which electrons respond to an applied electric field [41]. The Fermi velocity can be obtained by using the following formula:

$$v_F = \frac{\hbar}{m} \left(\frac{3\pi^2 n}{V} \right)^{1/3} \quad (2.9)$$

wherein \hbar is the reduced Planck constant, m is the mass of the electron, n is the number density of the electrons, and V is the volume of the material [42].

There are two simplifications that can be applied to the above equations. The first is that the mean velocity of the electrons (U_e) can be assumed to be equal to the Fermi velocity (v_F), and the second is that the relaxation time of the electrons (τ) can be expressed as [38]:

$$\tau = 3 \times 10^{-14} \quad (2.10)$$

To further explore the relationship between thermal conductivity and electrical resistivity, the Wiedemann-Franz law can be introduced. The law provides a correlation between the two material properties [43]. Following the Wiedemann-Franz law, the product of the electron thermal conductivity (λ_e) and the electrical resistivity (ρ) is proportional to the Lorenz number (L_0) and the absolute temperature, (T), as can be seen from the following equation:

$$\lambda_e \cdot \rho = L_0 \cdot T \quad (2.11)$$

where ρ is the electrical resistivity and L_0 is the Lorenz number [43]. The Lorenz number is given by:

$$L_0 = \frac{\lambda_e \cdot \rho}{T} = \left(\frac{\pi^2}{3}\right) \cdot \left(\frac{k_B}{e}\right)^2 \cdot T \quad (2.12)$$

where k_B represents the Boltzmann constant, e is the electron charge and T is the absolute temperature [36].

By calculation of the free electron thermal conductivity, the thermal conductivity for materials with high electrical conductivity, such as metals, can be solved, since their main component of thermal conduction is the free electron thermal conductivity [36]. As materials, including metals, will be studied for their thermal conductivity throughout the project, it is considered necessary to understand the theory behind thermal conductivity.

2.3.2 Phonon Thermal Conductivity

The second component of the total thermal conductivity is due to phonon conduction, where the quantised vibrational modes are treated as quasi-particles. The phonons collide with each other, similar to molecules in a gas, and therefore the thermally excited solid can be treated as a gas full of phonons [36]. As mentioned by Strandberg [36], dielectrics, such as ceramics and polymers, transfer energy mainly by phonon conduction. The following equation defines the expression for the phonon thermal conductivity:

$$\lambda_p = \frac{C_v \cdot U \cdot L_p}{3} \quad (2.13)$$

where C_v is the specific heat of the phonons also called the lattice specific heat, U is the phonon velocity and L_p is the mean free path of the phonon between collisions [34]. The Debye model can be used to calculate the heat capacity (C_v) in the

equation 2.13. The Debye model gives an expression for the heat capacity of a solid as a function of temperature as follows:

$$C_v = 9R * \left(\frac{T}{\theta_D}\right)^3 * \int_0^{\theta_D/T} \frac{x^4}{(e^x - 1)(1 - e^{-x})^2} dx \quad (2.14)$$

where R is the molar gas constant, T is the temperature of the solid, θ_D is the Debye temperature of the solid and x is the integration variable [44]. The Debye temperature is usually used to evaluate the stiffness of a crystal, where the higher the Debye temperature, the greater the bond strength of a crystal [45], which provides insights into the thermal transport properties of a material. The following equation can be used to calculate the Debye temperature:

$$\theta_D = \frac{\hbar}{k_B} \left(\frac{3n}{4\pi V}\right)^{1/3} \quad (2.15)$$

where \hbar is the reduced Planck constant, k_B is the Boltzmann constant, n is the number density of atoms or molecules, and V is the volume of the solid [46].

The phonon velocity (U) determines how fast the phonons move in the material and is defined by:

$$U = \frac{\omega}{k} \quad (2.16)$$

where ω phonon frequency and k is the wave number of the phonons [46].

The final parameter in the equation 2.13 is the mean free path of the phonons (L_p), which is related to the relaxation time (τ) and the phonon velocity (U) as follows [47]:

$$L_p = U \cdot \tau \quad (2.17)$$

By calculating the phonon thermal conductivity, the thermal conductivity for dielectrics can be solved, since they mainly transfer energy by phonon conduction [36]. As materials, including dielectrics, will be studied for their thermal conductivity throughout the project, it is considered necessary to understand the theory behind phonon thermal conductivity.

2.4 Boltzmann Transport Equation

The Boltzmann transport equation is a mathematical description of the transport of particles in a material subjected to the influence of an external field, such as a temperature gradient. The equation describes the variation of the distribution function of particles with respect to time and position, taking into account factors such as scattering and collisions with other particles. The Boltzmann transport equation is defined as follows:

$$\frac{\partial f}{\partial t} + \frac{\mathbf{p}}{m} \cdot \nabla f + \mathbf{F} \cdot \frac{\partial f}{\partial \mathbf{p}} = \left(\frac{\partial f}{\partial t} \right)_{\text{coll}} \quad (2.18)$$

where f is the distribution function of the particles, \mathbf{p} is the momentum vector, \mathbf{F} is the external force acting on the particles, and $\left(\frac{\partial f}{\partial t} \right)_{\text{coll}}$ is the collision term, which considers the effects of collisions and scattering [48].

The Boltzmann transport equation can further be applied to the specific heat, in equation 2.14, to derive a different form by considering the phonon distribution and energy modes. The specific heat can be rewritten based on the Boltzmann transport equation as follows:

$$C_v = \frac{3\rho L_{e,p}}{m \cdot \mathit{integral}} \cdot \frac{1}{x_{\text{sorted}}^2 \cdot k_B} \quad (2.19)$$

In this equation, ρ represents the density of the material, $L_{e,p}$ is the particle mean free path, m is the atomic mass, and $\mathit{integral}$ is the result of the numerical integration of the integrand term in equation 2.14.

The Boltzmann transport equation provides a theoretical basis for understanding the behaviour of electrons, phonons and other charge carriers in materials. Both metals and dielectrics have unique properties that make the Boltzmann transport equation particularly useful. For metals, the Boltzmann transport equation allows the behaviour of free electrons, which are responsible for heat conduction, to be analysed, and for dielectrics, the Boltzmann transport equation helps to understand the thermal conductivity resulting from lattice vibrations or phonons.

3

Methodology

The following chapter outlines the methodology used in this thesis. According to the product development process model presented by Ulrich et al., a development endeavour should be initiated by an opportunity identification phase, followed by a concept development phase [32]. Within the opportunity identification and concept development phase, design considerations for the product platform and architecture are analysed and stakeholder needs are elicited and translated into requirements. The focus of this thesis, on the other hand, is the creation of a handbook for the development of static hardware for future quantum computers, and following the steps suggested by Ulrich et al. [32] helps to compile the information necessary for the handbook. Therefore, the method of performing a functional analysis in relation to the design considerations is described, as well as detailing how stakeholders and their needs were identified and analysed and elicited into requirements. The methods used for the two materials studies are also described, including a literature review, two calculation attempts and predictions made. Finally, the chapter concludes by presenting the methods used for simulations.

3.1 Functional Analysis

In order to gain a better understanding of what ultra-low temperature hardware is and what functions it can have, it was decided to further analyse SCALINQ's product LINQER. The LINQER was chosen because it is an appropriate example of non-electrical hardware for quantum computing and because the project was carried out in collaboration with SCALINQ. The collaboration made it possible to obtain more detailed information about the product that might otherwise have been considered confidential, leading to a better understanding of the product.

One tool that can be used to gain a better understanding of what a concept or product should achieve is the function-means tree [49]. The function-means tree can help break down a broad function into several smaller ones, making them more manageable and easier to understand, often called functional decomposition. The function-means tree can also help to come up with new ways of solving and satisfying the needs of the function [50]. The function-means tree tool was therefore considered a suitable tool to use for quantum computing hardware as they are complex and difficult to understand with multiple functions. Furthermore, the tool seemed appropriate as the quantum computing market is rapidly evolving and new solutions to old problems need to be found. Functional modelling is another tool that could

be used to gain a better understanding of the product [51], however, functional modelling was considered less efficient as it examines the flow of functions, matter and energy, whereas the LINQER does not have a flow of either functions or matter, only energy.

Using the function-means tree involves several steps. The first step was to define the main function of what is being analysed. The following step includes hierarchically breaking down that function and specifying what means could satisfy that function. Thereafter, the means need to be analysed in order to find out what functions could satisfy each means. The process is iterative until a satisfactory level is reached [50]. It is important to keep track of which mean answers which function, and which function answers which mean, and this is usually done by drawing up the functions and means and linking them together. The result of drawing up the functions, means and links usually ends up representing a tree-shaped structure.

The process of using the function tree started with a brainstorming session between the authors where each function was written down. The functions were then discussed as to which was the main function of the LINQER. The main function was then entered into the website efm-modeler [52] as the top functional requirement (FR). The website was chosen for the project on the recommendation of the project supervisor at Chalmers University of Technology. The design and components of the LINQER were then analysed to identify the means of fulfilling the function. The identified means were then established as design solutions (DS). The identified means were then analysed to identify functions that satisfied these means. The process was repeated until the authors were unable to identify any further functional requirements for the means. To simplify the process, constraints (C) were set to reduce the number of levels in the function-means tree. As the website used did not allow for constraints, they were added afterwards using Microsoft PowerPoint.

3.2 Stakeholder Identification & Analysis

Although the functional analysis performed using the function-means tree provided a good understanding of the product from the product developer's point of view, it lacked information from other stakeholders of the product and how they understood the product. When developing a product, it is important to understand the market and the stakeholders of that product, and the process is considered a critical part of product development [32]. The process helps to identify the individuals or groups that may have an influence on the success or failure of the product [32]. Therefore, understanding the stakeholders was a top priority and it was of interest to explore the point of view of other stakeholders. However, it was not known who these stakeholders were. It was therefore decided to carry out a literature study with the aim of identifying the stakeholders for ultra-low temperature hardware for quantum computers. The decision to conduct a literature review to identify stakeholders was based on the need to get a broader view than the internal research of the company SCALINQ and Chalmers University of Technology. However, it should be noted that

SCALINQ and Chalmers University of Technology were included in the stakeholder identification. In addition, SCALINQ did not provide sufficient information on stakeholders, which may be due to confidentiality but could have been because of a lack of information. By carrying out the stakeholder identification and analysis, the risk of lack of information was considered to be reduced. The process for eliciting requirements is shown in Figure 3.1.

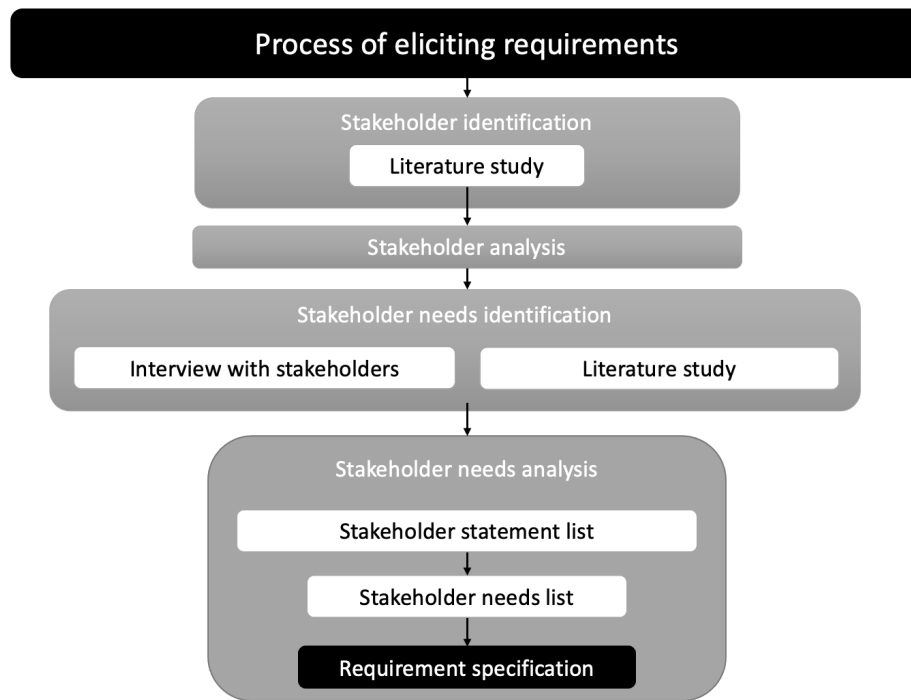


Figure 3.1: The process applied for eliciting requirements.

3.2.1 Stakeholder Identification - Literature study

The initial aim of the literature study was to identify the stakeholders for ultra-low temperature quantum computing hardware, but due to a lack of available resources, it was decided to conduct a stakeholder analysis for a complete quantum computer instead. The literature study involved a systematic review of relevant academic and industry publications to identify potential stakeholders. Several databases were used to ensure a comprehensive review, including Scopus, ResearchGate, arXiv, ScienceDirect, Google Scholar and the use of Google Search. The literature was identified using keywords such as those listed in table 3.1.

Table 3.1: Collection of the most frequently used keywords in the stakeholder literature study.

Customer	End-users	Hardware
Industry	Investors	Policy
Quantum computing	Regulatory	Researchers
Security	Software	Stakeholders
Suppliers	Ultra-low temperature	User

The possibility of publication bias for the literature study conducted was considered to be low as few publications were found on the topic. There was no specific exclusion of certain types of publications or authors, but the searches and keywords were limited to English, potentially excluding relevant information from non-English publications.

3.2.2 Stakeholder Analysis - Literature study

The main objective of the stakeholder analysis was to structure the identified stakeholders into key stakeholder groups. The aim of the study was not to produce an exhaustive list of all possible stakeholders but rather to identify the key stakeholder groups and understand how and to what extent they could influence the product or the product development process. The underlying factor behind the choice of the objective was driven by the limited information available on stakeholders. However, the approach was considered valid because it allowed a more focused analysis of the influence of each stakeholder group, compared to simply listing as many companies, groups or individuals as possible. The stakeholder analysis started with a discussion session among the authors to analyse the influence of each stakeholder. The stakeholders identified from the literature study were then classified into four groups: primary stakeholders, secondary stakeholders, tertiary stakeholders and general stakeholders. The stakeholders were classified according to their degree of influence on the product, with the primary stakeholders having the most influence, followed by the secondary stakeholders, then the tertiary stakeholders and finally the general stakeholders.

3.3 Stakeholder Needs Identification & Data Collection

With the stakeholders identified, their needs and wishes could be explored. According to Ulrich et al, [32], analysing the needs, wishes and expectations of different stakeholders allows a company to better understand them and create a product that meets their needs. In addition, the stakeholder analysis can uncover new opportunities for growth and success by leveraging the insights gained [32]. However, before the needs could be analysed, they first had to be identified and collected.

It was decided to carry out the identification and collection of stakeholder needs using two different methods. The first method was to conduct in-depth interviews with the primary stakeholder group. The decision to use in-depth interviews was based on the suggestion by Ulrich et al. that in-depth interviews should be used as the main method of data collection [32]. The decision to use interviews rather than observations and surveys was made for a couple of reasons. The first reason is related to the complexity of the industry and research area of quantum computing, and that not all stakeholders may have sufficient knowledge or expertise to provide relevant responses to survey questions or observations. The second reason was the limited stakeholder pool, as the number of stakeholders in quantum computing is relatively small, which could have led to difficulties in obtaining representative data through surveys. In order not to exclude the remaining stakeholder groups, it was decided to use an additional data collection method to identify stakeholder needs. The additional method involved all stakeholder groups, including the primary stakeholders and was performed by conducting a literature study. The following subsection presents the methodology used to carry out the two methods of identifying and collecting stakeholder needs.

3.3.1 Stakeholder Needs Interviews

The first method used to gather data on stakeholder needs was to conduct in-depth interviews with the primary stakeholder group. Due to the complexity of the industry and the limited number of stakeholders, it was important to obtain as much information as possible from the stakeholders in order to understand their needs and wishes. The interviews were therefore conducted using a semi-structured interview guide with both open-ended and closed-ended questions.

The interview guide included specific areas of interest that had been identified from the literature study as important to gain more knowledge about. The areas were: problems with the current product, use of the product, cost, improvements, performance and what information was currently desired but either difficult to find or not available. Several open and closed questions were formulated for the areas. In addition to the questions relating to the areas of interest, a question was posed about the interviewee's background where the interviewee was able to explain their knowledge and area of expertise. The reason for this question was to be able to critically analyse answers from outside their area of expertise or background.

The method of selecting interviewees varied throughout the interview process. The first two interviews were based on recommendations from SCALINQ, arguing that they had a good knowledge of the technology and were users of the product. After each interview, the interviewee was asked to recommend other people to contact. These recommendations led to interviews where the same question was asked, which led to further interviews. The method used is called snowball sampling because the number of participants in the process grows like a snowball rolling in the snow [53]. However, the method had a disadvantage in that it had a component of convenience sampling, as the recommendations often led to people with similar expertise working or researching at Chalmers University of Technology. Another method used was

to contact persons or groups of interest, some of which were authors or companies related to low-temperature hardware. The interest-based method also had a disadvantage, which was that there was little interest in participating. Another drawback that hindered further interviews was the need for SCALINQ's approval before each interview due to conflicting interests and confidentiality.

A total of eight one-hour interviews were conducted with participants who were LINQER users, quantum computing researchers, space scientists, low-temperature hardware manufacturers or SCALINQ employees. The interviews were conducted anonymously to allow the interviewee to provide as much information as possible. All interviews were conducted face-to-face, with the exception of one interview conducted on Microsoft Teams. The interviews were recorded with the interviewee's permission and transcribed for further analysis. A summary and the transcript were then sent to the interviewee to ensure that the information had been interpreted correctly and to give them the opportunity to revise their answers or clarify information that was not apparent in the answer during the interview. The aim of the interviews was to conduct them in a semi-structured manner, which resulted in the interview being tailored to the individual participant. By using a combination of open-ended and closed-ended questions, the interviews allowed for the free and open expression of thoughts and ideas while ensuring that the discussion remained focused on the predetermined topics. The approach facilitated the extraction of as much knowledge and information as possible from the interviewees.

In addition to interviewing the primary stakeholders, an in-depth interview was conducted with a professional technical writer to gather further information on how to write technical documentation and how to present complex data and information. The interview was considered to be a valid approach to present the data collected from the other interviews in an appropriate way, as the project deliverables require the development of a technical handbook. The technical writer was selected using the convenience method. As this interview had a different aim and scope compared to the other interviews, a separate interview guide was created, which was semi-structured and included both open-ended and closed-ended questions.

3.3.2 Stakeholder Needs Literature study

In order to gain a more comprehensive understanding of all stakeholder needs and the methods and techniques used by stakeholders in research and product realisation, a literature study was conducted. The aim of the study was to identify both stakeholder needs and product needs. The product needs researched related to the must-haves needed for the development of hardware used in quantum computers. It was decided to refine the product needs based on the results of the functional analysis, which resulted in four different groups of product needs to be investigated. This refinement was performed to make the literature search more precise and was used as the basis for the literature study carried out. The first group of product needs identified were those caused by the environment in which the hardware is operated. The second and third product need groups identified are related to mechanical, thermal and thermo-mechanical needs caused by mechanical stresses and

stresses caused by temperature gradients and the extreme temperatures to which the product is subjected. These groups were initially separated but were then combined due to their interdependencies. The fourth and final group of product needs were those related to joining methods, both in terms of joining the product to the dilution refrigerator and joining the components that make up the product. The aim of the study was to identify essential characteristics and data for the four different groups, which would help the future research of the thesis.

With the identified product need groups and stakeholders in mind, keywords were generated in a brainstorming session between the authors. The study was then conducted using a systematic approach to search and analyse the literature, using specific keywords related to the product need groups and stakeholders. The literature search was carried out using the online databases Scopus, ResearchGate, arXiv, ScienceDirect, Google Scholar and the use of Google Search. In addition to the online databases, physical books were searched in the Chalmers Library. The keywords used are presented in table 3.2 and were used in different combinations and searched across the different databases.

The literature was then screened for relevance based on the criterion that the literature had to be related to either quantum computing, low-temperature applications or theories of mechanics and thermodynamics. A critical evaluation of the sources used was carried out to ensure the quality of the literature study. The sources were evaluated based on their relevance, validity and reliability. The evaluation process included an analysis of the author's credentials, the journal or conference in which the research was published, and the methodology and data of the research. The selected literature was then analysed in depth to extract the relevant information in relation to stakeholder and product needs.

Table 3.2: A collection of keywords used in the stakeholder needs literature study.

Cryogenic	Cryogenic cooling	Diamagnetic
Dilution refrigerator	Engineering	Environmental requirements
Finite element analysis (FEA)	Heat conduction	Heat transfer
Heat radiation	Joining methods	Liquid-Helium temperature
Low-temperature	Low-temperature physics	Magnetic properties
Magnetic shielding	Magnetic susceptibility	Material properties
Materials	Mechanical design	MilliKelvin
Mounting of quantum hardware	Needs	Operating temperature
Opportunities	Quantum computer	Quantum computing
Quantum physics	Requirements	Space applications
Structural	Stress and strain analysis	Sub-kelvin
Superconducting	Superconductivity	Thermal conductance

Thermal conductivity	Thermal diffusivity	Thermal expansion
Thermal expansion coefficient	Thermal management	Thermal radiation
Ultra-low temperature	Vacuum	

3.3.3 Stakeholder Statements list

The extracted information from both the interviews and the literature study was organized and summarized to create a comprehensive overview of the current state-of-the-art in the field. It was decided to organize the information in a Microsoft Excel document where the exact statement from the data collection was inserted. The intent of compiling the results from the two data collection methods was to make comparison easier. Each statement was then assigned to a specific item according to which subject or theme it touched upon. The different items the statements were assigned to can be seen in Table 3.3. By assigning each statement to an item, the statement needed to be broken down, which enabled a better understanding of each statement. A column was also added for where the source came from to be able to keep track of the statements.

Table 3.3: The different items the statements were assigned to.

Cleanliness	Cost	Delivery time
Design	Dimensions	Handbook
Manufacturing	Material	Noise
Problems	Scaling up	Service life
Shielding	Simulation	Thermal
Use	Verification	

3.4 Stakeholder Needs Analysis

The following section describes the methods used to analyse and translate the raw data in the form of stakeholder statements into stakeholder needs. The method for eliciting requirements based on stakeholder needs is then described.

3.4.1 Stakeholder Needs List

As mentioned in Section 3.2, the process of identifying stakeholder needs is an integral part of the product development process. The identified needs can then be used as a high-quality channel between stakeholders and product developers [32]. A method inspired by Ulrich et al. [32] was used to translate stakeholder statements

into stakeholder needs. The process of identifying customer needs according to Ulrich et al. [32] consists of five steps. The first step is to collect raw data from customers. In the case of this thesis, the first step has been carried out and presented in previous sections with the methods used for the stakeholder interviews and the literature review of stakeholder needs.

The second step was to interpret the raw data in terms of customer needs. As the stakeholder statements only provided raw data, it was necessary to translate them into interpreted needs. Therefore, a similar structure to the stakeholder statement list was created for the stakeholder needs using Microsoft Excel. Each statement listed in the data template was then translated into stakeholder needs. It is important to note that a statement could lead to multiple needs and in the case of this thesis some statements were not translated into needs as they only consisted of useful information for other parts of the thesis. However, to ensure effective translation, it was decided that the two authors should carry out the translation separately, which was done because individuals can translate the same statements into different needs [54]. The two different translations for each need were then compared where they were sometimes the same or similar, and in this case, the duplicate was removed or the need was rewritten so that the two needs could be used as a single need. In the case of two different needs, both were kept. When writing the needs five guidelines from Ulrich et al., [32] were followed and a column was added to the spreadsheet to indicate which statement the need came from to allow easy tracking.

The third step of the process according to Ulrich et al., [32], was to organise the needs into a hierarchy of needs. The argument for carrying out this step was that it was intuitive and that many teams could successfully complete the task without detailed instructions [32]. The argument for performing this step was considered weak and did not justify the work needed. It was therefore decided not to organise the needs into a hierarchy and instead to organise the needs into different items or themes, as was done with the list of stakeholder statements, as this was considered to add more value.

The fourth step was to determine the relative importance of the needs. The reason for this step is that a list alone does not provide information about the relative importance stakeholders attach to different needs, and developers need to make trade-offs and allocate resources when designing the product [32]. To make these trade-offs correctly, a sense of the relative importance of needs is essential. Ulrich et al, [32] mention two approaches that could be used to perform this step, the first being to rely on the consensus of the team members based on their experience with the stakeholders and the second being to base the assessment on further stakeholder surveys. For this thesis, the second approach would have been the most accurate method of determining the importance of the needs, but a trade-off had to be made due to the time-consuming nature of the process and the small number of stakeholders in the potential survey pool. It was therefore decided to rely on the consensus of the authors to establish the relative importance of the consensus.

The process of determining the relative importance of the needs was carried out by assigning a score of one to five to each need. The scores were determined based on

various inclusion and exclusion criteria. A need was given a score of one if it was considered undesirable by stakeholders and they would not consider a product with this feature. A score of two was given if the need was not considered important by stakeholders, but they would not mind having it in the product. A need was given a score of three if it was considered nice to have but not necessary. A score of four was given if the need was highly desirable but stakeholders would still consider the product without it. Finally, a need was given a score of five if it was considered critical and stakeholders would not consider the product without it.

The fifth step of the process according to Ulrich et al., [32], is to reflect on the results and the process. The fifth step was carried out by analysing the results of the needs and ensuring that the statements reflected the needs and their importance. The method of compiling the information into stakeholder statements was found to be helpful in finding both stated and implicit needs, as it simplified the process of translating a statement into specific needs, as well as identifying patterns that might emerge from the information gathered.

3.4.2 Requirements Specification

The creation of a requirements specification is a crucial step in the development process as it bridges the gap between stakeholder needs and the final product design [32]. The stakeholder needs were written in the "language of the stakeholder" and needed to be translated into precise, measurable metrics with associated values that the product must meet or exceed. To translate the needs into specifications, each need was considered in turn to determine which precise, measurable characteristic of the product would reflect the degree to which the product met that need. The translation of each need was then entered into a spreadsheet created using Microsoft Excel. The corresponding need number was then added to a column in the spreadsheet to allow transparent tracking from statements to needs to requirements. Other columns were then added, inspired by the final specifications of Ulrich et al, [32]. These columns were metric number, importance, units, marginal value and ideal value. The values in the importance columns were added according to the importance ratings of the needs they reflected. In cases where a metric represented a single need, the importance rating was transferred directly, but for metrics related to multiple needs, importance was determined by considering the importance of the needs and their relationship to each other.

The process of filling in the marginal and ideal values was heavily based on stakeholder needs. However, some values were filled in based on certain constraints, such as the dimensions of the dilution refrigerator, and some could not be filled in because further research of the area was needed to set specific values. The marginal value corresponds to the lowest acceptable value that the product must meet in order to be commercially viable, and the ideal value corresponds to the desired or aspirational level of performance that stakeholders would like to see in the product. The units column then correlates with both the metric and the marginal and ideal values, providing a clear understanding of the level of performance required to meet stakeholder needs.

In addition to the previously added columns, another column was added, inspired by Pahl et al., [55], in order to verify that the product meets the stated requirements. The verification column contained only short sentences about verification methods, and it was therefore deemed necessary to create a separate document explaining the verification methods. The purpose of the separate document was to make the verification process more transparent and increase the likelihood that the requirements would meet the stated values. By including a verification column and creating a list of verification methods, the quality of the spreadsheet was considered to be improved.

The aim of translating the needs into specifications was not to produce a final requirements specification but to produce an initial requirements specification. Ulrich et al, [32] mention that for technology-intensive products, requirements specifications are usually created at least twice, with the first iterations usually including the target specification, which reflects the hopes and aspirations of the team, and where the constraints of the technology are often unknown. As quantum computing hardware is a technology-intensive product where little research has been performed, it was considered appropriate to produce an initial requirements list to help future developers produce a final specification at a later stage.

3.5 Materials Study

The following section presents the methodology used to research possible materials that could be suitable for use in ultra-low temperature hardware, and the methodology used to ensure that the materials used in product development meet the requirements of the stakeholders. The methodology used consisted of a comprehensive literature review, attempts to calculate material properties and prediction of material properties. Figure 3.2 illustrates the process performed for the materials study.

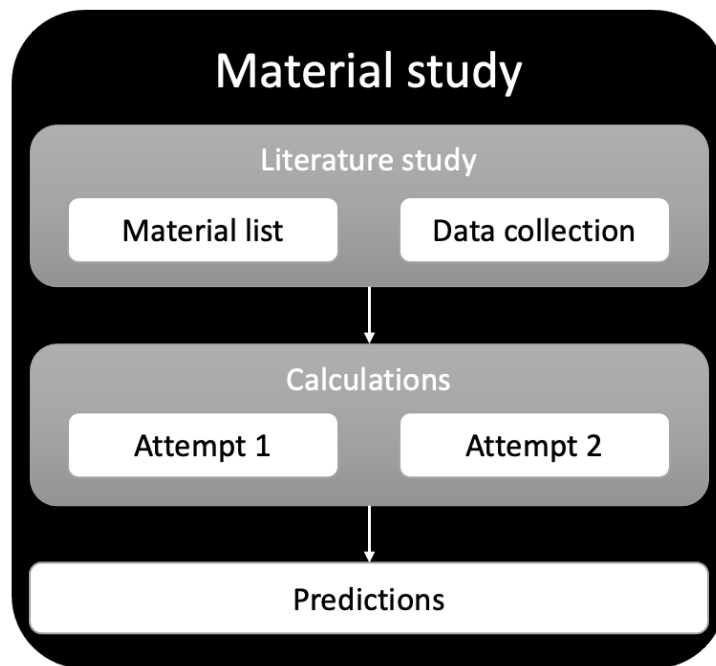


Figure 3.2: The process for the materials study.

3.5.1 Materials Literature Study

The initial stages of the materials literature study were undertaken with the aim of identifying suitable materials for use in cryogenic environments. A distinction was made to include not only ultra-low temperature materials but the full cryogenic range (below 123.15 Kelvin). The study included a review of literature on a range of topics including quantum computing, space technology and research, and cryogenic development. Several databases were used to ensure a comprehensive review, including Scopus, ResearchGate, arXiv, ScienceDirect, Google Scholar and the use of Google Search. The literature was retrieved using appropriate keywords and a selection of the most commonly used keywords can be found in table 3.4. The snowballing technique was also used to identify further relevant research. The literature search was not limited to publications within a specific time period due to the small number of publications in the last decade.

Table 3.4: A collection of the most occurring keywords in the materials literature study.

Cryogenic	Dilution refrigerator	Heat conduction
Diamagnetic	Engineering	Heat transfer
Liquid-Helium temperature	Low-temperature physics	Magnetic properties
Materials	Magnetic susceptibility	Material properties
MilliKelvin	Quantum computer	Quantum computing
Structural	Sub-kelvin	Superconducting

Quantum physics	Space applications	Superconductivity
Thermal conductivity	Ultra-low temperature	

All relevant publications identified from the literature search were analysed to determine their suitability for use in a cryogenic environment. Each material mentioned in the literature and deemed suitable was added to a list created and structured using Microsoft Excel. The list was created and structured according to the name of the material and the source from which it was obtained. To ensure that all relevant materials were included in the list, the materials mentioned in the interviews in subsection 3.3.1 were added to the list. When no further relevant literature was found, the list was considered complete. However, it is important to note that the list is not exhaustive and new material may be added in the future. It is therefore recommended that the list is regularly reviewed and updated to ensure that it remains current and relevant. Each material name was then checked to ensure that there were no alternative names for the same material, to save time when searching for properties of the materials. The check was carried out because different authors used different names or acronyms for the same materials.

The next step in the materials study was to investigate whether the identified materials could meet or exceed the stakeholder requirements. It was decided that materials that could not meet or exceed the requirements would be eliminated from the list. The sorting was performed according to three specific requirements. The first sorting requirement was related to magnetic properties and was carried out by searching and reviewing the literature to obtain data on the magnetic properties of all the remaining materials. An important note for the search is that the magnetic properties of a material can vary with temperature. Therefore it was assumed that if no magnetic information was found at cryogenic temperatures, the material was assumed to have the same magnetic properties as the data found for the lowest temperature. If no data was found, it was decided that the material should be discarded.

Thereafter followed the second sorting, where materials with superconducting properties from 300 Kelvin down to 10 milliKelvin had to be researched. The research was carried out by reviewing the literature using the same methodology as the first phase of the materials literature study. If the material had superconducting properties in the specified temperature range, the material was eliminated.

After the first two sortings, it was decided to study the thermal conductivity of the remaining materials at temperatures from 300 Kelvin down to 10 milliKelvin. The study was carried out by searching the literature for data on the thermal conductivity of the remaining materials. The literature was found through the same databases as the initial stage, where most of the data was found by researching the thermal conductivity of one material at a time, as it was difficult to find data on multiple materials from the same source. However, there were a few resources that included several materials at once that were of interest to the project and may assist in future

research, these were the: "Cryogenic Material Properties Calculators" provided by the National Institute of Standards (NIST) [121], "CRC Handbook of Chemistry and Physics" by Rumble [56], and the three volumes 1, 2 and 3 of "Thermophysical Properties of Matter-The TPRC Data Series" by Touloukian et al., [57, 58, 59].

An important note is that the data collection came from several sources, where the data had different error rates, where measurement methods differed and the production methods of test samples varied. Therefore, the comparison between materials could be misleading on the micro-level but at the macro-level, the data is considered useful and better than no compiled comparison as is currently available. To make the data more reliable, the materials of interest should be tested using the same method of measurement and preparation of samples as well as with similar error rates. However, the task of carrying out these tests was considered too time-consuming for the present project but is recommended for future and further research with materials of interest.

However, it was found that it was impossible to find data on any materials below 1 Kelvin, with the majority only having data down to 4 Kelvin, and in the worst cases, thermal conductivity data could only be found for materials at room temperature. It was therefore decided to calculate the thermal conductivity of all remaining materials.

3.5.2 Materials Study calculations

Due to the lack of data on thermal conductivity at ultra-low (>1 Kelvin) and very-low temperatures (1-10 Kelvin), it was decided to calculate the missing thermal conductivity values for all remaining materials of interest. The calculations were carried out in two attempts using two different methods, both using the Python programming language. It was decided to use a programming tool instead of doing the calculations by hand in order to minimise the time taken and the number of errors that could occur. The use of a programming tool allowed several materials to be calculated in a short period of time compared to hand calculations. In addition, Python was chosen because it offers ready-made packages that can be used for calculations and because the authors have previous experience in using Python. The data used for the calculations were collected from the materials study.

3.5.2.1 Materials study calculations - First attempt

The first attempt to calculate the thermal conductivity at ultra-low temperatures was made with the aim of calculating the free electron thermal conductivity, as presented in subsection 2.3.1. It was decided to calculate the free electron thermal conductivity due to it being the main carrier of heat in metals and most of the materials to calculate the thermal conductivity were metals or metal alloys. The attempt further included the use of the Boltzmann transport equation, as presented in section 2.4, and the Wiedemann-Franz law, as presented in subsection 2.3.1. It was decided to use the Boltzmann transport equation because of a suggestion made

by one of the interviewees. The inspiration for using the Wiedemann-Franz law to calculate thermal conductivity came from the literature study where Triqueneau et al., [60] used the law for a similar purpose. However, it was also mentioned by Shirron et al., [61] and Gloos et al., [62] that the law can overestimate the thermal conductivity of some materials. As the intent of getting values of the thermal conductivities for the researched materials was to compare the materials, the risk of overestimating the thermal conductivity was assumed to be low enough to be satisfactory for its use.

The calculations were performed by first assigning a temperature of interest. A function was then defined to calculate the thermal conductivity using the temperature of interest as an argument. The function was created with the secondary intent of calculating the relaxation time of the electrons, the Fermi velocity and the mean free path of the electrons using the equations 2.10, 2.9 and 2.8. In order to perform these calculations a number of constants had to be defined. The constants defined were the Boltzmann constant, the reduced Planck constant, the density of the material, the volume of an atom, the number density of the material, the mass of an electron and the charge of the electron.

Before calculating the relaxation time of the electrons, the Fermi velocity and the mean free path of the electrons, a variable x was calculated using the defined constants. The variable x represents the ratio of the thermal energy of the system to the energy of the system's electrons. The relaxation time of the electrons, the Fermi velocity and the mean free path of the electrons were then calculated using the defined constants. The free electron thermal conductivity was then calculated using the calculated relaxation time of the electrons, the Fermi velocity and certain defined constants, as seen in equation 2.4, and by numerically integrating an expression derived from the Boltzmann transport equation, Equation 3.3 using the trapezoidal rule. The code defined the *integrand* as a function of the variable x_{sorted} . The variable x_{sorted} was sorted to give the *integrand* a smooth variation. The *integrand* had two parts where the first part applies to $x_{sorted} \leq 100$ and was given by:

$$x_{sorted}^4 \frac{e^{x_{sorted}}}{(e^{x_{sorted}} - 1)^2} \quad (3.1)$$

The second part of the integrand applies to $x_{sorted} > 100$ and was defined by:

$$x_{sorted}^4 \left(1 - \frac{2}{e^{2x_{sorted}} + 1} \right) \quad (3.2)$$

After calculating the *integrand*, the free electron thermal conductivity was calculated with the following expression:

$$\lambda_e = \left(\frac{3\rho L_e}{m \int \frac{1}{x_{sorted}^2 k_B} \text{integrand} dx_{sorted}} \right) \cdot \left(\frac{1}{x_{sorted}^2 k_B} \right) \quad (3.3)$$

where ρ is the density of the material, L_e is the mean free path of the electrons, m is the mass of an electron and k_B is the Boltzmann constant.

In order to check the accuracy and to see if calculations were performed correctly, the thermal conductivity was calculated at very-low temperatures and compared with the actual values of thermal conductivity at those temperatures. It was found that the compared values differed significantly and it was assumed that the problem was related to the integration. Therefore, the code was modified to create an integration variable in an array of 1000 equally spaced values between zero and the variable x . The integral was then calculated using Simpson's rule instead of the trapezoidal rule, where the thermal conductivity then was calculated. Simpson's rule was used due to it having better accuracy than the trapezoidal rule [63].

The changes made did not significantly improve the accuracy of the code, and the values were still completely off compared to the actual values. Solving the Boltzmann transport equation is a complex task and requires making several approximations and assumptions, including the relaxation time approximation, which assumes that the scattering of phonons is described by a single relaxation time, and the isotropic approximation, which assumes that the scattering of phonons is the same in all directions. These assumptions may be the cause of the inaccurate thermal conductivity values.

Due to the fact that the calculated and actual thermal conductivity values did not match or were close to each other, combined with the author's lack of knowledge of the equation itself and its components, it was decided to try a different method for calculating thermal conductivity at ultra-low temperatures.

3.5.2.2 Materials study calculations - Second attempt

The second attempt to calculate the thermal conductivity at ultra-low temperatures was performed by calculating the total thermal conductivity, as presented in Equation 2.3 while using the Debye model of solids. The calculation using the Debye model was inspired by Ekin [64] as well as mentioned in Bar-Cohen [65], Shu et al. [66] and Barron et al. [15].

The second code had some similarities to the first code attempted as the free electron thermal conductivity was calculated in the same way. Further constants were added in comparison to the first attempt, such as the lattice constant of the material. The constants were then used to calculate the heat capacity according to the Debye model, as presented in Equation 2.14, the Debye temperature, as presented in Equation 2.15, the phonon velocity, as presented in Equation 2.16, and the mean free path of phonons, according to Equation 2.17.

A sub-function was then defined as an integrand function that calculated the contribution of each phonon to the thermal conductivity. The function allowed the number of integration points to be varied and numerically integrated using the "fixed_quad" function from the `scipy.integrate` module [67]. Finally, the function calculated and returned the total thermal conductivity of the material at the input temperature, using the integral, the constants and the Debye temperature.

The same check on accuracy and whether the calculations were performed correctly was carried out by comparing the calculated thermal conductivity with the actual thermal conductivity of the material at very low temperatures. The comparison again produced an incorrect result. A likely cause of the incorrect results was the complex nature of the calculations, where assumptions made may not hold true. The assumptions made were that the electrons behave like a free Fermi gas, that thermal transport is dominated by phonon vibrations, and that the phonon relation is isotropic and temperature independent.

An attempt was made to improve the accuracy of the calculations by varying the number of integration points. However, changing the number of integration points did not significantly change the results. It was therefore concluded that the calculations may not be reliable at very low temperatures. The reliability aspect, as well as the fact that the calculations can be extremely difficult to perform correctly, were points raised by respondents who recommended that simulations should be carried out instead. Due to the limited time available for the thesis, it was decided not to attempt to calculate the thermal conductivities further and instead to predict values that could be used for simulations, as the thermal conductivity of all the materials appeared to be either linear or polynomial.

3.5.3 Materials Study - Predictions

Before predicting the thermal conductivity of the remaining materials of interest, it was decided to remove materials that did not have enough data points to make a prediction. It was therefore decided to exclude all materials that did not have thermal conductivity data below 10 Kelvin. The temperature of 10 Kelvin was chosen to increase the accuracy of the predictions, as values closer to the ultra-low temperatures yield better accuracy and some materials showed a change in thermal conductivity below this temperature. The excluded materials may still be of interest, but were excluded from the thesis due to time constraints, but should be tested for further research.

When the materials with insufficient data were sorted out, Python was selected to predict data for the ultra-low temperatures of 10 and 20 milliKelvin. Python was chosen because of its ability to use pre-built machine learning packages and because the authors had previous experience with the programming language. As mentioned in Section 3.5.2.2, the actual values of the thermal conductivities were found to have either linear or polynomial characteristics, and it was therefore determined to create code that could perform both linear and polynomial regression.

The code started by importing the necessary packages NumPy, Matplotlib, Scikit-learn's Support Vector Regression (SVR), Linear Regression and Polynomial Feature. The actual thermal conductivity values of a material and its corresponding temperatures were then imported as pairs into arrays. The arrays were then divided into different training sets. The number of training sets varied from two to three, depending on the number of local maxima and minima. The splits were made to make

the data more accurate over the selected ranges, as it became apparent that a single range for all data pairs gave inaccurate values. The sets were then visually analysed to determine if their regression was either linear or polynomial and, depending on their characteristics, they were manually assigned the appropriate regression model. The manual analysis was performed by plotting the values of thermal conductivity and temperature and analysing the graph with a ruler. If the set had a polynomial characteristic, it was assigned to a third-degree polynomial regression model, and if the set had a linear characteristic, it was assigned to an SVR model with a fitted radial basis function kernel. The models then predicted the thermal conductivities at the assigned temperatures, and a check was added to ensure that the predicted thermal conductivities were either larger or equal to zero. The reason for this check was that the value of the thermal conductivity cannot be negative.

The predicted thermal conductivities at cryogenic temperatures, including very-low temperatures, were then compared to the actual values to ensure satisfactory prediction. With satisfactory predictions, training based on the sets was then performed to predict the thermal conductivity at 10 and 20 milliKelvin. A further check was performed to ensure non-negative values of the predicted thermal conductivities. The final part of the code involved plotting the actual values, the prediction made at the actual temperatures and the predicted values at 10 and 20 milliKelvin. The values were also printed to the console for further analysis. The full code can be found in Appendix A.

Due to the manual processes involved, it was decided that it was necessary to make predictions for one material at a time. Once the thermal conductivities had been predicted for all the materials, they were compiled into a list for easier comparison. The three materials with the highest actual thermal conductivities at 10, 5, 3.03, 2.5, 2, 1.66 and 1 Kelvin, as well as the top three materials with the highest predicted thermal conductivities at 10 and 20 milliKelvin were selected to move forward. However, it is important to separate the actual values from the predicted values and to note that the predicted values only give an indication of which materials may perform well at ultra-low temperatures. The predicted values should not be used as anything other than an indicator as they may be completely different from reality.

3.6 Ansys Granta EduPack Materials study

As the materials study carried out only included materials mentioned in the literature for cryogenic applications, it was decided to try to make the study more comprehensive and to find new materials that might not have been mentioned in the literature but might be suitable. It was therefore decided to use the software called Ansys Granta EduPack [68], which is a database of materials and process information that is kept up to date and includes materials selection and plotting tools. The software was chosen because it was available at Chalmers University of Technology and the authors had previous experience of using it. However, it was not known whether the software could be used at cryogenic temperatures and especially ultra-low temperatures, and an experimental material selection process was

therefore carried out both to test the suitability of the software and to find potential materials that could be used in the development of quantum computing hardware.

The experimental material selection process began with the selection of a complexity level within the software. The third and highest level of complexity was selected, which provided a selection of 4181 materials. Limitations were then applied based on the desired properties to narrow down the potentially suitable materials. The limitations applied were based on the desired properties and data from the requirements specification. The process of applying limitations to the materials selection presented some challenges. One of the main issues was the inability to include all the required properties, such as those related to superconductivity. In addition, temperature constraints were problematic as only the service temperature could be specified, resulting in a large pool of materials that may not be suitable for the desired temperature range. Despite these problems, the remaining materials were plotted according to the properties of interest based on the requirements specification. However, a significant problem was observed during the plotting process. The data displayed on the plot was limited to room temperature conditions, making the software unsuitable for selecting materials for ultra-low temperature hardware applications. It was therefore decided not to continue with the material selection process using the software, as the problems identified would have too great an impact on the results.

It is important to note that although the software's limitations make it less suitable for initial material selection for ultra-low temperature hardware, it can still be used in later stages of the product development process. For instance, Ansys Granta EduPack includes a wide range of tools and process information for many materials that could be used in the selection of manufacturing methods.

3.7 Simulations

The aim of the simulations in the thesis was twofold. Firstly, to investigate the feasibility of simulations at very-low and ultra-low temperatures. Secondly, to demonstrate how simulations can effectively assist in the identification and elimination of materials that do not meet the specified requirements. In order to achieve the aims, research was carried out to determine which simulation software should be used. The first requirement for selecting the software was that it had to be available through Chalmers University of Technology. It is important to note that this requirement limited the available software options and could potentially affect the results. It is possible that there are other software tools better suited for simulations at very-low and ultra-low temperatures that were not investigated in the study. Through both the literature identified throughout the thesis and the interviews conducted, it became apparent that two simulation software tools were more commonly used. The two software tools were Ansys Engineering Simulation software [126] and COMSOL Multiphysics [69]. However, it was only found that the two software were able to perform simulations at very-low temperatures and nothing was found regarding

ultra-low temperatures. A decision had to be made between the two options. In the end, Ansys was chosen because of the author's previous experience with it.

3.7.1 Verification of Simulations at Ultra-low temperatures

In order to verify that simulations were possible at ultra-low temperatures, it was decided to simulate a single, simple component. The component simulated was a cylinder, chosen because of its similarity to the LINQER sample holder and the fact that the LINQER is mostly composed of cylinders. The cylinder was designed in the CATIA V5 CAD [70] software and was imported into Ansys Mechanical. An important consideration in the design of the cylinder was that there should be no sharp edges, as sharp edges in the geometry increase the stresses at the edges [71], which could lead to inaccurate results. By using a simpler geometry to analyse the stresses, it was considered easier to verify whether simulations could be performed at ultra-low temperatures than with a more complex geometry. The cylinder used for the verification simulations is shown in Figure 3.3.

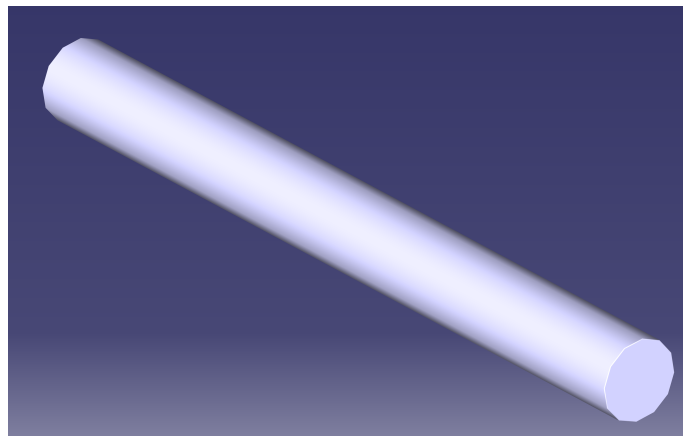


Figure 3.3: The cylinder designed in CATIA V5 and used for the verification simulations in Ansys.

The next step was to decide what quantities, variables or behaviours to simulate, which was done by analysing the list of requirements and the verification methods documents presented in Chapter 4. Requirement 4.4, as listed in Table 4.4, was selected for further investigation, which states that there must be a design safety factor, requiring the stresses to be significantly lower than the yield strength of the material. This requirement was selected due to that it could be used to further sort out materials that can not be used for the application.

With a requirement selected and to be investigated, a simulation was set up to find the equivalent Von Mises stress, due to the temperature gradient of the cylinder head being cooled from room temperature to a selected temperature. A further behaviour set to investigate was the deformation in the component and it was selected to

simulate the total deformation and the directional deformation. The deformation analysis was carried out with the intention of aiding the analysis of the stresses. It was decided to run two simulations with different selected temperatures to verify the material used in the simulation and the simulation itself. In selecting the material to be used, it was found that Ansys had material data down to 3 Kelvin, thus not in the ultra-low temperature range. The temperature of 3 Kelvin was therefore used as a sorting criterion for materials to be simulated from the material list, as only one material was to be simulated. A total of eleven materials in the material list had data down to 3 Kelvin. It was therefore chosen to sort out materials composed of several materials as the composition between the material in the material list and in Ansys could be different. After the second sorting only four materials remained and one of these was selected based on having the highest thermal conductivity. As there were two temperatures to simulate, one at 3 Kelvin and one at the ultra-low temperature of 10 milliKelvin, and two different types of a selected material to simulate, one with material data from Ansys and one based on data found in the literature, the total number of simulations to be performed was four.

The process of incorporating a new material into Ansys involved a two-step approach. First, the existing material data was copied from Ansys as a starting point. This step was necessary because the literature did not provide data for all the required properties. Secondly, the copied material data was changed by integrating the available properties and data from the literature. The second step was to address the fact that the default temperature limit set by Ansys was not low enough for ultra-low temperature simulations, as its limit was set at 3 Kelvin. It was, therefore, necessary to adjust the lower temperature limit of the range to 10 milliKelvin to enable Ansys to simulate accurately at ultra-low temperatures.

The first two simulations were performed with the selected temperature of 3 Kelvin for the two materials. The simulation setup for the simulations is visualised in Figure 3.4. By using the two different material data sources, it was possible to verify that the added material data had been correctly applied, which was considered necessary in order to later perform simulations at ultra-low temperatures. The verification was based on a comparison of the different stresses and deformations. The comparison gave similar results and it was therefore deemed acceptable to proceed with the added material data from the literature in order to be able to run simulations at ultra-low temperatures.

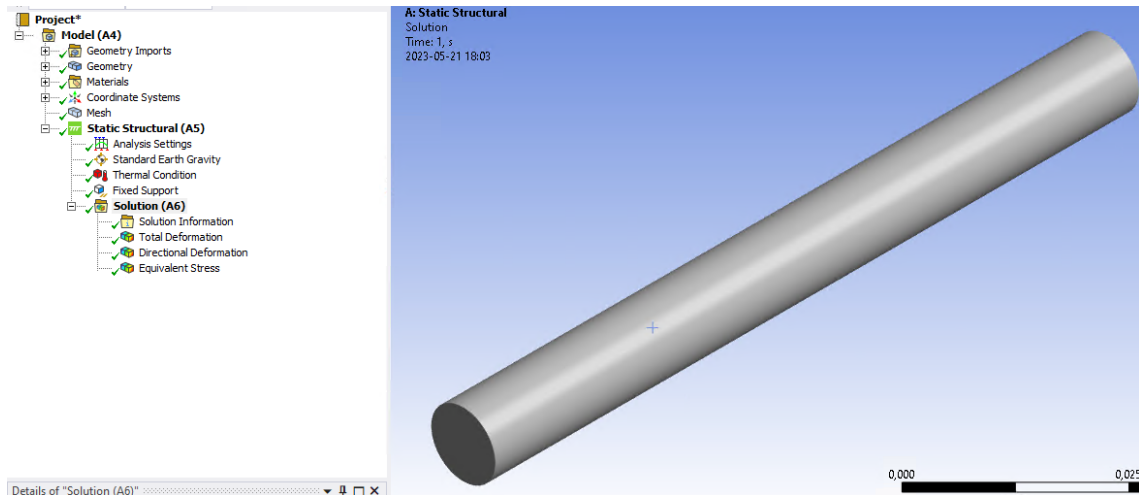


Figure 3.4: Ansys simulation environment with the simulation setup to the left side.

The last two simulations were then performed with the same simulations setup except that the selected temperature was set to 10 milliKelvin. The stresses and deformations were then compared with the results for 3 Kelvin to check for similarity and to verify that the stress at 10 milliKelvin was not lower than at 3 Kelvin, which would have indicated an error as the deformations were greater. The check showed that Ansys could perform simulations at ultra-low temperatures, but it is important to note that the stress values given have not been verified with actual tests and should therefore only be used for applications where results can have a low degree of certainty.

To ensure a fair comparison between all simulations, certain standard parameters were applied. These included maintaining consistent gravity in the same direction, using fixed supports in the same locations and enforcing the same temperature conditions. The initial temperature of the object was set at 295.15 Kelvin (room temperature), while the final temperatures for the initial simulations were set at 3 Kelvin and an ultra-low temperature of 10 milliKelvin for the subsequent simulations.

3.7.2 Ultra-Low Temperature Sample Holder Simulations

As the ultra-low temperature simulations were deemed acceptable, it was decided to proceed with the verification of Requirement 4.4 from Table 4.4 and perform simulations using the LINQER instead of the simple cylinder. As the project was time constrained, it was decided to simplify the design of the LINQER to speed up the simulation setup and analysis of the results and to avoid revealing confidential information about the LINQER.

It was further decided to create two different types of simplified versions of the LINQER to ensure more reliable results. The first version was made as a complete

component, meaning that the product had only one component where no joining methods were required. The first version made from a single component will be referred to hereafter as "single component sample holder". The second version was made as a two-component product where the mounting feet to the dilution refrigerator were one component and the rest of the LINQER was the second component. The second version made up of two components will hereafter be referred to as the "dual component sample holder". By designing the versions as either a single component or two components, it was possible to avoid simulating joining methods such as screws, which would have resulted in a more time-consuming simulation setup and results analysis.

The designs of the two versions were made in the CATIA V5 software and by measuring the features of the LINQER 52, such as the diameter and thickness of the horizontal plates, the location of the vertical cylinders connecting to each plate and their respective dimensions. The CATIA V5 software was chosen to design the versions as the authors had previous experience in using the software. Both versions of sample holders had a small radius fillet applied to all sharp edges to eliminate the risk of excessive stress on the sharp edges [71]. The designs created for the two versions inspired by the LINQER 52 can be seen in Figures 3.5 - 3.8.

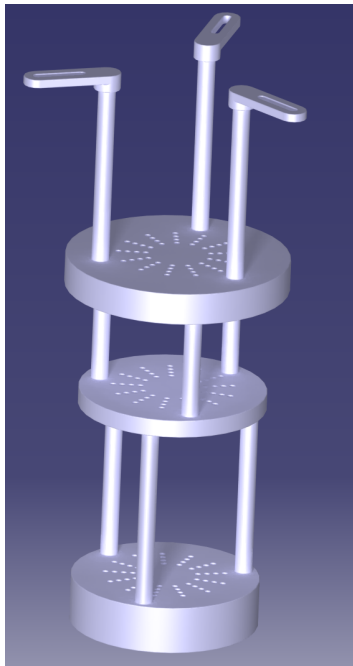


Figure 3.5: Single component sample holder.

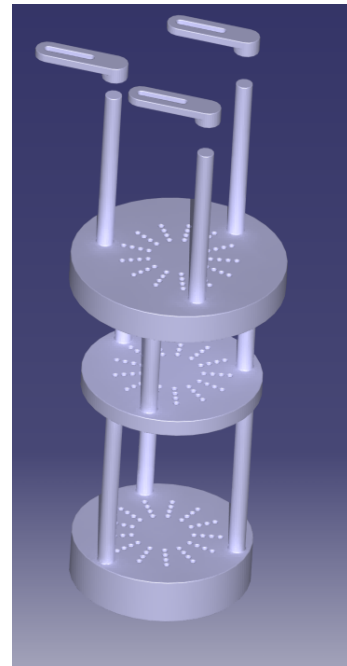


Figure 3.6: Dual component sample holder.

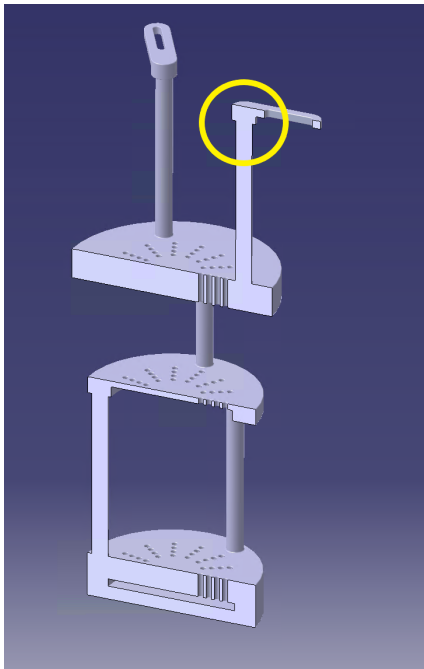


Figure 3.7: Single component sample holders cross-section view.

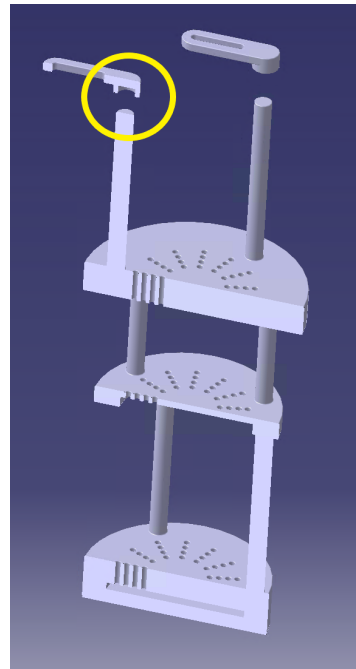


Figure 3.8: Dual component sample holder cross-sectional view.

In addition, 52 holes were created to resemble the real LINQER 52, but the placement of the holes was performed differently from the real LINQER to ensure that no sensitive information about the LINQER 52 was revealed, as the results of the simulations will be public. The differences in hole placement can be seen in figures 3.9 and 3.10.

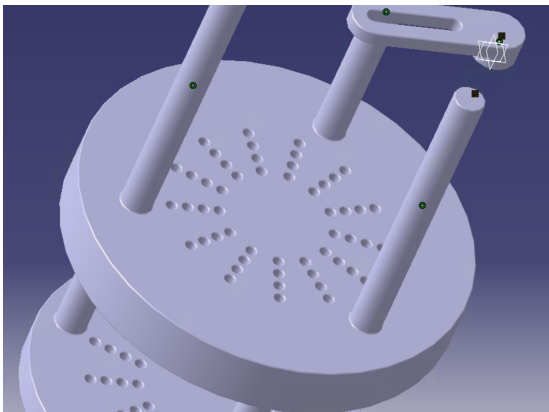


Figure 3.9: Hole placements for the two versions created.

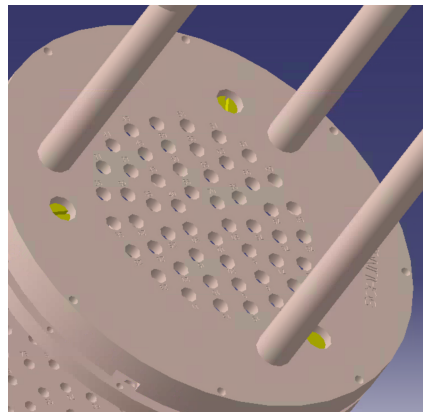


Figure 3.10: Actual hole placement for the LINQER 52.

The simulations were set up as in subsection 3.7.1 with a temperature gradient applied to the top of the sample holders ranging from room temperature down to both 3 Kelvin and 10 milliKelvin. The simulations performed included equivalent Von Mises stress and the deformations, total deformation and directional deformation.

The maximum Von Mises equivalent stress that occurred was then compared to the material's yield strength at ultra-low temperatures to analyse if the safety factor was met. Similar to the simulations performed in subsection 3.7.1, two different silvers were used to enhance the verification and suitability of materials through simulation. The use of the two silvers aimed to explore the disparities between materials with well-defined properties and those with limited information, and to assess the software's computational capabilities in handling such variations. As there were two geometries to simulate, each with two different materials and at two different temperatures, a total of eight simulations were required.

It was considered acceptable to run the simulations with the simplified versions to find out if the materials would meet the requirement for the safety factor. The reasoning behind this consideration was that the simulation with the simplified versions does not in any way verify that the material is suitable to meet all the requirements of the specification.

4

Findings

The following chapter presents the findings of the research carried out in the project. The findings presented include the functional analysis carried out, the stakeholder identification and analysis, the stakeholder needs data collection and analysis, the extensive materials studies and the verifying simulations.

4.1 Functional Analysis

Functional analysis, using the function-means tree method [49], proved effective in improving the understanding of the product, encompassing both the primary function and sub-functions, together with the means required to perform the functions. Through the analysis, the primary function was identified as 'accommodate sample', meaning that the entire product was the design solution or means to perform the function. The design solution 'Sample holder' was identified as being constrained. The constraints dictated the use of non-magnetic materials with high thermal conductivity for the complete product where the constraint further follows down to the sub-functions and their means.

The product was then systematically divided into five distinct functions, each of which performed a unique function in its operation. These functions included:

- Transfer heat - heat generated by the sample must be efficiently transferred away from the sample itself to ensure optimum thermal management.
- House sample - the sample must be installed in a secure and stable enclosure to protect it from external influences and maintain its integrity.
- Shield sample - the sample must be shielded from the environment, noise and interference to ensure reliable measurements.
- House cables - cables from the dilution refrigerator must be housed in order to be connected to the sample.
- Provide mounting to the dilution refrigerator (DR) - the sample must be connected to the DR as it acts as a heat sink for the product.

The means to achieve each function were then identified, along with the sub-functions and sub-means. The final function-means tree is shown in Figure 4.1, which illustrates all the functional requirements and design solutions identified.

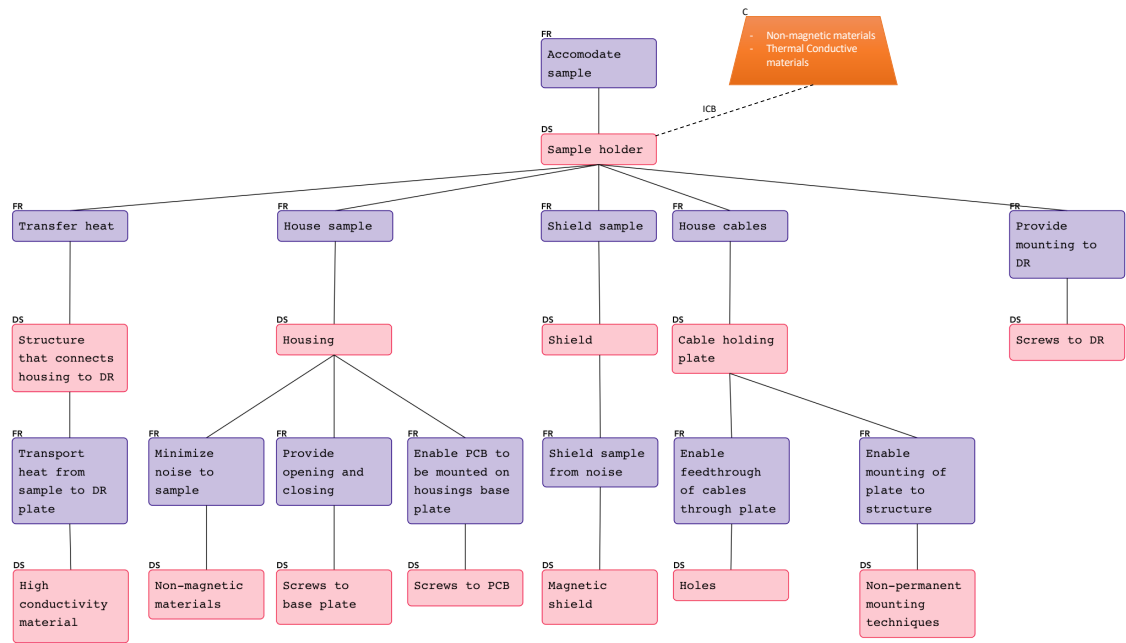


Figure 4.1: Function-means tree illustrating the functions and means of the LINQER. The acronyms in the figure stand for Constraints (C), Is Constrained By (ICB), Functional Requirement (FR) and Design Solution (DS).

4.2 Stakeholder Identification & Analysis

The following section presents the findings from the stakeholder identification performed by reviewing the literature and the results from the analysis, which provides insight into the various stakeholder groups and their influence on the development and utilisation of quantum computer hardware.

4.2.1 Stakeholder Identification - Literature study

The research of stakeholders by utilising literature as a source was discovered to be difficult as no resources explicitly related to the stakeholders and were only mentioned as a side effect of presenting or discussing other things. However, two sources were thought to be of specific interest. Hughes [72] mentioned stakeholders such as students, university educators and administrators, policymakers, funding agencies and quantum companies. The second source of interest was the Quantum Manifesto for Quantum Technologies [73], which discusses the role of science in society and science communication. The quantum manifesto only mentioned academia, business and policymakers as relevant stakeholder groups where the public only was featured as the target for educational activities. Further research by compiling multiple sources of information led to finding stakeholders such as customers, users, suppliers and those affected by regulations.

Customers

The stakeholders identified through the literature search considered as customers of quantum computer hardware included government agencies, research institutions, and private companies. These stakeholders have shown a high degree of interest in the field of quantum computing and its potential applications.

Government agencies such as the National Security Agency (NSA) and the National Aeronautics and Space Administration (NASA) have acknowledged the strategic importance of quantum computers for both national security and space applications. The NSA has acknowledged the potential of quantum computers in enhancing cryptography and cybersecurity measures [74]. NASA, on the other hand, sees quantum computing as a tool for solving complex problems in space missions and data analysis [75, 76].

Research institutions, including universities and national laboratories, are intensively studying quantum computing for scientific research purposes. The research institutions aim to leverage the power of quantum computers to advance fields such as chemistry, material science, and fundamental physics. These institutions are leading the way in exploring the potential of quantum computing to solve complex computational problems and developing new algorithms. Research institutions were identified as stakeholders due to the fact that the majority of the authors of the relevant literature reviewed were associated with universities.

Private companies across various industries were also found to be a part of the stakeholders considered as customers [77, 78]. Companies in finance, healthcare, transportation, and other sectors are recognizing the potential of quantum computers to revolutionize their operations [79].

The involvement of these diverse customers reflects the broad scope of applications and the high level of interest in quantum computing. Understanding the needs, expectations, and potential challenges faced by these customers is crucial for aligning objectives and outcomes with their requirements.

Users

The technology of quantum computers can be considered quite new and its potential has not yet been realised to its full extent where developments are made constantly. Therefore, the users are still closely linked to customers as industry use is currently at the start of emergence as well as public use. The users can therefore be considered as the operators of the purchasing customers, which can be the same person. These persons or users were found to be researchers and scientists in fields such as physics, chemistry, and materials science, as well as engineers and developers working on quantum computing hardware and software [80, 81, 82].

Suppliers

The stakeholders considered as suppliers to quantum computer companies can include manufacturers of materials, components, and equipment used in the construction and operation of quantum computers. These can further include suppliers of cryogenic equipment, superconducting materials, and electronic components such

as amplifiers and detectors. Additionally, suppliers of software and services such as quantum algorithms development may also be considered as suppliers to quantum computer companies.

In a report by Hyperion research, Sorensen [83] presented results from a survey performed with 108 suppliers in the quantum computing field. A result from the survey showed that 54% of organisation's major activities were research, whereof algorithm and theoretical research stood for almost 22% of the major activities in quantum computing organizations, and software research around 20% and hardware research only 12% [83]. Other major activities presented were software product development, hardware product development, hardware and software sales and lastly venture capital and corporate quantum computing funding [83].

Regulations

To identify additional stakeholders, the regulatory landscape was studied to find who is regulated and for whom. However, it was found that there are currently no specific regulations solely focused on quantum computers. Instead, the regulations that apply to quantum computers are determined by the specific applications for which they are used

Quantum computers must adhere to existing regulations in the field of information technology and data protection, such as the General Data Protection Regulation (GDPR) [84]. Furthermore, organisations dealing with sensitive information may be subject to regulations such as the Federal Information Security Modernization Act (FISMA) or the Health Insurance Portability and Accountability Act (HIPAA) [85, 86].

In the United States, quantum computers employed for national defence or intelligence purposes may be subject to regulations from the Department of Defense or the Intelligence Community [87]. In addition, due to the dual-use nature of quantum technology, export control regulations apply [88].

Within the European Union, quantum technology is considered a strategic technology and is subject to the EU Dual-Use Regulation (EC) No 428/2009 [89]. Moreover, the research and development of quantum technology may be subject to regulations related to data protection, intellectual property, and competition law [90].

The identified stakeholder subjected to regulations were quantum computer companies, government agencies and institutions, research institutions and universities, organisations handling sensitive information, exporters of quantum technology and the public.

4.2.2 Stakeholder Analysis - Literature study

The identified stakeholders were then divided into four groups according to their influence. Primary stakeholders are those who have the most direct influence on the product and its development, which were considered to be the quantum computing

companies developing the products, the customers and users of the product, and the academic and industrial research community, as they are the developers of the technology and products used. Secondary stakeholders are those indirectly affected by the product, such as government agencies, regulators and policymakers, as they regulate what can be developed and how the product will be used. Funding agencies and research institutions were also considered to be secondary stakeholders, as development and research are heavily dependent on funding agencies and the research carried out by research institutions. Tertiary stakeholders include stakeholders that are indirectly involved in the product development process, such as suppliers of cryogenic equipment, superconducting materials, electronic components, software and services, as well as manufacturers of the materials, components and equipment used to realise the quantum computer. General stakeholders are those with a general interest in the product, such as the public, companies dealing with sensitive information, and civil and military applications. Figure 4.2 illustrates the stakeholder groups in hierarchical order according to their influence and the stakeholders within each group.

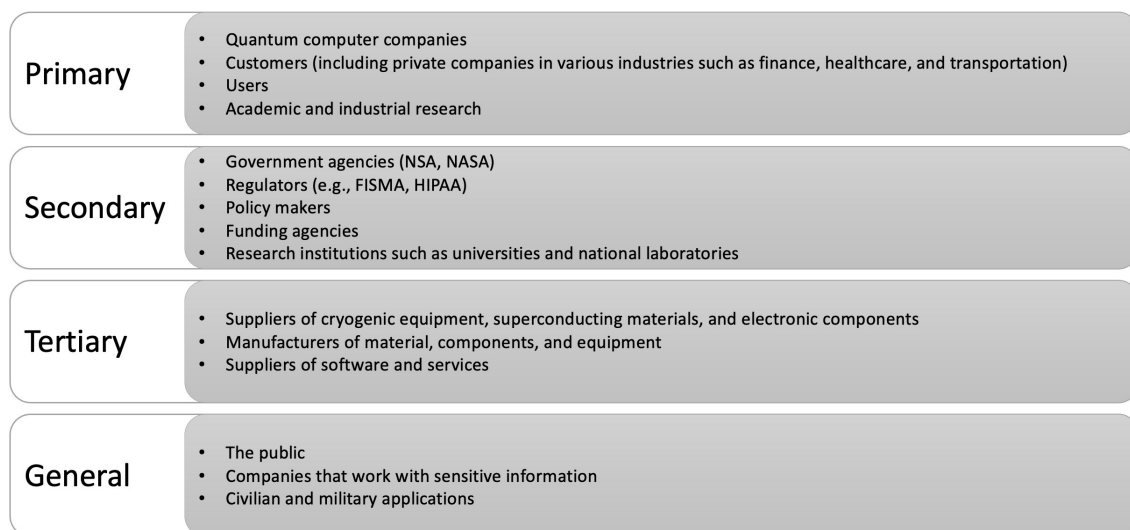


Figure 4.2: The classification of stakeholders into four distinct groups: Primary, Secondary, Tertiary and General. Each group represents a different level of influence with the individual stakeholders presented.

4.3 Stakeholder Needs Identification & Data Collection

The following section presents the results of the data collected, focusing on stakeholder needs with findings from the primary stakeholder interviews and the stakeholder needs literature study. In addition, the results of the interview with the technical writer are presented. The information obtained from these sources pro-

vides valuable input for understanding the requirements and implications related to the development of quantum computing hardware.

4.3.1 Stakeholder Needs Interviews

The valuable insights shared by the primary stakeholders during the interviews have been collected and organised for easy access and can be found in Appendix B.1. To highlight the importance and breadth of these statements, a selection of informative statements is presented in Table 4.1. These selected statements represent the range of perspectives and opinions expressed by stakeholders, capturing the essence of their contributions and enhancing the overall understanding of the findings.

Table 4.1: Summary of selected statements from primary stakeholders.

Number	Item	Statement
S55	Cost	Performance over price, but price needs to be reasonable
S75	Delivery time	The hardware for quantum computers must be delivered within a reasonable timeframe, preferably fast delivery and short lead times, to meet the customer's requirements and expectations.
S10	Dimensions	The footprint of the connectors determines how big your sample holder needs to be for you to be able to insert it and let it go. As we try to be as small as possible, the height is also related to not wanting to risk too much free space around your sample.
S24	Material	We would like a sample holder that oxidizes less. In principle, it should not oxidize, but if you touch it, you will help build up a side layer that lowers the thermal conductivity.
S39	Material	As components are put into vacuum, it is important that contaminated components are not used as degasation can occur. The contamination on the components can then evaporate and get stuck on the cryogenic wall, which is unwanted.
S59	Material	Materials properties that are desirable is: Cryogenic compatible, as thermally conducting as possible and non-magnetic.
S91	Material	That they don't break or become brittle when cooled

Table 4.1 continued from previous page

Number	Item	Statement
S97	Material	This is called the Meissner effect and occurs in a superconductor when you are below its T_c . Then the magnetic field does not pass through the material. This is controlled by the diamagnetism of the material and when a magnet approaches a superconductor, a current is induced in the superconductor. Since there is no resistance to the current, the current continues to flow and thus induces its own magnetic field that repels the field of the magnet. So I guess paramagnetic materials are not desirable.
S106	Material	Thermal conductivity, non-magnetic and low temperature resistance.
S11	Shielding	But when it comes to the shield, you want it to be as long as possible and have as small a diameter as possible, because the shielding really depends on how the shield is designed.
S36	Thermal	Currently, data is missing at low temperatures and most often only data at room temperature is provided. It is therefore important that components function as advertised at very low temperatures, as things changes at these low temperatures.

4.3.2 Interview with Technical Writer

Further information on how to write technical documentation and how to present complex data was gathered by interviewing a technical writer. The findings from the interview have been incorporated into the thesis, enhancing its comprehensiveness and providing valuable insights. While the full findings can be found in the report, a summary is provided below, highlighting the key points articulated by the technical writer:

- It is important to adjust the technical documentation to the user.
- The documentation should be updated continuously.
- The documentation is written in Simplified Technical English, meaning that the text should be short, concise and straight to the point.
- The technical writer keeps in mind that the documentation will be translated into different languages.
- The documentation is written using "Topic-based authoring", meaning that it should carry itself and the information should be comprehensible out of context.

4.3.3 Stakeholder Needs Literature study

The valuable insights found during the stakeholder needs literature study has been collected and organised and is found in Appendix B.2. Each statement carries its own significance and contributes to the overall understanding. However, to provide a concise overview that captures the essence of the statements, a summary was compiled that incorporates some key points from the collection of statements and is presented in Table 4.2.

Table 4.2: A collection of stakeholder statements, identified through the literature study.

Number	Item	Statements
L2	Dimensions & Performance	Dilution refrigerators have limited space and cooling capacity which puts a need on space optimization and cooling properties of quantum computing hardware [11]
L10	Material	The minimization of residual magnetic fields inside the shield is crucial where components such as screws, RF connectors and cables need to be non-magnetic [5].
L9	Noise & Material	Magnetic fields can lead to interferences and errors in computation. It is therefore necessary to minimize magnetic fields and to shield the sample from the magnetic fields [5, 11, 92, 93, 27].
L4	Thermal	The significant reduction of temperature in the dilution refrigerator has pronounced effects on the properties of materials and the behavior of the system [19, 64, 91, 15].
L7	Thermal	The hardware needs to be able to withstand temperatures from room temperature down to 10mk and to avoid thermal excitation within this range or when operated [11, 14, 24, 18].
L13	Thermal	As materials change due to temperature it is therefore necessary that different materials on the same hardware have a uniform and controlled change. Furthermore, if the hardware is coupled with the sample, the hardware needs to have the same change as the sample [64].
L25	Thermal	Since the hardware and the sample is conductively cooled by mounting it on the cold plate, usually in vacuum, there is a need for all thermal joints between the sample and the cold plate to have a high thermal conductivity [64]

4.4 Stakeholder Needs Analysis

The following chapter presents the results of translating the stakeholder statements into stakeholder needs. Then, the results of eliciting a requirement specification based on the stakeholder needs list are presented.

4.4.1 Stakeholder Needs List

The stakeholder statements from both the interviews and the literature study were translated into needs. The needs were then compiled in a stakeholder needs list. The list can be seen in Table 4.3 and includes the identified needs of the stakeholders, their importance, their item or theme, and the corresponding statement number.

Table 4.3: The stakeholder needs list, sorted based on item.

No.	Item	Statement No.	Need	Imp.
2	Cleanliness	S38, S162, S163	Visual cleanliness is a must	4
72	Cleanliness	S109	The surfaces should be free from oil and cutting liquids	4
3	Cost	S18, L3	There is a need for different sizes of sample holders to reduce cost.	3
4	Cost	S35	Reduce cost of sample holder	4
5	Cost	S55	Maximize performance over price	5
6	Cost	S55	The price needs to be reasonable	4
9	Cost	L20, S168	Hardware must be designed and manufactured to be cost-effective without compromising functionality, reliability and performance.	4
10	Delivery time	S75	The hardware should be delivered within a reasonable time-frame	2
70	Delivery time	S171	Delivery time of 3 to 4 weeks	3
14	Design	S31	Larger sample holders should be able to handle at least two samples	4
15	Design & Thermal	S44, S67, S88, L5	The sample holder should manage and accommodate all necessary cables	5
16	Design	S17, S19, S20, S58, S150	The sample holder should be able to handle at least 16 cables and up to 300	5

Table 4.3 continued from previous page

No.	Item	Statement No.	Need	Imp.
19	Design & Dimensions	S2 & S33	Minimize size of sample holder without compromising performance	3
62	Design & Material	S76, S80, L23	The hardware must be able to withstand mechanical loading at low temperature in the form of its own weight and the weight of the sample.	5
47	Design	L3	Scalable platforms to continue developments within the field	4
17	Dimensions	S10, S144, S146, S147, S148	The sample holder should provide enough space to be able to install connectors	5
18	Dimensions	S10	Minimize free space around the sample	4
20	Dimensions	S11, S139, S140, S151	Maximize the height of the shield	4
21	Dimensions	S11, S139, S140, S151	Minimize the diameter of the shield	4
22	Dimensions	S66, L2	The sample holder's dimensions are limited by the dilution refrigerator	5
23	Installation	S4, S49, S142	Minimize errors in the installation	4
24	Installation	S6, S50	Enable dismounting of cables	5
26	Installation	S7	Enable dismounting of the bottom plate	5
67	Installation & Thermal	S159	Ensure proper connection for thermal link	4
28	Manufacturing	S25	Minimize surface roughness on contact areas between base plate and sample holder	3
29	Material	S22, S26, S46, S53, S59, S61, S68, S97, S106, S135, S136, S138, L9, L10	All components needs to be non-magnetic	5
30	Material	S24, S112, S137, S161	Minimize oxidation	4
31	Material	S39, S95	No material with degassing properties to be used	4

Table 4.3 continued from previous page

No.	Item	Statement No.	Need	Imp.
32	Material	S59, S80, S91, L4, L7	Materials must be cryogenic compatible	5
33	Material	S62	Materials for the non-electric hardware should not become superconducting	5
35	Material	S71, S95, S107, L16, L25	The hardware should be able to operate in vacuum	5
37	Material & Design	S81, S96	Hardware must be designed with a safety factor	5
38	Material	S97, S156, S157	The paramagnetic properties of non-magnetic materials should be avoided	5
39	Materials	S73, L19	The material should be resistant to corrosion	4
40	Materials & Verification	S36, S74, S84	Reliable datasheets for used materials	5
66	Material	S154	Nonmagnetic level sub 10 Gauss	5
41	Noise	S3, S32, S41, S130, L6, L8, L9	Shield from high frequency noise caused by electrical, radiation, magnetic sources and from outside the cryostat	3
42	Noise	S34, S37, L1, L8	Minimize effects from the noise created by the cryogenic systems around the sample holder.	4
43	Noise	S52	Less overall noise in the system over thermal conductivity	5
44	Noise	L1	Increased stability, reliability and accuracy to achieve precise results	4
45	Noise	S129, L6	Minimize blackbody and heat radiation from the environment	2
48	Service life	S45, S56	The sample holder must have a minimum service life of two years	5
68	Service life	S164	Average service life should be 3 years	4
34	Thermal	S42, S159, L24	Maximize thermal anchoring of non-electric hardware	4

Table 4.3 continued from previous page

No.	Item	Statement No.	Need	Imp.
50	Thermal	S1, S65, S70, S111, L4, L13, L15	Controlled and uniformed change due to temperature change	4
51	Thermal	S64	The hardware must be able to operate in 10 mK	5
53	Thermal	S29	The temperature near the sample should be approximately 20 mK	5
54	Thermal	S36, S91, S108, L4, L7	The hardware should be able to cope with the temperature changes from room temperature to 10 mk	5
55	Thermal	S63, S69, L12, L24	Minimize cool down time	2
56	Thermal	S85, S88, L11	The heat generated at the the experimental flange of the Bluefors LD400 can not exceed more than 15 mW at 20 mk	4
57	Thermal	L14, L15	Strain-free mounting due to thermal contraction	4
58	Thermal	L24	Adaptation of the specific heat and thermal diffusivity	3
59	Thermal	L25	All thermal joints between the sample and the cold plate should have a high thermal conductivity	4
60	Thermal & Material	S23, S59, S66, S106, L2	Maximize thermal conductivity	5
61	Thermal & Material	S23	Fast cool down of components	3
63	Verification	S27, S74, S90, S92, S123	Components should be both virtually and physically tested before delivery	4

4.4.2 Requirement Specification

To effectively address the stakeholder needs, it was necessary to translate them into specific, measurable, tangible and quantifiable requirements. However, it is important to note that the requirement specification provided in Table 4.4 serves as

an initial iteration rather than a final version. Additional studies and assessments are necessary to determine the feasibility and readiness of the technology in meeting these requirements. The requirement specification in Table 4.4, includes the metric number, the correlated needs number, the requirement itself, its importance, the unit to measure it and the marginal and ideal values. Furthermore, verification methods for the requirements are included where an explanation of these methods can be seen in Table 4.5.

Table 4.4: Requirement specification for a sample holder based on the stakeholder needs.

Metric No.	Need No.	Requirement	Imp.	Units	Marginal value	Ideal value	Verification
1.		Cleanliness					
1.1	2	No observable contamination	2	Meter	0.3	<0.3	Visual inspection ¹
1.2	72	Oil free surface	4	Meter	0.3	<0.3	Visual inspection ¹
2.		Cost					
2.1	3, 4, 6, 9	Unit cost	4	Cost/Unit	€ 20 000	<€ 20 000	Economical analysis ²
3.		Lead time					
3.1	9, 10, 11, 70	Maximum lead time from order to finished product	3	Weeks	3-12	<3	Lead time analysis ³
4.		Design					
4.1	14	Minimum number of samples accommodated	4	Pcs.	1	>=1	Measurement in CAD ⁴
4.2	15, 16	Maintain operational temperature	5	milliKelvin	20	<20	Thermal simulation ⁵
4.3	15, 16	Accommodate cables	5	Pcs.	1-300	>300	Measurement in CAD ⁶
4.4	9, 37, 50, 57, 62	Design safety factor of 1.5-2	5	Binary	Pass	Pass	Simulation + Tensile test ⁷
4.5	23, 27	Numbering of the cable connections	4	Binary	Pass	Pass	Visual inspection ⁸

Table 4.4 continued from previous page

Metric No.	Need No.	Requirement	Imp.	Units	Marginal value	Ideal value	Verification
4.6	27	Pre-installed cables	3	Binary	No pass	Pass	Measurement of connectivity + Visual inspection ⁹
4.7	26	Dismountable sample housing	5	Binary	Pass	Pass	No permanent fastening/joining methods ¹⁰
4.8	24	Enable mounting and dismounting of cables	5	Binary	Pass	Pass	No permanent fastening/joining methods ¹⁰
4.9	25	Enabling multiple cable installation at the same time	3	Binary	No Pass	Pass	Installation test ¹⁰
5.		Dimensions					
5.1	17, 19, 20, 22, 47	Maximum sample holder height	4	mm	337	N/A	Measurement in CAD + limited by space in LD400 ¹¹
5.2	17, 19, 21, 22, 47	Minimum sample holder diameter greater than PCB	4	Binary	Pass	Pass	Measurement in CAD ¹²
5.3	17, 19, 24	Minimum sample holder height	5	mm	>=115.5	N/A	Measurement in CAD + Physical constraints ¹³

Table 4.4 continued from previous page

Metric No.	Need No.	Requirement	Imp.	Units	Marginal value	Ideal value	Verification
5.4	20, 22	Additional height of the shield in relation to the sample holder's top-to-bottom dimensions	4	mm	0	>0	Measurement in CAD ¹⁴
5.5	18, 19	Minimize free space around sample	4	mm ³	N/A	0	Further research required ¹⁵
5.6	41, 43, 44, 45	Minimize diameter to minimize interference	3	W	N/A	N/A	Further research required ¹⁵
5.7	41, 43, 44, 45	Maximize height to minimize interference	3	mm	N/A	N/A	Further research required ¹⁵
5.8	55, 60	Minimize height to maximize heat transfer	3	mm	N/A	N/A	Further research required ¹⁵
6.		Material					
6.1	29, 38, 44	Diamagnetic properties	5	Binary	Pass	Pass	Negative magnetic susceptibility ¹⁶
6.2	33	No superconductive properties	5	Binary	Pass	Pass	Further research required ¹⁵
6.3	51, 52, 54, 58	Minimum service temperature	5	milliKelvin	10	7	Material selection ¹⁷
6.4	30 & 39	Minimize oxidation and corrosion	4	Subj.	3	1	Oxidation and corrosion properties ¹⁸

Table 4.4 continued from previous page

Metric No.	Need No.	Requirement	Imp.	Units	Marginal value	Ideal value	Verification
6.5	55, 58, 59, 60, 61, 67	Maximize thermal conductivity	4	W/(m·K)	N/A	INF.	Further research required ¹⁵
6.6	40	Minimum temperature with reliable data that the data sheet must contain	5	Kelvin	4	0.01	Further research required ¹⁵
6.7	54, 55, 58, 61, 67	Minimize specific heat	3	(J/kg-K)	N/A	N/A	Further research required ¹⁵
6.8	31, 35	Minimum vacuum pressure to withstand	5	mbar	10^{-5} [14]	$<10^{-8}$	Material selection ¹⁹
7.		Product					
7.1	47, 68	Product lifespan	4	Years	2	>2	Physical tests ²⁰
7.2	41, 42, 43, 44, 45	Minimize interference from external noise	4	W	N/A	0	Further research required ¹⁵
8.		Shield					
8.1	41, 42, 43, 44, 45	Accommodate compatibility with interference shield	4	Binary	Pass	Pass	Measurement in CAD ²¹
8.2	21, 22	Minimum clearance between shield and sample holder	3	mm	0.2	N/A	Measurement in CAD ²²

4. Findings

Table 4.5: Explanations of the verification methods noted in the requirement specification.

Note	To verify:
1	A visual inspection must be performed to confirm that the product is not superficially contaminated from the specified distance.
2	That the cost will be less than specified, a cost analysis including materials and manufacturing will need to be carried out.
3	That the lead time is below the marginal value, manufacturing methods must be evaluated and timed. Lead time in this aspect is defined as the time from the order being accepted to the order is finished for delivery.
4	The number of samples to be accommodated, a product draft and CAD software will be used to confirm that the space is large enough to accommodate at least one sample.
5	To verify that the sample holder will be able to maintain the operating temperature, a thermal simulation must be performed to investigate the thermal load and thermal effects on the sample holder.
6	That the sample holder will accommodate the number of cables, a draft and design must be made using CAD software.
7	That the system will resist deformation and cracking, a safety factor is applied to avoid the risk of failure of the sample holder during cooling, use and heating.
8	That the cable holders are marked, a visual inspection must be performed from a specified distance with the markings visible.
9	That the cables are pre-installed, a visual inspection from the specified distance confirms that the cables are installed, and by measuring the cable connection using a signal test.
10	That parts and cables are dismountable, no permanent fixing methods can be used.
11	The height of the sample holder, measurements in CAD software must be performed to ensure that it does not exceed the internal dimensions of the Bluefors LD400.
12	That the diameter of the sample holder is larger than the PCB, measurements using CAD software must be performed.
13	The minimum height of the sample holder, design and CAD software must be used to confirm that the minimum distance is the measurement of the sample housing plus the measurement of an average sized hand to be able to change cables.
14	The height of the shield, CAD software must be used to ensure that the height of the shield is at least the height of the sample holder.
15	Further research is required to provide specific values.
16	That materials with diamagnetic properties are used, the material magnetic susceptibility must be less than zero.

Table 4.5 continued from previous page

17	That materials are suitable for the specified service temperature, the materials must be added and simulated in simulation software.
18	Oxidation and corrosion, the materials used and their oxidation and corrosion properties shall be studied to ensure that oxidation and corrosion are minimised. The subjective measure represents a material's resistance to corrosion and oxidation, with higher values indicating that materials have less resistance to corrosion and oxidation.
19	That the material can operate at the specified vacuum level, a material selection must be made from a list of materials confirmed for the specified vacuum pressure.
20	The service life of the product, physical tests such as cooling and heating cycles must be carried out to confirm that the product can withstand the specified service life.
21	That the shield is compatible with the sample holder, a product draft and CAD software must be used to confirm compatibility.
22	The diameter, a product draft and CAD software must be used to ensure that the dimension is met and that the dimension varies with the diameter of the sample holder.

4.5 Materials Study

The following section presents the results of the materials study. The findings presented are related to the material literature study carried out and the predictions made for the thermal conductivities of the remaining materials suitable for quantum computing hardware at ultra-low temperatures.

4.5.1 Material Literature Study

A literature study was undertaken with the primary objective of identifying a comprehensive selection of materials specifically suitable for cryogenic applications. The study resulted in a total of 117 material names being obtained from various sources and examined in detail. The materials found were compiled and collected and are shown in Table 4.6.

4. Findings

Table 4.6: Identified materials for cryogenic applications through the literature study.

Material name	Source
Copper, Yttrium Barium Copper Oxide (YBCO)	[94]
Stainless Steel 316	[64]
Stainless Steel 303	[36]
Stainless Steel 321	[64]
Stainless Steel 347	[36]
Inconel 718	[15]
Stainless Steel 304	[64]
Stainless Steel 304 (annealed)	[64, 95]
Stainless Steel 304 (cold rolled 50%)	[64]
Stainless steel 304LN	[96]
Stainless Steel 304N (annealed)	[64]
Stainless steel 316LN	[96]
Aluminium 2014-T651 (precip hardened)	[64]
Aluminium 2024-T5	[64]
Aluminium 6061	[96, 95]
ETP Copper	[97]
Stainless steel 310	[15]
Lithium	[64]
Magnesium	[64]
Molybdenum	[64]
Niobium	[96, 98, 64]
Platinum	[64]
Sodium	[64]
Titanium	[96, 64]
Tungsten	[64]
Vanadium	[64]
Aluminium	[65, 64]
Potassium	[64]
Titanium A-110AT	[64]
Ti6Al4V	[15, 64]
Beryllium copper (High strength)	[99, 15]
Constantan	[36]
Aluminium 5052-0	[64]
Aluminium 1100	[65, 96, 64]
Aluminium 1100-O (RRR=14)	[64]
Brass	[36, 64]
Copper - lead	[36]
Aluminium 3003	[15, 36]
Aluminum Nitride (AlN)	[100]
Beryllium Oxide (BeO)	[64]
Invar	[96]
Mild steel	[36, 64]
Cobalt	[64]
Fe (zone purified)	[64]

Table 4.6 continued from previous page

Material name	Source
Fe-9%Ni (quenched and tempered)	[64]
Iron	[64]
Nickel	[64]
Cryoperm	[31]
Monel (drawn)	[36]
Copper, Oxygen-free copper (UNS C10200)	[64]
Admiralty brass (annealed) [approximately 70% copper and 30% zinc]	[64]
Alumina	[64]
Annealed Pyrolytic Graphite (APG) (// to layer planes)	[64]
Beryllium	[64]
Beryllium copper (High conductivity, 0.2-0.7% [101])	[99, 15]
Bismuth (99.997% pure)	[102]
Cadmium (Well annealed 99.9995 pure)	[64]
Copper (99.95% annealed)	[64]
Copper (cold drawn 60%)	[64]
Copper (OFHC), (RRR=100)	[64]
Copper (OFHC), (RRR=150)	[103]
Copper (OFHC), (RRR=20)	[64]
Copper (OFHC), (RRR=300)	[64]
Copper (OFHC), (RRR=500)	[64]
Copper (RRR=50)	[103]
Copper-2%Be	[64]
Copper, 99.999% pure copper	[36]
Copper, Elec. T.P, OFHC	[36]
Copper, Electrolytic tough pitch 99.95% pure copper	[36]
Copper, Electrolytic-tough-pitch (ETP) copper (UNS C10300)	[64]
Copper, High-purity	[65]
Copper, OFHC copper	[65, 96, 95]
Copper, Oxygen-free copper (UNS C10100)	[64, 23]
Cu-Ni60-40	[64]
Diamond (High -purity, high-perfection, water-white)	[64]
Epoxy (unfilled)	[64]
Gold (Well-annealed 99.999% pure)	[64]
Graphene	[104].
Indium	[36]
Kapton	[96, 64]
Lead	[64]
Mylar	[64]
Nylon	[64, 36]
Perspex	[36]
Phosphor bronze	[64]
Phosphorus deoxidized Copper	[64]
Polycarbonate	[64]
Quartz	[96, 36, 64]
Sapphire	[65, 64]

Table 4.6 continued from previous page

Material name	Source
Silicon	[65, 105], [106, 64]
Silver (Well-annealed 99.999% pure)	[65, 64, 36]
Tellurium Copper	[36]
Zinc (Well-annealed 99.999% pure)	[64]
Fe-Ni-Cr-N	[96]
Fe-Mn-Cr-N	[96]
MLI	[64]
G-10 (fill)	[64]
G-10 (warp)	[64]
G-10 Fiberglass epoxy (normal direction)	[64]
G-10 Fiberglass epoxy (warp direction)	[64]
Aluminium 6063	[96]
Aluminium 6063-T5	[64]
Aluminium 99%	[36]
Epoxy (NASA#2)	[64]
Inconel 908	[96, 64]
Pyrex	[36, 64]
Teflon	[96, 64, 36]
TFE	[64]
Chromium	[64]
Aluminium (200)	[64]
Aluminium (RRR=1000)	[64]
Aluminium 1101-F	[64]
Aluminium alloy 5145-C	[36]
Coalesced	[36]
Coalesced-annealed	[36]
IMI 7031 varnish	[64]
K-core	[64]

In order to assess the suitability of the 117 materials for the intended quantum computing applications, a detailed analysis was carried out, with particular emphasis on their magnetic properties. The importance of the analysis stemmed from the requirements list in Table 4.4 under Criterion 6.1, which specified the need to use only diamagnetic materials. As a result of this analysis, materials exhibiting any other form of magnetism were eliminated from further consideration, leaving only the select group of diamagnetic materials that met the requirement. The remaining 42 diamagnetic materials have been compiled and presented in Table 4.7. The table serves as a resource for researchers, engineers and stakeholders interested in identifying and exploring suitable diamagnetic materials for cryogenic applications.

Table 4.7: The material list, including materials for cryogenic applications found in the literature that are diamagnetic.

Material name	Source	Magnetic property
Alumina	[64]	Diamagnetic [107]
Annealed Pyrolytic Graphite (APG) (// to layer planes)	[64]	Diamagnetic [108]
Beryllium	[64]	Diamagnetic [109]
Beryllium copper (High conductivity, 0.2-0.7% [101])	[99, 15]	Diamagnetic [110]
Bismuth (99.997% pure)	[102]	Diamagnetic [111]
Cadmium (Well annealed 99.9995% _{oo} pure)	[64]	Diamagnetic [111]
Copper (99.95% annealed)	[64]	Diamagnetic [111]
Copper (cold drawn 60%)	[64]	Diamagnetic [111]
Copper (OFHC), (RRR=100)	[64]	Diamagnetic [111]
Copper (OFHC), (RRR=150)	[103]	Diamagnetic [111]
Copper (OFHC), (RRR=50)	[64]	Diamagnetic [111]
Copper (OFHC), (RRR=300)	[64]	Diamagnetic [111]
Copper (OFHC), (RRR=500)	[64]	Diamagnetic [111]
Copper (RRR=20)	[103]	Diamagnetic [111]
Copper-2%Be	[64]	Diamagnetic [109, 111]
Copper, 99.999% pure copper	[36]	Diamagnetic [111]
Copper, Elec. T.P, OFHC	[36]	Diamagnetic [112, 111]
Copper, Electrolytic-tough-pitch (ETP) copper	[36]	Diamagnetic [112, 111]
Copper, Electrolytic-tough-pitch (ETP) copper (UNS C10300)	[64]	Diamagnetic [112, 111]
Copper, High-purity	[65]	Diamagnetic [111]
Copper, OFHC copper	[65, 96, 95]	Diamagnetic [112, 111]
Copper, Oxygen-free copper (UNS C10100)	[64, 23]	Diamagnetic [112]
Cu-Ni60-40	[64]	Diamagnetic [113]
Diamond (High-purity, high-perfection, water-white)	[64]	Diamagnetic [114]
Epoxy (unfilled)	[64]	Diamagnetic [111]
Gold (Well-annealed 99.999% pure)	[64]	Diamagnetic [111]
Graphene	[104].	Diamagnetic [115]
Indium	[36]	Diamagnetic [111]
Kapton	[96, 64]	Diamagnetic [116]
Lead	[64]	Diamagnetic [111]
Mylar	[64]	Diamagnetic [117]
Nylon	[64, 36]	Diamagnetic [117]
Perspex	[36]	Diamagnetic [118]
Phosphor bronze	[64]	Diamagnetic [97]

Table 4.7 continued from previous page

Material name	Source	Magnetic property
Phosphorus deoxidized Copper	[64]	Diamagnetic [113]
Polycarbonate	[64]	Diamagnetic [117]
Quartz	[96, 36, 64]	Diamagnetic [119]
Sapphire	[65, 64]	Diamagnetic [119]
Silicon	[65, 105, 106, 64]	Diamagnetic [111]
Silver (Well-annealed 99.999% pure)	[65, 64, 36]	Diamagnetic [111]
Tellurium Copper	[36]	Diamagnetic [119]
Zinc (Well-annealed 99.999% pure)	[64]	Diamagnetic [120]

A further analysis was carried out to check the viability of the remaining 42 materials for quantum computing applications. The analysis was carried out to assess the superconducting properties of the materials below 300 Kelvin. The analysis was based on the requirement outlined in Table 4.4, under Criterion 6.2, which prohibits the use of materials that exhibit superconductivity. The results showed that some materials became superconducting and were therefore not suitable for the application, as a superconducting material does not conduct heat. The remaining 35 non-superconducting materials are listed in Table 4.8.

Table 4.8: The material list, including the materials found in the literature for cryogenic applications, which are diamagnetic and not superconducting.

Material name	Source	Magnetic property	Super-conducting
Alumina	[64]	Diamagnetic [107]	-
Annealed Pyrolytic Graphite (APG) (// to layer planes)	[64]	Diamagnetic [108]	-
Beryllium copper (High conductivity, 0.2-0.7% [101])	[99, 15]	Diamagnetic [110]	-
Copper (99.95% annealed)	[64]	Diamagnetic [111]	-
Copper (cold drawn 60%)	[64]	Diamagnetic [111]	-
Copper (OFHC), (RRR=100)	[64]	Diamagnetic [111]	-
Copper (OFHC), (RRR=150)	[103]	Diamagnetic [111]	-
Copper (OFHC), (RRR=50)	[64]	Diamagnetic [111]	-
Copper (OFHC), (RRR=300)	[64]	Diamagnetic [111]	-

Table 4.8: The material list, including the materials found in the literature for cryogenic applications, which are diamagnetic and not superconducting.

Material name	Source	Magnetic property	Super-conducting
Copper (OFHC), (RRR=500)	[64]	Diamagnetic [111]	-
Copper (RRR=20)	[103]	Diamagnetic [111]	-
Copper-2%Be	[64]	Diamagnetic [109, 111]	-
Copper, 99.999% pure copper	[36]	Diamagnetic [111]	-
Copper, Elec. T.P, OFHC	[36]	Diamagnetic [112, 111]	-
Copper, Electrolytic-tough-pitch (ETP) copper	[36]	Diamagnetic [112, 111]	-
Copper, Electrolytic-tough-pitch (ETP) copper (UNS C10300)	[64]	Diamagnetic [112, 111]	-
Copper, High-purity	[65]	Diamagnetic [111]	-
Copper, OFHC copper	[65, 96, 95]	Diamagnetic [112, 111]	-
Copper, Oxygen-free copper (UNS C10100)	[64, 23]	Diamagnetic [112]	-
Cu-Ni60-40	[64]	Diamagnetic [113]	-
Diamond (High-purity, high-perfection, water-white)	[64]	Diamagnetic [114]	-
Epoxy (unfilled)	[64]	Diamagnetic [111]	-
Gold (Well-annealed 99.999% pure)	[64]	Diamagnetic [111]	-
Graphene	[104].	Diamagnetic [115]	-
Mylar	[64]	Diamagnetic [117]	-
Nylon	[64, 36]	Diamagnetic [117]	-
Perspex	[36]	Diamagnetic [118]	-
Phosphor bronze	[64]	Diamagnetic [97]	-
Phosphorus deoxidized Copper	[64]	Diamagnetic [113]	-
Polycarbonate	[64]	Diamagnetic [117]	-
Quartz	[96, 36, 64]	Diamagnetic [119]	-
Sapphire	[65, 64]	Diamagnetic [119]	-
Silicon	[65, 105, 106, 64]	Diamagnetic [111]	-
Silver (Well-annealed 99.999% pure)	[65, 64, 36]	Diamagnetic [111]	-
Tellurium Copper	[36]	Diamagnetic [119]	-

Before further analysis, it was decided that each of the materials listed in Table 4.8 should be examined in detail. Through a literature review and examination of the characteristics of these materials, it was discovered that five of them had similarities that made them essentially duplicates with no apparent differences. In order to streamline the analysis process and avoid redundant evaluations, it was deemed appropriate to focus only on the material that served as the representative duplicate for each group. The duplicate materials identified were as follows:

- "Copper, Electrolytic-tough-pitch (ETP) copper (UNS C10300)" (considered the same as "Copper, Electrolytic-tough-pitch (ETP) copper")
- "Copper, High-purity" (considered the same as "Copper (OFHC), (RRR=500)")
- "Copper, OFHC copper" (considered the same as "Copper (OFHC), (RRR=500)")
- "Copper, Oxygen-free copper (UNS C10100)" (considered the same as "Copper (OFHC), (RRR=500)")
- "Copper, 99.999% pure copper" (considered the same as "Copper (OFHC), (RRR=500)")

Merging these duplicate materials into a single material allowed for a more streamlined analysis, eliminating unnecessary repetition and allowing for a focused assessment of their characteristics.

The remaining 30 materials were then analysed in terms of thermal conductivity. The analysis was carried out in accordance with requirement 6.5 of Table 4.4, which emphasised the need to maximise thermal conductivity. However, it was found that obtaining reliable cryogenic thermal conductivity data for some materials proved challenging as such information was scarce in the available literature. Despite the scarcity of information, careful research provided valuable insights into the thermal conductivities of the remaining materials at various temperatures. The results are documented in Table 4.9 and provide a valuable reference for evaluating the thermal performance of these materials at room temperature and at 90, 70, 40, 4, 3, 2 and 1 Kelvin.

Table 4.9: Material list with thermal conductivities at different temperatures.

Material name	λ_t at room temperature	λ_t at 90K	λ_t at 70k	λ_t at 40K	λ_t at 4K	λ_t at 3K	λ_t at 2K	λ_t at 1K
Alumina	36 [58]	-	-	-	-	-	-	-
Annealed Pyrolytic Graphite (APG) (// to layer planes)	2000 [58]	4730 [58]	3650 [58]	1630 [58]	-	-	-	-
Beryllium copper (High conductivity, 0.2-0.7% [101])	-	-	34.07563 [121]	21.47568 [121]	1.87877 [121]	1.40240 [121]	0.89991 [121]	-
Copper (99.95% annealed)	-	-	-	-	-	-	-	-
Copper (colled drawn 60%)	-	-	-	-	-	-	-	-
Copper (OFHC), (RRR=100)	396.324 [121]	486.98 [121]	603.558 [121]	1485.109 [121]	642.297 [121]	-	-	-
Copper (OFHC), (RRR=150)	397.641 [121]	492.66 [121]	615.476 [121]	1628.794 [121]	961.763 [121]	-	-	-
Copper (OFHC), (RRR=50)	392.368 [121]	465.129 [121]	561.112 [121]	1163.361 [121]	320.383 [121]	-	-	-
Copper (OFHC), (RRR=300)	397.874 [121]	501.022 [121]	638.502 [121]	1833.292 [121]	1888.379 [121]	-	-	-
Copper (OFHC), (RRR=500)	401.187 [121]	508.864 [121]	645.921 [121]	1975.835 [121]	3181.685 [121]	-	-	-
Copper (RRR=20)	-	-	-	-	-	-	-	-
Copper-2%Be	105 [122]	-	34.076 [56]	21.476 [56]	1.879 [56]	1.402 [56]	0.8999 [56]	0.3161 [56]
Copper, Elec. T.P, OFHC	-	-	-	-	-	-	-	-
Copper, Electrolytic-tough-pitch (ETP) copper	388 [122]	-	-	1180 [57]	320 [57]	-	-	-
Cu-Ni60-40	-	18.9 [57]	-	-	-	-	-	-
Diamond (High-purity, high-perfection, water-white)	2310 [58]	11000 [58]	12000 [58]	8020 [58]	26.6 [58]	11.5 [58]	3.41 [58]	0.437 [58]
Epoxy (unfilled)	-	-	-	-	-	-	-	-
Gold (Well-annealed 99.999% pure)	315 [57]	348 [57]	358 [57]	520 [57]	1710 [57]	1310 [57]	885 [57]	444 [57]
Graphene	-	-	-	-	-	-	-	-
Mylar	-	-	0.1526 [56]	0.1158 [56]	0.03978 [56]	0.03610 [56]	0.03092 [56]	-
Nylon	0.337 [121]	0.309 [121]	0.282 [121]	0.2 [121]	0.012 [121]	-	-	-
Perspex	-	-	-	-	0.00057 [58]	-	-	-
Phosphor bronze	-	-	-	51.4 [123]	4.11 [123]	3.19 [123]	1.95 [123]	-
Phosphorus deoxidized Copper	340 [124]	-	-	85 [57]	6.5 [124]	-	-	-
Polycarbonate	-	-	-	-	-	-	-	-
Quartz	10.4 [125]	45 [125]	66 [?]	179 [125]	-	-	-	-
Sapphire	46 [58]	640 [58]	1530 [58]	12000 [58]	-	-	-	3.9 [58]
Silicon	148 [57]	1340 [57]	1680 [57]	3530 [57]	226 [57]	99.8	31.7 [57]	4.48 [57]
Silver (Well-annealed 99.999% pure)	427 [57]	460 [57]	497 [57]	1050 [57]	14700 [57]	11500 [57]	7830 [57]	3940 [57]
Tellurium Copper	-	-	-	-	-	-	-	-

The materials with insufficient thermal conductivity data were then sorted out. The sorting was based on requirement 6.6 in Table 4.4, which states that materials must have reliable data down to temperatures of 4 Kelvin. However, it was decided to include all materials that had data at cryogenic temperatures, which meant that the materials only had to have data at and below 123.15 Kelvin. The temperature of 123.15 Kelvin was set to ensure that materials that may have the potential to have high thermal conductivity at ultra-low temperatures were not excluded. The inclusion was made on the basis that reliable data can be obtained by testing the materials of interest in future studies.

After the sorting, 21 materials remained, and all the thermal conductivity data found for the materials are presented in Appendix C.1 - C.21. However, the lowest temperature with data found for the materials was at 1 Kelvin with many materials having the lowest data at much higher temperatures, which does not meet or exceed requirement 6.6, and therefore an attempt was made to calculate the thermal conductivity at the ultra-low temperatures of 10 and 20 milliKelvin. The results of the calculation were found to be invalid and are therefore not shown.

4.5.2 Materials Study predictions

After identifying the invalidity of the calculations of thermal conductivity at ultra-low temperatures, further analysis was conducted to make predictions based on the gathered thermal conductivities. The analysis aimed to bridge the data gap and provide valuable insights. The results, presented in Table 4.10, encompass the remaining 21 materials with actual thermal conductivity data ranging from 10 Kelvin down to 1 Kelvin, accompanied by predicted values at ultra-low temperatures of 10 and 20 milliKelvin.

At temperatures of 10, 5, 4, 2, and 1 Kelvin, Silver exhibits the highest thermal conductivity among the materials considered. Following closely, Copper (OFHC), (RRR=500) attains the second-highest thermal conductivity at temperatures of 10, 5, and 4 Kelvin, but surpasses all others at the predicted temperatures, with silver as the second highest. Copper (OFHC), (RRR=300) secures the third-highest thermal conductivity values at temperatures of 10, 5, and 4 Kelvin, as well as at the predicted temperatures. Lastly, Gold emerges as the material with the second-highest thermal conductivity at 2 and 1 Kelvin. The thermal conductivity plots for the four materials can be seen in Figures 4.3-4.6, and the remaining material's thermal conductivity plots can be seen in Appendix D. In the figures and in Appendix D, the plots show the thermal conductivity of the materials as a function of temperature, where the blue dots represent the actual data, the yellow dots represent the predicted values at temperatures corresponding to the actual data points, and the predicted values as red dots. When the blue and the yellow dots overlap, the dots can be visualised as purple, meaning a high accuracy of the predictions.

Table 4.10: Actual and predicted thermal conductivity at a variety of temperatures for the remaining materials.

Material	Actual										Predicted			
	λ_t at 10 K	λ_t at 5 K	λ_t at 4 K	λ_t at 3.03 K	λ_t at 2.5 K	λ_t at 2 K	λ_t at 1.66 K	λ_t at 1K	λ_t at 20mK	λ_t at 10mK				
Annealed Pyrolytic Graphite (APG) (// to layer planes)	81	-	-	-	-	-	-	-	0.00	0.00				
Beryllium copper (High conductivity, 0.2-0.7% [101])	4.95496	2.35801	1.87877	-	-	0.89991	-	-	0.00	0.00				
Copper (OFHC), (RRR=100)	1539.91558	783.2086	642.29696	-	-	-	-	-	253.18	252.68				
Copper (OFHC), (RRR=150)	2274.74662	1173.12811	961.76251	-	-	-	-	-	372.36	371.59				
Copper (OFHC), (RRR=50)	778.14877	391.87389	320.38313	-	-	-	-	-	114.71	114.42				
Copper (OFHC), (RRR=300)	4319.90467	2357.60035	1888.37931	-	-	-	-	-	441.63	439.21				
Copper (OFHC), (RRR=500)	6877.72	3896.211	3181.685	-	-	-	-	-	1155.92	1156.03				
Copper-2%Be	4.955	-	1.879	-	-	0.899	-	0.3161	0.00	0.00				
Copper, Electrolytic-tough-pitch (ETP) copper	800	400	320	-	-	-	-	-	54.91	54.28				
Cu-Ni60-40	-	-	-	0.56	-	-	-	-	0.00	0.00				
Diamond (High-purity, high-perfection, water-white)	324	50.2	26.6	-	-	3.41	-	0.437	1.67	1.70				
Gold (Well-annealed 99.999% pure)	2820	2070	1710	-	-	885	-	444	20.52	16.26				
Mylar	0.04791	-	0.03764	-	-	0.03092	-	-	0.03	0.03				
Nylon	0.03902	-	0.01245	-	-	-	-	-	0.00	0.00				
Perspex	-	0.0006	0.00057	-	0.00049	-	-	-	0.000279	0.000278				
Phosphor bronze	-	-	-	3.19	-	-	1.45	-	0.00	0.00				
Phosphorus deoxidized Copper	19.3	9.1	6.5	-	-	-	-	-	0.00	0.00				
Quartz	1650	400	-	-	-	-	-	-	0.00	0.00				
Sapphire	2900	410	-	-	-	-	-	3.9	0.00	0.00				
Silicon	2110	424	226	-	-	31.7	-	4.48	0.00	0.00				
Silver (Well-annealed 99.999% pure)	16800	17200	14700	-	-	7830	-	3940	472.51	440.17				

4. Findings

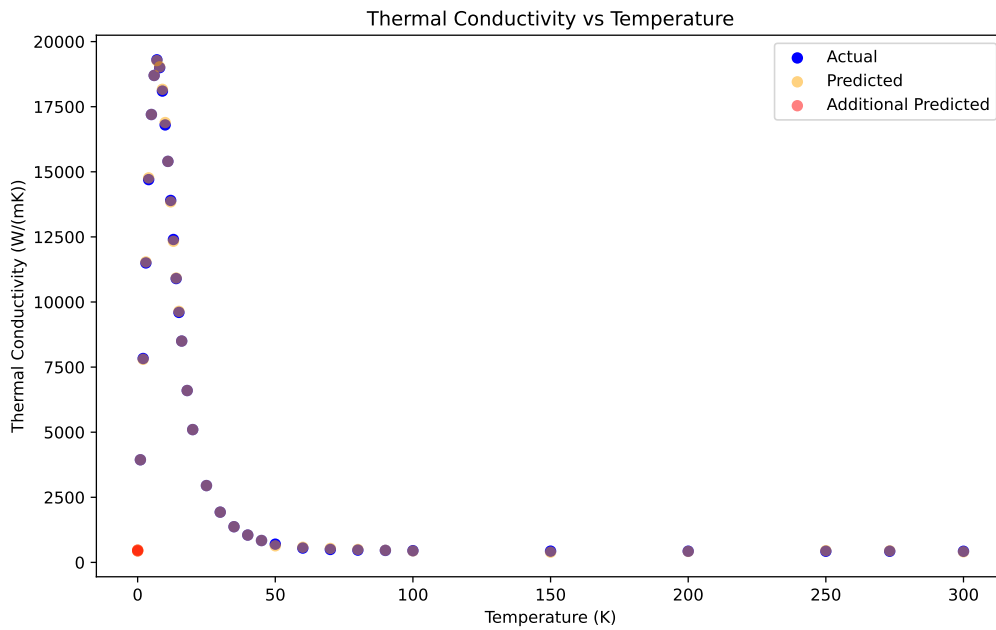


Figure 4.3: Plot showing the thermal conductivity of silver as a function of temperature, with actual data obtained from Touloukian et al. [57], predicted values at temperatures corresponding to the actual data points and predicted values at 10 and 20 milliKelvin.

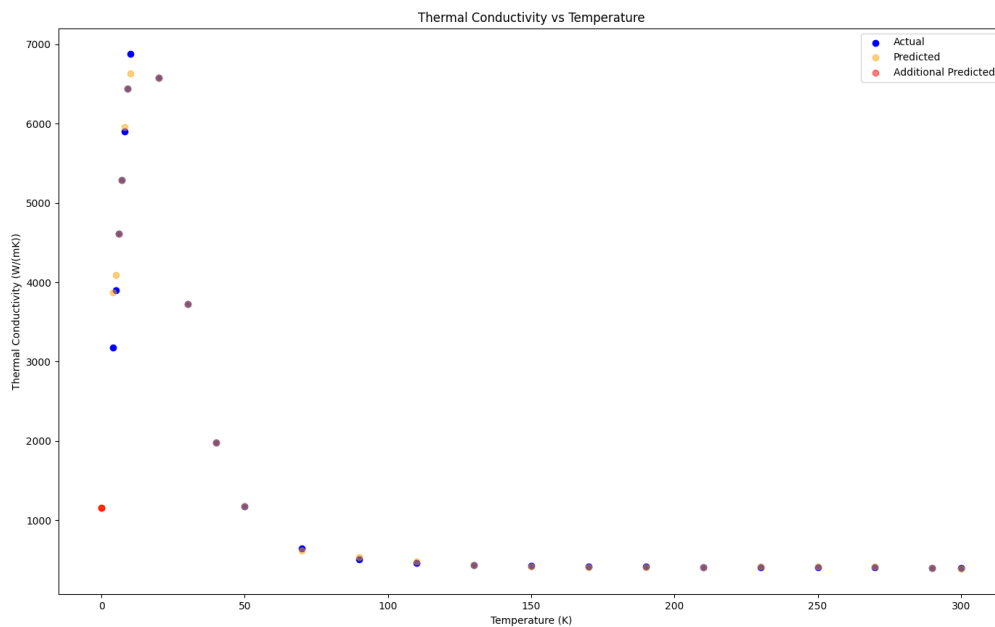


Figure 4.4: Plot showing the thermal conductivity of Copper (OFHC), (RRR=500) as a function of temperature, with the actual data obtained from the National Institute of Standards and Technology [121], the predicted values at temperatures corresponding to the actual data points, and predicted values at 10 and 20 milliKelvin.

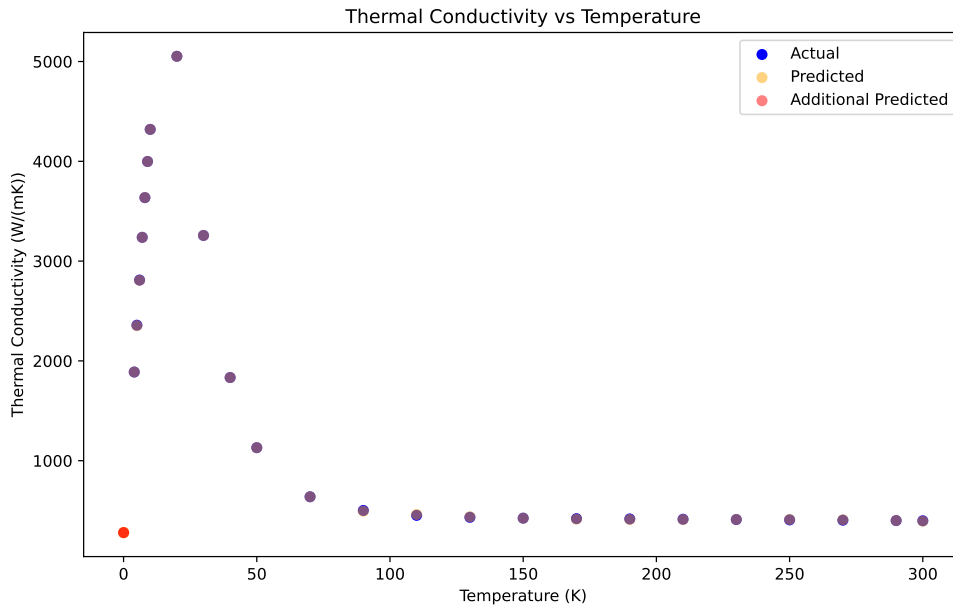


Figure 4.5: Plot showing the thermal conductivity of Copper (OFHC), (RRR=300) as a function of temperature, with actual data obtained from the National Institute of Standards and Technology [121], the predicted values at temperatures corresponding to the actual data points, and predicted values at 10 and 20 milliKelvin.

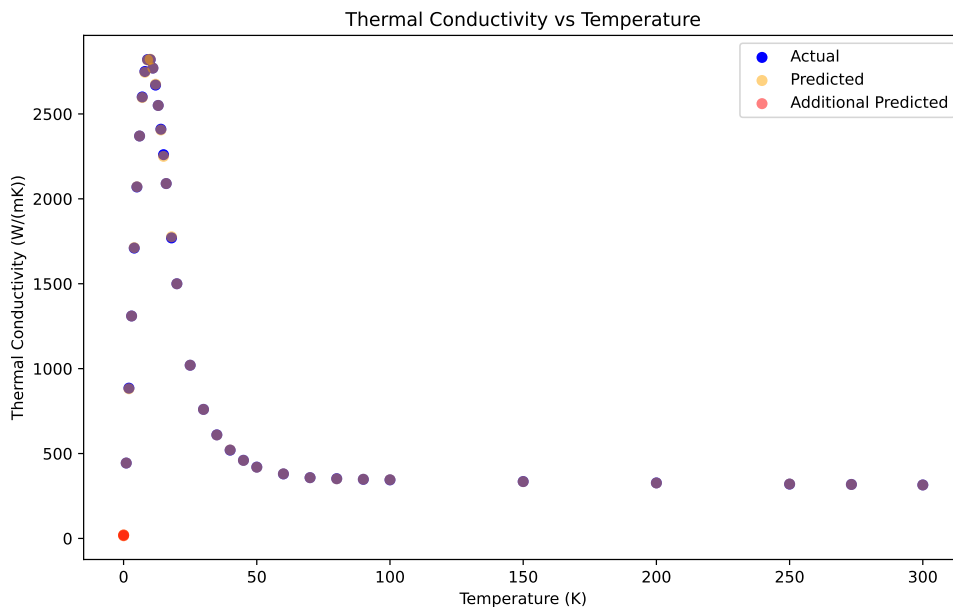


Figure 4.6: Plot showing the thermal conductivity of gold as a function of temperature, with actual data obtained from Touloukian et al. [57], predicted values at temperatures corresponding to the actual data points, and predicted values at 10 and 20 milliKelvin.

4.6 Ansys Granta EduPack Materials study

Due to the limitations of the Ansys Granta EduPack software, which only provides data at room temperature, attempts to obtain valid results for the desired analysis were unsuccessful. Hence, the inherent limitations of the software limited the ability to investigate temperature-dependent data.

4.7 Simulations

The following section presents the results of the simulations carried out. Firstly, a material selection had to be defined in the software before the simulations could be performed. The results of the material selection are presented below followed by the results of the verification simulations. Finally, the results of the ultra-low temperature simulations carried out on simplified versions of the LINQER 52 are presented in the last sub-section.

From section 4.5, the material with the highest thermal conductivity was silver. In combination with having the highest thermal conductivity, silver is known to be a relatively soft material. It was therefore considered a fitting example to run simulations with to see if it met or exceeded Requirement 4.4 (Design-safety factor of 1.5-2) in Table 4.4. While using Ansys to set up the simulations it was found that the Ansys material database had different material data than that found in the literature study. The thermal conductivity data for silver in the Ansys material database can be seen in Table 4.11 where the lowest data included is at 3.05 Kelvin. The density data for silver in the Ansys material database only include one data point which was that the density at 23 Celsius (296.15 Kelvin) was 10490 kg/m³ [126]. The coefficient of thermal expansion data for silver in the Ansys material database can be seen in Table 4.12 where the lowest data included is at 3.05 Kelvin. It was therefore decided to copy the material data from Ansys and add the data from the literature study to be able to run simulations at ultra-low temperatures (<1 Kelvin). Hereinafter, the silver from the Ansys material database will be referred to as "Ansys silver" and the material data from the literature study will be referred to as "modified silver".

Table 4.11: Thermal conductivity data and temperature for pure Silver (Ansys silver) found in the Ansys material database [126].

Temperature (K)	Thermal conductivity (W/(m·K))
3.05	11350
48.55	745.9
94.15	444.8
139.65	425.1
185.22	421.8
230.78	421.1

276.33	420.5
321.89	419.4
367.44	417.8
413.05	415.7
458.55	413.2
504.15	410.4
549.65	407.4
595.25	404.2
640.75	400.8
686.35	397.2
731.85	393.6
777.45	389.9
823.05	386.2
868.55	382.4
914.15	378.6
959.65	374.8
1005.25	371
1050.75	367.1
1096.35	363.2
1141.85	359.2
1187.45	355.1
1233.05	350.8

Table 4.12: Coefficient of thermal expansion data and temperature for pure Silver (Ansys silver) found in the Ansys material database [126].

Temperature (K)	Coefficient of thermal expansion (C^{-1})
3.05	$1.444 \cdot 10^{-5}$
65.15	$1.709 \cdot 10^{-5}$
127.25	$1.815 \cdot 10^{-5}$
189.43	$1.883 \cdot 10^{-5}$
251.57	$1.942 \cdot 10^{-5}$
313.71	$1.991 \cdot 10^{-5}$
375.85	$2.031 \cdot 10^{-5}$
438.05	$2.064 \cdot 10^{-5}$
500.15	$2.091 \cdot 10^{-5}$
562.25	$2.112 \cdot 10^{-5}$
624.45	$2.13 \cdot 10^{-5}$
686.55	$2.143 \cdot 10^{-5}$
730.75	$2.155 \cdot 10^{-5}$
810.85	$2.165 \cdot 10^{-5}$
873.05	$2.175 \cdot 10^{-5}$

The results of the modified material data for thermal conductivity were obtained

4. Findings

from the materials study in section 4.5 and are presented in Table C.19 in Appendix D. Further, the result of the extended material data for density can be seen in Table 4.13.

Table 4.13: Density data and temperature for pure Silver (Modified silver) according to Smith et al. [128].

Temperature (K)	Density (kg/m ³)
300	10490
280	10510
263	10520
247	10530
229	10540
211	10550
196	10560
177	10570
159	10580
138	10590
120	10600
99	10610
77	10620
39	10632
30	10633
20	10633
10	19633
1	19633

The result of the extended material data for the coefficient of thermal expansion can be seen in table 4.14.

Table 4.14: Coefficient of thermal expansion data and temperature for pure Silver (Modified silver) according to Smith et al. [128].

Temperature (K)	Coefficient of thermal expansion (C ⁻¹)
110	$1.9 \cdot 10^{-5}$
100	$1.5 \cdot 10^{-5}$
90	$1.4 \cdot 10^{-5}$
80	$1.3 \cdot 10^{-5}$
70	$1.1 \cdot 10^{-5}$
60	$9.8 \cdot 10^{-6}$
50	$8.0 \cdot 10^{-6}$
40	$5.8 \cdot 10^{-6}$
30	$3.4 \cdot 10^{-6}$
20	$1.2 \cdot 10^{-6}$

10	$1.4 \cdot 10^{-7}$
9	$9.0 \cdot 10^{-8}$
8	$7.0 \cdot 10^{-8}$
7	$4.9 \cdot 10^{-8}$
6	$3.4 \cdot 10^{-8}$
5	$2.3 \cdot 10^{-8}$
4	$1.7 \cdot 10^{-8}$
3	$1.2 \cdot 10^{-8}$

4.7.1 Verification of Simulation at Ultra-low temperatures

Below are the results of the four simulations carried out on the simple cylinder to validate if the Ansys simulation software could be used under ultra-low temperature conditions. In addition, these simulations were performed to verify the validity of the modified material used in the study compared to the material from the Ansys material database. The findings were focused on equivalent Von Mises stress, directional deformation and total deformation.

The equivalent Von Mises stress for the simple cylinder at 3 Kelvin with Ansys silver can be seen in Figure 4.7, where the maximum equivalent Von Mises stress was $1.2433 \cdot 10^8$ Pascal. The result for the simple cylinder with the modified silver in terms of equivalent Von Mises stress can be seen in Figure 4.8, where the maximum equivalent Von Mises stress was $1.5075 \cdot 10^8$ Pascal.

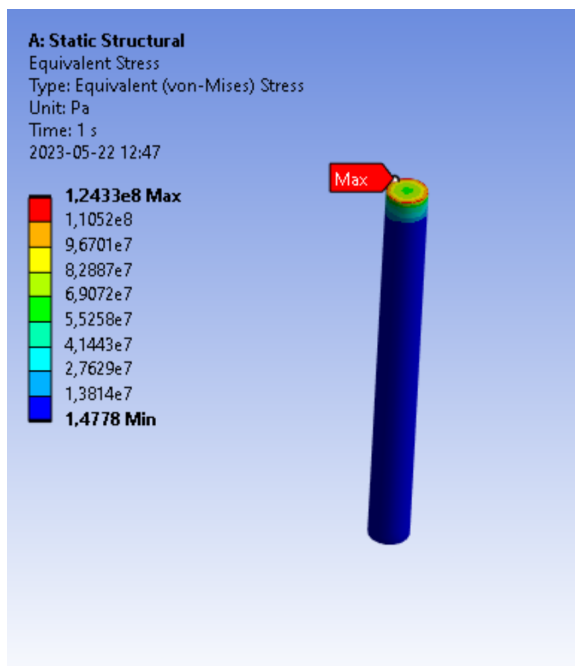


Figure 4.7: Equivalent stress Ansys silver at 3 Kelvin.

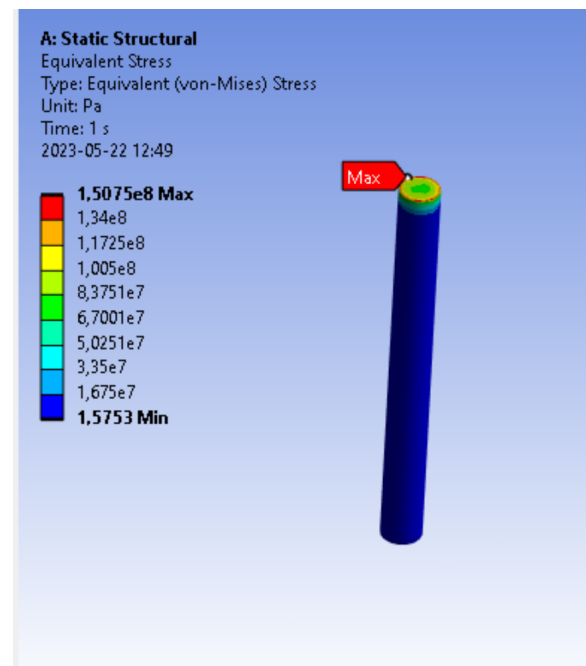


Figure 4.8: Equivalent stress modified silver at 3 Kelvin.

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The results of the simulations demonstrate that the stress concentration is at the top radius where the temperature gradient is applied. The result is considered valid in terms of where the highest stress occurs as it is close to the temperature gradient and at a relatively sharp corner. The observed equivalent stresses reveal that the stress in the modified material is higher than the Ansys material by a value of about $0.3 \cdot 10^8$ Pascal.

The simulation produced informative results regarding the directional deformation of the cylinder at 3 Kelvin, as shown in Figure 4.9 for the Ansys silver and Figure 4.10 for the modified silver. It is worth noting that the maximum directional deformation is located at the free bottom end (the red part of the cylinder). The maximum value in this case relates to the contraction of the cylinder, while a negative value indicates that the fixed end (the blue part of the cylinder) has elongated downwards. Table 4.15 provides a detailed comparison of the deformation values for each case.

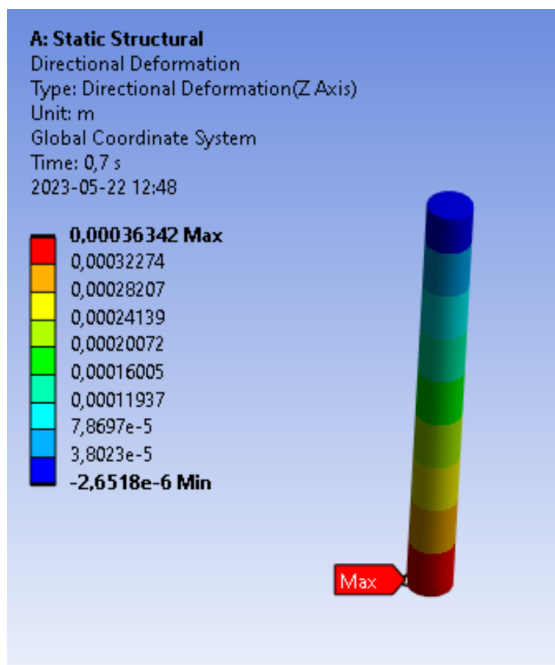


Figure 4.9: Directional deformation with Ansys silver at 3 Kelvin.

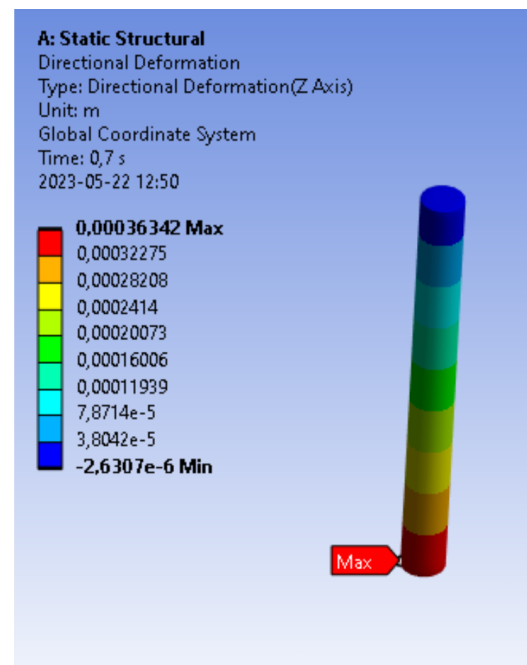


Figure 4.10: Directional deformation with modified silver at 3 Kelvin.

Table 4.15: Positive and negative deformation at 3 Kelvin.

Type	Positive directional deformation at 3 K (m)	Negative directional deformation at 3 K (m)
Cylinder (Ansys silver)	0.00036342	$-2.6518 \cdot 10^{-6}$
Cylinder (modified silver)	0.00036342	$-2.6307 \cdot 10^{-6}$

The simulation results for the total deformation of the cylinders at 3 Kelvin showed consistent results as shown in Figures 4.11 and 4.12. These figures provide a visual

representation of the deformation characteristics observed during the simulation. To further evaluate the extent of deformation, the maximum deformation values have been compiled in Table 4.16.

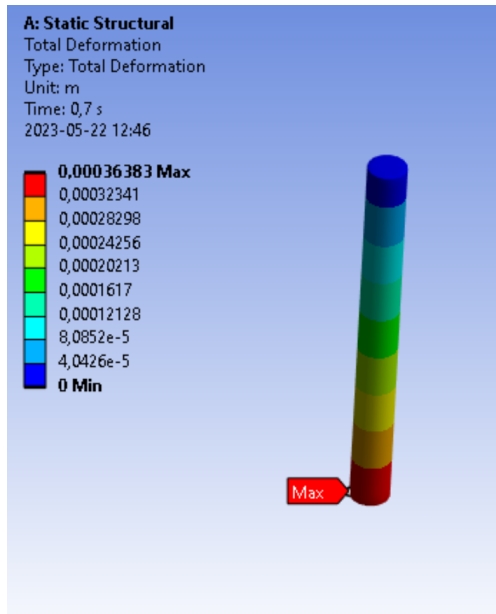


Figure 4.11: Total deformation Ansys silver at 3 Kelvin.

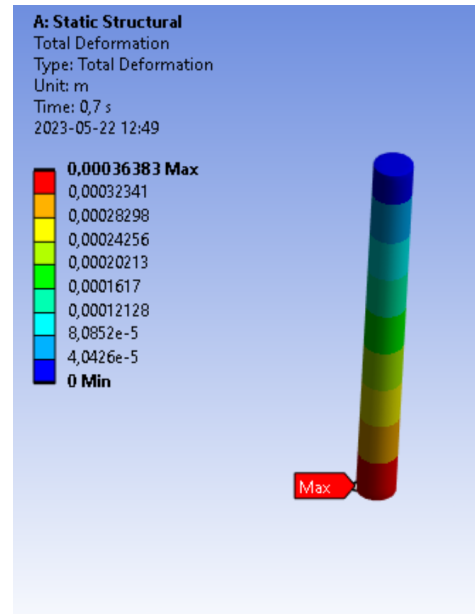


Figure 4.12: Total deformation modified silver at 3 Kelvin.

Table 4.16: Total deformation of the cylinders at 3 Kelvin.

Type	Total deformation 3K (m)
Cylinder (Ansys silver)	0.00036383
Cylinder (modified silver)	0.00036383

The next step in the verification process was to run the final two simulations to compare the behaviour of the cylinders made from two different silver materials at a temperature of 10 milliKelvin. The primary objective was to investigate and analyse the variations in material properties and their effect on the simulation results. The simulations were performed using Equivalent Stress Analysis, which provides valuable insight into the stress distribution within the cylinders. The results obtained are shown in Figures 4.13 and 4.14, which provide a visual representation of the stresses observed in the simulations. The maximum equivalent stresses for the 10 milliKelvin simulations are summarised in Table 4.17.

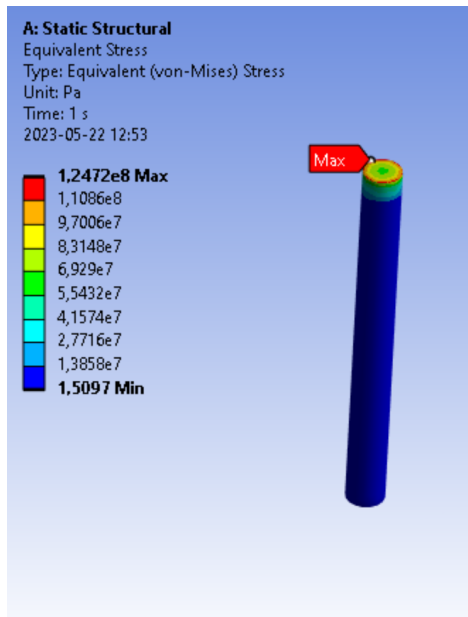


Figure 4.13: Equivalent stress for Ansys silver at 10 milliKelvin.

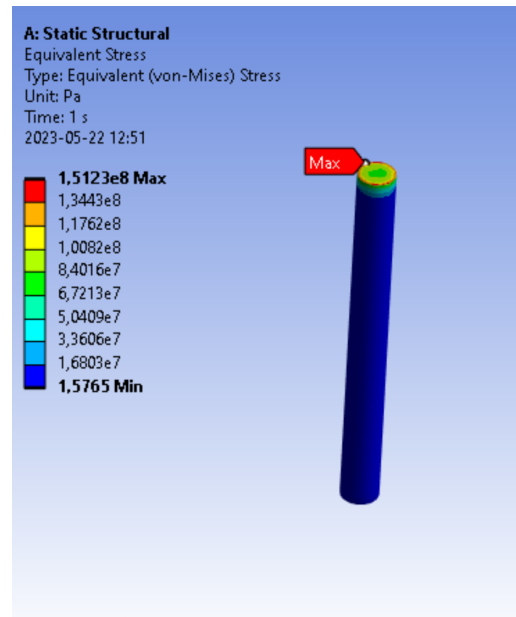


Figure 4.14: Equivalent stress for modified silver at 10 milliKelvin.

Table 4.17: Equivalent stress at 10 milliKelvin for the two cylinders.

Type	Equivalent stress 10 mK (Pa)
Cylinder (Ansys silver)	$1.2472 \cdot 10^8$
Cylinder (modified silver)	$1.5123 \cdot 10^8$

The directional deformation simulation results at 10 milliKelvin exhibited notable characteristics, with similarities observed between the results for maximum deformation (contraction) located at the free end, and minimum deformation (elongation) in the fixed end, at 3 Kelvin, as shown in Table 4.15. The simulation outcomes for the directional deformation are presented in Figure 4.15 and 4.16, providing a visual representation of the observed deformation. The maximum and minimum directional deformation for the two cylinders at 10 milliKelvin is shown in Table 4.18.

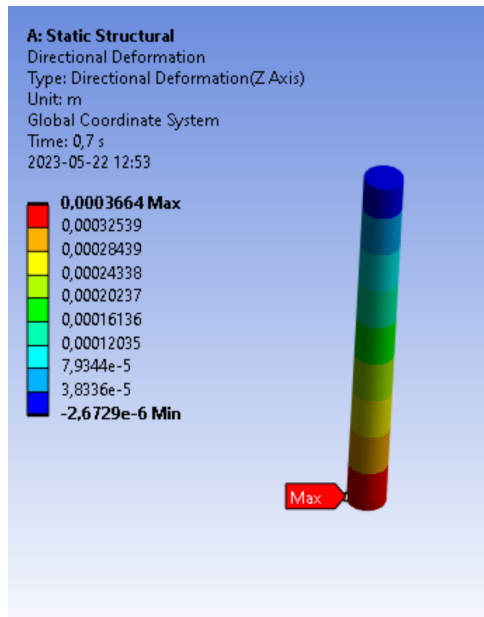


Figure 4.15: Directional deformation for the Ansys silver at 10 milliKelvin.

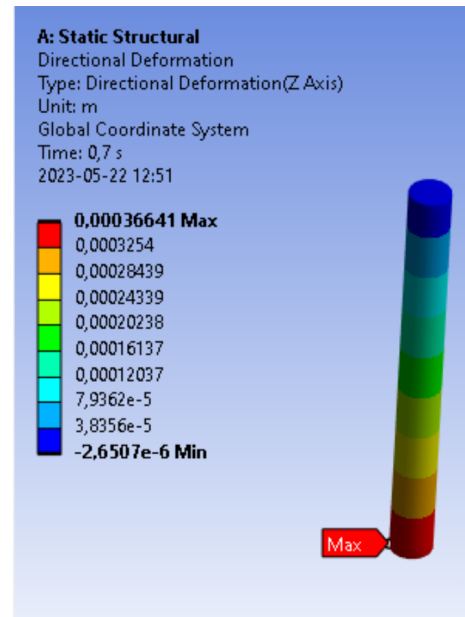


Figure 4.16: Directional deformation for the modified silver at 10 milliKelvin.

Table 4.18: Maximum and minimum directional deformation at 10 milliKelvin for the two cylinders.

Type	Directional deformation 10 mK (m)	Directional deformation 10 mK (m)
Cylinder (Ansys silver)	0.0003664	$-2.6729 \cdot 10^{-6}$
Cylinder (modified silver)	0.00036641	$-2.6507 \cdot 10^{-6}$

The simulation of the total deformation for the cylinder at 10 milliKelvin gave the results shown in Figures 4.17 and 4.18. The simulations show that both cylinders have similar overall deformation characteristics. This finding highlights the consistency in the structural response and behaviour of the cylinders under the specified temperature conditions. A summary of the maximum deformation values obtained from the total deformation simulation is given in Table 4.19.

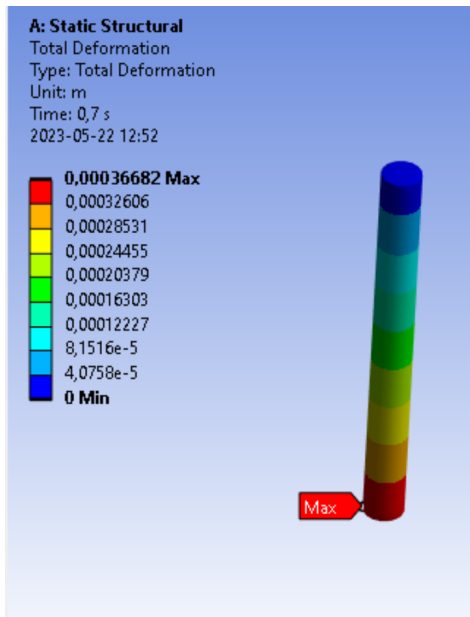


Figure 4.17: Total deformation for the Ansys silver at 10 milliKelvin.

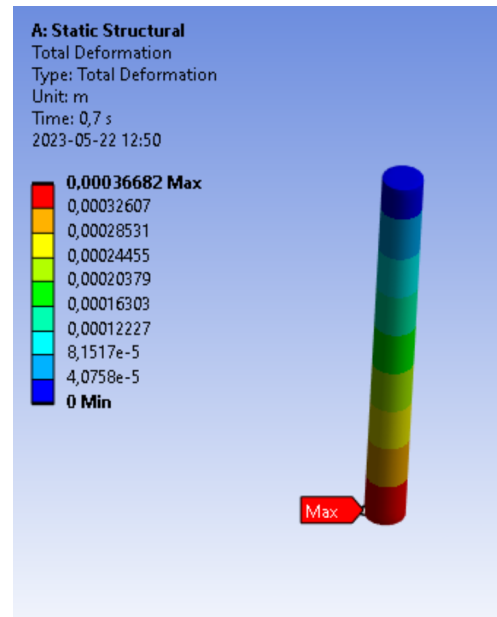


Figure 4.18: Total deformation for the modified silver at 10 milliKelvin.

Table 4.19: The maximum total deformation for the cylinders at 10 milliKelvin.

Type	Total deformation 10mK (m)
Cylinder (Ansys silver)	0.00036682
Cylinder (modified silver)	0.00036682

4.7.2 Ultra-Low Temperature Sample Holder Simulations

The following subsection presents the results of the Ansys static structural simulations, both at 3 Kelvin and 10 milliKelvin, for both the single-component and dual-component sample holders. A total of eight simulations were carried out, focusing on deformation and stress. The reason for running simulations at both 3 Kelvin and 10 milliKelvin were to be able to compare and analyse the results for validity and to gain a better understanding of how the ultra-low temperature affects the sample holders. To ensure valid results comparable to the simulations carried out on the cylinders in the previous subsection, the simulation setup was carried out in the same way, except that the design was different. In other words, the cylinders were exchanged for the two sample holders created. However, the exchange resulted in the substitution of a simple component for a more complex component.

Stress Analysis

The simulations carried out were focused on the equivalent stresses and the results shown in Figures 4.19 - 4.26, where the dark blue corresponds to a lower amount of stress, while a yellow or red colour indicates higher stress. The maximum values of equivalent stresses are presented in Table 4.20 for the eight simulations.

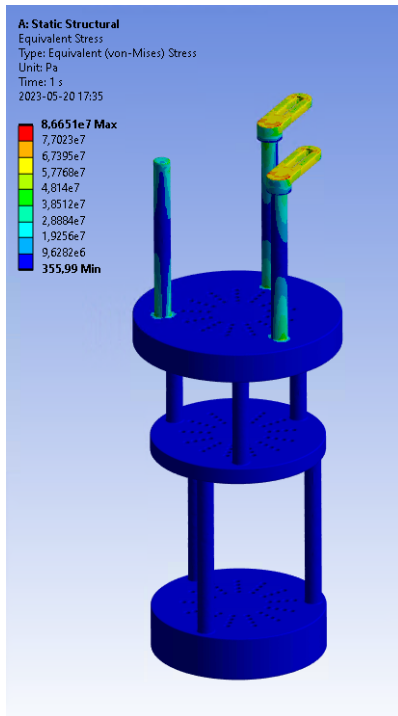


Figure 4.19: Equivalent stress for the dual component sample holder with Ansys Silver at 3 Kelvin.

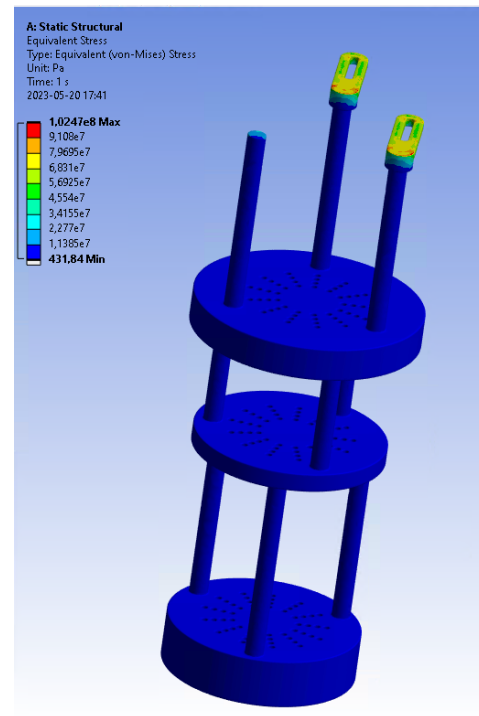


Figure 4.20: Equivalent stress for the dual component sample holder with modified Silver at 3 Kelvin.

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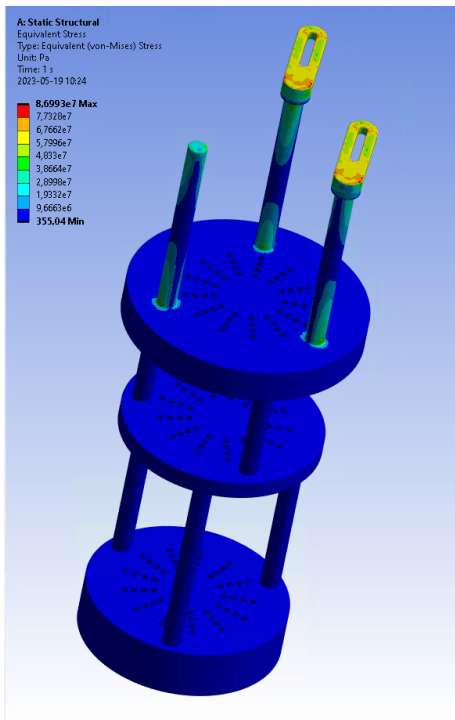


Figure 4.21: Equivalent stress for the dual component sample holder with Ansys Silver at 10 milliKelvin.

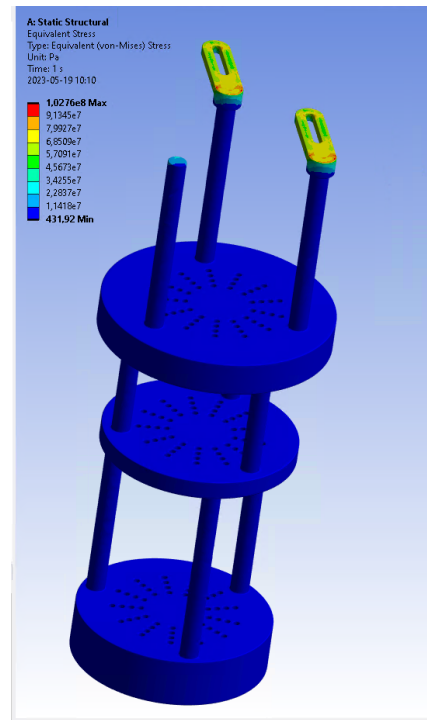


Figure 4.22: Equivalent stress for the dual component sample holder with modified silver at 10 milliKelvin.

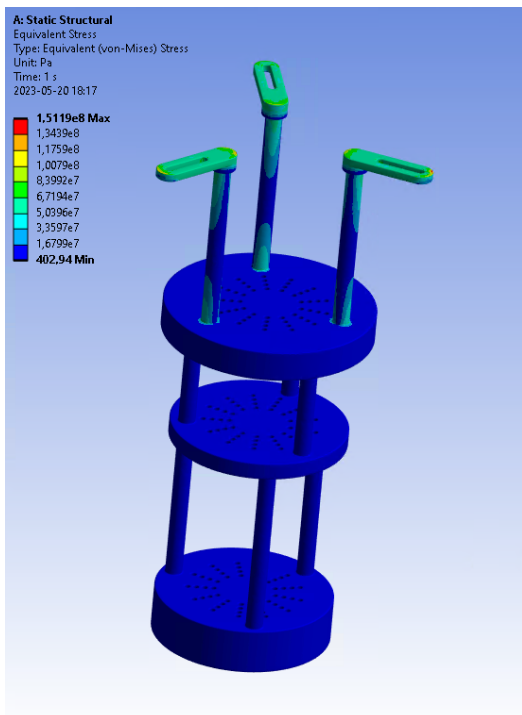


Figure 4.23: Equivalent stress for the single component sample holder with Ansys Silver at 3 Kelvin.

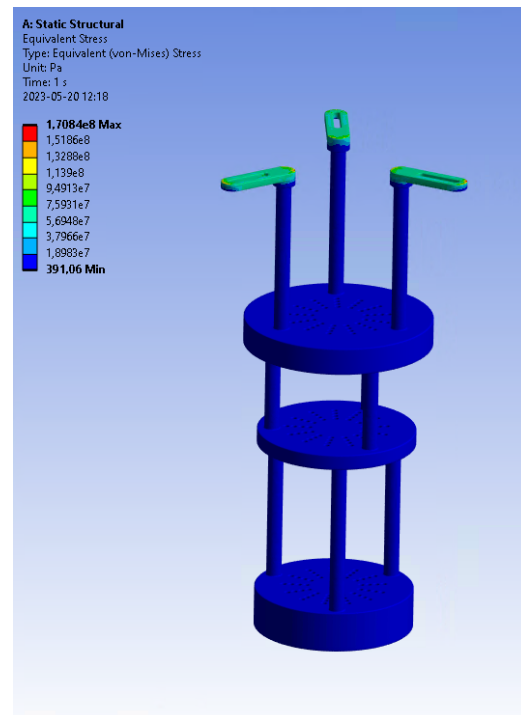


Figure 4.24: Equivalent stress for the single component sample holder with modified Silver at 3 Kelvin.

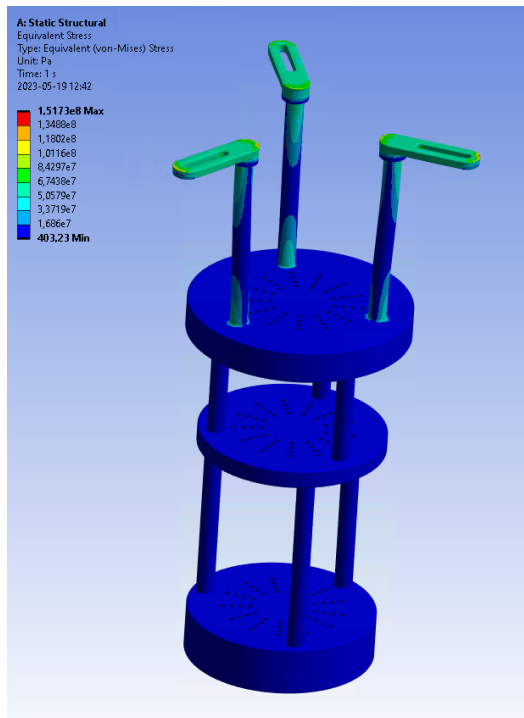


Figure 4.25: Equivalent stress for the single component sample holder with Ansys Silver at 10 milliKelvin.

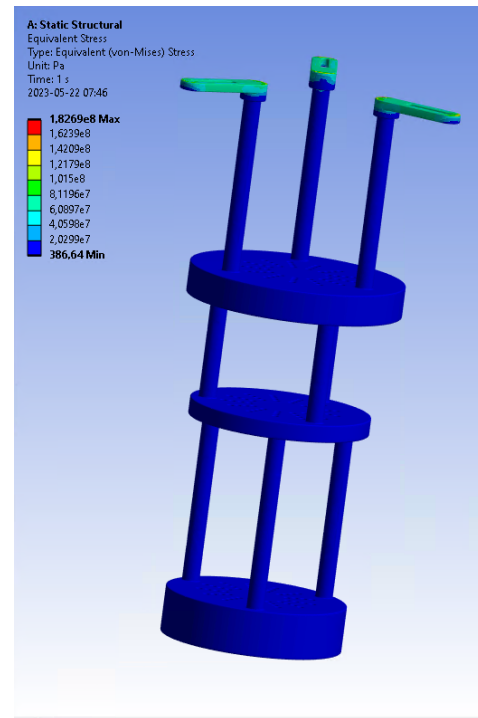


Figure 4.26: Equivalent stress for the single component sample holder with Modified silver at 10 milliKelvin.

Table 4.20: Summary of the maximum values of the equivalent stresses from the eight simulations at 10 milliKelvin and 3 Kelvin.

Type	Equivalent Stress 10mK (Pa)	Equivalent Stress 3K (Pa)
Dual component (modified silver)	$1.02760 \cdot 10^8$	$1.02470 \cdot 10^8$
Dual component (Ansys silver)	$8.69930 \cdot 10^7$	$8.66510 \cdot 10^7$
Single component (modified silver)	$1.82690 \cdot 10^8$	$1.70840 \cdot 10^8$
Single component (Ansys silver)	$1.51730 \cdot 10^8$	$1.51190 \cdot 10^8$

Deformation Analysis

In the simulations, two distinct types of deformation analyses were conducted, which were directional deformation and total deformation. The results of the directional deformation analysis will first be presented, followed by the total deformation analysis results.

Figure 4.27 and 4.28 provide a visual representation of the directional deformation observed in the dual component sample holder at 3 Kelvin. Similarly, Figures 4.29 and 4.30 illustrate the directional deformation at 10 milliKelvin.

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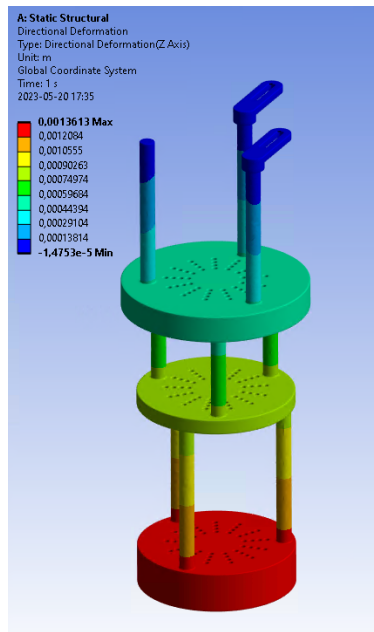


Figure 4.27: Directional deformation for the dual component sample holder with Ansys Silver at 3 Kelvin.

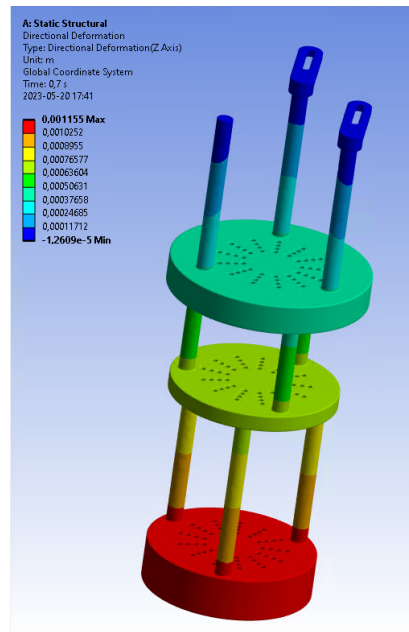


Figure 4.28: Directional deformation for the dual component sample holder with modified Silver at 3 Kelvin.

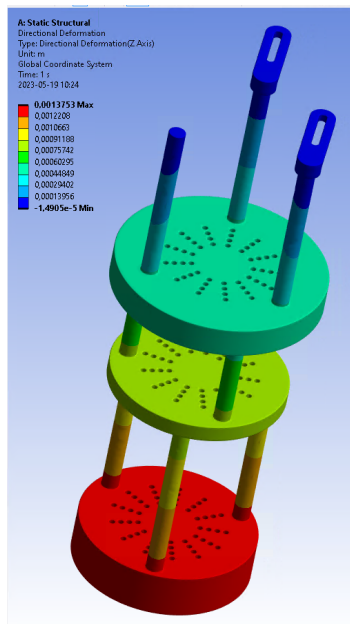


Figure 4.29: Directional deformation for the dual component sample holder with Ansys Silver at 10 milliKelvin.

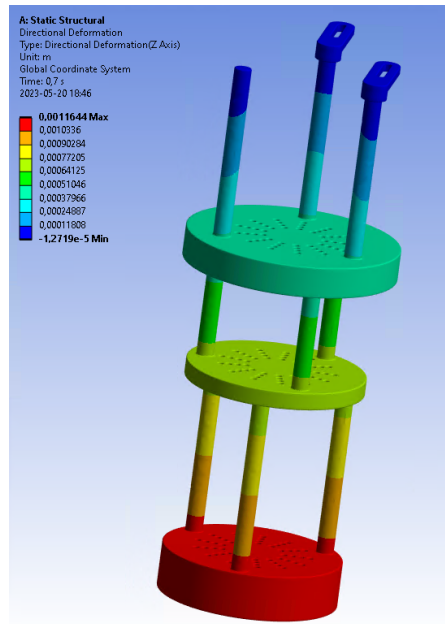


Figure 4.30: Directional deformation for the dual component sample holder with modified Silver at 10 milliKelvin.

The simulation for the single component sample holder in terms of directional deformation is shown in Figures 4.31 and 4.32 for 3 Kelvin and the 10 milliKelvin simulations are shown in Figures 4.33 and 4.34.

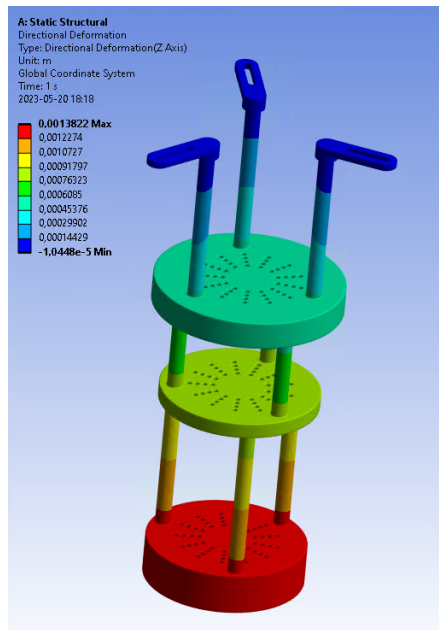


Figure 4.31: Directional deformation for the single component sample holder with Ansys Silver at 3 Kelvin.

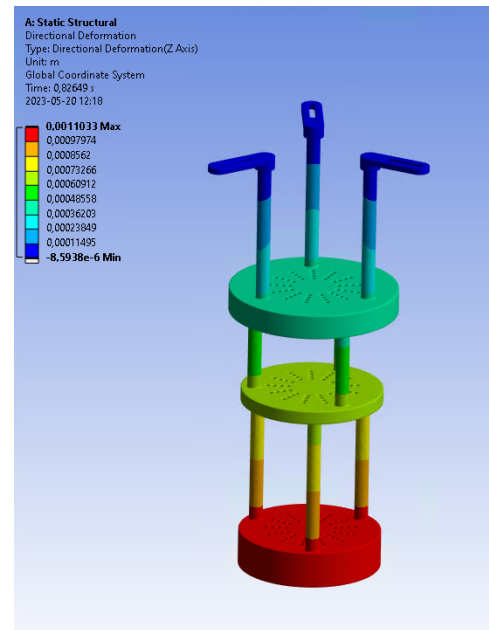


Figure 4.32: Directional deformation for the single component sample holder with modified Silver at 3 Kelvin.

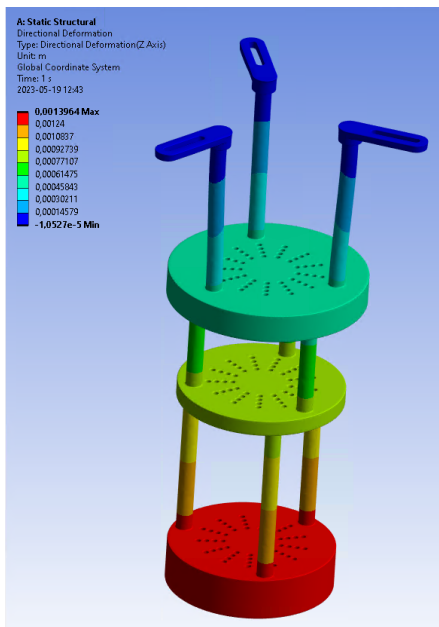


Figure 4.33: Directional deformation for the single component sample holder with Ansys Silver at 10 milliKelvin.

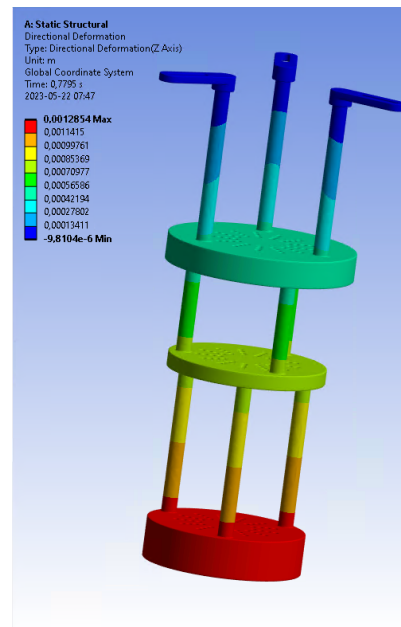


Figure 4.34: Directional deformation for the single component sample holder with modified silver at 10 milliKelvin.

A summary of the directional deformation obtained from the simulations is given in Table 4.21, where the maximum and minimum directional deformation are shown. The maximum value indicates that the free end has contracted upwards and the

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minimum value negative value indicates that it has elongated.

Table 4.21: A summary of the directional deformation for the two sample holders, at 3 Kelvin and 10 milliKelvin, with the two different materials.

Type	Maximum Directional Deformation at 10mK (m)	Minimum Directional Deformation at 10mK (m)	Maximum Directional Deformation at 3K (m)	Minimum Directional Deformation at 3K (m)
Dual Component (modified Silver)	0.0011644	-1.27190·10 ⁻⁵	0.001155	-1.26090·10 ⁻⁵
Dual Component (Ansys Silver)	0.0013753	-1.49050·10 ⁻⁵	0.0013613	-1.47530·10 ⁻⁵
Single Component (modified Silver)	0.0012854	-9.81040·10 ⁻⁶	0.0011033	-8.59380·10 ⁻⁶
Single Component (Ansys Silver)	0.0013964	-1.05270·10 ⁻⁵	0.0013822	-1.04480·10 ⁻⁵

Furthermore, the results of the total deformation characteristics at different temperatures are presented in Figures 4.35 - 4.42. The simulations for the dual component sample holder can be seen in Figures 4.35 and 4.36 show the simulations performed at 3 Kelvin, while Figures 4.37 and 4.38 show the simulations performed at 10 milliKelvin. For the single component sample holder simulations, Figures 4.39 and 4.40 show the results obtained at 3 Kelvin, while Figures 4.41 and 4.42 show the simulations performed at 10 milliKelvin. The results are similar to the previous simulations with the cylinders described in section 4.7.1, as the bottom of the sample holder is not constrained and can move freely, thus contracting upwards and giving a larger value, while the fixed end does not deform upwards as it is constrained.

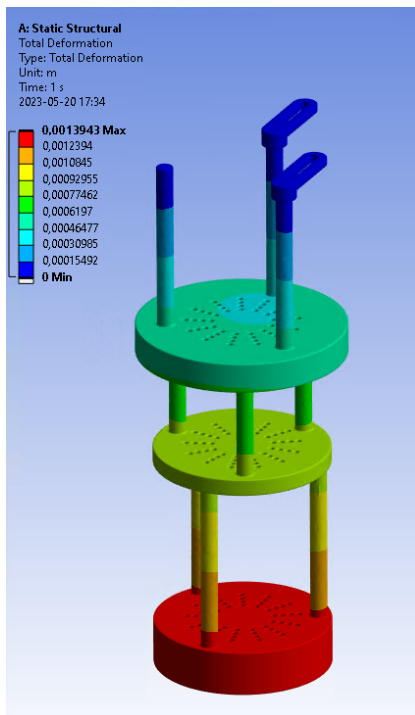


Figure 4.35: Total deformation of dual component sample holder at 3 Kelvin with Ansys silver.

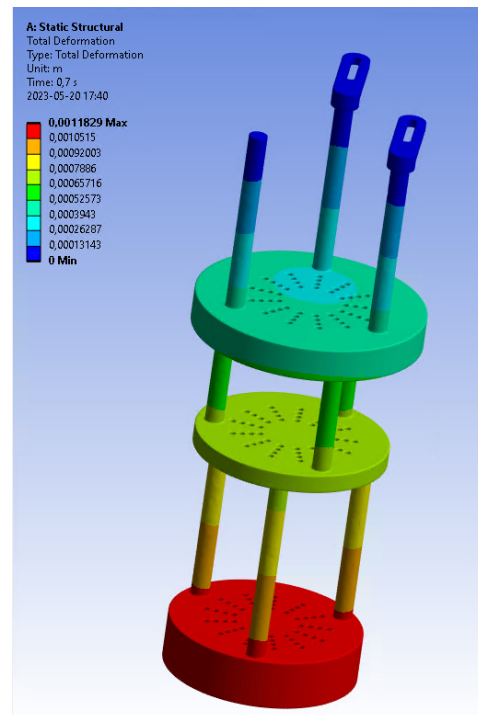


Figure 4.36: Total deformation of dual component sample holder at 3 Kelvin with modified silver.

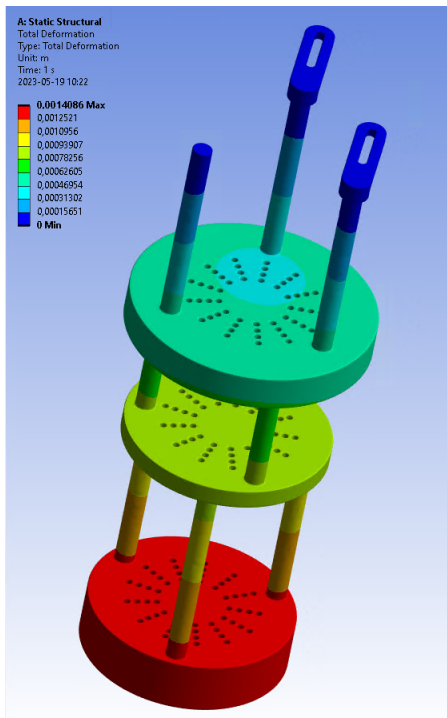


Figure 4.37: Total deformation of dual component sample holder at 10 milliKelvin with Ansys silver.

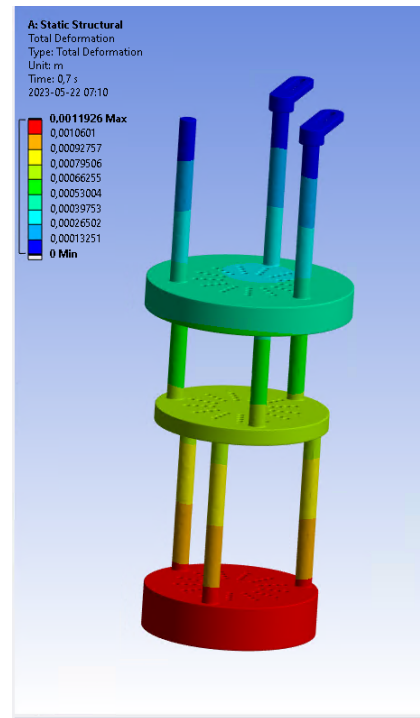


Figure 4.38: Total deformation of dual component sample holder at 10 milliKelvin with modified silver.

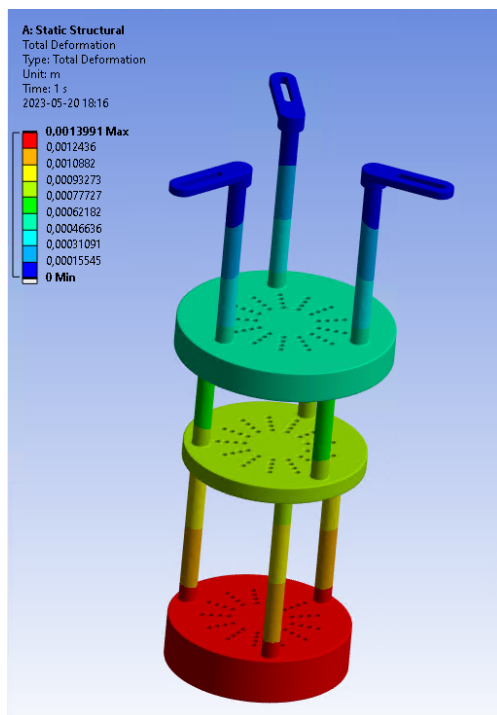


Figure 4.39: Total deformation of the single component sample holder with Ansys Silver at 3 Kelvin.

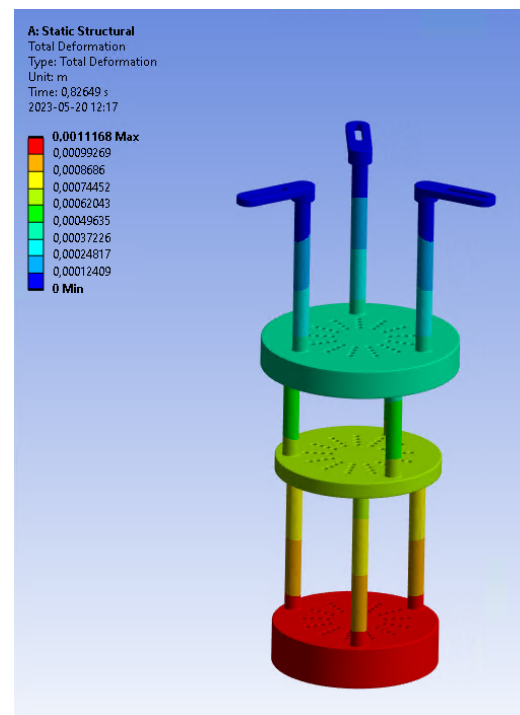


Figure 4.40: Total deformation of the single component sample holder with modified Silver at 3 Kelvin.

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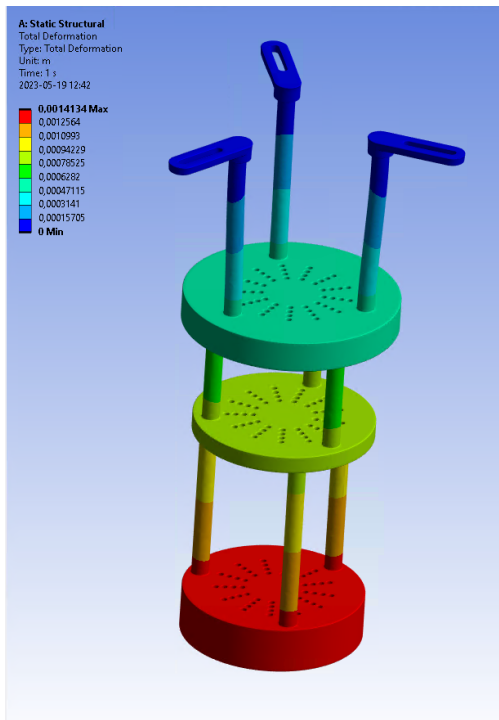


Figure 4.41: Total deformation of the single component sample holder with Ansys Silver at 10 milliKelvin.

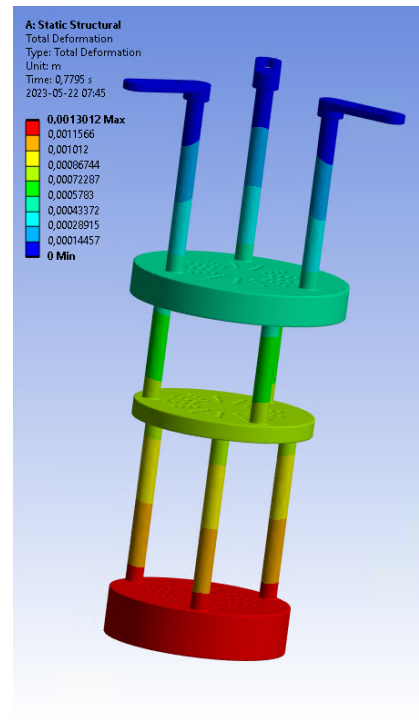


Figure 4.42: Total deformation of the single component sample holder with modified Silver at 10 milliKelvin.

The simulations carried out on two different sample holders, at two temperatures, 3 Kelvin and 10 milliKelvin, and with two different materials, provided data on total deformation. The maximum total deformation values collected from each simulation are summarised in Table 4.22.

Table 4.22: In this table the maximum value for total deformation can be seen for the eight simulations made.

Type	Total Deformation 10mK (m)	Total Deformation 3K (m)
Dual component (modified silver)	0.0011926	0.0011829
Dual component (Ansys silver)	0.0014086	0.0013943
Single component (modified silver)	0.0013012	0.0011168
Single component (Ansys silver)	0.0014134	0.0013991

Based on the simulations performed it could be decided whether or not silver was a suitable material to use for the application. As seen in Table 4.20, the maximum equivalent stress that occurred for the simulations at 3 Kelvin ranged from 86.651 MPa to 170.840 MPa and at 10 milliKelvin ranged from 86.993 MPa to 182.690 MPa. For silver to have a safety factor of 1.5 - 2, its yield strength would have to be between 129.9 MPa and 365.38 MPa. However, the actual yield strength of silver at ultra-low temperatures was found in the materials study to be between 50 and 75 MPa [128]. The results indicate that silver is not suitable for this application

as it does not meet requirement 4.4 with the constraints, design parameters and simulation setup applied.

5

Discussion

The following chapter discusses the methods used and the results obtained throughout the project. Firstly, the discussion of the functional analysis is presented, followed by the stakeholder identification and analysis. Thereafter, the discussion of stakeholder needs identification, data collection and analysis is presented. The discussion of the materials study is then presented and followed by the discussion of the simulations. Finally, a discussion of societal, ethical and ecological aspects is presented and the chapter concludes with a summary of the complete discussion. Prior to discussing the methods and results, a brief summary of the project's research questions and how they correlate to the methods and results are presented in Figure 5.1 and a summary of the limitations is provided below.

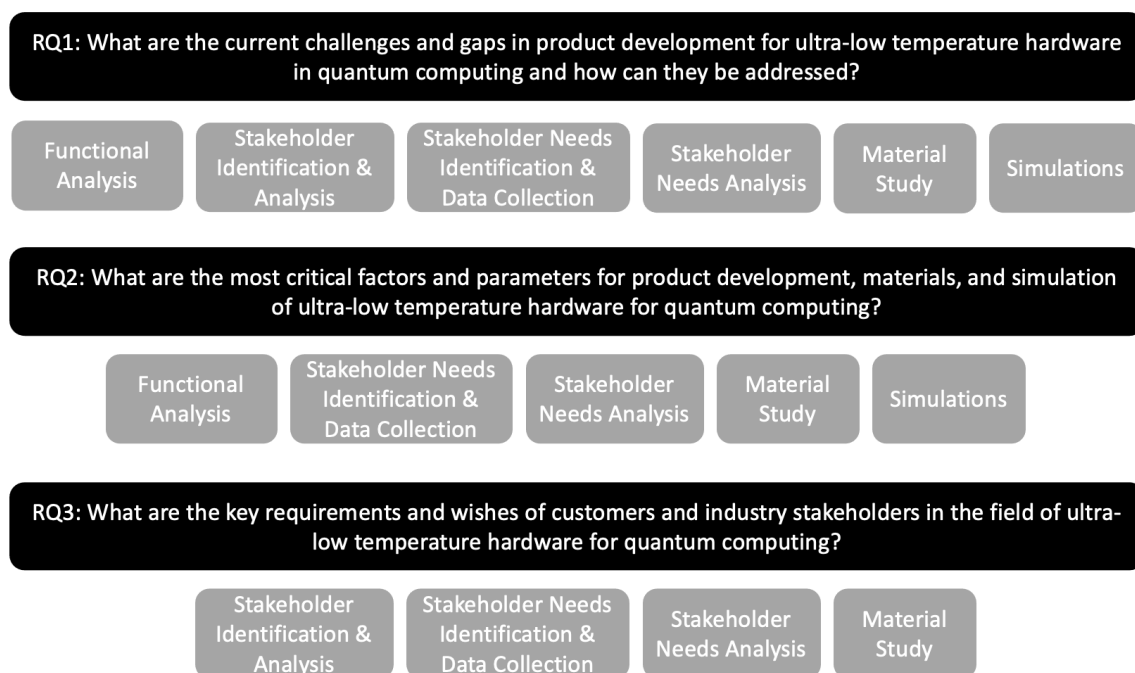


Figure 5.1: Summary of the three research questions and how they relate to the methods and results.

The project was limited in accordance with section 1.4, which could have had an impact on the methods used and the results obtained. A summary of the limitations that affected the project is described hereafter. The project was limited to a specific

type of quantum computer and a specific type of dilution refrigerator, which may cause the results obtained in the project to be inapplicable to other types. The project was also limited to non-electrical structural hardware, and the methods and results used may not be applicable to other types of quantum computing hardware. In addition, the simulations carried out in the project were limited to focusing on the thermal and mechanical properties of the hardware, which means that other factors, such as magnetic properties, which could affect the results obtained, were not investigated.

5.1 Functional Analysis

With regard to RQ1, the functional analysis enabled a better understanding of the ultra-low temperature hardware and its functions by examining SCALINQ's LINQER product. By gaining a better understanding of the functions that the LINQER and similar ultra-low temperature hardware should perform, potential gaps and challenges were identified in the development of quantum computing. The gaps of information found were related to heat transfer in which the function analysis found that materials with high thermal conductivity should be used. These materials were unknown at the start of the project and were a gap that needed to be filled. Furthermore, a gap in information found was related to that non-magnetic materials should be used to minimize noise to the sample, however, the magnetic properties of the material at ultra-low temperatures were unknown.

For RQ2, the analysis with its functional decomposition approach facilitated the identification of some critical factors and parameters for product development and material selection. By decomposing the main function of the LINQER and analysing its means, the analysis revealed important factors such as efficient heat transfer, secure sample housing, sample shielding, cable housing and connection to the dilution refrigerator. These factors were critical in ensuring optimum thermal management, sample protection, reliable measurements and proper integration with the heat sink.

The approach chosen is in line with one of the aims of the project, which was carried out by studying a product at the current state of the art and identifying the challenges associated with the development of ultra-low temperature hardware for quantum computing. By performing a function analysis, useful insights were gained that fill the existing gap in consolidated information for ultra-low temperature hardware. This analysis not only enhances the understanding of quantum computing hardware development but also improves the efficiency of the development process by identifying additional features that contribute to a better product. In addition, this in-depth understanding of the product has the potential to uncover latent needs that stakeholders may have but find difficult to articulate. By investigating the complex features of the product with the functional analysis, a clearer understanding of what stakeholders really want could be obtained. This addresses the challenge of identifying and satisfying latent needs and provides valuable information for product development.

5.2 Stakeholder Identification & Analysis

The purpose of the stakeholder identification and analysis was to identify the stakeholders in quantum computing in order to be able to identify their needs. The approach taken was to review and analyse the available literature on quantum computing stakeholders. Several databases were used to gather information on stakeholders which were considered as an effective approach in broadening the scope of the search and increasing the chances of identifying relevant literature. However, it is important to acknowledge that the search may not have been exhaustive, as certain databases or sources may have been missed, and the lack of specific exclusion criteria based on publication date may have resulted in the inclusion of outdated information. As the field of quantum computing is rapidly evolving, the stakeholders may have changed over time. In addition, restricting the search to English-language literature may have limited the inclusion of valuable findings from non-English sources.

The research focused on identifying stakeholders in the field of quantum computing as a whole, rather than specifically targeting stakeholders related to ultra-low temperature hardware. The focus of the field as a whole was due to a lack of available resources that explicitly addressed stakeholders in the context of ultra-low temperature hardware. While the approach provided a broad understanding of the stakeholders involved in quantum computing, it may not have captured all potential stakeholders. Further, it is important to note that the aim of the study was to identify key stakeholders rather than to provide an exhaustive list of specific stakeholder organisations, groups, or people. In addition, the lack of access to confidential information and the inability to analyse a specific company and their interactions with other organisations hindered the comprehensive identification of specific stakeholders.

The classification of stakeholders according to their level of influence was a subjective decision made by the authors and was not based solely on existing literature. While this approach provided a hierarchical representation of stakeholders, it should be recognised that real-world influence and relationships between stakeholders may differ from the author's understanding.

A more detailed analysis is needed to gain a full understanding of stakeholders and their needs. The analyses could include competitor analysis, benchmarking studies and further research into specific organisations, groups or individuals that play a significant role as stakeholders in the development and use of quantum computing hardware. By investigating the stakeholder landscape in more depth, a more accurate representation of their needs and requirements can be achieved, resulting in better-informed decisions and design solutions.

The approach helped to answer RQ1 as it was found that there are currently gaps in information about who the stakeholders are and that not knowing who they are, makes it difficult to address them. Another challenge within the field of quantum computing development that was identified through the stakeholder research was the

level of secrecy and confidentiality that makes it difficult to collaborate, co-develop and learn from others. By creating a public handbook for quantum computing hardware development, it is hoped that this secrecy gap can be bridged and discussions between developers can be initiated, leading to further learning and information sharing.

In relation to RQ3, the approach is considered to have contributed to the answer as it identified the stakeholders whose key needs and wishes could be studied based on the identified stakeholders. Despite the potential limitations, the approach used and the results obtained are considered valid and helpful for SCALINQ as a company, but also for the field of quantum computing as a whole, as no prior publications specifically on stakeholders were found. However, further research should be conducted to make the list more accurate and detailed and to include future stakeholders that may emerge.

5.3 Stakeholder Needs Identification & Data Collection

The identification of stakeholder needs and the data collection process used in the project was designed to address the problem statement, fulfil the purpose and answer the research questions. The approach, therefore, correlates with and helps to answer all the research questions. By identifying stakeholder needs, the current challenges, gaps, critical factors and parameters, materials and simulations were investigated and identified. The stakeholder needs identification approach also filled significant gaps in the available information and comprehensive data for the development of ultra-low temperature hardware. The information gained from the data collection will further assist in overcoming difficulties and reducing the time required for hardware development. The results contribute to the overall advancement of quantum computing hardware and facilitate the creation of more efficient and reliable products.

The use of two different methods of data collection, namely in-depth interviews and a literature study, was considered a valid approach to gathering comprehensive data on stakeholder needs related to the development of quantum computing hardware. The in-depth interviews with primary stakeholders, including users, customers and researchers, provided valuable opportunities for discussion and direct exchange of information. The interviews enabled a better understanding of what stakeholders wanted and provided insights into their perspectives and opinions. However, it should be noted that the pool of potential interviewees was relatively small and interest in participating was low. The limited number of participants may have affected the representativeness of the data collected. In addition, the primary stakeholders interviewed were associated with either Chalmers University of Technology or SCALINQ, which may have limited the diversity of perspectives. The number of interviews proved to be appropriate, as the information gained stagnated after conducting five to six interviews, with the seventh and eighth interviews generating only

a small amount of new information. Furthermore, the decision to conduct interviews rather than surveys or focus group interviews was justified by the complexity of the research area. Not all stakeholders may have had sufficient knowledge to provide relevant answers to the survey questions, and the limited number of stakeholders could have made it difficult to obtain representative data through surveys.

The method of sending the key points and a summary of the interview to the interviewees was considered a valid approach as it invited the interviewee to backtrack their statements. The method ensured accuracy and helped to avoid misinterpretation of the information discussed during the interviews, especially on complex topics.

Although the number of interviews conducted was considered appropriate, it is recommended that more interviews should be conducted to explore a wider range of stakeholders. Conducting interviews with stakeholders from different backgrounds and organisations would improve the findings and provide a more representative view of stakeholder needs.

A literature study focusing on stakeholder needs was carried out to complement the interviews with primary stakeholders. The complementary data collection proved to be a valid approach as it provided information on the limitations of existing technologies and stakeholder needs from various stakeholders. The approach, therefore, broadened the scope of the identification and collection of stakeholder needs and improved the overall understanding of the needs. To strengthen the validity of the literature study, several databases were used for the literature search, which was considered a good approach to collecting relevant and reliable information.

A point that further validates the results was that some of the needs expressed through the interviews and the literature study were similar. Although there were limitations in terms of the stakeholder pool and interest in participating, the results from both methods provided valuable information on stakeholder needs that can contribute to the development of quantum computing hardware.

5.4 Stakeholder Needs Analysis

The stakeholder needs analysis conducted in the project aimed to specify the needs of different stakeholders in quantum computing hardware. The analysis process followed a well-known method inspired by Ulrich et al. [32] for translating stakeholder statements into stakeholder needs. However, it is important to recognise the potential for bias in the interpretation of stakeholder statements into needs.

To reduce the risk of bias in the translation process, it was decided that the two authors would carry out the translation independently. This approach was chosen because different people may interpret the same statements differently [54]. By having two people involved in the translation, the authors aimed to cover a wider range of potential needs and reduce individual bias.

While the translation process inspired by Ulrich et al. [32], was successfully completed, the third step of organising the needs into a hierarchy was not carried out. This step, as outlined by Ulrich et al. [32], could have provided a clearer understanding of the relationships between different stakeholder needs. However, due to resource and time constraints, it was decided not to undertake this step in the current study.

Determining the relative importance of the needs identified was another challenge. Rather than conducting stakeholder surveys to determine the importance of each need, the authors relied on their consensus. This decision may have introduced bias into the analysis, as individual preferences and perspectives were not taken into account. In future research, it would be beneficial to conduct stakeholder surveys to obtain a more objective assessment of the importance of each need.

It is important to note that the requirement specification developed in this study was an initial version and not a final specification. Ulrich et al. [32] suggest that for technology-intensive products, requirement specifications are typically created at least twice, with the first iterations representing the hopes and aspirations of the team, given the unknown constraints of the technology. As quantum computing hardware was considered to fall into the category of technology-intensive products where limited research has been conducted, it was considered appropriate to produce an initial requirement specification. The initial specification will help future developers to produce a final specification at a later stage, taking into account advances in the field and a deeper understanding of the technology. As a result, some ideal and marginal requirements in the initial specification could not be filled in.

The stakeholder needs analysis and subsequent requirements specification generated in this study can serve as a valuable channel for communication between stakeholders and product developers in the context of quantum computing hardware. Despite certain limitations, such as the potential for bias in the translation process and the lack of a hierarchical organisation of needs, the results provide an initial foundation for future research and development in the area which currently does not exist. It is recommended that future studies address these limitations, conduct stakeholder surveys to assess the importance of requirements, assign values to requirements, and iterate the requirements specification to reflect evolving technology and knowledge.

By identifying and transforming stakeholder statements into needs and then requirements, RQ3 can be answered with the Tables 4.3, 4.4 and 4.5. These tables together provide a comprehensive understanding of the key stakeholder needs and wishes by presenting the consolidated stakeholder needs, requirement specifications and verification methods. The purpose of the thesis was also to identify the specific customer and industry stakeholder needs and requirements for the hardware, which can be considered achieved by being able to answer the third research question.

The tables also provide new information on stakeholder needs and requirements, which have filled some of the gaps and challenges in product development. The Tables 4.3, 4.4 and 4.5 therefore contribute to answering RQ1. However, the fact that

further research is required to produce a final requirement specification, as opposed to the initial requirement specification in Table 4.4, indicates that there are still gaps that need to be filled. In addition, the tables also include the most critical factors and parameters for product development, materials and verification of ultra-low temperature quantum computing hardware, which contributes to answering RQ2.

To further address the purpose of the thesis, various approaches were used to identify, collect, and analyze stakeholder needs. The methods used for these processes included functional analysis and stakeholder identification and incorporated the investigation of the current state of the art and its challenges. The findings from these efforts provide valuable insights that can be used to create a new product that pushes the boundaries and expands the frontiers of knowledge.

5.5 Materials Study

A critical gap identified through performing the function analysis, conducting interviews and reviewing literature was consolidated information on materials, including comprehensive material data. Without these resources, the process of designing and manufacturing quantum computing hardware becomes more difficult and time-consuming. Efforts were therefore made to investigate what materials are currently in use and considered state-of-the-art for cryogenic applications that could be suitable for quantum computing hardware and to compile material data for these suitable materials. With this data, SCALINQ could use it to help establish a standardised process for developing its products, saving time and resources and increasing the efficiency and consistency of its hardware development process, ultimately leading to better products for its customers.

A common consensus found between the stakeholders interviewed and the literature studied was the statement that copper should be used, as shown in Table B.1. The interviewed stakeholders could not specify why it was used but replied that it had always been used and that everyone else used it. From the list of materials in table 4.10, ten of the 21 materials were either copper or copper alloys. However, all of the materials consisting of copper did not perform as well when considering thermal conductivity at very-low and ultra-low temperatures.

Beryllium copper showed a gradual decrease in thermal conductivity as temperature decreased and dropped to zero for the predicted values at ultra-low temperatures. The drop suggests that beryllium copper becomes less effective at conducting heat as the temperature approaches absolute zero (0 Kelvin). Copper-2%Be shows a similar trend to Beryllium Copper, indicating that the addition of beryllium reduces the thermal conductivity of copper.

Copper (OFHC) with different RRR (Residual Resistance Ratio) values has higher thermal conductivities compared to beryllium copper and retains higher conductivity at lower temperatures. The thermal conductivity of copper (OFHC) with different RRR values also shows a temperature-dependent behaviour. The higher the RRR,

the higher the thermal conductivity. As the temperature decreases, the thermal conductivity decreases for all RRR values, but the magnitude of the decrease is greater for lower RRR values.

Thermal conductivity data for the copper-nickel alloy, Cu-Ni60-40, was sparse in the literature, but by comparing its thermal conductivity at 3.03 Kelvin with that of beryllium copper at 4 Kelvin, it could be seen to be in line with the thermal conductivity of beryllium copper, if not lower. The low thermal conductivity at 3 Kelvin suggests that Cu-Ni60-40 becomes a poor thermal conductor at ultra-low temperatures.

Electrolytic tough pitch (ETP) copper shows a significant temperature-dependent decrease in thermal conductivity. The ETP copper performs better than beryllium copper and Cu-Ni60-40 at very-low temperatures, but not as well as copper (OFHC).

This analysis helps to answer the question of why copper could be a valid material to use, which the stakeholder could not answer. However, not all copper is recommended to be used. The materials study shows that copper (OFHC) is the best-performing copper material and has an increase in thermal conductivity with higher RRR values and is therefore recommended if a copper material is preferred.

The predictions made are only indicators of what the thermal conductivity could be and are in no way proof that they will be these values. The predictions are intended to be a tool to find out the thermal conductivity trends of materials in order to make recommendations for real-life tests which can then verify the actual thermal conductivity of the material. The recommended materials to start testing are as follows:

- Silver (well-annealed 99.999% pure)
- Copper (OFHC), (RRR=500)
- Copper (OFHC), (RRR=300)
- Gold (well-annealed 99.999% pure)

The four materials are recommended to start testing as these materials have been shown to have high thermal conductivity at 10 Kelvin and below, as well as high predicted thermal conductivity at 10 and 20 milliKelvin, as shown in the table 4.10. However, it is important to note that the list of materials is not exhaustive and new materials may be added in the future. It is therefore recommended that the list is reviewed and updated regularly to ensure that it remains current and relevant. For further research, it would be interesting to investigate alloys of these materials as they could reduce costs while still providing high thermal conductivity.

Despite the failure of the thermal conductivity calculations carried out in this thesis, it is important to emphasise that the failure of these specific attempts does not mean that calculations cannot be successfully carried out. The complexity of the calculations prevented the authors from obtaining meaningful results. However, it is recommended that further efforts be made to explore alternative approaches and techniques in order to achieve meaningful results in future studies.

As the material list helped to fill an information gap in the field of ultra-low temperature quantum computing hardware, it also helped to answer RQ1. However, there are still gaps of information related to missing data in the materials list that need to be filled by further physical testing. Sorting the identified materials according to critical factors and parameters based on stakeholder requirements, such as magnetic properties, superconducting properties and thermal conductivity, is considered to address RQ2 and RQ3.

As the materials study investigated the current state of the art in order to produce a list of suitable materials, including material data, that could be used in quantum computing hardware, the purpose was considered to have been followed. In doing this, the thesis sought to push the current boundaries and expand the frontiers of knowledge by thoroughly investigating different materials.

5.6 Ansys Granta EduPack Materials study

As the materials study carried out only included materials mentioned in the literature for cryogenic applications, it was decided to try to make the study more comprehensive and to find new materials that might not have been mentioned in the literature but could be suitable for the application. The Ansys Granta EduPack software was chosen to perform the complementary material search. However, it was not known whether the software could be used at cryogenic and especially ultra-low temperatures, and therefore an experimental material selection process was carried out both to test the suitability of the software and to find potential materials that could be used in the development of quantum computing hardware.

The method of using the software proved to be problematic both in terms of applying constraints and properties based on the requirement specification, Table 4.4, such as those relating to superconductivity, and in terms of temperature constraints where only the service temperature could be specified. Furthermore, the data presented within the software proved to be limited to room temperature conditions, making the software unsuitable for selecting materials for ultra-low temperature hardware applications. It was therefore decided not to continue with the material selection process using the software, as the problems identified would have too great an impact on the results.

It is important to note that although the limitations of the software make it less suitable for initial material selection for ultra-low temperature hardware, it can still be used in later stages of the product development process. As an example, Granta EduPack includes a wide range of tools and process information for many materials that could be used in the selection of manufacturing methods.

5.7 Simulations

Ansys simulation software was selected to support the process of verifying the suitability of materials according to the requirements specification. The selection was based on the limitation that only software available at Chalmers University of Technology could be used and on recommendations from both the interviews and the literature reviewed. However, it was not known whether the software could be used for ultra-low temperatures. Therefore, an experimental study with a simple cylinder was carried out to verify if Ansys could be used for the intended purpose. It should also be noted that neither of the authors has any specific training in ultra-low temperature thermomechanical stress analysis, which would have been beneficial to the reliability of the results.

Verification of the use of the Ansys simulation software was based on a comparison of simulations of equivalent von Mises stresses and deformations at 3 Kelvin and 10 milliKelvin for the silver provided in Ansys and for the modified silver, on the cylinder. By analysing the stresses it could be seen that at 3 Kelvin the stresses differed between the two silver materials. However, the difference is considered valid as the change in material data for the coefficient of thermal expansion was changed to lower values and the density was increased for the modified silver at lower temperatures. By considering the difference in stress to be valid, the use of the modified material was justified.

To further validate the simulations performed at 10 milliKelvin on the cylinder, the stresses at 3 Kelvin and 10 milliKelvin were compared. As the stress for both materials increased by the same factor as the temperature was lowered, the use of the 10 milliKelvin simulations was considered verified. Had the stresses been lower at the lower temperature, the simulations would have been considered invalid as the deformation increased at the lower temperature leading to higher stresses.

With both the modified material and the simulations at 10 milliKelvin considered verified and usable, simulations were performed on simplified LINQERs to further assess whether silver would be a suitable material to use by analysing requirement 4.4 in Table 4.4. Similar to the simulations of the simple cylinder, simulations were performed on the simplified LINQERs with stress and deformation analyses.

When comparing the deformations resulting from the directional and total deformation analysis at temperatures of 3 Kelvin and 10 milliKelvin, an observation emerges which is that the free end consistently compresses upwards in all simulations. This behaviour is consistent with the expected outcome of the simulations. The underlying motivation for this phenomenon lies in the relatively negligible gravitational force exerted on the sample holder compared to the significant thermal stress attempting to compress the component. Based solely on the visual representations of the figures generated by Ansys, a notable observation emerges which is that the simulations show consistent deformation and stress patterns across all cases. The notable difference, however, lies in the varying magnitudes of deformation and stress within each simulation. A closer examination of the deformation values reveals that

the modified material generally exhibits reduced levels of expansion and compression in terms of directional deformation. This finding is consistent with the adjusted values derived from the Ansys material database and the relevant literature on the material properties of pure silver.

Comparing the simulation values for equivalent stresses on the simplified LINQERs, it can be seen that the concentration occurs near sharp edges, which is consistent with all simulations and is located at the radius from the fixed end of the face. The maximum equivalent stresses were then compared with the yield strength of the silver to check that there was a safety factor of 1.5 - 2 as stated in requirement 4.4. The maximum equivalent stress that occurred for the simulations at 3 Kelvin and 10 milliKelvin both ranged higher than the yield strength of silver and the safety factor was not met. The fact that the safety factor is not met implies that silver is not a suitable material to use for this application as it does not meet requirement 4.4.

It should further be noted that the simulation values presented should only be considered as indicators and not as actual values. To obtain actual values, real physical tests of the materials must be carried out to verify the simulation values. The simulations using silver as the material was carried out to show how the materials could be verified against the requirement specification. Further simulations are required to validate all the materials in the material list, Table 4.10, but the simulations performed using the cylinders and simplified sample holders demonstrate that simulations at ultra-low temperatures can be performed using the Ansys simulation software, although real physical tests are required for validation.

The simulations were carried out because it was found through the interviews that simulations at ultra-low temperatures were challenging and that there was a gap in information on how they should be carried out. Through the simulations performed in the project, the challenge was recognised and an attempt was made to fill the information gap, which helps to answer RQ1.

Furthermore, it is considered that the simulations carried out can be used as guidelines for future simulations and could help to identify critical factors for product development and materials at ultra-low temperatures, which correlates with RQ2. However, RQ3 cannot be answered by simulations alone, but simulation can be used as a tool in the development of future products or material selection to verify that the key requirements and wishes of stakeholders are met.

5.8 Societal, Ethical, and Ecological aspects

As quantum computing develops, it will be important to consider the societal, ethical and environmental implications of its development and use. The potential societal, ethical and environmental impacts of quantum computing are discussed in the following subsection.

By creating information and knowledge that can help product developers build better and more scalable quantum computers, the thesis can be seen as assisting quantum computers to gain more computing power. When quantum computers become significantly more powerful than traditional and supercomputers, they have the potential to be used in a wider range of fields and industries. Their use in different fields and industries may have both positive and negative social, ethical and environmental aspects.

A promising field of application for quantum computers is the pharmaceutical industry, where quantum computers can be used in drug development. The application of quantum computers in drug development can help to design drugs to combat harmful diseases and conditions more efficiently. However, computing power can also pose some risks, as it can be used to develop harmful viruses and diseases. The technology can also be used by military organisations to create new forms of chemical warfare.

In addition, superior computing power has the potential to compromise personal security by being able to break the encryption codes used in various forms of online communication and financial transactions. The ethical implications of this are negative, as it increases the possibility of privacy violations. Quantum computers also have the potential to be used for surveillance, which could enable the collection of sensitive information that can be used for malicious purposes by governments, corporations or other entities.

Quantum computers also have an impact on the environment because they use more energy than conventional computers when operated. As quantum computers are scaled up, they are expected to require even more energy to operate. Depending on where the energy is sourced, this could lead to increased emissions and negative environmental impacts. It is therefore important to consider the environmental impact of the development and use of quantum computers and to work towards sustainable solutions to mitigate this impact.

The materials needed to produce a quantum computer will have their own societal, ethical and environmental aspects to sourcing and manufacturing the hardware. The environmental impact of mining materials and manufacturing can lead to the destruction of wildlife habitats. The use of chemicals to extract some metals can lead to water pollution, affecting both wildlife and humans. Mining dust and emissions can further pollute the air, worsening air quality and harming animals and humans. Transporting materials to manufacturing facilities releases emissions, and excess emissions can have an impact on the environment. The materials selected during the development phase of quantum computers and their components, such as hardware, must take these aspects into account in order to mitigate risks and reduce pollution.

Consideration of the ethical aspects of mining materials and manufacturing hardware for quantum computers is crucial. It is important that companies act transparently and responsibly, both towards their mining and manufacturing workers and towards the communities affected by the mining and production of materials. Human rights

and working conditions are of paramount importance and companies should take steps to ensure that their operations do not have a negative impact on these rights.

From a societal perspective, there are both positive and negative aspects to exploring and producing materials. The positive aspects are that it creates jobs for people, as minerals and materials can become part of a country's international trade. The negative aspects and risks related to mining and exploration, in addition to those mentioned above, are that depending on where the materials are located, it may make it more difficult for other businesses and activities to operate in the surrounding area.

The development of quantum computers has many aspects to consider, which can be both beneficial and harmful to humanity and the environment. These aspects have been considered throughout the project, but it should be noted that the purpose of this Master's thesis is to provide the basis for a handbook for the development of ultra-low temperature quantum computing hardware, and not a recommendation for the operation and use of quantum computers.

5.9 Summary of Discussion

The functional analysis performed on the LINQER product provided a comprehensive understanding of ultra-low temperature hardware and its functions. It identified gaps and challenges in the development of quantum computing, particularly in the areas of heat transfer and material properties. Functional decomposition identified critical factors and parameters for product development and material selection, including efficient heat transfer, secure sample housing, sample shielding, cable housing and connection to the dilution refrigerator. The analysis filled information gaps and highlighted the importance of high thermal conductivity and non-magnetic materials in quantum computing hardware.

The purpose of the stakeholder analysis was to identify stakeholders in order to understand their needs. The analysis was based on a literature study and focused on stakeholders in the broader field of quantum computing, rather than specifically targeting stakeholders in ultra-low temperature hardware due to limited resources. The analysis revealed gaps in stakeholder information and identified challenges related to secrecy and confidentiality that hinder collaboration and learning. A potential solution is the creation of a public handbook for hardware development, like this thesis, to facilitate information sharing. Further research is needed to refine the stakeholder list, including competitor analysis and benchmarking, to gain a comprehensive understanding of stakeholders, particularly in hardware development and emerging stakeholders, and to improve accuracy and detail.

The identification of stakeholder needs and data collection identified critical factors, challenges, gaps, parameters, materials and simulations. It filled significant information gaps for ultra-low temperature hardware. In-depth interviews with primary stakeholders provided valuable insights, but the limited number and specific

affiliations may have affected the representativeness of the data. A literature study complemented the interviews and broadened the perspective. While the number of interviews was considered appropriate, interviews with a wider range of stakeholders would enhance the findings.

The stakeholder needs analysis focused on the specification of stakeholder requirements for quantum computing hardware. A methodology inspired by Ulrich et al. [32] was used to transform stakeholder statements into needs and then into requirements. The requirement specification developed in this project is an initial version intended for ongoing refinement to incorporate evolving technology and knowledge to produce a final requirement specification in the future. The conducted stakeholder needs analysis can serve as a valuable communication channel between stakeholders and product developers in the field of quantum computing hardware. The generated stakeholder needs and requirements tables provide insights for product development and can help to advance quantum computing hardware knowledge for continuous improvement and progress in the field.

The materials study aimed to fill a critical information gap on materials for quantum computing hardware. Copper was widely recommended by stakeholders, particularly copper (OFHC), which showed superior thermal conductivity compared to other copper variants. However, materials such as beryllium copper and Cu-Ni60-40 showed reduced efficiency as thermal conductors at ultra-low temperatures. The analysis provided valuable insights into material suitability, highlighting copper (OFHC) with higher RRR values, pure silver and pure gold as the preferred choices to begin physical testing. The materials study has filled information gaps, but further physical testing is required to fill the remaining gaps in materials data and validate the predictions made. Future research into alloys derived from the recommended materials is recommended to be performed as they can reduce costs while maintaining the desired thermal conductivity. Overall, the materials study has increased knowledge and advanced the field of quantum computing hardware by providing valuable insights into materials and their properties.

The selection of Ansys simulation software aimed to evaluate material suitability, although its compatibility with ultra-low temperatures was uncertain. To address the uncertainty, an experimental study was carried out to confirm its applicability. The experimental study validated its use in ultra-low temperature scenarios, but further physical testing is required for verification. Simulations on simplified LINQERs assessed the viability of silver as a material by analysing stress and deformation. However, equivalent stresses were concentrated near sharp edges, exceeding the yield strength of silver and failing to meet the safety factor of the requirement specification. It is crucial to consider simulation values as indicators, emphasising the need for physical testing to validate them and assess material suitability. The simulations aimed to address the challenge of ultra-low temperature simulations and fill the information gap. The performed simulations provide valuable guidelines for future simulations and help to identify critical factors for product development and material selection at ultra-low temperatures.

6

Conclusions & Recommendations

The following chapter provides the overall conclusions of the project, presented in the context of the project's purpose and research questions. The chapter concludes with recommendations for future research.

6.1 Conclusions

The aim of the thesis was to create a comprehensive product development handbook for ultra-low temperature quantum computing hardware, which has been achieved as the thesis itself can serve as a handbook. From the outset, the aim was to produce a separate document, more condensed than the full thesis, to act as a handbook. However, due to time constraints and the need for further research, it was considered appropriate to use the thesis as a handbook.

Further, the purpose of the thesis was to investigate the current state of the art and its challenges in the development of ultra-low temperature quantum computing hardware in order to push the existing boundaries and expand the frontiers of knowledge. This purpose is considered to have been achieved following the answer to the research question RQ1: "*What are the current challenges and gaps in product development for ultra-low temperature hardware in quantum computing and how can they be addressed?*"

The functional analysis carried out using the Function-Means Tree helped to identify challenges and gaps such as those related to heat transfer and the need for high thermal conductivity, magnetic susceptibility and the need for non-magnetic materials. These challenges related to material properties were due to that no comprehensive and consolidated list of materials including their data at very-low and ultra-low temperatures existed. The challenges were overcome and the gaps were then filled by carrying out a materials literature review and a materials study to identify suitable materials that had high thermal conductivity, were non-magnetic with diamagnetic properties and were not superconducting to achieve heat transfer as presented in Table 4.10 and the short summary below in Table 6.1 of the four material with the highest thermal conductivity at ultra-low and very-low temperatures. Other information gaps were identified regarding who the stakeholders in quantum computing are, which are considered to be filled by the information presented in section 4.2 and Figure 4.2.

Table 6.1: Summary of the four materials with the highest thermal conductivity.

Material name	Actual λ_t at 4 K	Predicted λ_t at 10 mK
Silver (well-annealed 99.999% pure)	14700 $W/(m \cdot K)$	440.17 $W/(m \cdot K)$
Copper (OFHC),(RRR=500)	3181.69 $W/(m \cdot K)$	1156.03 $W/(m \cdot K)$
Copper (OFHC),(RRR=300)	1888.38 $W/(m \cdot K)$	439.21 $W/(m \cdot K)$
Gold (well-annealed 99.999% pure)	1710 $W/(m \cdot K)$	16.26 $W/(m \cdot K)$

Another challenge within the field of quantum computing development that was identified through the stakeholder research was the level of secrecy and confidentiality that makes it difficult to collaborate, co-develop and learn from others. By creating a public handbook for quantum computing hardware development in the form of this thesis, it is hoped that this secrecy gap can be bridged and discussions between developers can be initiated, leading to further learning and information sharing. Stakeholder identification then enabled the identification of stakeholder needs, where further challenges and gaps were identified, studied and addressed. A fundamental challenge and information gap identified was that the stakeholder needs were not known at the outset, which the Tables 4.3, 4.4 and 4.5 are intended to address. However, the fact that further research is required to produce a final requirement specification, as opposed to the initial requirement specification in Table 4.4, indicates that there are still gaps to be filled.

Further challenges were related to thermomechanical simulations at ultra-low temperatures, as it was unknown if simulations could be performed and how to perform them. Section 3.7 is considered to answer the question of how to perform thermomechanical simulations with a focus on stresses and deformations, and the results presented in section 4.7 show that simulations in Ansys simulation software are possible. However, further investigations and physical tests are required to validate the results.

In order to achieve the purpose of creating a comprehensive product development handbook for ultra-low temperature quantum computing hardware, in addition to identifying challenges and gaps, the second research question RQ2 was posed and answered: "*What are the most critical factors and parameters for product development, materials, and simulation of ultra-low temperature hardware for quantum computing?*"

The identification of critical factors was achieved through a comprehensive analysis of stakeholder needs, which included interviews and a thorough review of relevant literature. These efforts resulted in the development of a requirement specification, as outlined in Table 4.4, which highlights the importance of specific factors and parameters. It is essential to note that the importance of each requirement varies, with the most critical requirements receiving an importance rating of 4 or 5. A summary of the requirements with importance of five can be seen in Table 6.2 below.

Table 6.2: Summary of the requirements with an importance of 5.

No.	Requirement	Imp.
4.2	Maintain the operational temperature of at least 20 milliKelvin.	5
4.3	Accommodate at least 1-300 cables.	5
4.4	Design safety factor of 1.5 - 2	5
4.7	Dismountable sample holder housing	5

4.8	Enable mounting and dismounting of cables	5
5.3	Minimum sample holder height	5
6.1	Diamagnetic properties	5
6.2	No superconductive properties	5
6.3	Minimum service temperature of 10 milliKelvin	5
6.6	Minimum temperature of 4 Kelvin with reliable data that the data sheet must contain	5
6.8	Minimum vacuum pressure of 10^{-5} mbar	5

Furthermore, the purpose of the thesis was to identify the specific needs and requirements of customers and industry stakeholders for the hardware. This purpose is considered achieved by answering the third research question RQ3: "*What are the key requirements and wishes of customers and industry stakeholders in the field of ultra-low temperature hardware for quantum computing?*" with the Tables 4.3, 4.4, 4.5, and the summary in Table 6.2. These tables together provide a comprehensive understanding of the key stakeholder needs and wishes by presenting the consolidated stakeholder needs, requirement specifications and verification methods.

6.2 Recommendations

A recommendation for future research is to undertake a more detailed stakeholder analysis to gain a full understanding of the stakeholders and their needs, specifically for the hardware itself and not for quantum computing as a whole. This could include competitor analysis, benchmarking studies and further research into specific organisations, groups or individuals that play a significant role as stakeholders in the development and use of quantum computing hardware. By exploring the stakeholder landscape in more depth, a more accurate representation of their needs and requirements can be achieved, leading to better-informed decisions and design solutions. As the field of quantum computing is rapidly evolving, stakeholders may change over time, therefore further research is important to keep up to date with current stakeholders.

It is further recommended that additional data collection through stakeholder interviews should be undertaken in order to gain a more comprehensive understanding of stakeholder needs. A future study should include a wider range of stakeholders from all identified stakeholder groups and from different backgrounds and organisations. As the interviews in this project only involved two organisations, SCALINQ and Chalmers University of Technology, it is considered that valuable knowledge can be gained from other research institutes, such as universities, and manufacturers of dilution refrigerators, such as Bluefors.

In order to improve the determination of the relative importance of the identified needs, it is suggested that stakeholder surveys be carried out to remove any bias that may have arisen. This approach will allow for a more objective assessment of the importance of each need, avoiding potential bias. Following the recommendation of Ulrich et al. [32], a stakeholder needs survey can be conducted in which stakeholders rank the importance of each need.

6. Conclusions & Recommendations

The initial requirements specification provides an initial basis for future research and development, and it is recommended that future studies address the limitations imposed by advances in technology and knowledge, and fill information gaps related to unassigned values in the initial requirements specification.

As the predictions made can only be used as an indicator of what the thermal conductivity may be at ultra-low temperatures, further research is required to determine the actual thermal conductivity of the materials. The recommended materials to start testing are presented in Table 6.1. Although silver was found to be unsuitable for the sample holder through the simulations performed, it may be a suitable material for other designs and applications at ultra-low temperatures and should therefore be included in the physical testing.

Further research related to the materials list includes filling in information gaps related to missing data at ultra-low and very-low temperatures and continuing the search for additional materials suitable for ultra-low temperatures using sources other than literature. The missing data first to be researched should be thermal conductivity, magnetic susceptibility, density, coefficient of thermal expansion and Young's modulus. To find further materials, it is recommended to investigate alloys of the materials presented in the materials list, as they may offer potential cost reductions while maintaining high thermal conductivity.

Further research is also needed to validate the simulation values obtained in Ansys to verify its use for ultra-low temperatures. The research should include physical testing of the materials to obtain actual values to compare with the simulated values. If the physical tests verify the use of the Ansys simulation software, further simulations should be carried out to validate all the materials in the material list.

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A

Python code for Prediction of thermal conductivity

```
import numpy as np
import matplotlib.pyplot as plt
from sklearn.svm import SVR
from sklearn.linear_model import LinearRegression
from sklearn.preprocessing import PolynomialFeatures

# Data on thermal conductivity at different temperatures in Kelvin
# Copper RRR=500 #thermal_cond = np.array([[300, 401.187],
[290, 402.114], [270, 404.119], [250, 406.376], [230, 408.967],
[210, 412.030], [190, 415.809], [170, 420.767], [150, 427.862],
[130, 439.285], [110, 460.669], [90, 508.864], [70, 645.921],
[50, 1173.483], [40, 1975.835], [30, 3724.367], [20, 6574.877],
[10, 6877.720], [9, 6439.948], [8, 5905.205], [7, 5287.587],
[6, 4608.648], [5, 3896.211], [4, 3181.685]])
# Beryllium copper #thermal_cond = np.array([[80, 37.14599],
[75, 35.68659], [70, 34.07563], [65, 32.31727], [60, 30.41602],
[55, 28.37661], [50, 26.20373], [45, 23.90194], [40, 21.47568],
[35, 18.92969], [30, 16.27016], [25, 13.50758], [20, 10.66293],
[15, 7.78080], [10, 4.95496], [9, 4.41050], [8, 3.87697],
[7, 3.35621], [6, 2.84973], [5, 2.35801], [4, 1.87877],
[3, 1.40240], [2, 0.89991]])
# Copper RRR=50 #thermal_cond = np.array([[300, 392.36824],
[290, 392.99900], [270, 394.31930], [250, 395.73911],
[230, 397.30134], [210, 399.08662], [190, 401.25321],
[170, 404.12731], [150, 408.42082], [130, 415.80255],
[110, 430.56184], [90, 465.12918], [70, 561.11180],
[50, 863.55906], [40, 1163.36060], [30, 1444.43283],
[20, 1367.85481], [10, 778.14877], [9, 700.66367],
[8, 622.30460], [7, 544.00651], [6, 466.81537],
[5, 391.87389], [4, 320.38313]])
# Copper RRR=100 #thermal_cond = np.array([[300, 396.32396],
[290, 397.16364], [270, 398.94228], [250, 400.88384],
[230, 403.04639], [210, 405.53271], [190, 408.53631],
[170, 412.44527], [150, 418.09390], [130, 427.42789],
[110, 445.46677], [90, 486.97990], [70, 603.55816],
[50, 1004.84628], [40, 1485.10936], [30, 2142.89682],
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[20, 2422.51026], [10, 1539.91558], [9, 1391.68965],
[8, 1239.02039], [7, 1084.67864], [6, 931.69175],
[5, 783.20860], [4, 642.29696]])
# Copper RRR=150 #thermal_cond = np.array([[300, 397.64132],
[290, 398.54113], [270, 400.45069], [250, 402.53899],
[230, 404.86638], [210, 407.53870], [190, 410.75424],
[170, 414.91032], [150, 420.86338], [130, 430.62031],
[110, 449.39313], [90, 492.66013], [70, 615.47615],
[50, 1055.80010], [40, 1628.79432], [30, 2551.37712],
[20, 3244.62985], [10, 2274.74662], [9, 2066.28652],
[8, 1846.82753], [7, 1621.19191], [6, 1394.75203],
[5, 1173.12811], [4, 961.76251]])
# Copper RRR=300 #thermal_cond = np.array([[300, 397.87390],
[290, 399.89108], [270, 403.70528], [250, 407.19619],
[230, 410.35347], [210, 413.22966], [190, 416.01455],
[170, 419.19407], [150, 423.90835], [130, 432.82352],
[110, 452.50634], [90, 501.02235], [70, 638.50229],
[50, 1130.46749], [40, 1833.29216], [30, 3257.07811],
[20, 5052.26743], [10, 4319.90467], [9, 3998.19213],
[8, 3636.07859], [7, 3238.15741], [6, 2809.90208],
[5, 2357.60035], [4, 1888.37931]])
# Gold # thermal_cond = np.array([[300, 315], [273.2, 318],
[250, 320], [200, 327], [150, 335], [100, 345], [90, 348],
[80, 352], [70, 358], [60, 380], [50, 420], [45, 460],
[40, 520], [35, 610], [30, 760], [25, 1020], [20, 1500],
[18, 1770], [16, 2090], [15, 2260], [14, 2410], [13, 2550],
[12, 2670], [11, 2770], [10, 2820], [9, 2820], [8, 2750],
[7, 2600], [6, 2370], [5, 2070], [4, 1710], [3, 1310],
[2, 885], [1, 444]])
# Beryllium #thermal_cond = np.array([[300, 194.9],
[280, 217.9], [260, 237.6], [240, 255.5], [220, 274.2],
[200, 298.0], [180, 333.3], [160, 390.7], [140, 489.9],
[120, 670.0], [100, 1014], [90, 1296], [80, 1693],
[70, 2243], [60, 2968], [50, 3823], [40, 4571], [30, 4685],
[20, 3611], [18, 3262], [16, 2887], [14, 2502], [12, 2120],
[10, 1754], [8, 1410], [6, 1082], [4, 741.4], [3, 551.1],
[2, 355.0], [1, 181.4]])
# Cadmium #thermal_cond = np.array([[300, 104],
[273.2, 104], [250, 105], [200, 106], [150, 108],
[100, 110], [90, 111], [80, 113], [70, 116], [60, 121],
[50, 128], [40, 141], [35, 151], [30, 167], [25, 192],
[20, 242], [15, 380], [10, 950], [8, 1930], [6, 4730],
[5, 7190], [4, 9660], [3, 11100], [2, 9630], [1, 5280]])
# pyrolytic graphite #thermal_cond = np.array([[300, 2000],
[273.2, 2230], [250, 2450], [200, 3250], [150, 4530],
[100, 4980], [90, 4730], [80, 4290], [70, 3650], [60, 2980],
[50, 2300], [40, 1630], [30, 990], [20, 420], [10, 81]])
# ETP Copper #thermal_cond = np.array([[293.15, 388],
[273.15, 390], [194.15, 400], [77.15, 550], [40, 1180],

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[30, 1410], [28, 1440], [20, 1330], [10, 800], [8, 635],
[6, 470], [5, 400], [4, 320]])
# Phosphorus deoxidized Copper #thermal_cond = np.array([
[293.15, 340], [273.15, 201], [100, 139], [80, 127],
[77, 120], [60, 110], [40, 85], [30, 66.5], [20, 43.5],
[10, 19.3], [8, 15], [6, 10.9], [5, 9.1], [4, 6.5]])
# Copper-2%Be #thermal_cond = np.array([[293.15, 105],
[120, 43.12], [100, 41.41], [90, 39.60], [80, 37.15],
[70, 34.08], [60, 30.42], [50, 26.20], [40, 21.48],
[30, 16.27], [20, 10.66], [18, 9.511], [16, 8.357],
[14, 7.207], [12, 6.069], [10, 4.955], [8, 3.877],
[6, 2.850], [4, 1.879], [3, 1.402], [2, 0.899], [1, 0.3161]])
# Diamond #thermal_cond = np.array([[300, 2310],
[273.2, 2630], [250, 2970], [200, 4040], [150, 6050],
[100, 10000], [90, 11000], [80, 11700], [70, 12000],
[60, 11300], [50, 9300], [45, 8020], [40, 6670],
[35, 5250], [30, 3950], [25, 2740], [20, 1710],
[18, 1350], [16, 1020], [15, 877], [14, 745],
[13, 620], [12, 510], [11, 409], [10, 324], [9, 246],
[8, 180], [7, 127], [6, 83.6], [5, 50.2], [4, 26.6],
[3, 11.5], [2, 3.41], [1, 0.437]])
# Mylar #thermal_cond = np.array([[80, 0.1567],
[70, 0.1526], [60, 0.1443], [50, 0.1319], [40, 0.1158],
[30, 0.09633], [20, 0.07349], [18, 0.06849], [16, 0.06337],
[14, 0.05816], [12, 0.05295], [10, 0.04791], [8, 0.04334],
[6, 0.03978], [4, 0.03764], [3, 0.03610], [2, 0.03092]])
# Nylon #thermal_cond = np.array([[4, 0.01245],
[6, 0.01983], [8, 0.02880], [10, 0.03902], [12, 0.05014],
[14, 0.06185], [16, 0.07388], [18, 0.08602], [20, 0.09811],
[30, 0.1543], [40, 0.1999], [50, 0.2352], [60, 0.2619],
[70, 0.2821], [80, 0.2974], [90, 0.3091], [100, 0.3179],
[120, 0.3298], [140, 0.3367], [160, 0.3405], [180, 0.3424],
[200, 0.3431], [220, 0.3428], [240, 0.3420], [260, 0.3406],
[280, 0.3389], [300, 0.3368]])
# Perspex #thermal_cond = np.array([[2.5, 0.00049],
[3.0, 0.00054], [3.4, 0.00054], [3.5, 0.00055],
[4.0, 0.00057], [4.5, 0.00058], [5.0, 0.00060],
[6.0, 0.00060], [9.0, 0.00060], [15.0, 0.00065],
[19.0, 0.00070], [21.0, 0.00077], [24.0, 0.00090]])
# PBronze #thermal_cond = np.array([[1.66, 1.45],
[1.83, 1.62], [2.07, 1.89], [2.16, 1.98], [2.38, 2.23],
[2.64, 2.52], [2.84, 2.77], [3.00, 2.96], [3.46, 3.49],
[3.66, 3.72], [3.75, 4.00], [1.95, 1.95], [2.24, 2.31],
[2.59, 2.71], [2.74, 2.89], [2.91, 3.07], [3.03, 3.19],
[3.19, 3.37], [3.36, 3.55], [3.69, 3.88], [3.86, 4.11],
[9.16, 10.8], [10.0, 11.9], [12.8, 15.5], [14.1, 17.3],
[19.7, 24.0], [21.3, 26.1], [25.5, 30.9], [30.3, 36.0],
[32.8, 38.3], [34.5, 40.5], [40.7, 51.4], [42.6, 48.9]])
# Sapphire #thermal_cond = np.array([[1, 3.9], [5, 410],

```

A. Python code for Prediction of thermal conductivity

```
[10, 2900], [15, 8700], [20, 15700], [25, 20200],
[30, 20700], [35, 17700], [40, 12000], [45, 7700],
[50, 5200], [60, 2650], [70, 1530], [80, 960], [90, 640],
[100, 450], [150, 150], [200, 82], [250, 58], [273.2, 52],
[300, 46]])
# Silicon #thermal_cond = np.array([[1, 4.48], [2, 31.7],
[3, 99.8], [4, 226], [5, 424], [6, 686], [7, 991],
[8, 1340], [9, 1720], [10, 2110], [11, 2480], [12, 2870],
[13, 3250], [14, 3600], [15, 3930], [16, 4220], [18, 4670],
[20, 4940], [25, 5140], [30, 4810], [35, 4130], [40, 3530],
[45, 3060], [50, 2680], [60, 2110], [70, 1680], [80, 1340],
[90, 1080], [100, 884], [150, 409], [200, 264],
[273.2, 168], [300, 148]])
# Silver thermal_cond = np.array([[1, 3940], [2, 7830],
[3, 11500], [4, 14700], [5, 17200], [6, 18700], [7, 19300],
[8, 19000], [9, 18100], [10, 16800], [11, 15400],
[12, 13900], [13, 12400], [14, 10900], [15, 9600],
[16, 8500], [18, 6600], [20, 5100], [25, 2950], [30, 1930],
[35, 1370], [40, 1050], [45, 840], [50, 700], [60, 550],
[70, 497], [80, 471], [90, 460], [100, 450], [150, 432],
[200, 430], [250, 428], [273.2, 428], [300, 427]])
# CuNi #thermal_cond = np.array([[3.03, 0.56], [5.12, 1.18],
[9.53, 3.13], [60.80, 17.7], [90.60, 18.9]])
# Quartz #thermal_cond = np.array([[5, 400], [7, 900],
[8, 1210], [9, 1500], [10, 1650], [11, 1680], [12, 1630],
[13, 1530], [15, 1250], [20, 720], [25, 460], [30, 318],
[35, 233], [40, 179], [45, 143], [50, 118], [60, 85],
[70, 66], [80, 54], [90, 45], [100, 39], [150, 23.1],
[200, 16.4], [250, 12.7], [273, 11.6], [300, 10.4]])

# Split the data into different sets
temp_range_low = thermal_cond[:, 0][thermal_cond[:, 0] <= 10]
print(temp_range_low)
temp_range_mid = thermal_cond[:, 0][(thermal_cond[:, 0] < 70) &
(thermal_cond[:, 0] > 10)]
print(temp_range_mid)
temp_range_high = thermal_cond[:, 0][thermal_cond[:, 0] >= 70]
print(temp_range_high)

y_low = thermal_cond[:, 1][thermal_cond[:, 0] <= 10]
print(y_low)
y_mid = thermal_cond[:, 1][(thermal_cond[:, 0] < 70) &
(thermal_cond[:, 0] > 10)]
print(y_mid)
y_high = thermal_cond[:, 1][thermal_cond[:, 0] >= 70]
print(y_high)

# Fit a polynomial regression model to a temperature range
```

```
poly = PolynomialFeatures(degree=3)
X_poly = poly.fit_transform(temp_range_high.reshape(-1, 1)
)
poly_reg = LinearRegression()
poly_reg.fit(X_poly, y_high)

# Fit a polynomial regression model to a temperature range
poly_mid = PolynomialFeatures(degree=3)
X_poly_mid = poly_mid.fit_transform(temp_range_mid.reshape(-1, 1)
)
poly_reg_mid = LinearRegression()
poly_reg_mid.fit(X_poly_mid, y_mid)

# Fit a support vector regression model to a temperature range
svr = SVR(kernel='rbf', C=5e4, gamma=0.01)
svr.fit(temp_range_low.reshape(-1, 1), y_low)

# Predict thermal conductivity at the given temperatures in
#thermal_cond
predicted_low = svr.predict(temp_range_low.reshape(-1, 1))
predicted_mid = poly_reg_mid.predict(poly_mid.fit_transform(
temp_range_mid.reshape(-1, 1)))
predicted_high = poly_reg.predict(poly.fit_transform(
temp_range_high.reshape(-1, 1)))
predicted = np.concatenate((predicted_low, predicted_mid,
predicted_high))

# Ensure predicted values are non-negative
predicted = np.maximum(predicted, np.zeros(predicted.shape))

# Create temperature range by concatenating the temperature sets ,
# and adding 0.01 Kelvin and 0.02 Kelvin
temp_range = np.concatenate((temp_range_low, temp_range_mid,
temp_range_high, np.array([0.01, 0.02])))

# Predict thermal conductivity for the added temperatures
additional_temps = np.array([0.01, 0.02])
additional_predicted_low = svr.predict(
additional_temps.reshape(-1, 1))
print(additional_predicted_low)
additional_predicted_mid = poly_reg_mid.predict(
poly.fit_transform(
additional_temps.reshape(-1, 1)))
print(additional_predicted_mid)
additional_predicted_high = poly_reg.predict(
poly.fit_transform(
additional_temps.reshape(-1, 1)))
print(additional_predicted_high)
```

A. Python code for Prediction of thermal conductivity

```
# Select the most fitting training method
additional_predicted = additional_predicted_low
#additional_predicted = additional_predicted_mid
#additional_predicted = additional_predicted_high

# Ensure predicted values are non-negative
additional_predicted = np.maximum(additional_predicted,
np.zeros(additional_predicted.shape))

# Concatenate all predicted values
predicted = np.concatenate((predicted.reshape(-1, 1),
additional_predicted.reshape(-1, 1)), axis=0)

# Output predicted thermal conductivity values
for i in range(len(temp_range) + len(additional_temps)-2):
    if i < len(temp_range):
        print("Predicted thermal conductivity at {:.2f} K:
        {:.2f} W/(mK)".format(temp_range[i],
float(predicted[i])))
    else:
        print(f"Predicted thermal conductivity at
        {additional_temps[i - len(temp_range)]:.2f} K:
        {float(predicted[i]):.3f} W/(mK)")

# Plotting the actual and predicted values
plt.figure(figsize=(10, 6))

# Plot actual values
plt.scatter(thermal_cond[:, 0], thermal_cond[:, 1],
label='Actual', color='blue')

# Plot predicted values
predicted_actual = predicted[:len(temp_range)]
plt.scatter(temp_range, predicted_actual, label='Predicted',
color='orange', alpha=0.5)

# Plot additional predicted values
additional_temps_all = additional_temps
additional_predicted_all = additional_predicted
plt.scatter(additional_temps_all, additional_predicted_all,
label='Additional Predicted', color='red', alpha=0.5)

plt.title('Thermal Conductivity vs Temperature')
plt.xlabel('Temperature (K)')
plt.ylabel('Thermal Conductivity (W/(mK))')
plt.legend()
plt.show()
```

B

Stakeholder Statements

Table B.1: Collection of the statements collected from the interviews performed with primary stakeholders.

Number	Item	Statement
S109	Cleanliness	Of course, there's also cleanliness, and that's important, and that you don't have any oils, or anything left. In any case, rinse it off in isopropanol and/or ethanol. But ideally, you should ultrasonically wash in some agent and there are some who do that when they want really clean and so on.
S110	Cleanliness	I usually tell them, and everyone knows that they may have to wash it if it is a necessity. And then when you handle it in a cryostatic environment, many people wear gloves.
S13	Cost	A small sample holder with around 20 connections would easily cost around €20,000. When you spend so much time and money on everything else, it's reasonable in relation to the cost of everything else. If you have already spent around €600,000, €20,000 is not that much. Often, we don't really look at the price because there is no other choice.
S168	Cost	I mean the main cost are of course the material and the labor cost to build it. Of course, there's something with the design,
S169	Cost	QDevil was charging €20,000 for their sample order and that's a lot.
S170	Cost	but then you could use that 20,000 to buy a local oscillator, which you cannot work without. Yeah, right. Yeah. And in-house, you can build something. Yeah, right. So that's much cheaper. So you it's of course small compared to the cost of the fridge, but you also have a very limited funding and and you just buy first the essentials. And then whatever is left, you have to wiggle around. So it's not always such an easy, sometimes an easy choice. And our center is well funded, thankfully. So we don't we we are right now in the position to make all these choices, but a lot of groups have to struggle to survive. So there it makes a lot of difference.
S18	Cost	Different sizes are sold because of reducing the price. It is cheaper with fewer connections. Two samples in one sample holder can be cheaper than buying two sample holders for each sample. Running cost does not change when using two samples
S35	Cost	To be able to scale up systems to thousands of qubits, costs need to go down for all parts.
S54	Cost	Sample holders in the industry is usually made in house but is estimated to cost 10-20 thousand euros without the cabling to produce.
S55	Cost	Performance over price, but price needs to be reasonable
S117	Delivery time	Takes a week if you have all the stuff at home to make an already made product.
S118	Delivery time	Most accept 2 weeks manufacturing time
S119	Delivery time	Takes a week to receive the materials to be processed
S120	Delivery time	There has rarely been a problem with our delivery times.
S15	Delivery time	The delivery time depends on the components. We usually see a minimum of 2 weeks and then it goes up to 12 weeks.
S57	Delivery time	Delivery time could be 1 day for simple components to 18 weeks or a couple of months for more expensive and precious parts.
S75	Delivery time	The hardware for quantum computers must be delivered within a reasonable timeframe, preferably fast delivery and short lead times, to meet the customer's requirements and expectations.

B. Stakeholder Statements

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S115	Design	It is rarely any really high tolerances that you need to make, because often too tight tolerances can cause problems, especially when assembling with copper and it should be easy to assemble and so on and that is rarely the problem.
S139	Design	make the sample holder the can longer instead of, so when it is longer, it protects its better from the magnetic field which you know. So these are the things that we are focusing more on before we go into, OK is OFHC copper good enough or not? That's a question we are not addressing now, but maybe in the future, yeah.
S140	Design	So we have something, I mean we have found that the higher the aspect ratio, the better is the shielding from magnetic field.
S141	Design	So if we have a device which is very sensitive, we try to put it at the bottom most instead of higher up.
S142	Design	We also make a circuit diagram because there are many cables and you want to make sure that not only it goes to the right cable, but also you're putting the right filters and attenuator. List for that. Particular device because different channels might require different attenuation levels, so we. Make a drawing a plan of that, and then we open it, we install it,
S143	Design	I think this is better because that means that you have to do less cable connections and cable connections. Again, you have to be extra careful when you're doing cable connection. You can't have anything loose, and the more you take it in and out the usually they will have wear and tear and over time they will go bad. So you want things to be as hard wired as possible with and you don't have to touch them
S144	Design	What we have is this SMA cables with the usual SMA connectors which we have to tighten everything every time. And sometimes you have so much wiring density over there, it's hard to reach there, so it's a bit inconvenient. It takes more time. So for this is smarter design and this is easier to load.
S146	Design	this cabling is sometimes a bit tricky and you have to reach places which are very hard to reach sometimes. So having a design where every connection is easy to reach would be very helpful
S147	Design	How much you can put this different sample holders in a very limited space, so these are more of accessibility issues which we which is sometimes a bit of an issue makes it harder to install these things.
S148	Design	So we will have more density of cables in a very in a smaller volume. That would be quite helpful. So there's another issue trend in quantum computing and people are coming up with commercial solutions to pack more cables. But more cables mean more, more lines to explore.
S149	Design	I think the minimum should be 8 (cables)
S150	Design	So we are working with our current plan is to not go beyond five qubits. That said, I mean that still pack requires a lot of cabling. So I think the number of cables that could require is of the order of 16 or something which is present in our fridge
S151	Design	One uses up 16, then the others cannot use any, so more is good. And for now, right now we have what, 12 cables, input lines and four output lines. I'm thinking about adding four more, but that would be quite sufficient.
S152	Design	So one thing we have tested, definitely that having a higher aspect ratio is very helpful. And even if we try to prevent as much magnetic field, there's always a little bit and then at some point it is asymptotically gets better. Right, for a lot of experiments, I said that's not been the bottleneck and we were in a good zone, but for some cases it would be important. So you want to have a higher aspect ratio for sure, but then I have not done this calculation myself, but my guess is that absolute values also matter.
S153	Design	I've often thought is that it's a bit too bulky. And being bulky means there's more material, more heat load. It takes longer to cool down, but when I asked somebody who actually made it, he said, like, yeah, but it also makes it, you know, more robust against temperature fluctuations. So there's a tradeoff.
S116	Design & Material	It is very rare that people want it. I think that if it's such really high vacuum stuff and if it's vacuum stuff that's going to heat, I think it's a bigger problem that there will be a containment that slowly leaks out. But if you have it when there are things to be cooled down, from what I have heard anyway, it is not such a big problem, because then it freezes. When it comes down to a temperature that freezes the air that is there and then it remains in screws and so on. In any case, people rarely think about it.

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S79	Design & Material	Using straight cables and pipes can cause stress in the material, use a radius so the cables wont crack
S87	Design & Material	after a certain length there is a certain dissipation. Then there is also a conductivity effect that takes over. As I mention in the dissertation, the joule effect decreases with the length of the cable.
S145	Design & Thermal	it adds to the thermal load, so this having a design where you have much smaller wiring is helpful.
S10	Dimensions	The footprint of the connectors determines how big your sample holder needs to be for you to be able to insert it and let it go. As we try to be as small as possible, the height is also related to not wanting to risk too much free space around your sample.
S100	Handbook	Safety is a very important section and chapter
S101	Handbook	The documents are updated continously, a couple of times a year
S102	Handbook	we have a built-in correction system in the writing software. We also have a "term bank", where a terminology manager has identified the specific words we should use.
S103	Handbook	legal requirements need to be taken into account. We comply with the "maskindirektivet
S104	Handbook	we do a lot of "topic-based authoring". That each instruction/portion should stand on its own; it should not refer to any previous paragraph to show a picture. The information should work out of context
S105	Handbook	We try to keep the text to "simplified technical English". Short and concise, straight to the point. We keep in mind that these will be translated and do not want to complicate the text.
S172	Handbook	So what would be very helpful is to have that references as much as possible so that future in the future people can make judgments based on those references.
S173	Handbook	And the other thing about this reference is that once you have found them, then other people will be citing those references in their papers. So from that reference you can go to whatever is the latest development
S174	Handbook	You should use the whatever is the latest of course, and when you don't find the latest you have to go back in time. So yes, it is still valuable.
S175	Handbook	Yeah, because if now I decide, OK, I need to know. Let's say titanium. What is the what is the thermal conductivity? Somebody did that in 1980s, which with instruments which were not accurate, which were done not that rigorously. It's still better than nothing.
S98	Handbook	we print a lot but the company offers a cloud service where the customer can access digital documents so it is up to the customer. A printed copy is included in the delivery, but the customer can buy other manuals.
S99	Handbook	we have chosen to organize the manual in a certain way, which information belongs to the operator. Yes, it is in the operator's manual. What information should be available for maintenance personnel, that's in the maintenance manual. Then I think this should be included, this information should be included as a legal requirement.
S111	Manufacturing	Sometimes solders can crack due to varying degrees of shrinkage in parts. Usually, a bellows or similar is built in to reduce the stresses
S113	Manufacturing	On really small things, there may be a limit to what the cutter can do and how precisely it does things.
S114	Manufacturing	Almost always measure with a calliper afterwards to ensure that it is right because it can happen that cutters wear out. You almost always have to check.
S122	Manufacturing	Too soft materials can cause problems in manufacturing.
S171	Manufacturing	of course, there are very few players who are doing it right. So when we decide to have a sample holder, we would like to have it in. Three to four weeks, I mean being reasonable because we want it next week, but trying to be reasonable three to four weeks.
S25	Manufacturing	We don't want a surface roughness that is very big because we want to place our samples in the sample holder and therefore, we want it to be as flat as possible and that all the parts fit together well.
S38	Manufacturing	There is currently no measure used for cleanliness, however it is usually nice if components look clean.
S60	Manufacturing	Cleanliness, it must be very clean.
S72	Manufacturing	Strict cleanliness is required for optimal operations.
S106	Material	Thermal conductivity, non-magnetic and low temperature resistance.
S107	Material	Yes, vacuum compatibility is, of course, important, but it is usually a question if you have plastics, for example.

B. Stakeholder Statements

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S108	Material	Brass could be a problem if you have higher temperatures. It doesn't seem, from what I have understood, that it is not a problem when you go from room temperature downwards.
S112	Material	With gold plating, the reflection holds, and they are carefully handled with gloves so usually no polishing is needed. However, regarding copper, it can oxidize quickly and needs treatment.
S131	Material	So we are it's more around microwave engineering than studying the materials we are still with the traditional materials such as copper and aluminum, and so on, and we pretty much know how they behave.
S133	Material	Sometimes we do explore a few other materials like an IBM nitride for actually superconducting qubit circuits instead of aluminum, but that's also a small process.
S134	Material	So it's usually the standard ones which are coppers. We use cables coaxial cables which are made of cupronickel
S135	Material	those things are quite some basic important checks, for example, that you don't want magnetic impurities on these materials.
S136	Material	when we want to goldplate something, we go to this particular vendor and not just any vendor because we are very sure that they provide non magnetic material in this plating.
S137	Material	I very much prefer if it is gold plated, so copper is what I am used to and I haven't. As I said, seen any particular reason to move away from copper yet? So copper is good enough, but what I really like is to have it gold plated, because then it does not oxidize, and oxidation is a problem. A lot of people, I don't think agree with that, but I think so. It's quite a it's quite an issue of course. And then when you oxidize, you have to be very sure that you don't have any magnetic impurities. That's really paramount, which means that it has to be very high quality plating.
S138	Material	No, you should not use brass. Yeah, that's the problem I think because a lot of brass have magnetic impurities, probably nickel. We use titanium screws again, specifically from a very specific vendor.
S154	Material	So somewhere around 10 Gauss and 10,000 Gauss is about one Tesla, so around something less than 10 Gauss we see. OK, this is nonmagnetic and we use it around our fridge.
S155	Material	We do and one thing we try to be doing is to use these wrenches which are also nonmagnetic, because when you're doing that, you could leave out some particles around there. Yeah, this is a practice we try to follow.
S156	Material	If it is paramagnetic then it gets magnetic when you know you put a magnetic field next to it, right? And since we are trying very hard not to put anything magnetic, it's not what we are worried about. I think it is something. Of course I say SCALINQ has to worry about. Probably as building good products and keep an edge, but for us in our experiments, again that has not been the bottleneck.
S22	Material	We want everything to be non-magnetic. Not many providers can provide really non-magnetic connectors.
S23	Material	We want to have a very good thermal conductance because we want things to cool down fast.
S24	Material	We would like a sample holder that oxidizes less. In principle, it should not oxidize, but if you touch it, you will help build up a side layer that lowers the thermal conductivity.
S26	Material	Anything that is magnetic must be avoided as it can cause fluctuations in the magnetic environment and depending on the type of qubits you have, this can shift their frequency and move it, which is something you want to avoid.
S39	Material	As components is put into vacuum, it is important that contaminated components are not used as degasation can occur. The contamination on the components can then evaporate and get stuck on the cryogenic wall, which is unwanted.
S46	Material	Components that are magnetic must be avoided.
S59	Material	Materials properties that are desirable is: Cryogenic compatible, as thermally conducting as possible and non-magnetic.
S61	Material	Problems finding non-magnetic materials in the industry
S62	Material	The non-electric hardware should not become superconducting.
S65	Material	Shrinkage has not been a problem but is important if you want to have a very precise system.

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S70	Material	As materials change due to temperature it is therefore necessary that different materials on the same hardware have a uniform and controlled change. Furthermore, if the hardware is coupled with the sample, the hardware needs to have the same change as the sample.
S73	Material	The materials used in quantum computing hardware must be corrosion-resistant to ensure their longevity and reliability.
S74	Material	Quantum computing hardware must have a reliable datasheet that provides accurate information about its specifications and capabilities. Testing must also be carried out in both virtual and physically correct environments to ensure the reliability and performance of the hardware.
S78	Material	It can be a balance between these two, the better conductivity but worse resistivity or vice versa, you have to check so that your signal arrives. If you have too much resistivity in your cable, you can lose so much signal from room temperature that the signal does not reach your component.
S80	Material	The problem in these temperature can cause material to become brittle, and if the wrong material is chosen it can be disastrous
S81	Material	our safety factor was 2. There are a few different schools of thought on this (safety factor) in some industries you want a factor of 5. We don't need to go that extreme, so 2-2.5 is what the book says. But there you have to think about 1 is rarely good, 1.5 at least, but it applies to what applications you want to do.
S85	Material	All components provide a certain amount of heat/energy at each stage, so we had to take that into account so that it did not exceed our maximum specification, with cables and various equipment.
S91	Material	That they dont break or become brittle when cooled
S92	Material	Test multiple cooling cycles, so the components wont break. It has to last for a long time.
S93	Material	So the main thing is that the material should be used in those temperatures, so for example if you look at stainless steel. You can't use martensitic stainless steels because their atomic structure is different from austenitic stainless steels.
S94	Material	Copper should be oxygen free
S95	Material	Because of vacuum, you want to eliminate outgassing/degassing
S96	Material	another factor has to do with deformations, a material can deform and then not return to its original shape, where the material can crack.
S97	Material	This is called the Meissner effect and occurs in a superconductor when you are below its T_c . Then the magnetic field does not pass through the material. This is controlled by the diamagnetism of the material and when a magnet approaches a superconductor, a current is induced in the superconductor. Since there is no resistance to the current, the current continues to flow and thus induces its own magnetic field that repels the field of the magnet. So I guess paramagnetic materials are not desirable.
S121	Material	I think the copper, if it's just sitting, I've never heard that it goes bad after. It can happen, so thermal conductivity decreases in bolted joints, whether it is true or not is probably divided and so on. I cannot assess how many cycles or how long.
S3	Noise	We think a lot about the frequency bandwidth, the frequency of the qubit and the resonators. You don't want a lot of high frequency noise because it can interfere with the behaviour of the superconducting material and create additional noise. So, we are really careful to protect our samples from any kind of noise, whether it is electrical, radiation or magnetic. So, we need a very quiet environment for our device, which can be achieved through filtering and shielding.
S34	Noise	It is important to consider the chip itself but also all the cryogenic systems around it.
S37	Noise	Noise needs to be considered as the quantum state is very sensitive even if the level of noise is very, very low.
S52	Noise	Less noise overall in the system over thermal conductivity.
S53	Noise	No noise known from the sample holder, but if something is magnetic it will create noise. The cables can create wave gaps for noise.

B. Stakeholder Statements

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S68	Noise	The minimization of residual magnetic fields inside the shield is crucial where components such as screws, rf connectors and cables need to be non-magnetic.
S8	Noise	The filtering is something that I think people are going to have to focus a little bit more on. This is because most companies create high-density lines, but then when you go to the lower stage, there's no equivalent to the filtration, so the filtration is still very extensive, but it still has a semi-connection. So, we have to work on the lower stage of the mixing chamber to make something that is compatible with this high-density line. Because yes, you save a lot of space above, but then you should do the same thing below. So that's why, you know, we shouldn't have any similar block or filter that sort of matches these high-density lines and saves space and works as well as the bulky filters that we are.
S9	Noise	It is important to look at the crosstalk. Two lines running very close together on the PCB can receive the transmitted signal from one of the lines to the other. I would expect crosstalk below minus 40 dB and very few losses and a reflection below minus 20 dB. In addition, I would like to see qubit pressure creating over 100 microseconds or nowadays even more, as more and more groups have longer life qubits. I wouldn't buy anything that has the measure of a 10-microsecond qubit.
S157	Problem?	So I understand why paramagnetic is not good to be around. But then again it's an engineering problem. You just see how bad it is and can you live with that or not? Because there's so many engineering problems that you have to keep on solving. So yeah, in that sense, quantitative analysis would be very helpful.
S126	Problems	So one of the main issues with quantum computing is, of course the errors and part of our part of the reason that errors come up is because you cannot initialize qubits to the ground state very well.
S127	Problems	Then you have the electrons which are which we call their temperature electron temperature and if you look at some literature around millikelvin temperatures, it's one of the big problems that once you go below 100 millikelvin. The temperature of the electrons decoupled from that of the phonons or the atoms, and there's a lot of effort put in designing these refrigerators or people doing experiments where they want to bring it down, because now the electron numbers is completely loose.
S130	Problems	And you could either spend another decade of trying to reduce it and people go very far to do that. You know that, right? So they even put the dilution refrigerator underground. Yeah, to protect it from cosmic rays. Cosmic rays also does this, so people go very far, but not everybody can do that, right.
S4	Problems	During the first installation, all cables must be inserted, and it is very easy to make a mistake. Especially if an experiment requires many cables, it is easy to make a mistake and think that one cable is connected to something else in the circuit board.
S49	Problems	Cables creates unwanted hassle as you have to install each cable separate and when scaling up systems to over a thousand cables the installation is a struggle and it quite hard to keep track of each cable.
S51	Problems	There is a need to figure out a way to go away from just dealing with one cable at a time.
S6	Problems	The only time you take apart the sample holder is if you realize that a cable is not working or if you cannot control a qubit in your chip. You would then disassemble the sample holder and test that particular cable.
S67	Problems	The rapid evolution of the number of superconducting qubits results in an ever-increasing amount of wires that the hardware must manage and accommodate.
S1	Scaling up	In this field, there is a need to investigate how much and how well components can be shrunk.
S16	Scaling up	In order to scale up, miniaturization is hard. Other components also need to be smaller, such as connectors. Because of this, components are sometimes made in-house instead of using ready-made components.

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S2	Scaling up	I think from the research point of view, we need to think how we can use the same for example control line to control more than one qubit.
S33	Scaling up	In order to scaling up systems it is not enough that it can handle a lot more things, in addition everything also has to work well together when you operate it
S14	Service life	I would say that I expect it to last 10 years.
S27	Service life	Quality tests are wanted
S56	Service life	Sample holder life expectancy should be as long as possible, but they are usually exchanged within 2-3 years due to developments in the field.
S11	Shielding	But when it comes to the shield, you want it to be as long as possible and have as small a diameter as possible, because the shielding really depends on how the shield is designed.
S41	Shielding	It is wanted to minimise the number of electromagnetic strays and electromagnetic fields that comes in from the surrounding and that's why you have a lot of these Shields around it to minimise the interference from outside world.
S90	Simulation & verification	Therein lies the biggest problem with ansys when loading external drawings that it flips out a bit. Then when you mesh that it causes some trouble if the mesh does not go through. This may be because the designer has constructed it poorly.
S124	Thermal	Regarding cracks due to cooling: I don't think that happens much actually, at least not when it comes to copper.
S125	Thermal	But every material at any given temperature is radiating out something
S128	Thermal	So when we connect these cables and everything, right, so these cables are supposed to actually not transmit so much heat. Because if you have heat then you will heat up the qubit, so you really are trying to reduce the thermal conductivity.
S129	Thermal	So everything radiates to a certain extent. It's really miniscule that most of the time we don't worry about it. But when we are talking about qubits. Yeah, that's when we worry about it.
S158	Thermal	So the moment we keep adding more stuff to the fridge, then it takes longer to cool down. There is no problem as in I mean if there's a more heat load, it will take longer.
S28	Thermal	The lowest temperature the refrigerator can reach is 7 millikelvin.
S29	Thermal	The temperature near the sample is usually around 20 mK.
S30	Thermal	In the lowest stage of the refrigerator, it is the chip and cables that create heat. The cryostat affects how much heat can be accepted by the sample and the cables
S31	Thermal	Even if you run two samples at the same time, we see no temperature change. We have never reached the heating point that Bluefors says the fridge can handle.
S32	Thermal	Black body/heat radiation from inside is not a problem because of the cold temperature. The problem is the black body/heat radiation from the outside.
S36	Thermal	Currently data is missing at low temperatures and most often only data at room temperature is provided. It is therefore important that components function as advertised at very low temperature, as things changes at these low temperatures.
S42	Thermal	Components that are thermally anchored needs to have high thermal conductivity.
S43	Thermal	Components that are not thermally anchored, like cables, are harder to cool them down and as a result the system takes a long time to cool down. This is because you cool it down by taking heat out of it using radiation. But radiation is a very slow process, and it is noticed that the last few milli Kelvin is very hard to get down to and could take several days or weeks to for it to go down.
S45	Thermal	It is desirable to have a system that is robust against multiple usage.
S63	Thermal	1-2 days for cool down, but it is wished to be less than a day for cool down. The fridge is the limiter for the cool down

B. Stakeholder Statements

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S64	Thermal	the coldest temperature that the hardware should perform at is 10 millikelvin, but 30 millikelvin is pretty good as well.
S69	Thermal	The Bluefors LD400 enables a fast cool-down which is under 24 hours to reach 10 mK, excluding the equipment on the experimental flange. To take advantage of the fast cool-down time of the experimental flange, the hardware mounted there should also be quick to cool down.
S71	Thermal	To achieve low thermal conduction loads it is necessary to remove conduction and convection heat transfer by using a vacuum insulation system.
S76	Thermal	The hardware must be able to withstand mechanical loading at low temperature in the form of its own weight and the weight of the sample.
S77	Thermal	When going from room temperature to millikelvin in your case, the heat coming from the room temperature must be dissipated in some way. Then it is the resistivity property of the material that is important but also the conductivity of the material plays a role.
S88	Thermal	Can check the cooling on each stage remove this, you will need cooling cables/heat sink to divert it, so check between each stage. If you have 300 cables all the way, it can be quite a lot of jouleheating.
S159	Thermal & design	if you have a cable which is slightly sticking out and it could contact between two plates. Which are supposed to be a different temperature than it is the a thermal link. Yeah, and that will lead to the fridge not cooling down when we tighten screws. We want to make sure that they are really tightened because if they are starting to shake that will give lead to some fluctuations in the temperature and it's not very stable
S160	Thermal & design	So having more cables of course adds to the heat load. However, right now we have been just keeping up with what the standard solution is.
S12	Use	It would be desirable to have cables pre-installed
S161	Use	So for example, when we are using a new sample holder which is copper, we would like to get rid of all oxides because if you have oxide then it does not thermalize immediately and that's we don't want that. We want our qubits to thermalize with the lowest point of the lowest temperature of the fridge.
S162	Use	Some rubbing material like even Scotch Brite. You can scratch away the oxide or what I like to do is use citric acid because citric acid kind of throws away the oxide on this copper. So I use citric acid is much faster and requires less work.
S163	Use	Visually shiny, we are happy.
S164	Use	So we often do thermal cycling in intervals of three months on average. So after every three months we will load a different sample. Somebody needs to load a sample, so that's the. That's the time period.
S165	Use	Three years, Three years average.
S166	Use	So what we know is that there are some packages in the lab where we have measured qubits with coherence time of 100 microseconds. All right. But the next time, if you get only 20 microseconds, you don't know with a new sample holder with a new qubit, you don't know if it's the qubit which is the limiting factor, or the sample holder. So that's why we keep good qubits, and that's how we characterize new sample holders to make sure that it does not limit our coherences.
S17	Use	Different numbers of qubits are used for the same sample holder.
S19	Use	The sample holder should be able to handle at least five qubits and no particular maximum. In the case of Chalmers, however, they prefer something that can handle up to 100 qubits.
S20	Use	The sample holder should be able to handle a minimum of 16 cables.

Table B.1 continued from previous page

S21	Use	The sample holder can also have other uses, such as performing physical experiments. The scaling then does not matter so much
S40	Use	To make sure that components do not get contaminated with fingerprints and grease from hands, gloves are used.
S44	Use	It is desirable to have a sample holder that can handle many cables at a very small footprint.
S47	Use	Big systems run for 1-3 months, smaller systems not more than once every two weeks.
S48	Use	Typically, you do not need to or want to disassemble the sample holder once all cables are fitted.
S5	Use	Currently, several bases are used that make it possible not to remove the sample from LINQER when you want to insert a new one. It takes some preparation to be ready to put the sample in the lower part of the LINQER and therefore multiple bases are used.
S50	Use	The cables are usually only installed once if they were installed correctly.
S58	Use	Three cables per qubit.
S66	Use	Dilution refrigerators have limited space and cooling capacity which puts a need on space optimization and cooling properties of quantum computing hardware.
S7	Use	Large chips are usually used for 3-4 months before being disassembled. Smaller chips can be used from one month to one year.
S123	Verification	I can imagine, but they themselves have probably already thought of that, to test the thermal conductivity and whether the electronics heat up down there and whether they can conduct the heat away. Then, if you would like to test which torque is ideal for the screw for that particular connection, you can test and experiment, or if you simulate.
S132	Verification	As you said, one Kelvin, it's pretty much usually a very good approximation to work at 10 millikelvin as well.
S167	Verification	So he simulated it, it it got it fabricated and somebody in the lab used it to measure the coherence times. They got a good number and they say, OK, it's good enough, but it is it very good or what are the rooms for improvement?
S82	Verification	I would suggest to do basic analytical calculation to check that ANSYS or COMSOL has done a correct simulation
S83	Verification	Simulations are a black box, without correct properties for the materials when they are cooled it can be difficult to trust the results
S84	Verification	If you have incorrect parameters on your properties, or filled in the table for conductivity, you may be deceived by the result.
S86	Verification	We started with thermal hand calculations and field studies with how much power can we allow the cables to let through.
S89	Verification	Calculate it by hand, it is quite common, then check with ANSYS, if we get the same or similar results or if we get completely different results, then you have made a mistake in ANSYS.

Table B.2: The stakeholder statements found through the literature study, including their literature statement number, and the item or theme they belong to.

Number	Item	Statement
L1	Noise	Quantum computing manufacturers must address the significant concern of quality of bits by developing quantum computers with improved stability, reliability, and accuracy to provide customers with precise results for complex computations and simulations [11]
L2	Dimensions & Performance	Dilution refrigerators have limited space and cooling capacity which puts a need on space optimization and cooling properties of quantum computing hardware. [11]
L3	Scale up	The rapid development of quantum computing requires scalable platforms to move forward [10].
L4	Thermal	The significant reduction of temperature in the dilution refrigerator has pronounced effects on the properties of materials and the behavior of the system [19, 64, 91, 15].
L5	Design	The rapid evolution of the number of superconducting qubits results in an ever-increasing amount of wires that the hardware must manage and accommodate [5, 14, 10].
L6	Thermal	Blackbody radiation and heat radiation can cause interferences with cables and with the sample. The radiation is therefore necessary to reduce [14, 15].
L7	Thermal	The hardware needs to be able to withstand temperatures from room temperature down to 10mk and to avoid thermal excitation within this range or when operated [11, 14, 24, 18].
L8	Noise	An effective quantum environment must provide thorough isolation from the various noise sources, both from the free space and from the transmission lines, while allowing the coherent transmission of control signals to perform fast quantum operations [5, 11].
L9	Noise & Material	Magnetic fields can lead to interferences and errors in computation. It is therefore necessary to minimize magnetic fields and to shield the sample from the magnetic fields [5, 11, 92, 93, 27].
L10	Material	The minimization of residual magnetic fields inside the shield is crucial where components such as screws, rf connectors and cables need to be non-magnetic [5].
L11	Thermal	The Bluefors LD400 provides more than 15 mW of cooling at 20 mk on the experimental flange and has a cooling power of about 0.5 mW when operated at 100 mK [30].
L12	Thermal	The Bluefors LD400 enables a fast cool-down which is under 24 hours to reach 10 mK, excluding the equipment on the experimental flange. To take advantage of the fast cool-down time of the experimental flange, the hardware mounted there should also be quick to cool down [30, 15, 65, 95]
L13	Thermal	As materials change due to temperature it is therefore necessary that different materials on the same hardware have a uniform and controlled change. Furthermore, if the hardware is coupled with the sample, the hardware needs to have the same change as the sample [64].

Table B.2 continued from previous page

Number	Item	Statement
L14	Thermal	As thermal contraction occurs on the hardware, there is a need for strain-free mounting techniques both for the hardware itself and the mounting to the dilution refrigerator [64]
L15	Thermal	Differential thermal contraction can affect the chip depending on the mounting method. It is therefore necessary to take into account the stress that different mounting methods and test film thicknesses may cause [64]
L16	Thermal	To achieve low thermal conduction loads it is necessary to remove conduction and convection heat transfer by using a vacuum insulation system [95, 65, 64, 23]
L17	Material	Defects, impurities and quasiparticles that are not in equilibrium in the bulk, surface and interfaces of the material reduce the coherence time. [64, 129]
L18	Cleanliness	Strict cleanliness is required for optimal operations [130].
L19	Material	The materials used in quantum computing hardware must be corrosion-resistant to ensure their longevity and reliability.
L20	Cost	Quantum computing hardware must be designed and manufactured to be cost-effective without compromising functionality, reliability and performance [95]
L21	Verification	Quantum computing hardware must have a reliable datasheet that provides accurate information about its specifications and capabilities. Testing must also be carried out in both virtual and physically correct environments to ensure the reliability and performance of the hardware.
L22	Delivery time	The hardware for quantum computers must be delivered within a reasonable timeframe, preferably fast delivery and short lead times, to meet the customer's requirements and expectations.
L23	Thermal	The hardware must be able to withstand mechanical loading at low temperature in the form of its own weight and the weight of the sample. [64]
L24	Thermal	In addition to thermal conductivity, there is also a need to adapt the specific heat of the hardware and its thermal diffusivity to increase the cooling rate [64, 15].
L25	Thermal	Since the hardware and the sample is conductively cooled by mounting it on the cold plate, usually in vacuum, there is a need for all thermal joints between the sample and the cold plate to have a high thermal conductivity. [64]

C

Thermal conductivity data

Table C.1: Thermal conductivity data for the material "Copper (OFHC), (RRR=500)" with data from the National Institute of Standards and Technology (2018) [121].

Temperature (Kelvin)	Thermal Conductivity (W/(m*K))
300	401.187
290	402.114
270	404.119
250	406.376
230	408.967
210	412.030
190	415.809
170	420.767
150	427.862
130	439.285
110	460.669
90	508.864
70	645.921
50	1173.483
40	1975.835
30	3724.367
20	6574.877
10	6877.720
9	6439.948
8	5905.205
7	5287.587
6	4608.648
5	3896.211
4	3181.685

Table C.2: Thermal conductivity data for the material "Beryllium copper (High conductivity, 0.2-0.7% [101])" with data from the National Institute of Standards and Technology (2018) [121].

Temperature (Kelvin)	Thermal Conductivity (W/(m*K))
80	37.14599
75	35.68659
70	34.07563
65	32.31727
60	30.41602
55	28.37661
50	26.20373
45	23.90194
40	21.47568
35	18.92969
30	16.27016
25	13.50758
20	10.66293
15	7.78080

C. Thermal conductivity data

Table C.2 continued from previous page

Temperature (Kelvin)	Thermal Conductivity (W/(m*K))
10	4.95496
9	4.41050
8	3.87697
7	3.35621
6	2.84973
5	2.35801
4	1.87877
3	1.40240
2	0.89991

Table C.3: Thermal conductivity data for the material "Copper (OFHC), (RRR=50)" with data from the National Institute of Standards and Technology (2018) [121].

Temperature (Kelvin)	Thermal Conductivity (W/(m*K))
300	392.36824
290	392.99900
270	394.31930
250	395.73911
230	397.30134
210	399.08662
190	401.25321
170	404.12731
150	408.42082
130	415.80255
110	430.56184
90	465.12918
70	561.11180
50	863.55906
40	1163.36060
30	1444.43283
20	1367.85481
10	778.14877
9	700.66367
8	622.30460
7	544.00651
6	466.81537
5	391.87389
4	320.38313

Table C.4: Thermal conductivity data for the material "Copper (OFHC), (RRR=100)" with data from the National Institute of Standards and Technology (2018) [121].

Temperature (Kelvin)	Thermal Conductivity (W/(m*K))
300	396.32396
290	397.16364
270	398.94228
250	400.88384
230	403.04639
210	405.53271
190	408.53631
170	412.44527
150	418.09390
130	427.42789
110	445.46677
90	486.97990
70	603.55816
50	1004.84628
40	1485.10936
30	2142.89682

Table C.4 continued from previous page

Temperature (Kelvin)	Thermal Conductivity (W/(m*K))
20	2422.51026
10	1539.91558
9	1391.68965
8	1239.02039
7	1084.67864
6	931.69175
5	783.20860
4	642.29696

Table C.5: Thermal conductivity data for the material "Copper (OFHC), (RRR=150)" with data from the National Institute of Standards and Technology (2018) [121].

Temperature (Kelvin)	Thermal Conductivity (W/(m*K))
300	397.64132
290	398.54113
270	400.45069
250	402.53899
230	404.86638
210	407.53870
190	410.75424
170	414.91032
150	420.86338
130	430.62031
110	449.39313
90	492.66013
70	615.47615
50	1055.80010
40	1628.79432
30	2551.37712
20	3244.62985
10	2274.74662
9	2066.28652
8	1846.82753
7	1621.19191
6	1394.75203
5	1173.12811
4	961.76251

Table C.6: Thermal conductivity data for the material "Copper (OFHC), (RRR=300)" with data from the National Institute of Standards and Technology (2018) [121].

Temperature (Kelvin)	Thermal Conductivity (W/(m*K))
300	397.87390
290	399.89108
270	403.70528
250	407.19619
230	410.35347
210	413.22966
190	416.01455
170	419.19407
150	423.90835
130	432.82352
110	452.50634
90	501.02235
70	638.50229
50	1130.46749
40	1833.29216
30	3257.07811
20	5052.26743

C. Thermal conductivity data

Table C.6 continued from previous page

Temperature (Kelvin)	Thermal Conductivity (W/(m*K))
10	4319.90467
9	3998.19213
8	3636.07859
7	3238.15741
6	2809.90208
5	2357.60035
4	1888.37931

Table C.7: Thermal conductivity data for the material "Gold (Well-annealed 99.999% pure)" with data from Touloukian et al. [57].

Temperature (Kelvin)	Thermal Conductivity (W/(m*K))
300	315
273.2	318
250	320
200	327
150	335
100	345
90	348
80	352
70	358
60	380
50	420
45	460
40	520
35	610
30	760
25	1020
20	1500
18	1770
16	2090
15	2260
14	2410
13	2550
12	2670
11	2770
10	2820
9	2820
8	2750
7	2600
6	2370
5	2070
4	1710
3	1310
2	885
1	444

Table C.8: Thermal conductivity data for the material "Annealed Pyrolytic Graphite (APG) (// to layer planes)" with data from Touloukian et al. [58].

Temperature (Kelvin)	Thermal Conductivity (W/(m*K))
300	2000
273.2	2230
250	2450
200	3250
150	4530
100	4980
90	4730
80	4290
70	3650
60	2980
50	2300

Table C.8 continued from previous page

Temperature (Kelvin)	Thermal Conductivity (W/(m*K))
40	1630
30	990
20	420
10	81

Table C.9: Thermal conductivity data for the material "Copper, Electrolytic-tough-pitch (ETP) copper" with data from Touloukian et al. [57].

Temperature (Kelvin)	Thermal Conductivity (W/(m*K))
293.15	388
273.15	390
194.15	400
77.15	550
40	1180
30	1410
28	1440
20	1330
10	800
8	635
6	470
5	400
4	320

Table C.10: Thermal conductivity data for the material "Phosphorus deoxidized Copper" with data from Touloukian et al. [57] and Copper Development Association Inc. [124]

Temperature (Kelvin)	Thermal Conductivity (W/(m*K))
293.15	340
273.15	201
100	139
80	127
77	120
60	110
40	85
30	66.5
20	43.5
10	19.3
8	15
6	10.9
5	9.1
4	6.5

Table C.11: Thermal conductivity data for the material "Copper-2%Be " with data from Rumble [56] and MatWeb [122]

Temperature (Kelvin)	Thermal Conductivity (W/(m*K))
293.15	105
120	43.12
100	41.41
90	39.60
80	37.15
70	34.08
60	30.42
50	26.20
40	21.48
30	16.27
20	10.66
18	9.511

C. Thermal conductivity data

Table C.11 continued from previous page

Temperature (Kelvin)	Thermal Conductivity (W/(m*K))
16	8.357
14	7.207
12	6.069
10	4.955
8	3.877
6	2.850
4	1.879
3	1.402
2	0.899
1	0.3161

Table C.12: Thermal conductivity data for the material "Diamond (High -purity, high-perfection, water-white)" with data from Touloukian et al. [58]

Temperature (Kelvin)	Thermal Conductivity (W/(m*K))
300	2310
273.2	2630
250	2970
200	4040
150	6050
100	10000
90	11000
80	11700
70	12000
60	11300
50	9300
45	8020
40	6670
35	5250
30	3950
25	2740
20	1710
18	1350
16	1020
15	877
14	745
13	620
12	510
11	409
10	324
9	246
8	180
7	127
6	83.6
5	50.2
4	26.6
3	11.5
2	3.41
1	0.437

Table C.13: Thermal conductivity data for the material "Mylar" with data from Rumble [56]

Temperature (Kelvin)	Thermal Conductivity (W/(m*K))
80	0.1567
70	0.1526
60	0.1443
50	0.1319
40	0.1158
30	0.09633
20	0.07349
18	0.06849

Table C.13 continued from previous page

Temperature (Kelvin)	Thermal Conductivity (W/(m*K))
16	0.06337
14	0.05816
12	0.05295
10	0.04791
8	0.04334
6	0.03978
4	0.03764
3	0.03610
2	0.03092

Table C.14: Thermal conductivity data for the material "Nylon" with data from the National Institute of Standards and Technology (2018) [121].

Temperature (Kelvin)	Thermal Conductivity (W/(m*K))
300	0.3368
280	0.3389
260	0.3406
240	0.3420
220	0.3428
200	0.3431
180	0.3424
160	0.3405
140	0.3367
120	0.3298
100	0.3179
90	0.3091
80	0.2974
70	0.2821
60	0.2619
50	0.2352
40	0.1999
30	0.1543
20	0.09811
18	0.08602
16	0.07388
14	0.06185
12	0.05014
10	0.03902
8	0.02880
6	0.01983
4	0.01245

Table C.15: Thermal conductivity data for the material "Perspex" with data from Touloukian et al. [58].

Temperature (Kelvin)	Thermal Conductivity (W/(m*K))
4.0	0.00090
21.0	0.00077
19.0	0.00070
15.0	0.00065
9.0	0.00060
6.0	0.00060
5.0	0.00058
4.5	0.00057
4.0	0.00055
3.5	0.00054
3.4	0.00054
3.0	0.00054
2.5	0.00049

C. Thermal conductivity data

Table C.16: Thermal conductivity data for the material "Phosphor bronze" with data from Simon [123].

Temperature (Kelvin)	Thermal Conductivity (W/(m*K))
42.6	48.9
40.7	51.4
34.5	40.5
32.8	38.3
30.3	36.0
25.5	30.9
21.3	26.1
19.7	24.0
14.1	17.3
12.8	15.5
10.0	11.9
9.16	10.8
3.86	4.11
3.69	3.88
3.36	3.55
3.19	3.37
3.03	3.19
2.91	3.07
2.74	2.89
2.59	2.71
2.24	2.31
1.95	1.95
3.75	4.00
3.66	3.72
3.46	3.49
3.00	2.96
2.84	2.77
2.64	2.52
2.38	2.23
2.16	1.98
2.07	1.89
1.83	1.62
1.66	1.45

Table C.17: Thermal conductivity data for the material "Sapphire" with data from Touloukian et al. [58]

Temperature (Kelvin)	Thermal Conductivity (W/(m*K))
300	46
273.2	52
250	58
200	82
150	150
100	450
90	640
80	960
70	1530
60	2650
50	5200
45	7700
40	12000
35	17700
30	20700
25	20200
20	15700
15	8700
10	2900
5	410
1	3.9

Table C.18: Thermal conductivity data for the material "Silicon" with data from Touloukian et al. [57].

Temperature (Kelvin)	Thermal Conductivity (W/(m*K))
300	148
273.2	168
200	264
150	409
100	884
90	1080
80	1340
70	1680
60	2110
50	2680
45	3060
40	3530
35	4130
30	4810
25	5140
20	4940
18	4670
16	4220
15	3930
14	3600
13	3250
12	2870
11	2480
10	2110
9	1720
8	1340
7	991
6	686
5	424
4	226
3	99.8
2	31.7
1	4.48

Table C.19: Thermal conductivity data for the material "Silver" with data from Touloukian et al. [57].

Temperature (Kelvin)	Thermal Conductivity (W/(m*K))
300	427
273.2	428
250	428
200	430
150	432
100	450
90	460
80	471
70	497
60	550
50	700
45	840
40	1050
35	1370
30	1930
25	2950
20	5100
18	6600
16	8500
15	9600
14	10900
13	12400
12	13900

C. Thermal conductivity data

Table C.19 continued from previous page

Temperature (Kelvin)	Thermal Conductivity (W/(m*K))
11	15400
10	16800
9	18100
8	19000
7	19300
6	18700
5	17200
4	14700
3	11500
2	7830
1	3940

Table C.20: Thermal conductivity data for the material "Cu-Ni60-40" with data from Touloukian et al. [57].

Temperature (Kelvin)	Thermal Conductivity (W/(m*K))
90.60	18.9
60.80	17.7
9.53	3.13
5.12	1.18
3.03	0.56

Table C.21: Thermal conductivity data for the material "Quartz" with data from Simon [125].

Temperature (Kelvin)	Thermal Conductivity (W/(m*K))
300	10.4
273	11.6
250	12.7
200	16.4
150	23.1
100	39
90	45
80	54
70	66
60	85
50	118
45	143
40	179
35	233
30	318
25	460
20	720
15	1250
13	1530
12	1630
11	1680
10	1650
9	1500
8	1210
7	900
5	400

D

Predicted Thermal conductivity plots

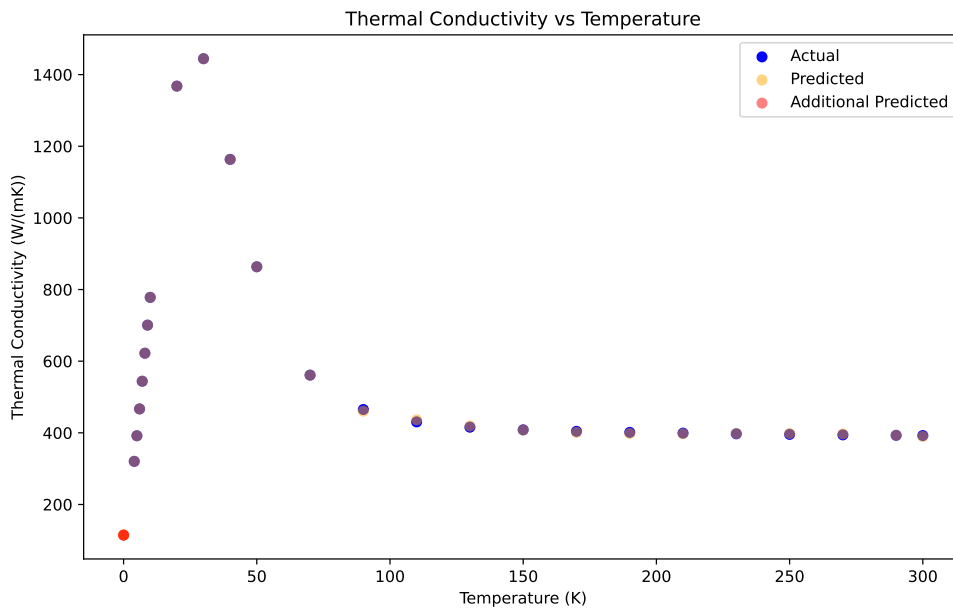


Figure D.1: The plot shows the thermal conductivity of Copper (OFHC), (RRR=50) as a function of temperature, with actual data obtained from the National Institute of Standards and Technology [121], predicted values at temperatures corresponding to the actual data points, and predicted values at 10 and 20 milliKelvin.

D. Predicted Thermal conductivity plots

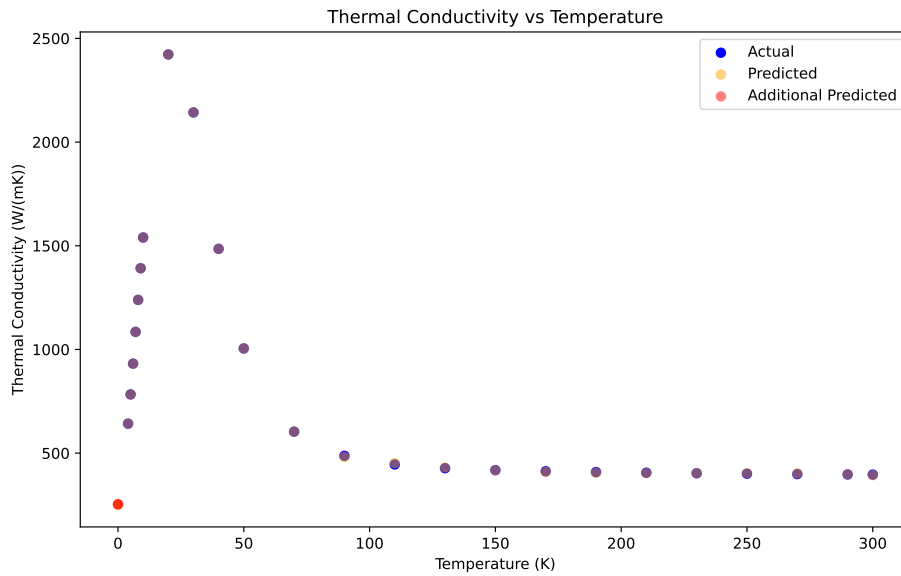


Figure D.2: The plot shows the thermal conductivity of Copper (OFHC), (RRR=100) as a function of temperature, with actual data obtained from the National Institute of Standards and Technology [121], predicted values at temperatures corresponding to the actual data points, and predicted values at 10 and 20 milliKelvin.

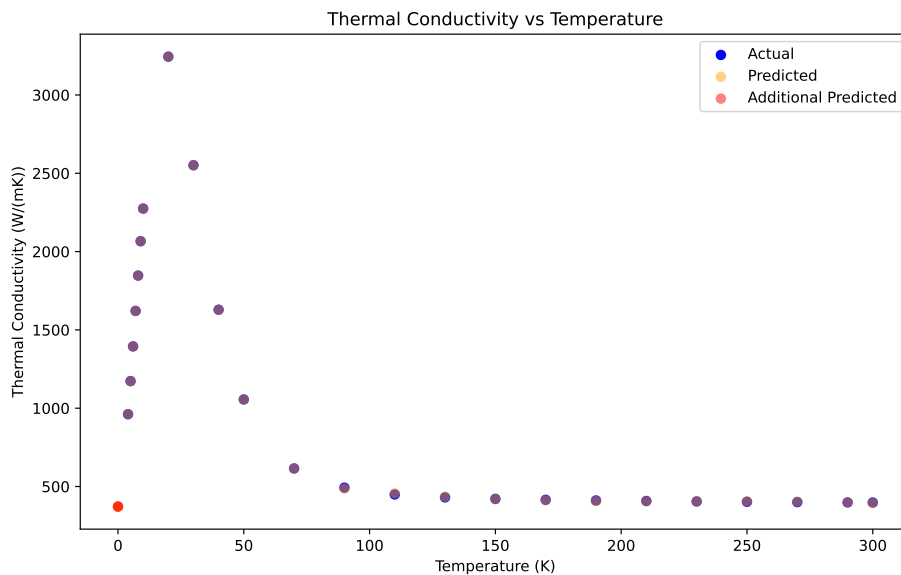


Figure D.3: The plot shows the thermal conductivity of Copper (OFHC), (RRR=150) as a function of temperature, with actual data obtained from the National Institute of Standards and Technology [121], predicted values at temperatures corresponding to the actual data points, and predicted values at 10 and 20 milliKelvin.

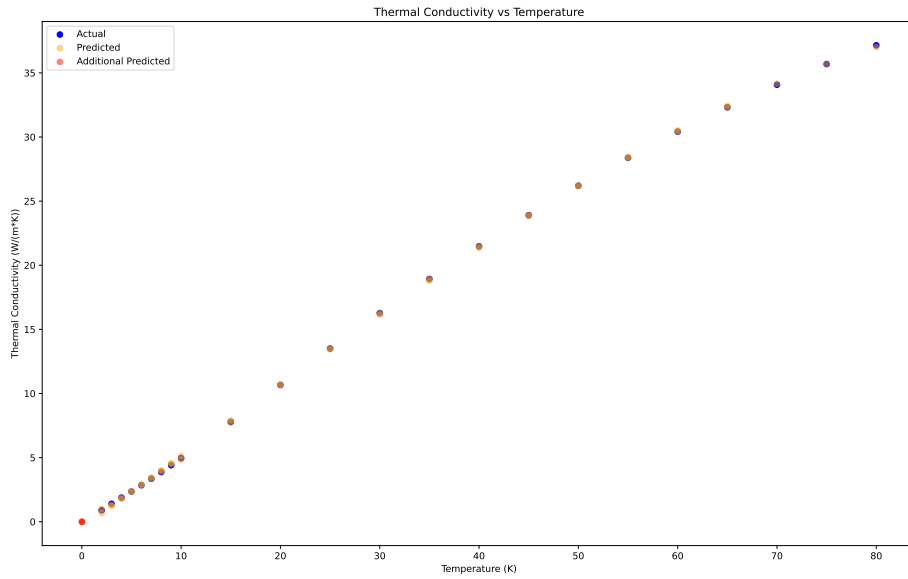


Figure D.4: The plot shows the thermal conductivity of Beryllium Copper as a function of temperature, with actual data obtained from the National Institute of Standards and Technology [121], predicted values at temperatures corresponding to the actual data points, and predicted values at 10 and 20 milliKelvin.

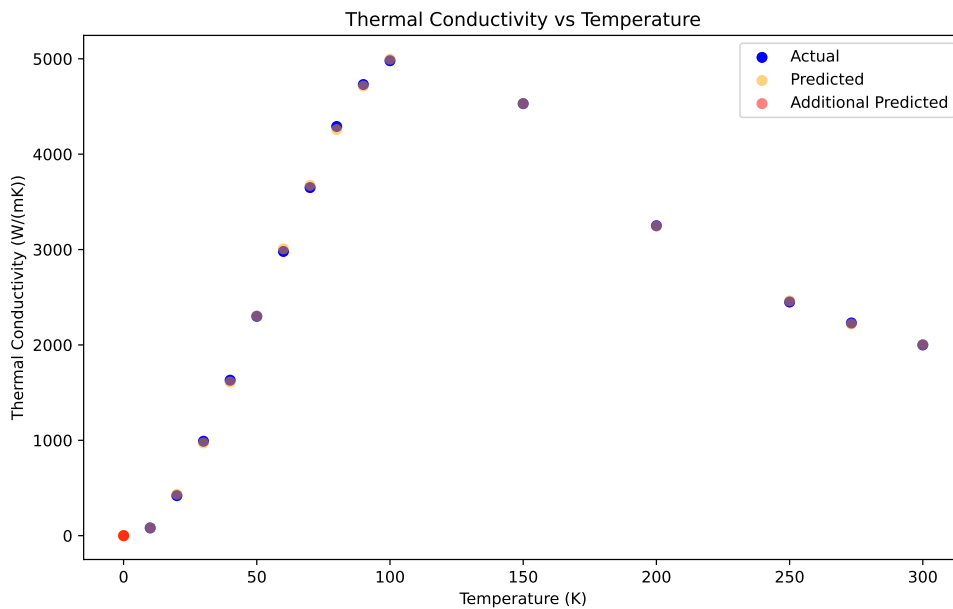


Figure D.5: The plot shows the thermal conductivity of Pyrolytic graphene as a function of temperature, with actual data obtained from Touloukian et al. [58], predicted values at temperatures corresponding to the actual data points, and predicted values at 10 and 20 milliKelvin.

D. Predicted Thermal conductivity plots

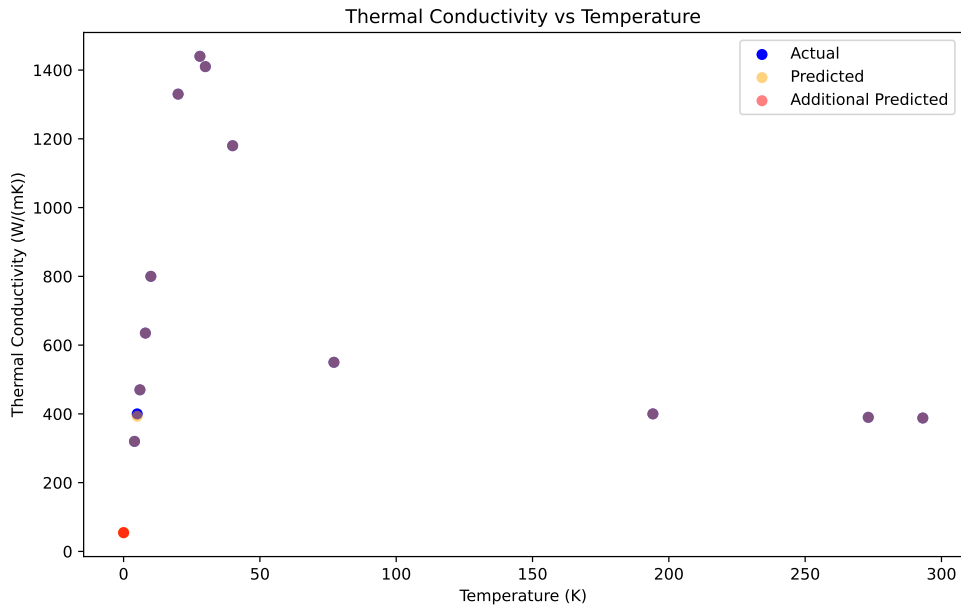


Figure D.6: The plot shows the thermal conductivity of Copper, Electrolytic-tough-pitch (ETP) copper as a function of temperature, with actual data obtained from MatWeb [122] and Touloukian et al. [57], predicted values at temperatures corresponding to the actual data points, and predicted values at 10 and 20 milliKelvin.

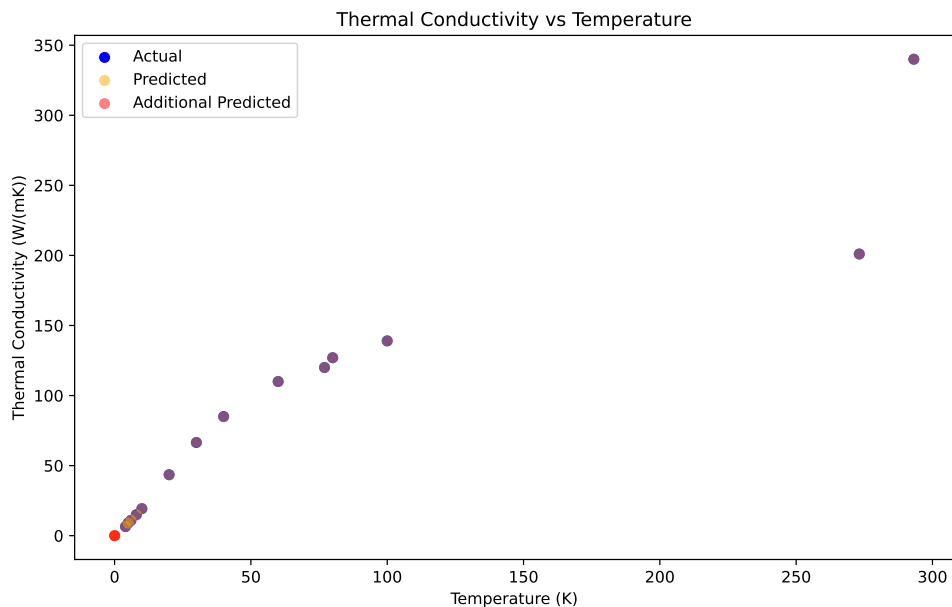


Figure D.7: The plot shows the thermal conductivity of Phosphorus deoxidized Copper as a function of temperature, with actual data obtained from Simon et al. [123], predicted values at temperatures corresponding to the actual data points, and predicted values at 10 and 20 milliKelvin.

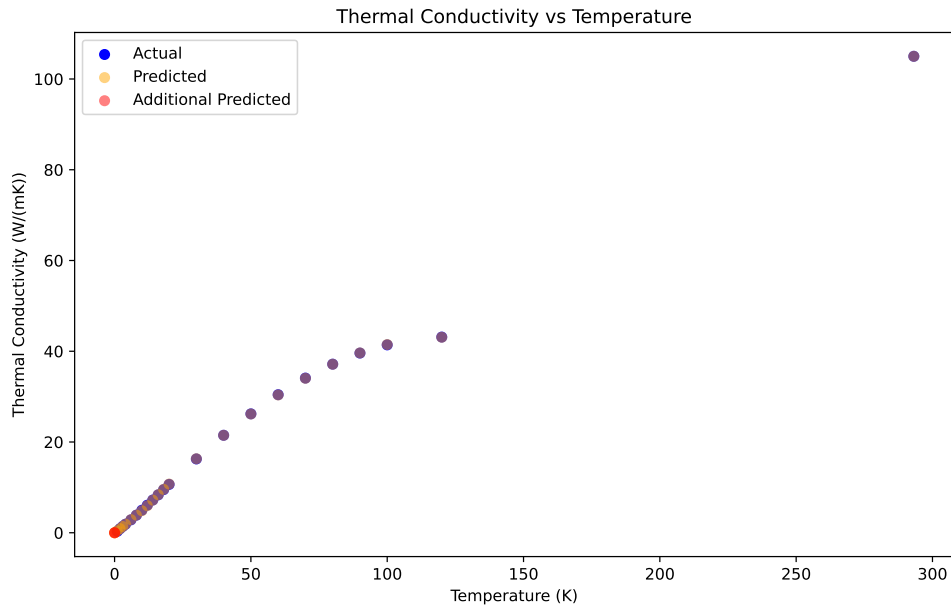


Figure D.8: The plot shows the thermal conductivity of Copper-2%Be as a function of temperature, with actual data obtained from MatWeb [122] and Griffin et al. [54], predicted values at temperatures corresponding to the actual data points, and predicted values at 10 and 20 milliKelvin.

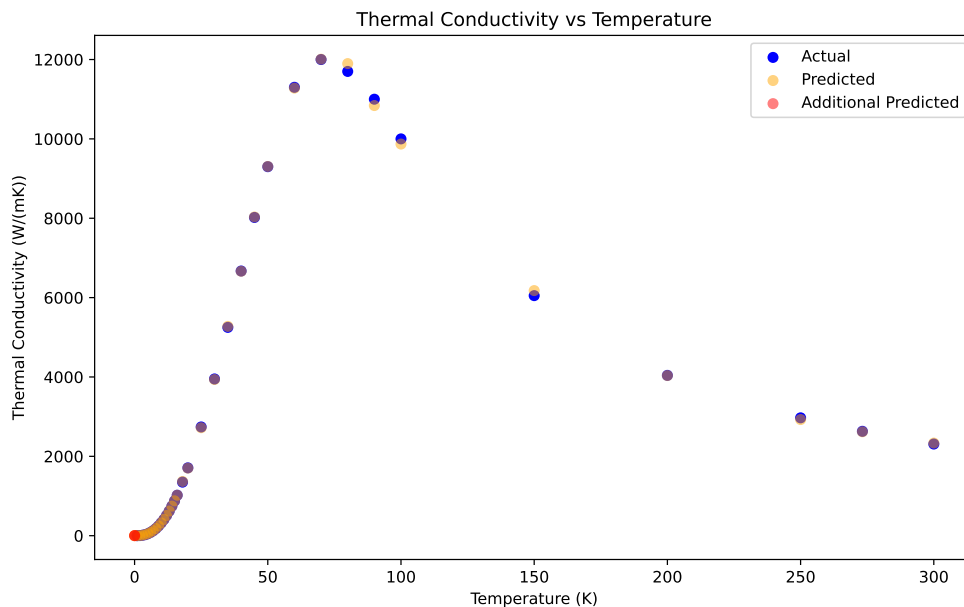


Figure D.9: The plot shows the thermal conductivity of diamond as a function of temperature, with actual data obtained from Touloukian et al. [58], predicted values at temperatures corresponding to the actual data points, and predicted values at 10 and 20 milliKelvin.

D. Predicted Thermal conductivity plots

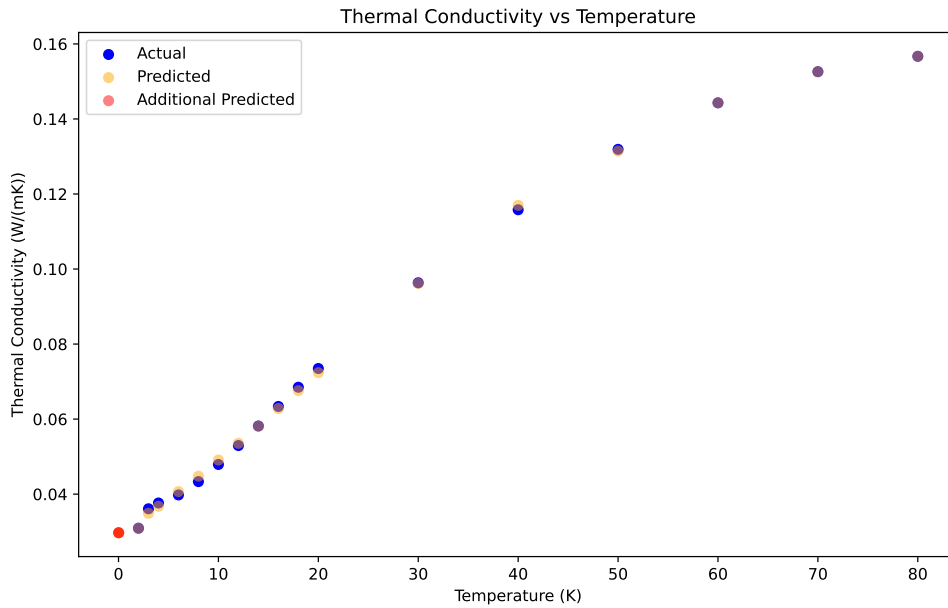


Figure D.10: The plot shows the thermal conductivity of Mylar as a function of temperature, with actual data obtained from Rumble [56], predicted values at temperatures corresponding to the actual data points, and predicted values at 10 and 20 milliKelvin.

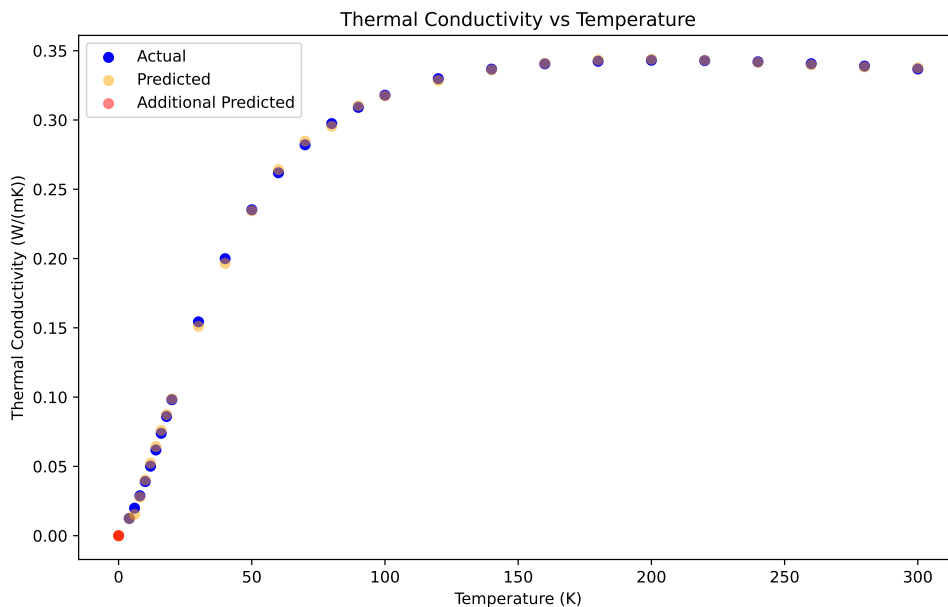


Figure D.11: The plot shows the thermal conductivity of Nylon as a function of temperature, with actual data obtained from the National Institute of Standards and Technology [121], predicted values at temperatures corresponding to the actual data points, and predicted values at 10 and 20 milliKelvin.

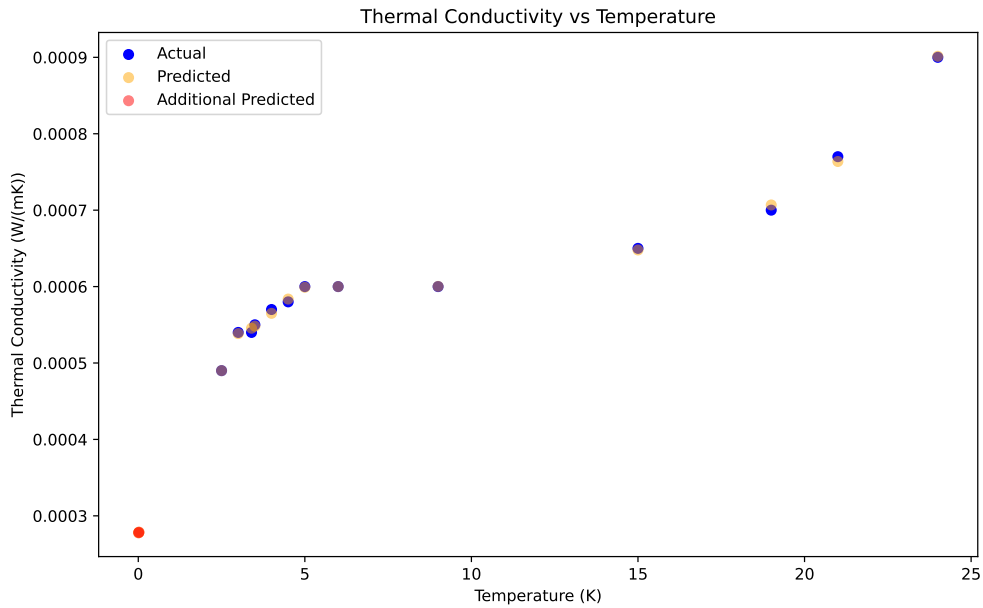


Figure D.12: The plot shows the thermal conductivity of Perspex as a function of temperature, with actual data obtained from Touloukian et al. [58], predicted values at temperatures corresponding to the actual data points, and predicted values at 10 and 20 milliKelvin.

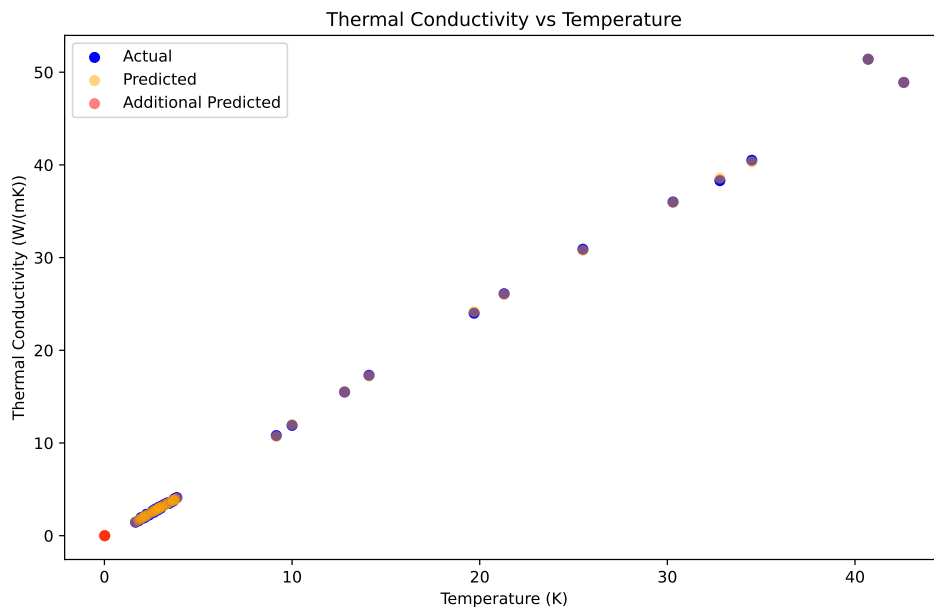


Figure D.13: The plot shows the thermal conductivity of Phosphor Bronze as a function of temperature, with actual data obtained from Simon et al. [123], predicted values at temperatures corresponding to the actual data points, and predicted values at 10 and 20 milliKelvin.

D. Predicted Thermal conductivity plots

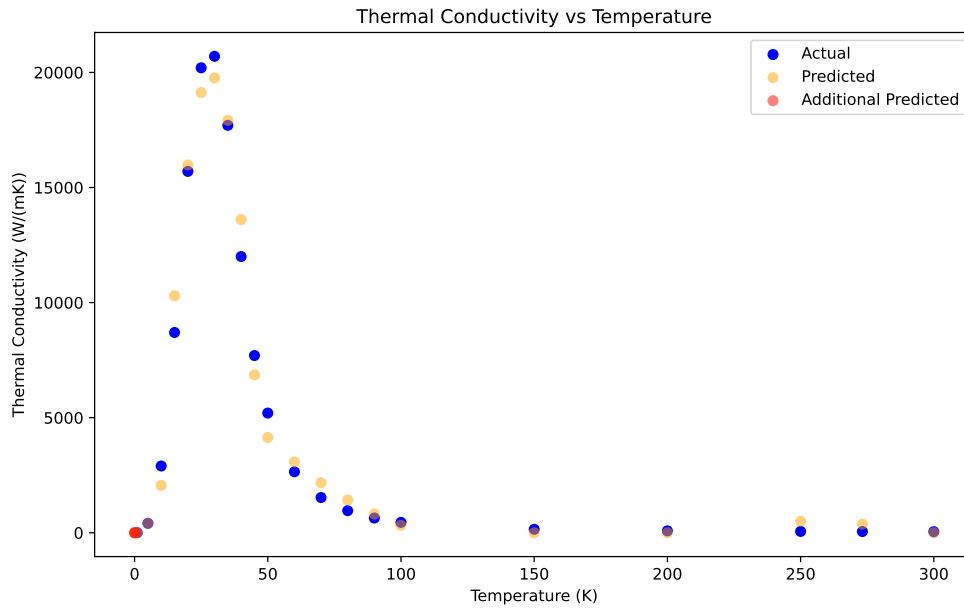


Figure D.14: The plot shows the thermal conductivity of sapphire as a function of temperature, with actual data obtained from Touloukian et al. [58], predicted values at temperatures corresponding to the actual data points, and predicted values at 10 and 20 milliKelvin.

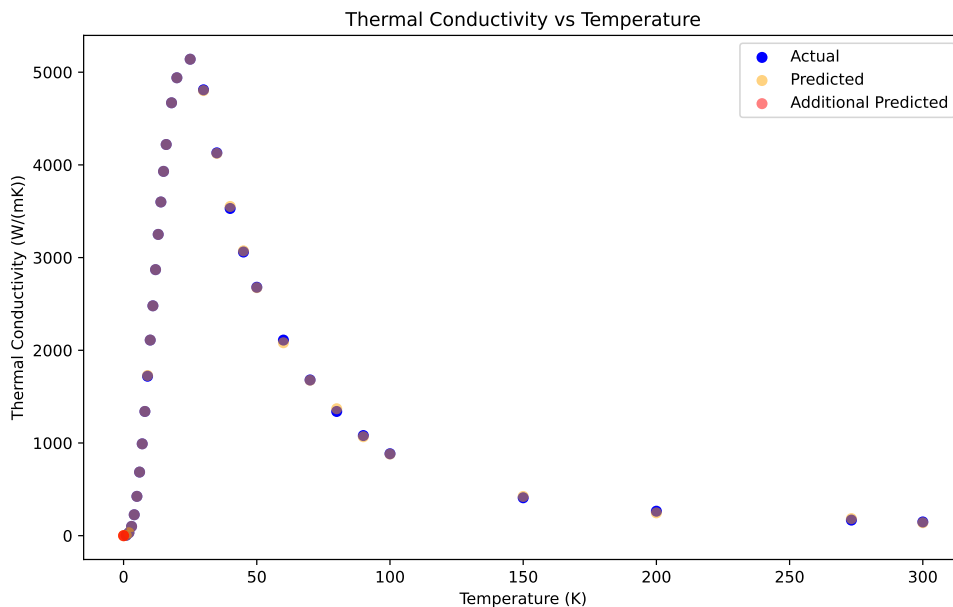


Figure D.15: The plot shows the thermal conductivity of silicon as a function of temperature, with actual data obtained from Touloukian et al. [57], predicted values at temperatures corresponding to the actual data points, and predicted values at 10 and 20 milliKelvin.

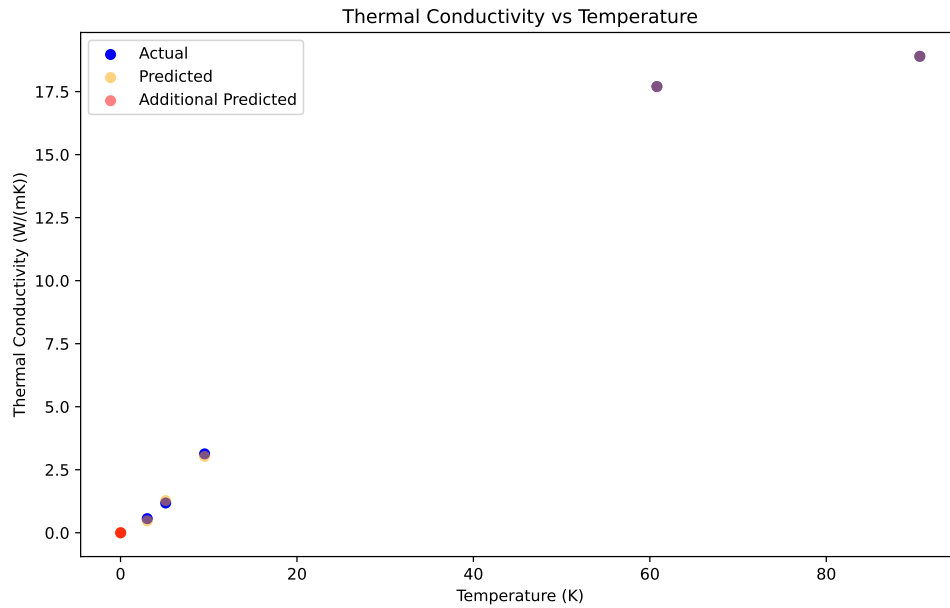


Figure D.16: The plot shows the thermal conductivity of Cu-Ni60-40 as a function of temperature, with actual data obtained from Touloukian et al. [57], predicted values at temperatures corresponding to the actual data points, and predicted values at 10 and 20 milliKelvin.

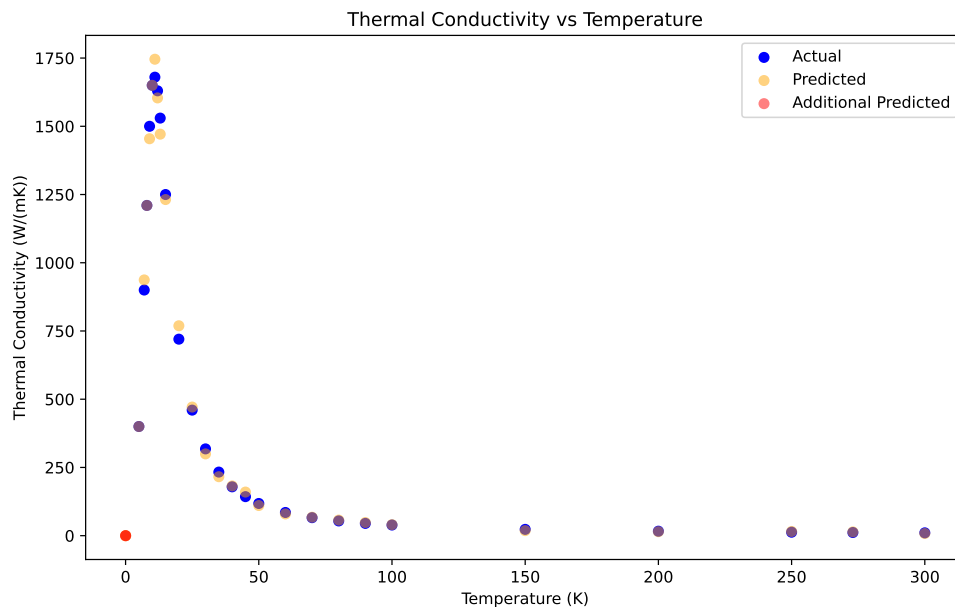


Figure D.17: The plot shows the thermal conductivity of quartz as a function of temperature, with actual data obtained from Simon et al. [123], predicted values at temperatures corresponding to the actual data points, and predicted values at 10 and 20 milliKelvin.



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