Mian Faran Hassan

Design of a Small-Scale Packer Element Tester

Hovedoppgave i Produsjon og Produkutvikling
Veileder: Christian Holden
Medveileder: Tarjei Skulstad
August 2023

Hovedoppgave

NTNU
Norges teknisk-naturvitenskapelige universitet
Fakultet for ingeniørvitenskap
Institutt for maskinteknikk og produksjon

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Kunnskap for en bedre verden

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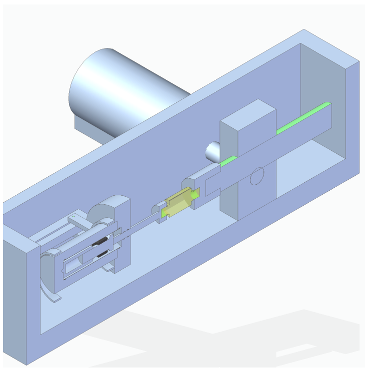

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NTNU – Trondheim
Norwegian University of
Science and Technology

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Mian Faran Hassan

Subsea Technology
Submission date: 31 August 2023
NTNU Supervisor: Christian Holden
Interwell Supervisor: Tarjei Nygaard Skulstad

Department of Mechanical and Industrial Engineering
Norwegian University of Science and Technology

Master Thesis

Summer 2023

for Mian Faran Hassan

Design of a Small-Scale Packer Element Tester

Background:

Packer elements are essential components of downhole tools used in the oil and gas industry. The ISO 14310 / API 11D1 standard specifies the requirements of plugs and packers used in oil and gas wells. To ensure the reliability and performance of these tools, they must be tested under high-pressure and high-temperature conditions. However, conducting full-scale V0 tests on the complete system is often challenging due to logistical, safety, and cost constraints. Therefore, there is a need for a small-scale packer element tester that can simulate V0 tests without testing the full system.

Objective:

The main objective of this thesis is to design and develop a small-scale packer element tester that can simulate ISO 14310 / API 11D1 full-scale V0 tests. The design requirements will be based on a literature review and interviews of relevant, experienced Interwell personnel. The proposed solution should be as representative to the full test as possible while taking into account health, safety, and environmental (HSE) considerations. The tester should be simple to use and operate, and must fit various packer element sizes. The final output of the project should be a complete design of the proposed solution.

Things to consider:

- Recreate all relevant parameters from the tool affecting the packer element in a real-life use case
- Adjustable test setup, for both parameters and sizes
- Log as much relevant data as possible
- Quantifiable output from test. Ideally more than approved/not approved

The project will involve the following steps:

1. Literature review and interviews: This will involve a comprehensive review of the existing literature on packer element testing, ISO 14310 / API 11D1 standard, and interviews with relevant Interwell personnel to identify their needs and requirements.
2. Design requirements: Based on the literature review and interviews, the design requirements for the packer element tester will be identified.
3. Conceptual design: Several conceptual designs will be developed and evaluated against the design requirements. The most suitable design will be selected.
4. Detailed design: The selected design will be further developed into a detailed design. This will mainly include the mechanical components of the system. Also an outline of the required functions of the electrical and software components of the tester should be made.

5. Prototype development (if time permits): A prototype of the packer element tester will be developed and tested under laboratory conditions.
6. Performance evaluation (if time permits): The performance of the prototype tester will be evaluated against ISO 14310 / API 11DI1 full-scale V0 test requirements.

Expected outcome:

The expected outcome of this project is the design basis for a small-scale packer element tester that can simulate ISO 14310 / API 11D1 full-scale V0 tests. The tester should be as representative to the full test as possible. The design of the proposed solution will be documented in a report outlining the design details of the packer element tester, including all relevant mechanical design details such as calculations and drafts. If time allows a prototype of the tester will be manufactured. The performance of the prototype tester will be evaluated against ISO 14310 / API 11DI1 full-scale V0 test requirements, and the HSE implications of the tester will be evaluated.

Project management:

- Weekly meetings scheduled by candidate.
- Candidate will be the responsible for the progress and organization of the plan.
- Check point between each step, before progressing to next to make sure the step is fully covered.

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Deadline:	31 August 2023

Abstract

This thesis aimed to design a small-scale packer element tester. The purpose of building this product is to enable Interwell to research and build more reliable bridge plugs. The method incorporated in designing a small-scale packer element tester was the Stanford Design School's "Five Step Design Thinking" process. The design thinking process' five steps were *Empathize*, *Define*, *Ideate*, and *Prototype*. These five steps were the backbone of the design process in this project.

A retrievable bridge plug is used for downhole operations in oil and gas wells. The plug is used to isolate or zone off sections of the well for maintenance, testing, and remediation. Interwell currently has a full-scale testing system, which tests the entire retrievable bridge plug per International Standards Organization (ISO) 14310 and American Petroleum Institute (API) 11D1 standards. The outcome of each test is either "approved" or "not approved," so if the plug is compliant, it can be used for an operation. However, when a plug does not seal as intended, there is no other outcome except that it failed the test and cannot be used for an operation. The outcome verifies the sealability of the bridge plug. The small-scale packer element tester must be designed to comply with the aforementioned industrial standards to emulate a full-scale test, but only on the packer element. The packer element is the only non-metal part of a bridge plug but has the most crucial function: to seal the well. Thus, Interwell desires to obtain more data about the behavior of the elastomer.

In the *Empathize* phase, a complete and comprehensive understanding of the end user's needs is gained through techniques like surveys, interviews, and shadowing. In addition, this phase also seeks to obtain information on the requirements and standards of the product being developed. The information gathered is then outlined in the *Define* phase, where design requirements are created for the packer element, and the setting for how to conceptualize the solutions is determined. This is followed by the *Ideate* stage, where concepts and solutions for the tester are brainstormed. Presenting the ideas to the end-user to gather feedback through this process, to mold the ideas to fit their needs. The packer element tester is den designed in the *Prototype* stage, where multiple iterations are computed before settling on the final design.

The designed packer element tester followed the first four out of the five stages mentioned above. The study needed more time to finish the fourth and fifth stages. Therefore, a single iteration design has been created. The design should be further iterated until its final form before manufacturing.

Sammendrag

Denne oppgaven hadde som mål å designe en små skala pakningstester. Hensikten med å bygge dette produktet er å gjøre det mulig for Interwell å forske på og bygge mer pålitelige broplugger. Metoden som ble innlemmet i utformingen av en småskala pakningstester var Stanford Design Schools "Five Step Design Thinking"-prosess. Designprosessens fem trinn var "Empathize", "Define", "Ideate" og "Prototype". Disse fem trinnene var ryggraden i designprosessen i dette prosjektet.

En uthentbar broplugg brukes til brønnoperasjoner i olje- og gassbrønner. Pluggen brukes til å isolere eller sone av deler av brønnen for vedlikehold, testing og utbedring. Interwell har i dag et fullskala testsystem, som tester hele den bropluggen i henhold til International Standards Organization (ISO) 14310 og American Petroleum Institute (API) 11D1 sine standarder. Utfallet av hver test er enten "godkjent" eller "ikke godkjent", så hvis pluggen er består testen, kan den brukes til en operasjon. Men når en plugg ikke tetter røret som tiltenkt, gir det ikke noe annet informasjon bortsett fra at den mislyktes i testen og ikke kan brukes til en operasjon. Resultatet verifiserer forseglingen til bropluggen. Småskala-pakningstester må være utformet for å være i samsvar med de ovennevnte industrielle standardene for å etterligne en fullskalatest, men bare på pakningselementet. Pakningselementet er den eneste ikke-metalliske delen av en broplugg, men har den mest avgjørende funksjonen: å tette brønnen. Interwell ønsker derfor å få mer data om oppførselen til elastomeren.

I "Empathize" fasen oppnås en fullstendig og omfattende forståelse av sluttbrukerens behov gjennom teknikker som spørreundersøkelser, intervjuer og å være med i hverdagen til sluttbrukerne. I tillegg søker denne fasen også å innhente informasjon om kravene og standardene til produktet som utvikles. Informasjonen som samles blir deretter skissert i "Define" fasen, hvor designkrav opprettes for pakningselementet, og det bestemmes hvordan løsningene til testeren kan konseptualiseres. Deretter følger "Ideate" stadiet, hvor konsepter og løsninger for testeren blir tiltenkt. Ideer blir presentert til sluttbrukeren for å samle tilbakemeldinger i dette stadiet, slik at ideene er tilpasset til deres behov. Pakningstesteren er designet i prototypestadiet, hvor flere iterasjoner beregnes før det endelige designet bestemmes.

Den utformede pakningstesteren fulgte de fire første av de fem trinnene nevnt ovenfor. Studien trengte mer tid for å fullføre det fjerde og femte trinnet. Så langt rakk designet å komme seg gjennom en første iterasjon. Designet bør itereres inntil det har nådd sluttbrukeren behov og fullført denne oppgavens formål.

Acknowledgements

I'd like to thank my Associate Professor Christian Holden, for his help both in regard to thesis, and the hiccups that occurred during this past year. I would also like to thank my supervisor at Interwell for this project Tarjei Skulstad, who has been patient and supportive of my ideas and helped me with the progress in my work. I extend my special thanks to my manager at Interwell, Torbjørn Buljo because without him I would not be able to complete my degree in the allotted time.

Secondly, I'd like to thank my mom who has been supporting me all these years, has always helped me follow my dreams, and made ends meet so I can go and be whatever I wanted to be. As well as encouraging my education through my youth, for which I am grateful and can proudly stand today having completed my master's degree. I would also like to thank my in-laws who have been very supporting of me over the past two years. Your love and care has made me feel whole. Thank you Lynn and Greg Taylor.

And last but definitely the most important person in my journey, is my now wife, Emma Rose Jolie Taylor. Her unrelenting support and her sacrifices have never gone unnoticed, without her I would not have the confidence, the tenacity, and the will to push on when times are hard. She has always pushed me to be the best version of myself and has been my biggest cheerleader. I am inspired by her kindness, hard work ethic, and caring attitude. Thank you Emma.

Trondheim, 31 August 2023

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Stud. MSc. Mechanical Engineering

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Chapter 1

Introduction

Testing equipment is essential when designing products and tools, as it ensures that the created product delivers desired performance and is reliable under expected operation. To qualify a tool for engineering projects and operations, it must comply with industrial standards, including testing the product according to those given specifications. By testing, an engineer can quantify and describe the capability of a product or tool and use the information gathered from testing to tailor the product to the end-user's requirements.

A testing system provides a safe and controlled environment to test a tool's capabilities. Whatever processes and environment a tool experiences in operation are emulated in the testing system, ensuring it can deliver desired functionality and tolerate its environment as designed. Thus, it eliminates any potential dangers that might occur, which can affect the safety of human lives, infrastructure, and other material assets.

Minor errors and mistakes can leave a bad experience for the end-user using the tool. Fixing and redesigning the tool when minor errors occur is time-consuming and costly both for the manufacturer and the end-user. Therefore, engineers must test their products to verify functionality as desired by the end-user, safety features that prevent unwanted disaster from occurring, and compliance with industrial standards.

1.1 Background

Interwell AS is a company that provides completion, intervention, and plug & abandonment (P&A) services to the oil industry on a global scale. Their Trondheim (Norway) facilities focus primarily on intervention, where plug and packers are their main product line. A plug or packer is a sealing device that stops fluid or pressure build-up from flowing past where the plug or packer is installed.

The critical component of the plug or packer that seals the well is an elastomer, also known as a packer element. The packer element is compressed between two metal parts on the plug (or packer) till it deforms radially into the well casing, creating an airtight seal between the plug and the casing wall.

Today, Interwell AS tests the sealing capabilities of plugs and packers by testing the entire system in a simulated closed tubing per industrial standards set by the International Organization for Standardization (ISO) and the American Petroleum Institute (API). As there are many different sizes of plugs, many different types of plugs, and packer elements made up of different materials, the logistical load of testing these tools and combinations is very high. Per industry standards ISO 14310 / API 11D1, a V0-test is the requirement to qualify a plug for industrial use, meaning that all of these combinations of tools would have to be individually tested to qualify for industrial use.

A V0-test is a test that evaluates if the system is leaking air past the sealing component at a set given pressure and temperature, more detail in chapter 2.1.3. While Interwell performs this test to ensure the safety of their products and to satisfy the customer's needs, it provides no data on the behavior of the elastomer under the exposed simulated well conditions, nor does it provide any indication of how much force the metal parts need to compress the elastomer to ensure an airtight seal, see table 1.1 for well conditions.

Thus, testing the entire system is costly, logistically difficult, and very time-consuming, making it difficult for the company to put resources towards this without compromising their competitiveness in the market.

1.2 Objectives

The main objective of this thesis is to conceptualize and design a small-scale packer element tester that can simulate ISO 14310 / API 11D1 full-scale V0 tests. The goal is to create a testing system that can tolerate and emulate well conditions described in table 1.1, while holding the elastomer in place to test its functionality in those conditions. In addition, it gives control over the sealability of the packer element by having control of force input into compressing the packer element.

	Min	Max	Units
Temperature	20	300	°
Pressure	0	20000	Psi

Table 1.1: Well Enviroment and Conditions

This report aims to document the design process that creates a small-scale packer element tester. If the testing system delivers the desired functionality, it could partially replace existing testing systems, where the entire plug assembly would not need to be qualified to industry standards every time a different elastomer is installed. Instead, only the packer element needs to be tested and qualified. The small-scale testing system will also reduce any overburdening of existing testing systems.

1.3 Methodology

The structural skeleton that will be used to design a small-scale testing system is called the five-step method of the Standford d.school Design Thinking Process (SDT), see figure 1.1[26].

SDT is an iterative and nonlinear process, meaning the steps defined in this process can be repeated as many times as needed, and the sequence of steps can also be changed [16]. A linear approach will be followed to simplify the design process, which is also suggested in the Stanford model [26]. The linear approach is illustrated below.

$$Empathize(E) \rightarrow Define(D) \rightarrow Ideate(I) \rightarrow Prototype(P) \rightarrow Test(T)$$

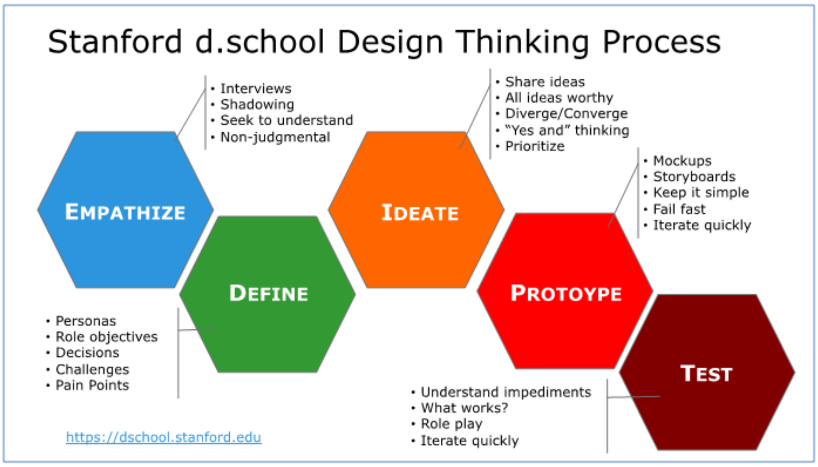


Figure 1.1: The Hasso Platter Institute of Design at Stanford's five-stage design thinking process [26]

Empathizing in design thinking refers to understanding and empathizing with the end-user. Empathizing aims to gain insight into the end-user's needs and understand their perspective. This step involves active listening, observing, and engaging with the user and may include techniques such as interviews, surveys, and shadowing their work [16].

In this report, the stage of empathizing will give an understanding of the background of how plugs work, what challenges the engineers at Interwell face, what industrial standards are used, and lastly, by using the techniques mentioned for the empathizing stage, will be utilized at Interwell AS premises and engineers, to obtain a complete and comprehensive understanding of the task given.

Defining is a crucial step in the design thinking process. The valuable information gathered in the empathize phase is analyzed and used to create a problem statement that defines the problem and the end-users needs. By defining the problem in this way, engineers can focus their efforts on developing solutions that address the root causes of the problem instead of treating its symptoms [16].

Thus, a clear and concise problem statement is generated for this report using the knowledge obtained in the empathizing phase, where design goals are created. Design goals define what is needed and desired in a small-scale packer element tester. The requirements and limitations for any potential design can be determined based on design goals. In addition, other design requirements and limitations can be set based on Health, Safety & Environment (HSE) policies at Interwell, environmental limitations in place of operation, physical limitations of plugs and packers, material limitations, and limitations set by industrial standards.

Ideation is the process of brainstorming and creative thinking, where ideas and potential solutions are formed. This stage can also be closely associated with the concept stage of any design, thus not focused on what is realistic or what challenges might come forth through the plethora of ideas [17]. The goal of this stage is to produce as many ideas as possible that solve the issue stated in the problem statement.

For the small-scale packer element tester, this would generate ideas within the design requirements framework and solve the design goals set in the defining phase. It generates many ideas to explore every possibility of solving the problem.

The *Prototyping* step uses the knowledge acquired in the previous stages to develop a preliminary 3D model of a possible physical solution that can be easily manufactured with simple hardware, such as cardboard. This stage aims to gather feedback from the end-user on the proposed solution. Such that the design can be modified as needed until it reaches its final form that satisfies the end-users needs.

In this report, only one design iteration was completed. The design iteration produced computer-aided design models and assembled the proposed design components. The design was presented to the end user at a design review to gather feedback. The design must be iterated before reaching the final design, which will be part of future work.

The final step mentioned in the SDT is *testing*. This step occurs at the end of a final design phase to ensure the final product's functionality, safety, and performance. However, outside the context of SDT, this stage can also be visited when prototyping a design, as prototyping is a form of testing.

For this report, this stage will not be covered, as due to time constraints of this project, there was not enough time to machine or print out the parts needed to perform functionality testing.

Chapter 2

Methodology

The methodology chapter follows the SDT method explained in chapter 1. Therefore, the first subchapter will be *Empathize*, followed by *Define*, followed by *Ideation Prototype*.

The *empathize* section will contain information on the plug's background, the existing testing system, the industrial standards that govern the plug tests, the end-user's experience with the current testing system, and how that information was obtained.

In the *define* section, information gathered from chapter 2.1 is honed and analyzed to determine the design requirements and generate a problem statement that is more detailed in finding a solution to this project. Additionally, the *define* section introduces forces, formulas, and calculation sheets that will govern the *ideation* phase that is to come.

In the *ideation* section, concepts and ideas will be generated. Multiple concept reviews with the end-user will be completed where those potential solutions will be explained such that the final solution can be deduced in participation with the end-user.

For this chapter's final section, *design and prototyping*, a proposed design will be presented, which will be the first iteration of the design after the concept phase.

2.1 Empathizing

The purpose of this section is to understand the problem statement given by Interwell AS as defined in section 1. The problem statement was to design a small-scale packer element tester, that can simulate the International Standards Organization (ISO) 14310 / American Petroleum Institute (API) 11D1 full-scale V0 tests. To obtain this understanding, the author employs the key methods used in the SDT models process of *empathizing* as summed up in a list below:

- Plug and packer basics
- Shadowing employees at Interwell
- Industry Standards
- Testing machine basics
- Interviews and surveys

It can be derived that the next step is to see how the employees work and what their needs are at Interwell. This involved shadowing the employees, as well as conducting interviews and surveys, to then analyze and understand what the company employees want.

2.1.1 Plug and packer basics

As mentioned in chapter 1, plugs or packers are device(s) that function as barriers in an oil or gas well. They are used primarily in the oil and gas industry and renewable energy such as geothermal energy [2]. The function of a bridge plug or packer is to isolate areas in the well for a temporary period. It does this by anchoring onto the wall of the well, referred to as the casing, and expanding the only non-metal part of a plug or packer, creating a seal between the plug and the casing wall. The word retrievable is used when referring to these bridge plugs, as they can be retrieved without having caused any damage to the casing when desired. A plug sealing a well is shown in figure 2.1 below.

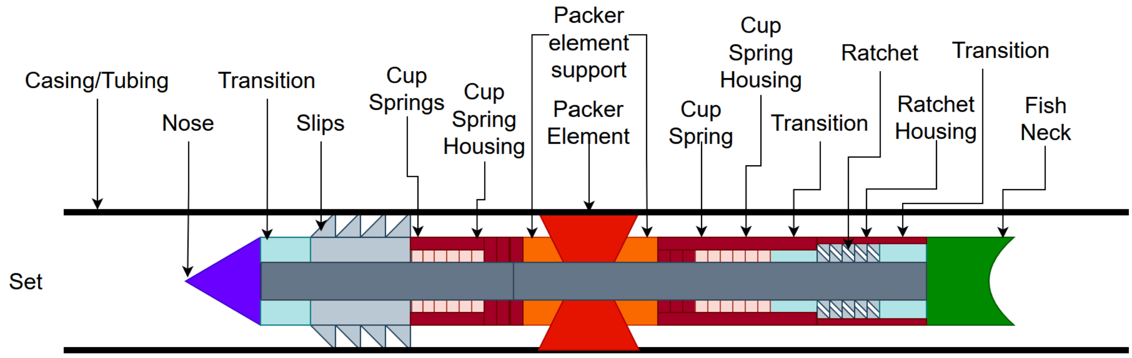


Figure 2.1: Bridge plug in set position

It is important to note that plugs and packers are different. The difference between a plug and a packer is that a packer lacks a nose cone and thus is open in the middle where fluid can pass through. A packer is seldom used alone and is almost always used with another packer or plug. The purpose of packers (often in a series of two or more) is to isolate a specific area and work similarly to a straw, where the two packers create zonal isolation in the well. If a well has water and oil coming out, the packers can isolate the water section and then work as a straw to provide access to the oil reservoir.

Another essential thing to note is that the packer and packer elements are different. *Packers* are plugs that have an opening so fluid can flow through and are used to block off pipe segments, whilst packer elements are rubber elements used in both plugs and packers that seal the flow of fluid on the outside of the plug. For simplicity, the rest of the report will only refer to plugs. For simplicity, the rest of the report will only refer to plugs, even though the applications of this report can be used interchangeably for packer tools as well.

Interwell provides four different categories of intervention plugs, as shown in table 2.1. The different types of plugs are used for different applications, as it is mentioned in their names. The plug relevant to the design of the test setup for this project is the Medium Expansion (ME) plug of size 385, namely ME 385. All ME sizes are designed to uphold table 2.1 properties. Similarly, all sizes of the other plug categories are to uphold the properties defined in the table. However, as Interwell desires to be able to test all given categories of plugs, thus the test bench designed should be flexible and scalable enough to accommodate the properties of a High Pressure & High Temperature (HPHT) and High Temperature & High Expansion (THEX) bridge plugs as well.

Interwell Intervention Bridge Plugs and Packers				
Name	Acronym	Max °C	Max psi	Expansion in %
Medium Expansion Retrievable Bridge Plug	ME	100	5000	20
High Expansion Retrievable Bridge Plug	HEX	110	4000	80
High Temperature and High Expansion Retrievable Bridge Plug	THEX	160	5000	51
High Pressure and High Temperature Retrievable Bridge Plug	HPHT	220	12500	22

Table 2.1: Overview over some of Interwell's intervention products and their features [6]

As it is evident, what separates the four categories of plugs in table 2.1 is pressure capacity, temperature range, and the amount of expansion it has. Unfortunately, no universal plug can reach desired performance in all three properties: high temperature, high pressure, and high expansion. There is a trade-off between each plug type, a trade-off that is shown in figure 2.2 by Interwell AS [4].

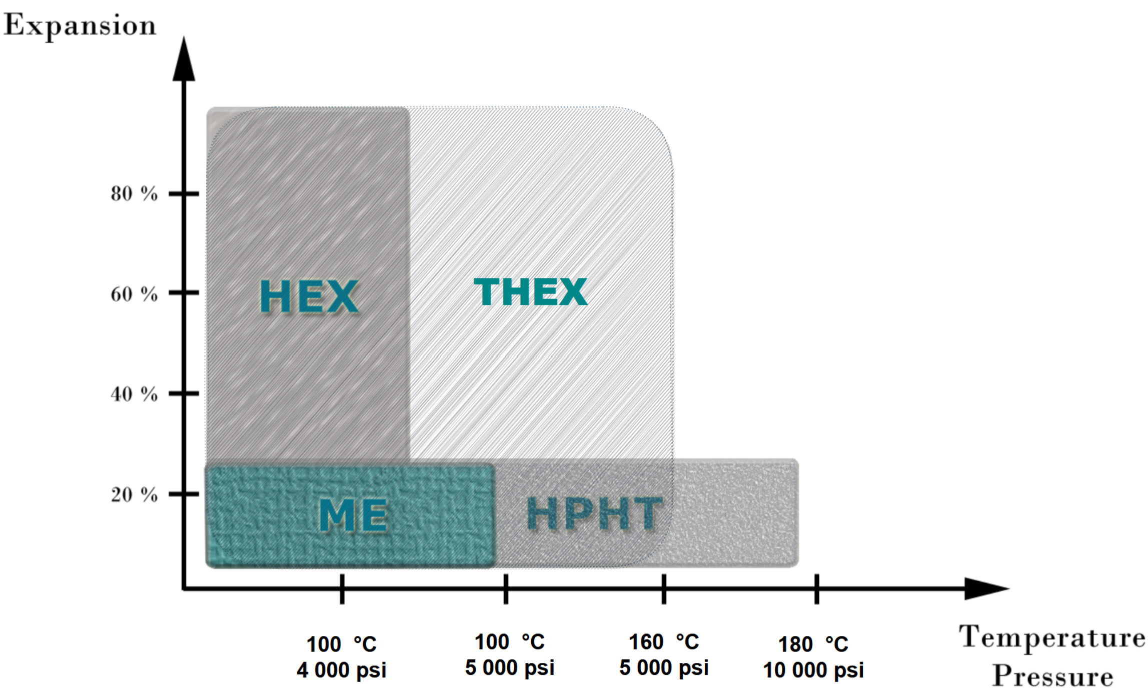


Figure 2.2: Comparison between the different plug types by Interwell [4]

2.1.1.1 Plug components and their functions

To better understand the functionality of a plug, a basic understanding of the components making up the plug must be attained. However, it is only necessary to analyze and understand of the components to understand how the plug works. The six components are given in the list below:

- Mandrel
- Slips
- Cup Springs
- Packer element (elastomer)
- Fish neck
- Finger coupling module

The six components contribute to the plugs three basic operations; run, set and pull. These three operations is what constitute the purpose and operation of the plug, figure 2.3 show the three settings of the plug. Based on the plug components functionality and understanding the load path passing through its components, the forces experienced by the packer element can be estimated.

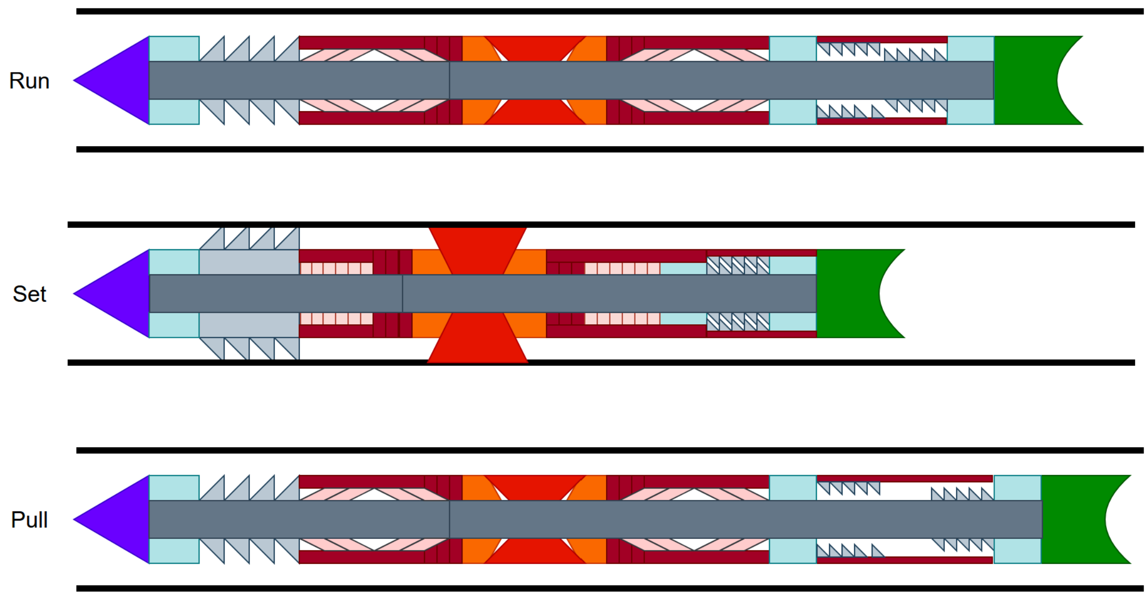


Figure 2.3: The plug settings in operation

Mandrel

The mandrel sits in the middle of the plug longitudinally. It has ratchets in certain areas, allowing for linear motion in one direction. The ratchet only exists on the fish neck side of the plug for ME plugs, as illustrated in figure 2.1. It is threaded on the nose end of the mandrel, and the transition part of the plug threads onto the mandrel. The nose cone is then threaded onto the transition part. The transition part is further connected to the slips module, which then connects to the cup spring house, and so on, down to the transition part next to the fish neck. Thus, the threaded end of the mandrel serves as the anchor point for all the parts towards the fish neck, including the fish neck. The mandrel is a concentric fixture for all the parts to sit on. The primary function is to hold all the elements of the plugs together and ratchet the plug when it goes from *run* to *set* position.

Fish neck

The fish neck is the connection point of a plug, where the *setting tool* connects to the plug. The setting tool performs all three operations on the plug: run, set, and pull. See figure 2.3 for the three stages. The fishing neck's design is dependent on international setting tool standards, such that it cooperative with the equipment that it connects to.

Slips

The slips or the slips module are the teeth that bite into the casing in the *set* position of the plug, as shown in figure 2.1. In the *set* position, the slips anchor the plug, holding the plug stationary. Moreover, all the pressure forces the plug is exposed to also go through the slips module and out to the casing. The slips module in set position is stiffened by the ratchet that has been *clicked* in place as the slips were pushed out to the casing wall.

Cup springs

Cup springs are resting inside the cup spring housing during *run* and *pull* operations but are activated during the *set* operation. The cup springs are squeezed in the set position, and with Newton's third law, a spring force is pushed back. The spring force that pushes back ensures sufficient force pushing slips and the packer element into the casing wall. The other thing the cup springs ensures is that in case of deformation of the plug or the tube around the plug, the plug stays stationary in the set position connected relative to the wall.

Finger coupling module

The finger coupling module has two parts, the finger coupling and a lock ring. Only the finger coupling is displayed in figure 2.5, labeled as "Ratchet Housing." Both the finger coupling and the lock ring have ratchet designs on them. The lock ring is an intermediate ring with a ratchet design on one side and an inverse ratchet design on the other. The lock rings function enables the mandrel to move in one direction, but to lock it in the inverse direction, thus allowing the plug to go from *run* to *set* position. The finger coupling is a fixed part attached to the outer body or the "housing" of the ratchet. It connects the mandrel to the plug body through the lock ring. The finger coupling is temporarily locked with the plug body using shear screws. When the shear screws break, the finger coupling is released from the plug body, deflating the slips, packer element and the cup springs back to their respective original *run* position.

Packer element

The packer element is the most critical part of a bridge plug and the reason for this project. The primary function of this part is to ensure it seals the well. This way, the well is sealed off, and any maintenance, equipment change, or other intervention can occur. The secondary function of the elastomer is centralizing the plug, as it provides the second point of contact between the plug and the casing wall. Packer element comes in different materials, depending on application and type of plug. The different materials allow for higher pressure and temperature. Some elastomers have a more elastic geometry allowing them to expand more than others, which are often used in HEX and THEX plug categories. The packer element is often supported by a support part called *packer backups*. Packer backups are congruent with the elastomer's longitudinal geometry and push the elastomer up into the casing wall. Due to tight tolerances, this motion also seals between the packer backups and the elastomer. Different varieties of elastomer for different plug types and applications is shown in figure 2.4 by Global Elastomeric Products [27].

Figure 2.4: Different types of Packer elements by Global Elastomeric Products [27]

2.1.1.2 Plug function

A plug has three operation modes, as shown in figure 2.3 and mentioned in previous sections. The three stages a plug goes through, as previously mentioned, are *run*, *set*, and *pull*. The three stages can be thought of as lowering the plug down the well to the desired depth (run), then sealing the well off during operation(set), and pulling it out when done (pull). According to Schlumberger AS dictionary definition, a bridge plug is "A downhole tool that is located and set to isolate the lower part of the wellbore. Bridge plugs may be permanent or retrievable, enabling the lower wellbore to be permanently sealed from production or temporarily isolated from a treatment conducted on an upper zone" [7]. What makes a bridge plug retrievable is that it can be unset from its location, having slips and packer elements that decompress at retrieval (pull). Common applications according to Northstar Downhole Specialists [30] are quote:

- Zonal Isolation
- Temporary shutting off well for repair
- Testing of production casing
- Pre-installation in completion tailpipe for packer setting
- Contingency packer setting
- Plugging of completions with damaged nipple profiles
- Hanging of completing accessories within tubing string
- Thru-Tubing completion

- Formation fracturing, acidizing, and testing

For this thesis, an analysis of each application is unnecessary, as the effect of all applications regarding forces affecting the plug are not subjective to an application but to the plug's design itself.

Stage one: Run

In the run-in-hole (RIH) stage, also known as *run*, the plug is connected by its fish neck to a *setting tool*, also known as a *running tool*. The plug is sent down the well until the desired depth is reached. The setting tool is used to *set* and *unset* (pull) the plug [8]. In the RIH stage, the plug slips are retracted, the packer element is at its resting state, none of the shear screws are broken, the cup springs are not charged with any springs force, and lastly, the ratchet has not bitten onto any teeth, as shown in figure 2.5. The maximum outer diameter (OD) of the plug is not breached by the teeth of the slips or the elastomer; they are usually retracted to the point where they are below the OD in the radial direction. The OD of the plug is determined by how narrow the casing it must pass through; see appendix C standard casing sizes by American Petroleum Institute [21].

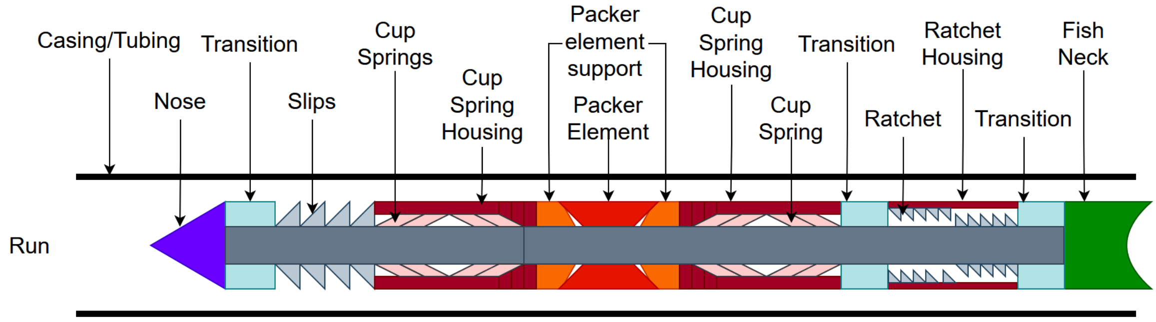


Figure 2.5: A typical bridge plugin run-in-hole position

Stage two: Set

In the *set* stage, also called the *setting* of the plug, the plug is to be installed at the desired depth it has reached. The fish neck, which is connected to the setting tool, is being held in place by the setting tool, while an internal piston from the setting tool adds force onto the mandrel. The force applied here is called *setting force*. Before the mandrel can start moving, the setting force must be high enough to break the shear screws holding the mandrel in place. Once the shear screws are sheared, the mandrel starts sliding forward, retching past the finger coupling teeth. While retching, the lock ring "jumps" over the teeth of the mandrel to allow the mandrel to move forward.

The push of the mandrel forward causes the slips to move out radially. Once the slips bite onto the casing wall, no longer able to expand more radially, the setting force which keeps pushing the mandrel now compresses the cup springs. As the cup springs get compressed, a spring force pushes onto the mandrel, and the slips. As the mandrel is retched into place, unable to move backward, the force is applied to the slips instead. The slips are locked into place, anchoring the plug into the wall.

However, the plug can be compressed even more as the load path compresses the packer element. The packer element deforms and moves radially as the packer backups are designed, so when compressed, they deform the structure of the elastomer into a radial cylinder. This motion continues until the packer element is pushed into the wall, and the corresponding cup springs are compressed. The packer element now seals the well from the lower part of the well to the upper. It is supported by the two packer backups, such that it cannot relax in that direction, and is structurally locked in place by the mandrel and the casing wall.

While sealing, two situations can occur, "pressure below" and "pressure above." Meaning a differential pressure on opposite sides of the packer element occurs. As the packer element tester will be testing only the packer element, instead it is essential to keep in mind that there needs to be a way to either turn the orientation of the packer element after a test (to test the other side) or to have a way to pressurize both sides of the packer element without disassembling the test setup.

Now, the plug has been anchored and sealed the well. The lock ring holds the mandrel from moving back, locking the plug internally. The set position of the plug is shown in figure 2.1 above. The setting tool is disengaged from the fish neck retrieved to perform any of the applications mentioned above.

Stage three: Pull

The setting tool is lowered onto the plug to retrieve the plug, connecting to the fish neck again. Once connected to the fish neck, the setting tool pulls on the fish neck until shear screws break from the pulling force, causing the finger coupling to disengage from the plug body, now freely moving with the mandrel. This motion releases the energy that was locking the slips in an outward position, and the packer backups move longitudinally along the plug's body, allowing the packer element to relax again. At this point, the plug is back to a position similar to the "run" stage, where its OD is now the same as when it was RIH. The plug is pulled out of the well, as it cannot be used further until the components inside are replaced and reset.

2.1.2 Shadowing

Shadowing in design thinking refers to observing and closely following individuals as they conduct their daily activities, typically in their natural environment. It's a research technique to gain deep insights into end-users perspectives, behaviors, and pain points, thus immersing the observer in their situation [12]. This method is precious when designing products that cater to specific end-user needs. For this report, the shadowing method that will be used is called "participatory." Participatory shadowing involves the observer engaging with the end-user performing the activity. The overarching goal for the observer is to deeply understand the testing process and the testing system that validates the plugs. The observer in this process is the author [25].

The first step of shadowing is choosing a participant. The most obvious choice was to select a lab technician who conducts tests on plugs at Interwells' facility. Two lab technicians are responsible for performing tests at Interwell's Trondheim facilities. The lab technician that the observer chose to shadow was the senior lab technician with 15 years of experience working at Interwell [5].

The next step was participating with the senior lab technician on some tests in the coming week. The observer participated in the two tests on plug type HEX and ME. The test process itself for all plug types is universal. So knowledge gained for testing one plug type contributes to understanding all plug types' testing processes [5].

As part of the shadowing process, the observer did perform several contextual inquiries with the lab technician to understand better the process and their opinions about the current test setup. To additionally verify the understanding of the test procedure, a copy of Interwell's "Full Scale Test Procedure ISO 14310 V0 for Bridge Plugs and Packers" and "Full Scale Test Procedure API 11D1 4th Edition V0-R for Bridge Plugs and Packers" was obtained, and analyzed with the notes from the shadowing sessions [4]. Thus a complete summary of the queries, the testing process, and the testing system are given below.

2.1.2.1 Existing testing system

A brief overview of the existing testing system is obtained in this section, where each component and its respective function are explained. The following objects are needed and used to conduct a test for the current testing system:

- Test cell
- Plug
- Pneumatic system
- Heating system
- Control Panel
- Electronic Setting Tool (EST)

Each of these six parts of the test setup provides functionality that tests a plug's sealability according to industrial standards. The plug's sealability stems from the packer element's behavior when prescribed by different forces and geometrical shapes. Thus, the packer element sealability is tested with differential pressures and changing temperatures. This study focuses on miniaturizing these parts to test the packer element alone. The six individual components of the system work independently and not coherently. Thus a human is needed to monitor and control each component as desired.

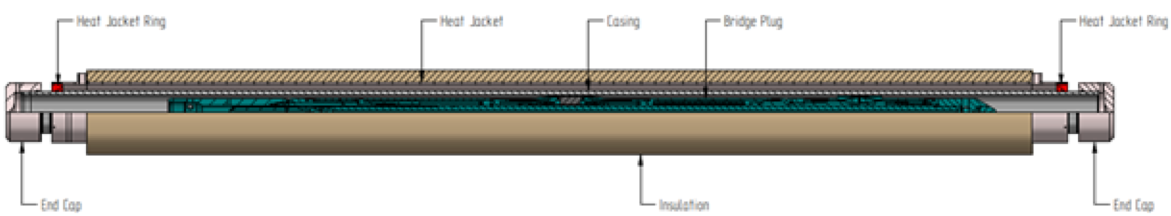


Figure 2.6: Test cell with plug inside by Interwell[4]

Test cell

The test cell is shown in figure 2.7 and 2.6 by Interwell. In figure 2.7, the test cell is the innermost tube that the slips of the plug bite into, and the elastomer expands onto the test cell's ID to seal the test cell from "above" to "below." The primary function of the test cell is to emulate the casing inside a well. The second function of the test cell is to be durable to the conditions it is exposed to during testing, such that the plug's functionality can be tested.

As seen in figure 2.6, end caps are on each side of the test cell. The end caps attach after the plug has been anchored and engaged inside the test cell. The primary function of the end caps is to seal the air inside the test cell from each end. The secondary function is to provide an access valve for pneumatic connection so air can be filled into the test cell's "above" or "below" area. The pneumatic link has an attached manometer, and each end cap has a pneumatic connection with the manometer connected to it, thus being able to measure the differential pressure of the side that is pressurized and not. One of the pneumatic links is further connected to a machine that pumps air/gas into either "below" or "above" the test cell.

Plug

The plug is the object being tested. It sits in the middle of the test cell, anchors to the test cell walls with its slips, and seals the test cell with the packer element. The plug is placed here and operated from a "run" to a "set" position with the EST. Each plug size has a corresponding test cell, and this is because each plug type has a different expansion ratio and generally different sizes to fit into different sizes well. Combining those two factors makes it impossible to create test cell sizes that overlap in plug type or dimensions, thus needing a test cell for each size plug. The plug can be seen in the middle, in figure 2.7.

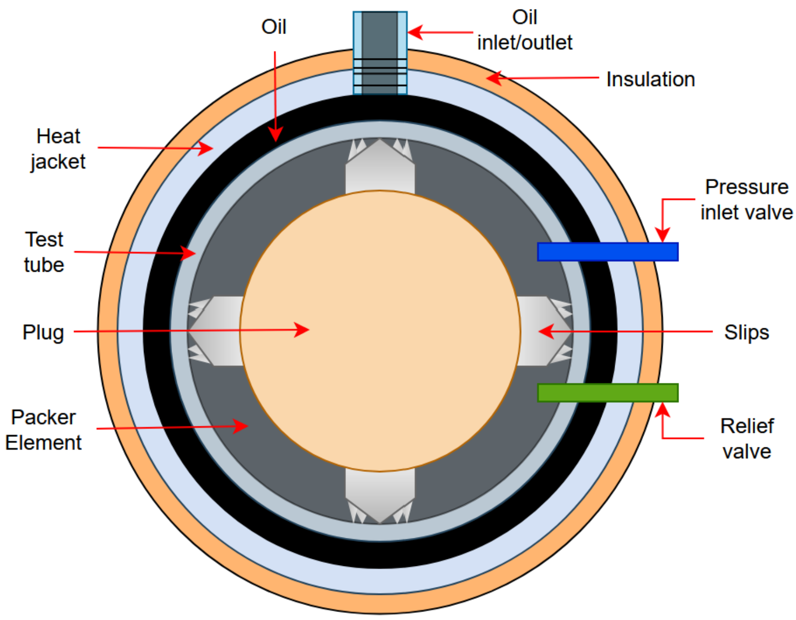


Figure 2.7: Sketch of the cross-section of a plug ready to be tested

Pneumatic system

The Pneumatic system comprises pneumatic pipes, valves, regulators, manometers, an air

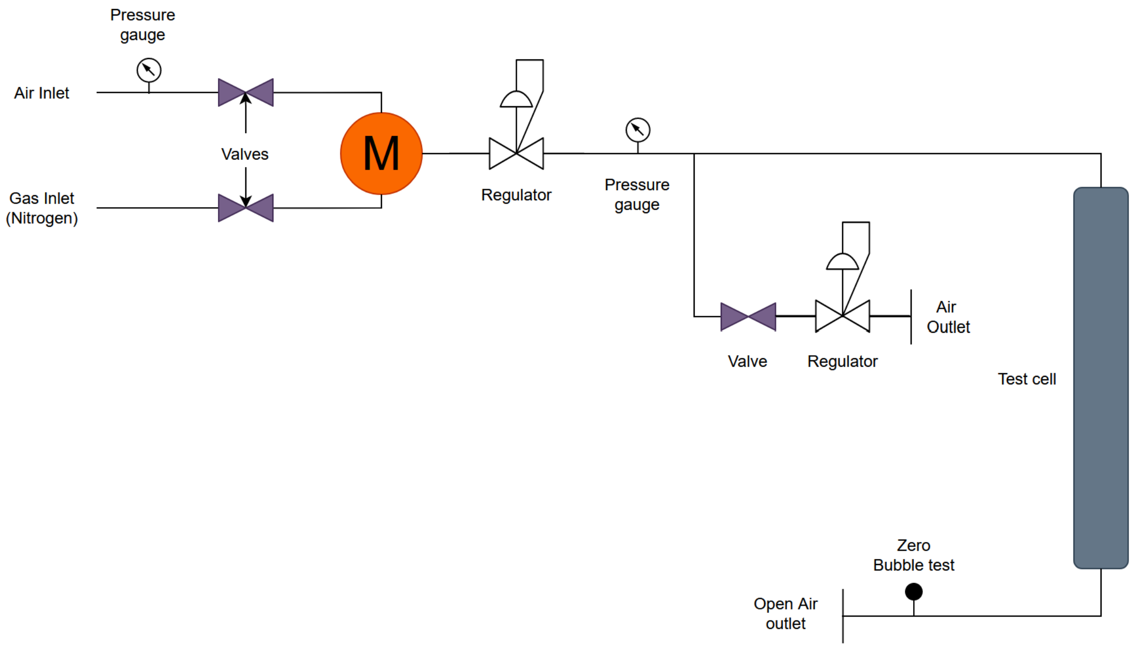


Figure 2.8: Schematics of the entire pneumatic setup

compressor, a bubble meter, and a nitrogen gas tank. A schematic of how the entire pneumatic system is set up is shown in figure 2.8.

The air is pumped through the air compressor, marked as "**M**," where the compressor pulls air either from the ambient air in the room or from a gas tank, in which case it is nitrogen gas and not ambient air. Then the air is compressed to a higher pressure and sent towards the regulator. The regulator ensures that a fixed amount of air is moving through the system; it regulates the speed of the motor to achieve a pressure increase of 25 bar/min into the test cell. The pressure gauge next to the regulator is a way for the operator (lab technician) to ensure that it is 25 bar/min moving through the pipes and that the system pressure is as expected. Then the air can move through to the valve or the test cell. Next to the valve, another regulator opens the valve if either the pressure is too high or there is a leak in the system, and it needs to depressurize the test cell from "above."

The setup is complex and designed so the system can bleed off air in any emergency. The system has a bleed-off valve "above" the test cell tank so that if it leaks, it opens the valve and depressurizes the test cell to prevent any unwanted scenario. There is an open outlet "below" the tank, so if the packer element does not seal as desired, the air that leaks through can be bled off from "below" through the outlet. Connected to the outlet is a bubble meter. The bubble meter measures any air that might come through the packer element and increase the pressure "below" area of the test cell. The bubble meter is the zero-bubble acceptance criterion set by the industry standards of air-tight plugs. More on the zero-bubble acceptance criterion in chapter 2.1.3.

Heating system

The heating system comprises the heat jacket, insulation, and heat exchange unit. The test cell is placed inside a heat jacket, which is then covered with insulation. The insulation material has a radiation-reflective coating and is made up of a glass-wool mixture. The heat jacket creates a space between the test plug and the jacket itself so that the test cell is always concentric on the heat jacket, and thus there is a uniform gap all around the test cell and the heat jacket. See figure 2.7 and 2.6 to see how the heated jacket physically sits around the test cell. Once the test cell is inside the heat jacket, oil is pushed into one of the heat jacket inlets and sucked out on the other. The heat exchanger has two functions: a pump that pumps oil in and out of the heat jacket, and the second is to heat the oil so the plug is slowly heated.

Control Panel

The lab technician operates the control panel, which operates the abovementioned systems. The control panel is proprietary information from Interwell; thus, no depiction of it is provided.

Electronic Setting Tool

The Electronic Setting Tool performs a similar task as the hydraulic setting tools used in wells for setting a plug [3]. The specific function is to operate a plug so that it goes from a *run* to a *set*, or from a *set* to a *pull* stage. A depiction of the EST is shown in figure 2.9. There is a load cell inside the setting tool, which measures how much force is applied. A specific amount of force must be applied to ensure desired performance from the plug. It is an expensive piece of equipment worth 500 000 NOK [4][5].

Figure 2.9: A picture of the EST by Interwell[3]

2.1.2.2 Testing the plugs

Testing the plugs is a summary of the lab technician's work and the test procedure documents from Interwell. It involves setting the plugs, heating them, and finally conducting the tests. All the equipment used is mentioned above. Due to Health, Safety, and Enviromental (HSE) concerns, the current test setup is buried inside a bunker outside the building of Interwell. It is to ensure that if a plug does not seal as intended and the test cell also leaks, it does not cause any harm to human life and any equipment around it. As mentioned earlier, the two tests the observer participated in were ME and HEX plug types. Each time a plug is ready to be tested, it comes directly off the assembly line.

Setting

The assembled plug is lifted using a crane and lifted to the test cell, where the lab technician pushes the plug inside the test cell while it is suspended in the air from the crane. The test cell dimensions are specific to the plug type and size. Such that the maximum OD of the plug with the slips engaged is also the test cell's ID minus 1/8 of an inch. Once inside the test cell, the plug is operated with an EST. The EST performs an operation that changes the plug's setting from *run* to a *set*, thus engaging the slips with the test cell wall and anchoring the plug. Simultaneously during this operation, the packer element is also pushed out to the test cell wall, sealing completely. Once completed, the EST is disengaged, and the test cell is closed with end caps threading on either side. The end caps have O-rings, sealing the test cell entirely from the room pressure.

Heating

The next step is heating the plug to the desired temperature; the customer often determines this by specifying what conditions they want to test the plug, including the pressure limit.

The heat exchanger pumps warm oil through a hollow cylindrical section of the heated jacket to heat the plug inside the test cell. An inlet and outlet to the heat jacket allow oil to enter/exit the test cell, see figure 2.7. It takes four hours to heat the plug to its core to the desired temperature [4]. The heat exchanger stays connected after the plug is heated to maintain temperature, cool it down, and heat it as needed during the testing phase.

Testing

When the plug has reached the desired temperature, pressure testing can begin to test the sealability of the plug to verify the plug for the V0 validation grade. The plug undergoes five cycles, where three sealability tests with a pressure difference occur concurrently "above" and "below" the packer element. Moreover, two tested the packer element's material sustainability during temperature change. Each cycle is held for 15 minutes to verify stability and test completion as intended. The five cycles are described in table 2.2 below:

Cycle number	Pressure direction	Temperature
1	Below	Maximum
2	Above	Maximum
3	Below	Maximum
4	Below	Minimum
5	Below	Maximum

Table 2.2: V0 Validation grade testing cycles

In cycle 1, the plug is pressurized to the maximum pressure from below while the temperature is at the specified maximum. Once stability is verified and no leak has occurred, the cycle is complete, and the plug is depressurized. Once the differential pressure on both sides of the packer element equals out, the system repressurizes from above while temperature stays at maximum specified levels. If no leak occurs, the system depressurizes again, at cycle 2 is complete.

Cycle 3 is the same as cycle 1; it verifies that the plug exposed to cycles 1 and 2 has not weakened its performance. Cycles 4 and 5 test the packer element's ability to handle temperature changes. In cycle 4, the temperature is lowered while the plug is pressurized from below. Once the minimum temperature reaches and the plug performs as desired, the temperature is raised again without depressurizing. Once the plug has reached the maximum specified temperature, and if it is still not leaking, cycle 5 is complete.

Finally, the test cell chamber is depressurized, and the temperature is lowered again to room temperature. The end cap is removed, and the plug is reconnected to the EST, where the EST performs the operation that changes the plug's state from *set* to *pull*. Furthermore, once the plug has been dislodged from the test cell, the EST is removed, and the plug is ready to be pulled out. A temporary restriction is installed where the end cap is placed, from which the plug is pulled out. The restriction tests if the plug maintains its original OD after the testing. Suppose the visual inspection of the packer element shows no signs of damage, and the plug had no bubbles in the bubble meter during pressure and temperature cyclic testing. The plug passes the V0 validation test grade for the test envelope requested by the customer. The test envelope is the specified properties to which the customer wanted the plug qualified. The test procedure documentation from Interwell gives a more detailed overview of the test. However, because it contains other non-relevant proprietary information to this thesis, a description was given in this chapter instead.

2.1.2.3 Lessons learned and key points

This section summarizes what was learned by the observer by shadowing the lab technician and having read the test procedure by Interwell. It contains a list of challenges the lab technician mentioned through contextual inquiries. One of the challenges the lab technician mentioned was the time it takes to test each plug. Through inquiry, the observer obtained an estimated time for each process and how long each test takes for a plug. The test envelope parameters for the ME plug are listed in table 2.3.

Property		Unit
Pressure	345	bar
Temperature	150	°C

Table 2.3: Test envelope for ME plug

Based on the test envelope, the information from the lab technician, and the information from Interwell's test procedure, an estimate of the time it takes to complete each task is listed in table 2.4, and the total time it accumulates to is 20 hours. Total time does not account for assembling the plug at the facility or redressing the plug after the completed test. If each work day is 7.5 hours, it takes 2.67 days to complete the test if everything goes smoothly and the plug passes. If not, it must be repeated, taking at least another 2.67 days. The lesson learned from this is why Interwell would like to create a small-scale packer element tester; after about three days of work, the plug might fail the test, and there is little information from the packer element on why it failed to seal the plug [5].

Another key point is that the control panel is out of the scope of this thesis, as the focus is to find the hardware parts that create a packer element tester. Creating or combining the software of devices that control pressure, temperature, and force is an extension of this project which will be addressed in future work, chapter 4.3. According to the lab technician, the

Process	Time (minutes)
Setup the test cell	30
Pre-heating	240
Pressurizing test cell	14
Cycle 1 (hold)	15
Depressurizing test cell	14
Pressurizing test cell	14
Cycle 2 (hold)	15
Depressurizing test cell	14
Pressurizing test cell	14
Cycle 3 (hold)	15
Cooling down	240
Cycle 4 (hold)	15
Heating up	240
Cycle 5 (hold)	15
Depressurizing test cell	14
Cooling down	240
Disassemble test cell	30
Inspection	15
Other	6
Total time	1200

Table 2.4: Processing time for each step of the V0 validation test

biggest challenges at the facility are that it takes 4 hours to heat the plug and that there are no more test facilities to facilitate more tests. Furthermore, the observer noticed the following list of things that are challenging during testing and at the test facility:

- No thermometer inside the test cell verifying the temperature level
- The plug relies on shear bolts; thus the setting force can not be adjusted without re-dressing the plug once it is *set*
- The bubble meter gives no other output except if there is or is not leakage from the plug
- No visualization of the test cell under testing

2.1.3 Industry standards

The industry standards section will describe the two standards Interwell AS uses to validate and verify their plugs and packers. Thus the standards' requirements and testing method is described below. International Standard Organization (ISO) and American Petroleum Institute (API) are the two organizations that provide standards on how to verify downhole equipment, such as plugs and packers. Although plugs or packers do not need to be verified before an operation, it is usual practice in the industry, and customers desire to acquire plugs that comply with these industrial standards according to [32]. Interwell's policy is to provide plugs and packers that comply with the standards [5].

The ISO is the organization that sets standards for many engineering processes around the world. ISO standards are often used in many industries by both customers and manufacturers alike to verify the quality and safety of their products [23]. American Petroleum Institute is an oil and gas trade association from the United States of America. Their role in the US is to advocate, promote and support technical advancements in the petroleum industry. In addition, API creates standards defining best practices and guidelines for the industry. API's standards and regulations are recognized globally and significantly impact the petroleum industry internationally due to their standards being based on quality, rigorous testing, and comprehensive coverage of practices in the industry [10].

The specific standard from ISO used to qualify plugs and packers is ISO 14310:2008 (E), namely "Petroleum and natural gas industries — Downhole equipment — Packers and bridge plugs, 2008 edition". Furthermore, the specific standard for API is API 11D1 4th Edition, namely "Packers and Bridge Plugs." Both standards are widely recognized and respected in the petroleum industry, providing a benchmark for quality and performance [1][11]. These standards ensure that plugs and packers meet the requirements for downhole applications, such as sealing wells or isolating zones. By adhering to these standards, companies can enhance operational efficiency, minimize risks, and maintain the integrity of their wellbore systems.

Both ISO 14310 and API 11D1 are standards that outline the design validation requirements for packer elements. However, there are some key differences between the two. ISO 14310 focuses on the performance and qualification of packer elements for use in oil and gas wells. At the same time, API 11D1 explicitly addresses the requirements for packer elements used in high-pressure, high-temperature (HPHT) environments. However, both standards have similar requirements for the design validation of packer elements for general and conventional well conditions. These include testing packer elements under various operating conditions, such as pressure, temperature, and fluid exposure. Both ISO 14310 and API 11d1 also specify the criteria for evaluating the performance and integrity of packer elements, including leak resistance, compression set, and extrusion resistance[11][1].

For this thesis, only the design validation requirements for the packer element from both standards are analyzed. As both standards have the same requirements for design validation, a detailed comparison of the criteria is unnecessary. ISO 14310 and API 11D1 have comprehensive guidelines on the testing procedures and test conditions to ensure the packer elements meet the required standards. Instead, a summary of the two standards' design validation for the packer element is provided below, and for this specific project, the two standards can be used interchangeably.

2.1.3.1 Testing Standards for Packer Elements

The ISO 14310/API 11D1 design validation section describes the different validation levels, the test method on each level, and the criteria to pass that design validation level. There are a total of 6 validation levels; V0 to V6. V0 is the highest level of validation, while V6 is the lowest. V6 is the customer (user) specified validation test method. However, most Interwell clients use V0 as a standard procedure for the plugs and packers they acquire, and as per Interwell company policy, they strive to qualify all their plugs for V0 as well. This report and project will focus on designing the test setup for a V0 validation level. Table 2.5 shows the different validation levels and their testing method and acceptance criteria [11][1].

Validation level	Test	Acceptance criteria	
V0	Gas + load + temperature	Accumulated gas	0 cm3
V1	Gas + load + temperature	Accumulated gas	<20 cm3
V2	Gas + load	Accumulated gas	<20 cm3
V3	Liquid + load + temperature	Pressure Drop	<1%
V4	Liquid + load	Pressure Drop	<1%
V5	Liquid	Pressure Drop	<1%
V6	Defined by customer	Defined by customer	N/A

Table 2.5: Validation levels for plugs and packers [1]

The liquid and gas test methods are the same; the only difference is that the fluid in the liquid test is a liquid, while in the gas test, it is a gas. Acceptance criterion changes depending on the type of medium used for the liquid or gas test. The test for liquid or gas comprises a cyclic test where pressure is applied using gas or liquid on either side of a plug or packer in a "set" position. In the "set" position, the sealing elastomer on the tool is expanded into the test cell wall, sealing one side of the tube from the other. More on the operational positions of a plug or packer in chapter 2.1.1.2. The liquid or gas test consists of applying the pressure alternating a minimum of two times on each side of the tool being tested, each time with a hold period of 15 minutes. Thus, Interwell has five cycles they perform on each plug or packer.

For V3 to V5 test, as it is a liquid test, the acceptance criteria are based on the loss of differential pressure between the pressurized side of the sealing device and the non-pressurized of the sealing device. The differential pressure loss must be less than one percent. For V0 to V2 validation level, a gas is used, and instead of measuring differential pressure loss, how much gas escapes through the sealing device is measured instead. For V1 and V2, the gas that escapes must be less than 20 cm3. For validation level V0 no gas must escape to the non-pressurized side of the plug.

For V2 and V4, there is an additional test that is performed, and it is the load test. The load test is an additional force applied to the plug while in the "set" position. The load tests the tool's shear-release features and checks that the plug can sustain any additional force while under operation. The load direction is both axial and tensile. Thus the force applied is equal to the maximum shear load a tool is supposed to sustain while still experiencing pressurized fluid from either side.

V0, V1, and V3 validation levels include a temperature test, where a tool, either a packer or plug, experiences temperature changes simultaneously as it goes through pressure and load testing. The test ensures that the behavior of a tool does not change and that the material making up the tool does not deform in such a way that it comprises the tool's functionality. The test that this report will aim to design a test setup for is the V0 validation level.

The specific validation grade V0 requirements that are important for the test setup to create a packer element tester include the need for the tester to accurately simulate downhole conditions, such as pressure and temperature, to ensure reliable and accurate results. Additionally, the tester should be capable of applying various axial load conditions to the packer element to assess its performance under different scenarios. Another crucial requirement for the test setup is the ability to precisely measure the deformation or displacement of the packer element during testing. It will allow the end-user to gather valuable data on the packer element's ability to withstand pressure and temperature.

Overall, having a packer element tester that fulfills these specific V0 requirements is essential for ensuring the reliability and effectiveness of the packer element in real-world oil and gas operations. Furthermore, the knowledge gained from the ISO 14310/API 11D1 industry standards will help induce the design requirements in chapter 2.2.2.

2.1.4 Interview and survey

To further understand the experiences of the end-users and people associated with this process, the author conducted interviews and sent out a survey. In design thinking, surveys and interviews are two additional research methodologies utilized to obtain insights and information from end-users and other relevant parties. These methodologies will further assist in better understanding the end-user needs, wants, and obstacles they face, which will help design the packer element tester. This section explains how the participants interviewed were chosen, the key points from the interviews, how they shaped the survey, what the survey concluded, and what lessons can be learned from it.

2.1.4.1 The end users

It is necessary first to define the end-user to ensure that the small-scale packer element tester is designed as needed by the end-user. This ensures that the interviews and surveys are conducted with those who will use the packer element tester. By involving the end-users in the design process, their input can guide the development of a packer element tester that meets their specific needs and addresses the shortcomings and challenges of the current setup. The end-user for this thesis is Interwell AS, the company itself. The company desires to create a platform to improve its plug technology while maintaining the supply for testing current products in the customer-delivery queue.

However, the specific participants for this project are those employed to improve plug technologies and the current test setup in the research and development (R&D) department and lab technicians associated with testing plug and packer elements. In addition, the product department from Interwell is also associated with the design of the test setup, as they are the primary users of the current test setup to test current plugs to customer specifications for Interwell. Thus they have the most experience with the current test setup and can give a thorough insight into the challenges and pain points of the current test setup.

The R&D depart was also divided into the R&D and *specialists* groups for the interviews and survey. At Interwell, although working closely with the R&D department, the specialists are considered their own group. Specialists include material scientists, load path analysts, heads of departments, and chief engineers. This group includes people who oversee projects, contributing with analysis and knowledge to help the design engineers design any project they seek.

2.1.4.2 Interviews

The interviews were conducted one-on-one, and they were conducted in a free-flow approach, in which a question was posed, but the end-user was free to answer the question as they saw fit and could expand to other issues that were not directly answering the question that was posed. It was only important that the end-users comments were relevant to the project. This open-ended approach fostered a genuine and comprehensive understanding of the end-users' thoughts, perspectives, and ideas. Appendix D contains the questions and answers from the interview. The identities have been changed to protect the anonymity of all end-users.

The interview questions were separated into two groups. The first set comprised general questions that were asked of everyone who was questioned. The second series of questions focused on the individual's job in the organization and its relation to this project. The general questions that were asked are given below after being translated into English:

1. What is the biggest challenge with the test setup that is used today?
2. If you were to test a packer element, which parameters would you want to measure?
3. What opportunities would occur if a test setup existed that was created as desired and described in the task given for this project?

The questions in this report are based on the task given by Interwell, which involves conducting full-scale V0 tests on complete systems due to logistical, safety, and cost constraints, see appendix A. The first question allows individuals working directly with the plug testing to elaborate on the challenges. The second question focuses on recreating relevant parameters from the tool affecting the packer element in real-life use cases, gathering information from Interwell employees about the necessary parameters for their product. The third question focuses on the "why" of the project, highlighting the engineers' goal, contribution to the industry, and how this project helps advance downhole equipment technology.

Product Champions

The first category of employees that were interviewed were Product champions. They are related to this project as they are the primary users of the full-scale V0 test setup, as they weekly qualify plugs that are tested and verified before being sent to a customer for operation. The questions asked to the Product Champions were:

1. How is the plug type you work with affected by the current test setup?
2. How do you suggest to improve the test setup that is existing today?
3. How do you suggest the setting force can be simulated on your specific plug type?
4. What is the casing size your plug is tested to?

The questions asked were reflective of their role at Interwell. As the desire to create a packer element tester that is capable of testing every type of plug, it was essential to gather knowledge about what kind of casing size the plug is tested to, how is the setting force administered on their specific plug type, what was the geometry of the plug around the packer element, and lastly how their respective plug type is affected by the current test setup and how the product champions think those issues can be resolved.

R&D Engineers

The second group that was interviewed was the R&D Engineers, and their role is to design and develop new solutions for downhole equipment, including downhole equipment itself. Part of this is also to understand what the issues are and thus develop better test methods to test the plugs so they can gather data, which in turn can aid them in developing new downhole equipment solutions. Thus, the R&D department wants to create a small-scale packer element to gain insight into the elastomer functionality. Thus the questions that were asked were the following:

1. What functionality do wish you to have in a small-scale test setup?
2. Are there other tests that are desired to be performed on the elastomer that are not defined by API or ISO?
3. Any external factors that need to be aware of that affect the test setup?
4. How would you have designed the test setup?

The questions here reflect the role of the people being interviewed. The questions were developed to understand what kind of functionality they would want, what tests they would like to perform, and from those tests, what kind of parameters are essential to this project, as well as if there are tests that they would like to do that are not defined by already mentioned ISO/API standards. Furthermore, if they have experimented with this before and if they did, what kind of test designs have they done before, and thus, how would they design a small-scale packer element tester.

R&D Specialists

Finally, the last group that was interviewed, were the specialist group. The questions that were asked, targeted their specific knowledge and experience in their respective field. The questions that were asked them were:

1. What forces and loads occur in a packer element during operation?
2. What material properties are affected by those forces and loads?
3. Which unwanted phenomena occurs in the plug when it goes from "run" to "set" and how does those phenomena affect the packer element?

The questions focused on the load paths during operation, which would help understand the stresses an elastomer is exposed to under operations. In addition, to understand how the elastomer responds to those and what material properties change by those loads. Furthermore, finally, if any unwanted things happen with the plug or the elastomer under the first two stages of the plug.

Summary of the interviews

Here is a summarized bullet point list of some of the concerns and knowledge gained from the interviews that apply to all the plug types:

- Limited test capacity (3 bunkers only)
- Long waiting times. A test cycle of a full assembly can take up to a week
- Long heating time, up to 4 hours. And still no way to verify the actually temperature in the plug.
- Lack of data obtained from testing
- Rapid Gas Decompression (RGD) in the O-rings might cause failed tests.

- Cost of tests is very high, up to 600 000 NOK per test [5], see figure 2.13 made by co-supervisor Tarjei Skulstad.
- Different versions of plugs are being released and different versions of elastomers come to the market as technology progresses. This makes the retesting and requalifying job more difficult.
- Hard to test small changes. Because it is unknown what causes failure of a test assembly and what causes success.
- Logistical challenges because every test ordered by a customer requires a specific casing size and a specific plug.
- Pressure system software has a bad PI control, it over pressurizes, and then waits for the system to catch up and then repeats the process.
- Lack of visualization of the packer element during testing
- HSE concerns confines all testing to the designated bunker area

Additionally, some remarks made by the end-user are described, including the backlash effect and continuous control of setting force, which are design flaws in the product itself as well as an explicit deficit in their current test setup.

A ratchet has a design flaw in that it has *backlash*. Backlash occurs when the slips are pushed into the casing wall and cannot be pushed any further in, causing the ratchet to stop. When the ratchet reaches the end of the last tooth it was climbing on, it falls back, reducing the amount of force it was using to push the slips into the wall. This loss of force reduces the force applied to the slips and packer elements pushed into the wall, weakening the anchoring of the plug as well as the sealing [31] [5].

Because of the backlash effect, additional cup springs are added to the assembly, ensuring sufficient force is applied to the system so that it is fixed in place inside the well. However, there has been no way of measuring the exact amount of force lost and thus needed for compensation. And because full-scale tests are so complex to setup and perform, this part of the design has been overengineered to ensure functionality. It is desired to find out exactly what this force accounts for and determine if there is a more efficient and precise way to measure and compensate for the force lost [5].

According to the end-user, having a method of controlling the setting force input can be extremely beneficial to the testing system. Because it enables minor adjustments to relieve pressure on the packer element and determine the amount of force required to achieve a proper seal. This allows for more precise and efficient packer operation. The continuous setting force system should also ensure that the applied force remains constant throughout the setting process and during testing, reducing the risk of damage or failure. Overall, this innovative mechanism improves the packer system's reliability and performance, resulting in a secure and effective sealing solution.

The bullet points above include the most frequent answers and relevant information from all the interviews. A detailed answer from each participant and their answers can be found in appendix D. These bullet points will help form the survey below.

2.1.4.3 Survey

The survey was conducted anonymously, and an email was sent to everyone in Interwell associated with the design and testing of downhole equipment. The idea was to verify and reaffirm the key points and information obtained from the interviews. In the survey, the participants were asked to answer the following questions:

1. What role do you have at Interwell?
2. What are the problems with current setup?
3. What features are desired for the small-scale test setup?
4. What is the motivation behind why those features are important to you?

At the beginning of the survey, the task from appendix A was displayed for the participants to read and gain context to the survey. The first question of the survey was posed so that the participants could choose the option of category (role) they belonged to at Interwell. They could only pick one option, see appendix E for a complete overview of the survey results and questions.

The following three questions of the survey were statements that were written down that were based on the interviews. Moreover, each participant was asked to rank them according to what they believed was most important and least necessary to them in this project. The key points that the participants were asked to rank in regards to "problems with the current test setup" were:

- Logistics (PAX/capacity, amount of test tubes, casing size, etc.)
- Test procedure (heating time, redress, setup, etc.)
- Lack of data obtained from a test
- Price for testing
- Unrealistic test setup

The results of the bullet points above are given in figure 2.10. According to the survey results, the biggest issue with the full-scale testing system is its logistics, and the second biggest is the test procedure. It is a consensus among most end-users that the current test setup is sufficiently realistic enough to emulate real conditions, while remembering that the most essential feature for the test setup to be realistic is that the test setup can perform the tests described by ISO 14310 and API 11D1. Statements 3 and 4 in figure 2.10, are not the biggest problems with the current setup, but in an ideal world, both of these problems should be resolved.

The second aspect asked to be ranked was the features desired in a small-scale packer element tester. The results from this are displayed in figure 2.11, where the key points that the participants were asked to rank for were the following:

- Pressure, Temperature, and V0 (mechanical properties) - existing in current test setup
- Mechanical behavior of rubber element (leak, expansion/contraction, distance, etc)
- Visual aids under testing (Camera, glass test tube, etc.)
- Modularity (different casing sizes and different elements can be tested)
- Realistic test setup (centralizing, vertical setup, etc.)
- Other properties

The numbers next to the ranking number explain how many people placed that statement in that location. So for instance, in figure 2.11, for statement 6, an average of 5.07 people placed that statement in rank 6. Thus ranking it lower and less important. This also means

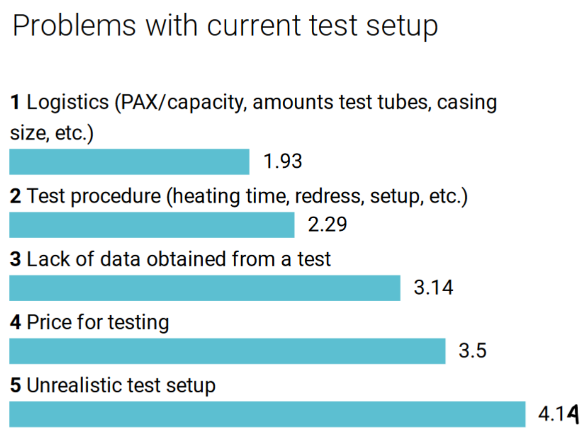


Figure 2.10: Survey results ranking "Problems with current setup"

that for figure 2.11, the top three statements almost tie in how they rank among all the people who ranked them. Where only two more people ranked statement 1 higher than statement 2, and only one more person ranked statement 2 higher than statement 3, and so on. This same system applies for all the other figures as well.

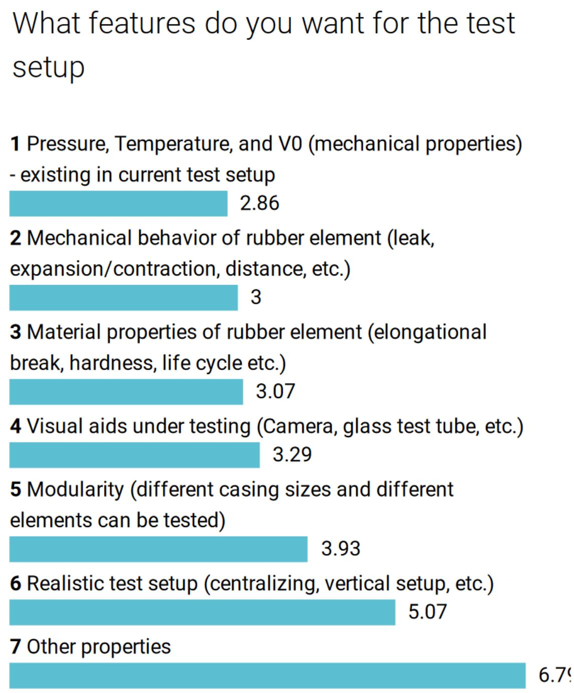


Figure 2.11: Survey results ranking desired in a small-scale test setup

Thus, for figure 2.11, the top three statements are the most important almost equally among the employees at Interwell. And the least important, according to everyone, for the same figure are the bottom three. However, statement 4 ranks somewhat important as a desired function for a test setup.

Finally, the participants were asked what motivation was behind developing a small-scale tester. The "motivation" for this was to unbiasedly get every individual's opinion on where they believed the packer element tester would serve Interwell company best and what kind of problems it would solve. The key points the participants were asked to rank in terms of motivation to create a small-scale packer element tester were the following:

- Research & Development
- Meet requests from customers faster
- Product backlog
- Expand test envelope of plug

The results for the final questions are displayed in figure 2.12, where most participating end-users believe this project will help the research and development of plugs, and the second most is helping with faster testing of plugs, thus allowing the company to deliver requests from their customers faster. And there is consensus among all end-users that it will not resolve issues regarding tests on older plugs or expanding the test envelope of a plug, as for that to happen, the entire plug needs to be tested according to ISO 14310/API 11D1. And there is no capacity or need for older and expired plugs to be tested now, when they are no longer produced, even if they are still in use somewhere around the world, as the focus should be on improving the efficiency and performance of current plug models.

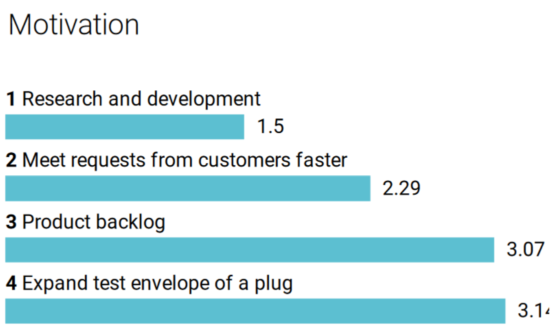


Figure 2.12: Survey results ranking "motivation"

2.1.4.4 Lessons learned from interviews and survey

This section summarizes the key points that have been obtained through the interview section and have been verified and established through the survey results. In addition, specific end-user comments are also documented here that directly relate to the design of the small-scale packer element. The most important and relevant comments from the interviews are listed here as well.

Essential needs

It is understood that the biggest challenge the end-user faces today is the logistical setup at the Trondheim facilities. It needs more capacity and personnel. In addition, an overload of material is needed to perform a single full-scale test. This issue cannot be addressed in this project because the problem addresses issues specific to the Trondheim facilities.

However, finding alternative testing methods can help mitigate the overload issue, which this project aims to achieve. Thus, it substantiates the need to create a small-scale packer element tester. The small-scale tester could be used as a preliminary screening tool, allowing for quicker and more frequent testing and potentially reducing the need for full-scale tests.

Small-scale testers can improve their test procedures by incorporating a better heating system, reducing the time it takes to heat up and cool down, and incorporating simple geometry and design for quick and easy redressing of plugs. This will save time and increase overall productivity in the packer element testing process.

A testing machine that is compatible with the current pressurization system is ideal, as it eliminates the need for additional equipment or modifications. The current system is controlled and safe and has been approved through a rigorous HSE process through local government laws.

Using known pressurizing equipment that meets safety standards is considered safe when testing a new machine. A compatible testing machine ensures accurate and reliable results, working seamlessly with the existing pressurization system. This saves time and resources by avoiding errors or inconsistencies that could arise from separate or modified equipment and eliminating the need for personnel training on unfamiliar equipment.

Finally, the features desired by end-users are consistent with the issues raised above, as the most important feature, which is listed as the most sought by end-users and is a prerequisite for this project, is the feature of duplicating the ISO 14310 / API 11D1 standard for testing plugs. This corresponds to the pressure, temperature, and force criteria covered in those standards. Thus, incorporating the ability to duplicate the ISO 14310 / API 11D1 standard for testing plugs would ensure that the end-users' requirements are met and that the equipment is capable of accurately and reliably testing packer elements according to industry standards.

Optional needs

Addressing other concerns ranked 3 and 4 in "Problems with current test setup." In rank 3, the issue is with "lack of data obtained from a test." According to the end-users in interviews, the additional data that is not obtained is primarily for elastomer material and mechanical properties. For the issue of the "lack of data obtained" from the "Problem of current test setup" question, this primarily refers to mechanical and material properties of the elastomer and to the visualization data of the elastomer that is also not obtained. However, through inquiry in interviews with the end-user, these are more optional and desires if possible, and not needs to enhance their current testing platform or capabilities. And if these optional features are included, it would lead more into R&D of a different product, namely elastomers, whilst Interwell AS, the company, has there best interest in focusing on enhancing their V0 ISO14310 / API 11D1 testing requirements.

Furthermore, the cost of testing is mentioned in the project task (see appendix A and can be calculated in the Excel sheet provided by Tarjei Skulstad, a snippet shown in figure 2.13. For proprietary reasons, the sheet is not provided. The cost ranges between approximately 50 000 NOK and 600 000 NOK, depending on the plug type, type of test, elastomer material, and size. If a small-scale tester works as intended and can be used as a prescreening tool for the elastomer prior to full-scale testing, the cost of testing will be reduced.

It is assumed that the lowest ranking issue with the current test setup is not a need or

Low Cost Example			High Cost Example		
Input			**Input**		
Test pipe dimension		2 3/8	Test pipe dimension		13 3/8
Product type		Plug	Product type		Plug
Technology		ME	Technology		HPHT
Rubber material		HNBR	Rubber material		FFKM
Type of test		Standard	Type of test		Extended
Test pipe		Standard	Test pipe		Custom
External inspector		No	External inspector		Yes
No. of tests yearly		150	No. of tests yearly		88
Fixed costs			**Fixed costs**		
Test facilities	kr	5 600	Test facilities	kr	9 589
Test department personel	kr	10 170	Test department personel	kr	17 414
Variable costs			**Variable costs**		
Test Cell	kr	3 023	Test Cell	kr	170 227
Redress Parts	kr	2 766	Redress Parts	kr	339 121
Redress Personel	kr	5 625	Redress Personel	kr	5 625
Test Personel	kr	9 000	Test Personel	kr	9 000
Test Engineer	kr	11 000	Test Engineer	kr	11 000
Inspection	kr	-	Inspection	kr	30 000
Total cost	kr	47 184	**Total cost**	kr	591 977

Figure 2.13: Cost example of testing a plug

desire of the end-user, as it is also ranked the lowest in the features question, implying that either that need is fulfilled or that it does not exist at all. However, Tarjei Skulstad wants the packer element tester to be modular enough to accommodate all plug sizes. As a result, the design should be simple yet adaptable, allowing any casing size and plug type to be installed with minor changes to the testing machine. This requirement will be addressed during the design process because it was explicitly requested, although it ranked fifth in the feature question and would have otherwise been overlooked.

2.2 Define

This subchapter uses the information from chapter 2.1 to determine requirements for a small-scale packer element tester. The subchapter establishes ideation criteria and establishes a theory for solving potential design challenges in the next subchapter. A bullet point list of topics discussed is given below:

- Theory
- Design requirements

The themes discussed in the theory dive into type of material and, establishing numbers of minimum and maximum thresholds for the packer element tester's performance as desired by the end-user. In addition, the theory briefly describes the strength calculation tool used by Interwell AS to design their products. This tool will design the walls' thickness to ensure that the packer element tester meets minimum requirements. The design requirements section outlines the necessary features and functionalities the tester should possess to effectively perform its intended task.

2.2.1 Theory

Co-supervisor Tarjei Skulstad, notified the author of the testing machine's maximum expected design performance criterion. This criterion is listed in the table 2.6. The performance criteria factors are based on the existing full-scale test model and the requirements of industrial standards. Thus, the parameters measured are pressure, temperature, and setting force. The specifications define the maximum that the test cell must be able to sustain during a test without failing to hold the elastomer stationary and without leaking gas outside the test cell, and the temperature change should not compromise the test cell's mechanical or material integrity. Finally, the components supporting the packer element must be sturdy enough to withstand the stresses and pressures applied to them.

		Unit (Imperial)		Unit (Metric)
Differential pressure	20000	Psi	1379	bar
Temperature	572	°F	300	°C
Setting Force	88 185	lb	40 000	kg

Table 2.6: Maximum small-scale packer element testers performance criteria set by end-user[5]

In contrast, no defined minimum criteria for the packer element tester performance exists. However, knowing that the plugs are not exposed to temperatures below zero, the minimum temperature criteria is above zero. The plugs experience a minimum pressure equivalent to atmospheric pressure, as the environment to which they are exposed is never below that [30] [4]. A force known as the setting force, is applied to operate the plug. For that procedure to occur, the setting force must be sufficient to anchor plugs and allow packer components to seal the well. This force must thus be greater than zero, and the plug size, plug type, and shear bolts determine its exact magnitude.

2.2.1.1 Strength Calculation Sheet

The strength calculation sheet from Interwell AS is their analytical approach for validating and controlling the ability of plug parts to withstand stress. According to the master thesis by Jon, who compared the model to Finite Element Analysis (FEA) techniques and concluded that the calculation sheet is reasonably accurate [29]. As a result, test setup parts will be designed using this calculation sheet. The strength calculation sheet can compute the thickness of any threaded cylinder, thickness of a cylindric part and thickness of a circular disk plate.

The mechanical properties of the material used in the design process have been adjusted and verified to 300 °C by Interwell personnel [4] in the strength calculation sheet. The material that will be used to design all parts in Stainless Steel (SS) 2541, as decided by the end-user [5]. The needed material's properties are obtained from research paper [35], provided in table 2.7. The strength calculation sheet will help determine the forces the different designed parts will experience and help dimension each part.

Temperature	20 °C	300 °C	
Mechanical Properties			Unit
Yield Strength	731	683	MPa
Tensile Strength	1158	1900	MPa

Table 2.7: Material Properties of SS2541 or S.A.E 4340 at 20 °C and 300 °C by [35]

2.2.1.2 Pressure vessels

Both the strength calculation sheet's calculation method and the form of the packer element imply that the test cell inside needs to have a cylindrical form to perform as intended. Thus, a basic understanding of how a pressure vessel functions is necessary to properly interpret the results from the strength calculation sheet. A pressure vessel is designed to contain fluids or gases at high pressures. A pressure vessel's ability to handle high pressure depends on its material strength, wall thickness and design. The material strength determines the maximum stress that the vessel can withstand, while the wall thickness ensures that the vessel does not rupture under high pressure [15].

Lame's equations are frequently employed to determine a pressure vessel's capacity to withstand high pressure. Lame's equations are divided into two types of pressure vessels: thin-walled and thick-walled cylinders.

For a pressure vessel to be considered thin-walled, the thickness of the cylinder wall must have a ratio where the outer diameter of a cylinder divided by the thickness (distance between outer and inner diameter) results in a ratio greater than 20. For the pressure vessel to be thick-walled, the ratio needs to be less than 20 [13].

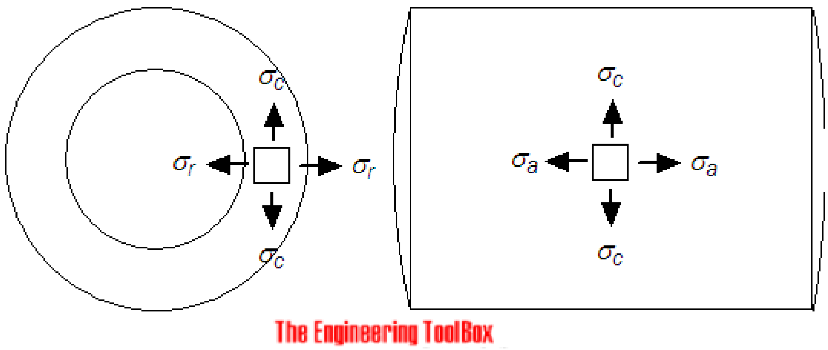


Figure 2.14: Cylinder stress tensors by [33]

In a pressure vessel, there is hoop stress. Hoop stress is caused by internal pressure, where the stress acts onto the internal walls of the cylinder circumferentially in each direction of the circular wall. The hoop stress is described in the equation 2.1, where σ_θ is the hoop stress, **F** is the pressure force acting on the cylinder walls, the **t** is the thickness of the cylinder wall, and the **l** is the axial length of the cylinder.

The hoop stress is described in the equation 2.1, where σ_θ is the hoop stress, **F** is the pressure force acting on the cylinder walls, the **t** is the thickness of the cylinder wall, and the **l** is the axial length of the cylinder [13]. Figure 2.15 obtained by [22] shows the hoop stress components. The σ_c in figure 2.14 is the same as σ_h in equations 2.1.

$$\sigma_h = \frac{F}{t * l} \tag{2.1}$$

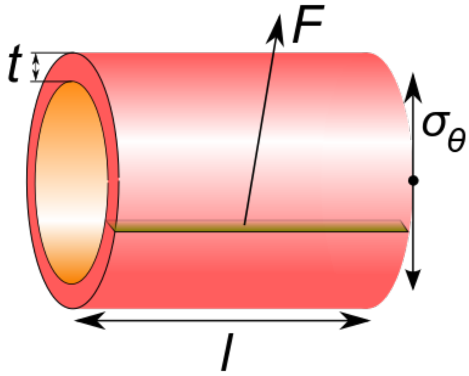


Figure 2.15: Components of hoop stress from [22]

For the packer element tester, there will be no external axial load onto the machine, as the axial load test from the industry standards in chapter 2.1.3 is only to test the plug's shear release features and its ability to stay anchored while in the "set" position. Therefore, for the design of the packer element tester, no axial stress component will be considered for any externally applied force. Depending on the design, axial stress will be evaluated for specific parts that experience axial forces as a cause of internal pressures. It is also safe to assume that while designing components, the pressure will be higher inside than outside. Thus, all outer pressure components are assumed to be gauge pressure and, therefore can be neglected in all equations.

Thin-walled cylinder

In a thin-walled cylinder, the radial stress is equal to the pressure acting on it, either internal or external. The axial stress on a closed cylinder with internal pressure acting on its wall is estimated in equation 2.2 obtained from [18]. According to [18], the hoop stress is two times the axial stress.

$$\sigma_a = \frac{P * r}{2 * t} \tag{2.2}$$

Equation 2.2 can be solved for the variable t, the cylinder thickness, if necessary to determine the thickness of the desired cylinder, the variables is shown in figure 2.15. The ideal way to determine the thickness of the cylinder is to solve for the hoop stress tensor, as it is the stress tensor that has the highest magnitude of stress in a thin-walled cylinder.

Thick-walled cylinder

The equations for a thick-walled cylinder are called Lame's equations by Gabriel Lame. The radial and hoop stress equations are a combination of the axial stress equation and the boundary condition (**B**), given in equation 2.3 and 2.4, which are obtained from [24]. The hoop stress for thick walls is given in equation 2.5, which is the axial stress subtracted by boundary condition. Finally, the radial stress is similar to the hoop stress, except it adds the boundary condition, as seen in equation 2.6 [24].

$$\sigma_a = \frac{p_i * r_i - p_o * r_o^2}{r_o^2 - r_i^2} \tag{2.3}$$

$$B = \frac{r_i^2 * r_o^2 (p_o - p_i)}{r^2 * (r_o^2 - r_i^2)} \tag{2.4}$$

$$\sigma_h = \sigma_a - B \tag{2.5}$$

$$\sigma_r = \sigma_a + B \tag{2.6}$$

If the thickness of the a thick-shelled cylinder is to be calculated either the internal or outside radius needs to be known, symbolized by $r_i and r_o$ respectively. Thus, if for instance the internal diameter (or radius) is known. Equations 2.2, 2.5 and 2.6 can be solved for r_o. The mathematically approach for solving these equations is straightforward, and thus the result for the solved equations are given in equations 2.7, 2.8 and 2.9.

$$r_o = r_i * \sqrt{\frac{p_i + \sigma_a}{\sigma_a + p_o}} \tag{2.7}$$

$$r_o = r_i * \sqrt{\frac{\sigma_h + p_i}{\sigma_h + p_o + \frac{r_i^2}{r^2} * (p_o - p_i)}} \tag{2.8}$$

$$r_o = r_i * \sqrt{\frac{\sigma_r + p_i}{\sigma_r + p_o - \frac{r_i^2}{r^2} * (p_o - p_i)}} \tag{2.9}$$

All of the variables used in the equations are defined in table 2.8. Additionally, the variable r is the location on the cylinder wall where the stress values are measured for equations with the variable. At $r = r_i$ for equation 2.5, the highest hoop stress is produced. The maximum stress generated by the radial equations 2.6 occurs when $r = r_o$ [34].

Symbol	Definition
p_i	Internal pressure
p_o	External pressure
r_i	Internal radius of the cylinder
r_o	Outside radius of the cylinder
r	Radius to point of interest in tube or cylinder wall
σ_a	Axial stress
σ_h	Hoop stress
σ_r	Radial stress

Table 2.8: Symbols describing variables of the cylinder

2.2.2 Design requirements

Based on the knowledge gained thus far, preliminary design requirements can be set to lay the foundation for the concept phase. However, design requirements through the next chapter 2.3 can be updated as needed or added as the design process continues. The design requirements will be based on the knowledge gained from the *Empathize* phase, including shadowing, industry standards, interviews, and surveys. In addition to the knowledge gained in the theory section 2.2.1 as well.

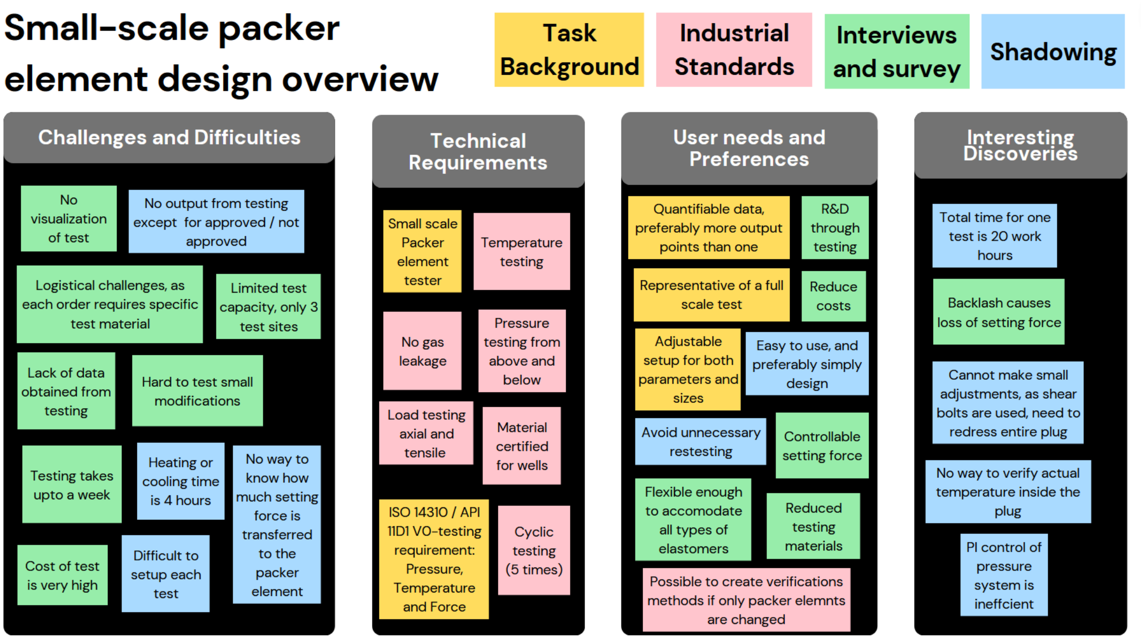


Figure 2.16: Overview of information gathered in the *empathize* phase

Figure 2.16 represents a clear and concise overview of the *Empathize* design thinking process. The diagram was designed to categorize the various stages of the *Empathize* phase, and then from each stage, whichever part shared a common theme with another part from a different stage was placed in the same column, representing the theme. This method aids in the identification of patterns and connections between various aspects of the empathize phase. The diagram effectively understands and implements the design thinking process by visually organizing the stages and their common themes.

The "Technical Requirements" column in figure 2.16 contains must-include design requirements, which are non-negotiable and serve as the baseline for each concept. The theory section 2.2.1 also contributes to these requirements, as the end-user prescribed them. These requirements serve as a framework for developing the concept, ensuring it meets the end-user's needs and expectations. The design can be optimized for optimal performance and functionality by incorporating theory knowledge. Thus, the design requirements (DR) are given in table 2.9, where each DR is labeled with an identification number (ID) and the requirement name and description.

Next, the DRs are prioritized from one to three. Priority number 1 represents a must-have, number 2 represents user needs and preferences, and number 3 represents extra unnecessary

ID	Requirement	Description
DR-1	Pressure containment	Test cell must be not leak any amount of gas for upto 20000 psi
DR-2	Temperature resistance	Test cell must be able to tolerate change in temperature and maintain its integrity for upto 300 °C
DR-3	Type of Material	Material that is used for nonmetal parts must be 34CrNiMo6 that is normalized
DR-4	Safety factor	The components of the test cell must be designed with a safety factor of 2 to meet HSE requirement
DR-5	Setting force	Able to deliver up to 40 ton of setting force
DR-6	Lock mechanism	Once the packer element is "set", a mechanism to lock the system, capable of resisting 20000 psi and setting force
DR-7	Adjustable setting force	Able to adjust setting force as desired during "setting" and after every test
DR-8	Compatible design	Test cell must have connectors that are compatible with existing pressurizing equipment and be able to fit inside the test bunker
DR-9	Modular test cell	Changeable inner diameter of the test cell to fit different sizes of packer elements or to test same elastomer at different casing sizes
DR-10	Easy to use	Design should be easy to use with little to no training
DR-11	Reduce cost	Fewer expendable components and simple design to avoid complex machining
DR-12	Easy to redress	Few to no components to change when preparing for retesting
DR-13	Faster heating	A quicker way to heat and cool down the test cell
DR-14	Data collection	More sensors measuring behavior of the packer element and the environment around

Table 2.9: Design requirements for test cell

features that would be nice to have. Furthermore, which parameter(s) are dependent on the DR is given, and which requirement group the DR belongs to is also described in table 2.10. The requirement groups are given in the list below:

- FR - Functional Requirement
- TR - Technical Requirement
- UR - Usability Requirement
- UE - User Experience (Needs) Requirement
- SF - Safety Requirement
- O - Other Requirement

ID	Priority	Design parameter	Type of requirement
DR-1	1	Sealing	FR and TR
DR-2	1	Mechanical properties	FR and TR
DR-3	1	Material properties	TR and SF
DR-4	1	Yield strength	SF and TR
DR-5	1	Force	FR and TR
DR-6	1	Yield strength	FR and SF
DR-7	2	Setting force	FR and UE
DR-8	1	Dimensioning and design	SF and UE
DR-9	2	Dimensioning and design	UR and UE
DR-10	2	User-friendly	UR, UE and SF
DR-11	3	Design	O
DR-12	3	User-friendly	UR and UE
DR-13	2	Efficient and temperature	FR and UR
DR-14	3	Sensory data; Temperature, setting force, pressure	UE, UR and O

Table 2.10: Design requirement priority and parameters

The DR listed out in tables 2.9 and 2.10, will be used to analyze the concepts and design in chapter 2.4. The concept and ideation phase begins next with the now set design requirements, which will be used to verify the presented ideas and ensure they meet the given DR. The end-user can be consulted to gather feedback and ensure the best idea suits their needs and desires. This process allows for brainstorming, generating creative ideas, and evaluating them against the design requirements. Consulting with the end-user ensures their perspectives are incorporated into the decision-making process, ultimately leading to a final concept that meets their needs and desires.

2.3 Ideation and concepts

The ideation chapter presents generated concepts, their features and flaws, and their degree of completion as a design requirement (DR). Feedback from concept reviews is given, leading to the chosen concept being chosen by the end-user, which is then designed in the prototyping chapter.

2.3.1 Concept 1

The sketch for Concept 1 can be seen in figure 2.17 where the packer element is placed inside of a test cell, which is in green color. The test cell has seals between the chamber to prevent gas leaks. The test cell is placed in a vertical orientation. The chamber is fixed onto the screw press machine platform with fixtures. The screw press is then operated by rotating the rotary lever, causing a linear downward motion of the piston attached to the threaded screw jack mechanism, thus compressing the packer element until a desired setting point. The setting point will equate to the desired setting force for the packer element. Once the desired setting force is reached, the operator can stop rotating the rotary lever. Since the screw press is a machine with a screw jack mechanism, it is self-locking, resisting any reaction force from the packer element and any pressure build-up. Thus, it is only necessary to ensure that the screw press threads are strong enough to tolerate static loads equivalent to the setting force and pressure force inside the test cell, multiplied by the safety factor. There is also a transmission bolt that helps translate the linear motion and also helps prevent any counter-rotation of the threaded area as an additional safety precaution. The screw press is fixed to the ground so that any reaction force or pressure force from the test cell ends up in the ground. The screw press must be large with modular piston heads to fit into the smallest packer element sizes. A load sensor is installed between the piston head and the rod that connects to it, which collects the load data and sends it to the operator, operating the screw press.

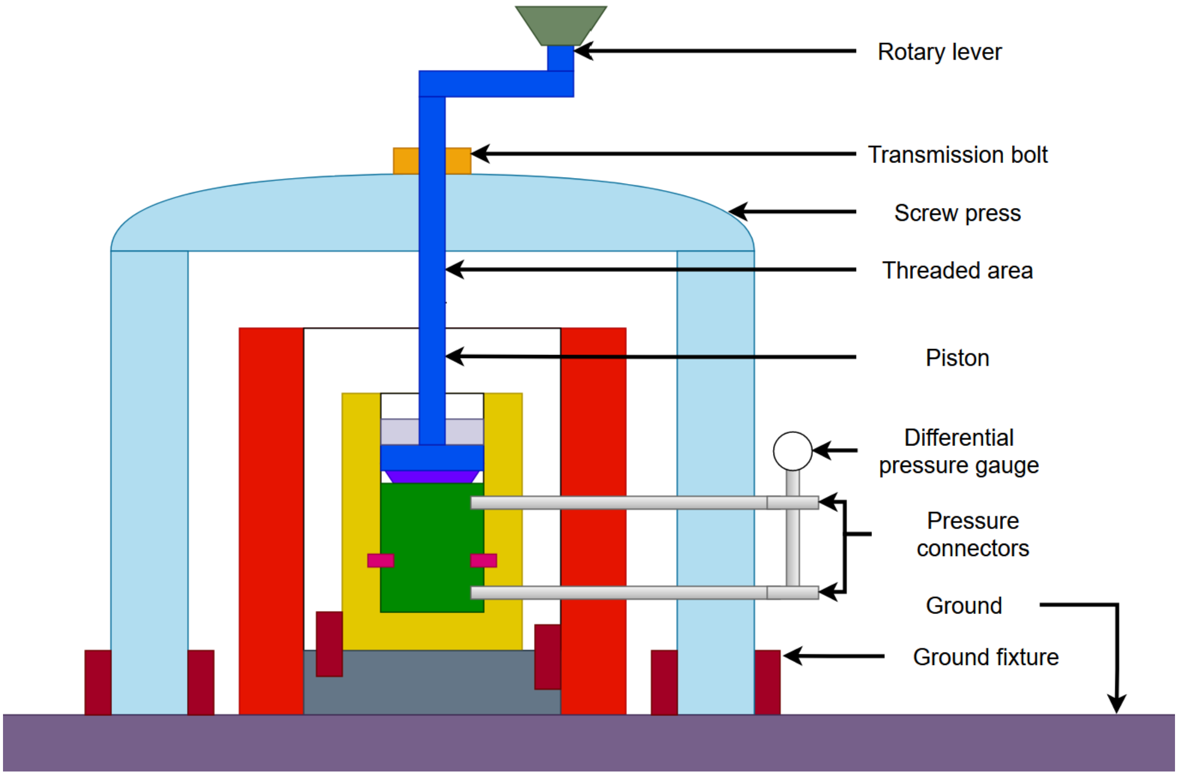


Figure 2.17: Concept 1 sketch

The heating oven will need to be custom designed around the test cell, the operating section of the screw press (the piston head), and a platform (the test cell chamber is placed upon). The oven will be hollow, thus open on the top and bottom. The bottom of the oven houses a base plate, on top of which the test cell chamber sits (and inside the chamber, the test cell). The top is left open for the piston to move through. In addition, the oven has a temperature sensor, which assists in preheating it before a test. The oven will have a fan that will help exchange heat through convection. To verify the actual temperature inside the test cell, a temperature sensor is placed around the neck of the screw jack piston to where it monitors the temperature as the piston moves into the test cell. Figure 2.18 illustrates the heating oven setup.

For pressurizing the test cell, two pressure lines go through the oven and the chamber

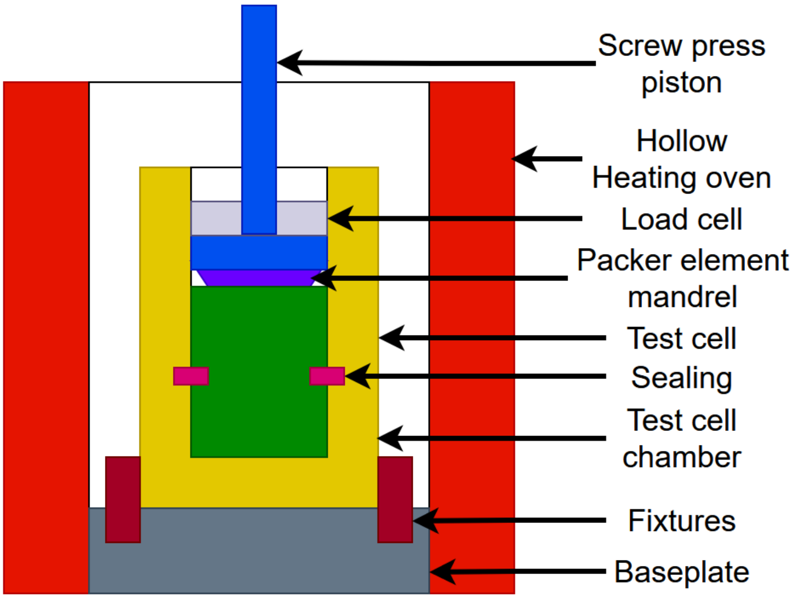


Figure 2.18: Concept 2 heating chamber sketch

wall connecting to the test cell through two holes designed for this specific purpose. One pressure line pressurizes the test cell, while the other monitors pressure difference and works as a pressure relief valve in case of a leak. On the outside, a differential pressure gauge (DPG) is connected to both pressure lines to collect data on pressure differences for the end-user. Between the test cell chamber and the test cell, there are seals ensuring no gas is leaked. The setup is vertical to create a closed force environment where the ground supports the entire setup. A more detailed sketch of the test cell is shown in figure 2.19.

Furthermore, the packer elements in the test cell are backed up by mock-up parts similar to those used in plugs to ensure little change in the design between the plug and the test setup. Each packer element will need its test cell and parts to support it. In addition, the piston head will not fit every size. The test cell has sealing O-rings on the bottom to ensure the gas does not leak from behind the packer backup.

2.3.1.1 Advantages and disadvantages

This section will discuss the concept's benefits and drawbacks as a review of which DRs it meets and which it does not. Any additional features or flaws in the concept will also be mentioned.

Table 2.11 is divided into four columns for DR validation of the concept: one for the ID of the DR in question; second, whether the DR is satisfied; third, whether it is not satisfied; and fourth, if it is unknown or yet to be determined. If the table has a checkmark in both the satisfied and unknown columns, it means that the concept has the potential to satisfy the DR, but more research is needed to confirm. It is too early in the concept phase to determine whether all DRs will be satisfied; however, it reflects on whether the concept and its features have the potential to meet the desired requirements, and that is what table 2.11 aims to

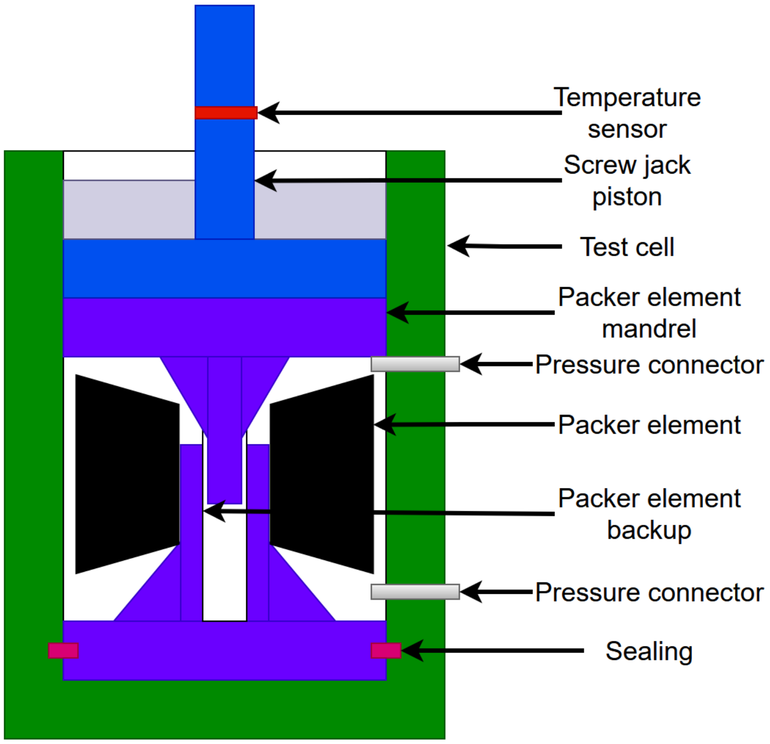


Figure 2.19: Concept 1 test cell sketch

capture. The table serves as a tool for evaluating the feasibility of the concept and identifying areas that require further investigation. This validation procedure aids in identifying gaps or areas for improvement for the concept, allowing for necessary adjustments before proceeding to the next development phase.

The potential features of Concept 1 seek to meet the majority of the DRs, as shown in table 2.11. The DR-9 was not chosen to fulfill this concept because a simple, easy-to-use design was prioritized over a complex design with many modular parts that could be difficult to assemble. Furthermore, a lock mechanism was deemed unnecessary for DR-6 because the screw press has self-locking features and thus provides adequate security.

The concept only partially meets DR-14 because it lacks a method of collecting data on the material properties of the packer element. This decision was made because it was deemed too dangerous for the gas to leak through the system if the test cell had many sensors that required holes to be placed inside the test cell, compromising the system's integrity. Additional features and flaws not necessarily associated with the DR are listed below, where **A** representing an advantage and **D** representing a disadvantage:

- **D**: There is no protective shield installed to prevent damage to the screw press
- **A**: The transmission nut can work as a secondary mechanism, locking the screw jack in place
- **A**: Simple design
- **D**: The vertical size of the screw jack could cause the test setup to not fit inside the low-ceiling bunkers used at Interwell's Trondheim facilities

ID	Satisfied	Not satisfied	Unknown
DR-1	✓		✓
DR-2	✓		
DR-3	✓		
DR-4			✓
DR-5	✓		
DR-6	✓	✓	
DR-7	✓		
DR-8	✓		
DR-9		✓	
DR-10			✓
DR-11		✓	
DR-12	✓		
DR-13			✓
DR-14	✓	✓	

Table 2.11: Design requirement validation for Concept 1

- **A**: All forces are in a closed loop system, going to ground
- **A**: Vertical testing orientation is representative of the orientation packer element's are placed in real operations
- **D**: Need a large screw press to produce 40 ton of setting force, might be unnecessary for a small packer element
- **D**: The temperature sensor is never on the inside of the test cell chamber where the packer element is thus the reading are still quite inaccurate
- **A**: DPG is a reliable way to check gas leak and measuring pressure loss compared to current test setup

2.3.2 Concept 2

Figure 2.20 depicts the sketch for Concept 2. Concept 2 is horizontal in orientation. As a result, the test setup is surrounded by a container to ensure that the forces generated by the screw jack and the test cell while operating are contained within the designated area. The container also protects against outside interference and accidents during the testing process. The container is secured to the ground with ground fixtures. The container is not tall, so it can easily fit into the Interwell facilities bunkers in Trondheim, which are about one meter in height but are horizontally spacious.

Gravity can cause the packer element to "set" at an angle during the setting operation because the setup is horizontal. An indentation is sketched out in the backup to prevent the packer element from tilting. As a result, the packer element and its components are concentric during the "setting" operation, as the screw jack compresses the packer element mandrel, causing the packer element backup to move into the indentation in the test cell wall.

A screw jack is used in Concept 2 to perform the packer element setting operation. The screw jack housing is screwed into the container's right wall. The motor and screw jack

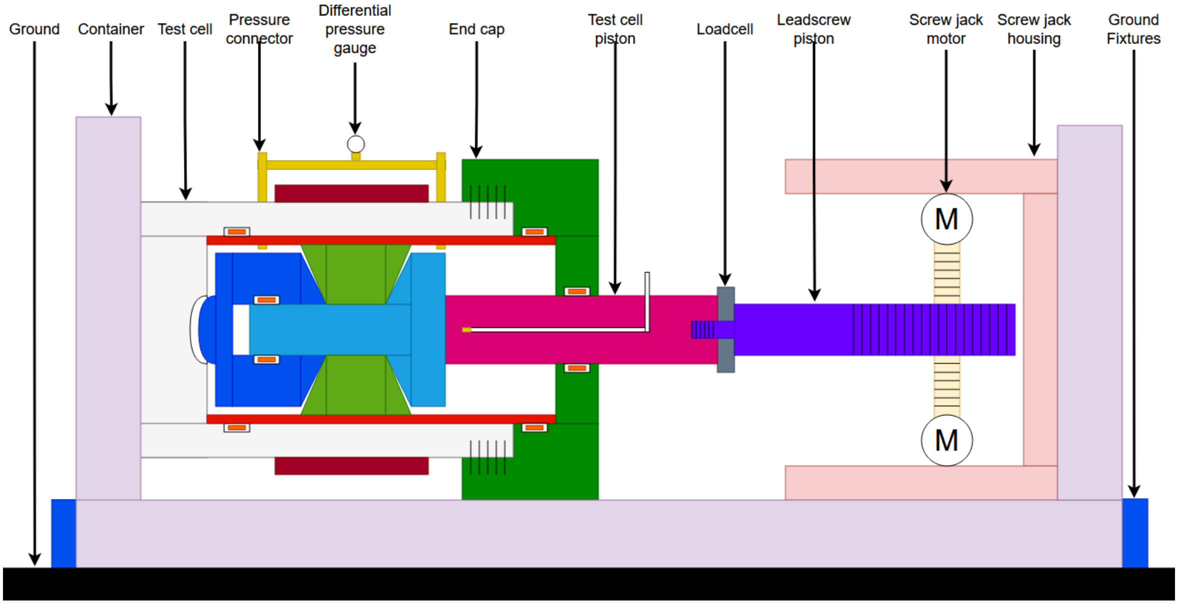


Figure 2.20: Concept 2 sketch

are housed within the screw jack housing. Because the exact shape or form of the screw jack will not be determined until the commercial screw jack acquired for this concept is decided, a simple illustrative design was completed. On the left end of the leadscrew piston is a threaded stud. The test cell piston can be attached to the threaded stud, allowing a load cell to fit between them and allowing the operator to measure the setting force. Additionally, depending on the size of the packer element, different test cell pistons can be attached to the threaded stud connection, allowing a screw jack (leadscrew) piston to be of a single size.

Concept 2 employs a heating tape to heat the packer element. The heating tape is flexible and can be easily removed and reattached. The blanket only covers the area around the test cell and heats it via conduction. As a result, no other materials are directly subjected to the heat, and the components around the test cell can be built with other materials if necessary. Furthermore, a temperature sensor is installed inside the test cell piston, which collects and transmits temperature data to the operator, allowing testing to begin once the temperature reaches the desired setting point.

A close-up sketch of a test cell is shown in 2.21. The illustration shows sleeves between the test cell and the packer element. The sleeves are meant to add modularity to the test cell. As a result, the test cell comes in a few different sizes, and depending on the size of the packer element, a corresponding sleeve can be inserted. As a result, fewer parts are required, and the sleeve is a simple cylinder that can be machined easily.

A close up test cell sketch is shown in figure 2.21. As seen in the sketch, there are sleeves that go in between the test cell and the packer element. The sleeves are suppose to give the test cell modularity. Such that the test cell comes in a specific size and the depending on which size a packer element needs to be tested, a corresponding sleeve can be inserted. Thus eliminating need for many parts, and the sleeve, is a simple cylinder that can be easily machined.

There are seals between the sleeve and the test cell to prevent air from escaping. The

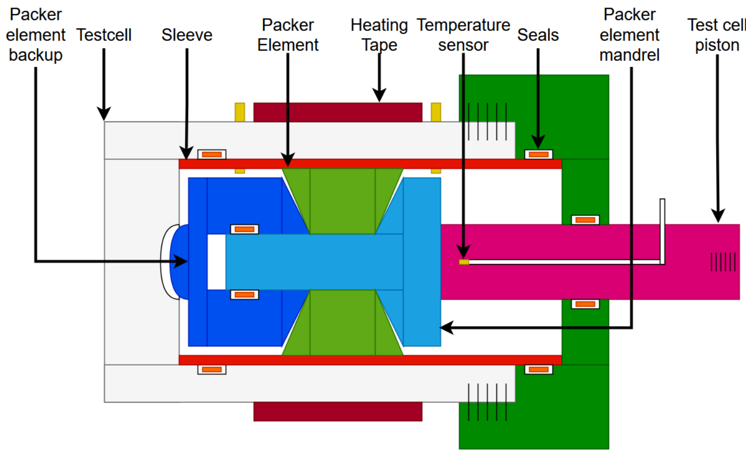


Figure 2.21: Concept 2 test cell sketch

pressure inlet and outlet are accessible through two holes in the test cell and sleeve. The inlet is above the backup packer element, which pressurizes the test cell. The outlet is above the packer element mandrel and serves as a pressure relief valve. The two pressure connectors are linked to a DPG, where any differential pressure change loss can be measured and transmitted to the operator.

The end cap attached to the test cell serves two functions: it holds and resists the pressure force that pushes the sleeves forward and seals the area to the right of the packer element. By resisting the pressure force from the sleeve, the end cap creates a closed loop for the force moving through the system. As a result of the force path, the entire container is in tension. However, if the container walls are dimensioned to be thick enough, the system stays intact and does not rely on any additional safety systems. Thus creating a safe and contained test setup. By sealing the area to the right of the packer element, if there is a leak, the leak rate can be determined by seeing how much the pressure increases as time goes on.

2.3.2.1 Advantages and disadvantages

This section will discuss the concept's benefits and drawbacks and review which DRs it potentially meets and which does not. Any additional features or flaws in the concept will also be discussed. Table 2.12 will, similarly to Concept 1, review all the DRs Concept 2 potentially satisfies, all the DRs it does not satisfy, and all the DRs that are unknown or yet to be determined. Following that, any advantages and disadvantages not covered by the DRs will be listed, like Concept 1, where **A** denotes "advantage" and **D** denotes "disadvantage."

Concept 2 meets the criteria set as priority one in table 2.10 as shown in table 2.12. If Concept 2 is chosen as the chosen design, all of the functional and technical requirements for the task can be potentially met.

Furthermore, the priority 2 DRs, DR-7, DR-9, and DR-14 have been met. A screw jack that can be easily adjusted after each test or during the "setting" phase makes DR-7 possible. The DR-9 was prioritized in this concept because the goal was to create a more complex

ID	Satisfied	Not satisfied	Unknown
DR-1	✓		✓
DR-2	✓		
DR-3	✓		
DR-4			✓
DR-5	✓		
DR-6	✓	✓	
DR-7	✓		
DR-8	✓		
DR-9	✓		
DR-10		✓	✓
DR-11	✓	✓	
DR-12	✓		
DR-13			✓
DR-14	✓	✓	

Table 2.12: Design requirement validation for Concept 2

concept that could provide a more comprehensive design to the end user. The disadvantage of having completed DR-9 is that DR-10 and DR-11 could not be completed.

The concept includes more complex machined components, such as the end cap, which threads onto the test cell and serves as a cover and seal for the internal components. The end cap must be designed to press against the sleeve resting in the test cell but not so tightly that it causes tension and potentially buckles the sleeve. The sleeve must also be machined such that it is short enough to prevent the end cap from threading completely onto the test cell. Because more components must be installed during the initial test setup, instructions on how to do so must be provided. Additionally, the heating tape might heat all the metal parts nearby, so it is vital to ensure the operators understand how to handle each component.

For DR-14, the situation is that Concept 2 has the same number of sensors as Concept 1. However, the temperature sensor is placed closer to the packer element to avoid inaccurate readings. Furthermore, because the temperature sensor is located inside a piston, it can be assumed that the time it takes the piston to heat all the way through on the inside to the desired temperature is approximately the same time it takes the packer element to heat up. However, because there are no sensors to measure the material properties of the packer elements, DR-14 is only considered partially complete.

Finally, a more direct heating system is installed for DR-13. However, the checkmark in table 2.12 is unknown because a heating tape via conduction is in the open air. There is also heat dissipation around the test cell and from the heating tape because it is not in an enclosed space. As a result, predicting whether or not the heating tape improves heating times is difficult. In addition, an insulation layer may be required.

For the features and flaws of Concept 2 that are not covered by table 2.12, a list is given below:

- **A**: Can easily fit into Interwell's horizontally (not vertically) spacious testing facilities
- **A**: Single screw jack piston is needed, as a test cell piston attaches onto it.

- **D**: There is not safety feature on top. What if it explodes above
- **D**: Heating from blanket might spread onto other components as well. Also no cooling function.
- **D**: If an additional piston is installed. Can it cause buckling at high loads?

2.3.3 Concept 3

Figure 2.22 shows a sketch of Concept 3. Compared to the other suggested concepts, Concept 3 is both more complex and less modular. Contrary to the other concepts, it offers collection of data variables through an infrared camera setup. Concept 3 also employs a hydraulic winch to achieve the required setting force. Since the test cell in Concept 3 only comes in one size, there must be a different size test cell for every different packer element.

Concept 3 uses a heated blanket to warm the packer element, much like Concept 2. Since the heating tape has no cooling function, cooling is accomplished by radiation caused by the ambient room temperature. Concept 3 employs a DPG to measure pressure loss, just like Concept 2 as well.

As previously mentioned, Concept 3 employs a winch to achieve the desired setting force. The winch is bought commercially. It is important to remember that winches that can pull 40 tons typically weigh 1.5 tons, but the weight of the spool is a crucial factor in the winch's weight and size. Here is one example of such a winch [20]. A winch usually comes with a load cell that measures the load the packer element is under during "setting" operation. Thus helping achieve the desired setting force [19].

In contrast to the other concepts, Concept 3 pulls to generate the setting force. It pulls on a specially designed packer element mandrel with a hook on one end while the other supports the packer element and packer element backup that rests on the mandrel. Pulling on the mandrel squeezes the packer element between the mandrel and the test cell. Brakes inside the winch lock the packer mandrel once the "setting" operation is complete. In addition, for safety, there is a nut lock on the outside of the test cell, resting on the threads of the packer element mandrel. This nut is tightened once the packer element is "set," so the test cell stays intact and unaffected if the winch fails suddenly. It can also be used to make minor adjustments of the setting force if necessary.

If the packer element fails during a test, the winch has a brake feature that should be able to prevent any damage to the winch function. In addition, the winch features something called a *holding load*. A *holding load* is a load capacity rating usually higher than the dynamic pull load capacity. This feature is activated when the winch is not pulling its load, allowing the brakes to engage. The *holding load* is a load capacity that allows the winch to hold any extra load added to the winch hook. This feature is useful for pressure testing, as pressure buildup can push on the packer element and mandrel, increasing tension on the winch wire. However, the winch's holding load feature ensures the entire system remains stationary as long as the pressure load does not overwhelm the capacity [19].

According to figure 2.23, the test cell in Concept 3 is fixed to the floor or wall with fixtures at three different locations, ensuring that the test cell is firmly fastened. Furthermore, seals are positioned between the test cell and the mandrel to stop gas leaks. A polymer-based transparent end cap is a feature of the test cell. The concept is that the end cap can be rated at a low pressure, such as 100 psi. It is adequate for the to record pressure loss and leakage

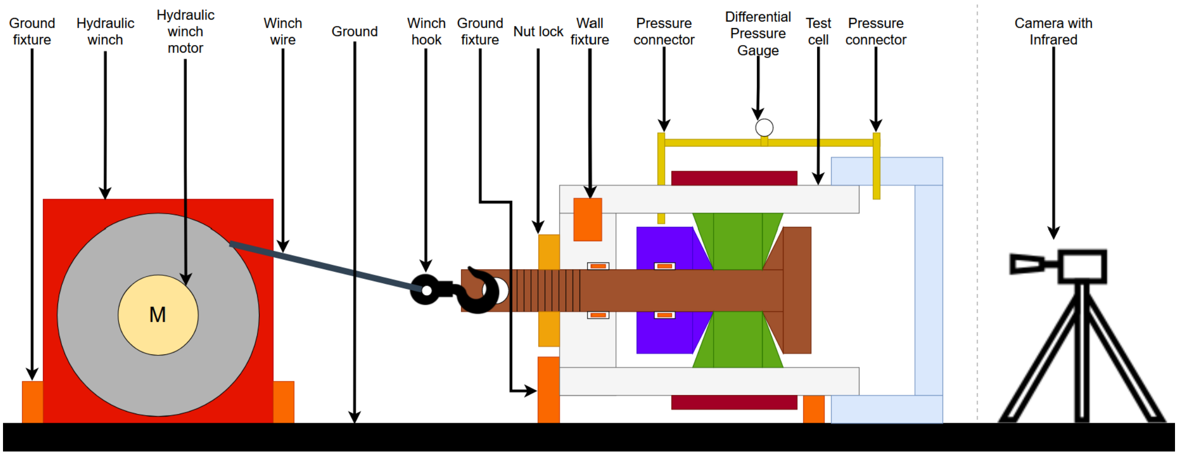


Figure 2.22: Concept 3 sketch

rate. If the gas leak exceeds that, the system will rapidly decompress because the end cap will blow off.

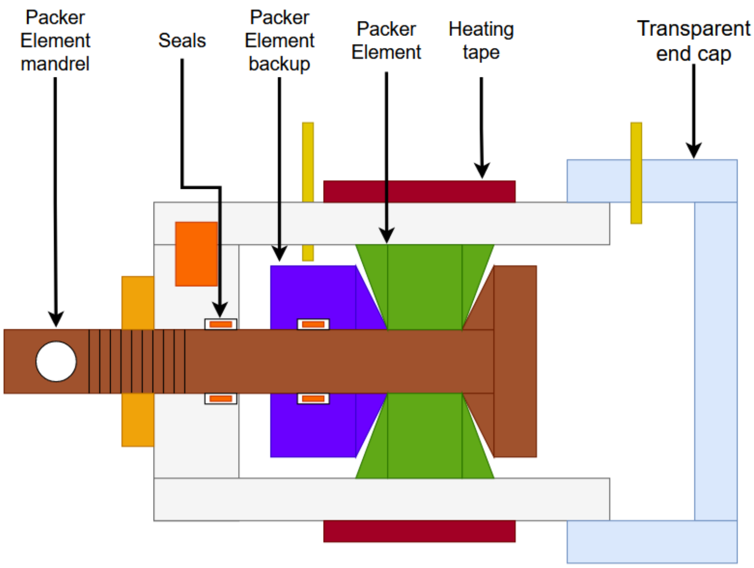


Figure 2.23: Concept 3 test cell sketch

The test cell is also made to have a transparent end cap because a camera will be mounted on the opposite side. During the setting operation and testing, the camera will be able to capture the packer element's shape, expansion, and decompression. The camera will also feature an infrared sensor to gauge the packer element's temperature. In order to determine how deeply the heat has penetrated the packer element during heating, the rate of temperature increase can be measured. As a result, it may be possible to develop a model that predicts the temperature inside the packer element much more accurately.

2.3.3.1 Advantages and disadvantages

This section will discuss Concept 3's benefits and drawbacks and review which DRs it potentially meets and which does not. Any additional features or flaws in the concept will also be discussed. Table 2.13 will, similarly to Concept 1 and 2, review all the DRs Concept 3 potentially satisfies, all the DRs it does not satisfy, and all the DRs that are unknown or yet to be determined. Following that, any advantages and disadvantages not covered by the DRs will be listed, like Concept 1, where **A** denotes "advantage" and **D** denotes "disadvantage."

ID	Satisfied	Not satisfied	Unknown
DR-1	✓		✓
DR-2	✓		
DR-3	✓		
DR-4			✓
DR-5	✓		
DR-6	✓		
DR-7	✓		
DR-8	✓		
DR-9		✓	
DR-10		✓	
DR-11		✓	
DR-12		✓	
DR-13			✓
DR-14	✓		

Table 2.13: Design requirement validation for Concept 3

DR-14, data collection, was the focus of Concept 3. to increase the number of sensors to collect as much data as possible. This concept used sensors such as a camera, an infrared sensor, a DPG, and a load cell sensor. Concept 3 can thus collect more data and meet the end user's needs. The design was more complicated due to conceptualizing a solution with one end open so that more data sensors could monitor that side, and as a result, DR-9 to DR-12 were not met. A straightforward and modular design was sacrificed in favor of this increased complexity to obtain more data.

Additionally, sealing a test cell with a mandrel through it is difficult. Another problem is that each packer element size necessitates a separate test cell because the test cell's hole must be the same size as the mandrel's, and the mandrel's dimensions must be compatible with the packer element.

All the requirements should be satisfied for DR-1 through DR-3 and DR-5 through DR-8. These are all the requirements with priority number 1 and were essential to a Concept meeting the task requirement. For DR-13, it is a similar situation as for Concept 2. It is unknown if a heating tape is an efficient way to heat the packer element. Moreover, the heating tape here as well does not provide any cooling. Finally, for DR-4, the safety factor requirement can only be satisfied in the design phase to dimension the components according to the safety factor requirement.

For the features and flaws of Concept 3 that are not covered by table 2.13, a list is given below:

- **D**: Safety concerns if the packer element fails. Can damage equipment, i.e. Camera and pressure connector and perhaps the DPG.
- **D**: Winch dimensions can be quite large. Winch example [20] is 3x3 in area and 2m in height.
- **D**: The angle of the wire, may cause the test cell to have a vertical force, which would put unnecessary strain on the test cell and cause additional wear and tear.
- **A**: Winch wire can be quite long, and be operated from a distance, thus keep the two system quite separate from each other, promoting safety.
- **A**: More sensors or data collection tools can be installed easily and monitored. Such as a tape can be installed after setting the elastomer and then letting go off the setting force, to see how it deflates.
- **A**: An easy access open end allows for exposing the packer element to acidic environments and collect relevant data of the elastomers behavior.

2.3.4 Comparison of concepts

A comparison study of the concepts is done in this section, which is presented to the end-user along with the concepts at a concept review. At the concept review, feedback was given, and the preferred concept by the end-user was chosen. The chosen concept was further refined based on the feedback received during the concept review.

Every concept was developed in light of the priority table 2.10. Whereas priority 1 DRs had to be satisfied in every case, the concepts tried to satisfy all other requirements but instead chose to focus on a single umbrella DR. In part because the priority 2 DRs frequently conflicted with one another. In order to still meet all the DRs of priority 1, for example, a more complex design must be imagined. Having more sensors also means being able to access more areas. As a result, it is challenging to meet the DRs necessary for a straightforward design. Similarly, it was challenging to come up with a straightforward, modular design because those two philosophies contradict one another. However, the main objective remained to try and meet all the DRs as the task required that.

A comparison study of the three concepts presented is shown in table 2.14. Where the properties of each of the concepts is presented. This helps inform the end-user on what to expect from each concept. In addition to presenting each concept to end-user individually.

The pressurizing system is the same one used in all concepts, as seen in table 2.14. Finding ideas and methods for designing a pressurizing system, heating system, and test cell would be too vast of a project. The pressurizing system also had the fewest problems because, as long as the test setup's connecting interface matched the pressure cables from the pneumatic pump, it would function as intended. Thus, retaining the existing solution for the pneumatic system simplified the project's overall product design process.

Furthermore, two concepts frequently share some of the properties of concepts. A shared property is the orientation and heating tape, as in Concepts 2 and 3. Both ideas use a heating tape to solve the heating problem, and their test setup is oriented horizontally. Concepts 1 and 2 also employ self-locking brakes and a method for applying the setting force. Their solutions are identical because both concepts feature a screw jack in their solution.

Properties	Concept 1	Concept 2	Concept 3
Force system	Jack	Jack	Winch
Force transmission	Screw	Screw	Hydraulic
Pressurizing system	Pneumatic air pump	Pneumatic air pump	Pneumatic air pump
Temperature	Heating oven	Heating tape	Heating tape
Heat transfer	Convection and Radiation	Conduction	Conduction
Brakes	Self-locking	Self-locking	Motor brakes
Orientation	Vertical	Horizontal	Horizontal

Table 2.14: Comparison of properties between the concepts

Some of the concepts were similar and were not further explored because only two solutions offered alternatives, which helped to streamline the design process. In chapter 4, the author details this choice's consequences.

2.3.4.1 Design requirement validation comparison

The next stage in understanding was comparing how many DR's did each of the concepts meet. In addition how did each of the concepts compare to the priority ranking as well, which is showcased in table 2.15.

ID	Priority	Concept 1	Concept 2	Concept 3
DR-1	1	✓	✓	✓
DR-2	1	✓	✓	✓
DR-3	1	✓	✓	✓
DR-4	1			
DR-5	1	✓	✓	✓
DR-6	1	✓	✓	✓
DR-7	2	✓	✓	✓
DR-8	1	✓	✓	✓
DR-9	2		✓	
DR-10	2			
DR-11	3		✓	
DR-12	3	✓	✓	
DR-13	2			
DR-14	3	✓	✓	✓
Total satisfied		9	11	8

Table 2.15: Design requirement comparison between the three concepts for all the satisfied conditions

As previously mentioned, all concepts met all priority 1 DRs, as shown in table 2.15. Therefore, it is more interesting to look at priority 2 and 3 DRs and see which concept tried to meet those to distinguish each. Concept 3 satisfies the fewest DRs, only satisfying 8 of them. One is priority 2, and only one satisfies priority 3.

Concept 1 has nine satisfied DRs, two of which are priority 3 and one is priority 2, making it the second-most successful concept, per the DR priority table 2.15. Furthermore, Concept 2 is the idea that has had the most success, as shown in table 2.15.

Moreover, Concept 2 is the idea that has had the most success, as seen in table 2.15. Two priority 2 DRs and a total of 11 DRs have been met by Concept 2. Additionally, Concept 2 has complied with three out of the three priority 3 DRs.

It is significant to note that choosing the best concept does not only depend on a comparison sheet of the number of DRs that could be satisfied. The end-user chooses which concept best satisfies their needs and wants, just as when the concepts are presented to them. As mentioned, whether some of the priority 2 DRs have been satisfied is still being determined. For instance, if the heating tape is more effective than the heating oven. Moreover, if any of the suggested heating options are more effective than currently available, the development of the concepts was based on priority 3 because it was difficult to determine with accuracy during the concept phase whether a DR of priority 2 is potentially met.

2.3.5 Feedback from end-user

All the information gathered thus far in his chapter 2.3 is now presented to the end-user for feedback on which concept they deem to be the one to focus on for the next stage of the design process. In addition, any feedback they may have is noted to edit and enhance the concept that needs to be designed. The end-user commented on the following for each of the concepts [5]:

Concept 1:

- Appreciate a vertical design
- Would need to custom make every components (including screw jack)
- Wish it could be modular, and suggested to add a solution for that.
- Seals between chamber and test cell are considered unnecessary
- Heating seems to be inefficient as it is in the open air
- Dislike the idea of having a very large screw jack for the smallest test cells.
- Needs seals in between the packer element mandrel and backup to ensure sealing does not escape that way
- temperature sensor can be placed closer/further down the piston
- Is it easy to take the packer backup out and in, and how much wiggle room is there.
- Likes the simple design

Concept 2:

- Greatly appreciates the modularity of the test cell
- It might not be easy to create an access point for the temperature sensors into the piston. Will need to me specially machined.
- Design which incorporates end caps, is similar to a full scale test system. Which comforts in the design being safe and reliable
- Container need to be custom designed. Suggested to add a hinged railing on top, to have a form of protection for above.

- Sealing the test cell for 20000 psi on the test cell piston side will require expensive seals that will be expensive to maintain. Suggesting to seal the right side of the test cell with a low pressure seals instead.
- A stud coming out of the indented test cell might be better, as when desire a intentional misalignment can be created to test the packer elements sealability if placed misaligned
- Worried that the test cell will be designed to accommodate the biggest packer elements, and the sleeves needed for the smallest packer elements will be unnecessarily big.

Concept 3:

- Likes the idea of a winch, however it is too big for the facility
- Like the idea of having a camera with infrared vision
- Worried about sealing between the packer element mandrel and test cell.
- Heating tape may be inefficient without insulation
- There is costly danger to having a weak end cap. It can blow out and destroy the camera.
- Do want a modular system, which this concept is not
- Similar to Concept 2, seals on a dynamic system for very high pressures have many risk factors and are very expensive to use and maintain

The end user thought Concept 2 best met their needs because it uses modularity, which they thought would be essential for their future as they hoped and sought to test many different packer element sizes rather than just one. They also appreciated the potential financial savings that could be realized by utilizing a modular system, as it would eliminate the need for purchasing multiple specialized equipment's for each packer size[5].

The dynamic seal for pressures up to 20,000 psi seemed quite expensive to obtain, according to the end-user for Concept 3, because it would require monitoring to prevent damages from rapid gas decompression. Additionally, Concept 1 did not address most of their desired features, Concept 2 did. The end-user also mentions that they have previously tried to develop a Concept 1 type of design. However, the data from it was lacking, and the setup was not modular, making it difficult to develop studies on the behavior of packer elements of various sizes. Thus, Concept 2 was selected by the end user [5].

2.4 Design and Prototyping

Concept 2 chosen by the end-user will be designed and dimensioned in this sub chapter. This sub chapter will address design simplification strategy, dimensioning of the test cell and its components, a preliminary design of a the entire system and finally a design review, which will solicit end-user input on the design thus far.

2.4.1 Design simplification strategy

This subsection will be further divided into "Design order" and "Casing size division," where "Design order" will establish the order in which the design process for Concept 2 will start. Additionally, different configurations of the test cell will be established for the "Casing size division" to accommodate the full range of casing sizes specified by API in appendix C.

2.4.1.1 Design order

In order to dimension the each component of Concept 2, a design order needs to be established. As seen in figure 2.24, a design order has been illustrated. Where "casing size" is the only independent variable. Casing sizes are sizes of well casing that are predetermined by the API. And companies who bore out the wells, bore out them to the specified casing size that is standardized by the API.

Interwell bases the design of its plugs and packer components on the API-provided casing size sheet, which is available in appendixC. The packer backup and mandrel are intended to support the packer element, support the well, and stop air leakage between the mandrel and the packer element. The mandrel and packer backup are designed to stop air leakage between the mandrel and the packer element, support the well, and support the packer element. The packer element mandrel's geometry is created with a flat surface facing the test cell piston to guarantee smooth contact. The backup geometry of the packer element has been altered to include an indentation to support the centralizing property of the test cell. The remaining geometry is a cutout of the original packer mandrel and backup used in plugs.

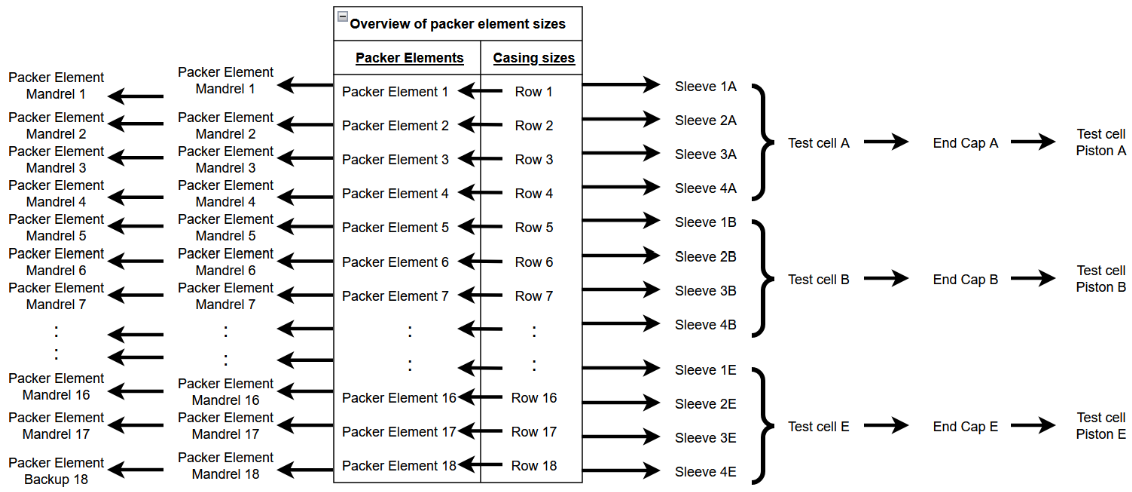


Figure 2.24: Design Order of Concept 2 components

The size of the test cell and the rest of the system must be determined based on the casing size (packer element size) and corresponding sleeve. The end-user expressed concern that the test cell would be designed to accommodate all casing sizes, leading to over-dimensioned components. To address this, multiple different configurations of test cells were proposed, accommodating a range of casing sizes instead of all of them. Each test cell covered several casing sizes with corresponding sleeves to maintain scalability within that range. As there are multiple different test cell sizes, multiple end caps must be provided to accommodate those sizes, and pistons must fit inside the end cap's opening.

When designing the heating tape, screw jack, and container for the testing setup, it is crucial to consider the following factors: the heating tape must withstand high temperatures and have adjustable settings for precise temperature control. Flexible industrial heating tapes, such as this one [28], are easy to wrap around any object, making them desirable. The screw jack should be sturdy and capable of exerting sufficient force to meet the desired criteria. The design segment requires fixtures to fasten the screw jack to the container, a threaded stud for the test cell piston, and a load cell to thread onto it. The container must have a secure fastening mechanism, strong walls, and a safety factor 2 to prevent potential fractures. The container is the final item to be designed, but preliminary designs can be designed to identify potential challenges or limitations in the testing system. Thus allowing for necessary adjustments before the final design is implemented.

2.4.1.2 Casing size division

The design order for Concept 2 is now established, and it is also established that the test cell will come in multiple configurations. However, it needs to be established how the API Casing size table is divided up, so how much of the range is covered by each configuration of the test cell, and thus how many configurations of the test cells are needed.

To establish this, the author needed to establish thick are the test cell walls for the biggest casing sizes and how thick are the walls needed for the smallest casing sizes. To do this, there were two ways, one was to use the strength calculation sheet obtained by Interwell, as previously mentioned. The other was to use the equations obtained in chapter 2.2, and create a model. It was chosen to do both, this way the theory could be verified and compared to the strength calculation sheet.

Strength calculation sheet

The results of the strength calculation are shown in Figure 2.25. Since the figure can be difficult to read, it is also posted in appendix G As seen in the figure, different test cell sizes were tested to see how they would divide. The author chose four different test cell sizes arbitrarily. In figure 2.25, the inner diameter of a casing size was entered under "d." The test cell was pressurized from the inside, so the pressure direction was set to "Pressure below," and the pressure was set to "Inside." As a result, the test cell was placed in tension, and the load direction was set to "Tension." The material was also chosen per DR-3, and Interwell employees changed the material's properties to reflect the impact of 300 °C on the material.

ItemID (Doc. No.)	Item Name (Title)	D [mm]	Tol min D Std List	Tol min D Custom [mm]	d [mm]	Tol max d Std List	Tol max d Custom [mm]	Pressure Direction	Pressure	Load direction	Situation	Material	Temp [°C]	sf low temp	sf high temp
Test_small_case_1		140	Default		76	Default		Pressure Below	Inside	Tension	Case_small 1	SS 2541 (800 MPa)	300°C	2,35	2,04
Test_small_case_2		165	Default		90,1	Default		Pressure Below	Inside	Tension	Case_small 2	SS 2541 (800 MPa)	300°C	2,34	2,03
Test_small_case_3		205	Default		112	Default		Pressure Below	Inside	Tension	Case_small 3	SS 2541 (800 MPa)	300°C	2,34	2,04
Test_small_case_4		225	Default		124,3	Default		Pressure Below	Inside	Tension	Case_small_4	SS 2541 (800 MPa)	300°C	2,31	2,01
Test_medium_case_1		230	Default		125,7	Default		Pressure Below	Inside	Tension	Case_medium 1	SS 2541 (800 MPa)	300°C	2,34	2,03
Test_medium_case_2		260	Default		144,1	Default		Pressure Below	Inside	Tension	Case_medium 2	SS 2541 (800 MPa)	300°C	2,31	2,01
Test_medium_case_3		275	Default		153,6	Default		Pressure Below	Inside	Tension	Case_medium 3	SS 2541 (800 MPa)	300°C	2,29	2,00
Test_medium_case_4		295	Default		164	Default		Pressure Below	Inside	Tension	Case_medium 4	SS 2541 (800 MPa)	300°C	2,30	2,00
Test_large_case_1		315	Default		174,6	Default		Pressure Below	Inside	Tension	Case_large 1	SS 2541 (800 MPa)	300°C	2,31	2,01
Test_large_case_2		395	Default		219,1	Default		Pressure Below	Inside	Tension	Case_large 2	SS 2541 (800 MPa)	300°C	2,31	2,01
Test_large_case_3		405	Default		224,4	Default		Pressure Below	Inside	Tension	Case_large 3	SS 2541 (800 MPa)	300°C	2,31	2,01
Test_huge_case_1		560	Default		252,7	Default		Pressure Below	Inside	Tension	Case_large 1	SS 2541 (800 MPa)	300°C	2,66	2,31
Test_huge_case_2		570	Default		311,8	Default		Pressure Below	Inside	Tension	Case_large 2	SS 2541 (800 MPa)	300°C	2,33	2,03
Test_huge_case_3		575	Default		317,9	Default		Pressure Below	Inside	Tension	Case_large 3	SS 2541 (800 MPa)	300°C	2,31	2,01

Figure 2.25: Dimensioning test cell from strength calculation sheet [4]

The strength calculation sheet's column "D" was used to generate the safety factor (SF) displayed on the far right in figure 2.25. Because it explained the high-temperature input under the "Temp" tab, the SF with "high temp" was used as the dimensioning variable. Consequently, understanding that 2 is the SF needed to comply with DR-4. The "D" tab was filled out with various numbers until the "high temp" SF tab showed an SF of 2. The test cell cylinder must be thick enough to withstand the forces applied, as indicated by the "D" and "d" in the diagram, representing the cylinder's inner and outer diameters, respectively. Table 2.16 represents the arbitrarily chosen sizes for the four configuration for the test cell.

Test cell configuration	Size	Inner Diameter (mm)	Outer Diameter (mm)
A	Small	112	205
B	Medium	164	295
C	Large	224.4	405
D	Huge	317.9	575

Table 2.16: Proposed sizes for test cell

A quick calculation can be performed to determine whether the test cell cylinders are thought of as having thick or thin walls based on the size obtained from table 2.16. Table 2.17 displays the calculation and classification of the type of cylinder from table 2.16. The calculation in table 2.17 compares the diameter of the test cell cylinders with a threshold value of 20, as mentioned in the theory section of chapter 2.2. If the diameter is above the threshold, the cylinders are classified as having thick walls. Conversely, if the diameter is below the threshold, they are classified as having thin walls. This classification helps in determining the structural properties of the test cell cylinders.

Test cell configuration name	Ratio	Type of cylinder
Small	4.45	Thick-walled
Medium	4.48	Thick-walled
Large	4.49	Thick-walled
Huge	4.47	Thick-walled

Table 2.17: Checking the diameter divided by thickness ratio of test cell

As expected, all the test cell cylinders calculated by the strength calculation sheet are thick-walled.

Python

The equations from chapter 2.2 were used to determine the thickness of the test cell configurations. Since it can be inferred from the strength calculation sheet that all test cell configurations should have thick walls, only the thick-walled cylinder equations from the theory section of chapter 2.2 will be used. Using Microsoft's Virtual Studio (VS) code editor, the equations were converted into Python code. Appendix F contains the snippet of code. The entire range of casing sizes provided by API in appendix C were used as input when Lame's equations were implemented to calculate the outer diameter.

The maximum stress value for radial stress is provided by the variable textitr when $r = r_o$. However, it produced equation 2.10 when included in Lame's radial stress equation. Additionally, the result is the same if the variable r is set to equal r_i. As a result, the thickness predicted by the radial stress equation was nonexistent. As a result, the radial stress result is discarded and left out of the Python code.

$$r_o = r_i \tag{2.10}$$

The outer diameter values for axial and hoop stress were greater than the inner diameter values. However, the hoop stress equation's numbers will produce a larger outer diameter value than the axial stress equation because the hoop stress value is greater. This suggests that the hoop stress more significantly impacts the overall size of the structure. Figure 2.26 displays the outcomes.

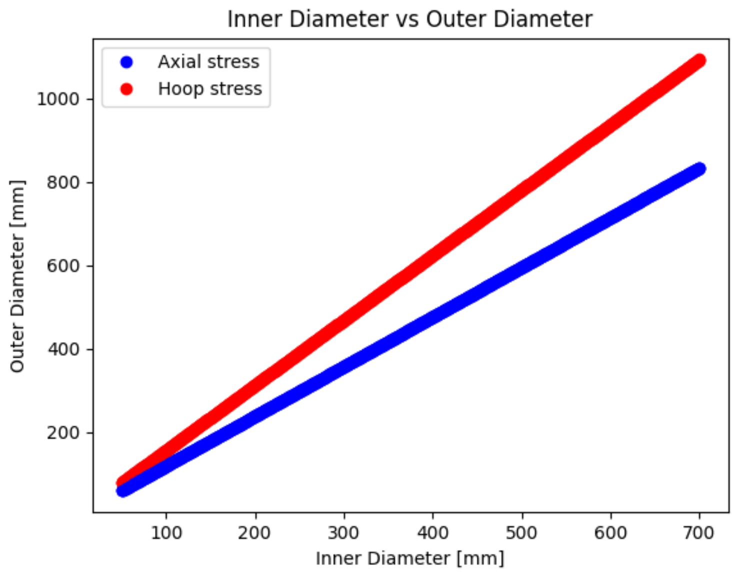


Figure 2.26: Python graph representing the thickness needed for a cylindrical pressure vessel

When using Lame's equations, which provide a streamlined model for resolving the thick-walled cylinder problem, a few presumptions are made. In order to extrapolate the material's yield strength for a temperature of 300 °C, a few other assumptions were also made. The following presumptions are made:

- The decrease in yield strength is linear to increase in temperature
- The material is isotropic
- Cylinder is made of homogeneous material
- Radial and hoop stress are
- A linear elastic behavior for the material
- Lame's equation are valid high stress and strains
- Temperature change does not affect density
- Every component is cylindrical in shape

As expected, in figure 2.26, it is evident that the test cell's required outer diameter increases as the inner diameter gets larger. The hoop stress equation sets the diameter to be 30% larger than the axial stress equation at each inner diameter step.

Comparison of results

A brief comparison is conducted between the Python model and the strength calculation sheet. Each of the four test cell configurations were printed out on the Python model, to see how much the two results differed. Figure 2.27, showcases the inner and outer diameters that were concluded by the strength calculation sheet in table 2.17.

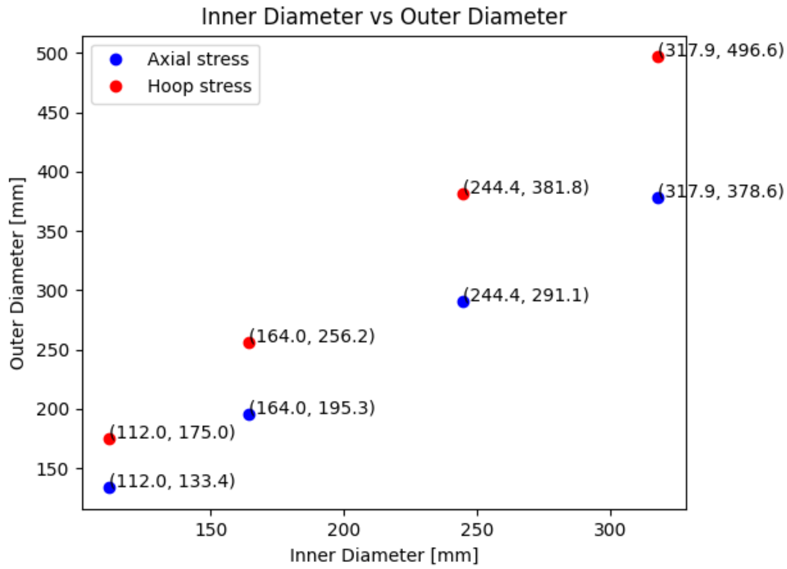


Figure 2.27: Python graph representing the thickness needed for a cylindrical pressure vessel

For configuration *small* from table 2.17, the outer diameter is calculated to be 205 mm. For the same configuration Lame's equations suggest that the necessary thickness should result into an outer diameter of 175 mm. Which is 15% smaller. And this trend continues into the bigger configurations as the graph is linear.

The Python solution is invalid because Lame's equations do not hold true under conditions of high stress or strain [9]. Due to this restriction, the Python solution cannot accurately determine the test cell diameter. Instead, use the solutions from the strength calculation sheet, which were created using more sophisticated mathematical models that account for high stress and strain conditions and temperature variations [5].

2.4.1.3 Choosing a single Packer Element

Choosing a single packer element to serve as the model for the remainder of the design process is the last step in the design simplification strategy. Limiting the test cell's size and configuration allows this project to concentrate on creating a working prototype rather than creating multiple prototypes simultaneously for various sizes and configurations.

The smallest configuration, "A" or "small" test cell, was selected in consultation with the end-user [5]. The 5" API casing size is the one that has been selected as the packer element size to pursue. The HNBR packer element 385-500 is the product's brand name. The packer element is the largest size packer element that fits into test cell configuration "A".

In addition, because of the chosen packer element type, data was collected on its dimension and supporting components, which are listed in table 2.18. These dimensions will help determine the length of the test cell and sleeve.

	Packer Element	Packer Element Mandrel	Packer Element Backup
Length (mm)	70	70+30=100	20+37+13+30 = 100
Inner Diameter (mm)	74.6	73.8	73.8
Outer Diameter for run (mm)	107	106.2	106.2
Outer Diameter for set (mm)	124.3	106.2	106.2

Table 2.18: Packer Element and its support components dimensions

The elastomer is described in table 2.18 as its supporting element. The mandrel must be at least 70 mm long because it is 70 mm long at "run". Furthermore, it must develop into an isosceles trapezoid. In order to complete the transformation from a pipe to a trapezoid, a 30 mm (arbitrary) length is added. The prerequisite for the packer backup is the exact opposite; it must be able to accept the mandrel. The mandrel must be seated inside the backup when the elastomer is in the "run" stage. Thus, 20 mm are added to its depth as a result.

The packer element's 37 mm stroke is then added, increasing the depth of the element further. 13 more millimeters are added for redundancy, and then 30 more millimeters are added so the backup has a plate where an indent can be made. The components' outer and inner diameters were given in their intended configurations and cannot be changed. Given that it only influences the components, the inner diameter is not important for the design of the test setup.

2.4.2 Dimensioning the components

This section will cover the dimensioning of the rest of the component based on the information gathered in the previous section. To categorize and structure the description of the design process for each of the parts, this section is further divided into each part as a sub section of this section. The goal of this section is to design the following components:

- Sleeve
- Test cell
- End-cap
- Test cell piston
- Container (initial design)

The test cell's back plate thickness, the test cell's thread and the end cap's thread, are all evaluated using the strength calculation sheet once more in order to dimension the test cell and the end cap. This guarantees that the test cell and end cap are made with the right amount of strength to withstand the necessary loads and pressures during testing.

Figure 2.28 shows that a 56 mm thick back plate is necessary for configuration "A" to withstand the forces and still meet DR-4's required safety factor of 2. The thread length and pitch on the test cell and end cap must match. Thus, whichever component has the longest

ItemID (Doc. No.)	Item Name (Title)	D [mm]	t [mm]	Material	Temp [°C]	sf low temp	sf high temp
Casing_small		205	56	SS 2541 (800 MPa)	300°C	2,31	2,01
Casing_medium		295	81	SS 2541 (800 MPa)	300°C	2,33	2,03
Casing_large		405	111	SS 2541 (800 MPa)	300°C	2,32	2,02
Casing_huge		575	157	SS 2541 (800 MPa)	300°C	2,31	2,01

Figure 2.28: Dimensioning test cell's back plate with the strength calculation sheet [4]

ItemID (Doc. No.)	Item Name (Title)	D_{thread} [mm]	Pitch[mm]	Thread position	Thread type	Tolerance Class	L [mm]	Pressure Direction	Situation	Material	Temp [°C]
Casing_small		205	6	External	Trapeziodal	Default	19	Pressure Below	Case_small 3	SS 2541 (800 MPa)	300°C
Casing_medium		295	6	External	Trapeziodal	Default	27	Pressure Below	Case_medium 4	SS 2541 (800 MPa)	300°C
Casing_large		405	6	External	Trapeziodal	Default	37	Pressure Below	Case_large 3	SS 2541 (800 MPa)	300°C
Casing_huge		575	6	External	Trapeziodal	Default	52	Pressure Below	Case_huge 3	SS 2541 (800 MPa)	300°C
End_cap_small		205	6	Internal	Trapeziodal	Default	19	Pressure Below	Case_small 3	SS 2541 (800 MPa)	300°C
End_cap_medium		295	6	Internal	Trapeziodal	Default	27	Pressure Below	Case_medium 4	SS 2541 (800 MPa)	300°C
End_cap_large		405	6	Internal	Trapeziodal	Default	37	Pressure Below	Case_large 3	SS 2541 (800 MPa)	300°C
End_cap_huge		575	6	External	Trapeziodal	Default	52	Pressure Below	Case_huge 3	SS 2541 (800 MPa)	300°C

Figure 2.29: Dimensioning test cell and end cap's threads with the strength calculation sheet [4]

thread length is the dimensioning one for the other. However, according to figure 2.29, the end cap and the test cell have the same thread length of 19 when the pitch is 6 mm. The pitch size was chosen arbitrarily (typical value). Having a long enough thread and deep enough grooves ensures that the threaded components can securely engage with each other, providing the necessary strength and stability to withstand the forces and meet the safety factor requirement. Also, proper thread engagement helps distribute the load evenly across the threads, reducing the risk of stripping or failure under stress.

2.4.2.1 Sleeve

The sleeve is the component with the simplest design requirements because it only uses three dimensions: ID, OD, and length. The sleeve created for Elastomer 386-500 is unique to the API casing size of the material. However, the length and OD of each of its sister sleeves (all associated with test cell configuration A) are the same. Depending on the size of the packer element and the corresponding API, they have different IDs. Since sleeve A is the largest sleeve, all sister sleeves of this sleeve are below 5" in casing size. Table 2.19, lists the sleeve's dimensions.

Length (mm)	100+80+20
ID (mm)	124.3
OD (mm)	127

Table 2.19: Dimensions of sleeve

The length of the sleeve for this particular design is the packer mandrel plus 80 mm from the depth of the packer backup in "run" position. In addition 20 mm were added for redundancy of space. The ID is determined by the elastomer OD in the "set" position. And the OD of the sleeve,is based on the standard sizes given in API casing size in appendix C. Based on these configurations a CAD model was drawn of the sleeve as shown in figure 2.30.

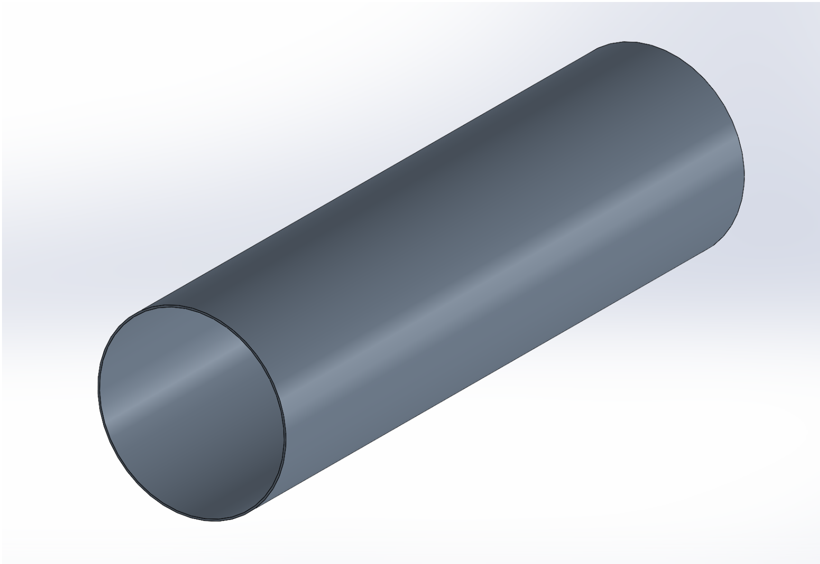


Figure 2.30: Computer Aided-Design (CAD) model of the sleeve

2.4.2.2 Test cell

The test cell's design is based upon he following factors: sleeve's length, sleeve's OD, back plate depth, length of thread that connects to the end cap, pitch of the thread. All the dimensions for the aforementioned parameters is given in table 2.20

Length (mm)	200+56+4
ID (mm)	127
OD (mm)	230
Threaded length (mm)	19
Thread pitch (mm)	6

Table 2.20: Dimensions of test cell

The dimensions from table 2.20, results in a preliminary CAD model as shown in figure 2.31

2.4.2.3 End-cap

The design of the test cell influences the design of the end cap. The outer diameter of the test cells determines the end cap's inner diameter. Additionally, the forces must be assumed to move into the end cap and through the sleeve. Thus, the end cap must be dimensioned accordingly. A strength calculation sheet analysis of the end cap can be done by inputting inner diameter and maximum pressure force values.Thus figure 2.32 gives out the findings.

The end cap has two inner diameters, one for the test cell and the other for the piston, and the latter needs to be determined. The smallest casing size diameter for configuration

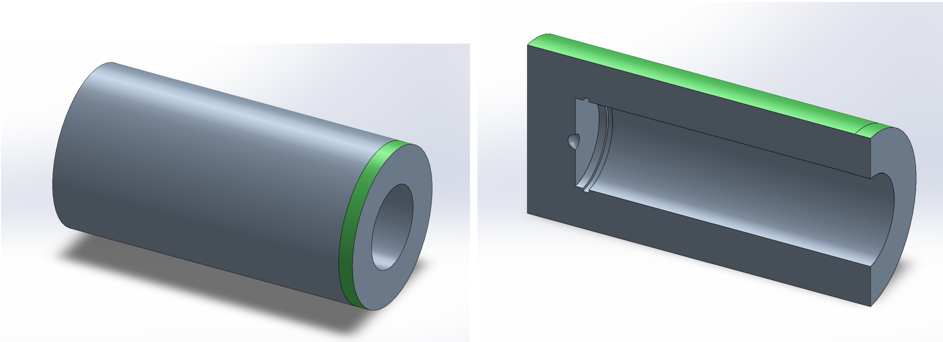


Figure 2.31: Multiple CAD views of test cell

ItemID (Doc. No.)	Item Name (Title)	D [mm]	t [mm]	Material	Temp [°C]	sf low temp	sf high temp
end_cap_small		410	112	SS 2541 (800 MPa)	300°C	2.31	2.01

. No.	ItemID (Doc. No.)	D [mm]	Tol min D Std List	Tol min D Custom [mm]	d [mm]	Tol max d Std List	Tol max d Custom [mm]	Pressure Direction	Pressure	Load direction	Situation	Material	Temp [°C]	sf low temp	sf high temp
end_cap_small		410	Default		230	Default		Pressure Below	Inside	Tension	end_cap_small	SS 2541 (800 MPa)	300°C	2.29	1.99

Figure 2.32: Strength calculation sheet for end cap

"A" or "small" is the piston diameter of the end cap. As a result, all packer element sizes, from the smallest casing size (end cap piston diameter) to the currently designed size, can fit within the piston opening. The end-cap dimensioning table 2.21 contains values from the tables 2.32 and the API casing table.

Length (mm)	19+112
ID test cell (mm)	230
ID piston (mm)	100
OD (mm)	410
Threaded length (mm)	19
Thread pitch (mm)	6

Table 2.21: Dimensions of test cell

From the table a preliminary design emerged which a CAD model has been made of, seen in figure 2.33

2.4.2.4 Test cell piston

The piston design is dependent on four variables; one is the end cap piston ID, which has been obtained; two is the temperature sensor dimensions; three is the screw jack piston stud dimensions and, four is the length of the piston. Neither the information regarding the temperature sensor or the screw jack piston is obtainable as neither product for those two solution shave been decided upon. For the preliminary design a a mock up of the thread size for he screw jack piston is drawn in a CAD model, and for now the temperature sensor design is ignored. Table 2.22 show cases the dimensions for the test cell piston.

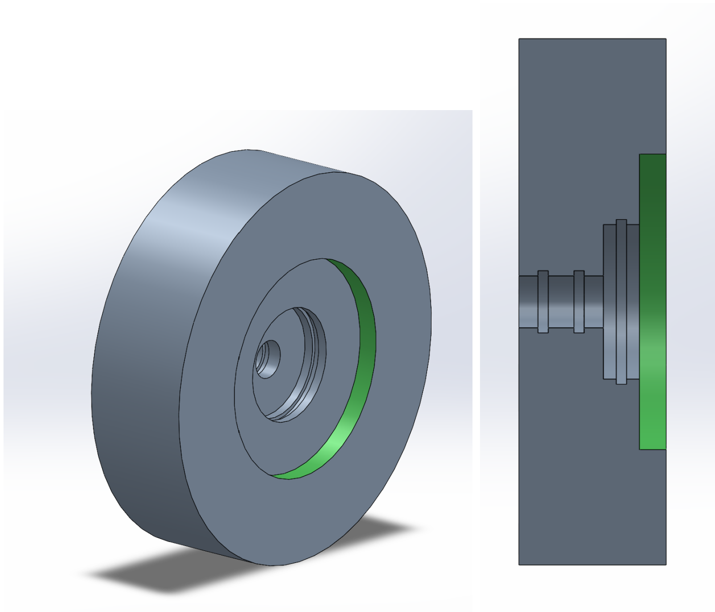


Figure 2.33: CAD model of End Cap

Length (mm)	50 + 112 + 50 = 212
ID (mm)	0
OD (mm)	100
Stud length opening (mm)	10 (assumed)
Stud size	Unknown

Table 2.22: Dimensions of test cell

The length of the the piston stud depends on the stroke length, which was 50 mm (including safety distance), plug the width of the end-cap which the piston must pass through, so 112 mm, and finally another 50 mm for redundant space, either for the stud from the piston or other space considerations that might not have been accounted for. The CAD model of the test cell piston is displayed in figure 2.34.

2.4.2.5 Container

A complete mock-up was made for the container, as the container lacks many of the dimensions needed to be designed. The mock-up allowed to verify the container's purpose and how the other components might fit into it. The mock up of the container is shown in figure

There are rests on the sides of the model, as shown in figure 2.35. It was proposed to be used as a placement for the test cell. Raising it from the ground can help the test cell be in a straight line with the jack screw piston, thus avoiding misalignment. The slits were created so the test cell could easily move back and forth as needed. However, if this system is implemented, a longer test cell piston must be designed, which could affect its mechanical properties, as it might weaken the long rod, causing it to buckle. Nevertheless, more study needs to be done if the proposed solution goes onto the final design.

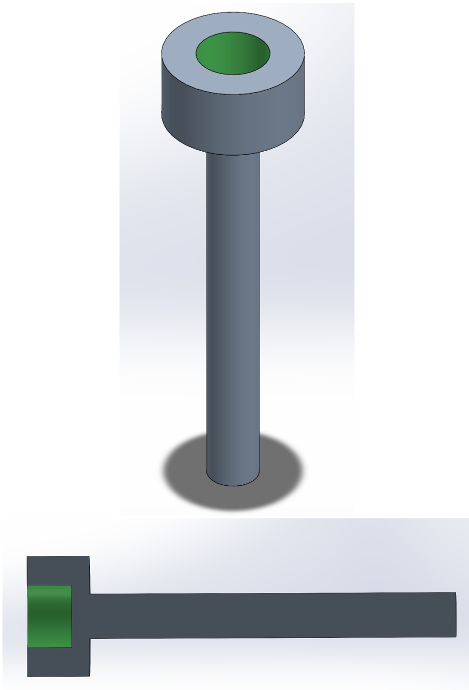


Figure 2.34: CAD model of test cell piston

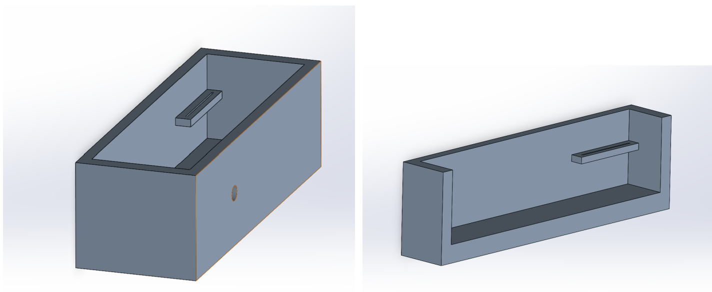


Figure 2.35: CAD mock up of the container

2.4.3 Other modules

This section briefly covers the other modules in the proposed design, namely the heating tape, the sealing system and the screw jack.

2.4.3.1 Heating tape

There is one heating tape commercially available here [28] as mentioned before. The properties of this heating tape are listed in table .

The heating tape brings with itself inherent flexibility. It is mere matter of choice. And this heating tape maybe as good as any. Regardless, as the design has been chosen now, if there is to be done a comparison study on multiple types of heating tapes from different manufacturers, more information needs to be acquired. And most manufacturers online do not publish info about their industrial high temperature products. Instead they asked to be

Temperature range	0-450 °C
Temperature control	Yes
Length	upto 10 m
Supply	230 V

Table 2.23: Properties of proposed heating tape by IHP [28]

contacted. So, if the end-user decides, that a variety of options need to be obtained, then more manufacturers will be contacted and in the future different brands of heating tape will be presented. For now the chosen heating tape is shown in figure 2.36, which is sold by International Heating Products (IHP) [28].

Figure 2.36: Picture of heating tape by IHP [28]

2.4.3.2 Screw jack

The screw jack is harder to find information on online, as most screw jack manufacturers do not provide product sheets, and would like to be contacted to provide more info and often seek to customize their products to their customers needs. Finding a screw jack was down prioritized, as finishing the test cell design deemed to be more important and useful for the end-user as they communicated to the author, thus the focus from the screw jack was put on hold [5]. However, as presented the screw jack in concept phase in section 2.3, is a viable option to contact and see if they could provide a customized product suited to the needs of this project.

2.4.3.3 Seals

In regards to seals, Interwell's sister company Seal engineering provides seals for all their products. The author reached out to them, but unfortunately they were on summer break, and thus a progress in determining the type of seals and sizes could not be accomplished either [14].

Chapter 3

Results

This chapter describes the conclusions reached using the "Design Thinking" Stanford design methodology. The chapter will summarize the results and insights into how the design solutions affected and resolved the given task and the end-user's needs. It will also cover the Health, Safety, and Environment (HSE) issues related to the design solutions, ensuring that they adhere to industry standards and that the construction of the test setup is secure for both users and the environment. Thus, the topics that will be discussed in this chapter will be the following, in order:

- Methodology
- Feedback from end-user
- Task
- Health Safety and Environment

3.1 Methodology

One of the goals of this thesis was to solve the the task with a scientific approach, such that it would follow a methodological procedure at each step. In addition, as the project was undertaken with little to no knowledge about Plugs and Packers, therefore it was determined that a structured approach to the problem would help the author of this project, incrementally gain more knowledge and keep progress with the project as well. It can be confidently attested by the author that parts of the "Design Thinking" approach helped the author tremendously in such a way that the project was streamlined and structured.

One way the product design process benefited from the "Design Thinking" approach was in the *Empathize* phase. The *Empathize* phase helped the author, who had little experience with Plugs and Packers from before, to obtain a comprehensive understanding, that would explain the task better and lay the foundation for what kind of idea need to be generated and what kind of solutions need to be assessed and how. In addition, by employing the techniques that were suggested in the *Empathize* phase, the author built a more interpersonal relationship with the end-user. Thus, not only understanding the problem better, but also harmonizing with the employees at Interwell, and thus understanding what their reasoning for this project is. The benefit of the rapport built with the end-user reflected into the *Ideation* phase of the project.

It encouraged the end-user to contribute more to the project with the author during the *Ideation* phase. The benefit was that it encouraged a collaborative environment where ideas and solutions could be explored between the author and the end-user. The collaboration led to the early identification of potential issues and constraints, making necessary modifications and improvements possible before the final solution was created. Additionally, the end-user's sense of ownership and satisfaction with the finished product was increased by including them in the ideation phase. The end-user is now attempting to develop this project further to turn it into a prototype as they establish a team at Interwell.

3.2 Proposed Design

The goal of the task in appendix A, was to develop a miniature version of the full-scale V0 tests for API 11D1 and ISO 14310's packer elements. Additionally, the end-user made some specific demands regarding the conditions and forces that the small-scale packer element tester needed to withstand. The project aimed to develop a final design that could be machined and tested.

Therefore, extensive research was conducted on the requirements and specifications of API 11D1 and ISO 14310's packer elements to ensure that the small-scale version would simulate the performance of the full-scale tests. In addition, to better understand the problem, the author engaged and interacted with the end-user using various techniques. The project's final result was a proposed design with much potential. Significant hurdles were overcome in the concept and ideation phase to breed the best idea suited to the task's requirements and the end-user operating this machine and using it for testing.

However, as mentioned, this project did not get to the finished design but a proposed design, which is the first iteration after the concept phase. The proposed solution from chapter 2.4 is assembled in figure 3.1. The project did not create a finalized design for a packer element tester, as there was insufficient time for this project (i.e., March to July). However, the end-user is satisfied with the progress and is building a team at Interwell that looks forward to absolving the last hurdles of the design phase: obtaining machinery, dimensioning the parts accordingly, and ensuring the final design meets all the safety criteria before its first performance.

That being said, the proposed solution is based on the chosen concept iteration from section 2.3. Where all the parts are the same as mentioned in that section, they are assembled in figure 3.1, with a mock up screw jack. The project has lots the potential to take huge leaps from this point on, as many of the challenges have already been addressed. Such as, in the ideation phase, where it has been determined now what the structure of the small-scale packer element tester shall look like. In addition,

3.2.1 Design requirement validation

A final assessment is done to the proposed design thus far, where it is checked how well the proposed design is performing thus far. Table 3.1 has replaced the "Unknown" column with the "Previously Satisfied" column. The new column check marks all the DRs that were previously satisfied. And all the check marks that are stand alone under "Satisfied" column, are the new DRs that are now satisfied.

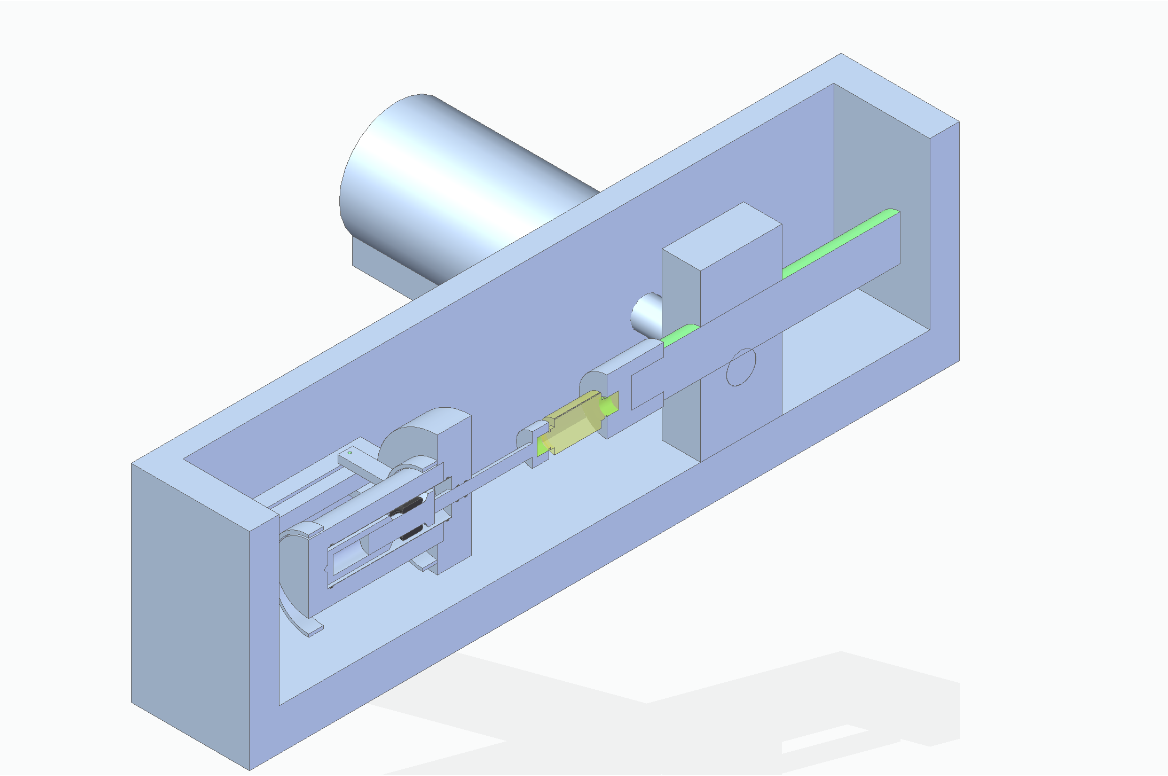


Figure 3.1: Proposed design

The DR satisfied with the proposed design is DR-4, which has been checked in table 3.1. The strength calculation sheet shows that all dimensions of the solution meet safety factor criteria, ensuring the suggested solution can be implemented without endangering users or the environment. The DR-4 checkmark also ensures that the solution is solidly built. However, a fatal flaw in the design process is the requirement to design a sealing system to stop gas leaks. Although conceptualized, it has yet to be designed. Communication with Interwell's exclusive sealing partner is ongoing, but the design does not meet DR-1, indicating that the idea is present but needs to be implemented. Furthermore, the solution can only be implemented once the sealing concept becomes a reality. Although it is worth mentioning that the grooves conceptualized, mocks ups have been drawn out in the proposed design, as can be seen in the CAD models in figure 3.1 and the CAD models in chapter 2.4. Lastly, DR-10 is still not met, as it contradicts the nature of the design; it might never be met until a redesign of the entire concept happens. However, that would lead to a different project.

3.2.2 Feedback from end-user

The proposed design was presented at a design review to the end-user. This design review served as an opportunity for the end-user to provide valuable insights and suggestions for improvement. Additionally, it allowed the end-user to stay updated on the advancements made in the project and ensure that their requirements were being met effectively. Therefore, end-user-specific feedback is listed below:

- When parts are machined, between the sleeve and the end gap there will be a small

ID	Previously Satisfied	Satisfied	Not satisfied
DR-1			✓
DR-2	✓		
DR-3	✓		
DR-4		✓	
DR-5	✓		
DR-6	✓		
DR-7	✓		
DR-8	✓		
DR-9	✓		
DR-10			✓
DR-11	✓		
DR-12	✓		
DR-13		✓	
DR-14	✓		

Table 3.1: Design requirement validation for proposed design

gap.Need to dimension the thinnest sleeve such that it can tolerate the stress applied in that gap, and that it does not buckle

- Instead of having an indent for centralizing, the end-user would like something they can attach and remove, so they can apply the centralizing effect when desired, and also create misalignment when desired
- Have a measuring tape or laser with tags glued on to the test cell piston, to measure the actual displacement during "setting" operation
- Need to dimension the thickness of the end cap, and the test cell with the seal groove as the dimensioning factor. Thus, need to potentially redo the calculation sheet once, seal sizes are determined

The feedback received by the end-user signifies that more iterations and more designing need to happen on the small-scale packer element test before finalizing the design. Design changes include performing finite element analysis on the thinnest sleeves to ensure they can withstand the required pressure and stress levels. In addition, it is necessary to revise the calculation sheet once the seal sizes are determined to ensure accurate results.

3.3 Health Safety and Environment

The risk assessment is a systematic examination of potential issues with the test configuration design and operation. It evaluates current precautions and identifies areas of potential harm to people, materials, equipment, or the environment. For this thesis no risk assessment was completed, as most of the project consisted of research and ideation. Thus, there were no potential risks to be assessed. For the future of this project, when the project is realized, the following factors are a few of many that need to be assessed:

- Handling of equipment while setting it up

- Handling hot equipment, which is still warm after using heat tapes to heat the packer element
- Ideally, the screw jack and the heating tape, like the pressurizing system, can be remote-controlled. Otherwise, human harm is potentially dangerous while operating the equipment.
- There is an inherent risk of damage to all equipment around the test cell, as testing elastomers is to see how and when they fail. For this precise reason, a container was designed to contain the test setup to prevent outbursts from becoming projectiles or harmful in any other way.

Chapter 4

Discussion and Conclusion

The challenges encountered during the research process and the challenges with the suggested product design are covered in the discussion chapter. It draws attention to the shortcomings in the design process and the scientific methodology. The discussion chapter will provide potential solutions recommended as part of future work. This thesis will be concluded by summarizing the given task and how it was resolved with the proposed product. Additionally, it will stress how crucial it is to consider user input and collaborate with end-users instead of relying solely on internal assessments. The discussion chapter is divided into the following subchapters:

- Challenges with methodology
- Challenges with the proposed product design
- Future work
- Conclusion

4.1 Challenges with methodology

The "Design Thinking" process is created to solve problems, where a team of people gather, and learn from the end-user about their occupation, and sometimes participate in it. This allows teams to immerse themselves and learn from the occupational source directly, what the challenges of "the occupation" are. However, in this endeavor, as a team of one person, the "Design Thinking" procedure has been slightly heavy for one person to address all parts of it. Especially because the project is quite vast with many dependent components for a team of one to resolve within three months.

However, having utilized the Stanford Design School "Design Thinking " approach to this project resulted in the following list of challenges:

1. As mentioned, the "Design Thinking" process is quite time intensive, with multiple stages that must be thoroughly explored and executed.
2. Another issue is the time spent *Empathizing*. It is a crucial step in the design thinking process. However, shadowing, interviewing, and gathering user data can be tedious and time-consuming, stealing time from designing the product.

3. *Empathizing* and engaging with users during the design process made it challenging to create unique solutions. Information gathered from end-user's revealed the test cell needed a cylinder, and using end-caps was standard practice at Interwell.
4. At times, it was difficult to know where the project was going and what the end product needed to look like. Because more time spent with each end-user increased the amount of input into what the product needed to be, which distracted from the actual task
5. Many of the calculation models were in place to use from Interwell, such as the strength calculation sheet. Which made this project a more product development project instead of a research project.
6. Because it was heavily advised to use the strength calculation sheet and little info was given on how it worked due to proprietary information, it was difficult to find mathematical models that could potentially compare to it.

The list above represents some of the challenges with the methodology of this project. The way to mitigate them would be to have a bigger time frame to do the project. For the "Design Thinking" model, the author would have liked to segment and shorten some parts of the *Empathize* phase, as some information provided was redundant, such as the surveys.

4.2 Challenges with proposed design

The proposed design was the first iteration after the concept phase, which inherently meant there was many design flaws that needed to be ironed out. A few of the challenges that have not been mentioned that should have been done with the product design are included in the following list:

1. Few concepts were created, thus not many ideas were explored. And an attempt to meet all the DRs was not attempted. Also in design of the test cell there was a lack creativity.
2. No finie element analysis was done on of the parts, which would have been a good way to verify each components structural integrity. And could observe how they behave under huge loads.
3. Not enough heating solutions were explored. And did not try to create a concept that would be compatible current heating system
4. Messy strength calculation sheet analysis. As new dimensioning factors were discovered, causing recalculating the test cell sizes.
5. How does the arbitrary division of the four configurations for the test cell affect other plug types with different API requirements (some plug are tested to max API other to nominal)
6. Instead of Lame's equation, which is not good at validating thick-shell cylinders at high stresses according to [9], why didn't I use Barlow's equation. Which is specifically often used in the oil indsutry to design the thickness of a pipe.

The two most significant challenges on the list above are the first and second. In order to have a fully comprehensive design, it would be ideal to explore more concepts, specifically within each project system, such as heating. The second is that no finite element analysis

(FEA) was performed. Before making a physical prototype, an FEA would have helped analyze the design and spot any flaws. Additionally, an FEA that analyzes the materials and a product's performance in the environments to which it is exposed should be part of any complete design process.

4.3 Future Work

The future work chapter consists of everything that should have been done, including issues mentioned in the discussion section or throughout the thesis that needed to be completed. Furthermore, it is a bullet-point list of recommended things. Here is the list:

- FEA analysis on components
- A comparison analysis with the strength calculation sheet and FEA
- Dimensioning the test cell and end caps according seal grooves
- Design the sealing system for the proposed design
- Design a centralizer that meets the end user's preferences to align or misalign the packer element at will
- Consider dividing the casing sizes into more configurations.
- Recommend obtaining a screw jack and heating blanket that can be remote controlled
- Creating a better software for the PI control of the pressurizing system
- Do a cost analysis of the cost of this test setup
- Machine drawings of the final design
- Manufacturing and testing the product
- Find a way to incorporate concept 3 into concept 2, and use camera and other sensors to gather more data

4.4 Conclusion

Design specifications for this project were established through thorough research, extensive communication, and interaction with the end-user. After discussion with the end user, one with a modular design that could accommodate packer elements of various sizes was selected from these three concepts. HNBR 386-500 packer element was selected as the packer element to base the concept on. Lame's equations and an Interwell strength calculation sheet were used in a comparison study to determine the test cell's thickness. Although the results varied quite a bit, it was decided to use the number from the calculation sheet because Lame's approximations are invalid at high stresses. A small-scale packer element tester was conceptualized through its first design iteration.

Appendices

Appendix A

Task given by Interwell

The following page contains the task that Interwell AS gave. The task is the entire reason behind this thesis. It explains the background, objectives, and steps needed to complete the design of a small-scale packer element tester.

Design of a Small-Scale Packer Element Tester

Background:

Packer elements are essential components of downhole tools used in the oil and gas industry. The ISO 14310 / API 11D1 standard specifies the requirements of plugs and packers used in oil and gas wells. To ensure the reliability and performance of these tools, they must be tested under high-pressure and high-temperature conditions. However, conducting full-scale V0 tests on the complete system is often challenging due to logistical, safety, and cost constraints. Therefore, there is a need for a small-scale packer element tester that can simulate V0 tests without testing the full system.

Objective:

The main objective of this thesis is to design and develop a small-scale packer element tester that can simulate ISO 14310 / API 11D1 full-scale V0 tests. The design requirements will be based on a literature review and interviews of relevant, experienced Interwell personnel. The proposed solution should be as representative to the full test as possible while taking into account health, safety, and environmental (HSE) considerations. The tester should be simple to use and operate, and must fit various packer element sizes. The final output of the project should be a complete design of the proposed solution.

Things to consider:

- Recrate all relevant parameters from the tool affecting the packer element in a real-life use case
- Adjustable test setup, for both parameters and sizes
- Log as much relevant data as possible
- Quantifiable output from test. Ideally more than approved/not approved

The project will involve the following steps:

1. Literature review and interviews: This will involve a comprehensive review of the existing literature on packer element testing, ISO 14310 / API 11D1 standard, and interviews with relevant Interwell personnel to identify their needs and requirements.
2. Design requirements: Based on the literature review and interviews, the design requirements for the packer element tester will be identified.

3. Conceptual design: Several conceptual designs will be developed and evaluated against the design requirements. The most suitable design will be selected.
4. Detailed design: The selected design will be further developed into a detailed design. This will mainly include the mechanical components of the system. Also an outline of the required functions of the electrical and software components of the tester should be made.
5. Prototype development (if time permits): A prototype of the packer element tester will be developed and tested under laboratory conditions.
6. Performance evaluation (if time permits): The performance of the prototype tester will be evaluated against ISO 14310 / API 11DI1 full-scale V0 test requirements.

Expected outcome:

The expected outcome of this project is the design basis for a small-scale packer element tester that can simulate ISO 14310 / API 11D1 full-scale V0 tests. The tester should be as representative to the full test as possible. The design of the proposed solution will be documented in a report outlining the design details of the packer element tester, including all relevant mechanical design details such as calculations and drafts.

If time allows a prototype of the tester will be manufactured. The performance of the prototype tester will be evaluated against ISO 14310 / API 11DI1 full-scale V0 test requirements, and the HSE implications of the tester will be evaluated.

Project management:

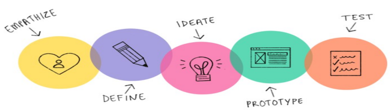
- Weekly meetings scheduled by candidate.
- Candidate will be the responsible for the progress and organization of the plan.
- Check point between each step, before progressing to next to make sure the step is fully covered.

Appendix B

Project Timeline

The following page contains the project timeline. The setup was created in Excel, and the method for the timeline is a Gantt chart.

Design and Development of a Small-Scale Packer Element
ulating ISO 14310 / API 11D1 Full Scale V0 Tests



Design Thinking

Design thinking is a non-linear, iterative process that teams use to understand users, challenge assumptions, redefine problems and create innovative solutions to prototype and test.

NTNU	Christan Holden
Interwell	Tarjei Skulstad
Candidate	Mian faran Hassan

Project Start: man, 3.13.2023

1

SIMPLE GANTT CHART by Vertex42.com

https://www.vertex42.com/ExcelTemplates/simple-gantt-chart.htm

mar 13, 2023 | mar 20, 2023 | mar 27, 2023

13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 1 2 3

m t o t f l s m t o t f l s m t o t f l s m

	TASK	PROGRESS	START	END
Empathize	**Phase 1 Literature Review and Interviews**			
	Create Project Plan	100 %	3.13.23	3.20.23
	Read Literature Review (Easter)	100 %	3.20.23	4.3.23
	Create Interview Questions and set up Interview	100 %	4.4.23	4.12.23
	Interview and gather data	100 %	4.11.23	4.18.23
	Analyze the data and set up a chart	100 %	4.18.23	4.25.23
	EXAM BREAK	N/A	4.25.23	5.25.23
	Write phase 1 into report	100 %	5.25.23	6.15.23
Define	**Phase 2 Design Requirements**			
	Outline the requirements from Lit. Review	100 %	5.25.23	5.29.23
	Outline the requirements from Interviews	100 %	5.29.23	6.1.23
	Evaluate force flow and read other thesis'	100 %	6.1.23	6.5.23
	Set up design parameters	100 %	6.5.23	6.9.23
	Write phase 2 into report	100 %	6.16.23	6.30.23
Ideate	**Phase 3 Conceptual Design**			
	Research possible solutions	100 %	6.9.23	6.13.23
	Devlop concepts	100 %	6.13.23	6.16.23
	Concept Review + Improve concepts	100 %	6.16.23	6.19.23
	Final Concept review	100 %	6.19.23	6.19.23
	Write phase 3 into report	100 %	6.30.23	7.21.23
	Phase 4 Detailed Design			
	Calculation sheet	100 %	6.19.23	6.22.23
	CAD Model + design review	100 %	6.22.23	6.25.23
	Project end	100 %	6.25.23	6.25.23
	Write into report - turn it in	100 %	7.21.23	8.30.23

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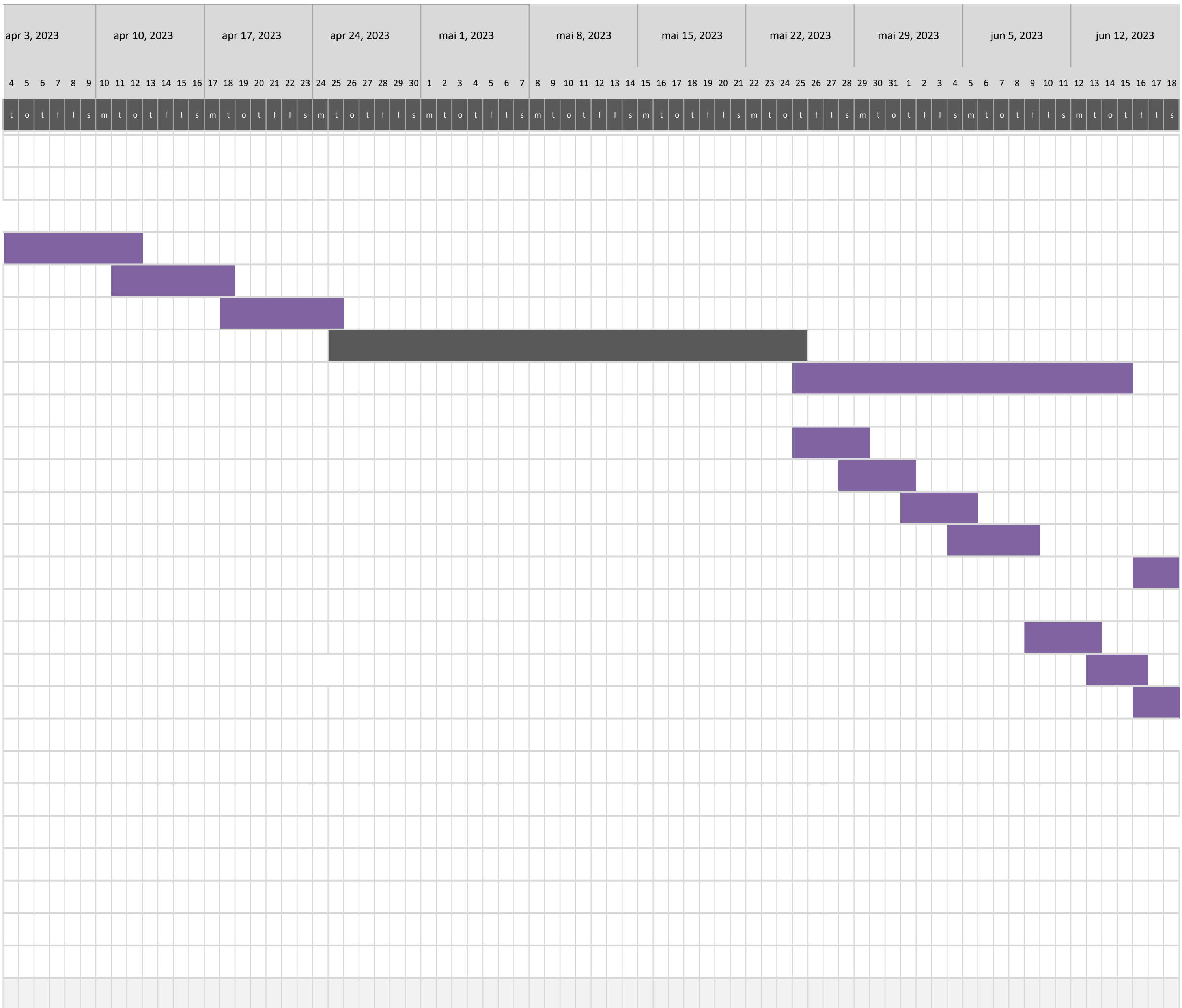
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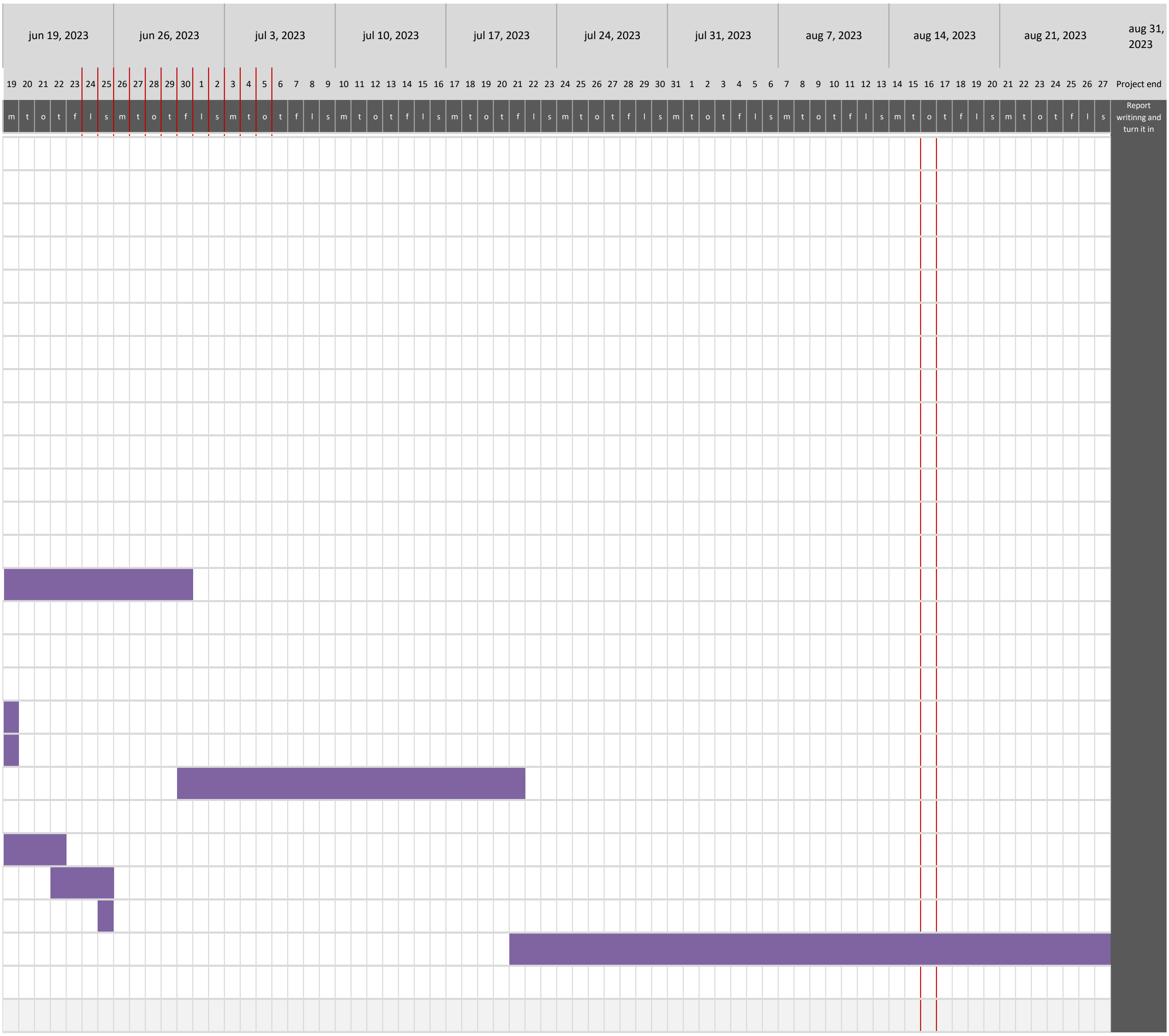
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Project end
Report writinng and turn it in

Appendix C

API Casing Size Table

The following page is the casing size for different size casings used in the oil industry. The standard casing size has been retrieved from Oilproduction [21].

OILProduction.net

API CASING TABLE SPECIFICATION

Size		Weight	ID		Drift		Capacity
Inches	mm	lbs/ft	Inches	mm	Inches	mm	bbl/100ft
4 1/2	114.30	9.50	4.090	103.89	3.965	100.71	1.63
		10.50	4.052	102.92	3.927	99.75	1.59
		11.60	4.000	101.60	3.875	98.43	1.55
		12.60	3.958	100.53	3.833	97.36	1.52
		13.50	3.920	99.57	3.795	96.39	1.49
		15.10	3.826	97.18	3.701	94.01	1.42
		16.60	3.754	95.35	3.629	92.18	1.37
		16.90	3.740	95.00	3.615	91.82	1.36
		17.70	3.696	93.88	3.571	90.70	1.33
		18.80	3.640	92.46	3.515	89.28	1.29
		21.60	3.500	88.90	3.375	85.73	1.19
		24.60	3.380	85.85	3.255	82.68	1.11
		26.50	3.240	82.30	3.115	79.12	1.02
5	127.00	11.50	4.560	115.82	4.435	112.65	2.02
		13.00	4.494	114.15	4.369	110.97	1.96
		15.00	4.408	111.96	4.283	108.79	1.89
		18.00	4.276	108.61	4.151	105.44	1.78
		20.30	4.184	106.27	4.059	103.10	1.70
		20.80	4.156	105.56	4.031	102.39	1.68
		21.40	4.126	104.80	4.001	101.63	1.65
		23.20	4.044	102.72	3.919	99.54	1.59
		24.20	4.000	101.60	3.875	98.43	1.55
		26.70	3.876	98.45	3.751	95.28	1.46
		32.00	3.620	91.95	3.495	88.77	1.27
5 1/2	139.70	13.00	5.044	128.12	4.919	124.94	2.47
		14.00	5.012	127.30	4.887	124.13	2.44
		15.50	4.950	125.73	4.825	122.56	2.38
		17.00	4.892	124.26	4.767	121.08	2.32
		20.00	4.778	121.36	4.653	118.19	2.22
		23.00	4.670	118.62	4.545	115.44	2.12
		26.00	4.548	115.52	4.423	112.34	2.01
		28.40	4.440	112.78	4.315	109.60	1.91
		29.70	4.376	111.15	4.251	107.98	1.86
		32.30	4.276	108.61	4.151	105.44	1.78
		36.40	4.090	103.89	3.965	100.71	1.62
		39.30	4.044	102.72	3.919	79.54	1.59
6	152.40	15.00	5.542	140.77	5.399	137.13	2.98
		18.00	5.424	137.77	5.299	134.59	2.86
		20.00	5.352	135.94	5.227	132.77	2.78
		23.00	5.240	133.10	5.115	129.92	2.67
		26.00	5.132	130.35	5.007	127.18	2.56
6 5/8	168.28	17.00	6.135	155.83	6.010	152.65	3.66
		20.00	6.049	153.64	5.924	150.47	3.55
		24.00	5.921	150.39	5.796	147.22	3.41
		28.00	5.791	147.09	5.666	143.92	3.26
		32.00	5.675	144.15	5.550	140.97	3.13
		35.00	5.575	141.61	5.450	138.43	3.02
		43.20	5.375	136.53	5.250	133.35	2.81
		69.63	4.375	111.13	4.250	107.95	1.86
7	177.80	17.00	6.538	166.07	6.413	162.89	4.15
		20.00	6.456	163.98	6.331	160.81	4.05
		23.00	6.366	161.70	6.241	158.52	3.94
		26.00	6.276	159.41	6.151	156.24	3.83
		29.00	6.184	157.07	6.059	153.90	3.71
		32.00	6.094	154.79	5.969	151.61	3.61
		35.00	6.004	152.50	5.879	149.33	3.50
		38.00	5.920	150.37	5.795	147.19	3.40
		41.00	5.820	147.83	5.695	144.65	3.29
		42.70	5.750	146.05	5.625	142.88	3.21
		44.00	5.720	145.29	5.595	142.11	3.18
		45.40	5.660	143.76	5.535	140.59	3.11
		49.50	5.540	140.72	5.415	137.54	2.98
		56.10	5.376	136.55	5.251	133.38	2.81
		58.00	5.240	133.10	5.115	129.92	2.67
		66.50	5.040	128.02	4.915	124.84	2.47
7 5/8	193.68	20.00	7.125	180.98	7.000	177.80	4.93
		24.00	7.025	178.44	6.900	175.26	4.79
		26.40	6.969	177.01	6.844	173.84	4.72
		29.70	6.875	174.63	6.750	171.45	4.59
		33.70	6.765	171.83	6.640	168.66	4.45
		39.00	6.625	168.28	6.500	165.10	4.26
		42.80	6.501	165.13	6.376	161.95	4.11
		45.30	6.435	163.45	6.310	160.27	4.02
		47.10	6.375	161.93	6.250	158.75	3.95
		51.20	6.249	158.72	6.125	155.58	3.80
		52.80	6.201	157.81	6.000	152.40	3.74
		55.75	6.201	157.51	6.176	156.87	3.74

Size		Weight	ID		Drift		Capacity
Inches	mm	lb/ft	Inches	mm	Inches	mm	bbl/100ft
7 3/4	196.85	46.10	6.560	166.62	6.500	165.10	4.18
8 5/8	219.08	24.00	8.097	205.66	7.972	202.49	6.37
		28.00	8.017	203.63	7.892	200.46	6.24
		32.00	7.921	201.19	7.796	198.02	6.09
		36.00	7.825	198.76	7.700	195.58	5.95
		40.00	7.725	196.22	7.6	193.04	5.8
		44.00	7.625	193.68	7.500	190.50	5.65
		49.00	7.511	190.78	7.386	187.60	5.48
		52.00	7.435	188.85	7.310	185.67	5.37
8 3/4	222.25	49.70	7.636	193.95	7.500	190.50	5.66
9 5/8	244.48	29.30	9.063	230.20	8.907	226.24	7.98
		32.30	9.001	228.63	8.845	224.66	7.87
		36.00	8.921	226.59	8.765	222.63	7.73
		38.00	8.885	225.68	8.76	222.50	7.67
		40.00	8.835	224.41	8.679	220.45	7.58
		43.50	8.755	222.38	8.599	218.41	7.45
		47.00	8.681	220.50	8.525	216.54	7.32
		53.50	8.535	216.79	8.379	212.83	7.08
		58.40	8.435	214.25	8.279	210.29	6.91
		59.40	8.407	213.54	8.251	209.58	6.87
		61.10	8.375	212.73	8.219	208.76	6.81
		64.90	8.281	210.34	8.125	206.38	6.66
		70.30	8.157	207.19	8.001	203.23	6.46
		71.80	8.125	206.38	7.969	202.41	6.41
9 3/4	247.65	59.20	8.560	217.42	8.500	215.90	7.12
9 7/8	250.83	62.80	8.625	219.08	8.500	215.90	7.23
10 3/4	273.05	32.75	10.192	258.88	10.036	254.91	10.09
		35.75	10.136	257.45	10.011	254.28	9.98
		40.50	10.050	255.27	9.894	251.31	9.81
		45.50	9.950	252.73	9.794	248.77	9.62
		51.00	9.850	250.19	9.694	246.23	9.42
		55.50	9.760	247.90	9.604	243.94	9.25
		60.70	9.660	245.36	9.504	241.40	9.06
		65.70	9.560	242.82	9.404	238.86	8.88
		71.10	9.450	240.03	9.294	236.07	8.67
		73.20	9.406	238.91	9.250	234.95	8.59
		76.00	9.350	237.49	9.194	233.53	8.49
		79.20	9.282	235.76	9.126	231.80	8.37
		81.00	9.250	234.95	9.094	230.99	8.31
11 3/4	298.45	38.00	11.150	283.21	10.994	279.25	12.08
		42.00	11.084	281.53	10.928	277.57	11.93
		47.00	11.000	279.40	10.844	275.44	11.75
		54.00	10.880	276.35	10.724	272.39	11.50
		60.00	10.772	273.61	10.616	269.65	11.27
		65.00	10.682	271.32	10.526	267.36	11.08
		66.70	10.656	270.66	10.500	266.70	11.03
		71.00	10.586	268.88	10.430	264.92	10.89
		73.60	10.532	267.51	10.376	263.55	10.78
		75.00	10.514	267.06	10.358	263.09	10.74
		76.00	10.500	266.70	10.344	262.74	10.71
		79.00	10.438	265.13	10.282	261.16	10.58
		80.50	10.406	264.31	10.25	260.35	10.52
		83.00	10.368	263.35	10.212	259.38	10.44
		87.20	10.282	261.16	10.126	257.20	10.27
		95.00	10.124	257.15	9.968	253.19	9.96
11 7/8	301.63	71.80	10.711	272.06	10.625	269.88	11.14
13 3/8	339.73	48.00	12.715	322.96	12.559	319.00	15.71
		54.50	12.615	320.42	12.459	316.46	15.46
		61.00	12.515	317.88	12.359	313.92	15.21
		68.00	12.415	315.34	12.259	311.38	14.97
		72.00	12.347	313.61	12.191	309.65	14.81
		77.00	12.275	311.79	12.119	307.82	14.64
		80.70	12.215	310.26	12.059	306.30	14.49
		83.00	12.175	309.25	12.019	305.28	14.40
		85.00	12.159	308.84	12.003	304.88	14.36
		86.00	12.125	307.98	11.969	304.01	14.28
		91.00	12.055	306.20	11.899	302.23	14.12
		92.00	12.031	305.59	11.875	301.63	14.06
		96.00	11.975	304.17	11.819	300.20	13.93
		98.00	11.937	303.20	11.781	299.24	13.84
		100.30	11.907	302.44	11.751	298.48	13.77
		102.00	11.889	301.98	11.733	298.02	13.73
13 1/2	342.90	81.40	12.340	313.44	12.250	311.15	14.79
13 5/8	346.08	88.20	12.375	314.33	12.250	311.15	14.88

Appendix D

Interviews on the end-user

The following page contains all the end-users questions and answers as part of the empathize section.

Background

Packer elements are essential components of downhole tools used in the oil and gas industry. The ISO 14310 / API 11D1 standard specifies the requirements of plugs and packers used in oil and gas wells. To ensure the reliability and performance of these tools, they must be tested under high-pressure and high-temperature conditions. However, conducting full-scale V0 tests on the complete system is often challenging due to logistical, safety, and cost constraints. Therefore, there is a need for a small-scale packer element tester that can simulate V0 tests without testing the full system. The main objective is to design and develop a small-scale packer element tester that can simulate ISO 14310 / API 11D1 full-scale V0 tests.

General Interview Questions

1. Hva er den største utfordringen i dag med det test oppsettet som eksisterer?
2. Hvis du skulle ha testet et pakningselement, hvilke parameter ville du målt?
3. Hvilke «future work»/muligheter kunne ha oppstått/jobbet på ved å ha et ønsket testoppsett som er beskrivelset i «Background»?

Interview Groups:

- Product Champions
- Specialists
- R&D Engineers

Interview questions specific to Product Champions

1. Hvordan er din spesifikk plugg påvirket av dagens testoppsett?
2. Hvordan foreslår du å løse problemet for å gjøre testoppsettet bedre ihht. Til dine ønsker og ISO/API krav?
3. Hvordan foreslår du at setting force kan bli simulert på din plugg type?
4. Hvilke ID er det pluggen din testes mot? Nominell API? MAX API? Etc.

Product Champions

- Participant 1
    - Svar:
        - Store krav til tilgjengelig utstyr, og forutsetter ledig kapasitet til workshop technician (som er kun en PAX) - > Personell (hvis de har ferie). Kapasitet begresning fordi bare 3 bunker som er tilgjengelig. Det går på bekostning av noe andre fordi både R&D og Produkt gruppa. Det er dritdyrt: koster 60 000 NOK å utføre en test. Og mange hundre tusen kroner å skaffe det og lage det. Ingen gode måter å test kvalitet til pakning på noen måte, hadde vært fint å kunne teste kvalitet på pakningen. Hvordan endrer pakningen etter at det er ferdig støpt og geometrien (geometrien er litt tilfeldig).

        - Usikker ... men sammenlignet med stål så er det rigide verdier (type E modul, UTS, yield stress, etc.). For HEX hadde vært interessant å teste pakningen ikke gummien. Hvor mye utvidelse den tåler, og hvor godt den sitter I metallet. Hvordan endrer geometrien endrer seg når den utvider seg. Kunne vært fint å se hvordan pakningen visuelt oppfører seg kun I setting force. tette evnen er mest kritisk.
        - 3 test bunker og en person som gjør at ting tar lang tid (logistikk). Og vi ha mange 100 produkter som kjemper om test kapasiteten. Og siden de ikke gjøres på forhånd. Oppvarming tar lang tid (4 timer, fordi sensoreren kan ikke måles I midten av testecellen) avhengig av hvor lang tid det tar. Alt må klargjøres fordi det er stort og tungt.
        - Jobben til Runar blir bedre fordi han kan møte forespørselene fra kundene raskere. Mye backlog av ting som bør gjøres og ikek blir gjort. Man gjør det man må gjøre først (kritisk prioritet). Forskning blir bedre.
        - Test envelope som sier noe om trykk /temperatur. Vanntett sealing. Test envelope er sjeldent komplett for produktene våres. Utvide produkt bruk. Test envolope ikke fungerer for alle produktene, fordi den temperaturen pluggen ikke skal brukes I, testes ikke. Type 4 grader (da ofte sitter pluggen dypt og det er over 50 grader der). Inkluder temperature cycle range.
        - Setting force = compression force. Oppsett å rotere på noe og rotasjonen fører til en setting force.
        - THEX settes mot MAX API og HEX settes mot NOM API. (men ofte testes til det kunden spør om).
        - Det skjer noe med pakning på lager (når det sitter langt tid), og UV lys. Levetid på pakninger? /Konsekvensen av pakning I temperatur evt. Annet over lang tid.
- Participant 2
    - Svar:
        - Lang ventetid, alt lang tid, logistikk. Vi må alltid teste horisontalt, skulle ønske vi kunne test veritkalt eller 30 grader (som kunden ønsker).
        - Trykk, temperatur og ekspansjon og materialer. Det som definer HPHT pakning. Temperatur og ekapsjon endrer seg. HPHT skal helst være ratet til høyest mulig
        - Temperatur svinging, 100 kg med stål, som må kjøles/varmes ned fra 177 grader til 37 og det tar lang tid (overnatt). Fysikk det tar tid før innerst I pluggen blir like varmt som utenpå.
        - Da teste mer, kunne fått bedre test konvolutt. Kunne test hver endring, lagre mer sikkert produkt. Teste til å øke kaapsitet til plugg. Finne flere konvolutter. s
        - Samme som over.
        - At vi tester horisontalt, og vi ikke kan teste veritkalt eller 60 grader. HPHT er begresnet på pressure rating, og testrør tåler ikke det. Hardhet på rør.
        - Usikkert. Best å ha testbrønn, kjøre alt som en virkelig brønn.
        - Tester ikke mye med settekraft for HPHT. Settekraft påvirker tettheten. PP trenger høyere settekraft. Sliter å få settetool for en PP.
        - MAX API

        - Funksjonstester, type: settesekvens. hva som settes først, backups beveger seg og setter ikke seg fast noe sted. Setting I vann slet, vet ikke om vi fanger noe vann I pakning. Pinning I pakningen, og to skjærskruer. Ideelt gjennomsiktig rør. settesekvens kan påvirke egenskap til pluggen. Double peak på EST log, det betyr at det er vann som var I pakning.
        - Pakningsmodul kan brukes som conv. Kit for å teste HPHT. PP kan brukes som helt plugg fordi den er så lite.
- Participant 3
    - Svar:
        - Å finne testrør, størrelsen er vanskelig å finne.
        - Trykk og temperatur, tetthet V0
        - Oppvarming
        - For at kunden skal bli fornøyd må fortsatt hele pluggen testes, så forbedrer ikke jobben til participant 3
        - Vanskelig å forenkle
        - Typisk å bli teste straddles mot nom api
        - Ikke med mindre kunder spør om noe
        - Teste med spacerpipe slik at det er kortlengde (halv meter lang).
        - Simulere settingforce med hydraulinsk. Tryggest å teste med shear screw for å simulere det som er I brønn. For å simulere sjokkeffekt.
        - Kundebestemt API
- Participant 4
    - Svar:
        - Avblødningshastighet skjer for raskt. Påvirker o kit mest. RGD (Rapid gas decompression) Rolig avblødning siste 50 bar for å unngå oppsprekning av gummien. V0 test har mange sykluser som påvirker dette. Finne hvor mye kreftene man trenger på elemntet for å teste tetthet. (avhengig av tempeartur og ID).
        - ME ringeene I pakningene skal ekspandere jevnt. Det vil gjerne de se. Tykkelsen og lengde av thimble og fjør I pakninga.
        - Vi vet at trykket til pakninga mot casinga må være større enn det som den blir påvirket av (diff trykk).
        - Det er gap mellom fjør og thimbles som påvirker me pluggen. Avstand mellom thimble er veldig viktig. Eksapansjon
        - Dette hjelper Robin, mye lettere å lage pakningstester for ME, fordi du bruker bare to koner (cones) for å stramme det opp. Sentrert pakning er viktig. Ha centralizer? For å sentrere slik at det ikke blir en variabel.
        - Ha teleskop opplegg, slik at man kan ha flere områder til test for flere størrelser. Ha utgangspunkt med MAX API I rør (fordi det er nye krav).
- Participant 5
    - Svar:
        - Hver person som skal teste noe må tegne opp sitt eget testoppsett. Vi har mye testustyr som er standard størrelse, men ifølge nye API rev. 5 standard er det ønske om å teste alt i MAX API og det har ikke testutsyr til alt der.

        - Ha bedre oversikt. Standardsering av tester som gjøres. Litt forskjellige materialer som er brukt på rørene. Hvis oversikten gjort ferdig, simen må sitte å beregne om noe tåler trykket før han kan si at noe kan testes. Hadde vært fint om det var ett fast standard utstyr slik at det er ferdig beregnet.
        - Pluggene er kun funksjonstester fordi de er tools.

Interview questions specific to Specialists

1. Hvilke krefter er det som går gjennom en pakning?
2. Hvilke material egenskaper som er påvirket? Og hvilke parameter er det som påvirker de?
3. Hvilke fenomener er det oppstår i når pluggen går fra «run» til «set»? Og hva skjer med pakning under testing?

Specialists

- Participant 6
    - Svar:
        - Tetthet, ISO 23936-2 tabell 2
        - Kompressjon, mekanisk sammentrykning, aksiell kompresjon og en radiell eksapansjon
        - Tykk vegget rør
        - Temperatur; kjemisk påvirking og mekanisk påvirkning -> direkte relatert.viskoelastitets, så det har en tidsfaktor.
        - HEX har stor elongation go break 615%. Strekklapper, basic testing.
        - Under OnenNOTE - >Elastisense.com
        - Lav temp. Drop test, slag test.
        - Hvordan skal en gummi kvalifiseringstest se ut?
        - Drit I ME inntil videre. Man for enorm stor spredning med ME. Begynn å se på HPHT/HEX, 0.4mm
        - Tenk på gapet mellom packerbackup og pakningslementet (gjeleder HEX, ikke HPHT).
        - Det er Gap I rosen til HPHT, og under vingene på konen.
        - Elongational break – hvor lang du tøye gummien før den breaker.
        - Mekanisk tøyning I pakningen, fint å ha glass til å se eksakt hva som skjer.
            - Test forslag: Fiber som kan legges inn I røret for å se hva tilstanding til tøyningen er
        - Spenning tøynings tilstand til gummien
        - Skjekke om pakningen er tett.
        - Type glass for testrør:
            - Vosstech som lager glassplugg, de lager glassplugg. Det er herding til glass.
            - Alt 2: En gjennomføring med linse med lys. Også kamera for å filme.
                - Fiberen ut I en av endelokk. Det finnes løsninger allerede der ut.
            - Alt 3: Bruk veggen til ett akvarie, men får ikke styrt tempearturen. Da kan få tøyningstilstanden til pakninselementet. Biaksielle spenninger.

        - Hva er 4000 psi diff trykk I trykk inn I pakningene. Hatt manometer I pakningene. Finne ut det interne trykket I pakninga.
- Participant 7
    - Svar:
        - 200000 nok.
        - Største utfordring er at test envolope er ikke complete. Gjennomstesting av pakningsmodul
        - Det som tar tid er stabilitet på trykk og temperatur. Og trykk varierer med temepratur. Stabil nok måling tar veeeeeldig lang tid. Spesielt med høy og lav temepratur som er krav I den nye rev. Av API. Atmosfæretrykket kan ha påvirkning, kan vi få lekkasje.
        - Stål er enkelt, man vet hvordan det oppfører seg. Men elastomer not so much.
        - Bra verdi for å svare på det usikre prossen med gummi. Mye billigere og sjappere turnover.
        - EST tool setter pakninga veldig sakte og sikkert. (5 –15 min). Krefter som oppstår I pakninga. Radiell strekk av pakningen, det skjer spesielt med HEX. Strekk I gummi gjør det svakere. Brusk tusj til å teste aksiell strekk.
        - Sentralisering (hvertfall for høyekspanderende). Viktig for sealing.
        - Bruke ting vi har. Live justering av settekraft. En side er låst og en bruke EST på å justere settekraft. Interface mot en EST. Dummy for nye plugger. Bruk det vi har virker. Bruk test ustyret.
        - Litt utopisk I glass pakning.
        - Endelokk som er gjennomsiktig. Sette kamera? Glasset tåler hvertfall 5000 psi. Godt kamera og lys.
        - Viktig med datalogging, og sensorer. Bruk dages testoppsett + EST logg.
- Participant 8
    - Svar:
        - Det er lite dynamisk, du må kjøpe en testcelle til 150000 nok -> se ingeniørlaget mal. Kort levetid på testcelle. Å få tak I en er ett problem. Vi har unøyaktige sensorer, så vi tester pluggene hardere. Svakhet I sensor på trykk og temperatur
        - Trykk, settekraft (hvor stor tap av settekrafta er). Teste fjæra? Fjærpakken fra pluggen I pakningtester. Veldig modulært for å test I flere casingsize. Temperatur. At det ekspanderer på riktig måte. Teste friksjon mot casing vegg I forskjellige situasjoner. Comperative study mellom tidligere pakninger og nye pakninger. Sjekke design parametre gjennom empirisk data.
        - Kraft som påvirker pakning: Ratchen og fjærkrafta.
        - Tidlig feedback. Ikke veldig interessant det man ser gjennom en gjennomsiktig glass. Concept ide.
        - Kompressjon, strekk, pakningssimuleringer.
        - Før til etter pakning: extrudering gjennom små gap, musepsising forårsaker hull I pakninga og det kan lage sprekker og at pakning sprenger. polymer kjedene henger sammen. Vulkanisering av polymer. Temperatur endrer karakterstikken til polymerer

        - Forrige pakningstester som var laget på Interwell, ikke var modulært/dynamisk. Lage den veldig modulært. Akkurat område rundt pakning kan modulært.
        - Tidligere ingeniør lagde gamle pakningstester, se på det.
- Participant 9
    - Svar:
        - Det koster: 200000 kr for testrør. Du kan gjøre max 10 tester I ett testrør.
        - Per est koster 100000-150000kr
        - Max temperaturen, extruderingsspalten, altså hvor mye plass er det for gummi, og trykk. Ekspansjonstester, hvor mye kan gummi ekspansderes før det sprekker
        - Flere mindre dårligere tester som ikke tar lang tid og bedre verfiserings v0 tester.
        - Alle plugg kategorier de har pakningsteknologi.
        - Gjenskap det som er I brønnen. Sette med EST for å sette med opprinnelige settetool
        - Nitrogen med lite fukt innhold, kan påvirke lekkasje. Høyt kvalitet for gassen. Tester mot nitrogen.
        - Teste forankring med trykk/tension test.
- Participant 10
    - Svar:
        - Altfor mange faktorer som går inn I den. Den er bra test I forhold til pluggen, men ikke optimal iforhold til pakningen. Man, vet aldri hva som skjer med pakninga.
        - V0 test, temperatur range, trykk og funksjonstest. Bedre å teste over spec.
        - Planlegging, ha riktig utstyr (plug delene), alt må rigges og oppvarming tar ett døgn.
        - Kan implementere nye ideer og løsninger.
        - Backup systemet til pakning er alt man trenger
        - Setter seg skjeivt, testcella har skadelig yttelse. Indre skader. Ting kan gå for fort I centralisering og altfor rask temperaturendring kan forsårsake svakheter.
        - Her er det urealistisk test scenario, fordi vi tester fra begge sider, og I realiteten har man kun trykk sykkel .
        - Ofte O ring kan ryke og må testes.
        - Starte med trykk simulering.
        - Rigget det opp til 4 og 12t timers testing. Utmatting av testustyr.
        - Sikkerhet: trykk, modulært system som tåler trykk.
- Participant 11
    - Svar:
        - Vanskelig å få gjennom forandringer. Hvis test ansvarlig gjør en liten endring så må hele testen gjøres på nytt og det er derfor det ikke gjøres.
        - Trykk og temperatur, tid. 12t test og 24 t. Tester.
        - Få bedre kvalitet og produksjon. Og produksjonstid. Kjøre små skala testing, kan få flere iterative prosesser og forbedringer.
        - Mekaniske motstanded er større fra utsida og den holdes. ETP sprekker opp når den blir varm. HNBR blir mjukere.

        - Usikkert. Fjæra har blåst ut. Gummi har revna, og gummien blir splittet opp (det er pulver).
        - Modulært bytte rør til den pakningen man tester.
- Participant 12
    - Svar:
        - Tidligere ingeniør kjørte pakningstester før I tiden. Han har ett excel ark med stoff
        - Måle displacement aksielt på pakningselement. Sette det mot kraft-akse.
        - Lokajson av bacheloroppgaver fra tidligere som er gjort på springforce hos Interwell
        - Ekstensormeter måler lengde → fint å ha
        - Ingeniører kjørte trykk sensor midt I pakninga-> ligger rapport->les
        - Spenning I høyest I enden av pakninga.

Interview questions for R&D Engineers

1. Hvilken funksjonalitet er det du ønsker deg for test oppsett?
2. Er det andre tester utenom ISO og API standard som dere ønsker?
3. Er det noen eksterne faktorer som påvirker designet av testoppsettet?
4. Hvordan ville du ha designet testoppsettet?

R&D Engineers

- Participant 13
    - Svar:
        - Tanken skal bare se hvor grensa til pakninga ligger
        - Kunne pakningen er god for, ikke interessert i backlash. V0 tester på pakning kun.
        - 3 ting: Sette pakning i Set, også teste temperatur og trykk. Og styre settekraft.
        - Største utfordring er at vi har 10-20 variabler og vi vet ikke hva som går feil med dagens tester. Vi har altfor mange type pakninger, har me , hex, thimbles etc.
        - HMS krav er, R&D rommet er midt i bygget. Høre med hvor vi kan ha test. Hu nye er på HMS. Testoppsettet er å teste så mange pakninger som mulig. Effektivisere varme med å sirkulere varming som i ett kjøleskap.
        - Modulbasert og oppvarming.
        - Andre tester kunne vært å ha rigg med O-ring, Rapid decompression gas (RGD), da revner O-ringene.
        - Enkelt å monter, ønsker å ha omløpshastighet på testing.
        - Trinnløsmotor som styrer settekraft, må ha mulighet til å ha låse av dette. Software hadde vært fint å ha. Hvertfall konsept/design
- Participant 14
    - Svar:
        - Sentralisering. Bedre å fokusere kun på en plugg kategori og heller lage forskjellige casing størrelser
        - Fokusere på vinkling av pluggen, for å se når den er tett og når den ikke er det
        - Måle avstand pakning displacer aksielt, måle mot settekraft og backlash
        - Temperatur, trykk og settekraft

        - Erstatte V0 test, slik at man finne ut hvor mye settekraft man trenger så man er i arbeidssonen før man tester hele pluggen i bunker.
        - Tanke: Tenk hva som skal til for at man kan lage en test slik at man ikke trenger å teste hele pluggen senere.
- Participant 15
    - Svar:
        - Tidligere kun målt trykk og temperatur. Istedenfor å sjekke om den er tett eller ikke, så gå til å se hvor mye /når.
        - Material egenskaper; hvor mye ekspandere det med temperatur. Hva er spenninga midt på elementet?
        - Skaler testen til 1000 psi? Slipper å teste til 10000 psi. Synliggjøre problemer problemene før. Når forsvinner gummi?
        - Vinkel på packerbackups /cones.
        - Andre tester: Stresstesting, kjører temperatur opp og ned. Simuler temperatur på lager over lang tid, finne levetid? Står på høytrykk over lang tid, når begynner det å lekke. Forskjellige varme i vulkanisering, hvordan kan vi se hvilken er bedre den andre.
        - Prioriteringsliste: modulært (høyt) -> viktigere å sammenlign to element, dvs. Usikker på hvilke (outputs, nest høyest) maipulere vinkelen, tetthet/lekkasjerate, trykk og temperatur og måle en respons -> hvilke krefter/spenninger inn i pakninga (trace punkter type tusj/teip). Ha flere løsninger? Glass og rør for forskjellige purpose.
        - Sette pluggen eksentrisk og slarker i ratchen. Eksentrisk-> sentralisering.
        - Andre: Geometrien til pakning. Registrer flest mulig parameter.
- Participant 16
    - Svar:
        - Informasjon om røret, type ruhet, ovalt, osv. Dreid etc.teste I både maskinerte rør og valset rør. Rør egenskapene.
        - Settekraft. Hvordan låser jeg pluggen? Teste backlacsh, med å teste ratchet?
        - Lage test oppsett for tach oppførsel. Jekk med mutter. Du bruker jekk til å sette på kraften, skrur inn mutter, slipper opp jekken, og da har du satt paknigen. En lastcelle på andre som måler kraft.
        - Hvor mye sig har du I pakningelementet, se hvor mye tap har du I kraftcella over tid. Hvor mye settekraft mister man ved temperatur.
        - Vosstech, glass plugg. Glass greia er veldig viktig.
        - 4.5" og 5.5" rør passer alle plugger og blir brukt mest.
        - Temperatur. Hvis det er kun stålrør, så kan vi kjøre det I ett varmeskap. Veldig viktig at det er samme temperatur.

Appendix E

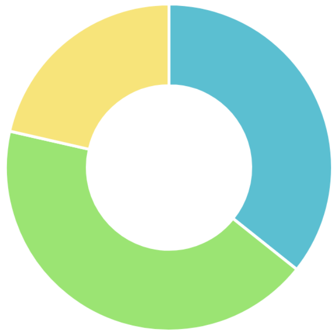
Survey results

The following pages contain the results from the survey that was conducted as part of the empathizing phase.

Understanding the preferences and needs of the end user's and affiliates to the

This survey was sent out to all the employees that interact or are associated with the packer element in the Trondheim department. To understand how the problem statement relates to them and their motivation for this project.

1 Which category do you belong to?



36% (5)
Product Champion

43% (6)
End-User (R&D + R&D-technician)

21% (3)
Specialist/other

(1.25)
Standard Deviation

(14)
Responses

2 Problems with current test setup

1 Logistics (PAX/capacity, amounts test tubes, casing size, etc.)
1.93

2 Test procedure (heating time, redress, setup, etc.)
2.29

3 Lack of data obtained from a test
3.14

4 Price for testing
3.5

5 Unrealistic test setup
4.1

3 What features do you want for the test setup

1 Pressure, Temperature, and V0 (mechanical properties) - existing in current test setup
2.86

2 Mechanical behavior of rubber element (leak, expansion/contraction, distance, etc.)
3

3 Material properties of rubber element (elongational break, hardness, life cycle etc.)
3.07

4 Visual aids under testing (Camera, glass test tube, etc.)
3.29

5 Modularity (different casing sizes and different elements can be tested)
3.93

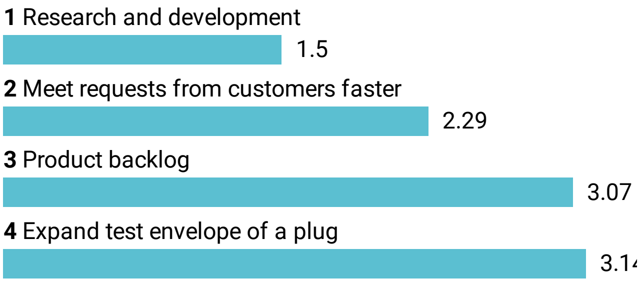
6 Realistic test setup (centralizing, vertical setup, etc.)
5.07

7 Other properties
6.7

4 If chosen other on last question specify

Ikke pga other, men for mekanisk testing av selve gummien så er det allerede karakteriseringstester for denne, livsløp inkludert. Da er enklaver mer viktig, men dette er på siden av testing i testcella og tilhører en material lab.

5 Motivation



Appendix F

Python code and its results

The following pages contain the results the Python code that was written to obtain an estimate on how thick the walls of a pressure vessel needed to be when exposed to a certain internal pressure including a safety factor of two. In addition all the results and graphs from that code are also given below.

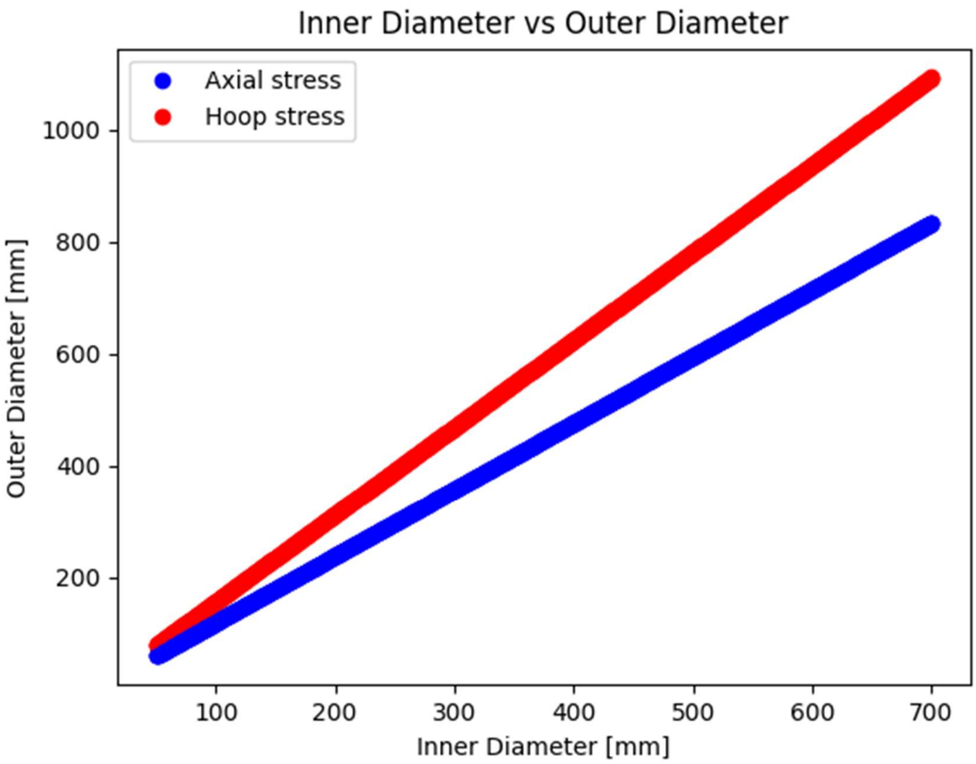
```
import numpy as np
import matplotlib.pyplot as plt

#Constants
psi_20 = 20000  #psi
p_i = psi_20*6894.76 #Pa Convert to pa from 20000 psi
p_o = 0.1*10**6 #Pa is atmospheric pressure
r_min = 25 #mm minimum diameter for test cell, based on the
    smallest plug size available
r_max = 350 #mm maximum assumed diameter for test cell, based
     on the largest plug size available
increment = 7 #increment for readius 350/50 = 14
#What is the allowable stress for ss2541 at 300 deg C if at
    20 deg C it is 800 MPa
# SS2541 is the same as 34CrNiMo6 and AISI 4340 and SAE 4340
# According to https://apps.dtic.mil/sti/tr/pdf/AD0008716.pdf
# SAE 4340 at room temeprature has a yield strength of 106
    000 psi which is 731 MPa
# SAE 4340 at 1000 F or 538 C, has a yield strength of 86 500
     psi which is 596 MPa
# Assume that the yield strength decreases linearly with
    temperature
# we interpolate to find the yield strength at 572 F or 300 C
# Formula for interpolation
# y = (y2-y1)*(x-x1)/(x2-x1)+y1
# y = yield strength
# x = temperature
# y1 = yield strength at x1
# y2 = yield strength at x2
```

```
# x1 = temperature at y1
# x2 = temperature at y2
SE = (300-20)*(596-731)/(538-20)+731 #MPa
#print(SE)
SE = (1/2)*SE*10**6 #Pa, divided by 2 for the safety factor

#Function to calculate wall thickness
#Formula from Lame's equation for thick walls
# p_i represents the internal pressure
# p_o represents the external pressure
# r_i represents the inner radius
# r_o represents the outer radius
# sigma_a represents the allowable stress of the material for
    axial stress
# SE represents the allowable stress of the material. In
   different cases SE will replace sigma's
##########
# Solving the equation using axial stress for thick walled
   cylinder
# Formula for axial stress
# sigma_a = (p_i*r_i^2 - p_o*r_o^2 )/(r_o^2 - r_i^2 )
# Solve for r_o from formula above
# r_o = np.sqrt((p_i*r_i**2 + sigma_a*r_i**2 )/(sigma_a + p_o
   ))

# plot r_i vs r_o to get the wall thickness
r_i = np.linspace(r_min, r_max, 1000)

def out_rad_axial(p_i, p_o, r_i, sigma_a):
    r_o = np.sqrt((p_i*r_i**2 + sigma_a*r_i**2 )/(sigma_a +
       p_o))
    return r_o

##########
# Solving the equation using circumferential stress for thick
    walled cylinder
# Formula for circumferential stress
# sigma_c = [(p_i*r_i^2 - p_o*r_o^2 )/(r_o^2 - r_i^2 )] - [
   r_i^2*r_o^2*(p_o - p_i)/(r^2*(r_o^2 - r_i^2 ))]
# maximum circumferential stress is at when r = r_i
# Solve for r_o from formula above
# r_o = r_i*np.sqrt((p_i+sigma_c)/(sigma_c - p_i +2*p_o))

def out_rad_circ(p_i, p_o, r_i, sigma_c):
    r_o = r_i*np.sqrt((p_i+sigma_c)/(sigma_c - p_i +2*p_o))
    return r_o
```

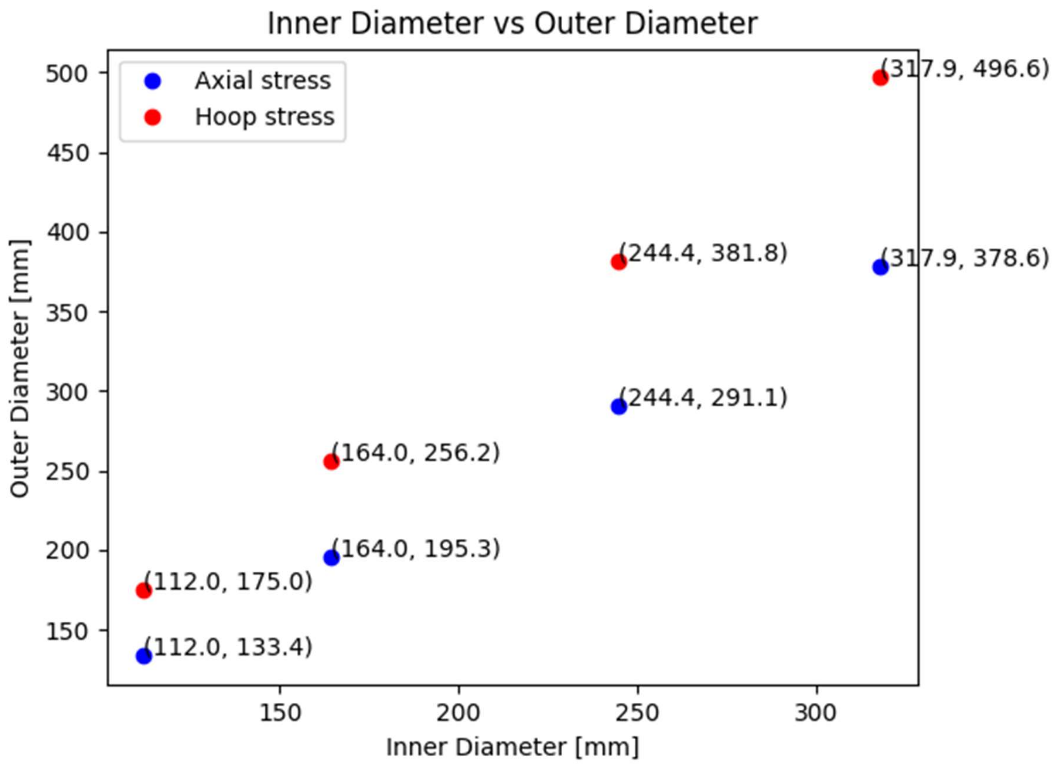
```
#plot r_i vs r_o to get the wall thickness. but multiply by 2
    to get the diameter instead for easier understanding
for i in range(len(r_i)):
    r_o = out_rad_axial(p_i, p_o, r_i[i], SE)
    plot3, = plt.plot(2*r_i[i],2* r_o, 'bo') # multiply by 2
        to get the diameter
    #plt.annotate('({:.1f}, {:.1f})'.format(2*r_i[i], 2*r_o),
        (2*r_i[i], 2*r_o))
    r_o = out_rad_circ(p_i, p_o, r_i[i], SE)
    plot4, = plt.plot(2*r_i[i],2*r_o, 'ro')
    #plt.annotate('({:.1f}, {:.1f})'.format(r_i[i], r_o), (
        r_i[i], r_o))
plt.xlabel('Inner Diameter [mm]')
plt.ylabel('Outer Diameter [mm]')
plt.title('Inner Diameter vs Outer Diameter')
plt.legend([plot3,plot4],["Axial stress", "Hoop stress"])
plt.show()



##########
# Solving the equation using radial stress for thick walled
   cylinder
# Formula for radial stress
# sigma_r = [(p_i*r_i^2 - p_o*r_o^2 )/(r_o^2 - r_i^2 )] + [
   r_i^2*r_o^2*(p_o - p_i)/(r^2*(r_o^2 - r_i^2 ))]
# maximum radial stress is at when r = r_o. measuring for r =
    r_i instead
# Solve for r_o from formula above
# r_o = r_i*
# and thus the wall thickness is zero

##############
#According to strength calculation, the inner diameter of the
    test cell is 112, 164, 244.4, 317.9 mm
D_in= np.array([112, 164, 244.4, 317.9])

#This results in inner radius of 56, 82, 122.2, 158.95 mm
R_i = D_in/2
#print(R_i)

##########
# link to the source where this formula was brought from
# https://www.engineeringtoolbox.com/thick-walled-cylinder-
   d_949.html
```

```
# Plotting for the specific diameter of d_out according to
    the strength calculation sheet

for i in range(len(R_i)):
    R_o = out_rad_axial(p_i, p_o, R_i[i], SE)
    plot1, = plt.plot(2*R_i[i],2* R_o, 'bo') # multiply by 2
        to get the diameter
    plt.annotate('({:.1f},␣{:.1f})'.format(2*R_i[i], 2*R_o),
        (2*R_i[i], 2*R_o))
    R_o = out_rad_circ(p_i, p_o, R_i[i], SE)
    plot2, = plt.plot(2*R_i[i],2*R_o, 'ro')
    plt.annotate('({:.1f},␣{:.1f})'.format(2*R_i[i], 2*R_o),
        (2*R_i[i], 2*R_o))
plt.xlabel('Inner␣Diameter␣[mm]')
plt.ylabel('Outer␣Diameter␣[mm]')
plt.title('Inner␣Diameter␣vs␣Outer␣Diameter')
plt.legend([plot1,plot2],["Axial␣stress", "Hoop␣stress"])
plt.show()
```

Results:



Inner Diameter vs Outer Diameter
Axial stress
Hoop stress
Outer Diameter [mm]
Inner Diameter [mm]
200
400
600
800
1000
100
200
300
400
500
600
700



Inner Diameter vs Outer Diameter
Axial stress
Hoop stress
Outer Diameter [mm]
Inner Diameter [mm]
(317.9, 496.6)
(244.4, 381.8)
(317.9, 378.6)
(244.4, 291.1)
(164.0, 256.2)
(164.0, 195.3)
(112.0, 175.0)
(112.0, 133.4)
150
200
250
300
350
400
450
500
150
200
250
300

Appendix G

Dimensioning the test cell

The following pages contain a snippet from the strength calculation sheet showcasing the the different test cell configurations that were proposed.

ItemID (Doc. No.)	Item Name (Title)	D [mm]	Tol min D Std List	Tol min D Custom [mm]	d [mm]	Tol max d Std List	Tol max d Custom [mm]	Pressure Direction	Pressure	Load direction	Situation	Material	Temp [ºC]	*sf low temp*	*sf high temp*
Test_small_case_1		140	Default		76	Default		Pressure Below	Inside	Tension	Case_small 1	SS 2541 (800 MPa)	300ºC	2,35	2,04
Test_small_case_2		165	Default		90,1	Default		Pressure Below	Inside	Tension	Case_small 2	SS 2541 (800 MPa)	300ºC	2,34	2,03
Test_small_case_3		205	Default		112	Default		Pressure Below	Inside	Tension	Case_small 3	SS 2541 (800 MPa)	300ºC	2,34	2,04
Test_small_case_4		225	Default		124,3	Default		Pressure Below	Inside	Tension	Case_small_4	SS 2541 (800 MPa)	300ºC	2,31	2,01
Test_medium_case_1		230	Default		125,7	Default		Pressure Below	Inside	Tension	Case_medium 1	SS 2541 (800 MPa)	300ºC	2,34	2,03
Test_medium_case_2		260	Default		144,1	Default		Pressure Below	Inside	Tension	Case_medium 2	SS 2541 (800 MPa)	300ºC	2,31	2,01
Test_medium_case_3		275	Default		153,6	Default		Pressure Below	Inside	Tension	Case_medium 3	SS 2541 (800 MPa)	300ºC	2,29	2,00
Test_medium_case_4		295	Default		164	Default		Pressure Below	Inside	Tension	Case_medium 4	SS 2541 (800 MPa)	300ºC	2,30	2,00
Test_large_case_1		315	Default		174,6	Default		Pressure Below	Inside	Tension	Case_large 1	SS 2541 (800 MPa)	300ºC	2,31	2,01
Test_large_case_2		395	Default		219,1	Default		Pressure Below	Inside	Tension	Case_large 2	SS 2541 (800 MPa)	300ºC	2,31	2,01
Test_large_case_3		405	Default		224,4	Default		Pressure Below	Inside	Tension	Case_large 3	SS 2541 (800 MPa)	300ºC	2,31	2,01
Test_huge_case_1		560	Default		252,7	Default		Pressure Below	Inside	Tension	Case_large 1	SS 2541 (800 MPa)	300ºC	2,66	2,31
Test_huge_case_2		570	Default		311,8	Default		Pressure Below	Inside	Tension	Case_large 2	SS 2541 (800 MPa)	300ºC	2,33	2,03
Test_huge_case_3		575	Default		317,9	Default		Pressure Below	Inside	Tension	Case_large 3	SS 2541 (800 MPa)	300ºC	2,31	2,01

Appendix H

HSE risk assessment

The following pages contain the HSE risk assessment completed using NTNU's system. Only a Norwegian version is available.

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