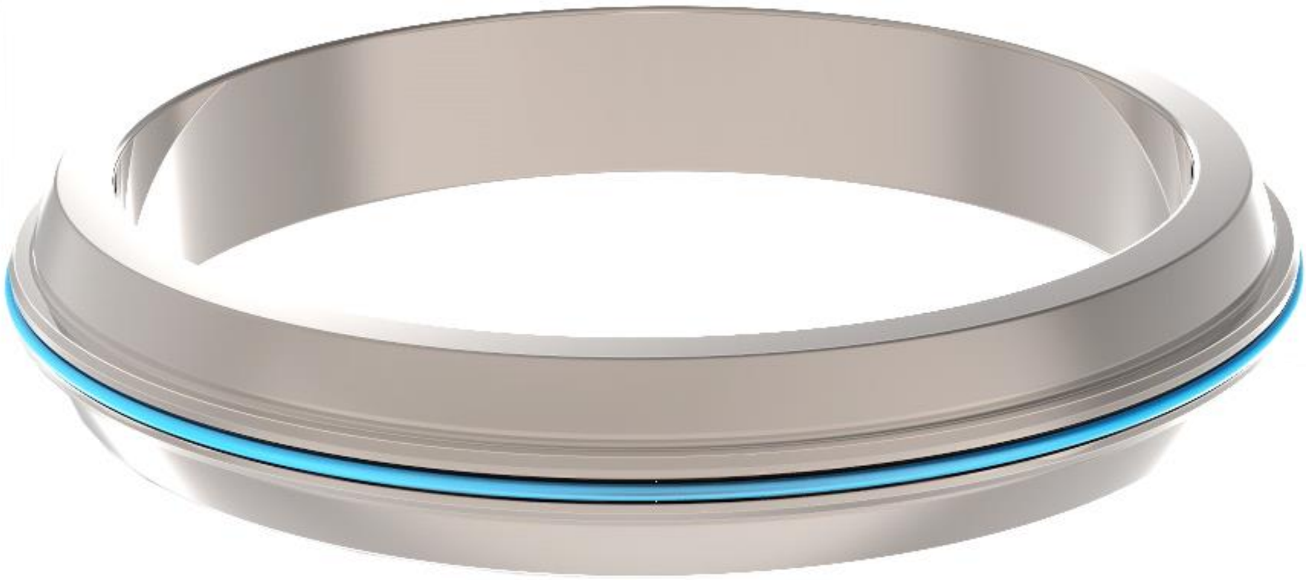

Design of a Seal Retainer Ring

Bachelor's thesis in product and production development

BENJAMIN GROZDANIC
BEN LISOWSKI
JOE MALESPINI
EVAN PATAKI
KARL STÅHLBERG
WILLIAM STÅHLBERG

Department of Product and Production Development
CHALMERS UNIVERSITY OF TECHNOLOGY
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BACHELOR THESIS 2016

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This bachelor's thesis covers the development of a seal retainer ring for Aker Solutions' TX Seals inside their 22-inch hubs.

BENJAMIN GROZDANIC
BENJAMIN LISOWSKI
JOE MALESPINI
EVAN PATAKI
KARL STÅHLBERG
WILLIAM STÅHLBERG

Department of Product and Production Development
Chalmers University of Technology
SE-412 96 Gothenburg
Sweden
Telephone +46 (0)31-772 1000

Cover:
Aker Solutions' TX Seal with a seal retainer O-ring

Gothenburg, Sweden 2016

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Preface

This bachelor thesis is an international cooperation between students from Chalmers University of Technology, Gothenburg, Sweden, and Pennsylvania State University, State College, USA. The students representing the Mechanical Engineering Program at Chalmers are: Benjamin Grozdanic, Karl Ståhlberg and William Ståhlberg. Representing Penn State are students Ben Lisowki, Joe Malespini and Evan Pataki. The project ran over one semester and covers 15 ECTS.

The team would like to express their gratitude to the sponsor Aker Solutions Inc., Houston Texas, USA, especially Korey LeMond, Engineering Supervisor, Aker Solutions ASA, Houston, Texas.

We would like to thank Seal Engineering AS (Fredrikstad, Norway) for graciously providing O-rings for the material testing stage.

We would like to thank our supervisor, Professor Mikael Enelund, Head of the M.Sc. Engineering Program in Mechanical Engineering, Chalmers University of Technology, for his excellent guidance and technical knowledge.

We would like to thank Senior Lecturer Göran Gustafsson, Product and Production Development, Chalmers University of Technology, for his superb guidance in product development and advice during the project.

The Penn State team would like to thank Assistant Professor Jason Moore at Penn State, for his valuable guidance throughout the project.

We would also like to thank Jonas Norlin at Ansys Inc., Gothenburg, Sweden, whose ANSYS assistance was invaluable to the project.

Finally, we would like to thank our examiner, Professor Ola Isaksson, Product and Production Development, Chalmers University of Technology, for his support and valuable input.

Executive Summary

Aker Solutions Inc., Houston, Texas, USA, supplies equipment used for the transportation of extracted crude oil from the seabed to the oil platform. One of the building blocks for installation of this subsea infrastructure is so called *tie-ins*, which are used to connect the subsea infrastructure and the pipelines that lead to the oil platform. To keep these connections leak-proof, Aker Solutions use their *TX seal*. Around this TX seal is an elastomer retainer ring that keeps it fastened to the connection hub during onshore installation procedures.

A team at Chalmers University of Technology and Pennsylvania State University were assigned a project with the objective of redesigning the retainer ring solution to optimize its functionality. The project focused on the larger sizes, 16 and 22-inch (410mm and 560mm) respectively, whose seals fail to be retained inside the hub when subjected to large impact forces. Focus was on the 22-inch seal as it was deemed to be the most troublesome variant. Besides being retained inside the hub, the TX seal must be easily removed using onshore hydraulic tools. This gives a force window between 15kN and 30kN, which the retention force must stay within. Aker Solutions stated that the current retainer ring solution is the most cost-effective compared to its competitors, and they would like to maintain this advantage.

The team generated eight solutions using patent research, product development methods and drawing from competitor alternatives. Less optimal solutions were eliminated using engineering methods such as elimination and Pugh matrices until three concepts, circular, square, and quad-lobe cross section, were left.

Simulations were carried out on the concepts in ANSYS and in addition to analyses on the current system in order to establish parameters such as proper coefficients of friction for the concept simulations. The simulations were comprised of stretching out the retainer ring over the seal inside the hub and then displacing the seal, simulating the removal process. From this, a reaction force could be obtained. Parameter studies were conducted on different diameters and shapes to find the one that yielded the best results.

Simulation results showed that the circular cross-section was the most optimal. Taking availability into account, the final recommendation for Aker Solutions is an O-ring with a cross-sectional diameter of 7.8mm of the material RU1 (ABR85), with a Shore hardness of 85, which is available from Aker Solutions' current vendor, Seal Engineering AS, with the low-cost requirement also being met.

The Chalmers team was given additional time to conduct physical material tests to verify several analytical assumptions and also to investigate a redesign of the whole system, broadening the original limitations set for the project. A solution was found that could advantageous to Aker Solutions, were they to consider such a redesign.

Sammanfattning

Aker Solutions ASA, Houston, Texas, USA, är ett företag som tillverkar utrustning som används vid transport av olja från havsbotten till oljeplattformen. En viktig del av denna undervattensinfrastruktur är så kallade *tie-ins* vilka är hubbkopplingar mellan rör som transporterar oljan till plattformen. För att hålla dessa kopplingar täta använder Aker Solutions *TX seals*. En tillhörande komponent är O-ringen i elastomermaterial, vars funktion är att hålla tätningen på plats inuti rören under hopmontering i land.

En grupp vid Chalmers Tekniska Högskola och Pennsylvania State University fick i uppdrag att designa en O-ring. Målet med projektet var att förbättra funktionaliteten hos de O-ringar som används av Aker Solutions. Detta gällde deras största modeller, i storlek 16 tum respektive 22 tum (406 mm respektive 559 mm), då dessa inte håller kvar tätningarna på plats inuti hubben när de belastas med yttre krafter. Förutom att hålla kvar tätningen inuti hubben, så måste tätningen gå att byta ut med hydraulverktyg som är tillgängliga på plats. Det ställer i sin tur krav på den kraft med vilken tätningen hålls kvar, som ligger i ett intervall mellan 15 kN och 30 kN. Aker Solutions konstaterade att deras nuvarande O-ringslösning var den billigaste på marknaden och att de om möjligt ville behålla denna fördel gentemot konkurrerande produkter. Dessutom ville företaget kunna köpa O-ringen som standardprodukt.

Med hjälp av patentundersökning, produktutvecklingsmetoder och alternativ från konkurrenter genererades åtta koncept fram. De sämre lösningarna eliminerades successivt med metoder som elimineringssmatris och Pugh-matriser tills tre koncept återstod: O-ring med cirkulärt, kvadratiskt och ”quad-lobe”-tvärsnitt, som skulle simuleras med FE-analyser.

Simuleringar utfördes med mjukvaran ANSYS till en början på den nuvarande lösningen för att etablera nödvändiga parametrar så som friktionskoefficienter som skulle användas i senare analyser. Analysens komplexitet låg i programmering av många kontaktpunkter tillsammans med deformation av hyperelastiska material. Detta resulterade i simuleringar där O-ringen sträcks över tätningen och sedan tvingas ut för att simulera utbytningssproceduren. För att få fram den optimala O-ringen gjordes en parameterstudie med varierande diameter för de tre olika koncepten.

Resultatet visade att ett cirkulärt tvärsnitt var det mest optimala. Slutligen eftersöktes marknaden för att finna lämpliga leverantörer, och den slutliga rekommendationen är en en O-ring med cirkulärt tvärsnitt med diameter 7.8mm i materialet RU1 (ABR85) med Shore-hårdhet 85 (skala A). Den här O-ringen finns tillgänglig hos Aker Solutions nuvarande distributör Seal Engineering AS inom de angivna prisgränserna.

Chalmersteamet gavs extra tid för att göra fysiska tester för att verifiera analytiska antaganden. En total omkonstruktion av systemet undersöktes också, i det fall det skulle vara av intresse för Aker Solutions.

1. Introduction and Background

The following section describes the background, problem statement, how the team plans to approach the problem and what limitations are set for the project.

1.1. Background

Aker Solutions Inc. (Houston, Texas, USA) supplies equipment for transporting crude oil from the seabed to the oil platform, where one of the essential components is tie-ins, which are connections between subsea equipment and the pipelines that transport oil to the oil platform.

One of the core components in ensuring that the tie-in connections are leak-proof, is Aker Solutions' TX seal, shown as (2) in Figure 2. Around the TX seal sits an elastomer retainer ring, shown as (3) in red, which ensures the seal is retained inside the hub (1) during the onshore installation procedures. In the summer of 2015, Aker Solutions was in the process of qualifying the 16 (406.4mm) and 22-inch (558.8mm) TX seals, when during an onshore testing procedure, a 16-inch TX seal weighing 28 pounds fell out of the hub due to impact forces that reached several thousand newtons.

This incident could have led to major injuries due to the heavy equipment and as such is a health and safety concern for Aker Solutions. The company has not experienced these problems with the smaller seals and therefore the project focuses on the 16 and 22-inch seals.

The project is a collaborative effort by students at Chalmers University of Technology in Gothenburg, Sweden and Pennsylvania State University in State College, Pennsylvania, USA for the Tie-Ins department at Aker Solutions in Houston, Texas, USA, responsible for connecting subsea equipment.

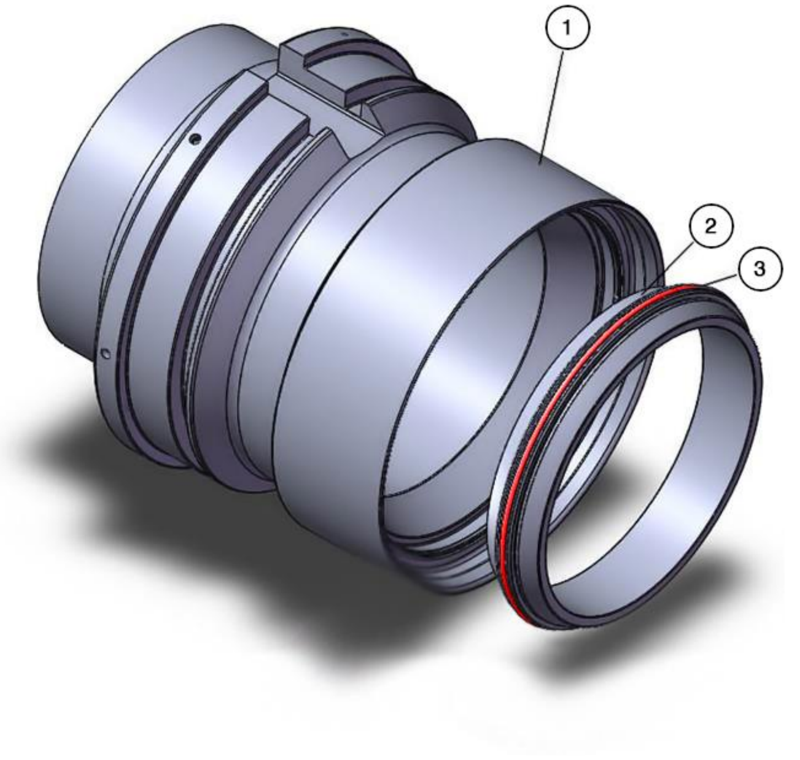


Figure 2. *The hub (1) pictured with the TX seal (2) and the elastomer O-ring (3) colored in red [1].*

1.2. Problem Formulation and Statement

The incident mentioned in the background section was caused by the failure of the retainer ring in retaining the TX seal when the hub is in an upright position, as pictured in Figure 3. The seal is retained partly by the friction forces between the elastomer retainer ring and metal hub, and partly by an extension of the hub, shown in the magnification in the bottom right of the figure. These were not sufficient to hold the seal in place. In addition to retaining the seal, the O-ring must not make the seal impossible to remove by the hydraulic tools that are available at the onshore site.

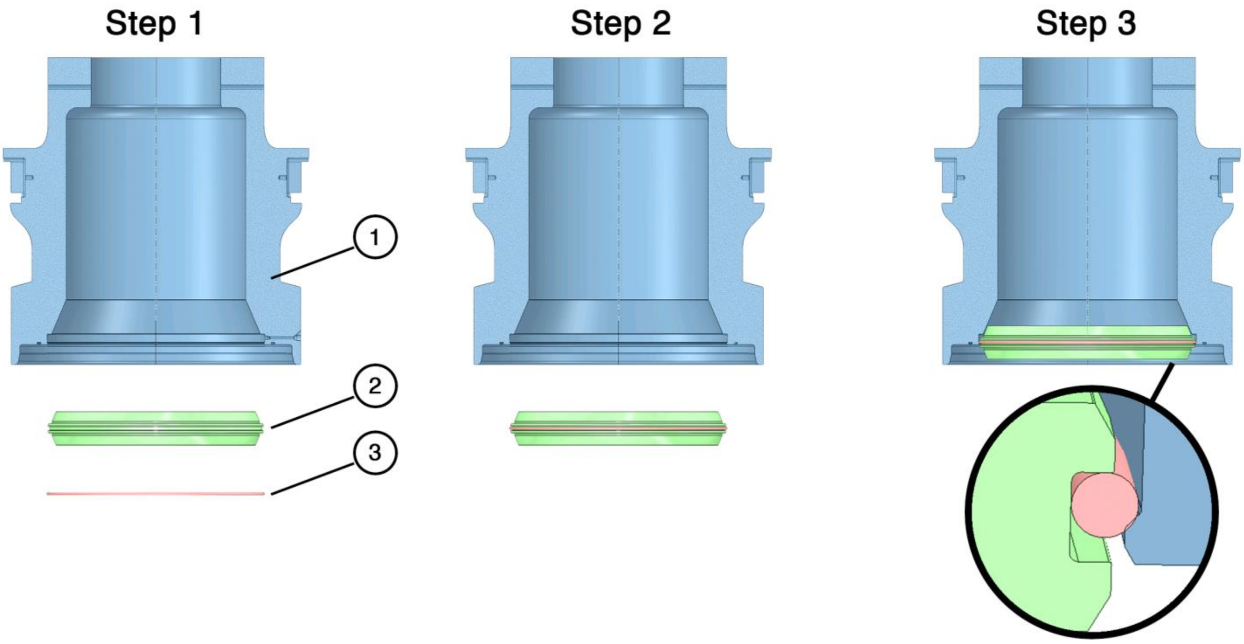


Figure 3. *Pictured is the hub (1), TX seal (2) and elastomer O-ring (3). Step 1: The hub is in an upright position with gravity acting downward in the picture. Step 2: The O-ring is stretched around the TX seal. Step 3: The TX seal is inserted into the hub, where the O-ring holds the seal in place.*

1.3. Objectives

The objectives set for the team of Pennsylvania State University and Chalmers University of Technology students are to design a seal retainer ring with sufficient friction to retain the 22-inch TX seals during onshore installation as well as having high predictability in terms of the force required to remove the seal, as the 22-inch is the worst-case scenario. The product must also meet Aker Solutions’ safety standards, be available as an off-the-shelf product of a cost in line with that of the current product. These are defined in Appendix 13.5 “Target Specifications”. Finally, the project is to be carried out in a timely manner within the allocated resources.

1.4. Scope of Work and Limitations

Per Aker Solutions’ request, the redesign is limited to only changing the O-ring, keeping the seal and hub geometries intact, and the final product will be a new type of O-ring. After a new design has been finalized and presented, the project will use the remaining time to focus on expanding Aker’s limitations. The team will investigate a redesign of the seal and hub to explore the possibility of a more advantageous retention mechanism. The project will use finite element (FE) software and other engineering software to verify compatibility and calculate the seal retaining function. If time permits it, verification of the analytical parameters will be done with functional tests.

1.5. Overall Approach

With the problem formally defined, the team will use previous experience, patent research and idea generation to create a wide range of possible solutions. Less optimal solutions are successively eliminated by evaluating them using an elimination matrix, which is based on the requirements set by the target specifications. The remaining concepts are evaluated in a *Pugh matrix* using the weighted needs established in an *analytical hierarchy process* (AHP) matrix. The concepts that are not eliminated in the matrix will finally be analyzed and optimized using the FE software ANSYS Mechanical (ANSYS, Inc.) [2]. A decision is made on the optimal solution and it is chosen as the final concept. After the final optimization and verification of the concept is done, a detailed design specification will be created.

Using the remaining time, material properties are verified by the use of physical tests on the current O-ring and an investigation into a redesign of the seal and hub will be done using the *computer assisted design* (CAD) software CATIA (Dassault Systèmes SE) [3].

2. Team and Project Management

The following section describes how the team is structured and how the communication with Aker Solutions will be carried out. A detailed analysis of potential risks is described, as well as ethical and environmental considerations.

2.1. Project Management

The project extends over one university semester and has been planned in detail by the creation of a Gantt chart [4], found in Appendix 13.4 ”Gantt Chart”. The Gantt chart illustrates the start and finish dates of significant milestones as well as smaller tasks for the project. Milestones have been highlighted in the chart to clarify their importance and for the team to get a sense of progression. In addition to every start and finish date, percentages of task completion are maintained to actively use the Gantt chart and carry it on throughout the project.

The deliverables are the most important milestones in the Gantt chart and the ones set by the sponsor Aker Solutions have been defined in Appendix 13.3 ”Learning Factory Industry Project - Deliverables Agreement”. Besides the ones set by Aker Solutions, additional internal deliverables have been added by Pennsylvania State University and Chalmers University of Technology. An exhaustive list of the project deliverables is found below. Delivery dates are found in Appendix 13.4 “Gantt Chart”.

- Project Proposal
- Weekly Update Memos
- Detailed Design Specification Report
- Poster (32 x 40”) for Showcase at Pennsylvania State University (internal)
- CAD files of the Retainer Ring
- ANSYS FE model project files
- Animations of FE simulations
- 3D-printed Visual Prototype (internal)
- One-Page Project Recap (internal)
- Final Presentation
- Final Report

Continuous communication between the teams at Penn State and Chalmers is vital for the project’s success and is maintained through meetings every Tuesday with both teams and their supervisors. Additionally, group communication on a daily basis will ensure that the project progresses in the right direction.

2.2 Team Management

To achieve the targets set in the Gantt chart and to lead the team forward, it has been decided to have a rotating project manager for the team. Each member covers the position of project manager for a period of two weeks, after which a final project manager is decided on to lead the team throughout the remainder of the project. The project manager is in charge of giving assignments to the team members, making sure everyone does their job and sends out the weekly memos every Friday. Both the Chalmers and Penn State team each have a secretary responsible for successful communication and managing of information through the project. To ensure proper conduct of every team member during the project, rules are set up in a group contract which is found in Appendix 13.1 "Group Contract".

2.3 Preliminary Economic Analysis

Penn State and Chalmers teams have separate budgets. The Penn State team was given a budget of USD 1000 which are planned to be used for a prototype of the seal and hub and to purchase the chosen seal retainer, if time permits. The Chalmers team is only limited by the resources available at their workshop. The Chalmers team is also given a budget of SEK 2000 for the purchase of the chosen seal retainer for presentation and material testing.

2.4 Risk Plan and Safety

The key to a successful project in terms of meeting project deadlines within allocated resources is risk identification and risk mitigation. The following section discusses the risk method used to find the risks, and measures that will be taken in order to reduce or eliminate the risks. The method that is used is Failure Mode and Effects Analysis (FMEA) using the method by DAAAM International [5]. This is used to identify and evaluate risks, their consequences and ways to mitigate them.

A table is created containing a description of each risk, its outcome, measures to minimize the risk and a fall back plan if the risk were to emerge. For each risk, the probability, lack of predictability and severity is estimated and multiplied together to obtain the *risk priority number*. This value falls into three categories.

The team identified 11 possible risks, found in Table 1. Out of these 11 there were four risks that were over the threshold of 100 in risk priority: "Insufficient knowledge", "Incorrect FE results", "Miscommunication with Aker Solutions" and "Failure to set up working FE model". These will be paid extra attention to throughout the course of the project are the biggest threat to the project. The FMEA is a tool that will be carried along during the entire project to meetings to see if any of the risks have emerged.

Table 1. The FMEA identifies the risks, outcomes, measure to minimize the risk and the fall back plan. These are the rated on probability, lack of preventability and severity, which are multiplied together to obtain a *risk priority value* on a scale of 1-1000. A risk priority number greater than 100 means extra attention needs to be paid to those risks during the course of the project. Four such risks were found. A risk priority number greater than 300 or a very high severity means measures have to be taken to eliminate the risk. No such risks were found.

Risk	Outcome	Measures to minimize risk	Fall back plan	Proba- bility	Lack of preventa- bility	Sever- ity	Risk Priority Number
Insufficient knowledge to do analysis	The analysis of the final product cannot be continued.	Start early with analysis assistance to make sure all the required knowledge is available .	Suspend project focusing all attention on solving the lack of knowledge.	5	5	8	**200**
Missed conferences, bad communication	Information between team involves gets lost or delayed.	Always prepare before conferences, double check when unsure about information.	Make sure all information from conference calls and other comunication is readily available at all times.	1	5	2	**10**
Bad work environment due to personal or opinion differences.	Loss of work, time and team spirit.	Make team members be attentive of each other to notice anything bad that might arise.	The current team leader will be the arbitrator in decision disagreements.	3	2	3	**18**
Late deliverables	The project gets delayed and risks not meeting other deadlines.	The project leader makes sure the project status is in line with the Gantt Chart.	Extra hours are put into the project in order to catch up to the schedule.	1	1	5	**5**
Aker Solutions not satisfied with the final product.	The project is a failures in the eyes of the customer.	Check up with the customer during the designing of the final product.	The extra time that the Chalmers team has will be used to improve the final product.	2	3	5	**30**
Incorrect FE results	The analyses give a false representation of the product.	Check with supervisors and double check analysis parameters to make sure everything is correct.	Extra work will be put in to correct the analyses.	6	3	6	**108**
A certain part of the project is carried out incorrectly.	The project may suffer as a whole and not reach its full potential.	Consult with supervisors when in doubt about the execution of part of the project.	Seek help from supervisors to get back on track and put in extra work for correct execution of task	8	3	4	**96**
Not enough time is allocated for a task.	The task is delayed	Continuously evaluate if the tast will be completed on time.	Reorder the Gantt Chart or put in etra work to make up for the delay.	6	3	5	**90**
Misscomunication with Akers Solutions	Wrong information leads to wrongly executed tasks	Double checking everything and sending weekly memos on process	Extra work will be put in to correct the mistakes.	4	6	5	**120**
Failure to set up a working FE model of the system.	The analysis of the final product cannot be continued.	Start early with FE analysis to ensure its feasability.	Simplify the analysis model and make use of hand calculations.	6	4	8	**192**
Incorrect or insufficient CAD files are provided by the sponsor.	The analyses do not represent reality.	Start early with analysis to make sure the CAD files leads to results that agree with the other information provided.	Put in extra work to make up for the incorrect results.	2	2	6	**24**

Risk value = P*LoP*S

P = "Probability that risk leading ot failure" on a scale of 1-10
LoP = "Lack of the risk being preventable" on a scale of 1-10
S = "The severity of the risk if it emerges" on a scale of 1-10

(green)	1-100
(yellow)	101-300
(red)	301-1000

2.5 Ethics Statement

The current design at Aker Solutions compromises safety when the retaining mechanism falls out. When a design is known to be unsafe and still is in operation, ethics come into play. A redesign of the retaining mechanism is ethically just. Safety is a core value at Aker Solutions.

The Aker Solutions design team places engineering ethics at the forefront of the team's values. Aker's website describes this value as, "essential that we do everything possible to ensure the safety of our employees, customers, subcontractors, consultants and other parties." Additionally, the American Society of Mechanical Engineers (ASME) describes ethics in their constitution. The constitution states that engineers will "advance the integrity, honor and dignity of the engineering profession" in three ways:

1. by helping human welfare by using knowledge and skill
2. by glorifying honesty and fairness in business and with the public
3. by making engineering more prestigious

Throughout the proposed project, the Aker Solutions Design Team will cherish these three parts of ethics as described by the ASME and the subsequent canon. Specifically, the design team will use their strengths to help engineer an innovative solution; an engineer should not be incompetent to compete unfairly and place others at risk. Additionally, the team will act as "faithful agents", avoiding conflicts of interest. During the patent search and alternative solutions search, the design team will respect proprietary information. Finally, a sustainable solution is essential to the design team's success in this project. While the design team realizes that the offshore oil and gas industry has challenging environmental effects, the team places sustainability at the forefront of its ethics issues. A harmful solution to the environment is not a solution at all, but a burden and a breach of ethics.

2.6 Environmental Statement

Bjarke Ingels, renowned Danish architect, stresses sustainability by saying it "can't be like some sort of a moral sacrifice or political dilemma or a philanthropic cause. It has to be a design challenge." The Aker Solutions Design Team is prepared to accept Ingels' challenge in their quest for a sustainable solution. Not only does a poor design hurt the Aker Solutions' reputation, but more importantly it hurts the only planet humans call home.

Moreover, the growing challenges of sustainability and stewardship are pushing engineering designs to unprecedented heights. The redesign of the retainer ring will challenge the sustainability of the design. The new design must optimize materials needed in quality and quantity. Additionally, the increased predictability will eliminate the seals that drop into offshore environments with the possibility to rust and damage subsea infrastructure and pipelines which could lead to leaking the oil.

2.7 Communication and Coordination with Aker Solutions

Continuous communication with Aker Solutions is kept on progress, verification of assumptions and to get clarification when in doubt. For this reason Chalmers and Penn State teams sets up meetings with Aker when felt necessary. The majority of communication is however held through email. The points of contact from Aker Solutions are Korey LeMond from the Tie-Ins department in Houston, Texas.

To present the current work and progress that has been made, the team sends weekly reports to Aker Solutions and the teams' respective supervisors. All files between the team and Aker Solutions are shared using a common cloud and communication is done via email and over the phone.

3. Customer Needs Assessment

The following section describes the needs of the customer, Aker Solutions. These were established over the course of two meetings with Aker Solutions. The information is first listed and analyzed in this section and is later quantified in Section 5.3 "Target Specifications".

The needs are additionally weighted in an AHP chart formulated in cooperation with Aker Solutions. The weighted needs are used in the Pugh matrix to rank concepts, which is found in Section 6 "Concept Generation and Selection".

3.1. Summary of the Customer Needs

The list shown below describes the needs of Aker Solutions established during the two meetings.

Needs:

- *Performance:* The ring needs to be able to retain the seal during impact loads to the system as well as the own weight of the seal. At the same time, the seal must not be impossible to be removed by hydraulic removal tools (ability to install is not a problem reported by the customer, but will be treated as an additional function of the retainer ring).

- *Safety:* It must be non-toxic according to OSHA/EU-OSHA [6, 7] as it is handled by workers.

- *Availability:* It must be an off-the-shelf product that is available from several vendors, preferably the current vendor Seal Engineering AS (Fredrikstad, Norway).

- *Durability:* It should resist oil and water and not deteriorate to the point of not meeting all the target specifications.

- *Cost:* It must be cost-effective, close to the cost of the current solution.

- *Reliability:* It should be reliable in terms of expected retention and ability to install and remove.

- *Ease of Implementation:* The onshore procedures should not have to be changed because of the new solution.

3.2. Weighting of Customer Needs

An Analytical Hierarchy Process (AHP) [8] chart is used for making complex decisions. The AHP weighs various needs against each other in order to figure out which are the most important ones. The results from the AHP can be used to better design a solution to a problem. Knowing which aspects are the most important gives the designer the ability to prioritize which wants are the most desired in the final design.

The AHP in Table 1 was formulated in cooperation with Aker Solutions using the methodology from the North Carolina State University [8]. The criteria are taken from the needs established in the previous Section 3.1 “Summary of the Customer Needs”.

Table 2. Analytical Hierarchy Process (AHP) is a pairwise comparison chart used to determine the weighting of the customer needs. The criteria are taken from the needs established in the previous Section 3.1 “Summary of the Customer Needs”.

	Perform-ance	Safety	Availa-bility	Dura-blility	Cost	Relia-bility	Ease of impl.	Total	Weight
Performance	1	4	2	2	0.5	1	1	9.5	15.4%
Safety	0.25	1	1	1	0.25	0.5	0.5	4.75	7.7%
Availability	1	0.5	1	1	0.25	0.5	0.5	4.75	7.7%
Durability	1	0.5	1	1	0.25	0.5	0.5	4.75	7.7%
Cost	4	2	4	4	1	2	2	19	30.8%
Reliability	2	1	2	2	0.5	1	1	9.5	15.4%
Ease of impl.	2	1	2	2	0.5	1	1	9.5	15.4%

From the AHP, the weighted customer needs are:

Performance: 15.4% Safety: 7.7% Availability: 7.7% Durability: 7.7%
Cost: 30.8% Reliability: 15.4% Ease of impl.: 15.4%

It can be seen that cost is the most important criterion. Second most important is safety, reliability and ease of implementation. These criteria are very close together and are all very important aspects for the success of the design. When designing the final solution the results from the AHP will be taken into account to obtain the best solution possible. The result from the AHP will also be used in the Pugh matrix, when weighing the different concepts against each other.

4. External Search

An external search is done in order to get familiarized with the previous solutions and ideas by making patent research and looking into existing products.

4.1. Patents

A patent search is carried out at the beginning of the product design project for multiple reasons. One reason is that knowing what has already been invented may help in thinking of new ideas. Another reason is to know what ideas are already patented so that they later on do not cause patent problems.

The following patents and alternative solutions concern designs of retainer rings and other methods of retaining circular geometries inside each other. Only the three listed below will be explored, as circular retaining is a mature technology and as such there are many retaining solutions available on the market.

4.1.1 Sealing Ring and Joint, Tommy J McCuistion (US 2841429 A)

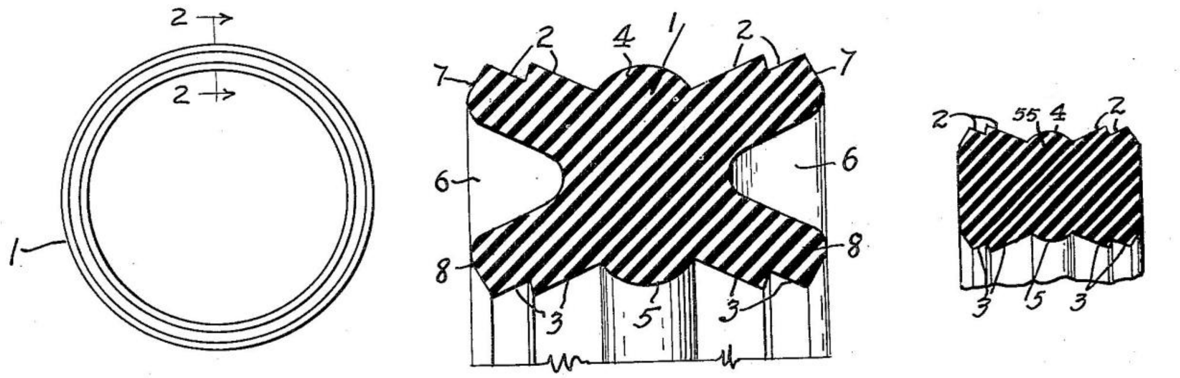


Figure 4. *Extract from US 2841429 A. The cross-sectional profile seen in the middle right illustration could provide deformations when inside the sealing geometry that would be interesting to explore [9].*

"... [It is the] object of this invention to provide a sealing ring which, when installed in a chamber, is deformed to varying degrees, with greatest deformation in those zones of the ring which are relatively flexible and have essentially a line contact with the chamber surfaces and with least deformation in those zones of the ring which are solid, thus not so flexible, and which have a surface contact, though relatively narrow, with the chamber surfaces." (Extract from US 2841429 A) [9]

The profile would be compressed when installed in the hub where it would likely provide uneven deformation when inside the hub as it yields a flat surface when deformed that is more flexible than a regular square profile. The deformations are radically different from that of the regular O-ring and as such are of interest.

4.1.2 Sealing Ring, Willem Bakker (US 2688506 A)

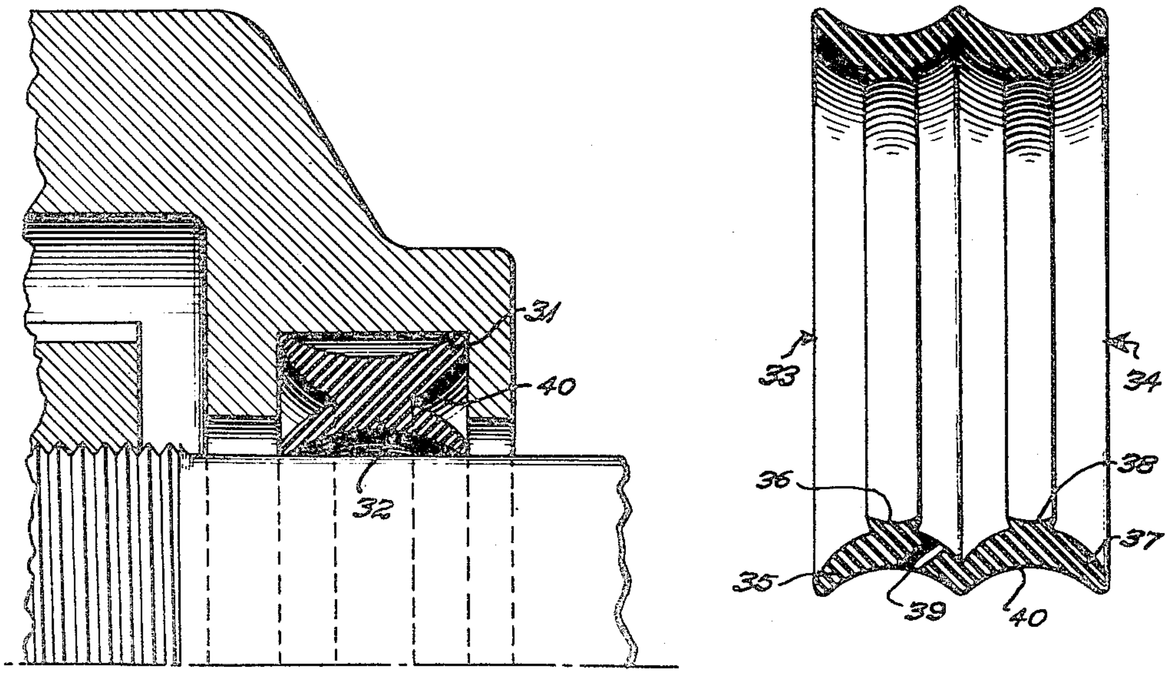


***Figure 5**. Extract from US 2688506 A. Similarly to the previous patent in section 4.1.1 the side geometry would provide a leverage point for extracting the retainer ring [10].*

This patent in Figure 5 is similar in nature to the previous patent in Section 4.1.1. Although the patent is concerned more with the seal property of the design, it remains an interesting design to consider in together with Section 4.1.1.

4.1.3 Sealing Means, Ernest J Svenson (US 2700561 A)

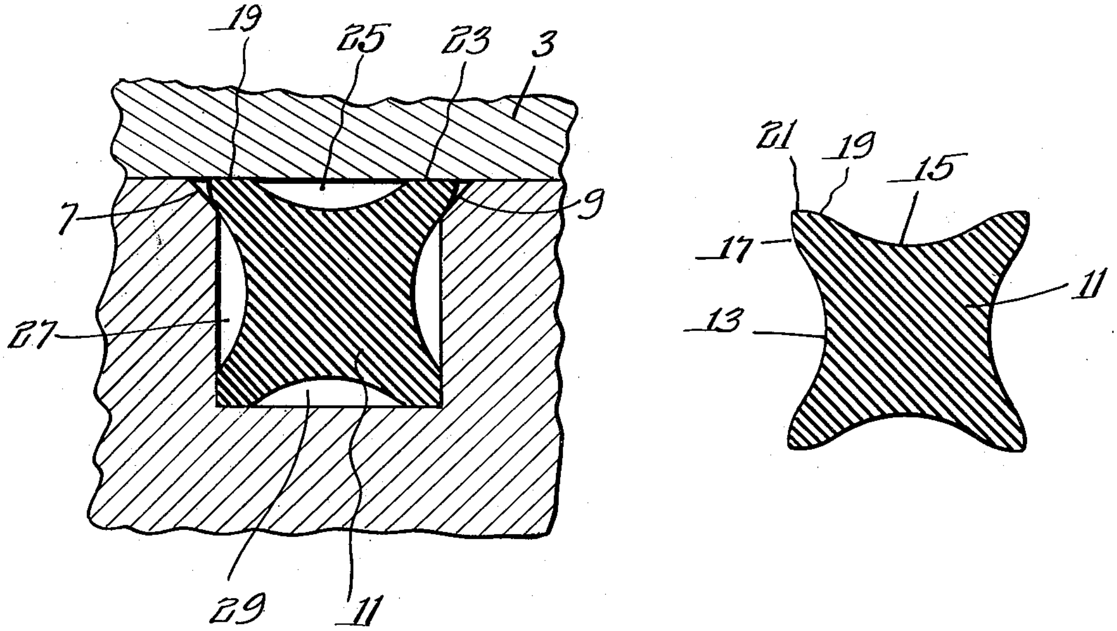


Figure 6. *Extract from US 2700561 A. The profile would likely be of oval shape when deformed, but because of its symmetrical nature is more likely to be found as an off-the-shelf ring than the previous patents [11].*

The profile in Figure 6, when in deformation between the seal and hub could be seen as an O-ring with four extensions that will likely result in an oval shape. It is still similar to the patents in Section 4.1.1 and 4.1.2, however, because of simple symmetrical geometry is more likely to be found as an off-the-shelf elastomer ring.

4.2. Existing Products

Retainer rings are a mature technology and as such there is a vast selection of geometries, materials and vendors already on the market. Seal Engineering supplies the current O-ring to Aker Solutions, which is an ISO 3301 O-ring available off-the-shelf. Aker Solutions wishes to maintain this high availability in the new design and it is therefore sensible to investigate the other products supplied by Seal Engineering.

There are only two properties that affect the performance of retainer rings, the cross-sectional profile and the material. However, predicting how a ring behaves inside a specific geometry is difficult. For this reason not many predictions can be made on how different properties affect the performance and are instead be left to the analysis stages of the project.

The following Sections 4.2.1 and 4.2.2 present different retainer profiles and materials that are supplied by Seal Engineering and are of interest for the project and will provide inspiration and guidance during the concept generation stage.

4.2.1 Retainer Ring Profiles

Presented below are different cross-sections that are of interest with brief descriptions taken from the catalogue "Sealing Solutions" [12] from Seal Engineering. The profiles are shown in Figure 7.

O-ring

An O-ring is a static retainer ring with "[…] proven reliability in multiple applications in every sector of industry. Excellent adaptation possibilities for diverse temperatures and media by selection of suitable seal material. Mainly used as static seal or as preloading element for composite-seals." [12]

Square Ring

Square ring is a static seal retainer "[…] mainly used for static applications or as gaskets. Excellent adaptation possibilities for diverse temperatures and media by selection of suitable seal material." [12]

Double Seal

Double seal is a static retainer ring with "Improved sealing compared to O-ring. During assembly no twisting will occur and there is no risk of bad backup ring position. O-ring and backup ring are more sensitive to pressure pulsing resulting in ingress of dirt between the sealing elements." [12]

K35-P

K35-P is a piston retainer ring and "[…] is an optimized alternative to conventional O-rings, especially for dynamic applications." [12]

K20-R

K20-R is a piston retainer ring and is a "Space saving, compact piston seal, suitable for standard O-ring housings. Advantage compared to O-ring: integrated active backup rings for high pressure. Design with stretch fit on inside diameter prevents twisting in dynamic applications" [12].

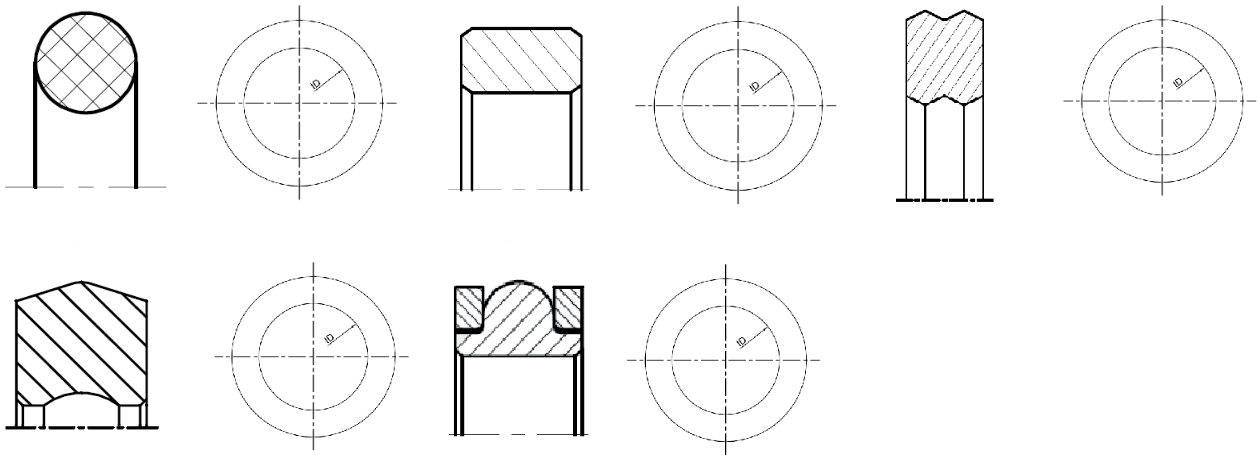


Figure 7. *From left to right: standard O-ring, square ring, double seal ring, K35-P ring, K20-R. These profiles are of interest and will be considered during the idea generation stage.*

4.2.2 Retainer Ring Materials

The listed materials are specifically for O-rings provided by Seal Engineering with brief descriptions of their uses and properties.

NBR (Nitrile-Butadiene-Rubber)

"NBR is the most common material used for O-rings, and has good resistance against mineral based oils, fuels and grease. NBR also exhibits low gas permeation and very low compression set. NBR is typically used for oil-based hydraulics, given that the temperature is within working parameters. Temperature range -35 ºC to 110 ºC. Extended range -50 ºC to 125 ºC." [12]

PU (Polyurethane)

"PU is extremely resistant to abrasion compared to most elastomers, and is often used for applications with high demands for longevity and/or high pressure. PU is also a natural choice for dynamic sealing. PU is available in many different compounds to suit a given application. Temperature range -50 ºC to 110 ºC. Extended range up to 130 ºC." [12]

FVMQ (Fluorsilicone-Rubber)

"FVMQ is a modified silicone often used [in oil applications because of its high resistance] against oils and fuels given large variations in temperature. FVMQ has the same good resistance to ozone and weathering as MVQ, and similar poor mechanical properties. Temperature range -60 º C to 200 ºC. Extended range -100 ºC to 210 ºC." [12]

PTFE (Polytetrafluorethylene, Teflon)

PTFE has excellent resistance against chemicals and temperature. PTFE is resistant to all known chemicals, acids and solvents except molten alkali metals and elementary fluorine at high temperatures. PTFE can have various fillers to suit a given application. Temperature range -200 ºC to 260 ºC [12].

5. Engineering Specifications

This section describes the analysis of the current product that together with the needs gathered from Aker Solutions is used to create the Target Specifications document. The target specifications are then related back to the customer needs in order to gain a better understanding of which customer need is represented by which specific items in the target specifications document.

5.1. Analyses of the Current Product

To get a better initial understanding of how the O-ring functions and interacts with the other components of the system, a design analysis of the current system is carried out. The analysis consists of outlining and measuring relevant parts of the seal, hub and O-ring. Together with the established needs of Aker Solutions, the information is translated into measurable targets that are used for the target specifications. The analyses are all based on the 22-inch seal and hub geometry, as it is considered by Aker Solutions to be more likely to lead to failure, since failure rate increases with seal size.

The design analysis makes use of the CAD models of the TX seal and hub that were provided by Aker Solutions. The O-ring presently in use in the 22-inch seal was modeled using CAD software based on the product specifications provided by Seal Engineering. Figure 8 shows a cutout of the system to more clearly demonstrate how the seal fits inside the hub. The models are used to get correct dimensions for the target specifications and also used during the concept generation as a guideline for the limiting aspects of the geometry.

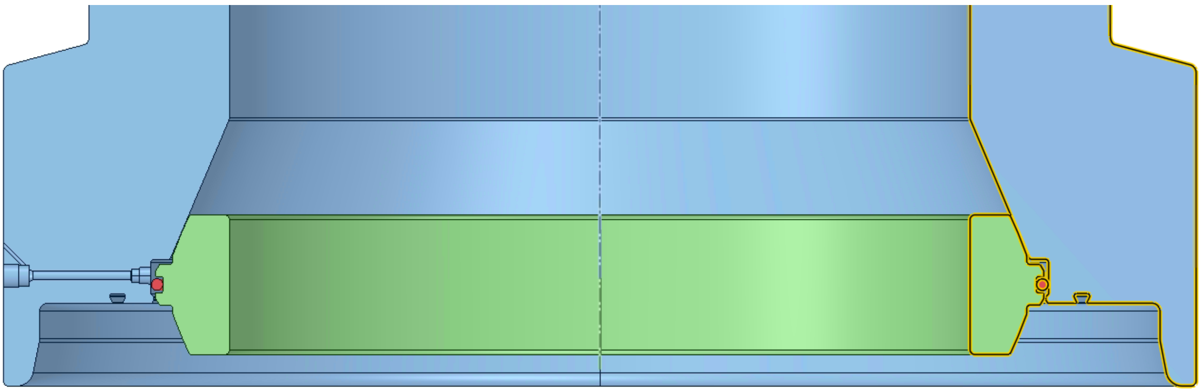


Figure 8. *Shown is a cutout of the system with the hub in blue, the seal in green and O-ring in red. The right portion will be used for the profile measurements that follow.*

The O-ring is an ISO 3601 size ring with an inner diameter D1=532.26mm and a cross-sectional diameter D2=6.99mm. Because its inner diameter is smaller than the outer diameter of the seal, it needs to be stretched around the seal, and in order for the ring to retain its volume, D2 decreases slightly. For the sake of simplicity in this design analysis, this change in D2 is neglected.

Because the distance between the seal and hub is 7.55mm, the 6.99mm O-ring does not reach the hub, illustrated more clearly in Figure 9. It becomes evident that the seal will slide down because of gravity until the ring touches the 1.7mm hub extension, where it will roll over the extension until the O-ring hits the seal at the top. When removing the seal, the ring is deformed further, because of the extension pushing against it. It is known that a force of approximately 7kN is exerted by the hydraulic tool during removal, and as such this is what the current 6.99mm ring is able to retain the seal with. However, the seal is also affected by axial impact loads which exceed this limit, and thus the seal falls out due to its own weight.

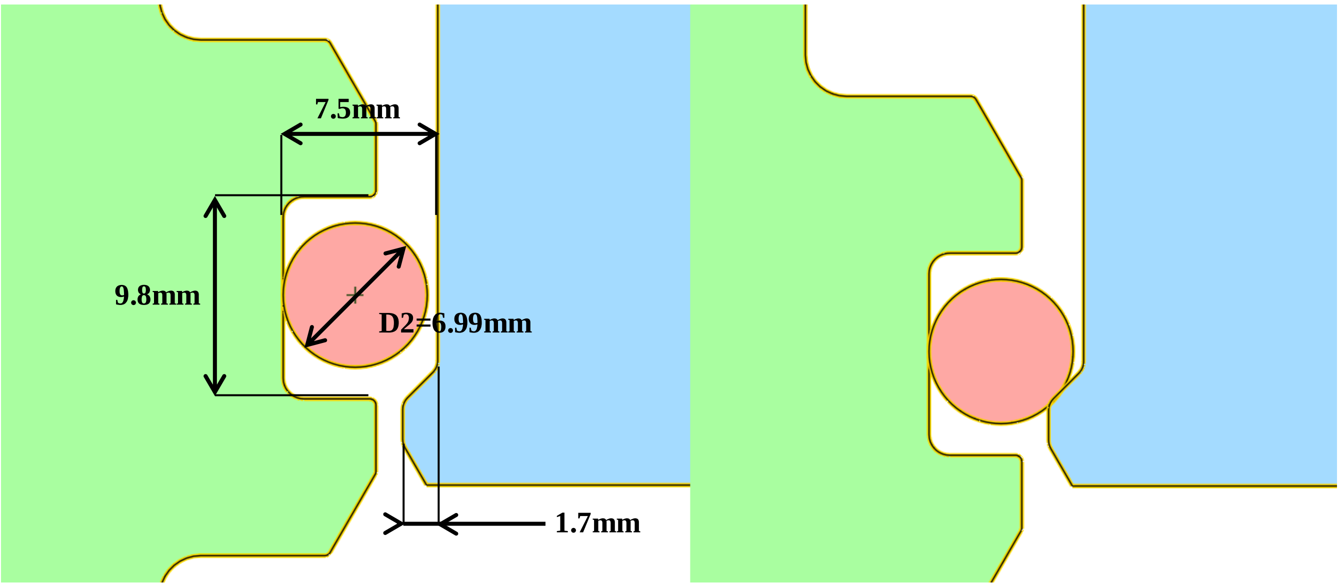


Figure 9. *Cross-sectional profiles generated from the CAD models. The left picture shows the measurements that are used in the target specifications: the seal-hub distance, the width of the seal groove and the distance the hub extends at end. To the right is shown the points where the O-ring comes into contact with the hub extension because of gravity acting on the seal. After this point the ring rolls until it reached the side of the seal groove.*

5.2. Target Specifications

The needs of the customer that were established and prioritized in Chapter 3 "Customer Needs Assessment" are quantified and put in the Target Specifications document, Appendix 13.5 "Target Specifications", where there is a distinction between required values and desired values. Some of the items such as a minimum retention force were not quantified until Section 7 after the FE analysis had been done. Below is a summary of the items in the Target Specifications document:

Summary of the Target Specifications:

- *Performance:* A retention force that is sufficient to retain the seal during impact loads. The removal force also needs to allow removal using onshore hydraulic tools. These two forces are one and the same, but they have different required and desired values. The upper and lower limits for these items were qualified during the initial FE analyses.

- *Safety:* It must retain the seal during impact loads, which is achieved by calculating what value is needed for a sufficient retention force and motivating why this is satisfactory to guarantee the retention of the seal. The hub and seal must also not be damaged by the solution, as well as being non-toxic according to OSHA/EU-OSHA as it is handled by workers.

- *Lifespan:* The retainer solution must last the lifespan of the seal, which gets replaced multiple times per year.

- *Availability:* A retainer solution that is cost-effective. The solution must not exceed USD 50 and there is a desire to get it as low as the current solution of USD 15. It should be an off-the-shelf component that is possible to analyze using FE software.

- *Durability:* It should resist oil and water and not deteriorate to the point of not meeting all the target specifications.

- *Size:* The solution must fit inside the hub and seal geometry and have a mass that is negligible compared to that of the seal.

5.3 Relating Target Specification to Customer Needs

To verify that the items in the target specifications document do indeed represent the customer needs and to get an understanding of which parts of the target specifications that relate to which need, a matrix is created that shows these interrelationships, shown below in Table 3. Along the top are the needs, and on the left are the specific quantified target specifications. The marks show which specification affects which need. Each need has to be represented by at least one target specification. If not, the target specifications have to be revised.

Table 3. The matrix shows the interrelationships between the customer needs and the quantified items in the target specifications. Along the top are the needs, and on the left are the specific quantified target specifications. The marks show which specification affects which need. Each need has to be represented by at least one target specification. If not, they target specifications have to be revised.

	Perform-ance	Safety	Availab-ility	Durability	Cost	Reliability	Ease of impl.
Friction force	x					x	
Temperature span	x					x	
Leaking oil	x	x				x	
Falling out while installing	x	x				x	
Damaging hub & seal		x				x	
Non toxic: OSHA/EU-OSHA		x					x
Lifespan				x	x	x	
Cost					x		
Off-the-shelf-product			x		x		
Ease of implementation			x		x		x
Resist oil	x			x			
Resist water	x			x			
Dim. after compression	x						
Radius	x						
Width	x						
Height	x						
Number of materials		x			x		
Recyclable		x			x		

6. Concept Generation and Selection

Before beginning the concept generation, a *function model* [13] is created. This model is used during the concept generation to act as inspiration during the idea generation. The generated ideas are then made concrete and put in a morphological matrix. The promising concepts are eliminated using an elimination matrix. The remaining concepts are then ranked using a Pugh matrix with the weighted needs of the customer from the AHP. From the Pugh matrix the worse concepts are weeded out and the remaining are further analyzed in FE software.

6.1. Function Model

The function model, shown in Figure 10, is in the form of a black-box diagram the gives a structured representation of the functions within the modeled system. In the model, red boxes indicate an unwanted action, grey are neutral and green are desired actions. The purpose of the function model is to improve the concept generation by enabling the team to think in terms of function, as it is not unlikely that each function can be improved in many different ways and a combination of improved functions could lead to the optimal solution.

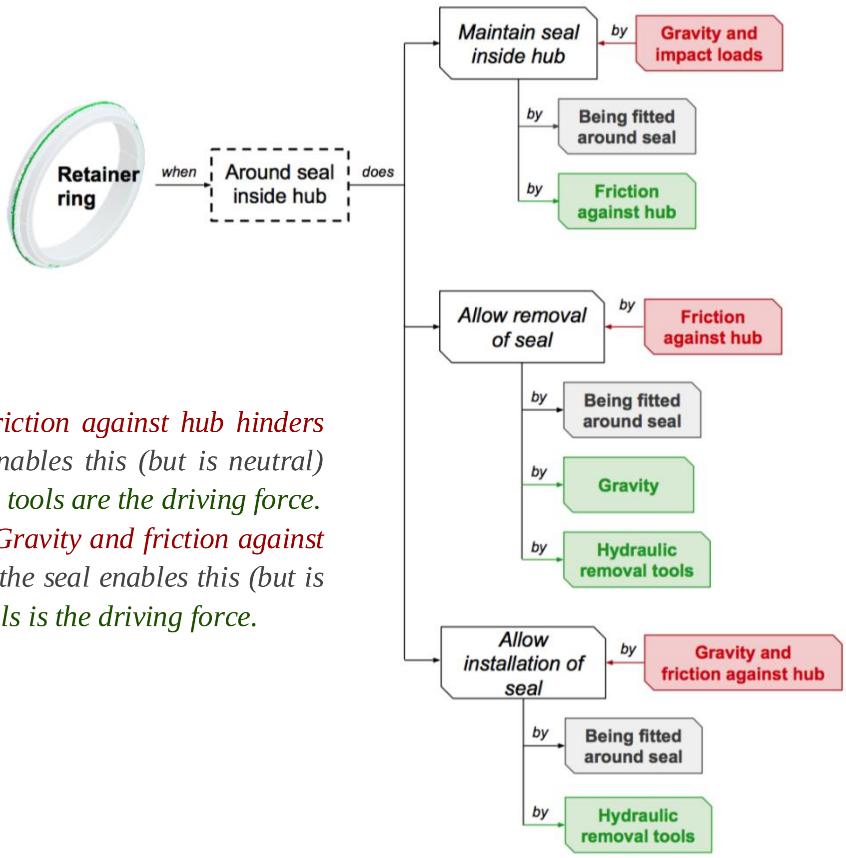


Figure 10. *A function model of the system. From left to right, the retainer ring (green), when around the TX seal inside the hub (dashed box), should either:*

1. Maintain seal inside hub, where: Gravity and impact loads hinder this, the retainer ring around the seal enables this (but is neutral) and friction against the hub is the driving force.

2. Allow removal of seal, where: Friction against hub hinders this, the retainer ring around the seal enables this (but is neutral) and gravity and use of hydraulics removal tools are the driving force.

3. Allow installation of seal, where: Gravity and friction against hub hinder this, the retainer ring around the seal enables this (but is neutral), and use of hydraulic removal tools is the driving force.

6.2. Concept Generation

Each member of the team individually produced concepts to bring to the idea generation; a group creativity technique by which efforts are made to find a solution to a specific problem by gathering a list of ideas spontaneously contributed by its members using the patents, existing products, engineering specifications and function model. This section is a presentation of seven concepts that the group considered possible from the results of the brainstorming.

Concept 1: Classic O-ring with Various Diameters

The standard O-ring with a circular cross section is the one used today. However, since it is too small to actually retrieve the seal inside the hub, Aker Solutions have applied Teflon tape around the seal to make the seal diameter bigger and with that allow a smaller O-ring. If the diameter of the O-ring is increased this could give sufficient retention force and turn out to be the best, cheapest and easiest solution.

Concept 2: Pressurized Top Hub - Hold Seal in Using Pressures

This proposed concept involves attaching a small cap to the hub to cover the TX seal. This cap would have a small air valve, and when air is pumped into the cap the pressure force would act on the seal in the opposite direction as the retention force. Ideally, the pressure force would be sufficient enough to overcome the friction force, or lack thereof, that is causing the TX seal to fall out of the hub.

Concept 3: Square Cross Section O-ring

This proposed solution is an O-ring with a square cross section. The main reason behind using a square O-ring would be to increase the frictional area. Currently a standard circular O-ring is used where the contact area is a point on the perimeter of the O-ring. With such small contact area the frictional force is not that strong. By introducing a square cross sectional O-ring, the entire side of the O-ring would be in contact with the seal and hub. With this increased contact area would come increased frictional forces holding in the TX seal. Figure 11 shows an O-ring with a square cross sectional area.

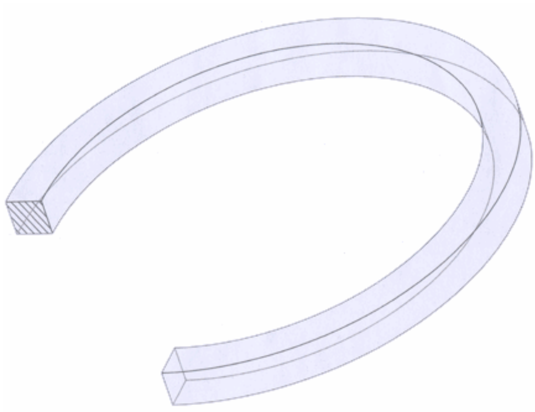


Figure 11. *Shown is a square O-ring design cut to show its profile [14].*

Concept 4: Quad Lobe O-ring

Seen in Figure 12, the Quad-Ring O-ring's primary advantage is to avoid spiral twist of O-rings caused by oscillating fluid pressures. The ability of the Quad-Ring design to avoid twisting under static and dynamic loads allows for longer O-ring life. This could apply to Aker's case because the seal is exposed to underwater pressure, as well as atmospheric pressure above the surface. For this project, the profile is instead explored because of its interesting deformation characteristics that may prove to be advantageous for retaining the seal.

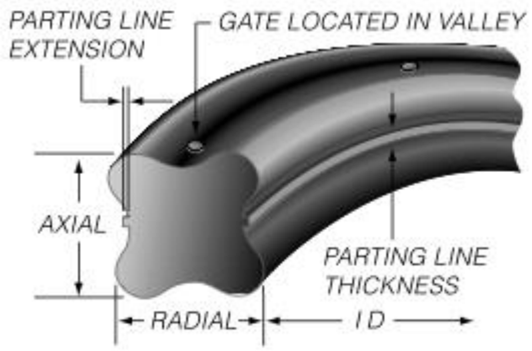


Figure 12. *Shown is one type of quad lobe O-ring design [15].*

Concept 5: O-ring Cross Section with Additional Rubber Studs

This concept is based on the traditional O-ring with circular cross section. The difference is that rubber studs are added for increased friction force. The theory behind the concept is the same as the one used for bikes where the faster ones have tires with plane surface and the ones with better grip have tires with studs. It might prove to be hard to model however.

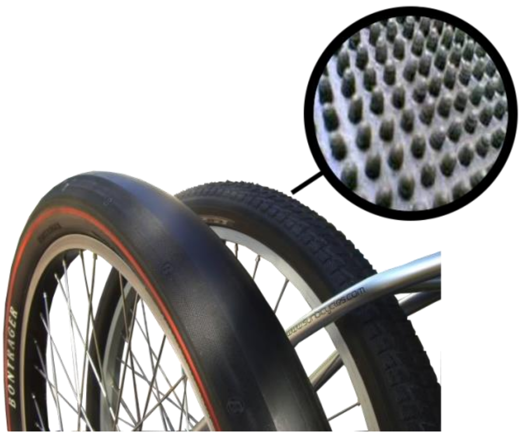


Figure 14. *The picture illustrates the difference between the two types of tires, with an example of rubber studs for the concept [16].*

Concept 6: Direction-Dependent Friction Retainer Ring

A retainer ring with orientation-dependent friction forces, with the ring not exerting equal force during installation and removal, could in theory enable low-friction installation while having a high friction retention of the seal against the impact loads. Illustrated in Figure 15 is one possible retainer ring profile that could theoretically achieve this.

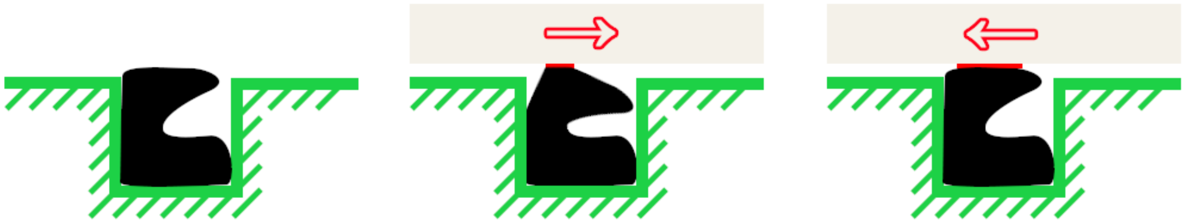


Figure 15. *Pictured is the profile of the seal pocket and a possible retainer ring profile. When the hub wall is dragged to the right, the rubber-to-metal area is decreased as the retainer ring profile is displaced into the pocket. When the hub wall is dragged to the left, the opposite occurs.*

Concept 7: Rope/Braid Retainer Ring

A retainer ring with the cross section as a braided rope, as seen in Figure 16 and 17, could provide interesting deformation characteristics and prove advantageous in retention of the seal.

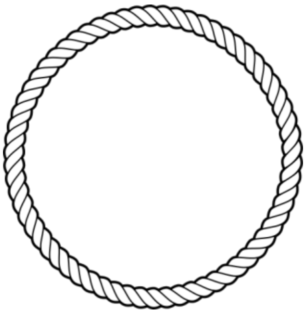


Figure 16*. Illustrating a simple profile of a traditional braided rope [17].*

Figure 17*. Illustrating a more complex braided cross section used in steel wires [18].*

Concept 8: Armor Rings

An armor ring is an elastomer O-ring coated in a Polytetrafluoroethylene (PTFE) coating. PTFE coating provides protection from harsh environments. This option could be suitable for Aker's application because it the type of PTFE could be picked to have a high coefficient of friction while the interior elastomer could provide great characteristics in regard to providing the best seal possible. A cross section of an armor ring can be seen in Figure 18.

Figure 18*. Illustrating the cross section of an armor ring [19].*

6.3. Morphological Matrix

A morphological matrix [20] is a tool for generating more solutions to choose among and evaluate by providing a structured and systematic way to generate a large number of possibilities, including many unique and some highly unusual options. A morphological matrix involves combining different characteristics into new combinations.

The matrix is made so that the profile outline of the retainer ring is separated into 5 sections. The upper section of the retainer ring can have up to 4 different shapes. The low section has also 4 different shapes. The height of the ring can also be different depending of what characteristic that is wanted. The ring performance will also be affected by its inward structure and surface, which is also a parameter in the matrix.

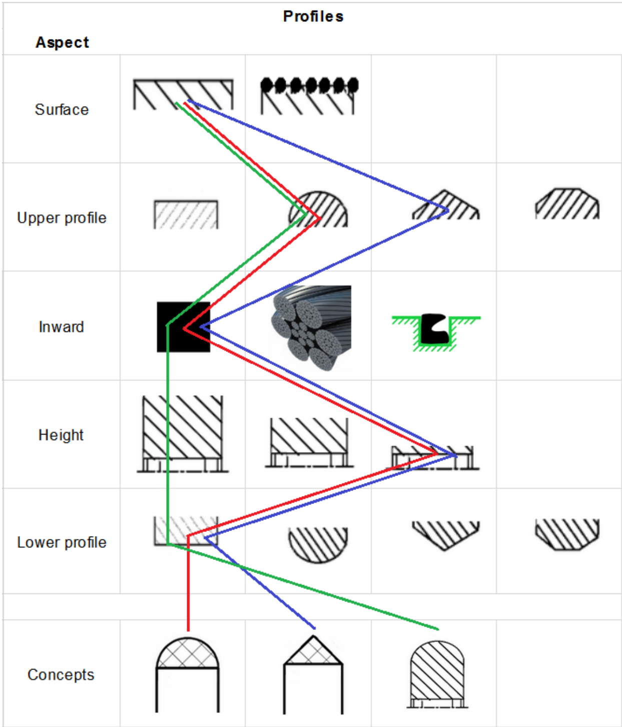


Figure 19. *The morphological matrix gives three interesting profiles by combining the new concepts with each other.*

Out of the different combinations, the interesting profiles that were found are shown in Figure 19. The D profile could prevent the otherwise very movable O-ring from not rolling around inside the seal. This quality can also be found in the second D profile with greater height. An advantage with the D profile is that the performance of the square profile may be combined with the O-ring profile. The last concept made has a triangular profile. This has, as the D profile with lower height, a smaller risk of rolling around inside the seal, since the height is lower.

The profiles from this morphological matrix can however not be used as additional concepts, as Aker Solutions require the retainer ring profiles to be available off-the-shelf. It used as a way to explore a broadening the limitations and can also be used during the redesign of the whole system. The concepts from the morphological matrix are all unique, and would therefore have to be custom-made from the reseller. This would not result in a cost neutral solution.

6.4. Concept Evaluation and Selection

Concept selection is a very important and complex step in the design process. In order to make the best decision for Aker Solutions, both an *elimination matrix* and a *Pugh concept selection matrix* is used. The elimination matrix is used to eliminate concepts that do not meet the established requirements set by the target specifications. The Pugh matrix is a quantitative way to rank multi-dimensional decisions in an organized and efficient fashion. The worst-performing concepts from the Pugh matrix are eliminated and FE analysis is carried out on the remaining ones.

6.4.1. Elimination Matrix

An elimination matrix [21] is made to eliminate all concepts that do not reach the requirements defined in the target specifications. The concepts that do not reach all of the requirements will not be further developed.

Table 3 shows that four of the eight concepts did not meet the requirement *Feasibility in terms of analyzing*. This means that it is not believed that the concepts are able to be accurately analyzed. More specifically, Concepts 2 and 7 cannot be analyzed as it is very hard to simulate their internal stresses. Concepts 5 and 7 have a high amount of contact surfaces which severely complicate simulations. The result from the elimination matrix below shows that Concepts 1, 3, 4 and 6 meet the requirements.

Table 3. With the help of the elimination matrix it is determined if the concepts meet all of the requirements that were established in the target specifications. Concepts that do not meet all of the requirements are eliminated. Four out of eight of the concepts meet these requirements.

	Concept Number							
Requirements	1	2	3	4	5	6	7	8
Cost	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Off-the-shelf product	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Feasibility in terms of analyzing	Yes	No	Yes	Yes	No	Yes	No	Yes
Resist oil	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No
Resist water	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Nontoxic acc. to OSHA/EU-OSHA guidelines	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Damaging hub and seal	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Ability to install O-ring onto seal	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Ability to remove O-ring from seal	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Verdict	**Yes**	No	**Yes**	**Yes**	No	**Yes**	No	No

6.4.2. Pugh Matrix

The different concepts are analyzed in a Pugh matrix [21]. The various concepts are ranked against different criteria on a scale of one through five, with five being the highest in fulfilling the given desire.

Table 4 shows the Pugh matrix used to rank the different concepts. The Pugh matrix uses the criteria that were weighted in the AHP to generate a total score for each concept which represents how promising a solution looks, and set a threshold for which concepts to eliminate.

Table 4. The Pugh matrix ranks concepts based on the established criteria. Each concept gets a score and a threshold is determined where the ones that do not reach the threshold are eliminated.

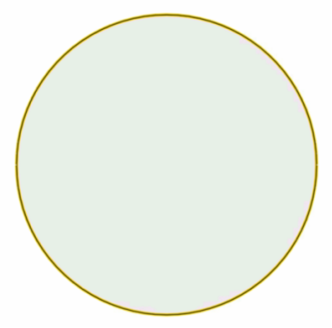
		Concepts							
		Standard O-Ring (ref)		**Square X-Section O-ring**		**Q-Lobe O-Ring**		**Direction Dependant O-ring**	
Needs	**Weight**	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score
Performance	0.154	**3**	0.462	**3**	0.462	**3**	0.462	**3**	0.462
Safety	0.077	**3**	0.231	**5**	0.385	**4**	0.308	**3**	0.231
Availability	0.077	**3**	0.231	**3**	0.231	**2**	0.154	**2**	0.154
Durability	0.077	**3**	0.231	**3**	0.231	**2**	0.154	**2**	0.154
Cost	0.308	**3**	0.924	**3**	0.924	**3**	0.924	**2**	0.616
Reliability	0.154	**3**	0.462	**4**	0.616	**3**	0.462	**2**	0.308
Ease of impl.	0.154	**3**	0.462	**3**	0.462	**3**	0.462	**2**	0.308
	Total Score		3.003		3.311		2.926		2.233
	Rank		**2**		**1**		**3**		**4**
	Continue	Yes		Yes		Yes		No	

Relative Performance	**Rating**
Much worse than reference	1
Worse than reference	2
Same as reference	3
Better than reference	4
Much better than reference	5

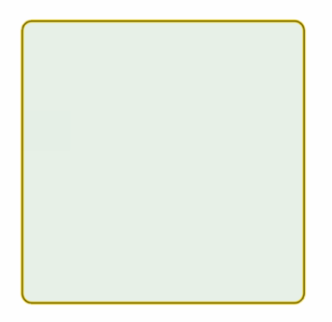
6.4.3. Chosen Concepts

Three concepts remained after the less optimal ones were eliminated. Since not all concepts are being pursued, this initial analysis was done without definitive metrics. The concepts that complete analysis will be performed on are:

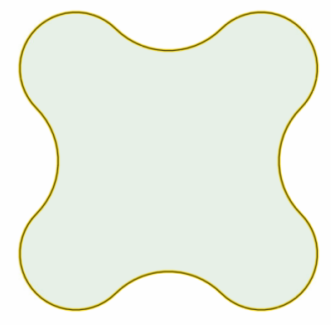
Concept 1: Classic O-ring



Concept 2: Square Cross-Section O-ring



Concept 3: Q-Lobe O-ring



7. Establishing Analysis Parameters

This section describes how the FE model is set up for use in the proceeding chapters. The CAD models are imported into ANSYS [2]. Rotational symmetry of the components allows for only the cross-sectional profiles to be modeled. For this reason, ANSYS is set as axisymmetric, which is highly advantageous as it requires much less computational power.

7.1. Analysis Setup

The axisymmetric model is loaded into the ANSYS Workbench. Contacts are created and a mesh is generated, shown in Figure 19. The two contacts (blue) with the O-ring (red) are set to *frictional*. A mesh is generated, with refinements along the contact edges and the surface of the O-ring, where they are in contact. A convergence study on a sequence of refined meshes was performed and it was concluded that a reasonable accuracy can be achieved by the current mesh within 2%.

The stretching of the ring is simulated by having a *remote displacement* act on the ring. In a second step, the displacement is released and the ring squeezes tightly onto the seal, as seen in Figure 20.

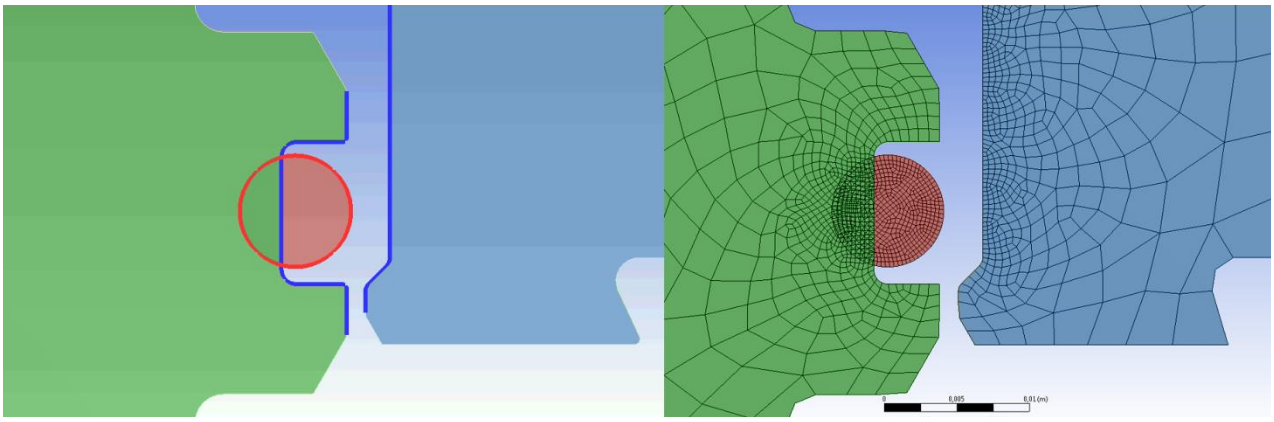


Figure 19. *On the left is shown the seal and hub contact edges in blue and the O-ring contact edge in red. On the right the mesh with refinements around the contact edges can be seen.*

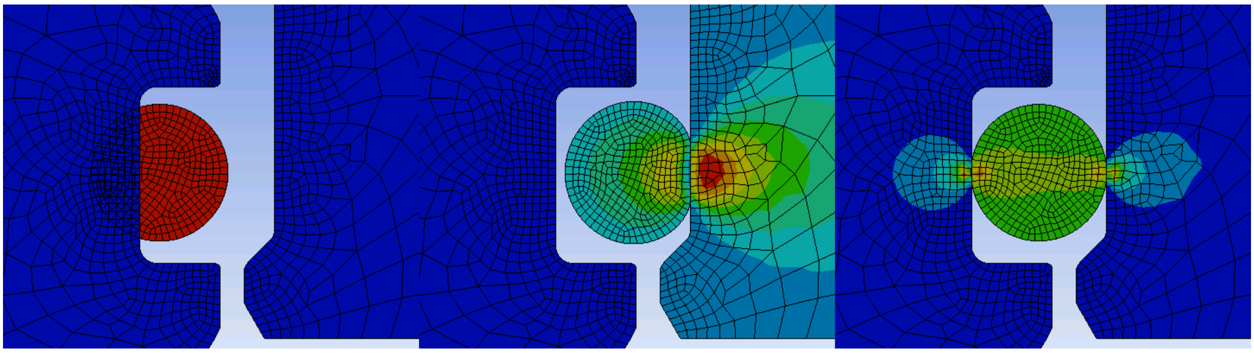


Figure 20. *A 7.6mm O-ring being simulated. In the first picture the diameter difference between the ring and seal can be seen. In the second step the ring is remotely displaced to reach around the seal. In the third step the displacement is released.*

7.2. Establishing Analysis Parameters

Three things need to be established before accurate analyses of the new profiles can be carried out, which are the material properties, friction coefficients and impact loads. Some of these are found by analyzing the current O-ring.

Material properties

It is known that the seal is made of titanium and the hub is assumed to be made of stainless steel. For these two components generic material data is used. The current O-ring and the new profiles are all made of NBR which is a hyper-elastic material. This makes it sensible to choose the Neo-Hookean material model for simulations as it is a simple method that can accurately model stress-strain behavior using only the initial shear modulus.

Normally elastomers are measured in Shore hardness [22], but the initial shear modulus can be calculated from this measure using the Battermann-Köhler (1982) formula

$$G_0 = 0.086 \times 1.045^H \text{ MPa}$$

where G_0 is the initial shear modulus and H is the Shore hardness. Data for relevant hardnesses is shown in Table 5.

Table 5. The initial shear modulus can be calculated from the Shore hardness using the Battermann-Köhler formula [23]. The current O-ring has a Shore hardness of 90±5 (A scale).

Shore hardness, H (A scale)	60	70	80	90
Initial shear modulus, G_0 [MPa]	1.21	1.87	2.91	4.52

Coefficients of friction

Obtaining accurate values for the coefficient of friction between two materials is difficult to do analytically. And one is forced to carrying out physical experiments of the materials in question. Coefficients for rubber-metal contacts are known to vary from 0.1 up to 0.7 [23], so one is forced to carry out physical tests on the materials in question to establish accurate values.

Furthermore, obtaining the correct friction forces is essential in obtaining accurate analysis results, as the friction affects how easily the O-ring is able to slide out of the hub. Fortunately, because the current removal force is known by value to be around 7kN, a parameter study with a range of friction coefficients can be made until a match in reaction force is found, shown in Table 6.

Table 6. A parameter study of a range of friction coefficients is made to establish a match with the current removal force.

		(Match)			
COF	0.1	0.15	0.2	0.25	0.3
F [N]	5981	7403	9226	11915	16870

As seen in the table above, a friction coefficient of 0.15 yields a retention force of 7403N, which is the closest match to the established 7kN retention force for the current system. A value of 0.15 is sensible considering the wet and oily surface conditions on shore, where rubber-metal contacts can get very slippery, unlike completely dry surfaces where a coefficient around 0.7 would have been more sensible [16].

Impact force

Lastly, a sensible impact force needs to calculated using the given impact load data. According to the data there is a mass of 8000kg that impacts the hub axially (and thus the seal). This mass has a velocity change of 0.5m/s on impact, but the impact time is not known. The force that is exerted on the seal can be calculated using the impulse-momentum equation:

$$F = m\frac{\Delta v}{\Delta t} = 8000\text{kg} \times \frac{0.5\text{m/s}}{\Delta t}$$

The equation is used to compute the impact force $\boldsymbol{F}$ from a range of different impact times $\boldsymbol{\Delta t}$, shown in Table 7.

Table 7. Various impact forces are obtained from the range of impact times.

$\boldsymbol{\Delta t}$ **[s]**	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
$\boldsymbol{F}$ **[N]**	40000	20000	13333	10000	8000	6667	5714	5000	4444	4000

It can be argued that collisions of several-metric-ton objects definitely have impact times greater than 0.1 seconds. A more likely estimate of a lower limit is 0.3 seconds. As the force increases as impact time decreases, only the lower limit is of interest. A $\boldsymbol{\Delta t}$ of 0.3 seconds yields an impact force of 13333N. This makes the weight of the seal (250N) negligible and the maximum force that would affect the seal at any one time can be rounded up to 15000N for the sake of simplicity.

To summarize, the parameters that are used in the following profile analyses are:

Hub material: **Generic stainless steel, linear elastic with E=193GPa, ν=0.31.**

Seal material: **Generic titanium alloy, linear elastic with E=96GPa, ν=0.36.**

O-ring material: **Hyper-elastic with G_0=4.52MPa (Neo-Hookean) and ν=0.48.**

Coefficient of friction: **0.15**

Target retention force: **15000N**

8. Detailed Design

The following chapter describes the analysis, results, and the final chosen design.

8.1. Analysis

With the three profiles having been modeled, they are imported in ANSYS Workbench, shown in Figure 22. The first two models are initially analyzed with the same cross-sectional diameter of 7.6mm except for the Q-lobe profile which has a height of 8.0mm in order to compensate for its more deformable shape.

A parameter study is done on a range of diameters for each profile as seen in Table 8.

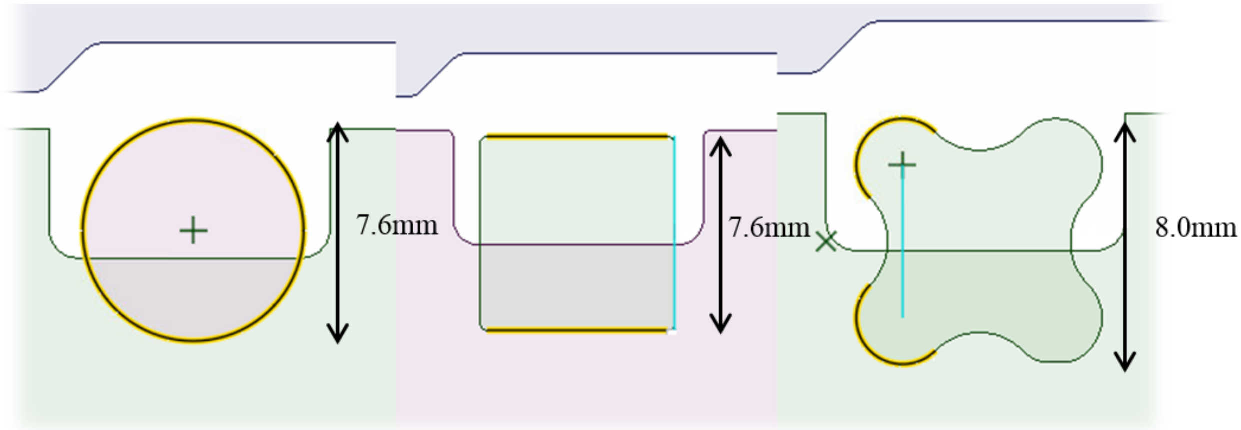


Figure 22. *Shown is the classic O-ring (initial diameter of 7.7mm), square (initial height of 7.6) and Q-lobe geometries (initial height of 8.0mm) in ANSYS.*

Table 8. This table shows the different diameters/heights that are to be analyzed in the parameter study for each profile.

	[mm]											
Classic O-ring	7.1	7.2	7.3	7.4	7.5	7.6	7.7	7.8	7.9	-	-	-
Square ring	-	-	-	-	7.5	7.6	7.7	7.8	7.9	8.0	-	-
Q-lobe ring	-	-	-	-	-	7.6	7.7	7.8	7.9	8.0	8.1	8.2

8.1.1. Square ring

The Square ring does not yields satisfactory deformations as the seal moves down as it gets caught in the hub extension, shown in Figure 23. The graph in Figure 24 shows how the reaction shows the reaction force increasing to unmanageable amounts.

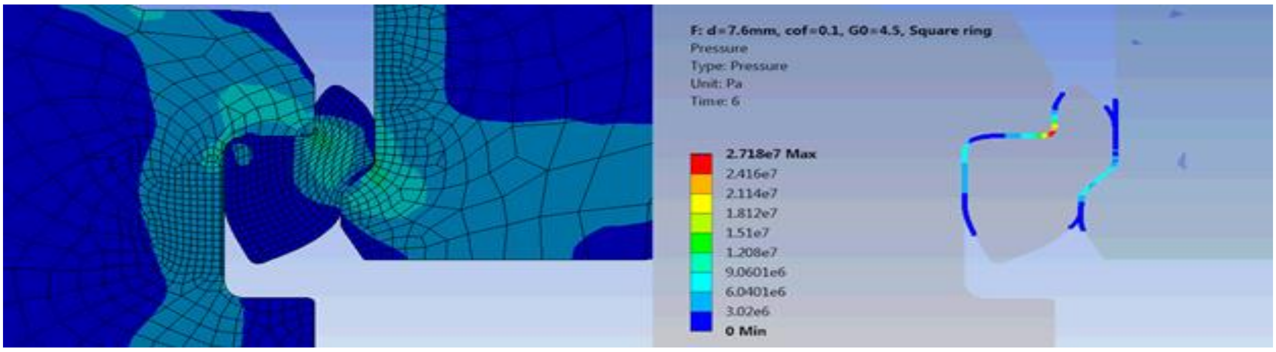


Figure 23. *The square cross section does not yield satisfactory deformations as the seal is moved down as the ring gets stuck.*

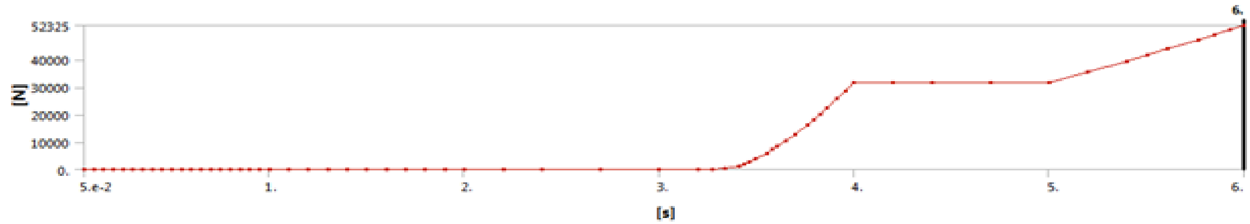


Figure 24. *The reaction force as the seal moves down. Because the square ring gets stuck the reaction force reaction becomes very high. Note the force is plotted against the time and the displacement.*

8.1.2. Q-lobe ring

The Q-lobe profile yields similar results, as seen in Figure 25. As such, the two profiles are eliminated from further analysis because the deformation of the O-ring is too high rendering it structurally deficient for its intended use.

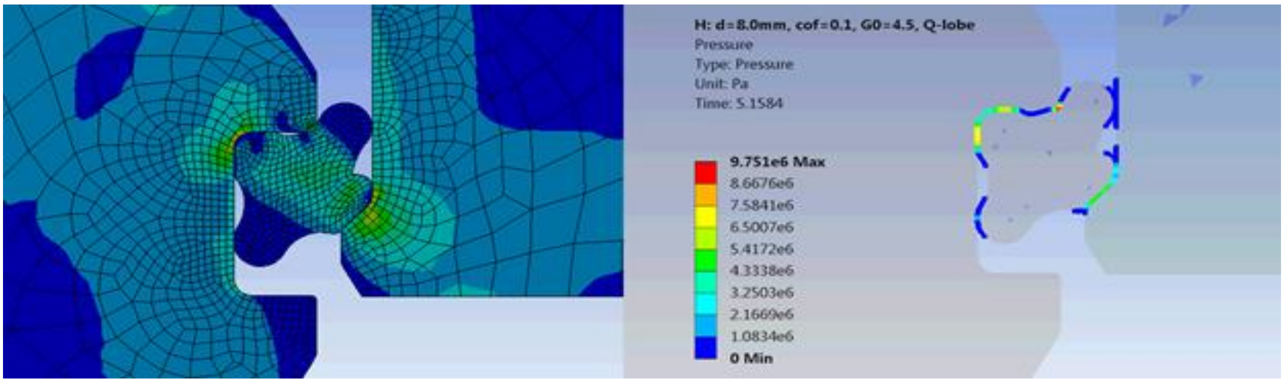


Figure 25. *The Q-lobe cross section does not yield satisfactory deformation results either and gets stuck as well.*

8.1.3. Classic O-ring

The classic O-ring does not experience the same problems as the first two profiles and does not get caught on the extension of the hub. Simulations are done for the diameters defined in Table 8.

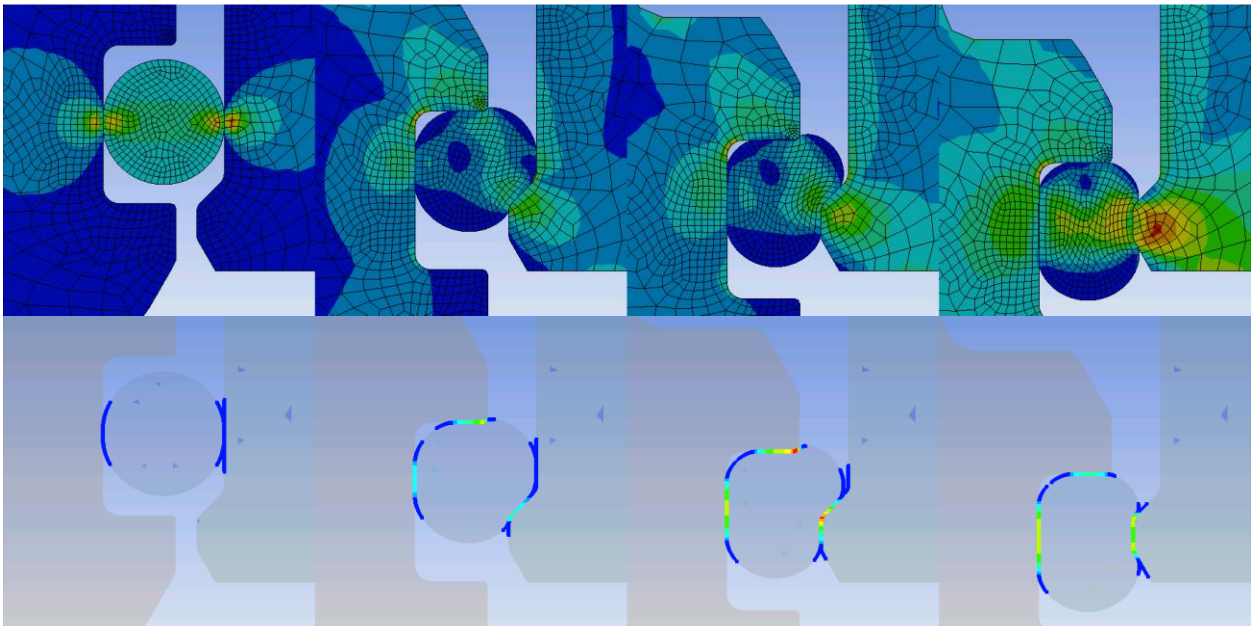


Figure 26. *Above is shown the equivalent stress on the O-ring step by step. Below is shown how the contact pressure varies in each step with the contact pressure peaking around step 3.*

The results that were collected from the parameter study analyses are shown in Table 9.

Table 9. This table shows how the retention force varies as the diameter changes on classic O-ring of NBR90 with H=90.

D2 [mm]	7.1	7.2	7.3	7.4	7.5	7.6	7.7	7.8	7.9
F [N]	9224	10781	11904	13710	16878	19522	22528	26245	29962

To meet a retention force of 15000N as the hardness varies by ±5, it is seen that a diameter D2=7.6mm meets this criteria, as shown in Table 10.

Table 10. Data collected from simulations on the 7.6mm cross-sectional diameter O-ring with a Shore hardness H=90 (A scale).

	H=85	**D2=7.6mm, H=90**	**H=95**
***F* [N]**	15793	19522	24367

However, during the Component Selection Process is was discovered that NBR90 is not commonly found in sizes above 6.99mm and is not provided by Seal Engineering. The O-ring material RU1, which of the type ABR85 is, however, available in sizes above 6.99mm and it is available from Seal Engineering. This material has a hardness of 5 less than the original material. Analyses were made on this material and the results are shown in Table 11.

Table 11. Data collected from analyses on the classic O-ring with cross-sectional diameter D2=7.8mm in RU1 (ABR85) with Shore hardness H=85 (A scale).

	H=80	**D2=7.8mm, H=85**	**H=90**
***F* [N]**	15860	19605	24471

As seen in Table 11, the new material ABR85 with an increased diameter yields results equal to the NBR90, although slightly higher. These results meet the all of the requirements discussed in Section 7.2 “Establishing Analysis Parameters”.

Animations of the ANSYS simulations of the final design as well as other simulations that were done can be found at:

https://chalmersuniversity.box.com/s/im6cx2u3oziag6sz2al304qid982advd

8.2. Component Selection Process

An O-ring with a cross-sectional diameter of 7.8mm is currently available from Seal Engineering in the material RU1, which is an ABR elastomer with a Shore hardness of 85 (A scale). The cost of this ring is comparable to the current ring, and should not exceed the USD 50 limit that was set. Although it is an off-the-shelf component, a technical drawing is shown below in Figure 27 for sake of clarity.

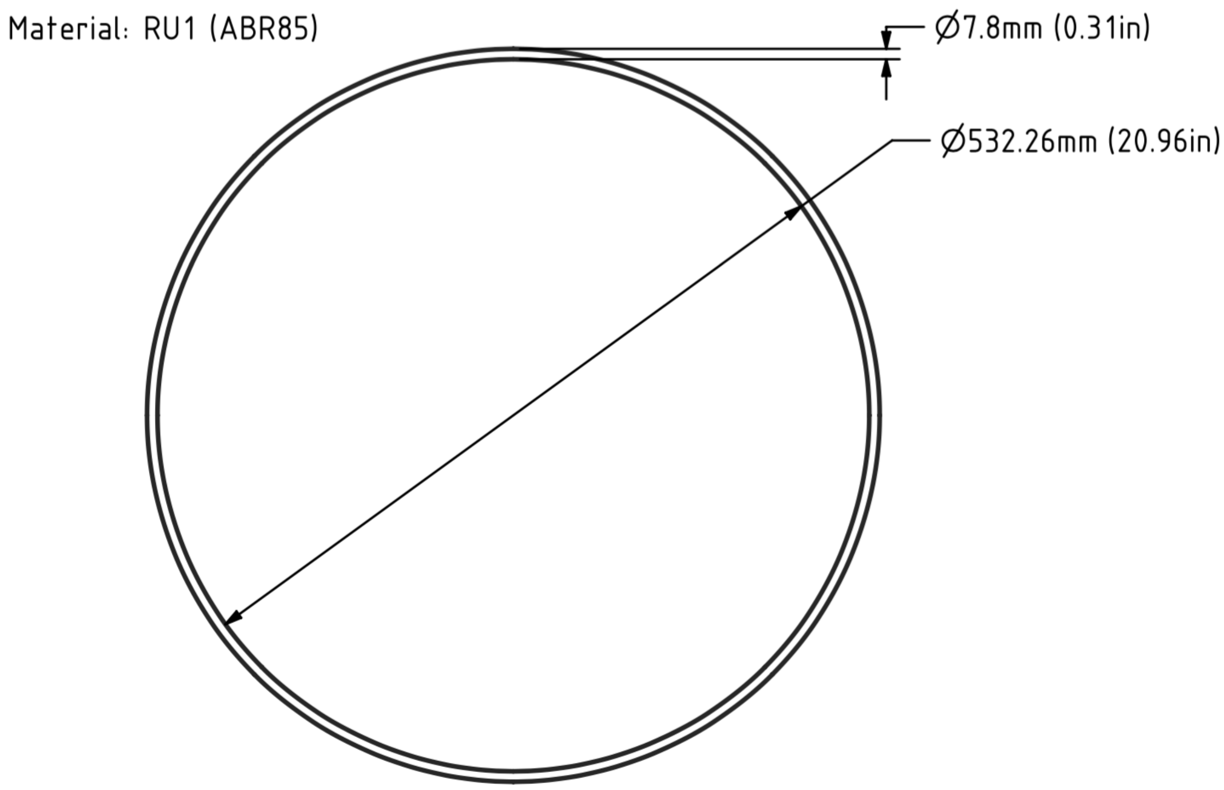


Figure 27. *The O-ring is made of RU1, an NBR85 material, with an inner diameter of 532.26mm and a cross-sectional diameter of 7.8mm.*

8.3. Physical Tests and Comparison with Calculated Data

Stretch tests were conducted on one of two 532.26mm×6.99mm NBR90 O-rings graciously provided by Seal Engineering, in order to obtain an accurate stress-strain curve of an NBR elastomer ring with a Shore hardness of 90. The tests were mostly motivated by the desire to verify the pre-analysis assumptions of the accuracy of the Batterman-Köhler formula and the Neo-Hookean stress-strain model. The Neo-Hookean model is known to describe material behavior well for small to medium strain, however for larger strains this is not always the case [24] and as such physical tests to assure the analyses are within the limitations of the Neo-Hookean model is desired.

Stress-strain tests were conducted on two sections that were cut out of one of the O-rings using a universal testing machine located at a testing lab at Chalmers. The force and displacement between the two cross heads was recorded and converted to the equivalent stress and strain. The two results were then combined and fitted using the least square method to a 4th order polynomial. Shown in Figure 28 is the fitted curve in purple. The maximum equivalent strain in ANSYS was found to be .56 and is marked by a vertical gray line. The stress-strain to the left of this line is therefore the portion that is relevant to the analyses.

Somewhat serendipitously, given that only two tests were conducted, the test data curve fits within the upper and lower hardness curves (yellow and blue respectively) up until the point of .56 strain where the gray line is located.

It is concluded that the Batterman-Köhler formula and the Neo-Hookean model do in fact represent the behavior of the actual O-ring well, as long as the strain does not stray too far from .56.

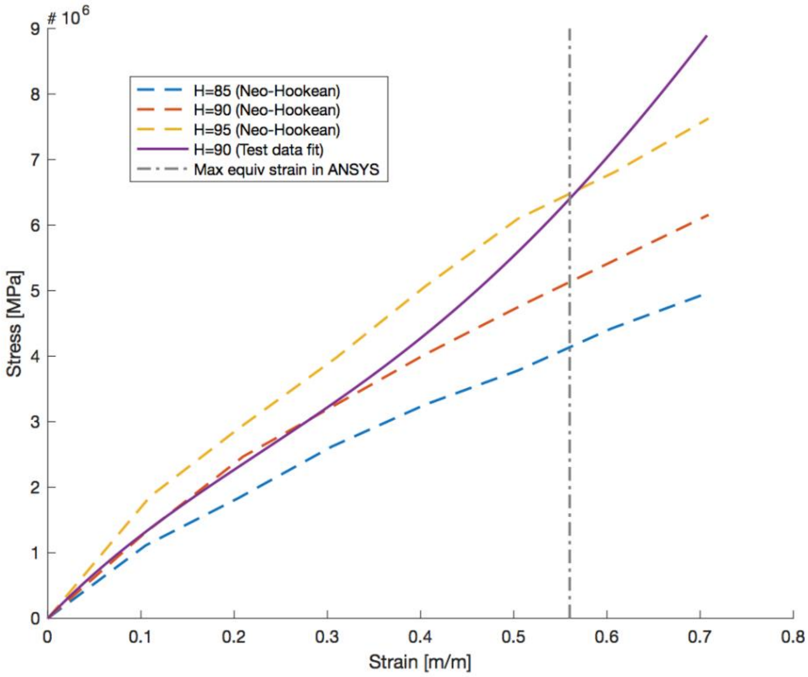


Figure 28. The purple curve is the fitted test data. It is shown that as long as the strain remains below .56, the test data stays between the upper and low hardness limits in yellow and blue respectively.

9. Broadening of the Limitations: Redesign of the Whole System

As was mentioned in the beginning of the project, the remaining time given to the Chalmers team is used to broaden the limitations that were set by Aker Solutions. This section explores a redesign of the whole system, including the hub and seal. Additionally, keeping the current 6.99mm O-ring would be advantageous as O-rings with inner diameters of 22 inches are only available in ISO sizes up 6.99mm. Using an ISO size O-ring means it is always highly available.

There are two apparent disadvantages with the current geometry. The groove that holds the O-ring is almost double the width of the ring, which makes the ring roll around when removing and installing the seal. This leads to unnecessary movement and instability leading to changes in reaction force as the seal moves up and down the hub.

The seal when being installed must be aligned with the hub before hydraulic tools can push the seal into the hub. The alignment could be made easier if the extension is moved up and the seal could be partially put inside the hub before the hydraulic tools push it in.

9.1. Redesign

The new seal design is shaped to conform to the circular nature of the O-ring, which prevents it from sliding around and ensures it is always evenly stretched around. The depth of the groove is also raised so that the 6.99mm O-ring reaches the hub. The hub extension is moved up as to allow the seal to be aligned to it before installation.

With all this geometry fixed apart from the hub extension, the width of the extension now becomes the parameter that determines the retention force. As such, a parameter study is done on the width of the extension to find a width that gives the required retention force of 15kN as determined in Section 7.2 “Establishing Analysis Parameters”.

Figure 29 shows the new geometry in thick green and blue lines overlaid on top the old geometry. It also clearly marks the hub extension width x that is to be studied.

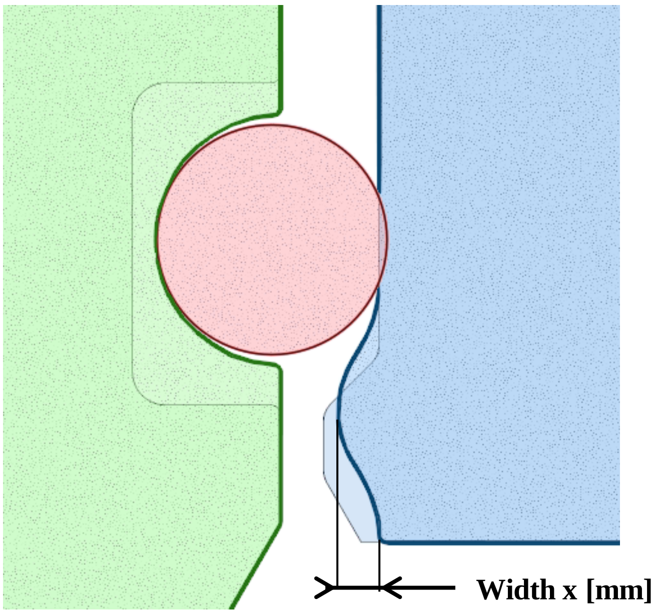


Figure 29. The new geometry is overlaid on top of the old geometry with the parameter width x to be determined.

9.2. Analysis

The analysis was done similarly to the ones in the previous section. With no obvious starting width, several widths were tested and were decreased or increased depending on if they were higher or lower than the 19605N retention force in Table 11. A match was found with a width of x=1.7mm, with the reaction force for the hardness with the upper and lower limits in Table 12. The deformation of the O-ring with step by step is shown in Figure 30.

Table 12. Data collected from analysis of width x=1.7mm with the new geometry and the original 6.99mm cross-sectional diameter O-ring with a Shore hardness H=90 (A scale).

	H=85	**D2=6.99mm, H=90, x=1.7mm**	**H=95**
***F* [N]**	16155	20173	24940

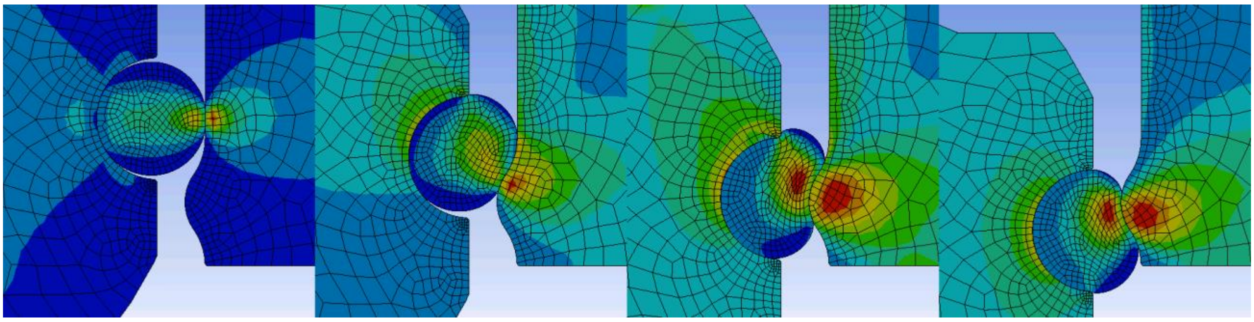


***Figure 30.** Pictured is the step-by-step deformation of the redesigned system. The colors are the equivalent stress in the material.*

An analysis with successful results has been achieved. It keeps the original 6.99mm O-ring but the new design does not allow it to roll around as described earlier, making it more stable. The O-ring can also be aligned inside the hub during installation, before hydraulic force is applied, as shown by Figure 31.

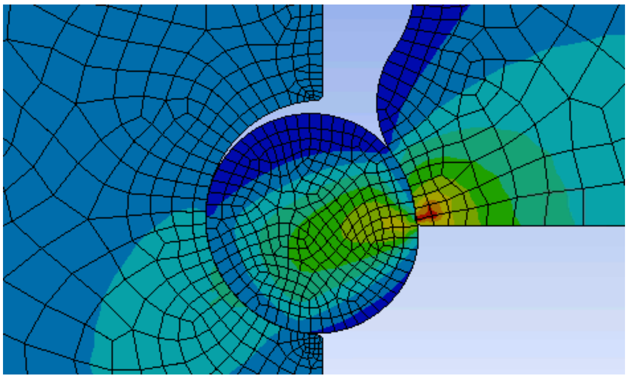


***Figure 31.** The seal can be aligned with the hub before the hydraulic force is applied. In the previous design, this was impossible.*

9.3. Final Redesign

This section describes the dimensions of the redesign, with all the dimensions shown in Figure 32. The seal groove is now semicircular, with a diameter slightly greater than the 6.99mm O-ring to allow a sufficient fit. The 7.5mm distance between the seal and hub remains the same compared to the current system design. The extension of the hub has a width of 1.7mm, which yields the desired retention force.

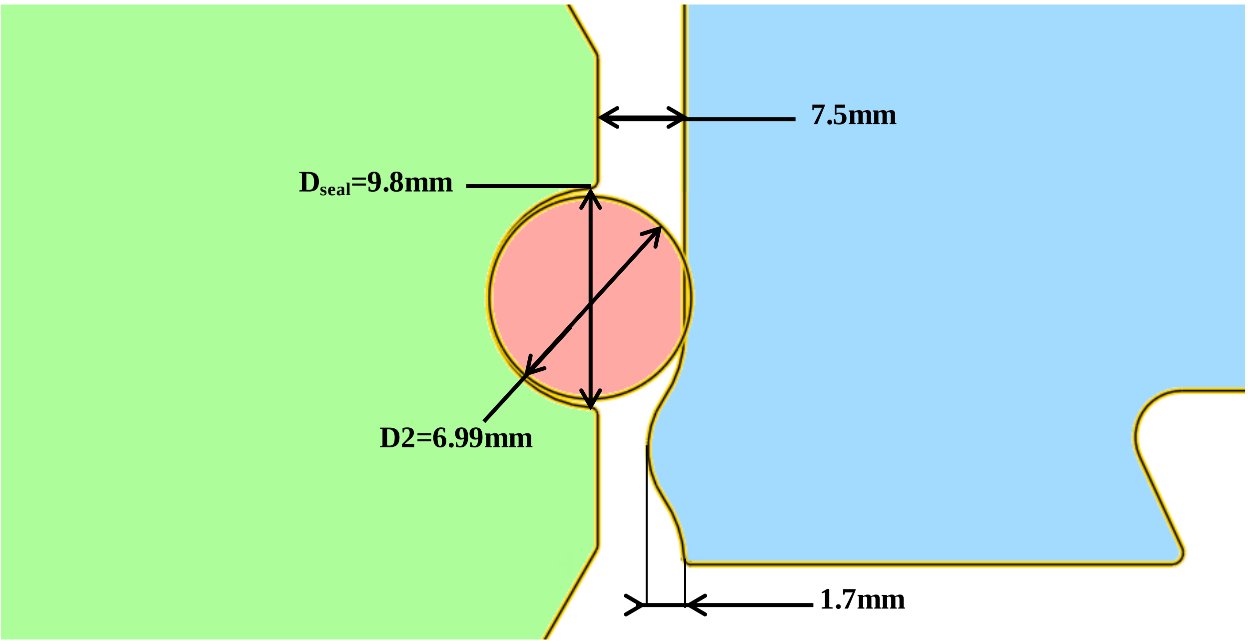


Figure 32. *Pictured is the final design of the system. The seal groove is semicircular with a diameter slightly greater than D2, to allow a good fit. The width of the extension hub is 1.7mm, which yields the desired retention force.*

10. Final Discussion and Recommendations

This chapter discusses the results and relays them more into words. The results together with the methodology, team management and collaboration are thereafter discussed and scrutinized to identify parts in the project were executed well and others that could have been done better. After discussing the results and the project in general, a conclusion is made and a recommendation to Aker Solutions on the solution to the given problem statement. Finally a recommendation on a plan forward for Aker Solutions is given, if they were to either use the recommended product or further develop the work accomplished so far.

10.1. Test Results and Discussion

The most important and valuable test results to discuss are the ones from the FE analysis, which can be seen in detail in Section 8.1.3 and in Section 9.2. The final 7.8mm O-ring in ABR85 successfully meets all of the established requirements by Aker Solutions. It retains the seal inside the hub during off shore installation and is still easy to install and remove. The price point is not far from the current solution.

No analysis can model the real world with perfect accuracy however. Although its accuracy has been confirmed by supervisors and ANSYS experts, one cannot possibly translate real world impact loads that affect the modeled system perfectly accurately into force variations in ANSYS. Looking at the material selection in ANSYS, even if it was sensible to use the Neo-Hookean stress-strain model because of the O-ring's hyperplastic properties, it is not a perfect representation of NBR. Finally, the axisymmetric model cannot account for real-world variations in how installation and removal force is applied.

For this reason, every requirement and assumption was done with certain safety margins. The maximum impact force requires the retention force to be at least 13333 N, but was rounded up to 15000N. The O-ring diameter gives a retention force of 19605N with a hardness of H=85. This hardness varies by ±5, and the worst-case scenario of H=80 yields a retention force of 15860N. With an upper limit of H=90 the retention force is 24940N, but still allows hydraulic tools with a limit of 30000N to install and remove the seal with a margin of 5060N.

It must be mentioned that simulating the type of problem of having a hyper-elastic ring stretch over a seal, have it be deformed and at the same time having several contacts where friction plays a crucial role in the deformations, is quite difficult and somewhat novel. The knowledge required to do so exceed that provided at university level courses and demanded ANSYS expertise as well as creativity and deep skills that were developed within the project team. Despite the difficulty, the team, its supervisors and ANSYS experts agree on the simulations' accuracy, reliability and stability.

Additional credibility with regards to the analysis is given by the physical material test that was conducted that showed the material property assumptions lead to a model that was accurate in comparison with the test results in terms of stress-strain and the conversion from hardness to initial shear modulus.

As mentioned throughout the report, the project was quite limited in terms of what geometry could be changed but very open regarding simulation technology and the use of software. During the additional time that Chalmers team was allotted, the limitations were broadened to redesign of the entire system to find out how this would have affected the final design. The broadening of the limitations did in fact result in a successful redesign with an improved retention force while maintaining the same 6.99mm cross-sectional diameter. More precisely, Aker Solutions could use the same O-ring they are using today and obtain a retention force of 20173N. Additionally, the redesign allows the seal to be perfectly aligned with the hub, while previously there is no way to align the seal and it instead had to be visually guided before the force by the onshore tools was applied. This solution is without a doubt better, but it is however debatable if this solution would be economically viable for Aker Solutions considering that both hub and seal geometries would need to be redesigned.

The methods used during the project have been successful. In particular the team's use of concept selection processes. Sometimes it is easy to simply choose a concept that seems the best, but the application of the processes has ensured successful elimination of the worse concepts to end up with the best. This gives us confidence to state that we have the ended up with the best possible solution out of the ones generated in the brainstorming. However, since simulations of this kind are difficult and non-trivial, many concepts in the selection process were eliminated because of their lack of feasibility in modeling and simulating. One cannot resist wondering if all concepts were feasible would the chosen concepts have been the same.

Finally, the team management and collaboration has been a success. The time zone difference is the only aspect which led to minor miscommunication at times. Besides that the team has functioned well and bonded, everyone showed respect to the current team leader and acted professional in their roles. The workload distribution has been even in each team, even though the project on the Chalmers team end was worth more university course credits than on the Penn State side. Nevertheless, working in an international team has been rewarding in terms of gaining relationships, learning about new cultures as well as gaining experience in professional international relations. This is discussed further in Appendix 13.2 "Contribution Report".

10.2. Conclusions and Recommendations

After designing, simulating, interpreting and the discussion above the conclusion can be made that the analyses and simulations are of such high quality that they give excellent results. They have therefore led to a successful decision regarding the redesign of the retainer ring that with confidence meets all Aker Solutions requirements. The team recommends Aker Solutions to order the 7.8 mm O-ring in ABR85 from Seal Engineering.

It is concluded that the product features include:

- In coherence with the design constraints of seal and hub geometry.
- Meets all quantified technical requirements within good safety margins.

- Elastomer material RU1 (ABR85) with a Shore hardness of 85 which is perfectly suitable for its working environment.
- Available as an off-the-shelf product by Seal Engineering, the current supplier of retainer seal for Aker Solutions.
- Within the price range of a USD 50 as required by Aker Solutions.

Additionally the team would like to recommend Aker Solutions do a full economic analysis of the redesigned system since it technical benefits are of interest, as it allows the use of the currently O-ring and most importantly adds additional functionality to the system.

Animations of the ANSYS simulations of the final design as well as other simulations that were done can be found at:

https://chalmersuniversity.box.com/s/im6cx2u3oziag6sz2al304qid982advd

10.3. Aker Solutions – Going Forward

For Aker Solutions going forward, it is important that they run physical tests on the system to ensure that the recommended O-ring works in its working environment where it will be affected by temperature changes, humidity and impact loads. Aker Solutions has informed us that they will be doing these physical tests in the beginning of 2017, and on the design team side everything indicates that Aker Solutions will succeed in this test with recommended O-ring. It is as mentioned in the recommendation also good to consider the additional redesign and do a full economic analysis to decide if its technical superiority weighs over its economic cost.

11. Self-Assessment

This chapter discusses on what the project managed to achieve based on the needs received from Aker Solutions.

11.1. Customer Needs Assessment

At the beginning of the project, 7 needs were: performance, safety, availability, durability, cost, reliability and ease of implementation.

The performance need is met at the final product does retain the seal according to simulations with good safety margins. The seal is also possible to remove with good margins as well. The safety need was met in terms of being non-toxic as the product is made of a well-known elastomer (ABR85) that is no more toxic that the current solution. The availability need is met as the product is an off-the-shelf solution available by Aker Solutions' current vendor Seal Engineering. The durability need is met as ABR85 is known to resist oil and water and does not deteriorate under these conditions. The cost need is met as the product has a cost close to that of the current solution. The reliability need is met as simulations show its reliability in retention force with good safety margins. The ease of implementation need is met as the product does not change any onshore installation procedures negatively. In fact, it improves them by not requiring Telfon tape to be added around the seal ring, which was the case of the current solution.

For this reason, the team considers 7 out of the 7 customer needs were met.

11.2. Global and Societal Needs Assessment

In this project, the team followed the three ethics constitutions made by ASME, detailed in Section 2.5 "Ethics Statement". These constitutions were followed by the team throughout the whole project and the team managed to fulfill them all. The first, helping the human welfare by using knowledge and skill, the team fulfilled by making the installation of Aker Solutions' TX seals safe and predictable. The second, glorifying honesty and fairness in business and with the public, the team fulfilled by showing the exact calculations and simulations done by the group to reach the final product. The third, making engineering more prestigious, the team fulfilled by setting up FE models of a previously unmodeled system which required advanced computer modeling knowledge, and arguing their correctness.

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13. Appendices

13.1. Group Contract

1. Team Members and Contact Info:
    1. Benjamin Grozdanic- benjamingrozdanic@gmail.com, bengro@student.chalmers.se - +46739960149
    2. Ben Lisowski - bliso249@gmail.com, btl5093@psu.edu - (412) 292-0067
    3. Joe Malespini - malespini10@gmail.com, jam6642@psu.edu - (860) 331-1256
    4. Evan Pataki - evanpataki5117@gmail.com, ecp5117@psu.edu - (570) 956-7939
    5. Karl Stahlberg - karlsta@student.chalmers.se - +46705277205
    6. William Ståhlberg - william.stahlberg@gmail.com, wilsta@student.chalmers.se - +46760160260
2. Team Mission Statement
   We intend to solve the proposed problem correctly with diligence, and within specification. We want to improve our team and professional skills, and to develop our abilities as product designers. Tertiary to these objectives, all group members aspire to receive an 'A'/'5' in the course.
3. Expectations

a. Meetings

i. Location - Leonhard 316 (Penn State) & Angelo (Chalmers)

ii. Time

1. With Penn State Group/Chalmers Group./Professors: Tuesdays @ 9:00AM EST or 15:00 CET
2. Acceptable Excuses: Hospitalization, Job interviews, Unexpected vehicle problems, Serious illness/Flu, Death in the family

iii. Advanced Notification- a group member must contact all other group members 24 hours before the next meeting or as soon as they know they will be absent.

b. Attendance

i. Meetings will start at exactly 9:00AM EST or 15:00 CET on meeting days; all members are expected to be participate. Failure to comply will count as one half of an unexcused absence.

ii. 1.5 unexcused absence and 3 excused absences are allowed per member

c. Performance

i. All group members must agree on workload distribution during meeting times.

ii. Work must be completed on time.

iii. All work must be reviewed by 2 team members aside from the member who completed the work before it is turned in.

d. Interpersonal Norms

i. No swearing during team meetings

ii. No jokes or pranks during teem meetings

iii. No surfing the Internet for things not pertaining to Senior Design work during team meetings

iv. No phone calls longer than 5 minutes during team meetings, Tom

v. No working on other homework/research during team meetings

e. Communication

i. Calling tree: e-mail is preferred over telephone contact

1. E-mail: when communicating via e-mail, Cc to all group members.
2. Phone: call all group members for subject matter pertaining to the group as a whole. Otherwise, call only group members that are needed and update other group members of the communication at the subsequent meeting.

3. Hangouts: For quick and easy contact the group has created a group chat on Google Hangouts.

2. Policy and Procedures

a. **Excused absence advanced notification**

i. Failure to notify other group members of an excused absence within the specified time limit will result in a first offense warning. Each subsequent failure to notify other group members of an excused absence will count as an unexcused absence unless it can be proven that the offender was physically unable to contact the group.

b. **Attendance policy violation**

i. For every .5 unexcused absences after the allowable 1.5 unexcused absences, a 2% deduction in the violating member's grade will result.

ii. For every 1 excused absence after the allowable 3 excused absences, a 2% deduction in the violating member's grade will result.

c. **Late work violation**

i. Shall any member turn in their work late, a 2% deduction in the violating member's grade will result.

d. **Violation of interpersonal norms**

i. Team members will hold each other accountable for when interpersonal norms are violated.

3. Team members' strengths & weaknesses "Roles"

a. **Evan Pataki**

Strengths: Logical, Hard Worker, Realistic/Efficient

Weaknesses: Passive, Stubborn, Easily Distracted

b. **Joe Malespini**

Strengths: Hard Worker, Detail Oriented, Team Players

Weaknesses: Get caught up in details, Stubborn, Impatient

c. **Benjamin Lisowski**

Strengths: Skilled technically in machine shop and Solidworks (Certified Solidworks Professional), Good Teammate, Big Picture Thinker

Weaknesses: Gets lost in certain details, Can become disinterested, Gets annoyed easily

d. **Benjamin Grozdanic**

Strengths: Productive/efficient, Fast learner, Gets the job done

Weaknesses: Careless, Impatient, Easily Distracted

e. **William Ståhlberg**

Strengths: Hard worker, Detail-oriented, Realistic

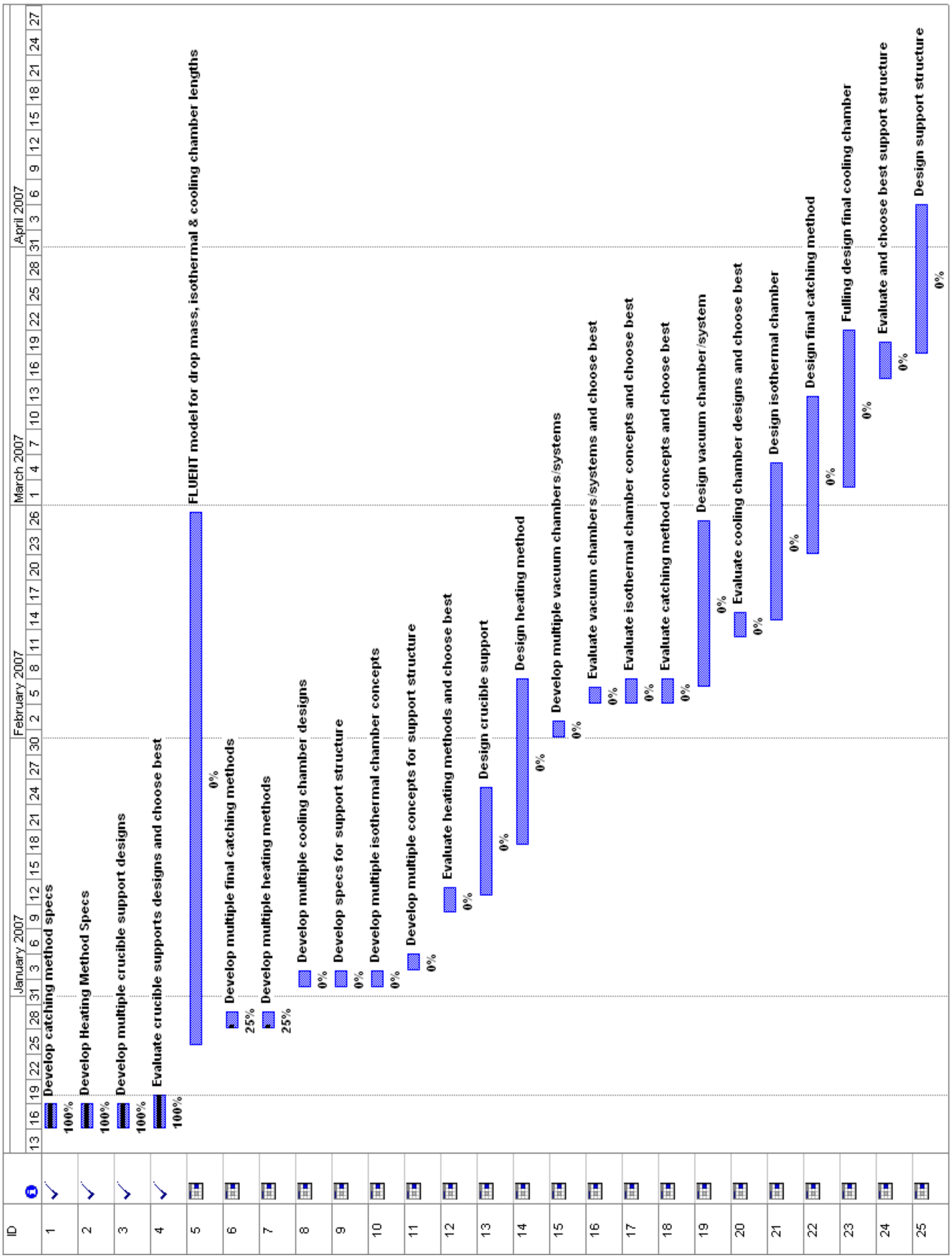
Weaknesses: Gets caught up in details, Prefers doing things calmly, Careful

f. **Karl Ståhlberg**

Strengths: Team player, Logical, Fast Learner

Weaknesses: Absent-minded, Time optimist, Impatient

4. Project Plan – General (each instructor will provide further info on requirements)



13.2 Contribution Report

Area of responsibilities

The Pennsylvania State University team had the main responsibility of planning how the project would proceed with a Gantt chart. There were some schedule differences; most importantly the Penn State team finished the project earlier than the Chalmers University of Technology, 2nd of May. Because the project was collaborative effort between two universities, there were different demands on the project and the thesis for each team. Because of this, the two teams needed to take responsibility not only for their own deadlines and demands but for the other university as well.

Both teams were responsible for collecting information about the project. The Chalmers team had the responsibility for the bibliography. All members of the teams were involved in understanding the problem, but William Ståhlberg and Benjamin Grozdanic took extra responsibility in gathering information from the sponsor, Aker Solutions. The Penn State team had extra responsibility when coming to hold up the communication between the teams and the sponsor. Karl Ståhlberg took extra responsibility when getting information in the method stage of the report.

In choosing product development methods and how to utilize them, both teams were equally responsible. It was clear from both universities of what was wanted in the report and therefore it was easy to follow these demands and which methods of development to be used. Karl however took extra responsibility making sure the methods of development were use in a correct way and in the correct order.

Regarding solving the problem statement, all members were involved and contributed with their own ideas.

Benjamin Grozdanic and William Ståhlberg took extra responsibility in setting up the FE models. All of the Chalmers team contributed to this part and had different angles which made up the discussion portion. Because the Penn State team project ended before the Chalmers teams project, they did not have as much time to spend on it.

Leading author of a section

All members in both teams were involved in all of the report. However, after the project had finished on the Penn State end, the Chalmers team used the remaining time for additional work. As such, Section 8.3 “Physical Tests and Conclusions” and Chapter 9. “Broadening of the Limitations: Redesign of the Whole System” were done solely by the Chalmers team.

13.3 Learning Factory Industry Project-Deliverables Agreement

Date __ 2-9-16_______________

Project Title Development of Seal Retainer Ring - GLOBAL PROJECT WITH CHALMERS

Sponsor Company: Aker Solutions

Company Contact Korey LeMond Phone 713-270-2891 Email korey.lemond@akersolutions.com

Faculty Coach **Jason Moore** Phone 814-865-1749 Email jzm14@psu.edu

Team Name **Aker Solutions Design Team**

Student Team (primary contact) Joe Malespini Email jam6642@psu.edu

Ben Lisowski	btl5093@psu.edu
Evan Pataki	ecp5117@psu.edu
Benjamin Grozdanic	bengro@student.chalmers.se
Karl Stahlberg	karlsta@student.chalmers.se
William Ståhlberg	wilsta@student.chalmers.se

Problem Statement:

The seal retainer used to hold the TX seals in place do not do so with high enough predictability. Aker Solutions would like a team of Penn State and Chalmers University students to provide a solution to a problem they are experiencing with their TX Seal's falling out on larger diameter pipes. The weight of the seal is too much for the O-ring friction lock to hold the TX Seal inside the pipe. A new method of holding the TX seals in place needs to be developed in order to safely retain them inside the pipe.

Deliverables:	**Delivery Date**
1) Final Report (copies to sponsor, instructor and Learning Factory)	PSU - May 2, 2016 CTH - May 17, 2016
2) Weekly update memos (status reports); delivery method:	Every Friday by midnight
3) Statement of Work (Project Proposal)	Feb 14 to instructors Feb 22 to Aker
4) Detailed Design Specification Report	March 23, 2016
5) Poster (32 x 40”) for Showcase	PSU - April 28, 2016 CTH - May, 27, 2016
6) One-Page Project Recap (submit to instructor)	PSU - May 2, 2016 CTH - May 17, 2016

Check below if this project involves:

x Non-Disclosure Agreement (attach copy of agreement to this form)

□ Loan of equipment, materials, documents (see next page)

Signatures: _ We agree to the deliverables listed above:

Team Members:

Project Sponsor date

date

date

Faculty Coach: date

date

date

date

Deliverables Agreement – **page 2**

Sponsor Supplied Items

In support of this project, we (project sponsor) agree to provide the following equipment, materials, or apparatus by the date listed.

The student team is responsible for returning all loaned items. The instructor reserves the right to withhold a final grade if loaned items are not returned, or if a copy of the final report is not delivered to the sponsor.

Item	Delivery Date	Check one	If Loan, Return Instructions
		□ donation □ loan	
		□ donation □ loan	
		□ donation □ loan	
		□ donation □ loan	

13.4 Gantt Chart

Aker Solutions Design Team Gantt Chart

Key		
Symbol	Meaning	Color
w	WIP	
-	To Do	
.	Complete	
.	Milestones	

Tasks	% Done	Start	End
Meet other team members	100%	Jan-14	.Jan-19
IP Agreement	100%	Jan-14	Jan-19
Non-Disclosure Agreement	100%	Jan-14	Jan-19
Meet team members	100%	Jan-19	Jan-19
Prepare Questions for Aker Solutions	100%	Jan-19	Jan-26
Gantt Chart	100%	Jan-19	Jan-26
Week 2 Status Report	100%	Jan-18	Jan-22
Group Contract	100%	Jan-18	. Jan-26
Week 3 Status Report	100%	Jan-25	.Jan-29
Week 4 Status Report	100%	.Feb-1	.Feb-5
Proposal Outline, Deliverables, and Gantt Chart	100%	.Jan-27	.Feb-8
Week 5 Status Report	100%	.Feb-8	.Feb-12
Project Proposal w/ Planning Report	100%	.Jan-27	.Feb-14
Arrangements for Proposal Presentation	100%	.Feb-15	.Feb-16
Week 6 Status Report	100%	.Feb-15	.Feb-19
Project Proposal w/ Planning Document Submission to Aker	100%	.Feb-15	.Feb-22
Project Proposal Presentation to Aker	100%	.Feb-23	.Feb-25
Week 7 Status Report	100%	.Feb-22	.Feb-26
Deliverables Agreement	100%	.Feb-29	.Mar-4
Week 8 Status Report	100%	.Feb-29	.Mar-4
Week 9 Status Report	100%	.Mar-9	.Mar-13
Week 10 Status Report	100%	.Mar-14	.Mar-18
Arrangements for Design Specification Report/Mid-Term Presentation	100%	.Feb-29	.Mar-22
Design Specification/Mid-Term Report Submission to Instructors	100%	.Feb-29	.Mar-23
Arrangements for Design Specifications Presentation to Aker	100%	.Feb-29	.Mar-24
Week 11 Status Report	100%	.Mar-21	.Mar-25
Adobe Connect Meeting	100%	.Mar-25	.Mar-31
Week 12 Status Report	100%	.Mar-28	.Apr-1
Week 13 Status Report	100%	.Apr-4	.Apr-8
Week 14 Status Report	100%	.Apr-11	.Apr-15
Week 15 Status Report	100%	.Apr-18	.Apr-22
Adobe Connect Meeting	100%	.Apr-21	.Apr-26
Penn State - Poster and Prototype Display	100%	.Mar-21	.Apr-28
Week 16 Status Report	100%	.Apr-25	.Apr-29
Final Report 1	100%	.Mar-21	.May-2
Peer Evaluations	100%	.Apr-25	.May-2
Learning Factory Deliverable to 314	100%	.Mar-21	,May-2
Leonhard Building Exit Cross Cultural Assesment	100%	.May-2	.May-2
Week 17 Status Report	100%	.May-2	.May-6
PENN STATE STUDENTS END HERE			
Week 18 Status Report (Chalmers)	100%	.May-9	.May-13
Week 19 Status Report (Chalmers)	100%	.May-16	.May-20
Final Report sent to disputing team (Chalmers)	100%	.May-17	.May-17
Written individual disputation (Chalmers)	100%	.May-17	.May-24
Week 20 Status Report (Chalmers)	100%	.May-23	.May-27
Oral disputation (Chalmers)	100%	.May-23	.May-27

Week #																					
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
Jan-11	Jan-18	Jan-25	Feb-1	Feb-8	Feb-15	Feb-22	Feb-29	Mar-7	Mar-14	Mar-21	Mar-28	Apr-4	Apr-11	Apr-18	Apr-25	May-2	May-9	May-16	May-23	May-24	May-27

13.5 Target Specifications

Aker Solutions Design Team		*Type of document*	**Target Specifications**		
		Project	**Design of a Seal Retainer Ring**		
		Function	**Retain the TX-seal inside the hub against gravity and impact loads**		
Metric No.	**Metric**	**Units**	**Desired Value**	**Required Value**	**Comment/Status**
1.	**Performance**				
	Retention force	N	>15,000	>13,333	Must be able to retain seal. Value was calculated at analysis stage.
	Removal force	%	<20,000	<30,000	Seal must be removable. Value was calculated at analysis stage.
	Temperature span 22"	Celcius (C)	-20 < T < 100	-20 < T < 50	Must withstand onshroe and subsea temperatures.
2.	**Safety**				
	Must retain the seal during impact loads	Assured by analyses		Yes	
	Damaging hub and seal	m		1e-9	The surface roughness may not exceed this value. This is not likely to be and issue as retainer solutions not have the hardness of steel and titanium.
	Non-toxic according to OSHA/EU-OSHA guidelines			Qualified	
3.	**Lifespan**				
	Lifespan	days	365	> (Lifespan of seal)	As the seal is replaced several times a year so will the retainer solution.
4.	**Availability**				
	Cost	USD	15	50	The current solution is priced at the desired value, which may be exceeded as the current solution does not work.
	Off-the-shelf product	Availability (No. suppliers)	5	1	A single supplier would suffice, but additional suppliers would be preferable.
	Not affect the current installation or removal procedure	Yes/No	Yes	No	
	Feasability in terms of FE analysis	Yes/No		No	Any viable solution will need FE analysis.
5.	**Durability**				
	Resist oil			Qualified	The solution must not deteriorate to the point of not meeting all the target specifications during its lifespan.
	Resist water			Qualified	The solution must not deteriorate to the point of not meeting all the target specifications during its lifespan.
6.	**Size**				
	Max profile width before compression	mm	<8.0	<9.8	A value above this would not fit the seal. A value above 8.0mm would not guarantee it being removable from the seal.
	Max profile height after compression	mm		<7.5	A value above this would not fit between the seal and hub.
	Max profile width after compression	mm		<9.8	It must be able to fit inside the seal.
	Inner radius 22"	mm		<269.5	Below this would not fit seal.
	Outer radius 22"	mm		<277	Above this would not fit hub.
	Weight	kg	<3	<0.5	The desired value is the typical weight of an O-ring but the required maximum weight is still negligible compared to the weight of the TX seal.
7.	**Environmental**				
	Mixed materials	Diff. types of mat. in product	1	2	The current solution uses a single material, an increase to more than 2 would make the solution unnecessarily complex for its function.
	Recycable	% of material recyclable	100%	0%	The current solution is an elastomer which has 0% reyclability but a solution that is recyclable is favorable.