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Installation and Bulkhead design of the Rigid Reservoir of the Ocean Battery

Bachelor Integration Project

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Abstract

As Ocean Grazer B.V. moves closer to building a large scale prototype of the Ocean Battery, it becomes more important to find a suitable solution to constructing the rigid reservoir of the Ocean Battery. Although, the rough design of the rigid reservoir segments has been established, detailed designs need to be created for the temporary and permanent bulkhead. Three permanent and four temporary bulkhead designs are created using a systematic design process in combination with bulkhead design recommendations from existing literature. The stability of the designs were assessed using finite element method (FEM) simulation, allowing the designs the be optimized for cost-effectiveness. Finally, the limitations of the research and recommendations for future development of the designs are discussed.

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Introduction

With current developments pushing the use of renewable energy sources, a new problem of responding to peaks and lows in the power net arises (Gallo et al., 2016) (Sinsel et al.,2020). To this end, energy storage systems(ESSs) can be used. The Ocean Battery from Ocean Grazer BV is such an ESS. The Ocean Battery is a scalable ESS up to MW scale for energy that is produced by renewable sources such as wind turbines and floating solar farms at sea (Ocean Grazer BV, 2022). The Ocean Battery design has been iteratively improved over the last years, with this project contributing to a new iteration. Designing a more cost effective solution for the construction of the rigid reservoir, a subsystem within the Ocean Battery, will be the focus of the research. Specifically, a permanent bulkhead and temporary bulkheads with a remote control release mechanism will be designed

Manually removable temporary bulkhead are currently employed in the construction of submerged structures (Lin et al., 2018). However, allowing construction workers to enter into a submerged structure dictates a safety factor of 8-15 for the entire construction to make the risk of failure very low (Porathur et al., 2018). This makes an underwater structure very expensive. Creating a remote control release temporary bulkhead will make manual removal redundant, meaning the safety factor of the rigid reservoir can be significantly lower. This method will be more cost effective and more safe than the currently used method, no humans will have to enter submerged reservoir segments.

The project design will be discussed first. This consists of the global project context, system description, problem analysis and statement, research objective and questions, proposed methods and tools to be used in the research together with validation of the results.

The research will consist of a literature review into the state of the art in bulkhead design in submerged construction and remote release mechanisms already in use in the subsea industry, followed by creating permanent and temporary bulkhead designs in SOLIDWORKS and performing FEM analyses and cost computations to validate the designs.

Research Design

Project Context

The Ocean Battery consists of 3 main parts: the hydro dam, the high-pressure bladder located on the ocean floor, and the low-pressure rigid reservoir located underneath the ocean floor. The ESS principle the Ocean Battery uses is storing potential energy on the ocean floor with water under high pressure in the high-pressure bladder. When there is a surplus of electrical energy generation from the nearby wind or solar farm, water is pumped from the rigid reservoir into the flexible bladder. This converts the electrical energy into potential energy that is stored until it is converted back into electrical energy in the case of an energy demand. The potential energy can be converted into electrical energy by letting the water flow from the flexible bladder through turbines under high pressure into the rigid reservoir. Although the Ocean Battery will be located in a saltwater environment, clean fresh water will be used for the energy storage inside the Ocean Battery. (Ocean Grazer B.V. 2015)

System Description

The subsystem considered in the research is the rigid reservoir, highlighted in the red boxes in figure 1 below. The rigid reservoir is a long cylindrical tube made up of individual smaller sections located underneath the ocean floor. The figure shows the final form and location of the rigid reservoir, however, the smaller reservoir sections, shown in figure 2, have to be lowered into a dredged channel in the ocean floor before being connected into one large sealed reservoir. During the process of lowering down the individual segments, the pressure inside and outside of the reservoir segment is different. Furthermore, the pressure on the outside of the segment changes with the depth below the water surface making it a highly dynamic system.

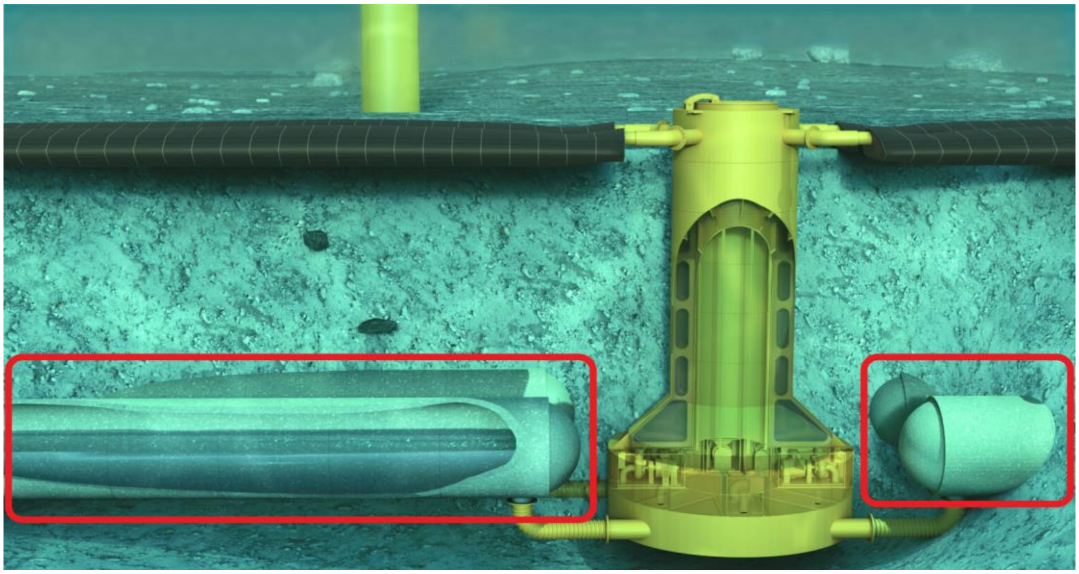

Figure 1: Overview of the Ocean Battery (Ocean Grazer BV, 2015)

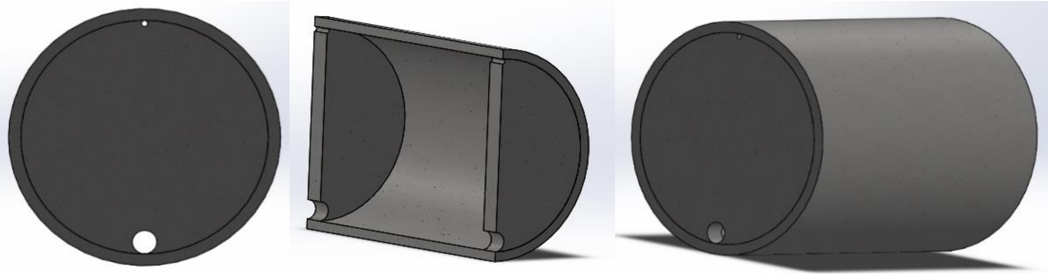

Figure 2: Schematic representation of the individual reservoir segments shown from different angles

From figure 2, it can be seen that the individual segments are hollow cylindrical tubes with two holes in the front and rear face at each end of the segment. From a meeting with the problem owner, it was decided that an inside diameter of 10 meters and a wall thickness of 1 meter will be used for the segment dimensions. The front and rear faces serve as partitions between the ocean water during the immersion phase. Hence from this point forward they will be regarded as the permanent bulkheads. A schematic representation of the permanent bulkhead is given in figure 3, where the light grey area denotes the permanent bulkhead, the dark grey area denotes the tube wall thickness and the two openings denote the passageways for the air and water flow.
To avoid the inflow of water during the immersion and installation of the reservoir segments, the holes have to be plugged with a temporary bulkhead during the immersion and installation phase. Thus, during the installation phase the reservoir segments will have two permanent bulkheads and four temporary bulkheads.

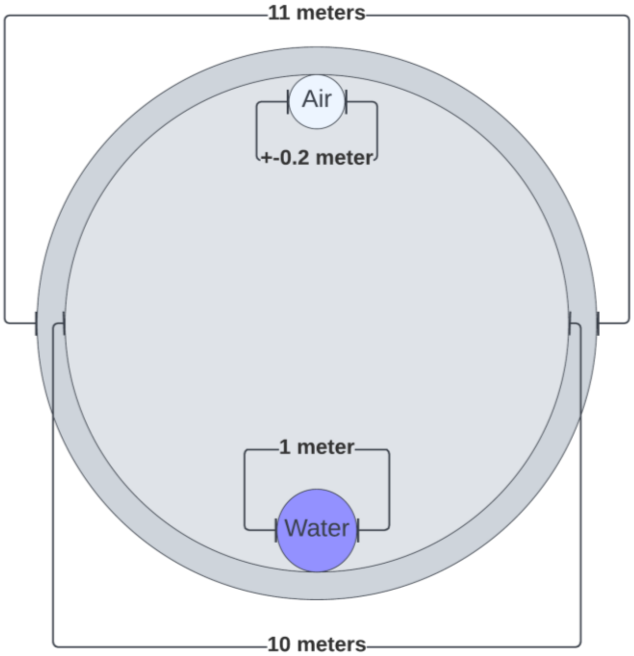

Figure 3: Schematic representation of the permanent bulkhead with outlined opening for the air and water flow during operation

Once the segments have been lowered down safely, they are connected using so-called Gina gaskets for the watertight seal to create the large reservoir. Only then can the temporary bulkheads be removed. In figure 4 an illustration shows this process for an immersed tunnel segment, globally the same principle can be used for the reservoir segments (Trelleborg Group, 2015).

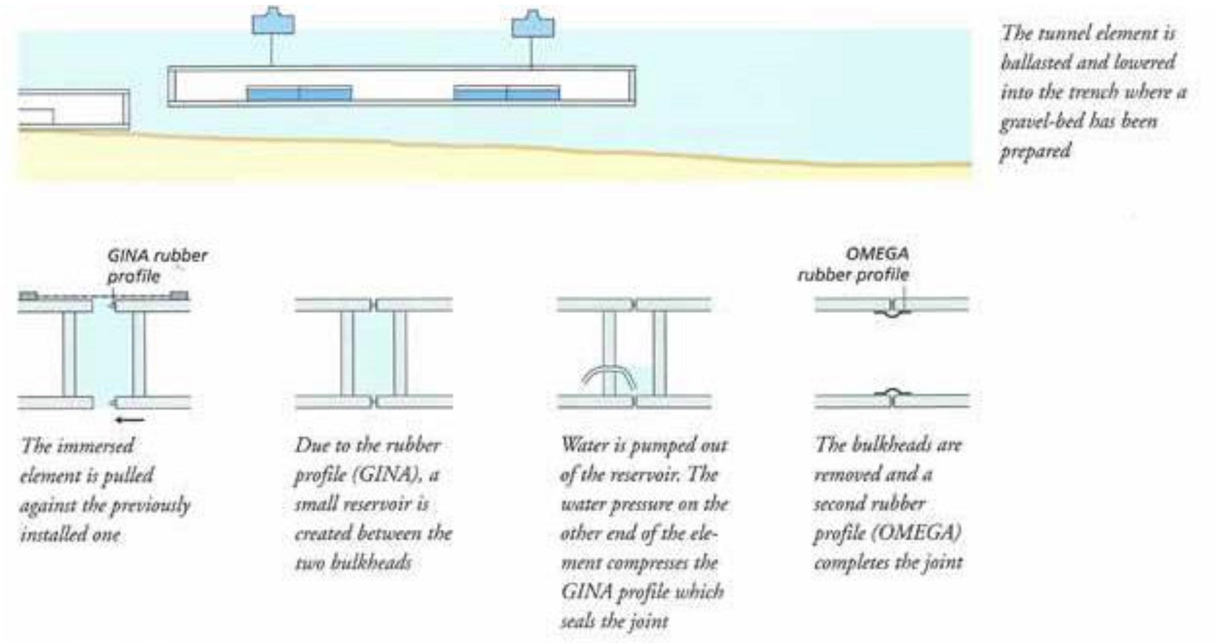

Figure 4: Illustration showing the installation procedure for an immersed tunnel segment (Trelleborg Group, 2015)

The research will focus on designing both permanent and temporary bulkheads such that the individual reservoir segments can be lowered into position and connected to each other remotely or, in other words, without using human workers in the water. The research will be conducted considering a total depth of 50 meters below the water surface, broken up into approximately 30 meters of water height and 20 meters of soil height when the reservoir is in its final position. The designs for the permanent and temporary bulkheads should be able to withstand the hydrostatic pressure at the selected depths.

Problem analysis

Building submerged structures via the proposed method in the project context is not a new problem, and it has been solved before in submerged tunnel building with numerous different methods (Akimoto et al., 2002) (Lin et al., 2018) (Niitsu et al, 1995) (Shishido et al., 1998) (Walter et al., 1997) However, all these methods make use of temporary bulkheads that are removed manually by workers inside the submerged structures after the individual segments have been connected. This is unwanted because of multiple factors:

- Extra safety margins have to be engineered into the construction because people are working in submerged structures. Submerged structures that allow human traffic into the structures have to have an increased factor of safety over normal constructions to mitigate the risk of flooding and loss of human lives in case the structure fails. These extra safety margins cause the initial build costs of the segments to increase.
- Costs of temporary bulkhead de-installation and dismantling are high because they have to be performed manually by skilled workers under challenging conditions

However, in underwater tunnel construction, these factors are of lesser importance because the structures have to be engineered for human traffic anyway and the bulkheads have to be dismantled to allow room for this human traffic(cars, trucks, trains, etc.).

In the case of the Ocean battery, the desire is to construct the rigid reservoir completely from the control center on the water surface. To fulfil this desire, the temporary bulkheads have to be removable remotely as well. This problem too has been solved with different solutions in the offshore industry and other challenging environments. (Shafiee et al., 2020) (Sotodeh et al., 2020) (Weilert et al., 2001).

Functional requirements

The temporary bulkheads could remain inside the reservoir when it is operational, as they can only be released when the reservoir is sealed off from the outside environment. This is not necessarily a problem as long as the flow of water through the reservoir is not obstructed. However, this approach decreases the reservoir capacity and creates a situation where the temporary bulkheads would be one-time-use.

From the provided needs, the temporary bulkheads have to meet the following functional requirements:

- Able to withstand the hydrostatic water pressure at a depth of 50 meters below the water surface.
- Have to be large enough to plug the holes in the permanent bulkhead when in use, thereafter as small as possible to optimize reservoir capacity.
- Have a remote control release mechanism.
- Have to be low cost as they will be one-time-use.

Stakeholder analysis

The problem owner in the current research is the company Ocean Grazer BV, as the research aims to solve an existing company design problem with regard to the Ocean Battery construction. Hence, the most important identified is Marijn van Rooij (CTO at Ocean Grazer BV), as this problem has the greatest interface with his department.

The other company executives, the CEO, and COO of Ocean Grazer BV are, of course, also important stakeholders in the research. However, their interest lies mainly in the implications of the research results. The final identified stakeholders are future investors/customers. Since these are projected stakeholders, their exact stake is not yet known. Nevertheless, a good indication can be gathered from systematic reasoning and is thus included.

All the identified stakeholders have aligned interests in the project, namely lowering construction costs/investment. It has to be kept in mind, however, that not all stakeholders assign the same value to this stake, hence a potential difference in involvement in the project has to be considered.

Design Standards

Keeping the functional requirements in mind, the bulkhead designs have to meet certain criteria to be allowed for use, yet no design codes directly apply to bulkheads. Following the Bureau of Reclamation, bulkheads can be designed and fabricated according to AISC and AWS D1.1. When designing a bulkhead, the working design loads (maximum water load, ice load, seismic load, etc.) must first be determined. The bulkheads must be designed to support forces applied by the maximum water pressure and stresses should always include the dry weight of the bulkhead. (Bureau of Reclamation, 2018)
Hence first the loading of the bulkheads must be determined before the design phase can commence.

Governing equations

The forces on the bulkheads will mainly originate from the hydrostatic pressure the water excerts on the faces of the bulkheads. The pressure is given by:

$$P = \rho_{water} g H + P_{atm} \tag{1}$$

Where P is the hydrostatic pressure [Pa], ρ_{water} is the water density [kg/m^3], g is the gravitational acceleration [m/s^2], H is the total height of the fluid column above the particle to the fluid surface [m], and P_{atm} is the atmospheric pressure [Pa].
The hydrostatic force in horizontal and vertical direction can then be calculated from:

$$F_{hor} = P_{centroid} A \tag{2}$$

Where F_{hor} is the horizontal component of the force on the submerged surface [N], $P_{centroid}$ is the pressure at the centroid of the vertical projection of the submerged surface [Pa], and A is the area of the vertical projection of the submerged surface [m^2]

$$F_{ver} = \rho_{water} V_{fc} g \tag{3}$$

Where F_{ver} is the vertical component of the force on the submerged surface [N], and V_{fc} is the volume of the fluid column directly above the curved surface [m^3].

When an object is immersed there is also an upward force created because the object displaces fluid as it is immersed, creating an upward lifting force called buoyancy. The buoyancy of the to be immersed object is given by the relation:

$$B = \rho_{water} V_{disp} g \tag{4}$$

Where B is the buoyancy force [N], ρ_{water} is the water density [kg/m^3], V_{disp} is the volume of water displaced by the object [m^3], and g is the gravitational acceleration [m/s^2]. Knowing this, the net buoyancy force can be determined by adding in the gravitational force from the objects' weight, giving:

$$F_{B,net} = -mg + \rho_{water} V_{disp} g \tag{5}$$

Where $F_{B,net}$ is the net buoyancy force [N], m is the objects' mass [kg] and the minus denotes the force direction of the gravitational force to be opposite of the buoyancy force.

The stress inside the reservoir segment and bulkhead walls caused by the forces applied to them can be calculated by either

$$\sigma = \frac{F}{A} \tag{6}$$

Where σ is the stress inside the material [Pa], F is the applied force [N], and A is the cross sectional area to which the force is applied [m^2]. In the case where the cross sectional area is difficult to determine, the stress can also be calculated by:

$$\sigma = \frac{Mc}{I} \tag{7}$$

Where M is the moment [Nm], c is the distance to the neutral axis [m], and I is the moment of inertia [m^4].

The safe working stress, when referring to a bulkhead gate or stoplog, should not exceed the following value (Bureau of Reclamation, 2018):

$$SS = 0.6F_{yield} \tag{8}$$

Where, SS is the safe working stress [Pa], and F_{yield} is the minimum yield stress of the material [Pa].

Problem statement

The current industry standard temporary bulkheads would be adequate to fulfil the needs of the Ocean Battery rigid reservoir. However, de-installation is costly, difficult, and dangerous, so a remote-controlled release temporary bulkhead is proposed as an alternative to the current method. It is unclear what combination of materials, shapes, and form of remote control release will yield a more cost-effective viable solution to the problem.

Research Objective

To design an optimal permanent and temporary bulkhead with a remote control release function for the temporary bulkhead with a safety factor of at least 2 within the constraints of the rigid reservoir segments, that provides Ocean Grazer BV with a competitive advantage with regard to placing the rigid Ocean Battery reservoir segments on the sea bed.
The viability of the design will be determined by analytical and FEM force analyses in which the safety factor of at least 2 is ensured, while optimality of the design will be determined by a cost calculation to physically create the proposed design. The research should be finished within 22 weeks.

Research Questions

The main research question is formulated as:

What temporary and permanent bulkhead design provides the most cost-effective solution to the problem with the given functional requirements and safety factor?

The following sub-questions will support answering the main research question.

a. What developments have been made in recent years?
    i. In the bulkhead design field?
    ii. In the remote-controlled release mechanism field?

b. What are the forces acting on the temporary and permanent bulkheads during all installation phases?
c. What are possible material, shape, and remote release system choices for the bulkhead designs?
d. Which of the possible design choices can withstand the hydrostatic forces at the chosen depth?
e. What is the most cost-effective combination of material, shape and remote release mechanism?

Methods and tools

Throughout the project and thus assisting in answering the subsequent questions, the engineering design cycle, as shown in figure 5 is used (Kamp, 2011). The cycle was chosen based on the applied nature of the project since it is an engineering design problem rather than a fundamental theory problem.

To aid in the design process itself, the systematic approach from Pahl and Beitz will be used. This method consists of four steps: Task clarification, conceptual design, embodiment design and detailed design (Pahl and Beitz, 2007). The method was chosen because of the systematic nature that creates clear steps and goals for an engineer to work towards and because it is one the most internationally accepted European design methods (Malmqvist et al. 1996).

Subquestions 1.a.i. and 1.a.ii. provide insight into the current state-of-the-art of both industries and represents the exploration phase in the design cycle. Ideas from both industry standards can serve as inspiration for the development of the new Ocean Battery bulkhead designs. The answer to these questions will be provided by a desk research approach of doing literature reviews within both fields of knowledge.

Subquestion 1.b. reflects conceptual design phase of the project, as it goes into the (hydrostatic) pressures and forces acting on the permanent and temporary bulkheads during all the installation phases. Using the governing equations, the conceptual design stresses and forces during the immersion from the surface to a depth of 50 meters and the later installation phase of vacuum sealing the reservoir segments when the pressure direction is reversed can be calculated.

The embodiment design stage of the research is reflected in subquestion 1.c. where the industry standards of question 1.a. and the conceptual design of subquestion 1.b. will be used as guidelines to create a number of possible bulkhead designs. The designs will be created with the help of Solid works. Because, it possesses all the modelling and simulation functions necessary for the project, and because it is one of the most widely used CAD software packages in the industry.

The fourth subquestion deals with the force analyses that have to be performed to ensure that the proposed designs meet the functional requirements and hold up to the conceptual design stresses. To ensure robustness of the designs, both analytical force analysis and FEM analysis in Solidworks will be used.

Answering the final subquestion deals with the financial side of the project. Provided more than one design passes the analyses, a cost comparison will be done between those designs to see which combination of factors produces the most cost-effective solution for Ocean Grazer B.V. Furthermore, a comparison with the current state-of-the-art(manual removal with divers) will be made to ensure proposed final design exceeds the current state-of-the-art.

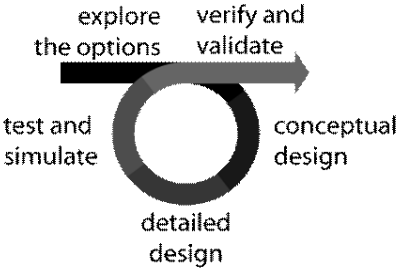

Figure 5: Engineering Design cycle (Kamp, 2011)

Deliverables and Validation

The artifacts that are to be delivered include, at least, final designs for the permanent bulkhead and the temporary bulkhead with a remote release mechanism, with an analytical and a FEM force analysis for both final designs.
The validation of the research can be assessed through a design validation process such as the one presented in figure 6. The final step of a real-life artifact, in figure 6 denoted as medical device, will not be reached for this project, and since the deliverables for the project are design outputs, these will be used for the validation process.
Internal validation, in the figure verification, is assessed by comparing the design output with the design input, in this case the functional requirements. Internal validation is reached through the force analyses proving that the final designs can handle the conceptual design stresses.
External validation, perhaps more importantly, will be assessed by comparing the design output to the user needs. Therefore, the economic and process side of the research have to be incorporated. Because to be useful, the proposed designs have to be more cost effective than the current state-of-the-art and actually useable in the Ocean Battery construction.
The useability will be checked by validating individual key elements(Safety factor, material selection, remote control options, etc) with the most important stakeholder(Ocean Grazer B.V. CTO, Marijn van Rooij) to validate that the individual elements will work in the Ocean Battery construction process, while the economic validation will be assessed through subquestion 1.e.

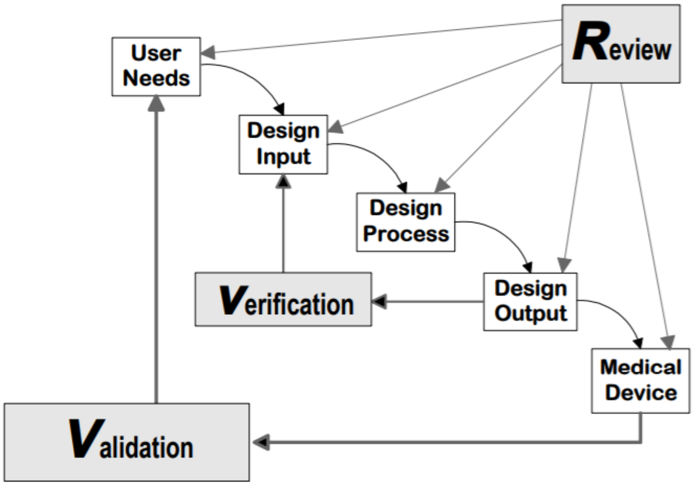

Figure 6 Design device validation process (Center for Devices and Radiological Health, 1997)

What development have been made in recent years?

In the bulkhead design field?

Theoretical design thicknesses

When designing a bulkhead, the design parameters to be determined are the required thickness, shape or radius of curvature. Which are governed by the cross-sectional area, estimated water pressure, material strength and the shape of the mounting surface. Numerous researchers and sanctioning bodies have adopted numerous different methods to create formulas for safe bulkhead thicknesses over the years. Most equations focus on one major strength property of the bulkhead material to make a thickness estimate. Some formulas use tensile strength as their major parameter, where others choose crushing strength, shear strength or water impermeability of the design material.

In general equations based on tensile strength of the bulkhead material estimate higher dam thickness than equations based on crushing strength, shear strength and water impermeability. That being said, the theoretical design equations are found to be inadequate as they consider only one of several important design parameters of the design material. Because, bulkhead failure comprises of multiple material property aspects it is important to utilize a numerical modelling approach in the design phase that accounts for all material properties. To this end, Porathur employs a strain-softening material, finite difference numerical approach. (Porathur et al, 2018)

(Yilmaz et al, 2018) uses different seal thicknesses, namely 30, 60, 90, and 120 cm, which are most commonly used in the Turkisch mining industry. All seal thicknesses are tested for different gallery geometries and cross-sectional areas in a numerical model to assess seal stability. The method aims to examine the effects of dimensional aspects such as larger gallery height with the same cross-sectional area on seal stability. The research team concludes that bulkhead stability increases mostly through increasing bulkhead thickness.

(Yao et al.,2007) too, proposes a system of theoretical formulae to determine thickness. In this system the critical buckling pressure is the major material strength property used to determine bulkhead thickness.

However, certain shape designs make it impossible to determine the critical buckling pressure analytically. In that case a safe estimate for the theoretical buckling pressure is obtained through a FEM analysis, after which the critical buckling stress and bulkhead thickness can be determined. Eventually, the researchers maintain a constant bulkhead thickness at 20 mm to test different strengthening techniques.

Material selection

(Porathur et al., 2018) uses M35 grade concrete in their simulations, it is a medium strength grade concrete with a compressive strength of 35 MPa when dry. Furthermore, it is the most commonly used grade of concrete for the application currently, and keeping the concrete grade constant highlights calculated theoretical thickness differences for different formulas. Also, M35 concrete shows good post-failure load bearing after reaching the peak value in tension and compression.

(Yilmaz et al., 2018) makes use of a different approach. Here four different classes of concrete, C14, C20, C30, and C40, are compared for different thicknesses, gallery geometries and gallery dimensions. Again the numbers after the 'C' refer to the compressive strength in MPa of the concrete class when it is dry. Simulation results show that material strength has a significant influence on the bulkhead stability for a bulkhead thickness smaller than 60 cm, for thicknesses greater than 60 cm the bulkhead stability increases more through a higher thickness rather than increasing the material strength.

In the case of (Yao et al., 2007), steel 980 is chosen as the application environment calls for a formable, high strength and relatively low weight material. 980 steel is a high strength, cold rolled steel with high ductility and yield strength. It is typically employed in high tensile stress environments.

Bulkhead shape

From (Porathur et al., 2018) and (Yilmaz et al., 2018), it becomes apparent that roadway or gallery dimensions are an important factor when it comes to bulkhead stability. To this end, it is found that greater roadway dimensions decrease the loadbearing capacity of a bulkhead. Even though, concrete structures with a higher width/height ratio exhibit significant post failure strength, denting occurs at the midpoint along the longest gallery dimension(height or width) of the bulkhead making it the most important dimension for seal stability after thickness.

For one modelling step, Porathur makes use of an arched bulkhead with a radius curvature of 12 meters with the outside curved surface facing the upstream direction. It is assumed this was done out of strength consideration, however the exact reason for the radius is not mentioned in the paper.

(Yao et al., 2007) recommends using a Radius/thickness(R/t) of 143 to optimize strength against material usage. Additional strength can be gained through a $\perp \frac{20\,X\,300}{20\,X\,100}$ main reinforcing bar and 6 radial reinforcement bars of 16a bulb flat to reinforce the spherical bulkhead if necessary. Additionally, 18a bulb flat bars can be used for the radial ribs to create another extra safety margin.

Safety factor and Failure criterion

In mining, temporary and permanent bulkheads are applied to close of inactive parts of a mine from undetected water ingress. These bulkheads are designed with a very safety factor, ranging between 8 and 15 (Porathur et al, 2018). The safety factor is chosen this high to protect miners in the active part of the mine from a flash flood through ground water seepage.
Concrete bulkheads remain stable for displacements up to 0.8-1 mm, although tensile cracks are formed on the surface. Displacements greater than 1 mm cause failure zones in the bulkhead structure independent of bulkhead thickness (Yilmaz et al., 2018). Eventually, bulkhead failure starts with tensile crack development on the outside of the displaced surface and ultimately fails through tensile and shear yielding on the inside of the displaced surface (Porathur et al., 2018) (Yilmaz et al., 2018).
For the 980 steel bulkhead the stability requirement is defined as such: $P_{th}/1.25P_{water}$ > 1. Meaning that the bulkhead is considered stable when the theoretical buckling pressure is 1.25 times greater than the designed hydrostatic pressure. This is considerably lower than for the concrete bulkheads, however in combination with other conservative choices for material strength properties the overall safety factor is somewhat higher (Yao et al., 2007).

Concluding, for concrete bulkhead thicknesses in this project, an initial thickness of 1 m will be used. This thickness will be increased or decreased based on the bulkhead stability results from FEM analyses to obtain a definitive thickness. The bulkhead stability will be assessed using a minimum safety factor of 2 and a maximum bulkhead displacement of 1 mm.
For steel bulkhead thicknesses, an initial thickness of 20 mm and an initial curvature radius of 2860 mm will be used. This thickness and curvature radius too, will be increased or decreased based on bulkhead stability results from FEM analyses. The assessment criteria for the steel bulkheads will be a minimum safety factor of 2.

In the remote-controlled release mechanism field?

Subsea all-electric, electric over hydraulic and pneumatic solutions

Subsea development is innovation more and more towards more simple, digital and cost-effective solutions. Electric subsea solutions without hydraulic components are an attractive and environmentally friendly alternative to hydraulic solutions as removing hydraulic fluid from control systems is favorable in regard the health safety and environment (HSE) (Abicht and Halvorsen, 2017 as cited in Sotoodeh, 2020).

There are more advantages outside of HSE, such as improved reliability, flexibility, functionality and cost effectiveness. While all-electric solutions have many parts that can fail, most electric valves have dual redundancy fail saves. In addition the ability to monitor actuator position(e.g. 10% open) from the control room also adds reliability. Whereas contaminated hydraulic fluid can cause failure of hydraulic solenoid valves and actuators, rendering them useless. (Larssen et al., 2016, as cited in Sotoodeh, 2020)

In subsea valve control, actuators using hydraulic or all-electric power sources are most common, however another remote control release option would be pneumatic actuators. In comparison with electric and hydraulic actuators, pneumatic actuators have the advantage of low cost, large output force/weight ratio, fast response, high adaptability to various circumstances and long lifespan (Du et al, 2018). Moreover, limited size pneumatic actuators are significantly more powerful than same size all electric actuators (Packard, 2022). That being said, energy consumption of pneumatic systems and the risk of systems leakage are similar to those of hydraulic systems. The upside being, compressed air has significantly less impact on the environment compared to hydraulic fluid. Table 1 provides an overview the comparison between electric, hydraulic and pneumatic actuators (Sotoodeh,2020).

Table 1 Electric, hydraulic and pneumatic actuator comparison adapted from (Sotoodeh, 2020)

Features and differences	Electric actuator	Hydraulic actuator	Pneumatic actuator
Energy consumption	Electrical power, which is lower compared with hydraulic	Hydraulic oil	Compressed air, which is similar to hydraulic
Environmentally friendly	More environmentally friendly	Less environmentally friendly	Neutral environmentally friendly
Space consumption	More compact	Less compact	More compact
Risk of leakage	No	Yes	Yes
Fail-Safe option	Yes, through spring and loss of power	Yes, through spring and loss of power	Yes, through spring and loss of power
Reliability	More	Less	More
Flexibility in usage in different locations	Yes	Yes	Yes

Actuator power supply

Because, the actuators also need to be supplied with power, this aspect also needs to be taken into account. For electric actuators this is done through copper electricity cables or batteries, for hydraulic actuators this is done through hydraulic lines filled with hydraulic fluid and for pneumatic actuators this is done through airlines. As most of the remote control release mechanism equipment will remain inside the rigid reservoir, it is essential the remaining equipment does not contaminate the fresh water inside the reservoir during operation. It is clear to see, that a pneumatic system has the smallest chance of contaminating the fresh water inside the reservoir as it does not introduce heavy metals and fluids into the systems.
Concluding, based on the characteristics of the actuator type solutions for the remote control release mechanisms described above, pneumatically powered actuators seem the best fit for use within the constraints of the Ocean Battery rigid reservoir.

Pneumatic actuator types

Linear and quarter turn rotary actuators are the most commonly used actuators in the subsea petroleum industry(Sotoodeh, 2020). However, linear and (multi-turn) rotary actuators are the most commonly used pneumatic actuators.

Linear actuators

In pneumatic linear actuators a piston connected to a rod is moved inside a bore to create a linear motion. The rod can be extended and retracted by supply opposite sides of the piston with compressed air, as can be seen in the schematic drawing of figure 7.
Pneumatic linear actuators are low cost, can generate precise linear motion and repeatability and they can handle extreme temperatures. However, pressure losses in the system effect both performance and efficiency of the actuator (Gonzalez, 2015).

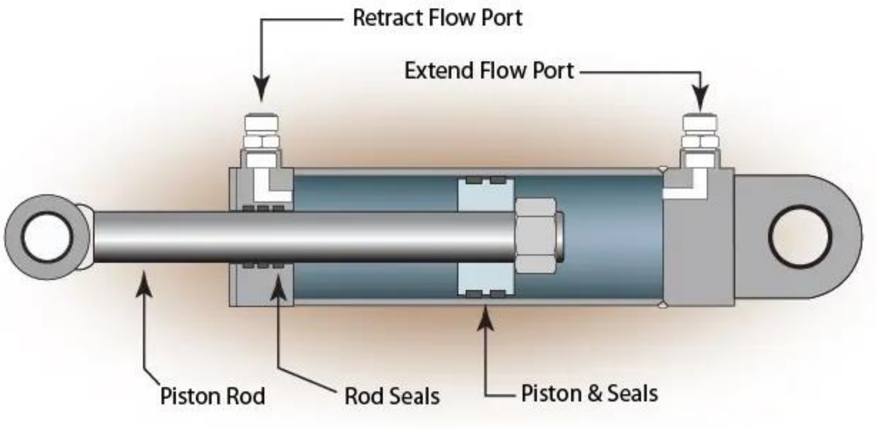

Figure 7 Pneumatic linear actuator (Source: Control Products Inc.)

Pneumatic quarter and multi-turn rotary actuators

Pneumatic quarter and multi-turn actuators operate fairly similar. Compressed air creates linear movement of the piston, then through a scotch and yoke or a rack and pinion the linear movement is transferred into rotary motion. Quarter turn actuators are often used to open and close ball valves as they are very suited for this task with a 90° rotary travel. On the other hand, multi-turn actuators are used when larger rotary displacement or higher precision is necessary (Sotoodeh, 2020). Figures 8 and 9 show a pneumatic quarter and multi turn actuator respectively.

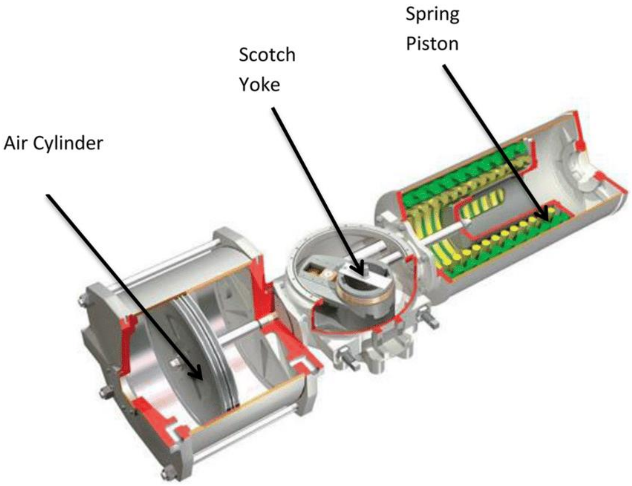

Figure 9 Pneumatic quarter turn actuator (Sotoodeh, 2019)

Figure 8 Pneumatic multi-turn rotary actuator (Source: Power and Motion)

Subsea signal transmission

In the case that a remote mounted actuator with a radiofrequency(RF) receiver is used, a remote method to activate the actuator is needed. However, acoustic communication data rates are restricted to approximately tens of thousands of kilobits per second for distances up to a kilometer. In addition, the speed of acoustic waves in the ocean is around 1500 m/s, meaning long range communication is paired with long delays (Arnon, 2010).
For the application of this project, using a depth of 50 meters, using acoustic waves would mean a response time of 0.03 seconds. Furthermore, sending an on/off signal for an actuator to a remote receiver is at all possible within the tens of thousands of kilobits of maximum data transfer. Hence, using conventional acoustic waves to activate actuators remotely should not be a problem for this project.

What are the forces acting on the temporary and permanent bulkhead during all installation phases?

For the most part, the function of the to be designed bulkheads will be served during the installation phase where a watertight reservoir segment is needed. The different forces and pressures acting on the bulkheads and the segment during installation are significantly dependent on the environmental conditions during the installation.
In the HZMB island and tunnel project in Hong Kong the criteria for the environmental constraints were taken as described in table 2. Precise environmental constraints have to be assessed for each individual installation case and location, however for the current project the criteria as mentioned in table 2 will be used. Furthermore, it is assumed that the safety factor for the designs is chosen such that environmental constraints have no significant influence on the stability of the bulkheads and only the hydrostatic forces have to be taken into account.

Table 2 Environmental conditions for installation of an immersed tunnel segment (Lin et al., 2018)

Environmental parameter	Criteria
Current velocity	≤0.6 m/s any time ≤ 0.5 m/s for the final installation in slot
Significant wave height	≤0.6 m
Wind velocity	≤ 10 m/s
Visibility	≥ 1000 m
Passing by vessel velocity	≤ 5 m/s for 7 h

Overview of the installation phases

The reservoir segments will be installed with all the permanent and temporary bulkheads in place to create watertight segments. In order to obtain adequate bulkhead designs, the loading of the bulkheads during operation have to calculated before the design phase starts(Bureau of Reclamation, 2018). In this case that means the loading of the bulkhead during all installation phases. Hence, an overview of all installation phases needs to be made. The installation of a reservoir segment consists of the following steps:

- Immersion phase
- Connection phase
- Draining phase
- Release phase

Figure 4, in the research design portion of this report, provides a visual representation of the installation phases.

Immersion phase

The immersion phase marks the start of the installation process, and during this phase the reservoir segment is lowered from the ocean surface to a depth of 50 meters. From eq. 1 it becomes apparent that the hydrostatic pressure acting on the outside of the segment increases linearly with the waterhead above the immersed surface. On the other hand, the pressure inside the segment remains constant because the inside of the segment is sealed off from the outside environment through the temporary and permanent bulkheads. For this research project the inside pressure will be kept at 1 atmosphere or 101.325 kPa for all installation phases.
Table 3 below, shows external and internal pressure acting on the bulkheads for the immersion phase for a waterhead from 0 to 50 meters at a water density of 1023.6 kg/m^3 (north sea water).

Table 3 External and internal pressures on the bulkhead for every 10 meters of depth during the immersion phase

Waterhead [m]	Pressure on the outside of the bulkhead [kPa]	Pressure on the inside of the bulkhead [kPa]
0	101,325	101,325
10	201,740	101,325
20	302,155	101,325
30	402,570	101,325
40	502,986	101,325
50	603,401	101,325

Connection phase

During the connection phase two individual segments are connected together using a Gina gasket to create a seal between the two concrete segments. To create this seal, a negative pressure in the cavity between two opposing bulkheads is needed to suck the reservoir segments together. This is a multi-step process.
First, two segments are placed end-to-end mechanically with a crane with a Gina gasket in between. At this point a small reservoir filled with seawater is created in the cavity between two opposing bulkhead. Initially the pressure inside this cavity is 6 atmospheres, the same as the outside ambient pressure.
Secondly, a negative pressure is created in the cavity between opposing bulkheads using a vacuum pump to enable the Gina gasket to create a permanent watertight seal. Ocean Grazer CTO Marijn van Rooij provided a worst case scenario where 1 atmosphere of absolute pressure would be necessary to enable the Gina gasket to create the seal. Using this pressure value of 1 atmosphere absolute as an assumption, the pressure inside the cavity will drop from 6 atmospheres to 1 atmosphere and the pressure on the outside and inside of the bulkheads will be equal as the internal pressure remains unchanged from the immersion phase. The pressure profile for the connection phase is summarized in table 4 below.

Table 4: Pressures on the inside and outside of the bulkhead for the connection phase

Pressure	Pressure on the outside of the bulkhead [kPa]	Pressure on the inside of the bulkhead [kPa]
At the start of the connection phase	603,401	101,325
At the end of the connection phase	101.325	101,325

Draining phase

The cavity between opposing bulkheads that is created during the connection phase is filled with sea water initially. Because, the Ocean Battery will not use salt water during operation this cavity needs to be drained. The water in the cavity can be drained out using multiple methods, i.e. pumping it out with a conventional water pump at the surface or using pressurized air to force the water out back into the sea through a drain tube in the bottom of the segment tube.

Both methods have positive and negative aspects. Pumping out the water does not introduce more significant pressures or forces into the cavity as the pressure in the cavity can remain at 1 atmosphere. However, the pump pressure would need to be considerable as the water needs to be elevated 50 meters before it can be discharged.

To force the sea water out with air pressure using a drain tube in the bottom of the segment tube, the pressure of the forcing air has to exceed the ambient external water pressure. In other words, the pressure in the cavity has to increase from 1 atmosphere to just above 6 atmospheres to force the sea water out. Because, the pressure in the cavity has to exceed the external ambient water pressure, the two connected segments will be forced apart.

Because, it is still unclear what exact method will be used to drain the cavity between the two opposing bulkheads, it is assumed that the sea water is pumped out as this option does not risk the two connected segments becoming detached.

Overall this means the pressure does not change during the draining phase, only the sea water in the cavity is drained out. Still, an overview of the pressures on the inside and outside of the bulkhead during the draining phase is provided in table 5.

Table 5: Pressures on the inside and outside of the bulkhead for the draining phase

Pressure	Pressure on the outside of the bulkhead [kPa]	Pressure on the inside of the bulkhead [kPa]
At the start of the draining phase	101.325	101,325
At the end of the draining phase	101,325	101,325

Release phase

The release phase can only commence once the pressures on both sides of the bulkhead are equal and the sea water has been removed from the cavity between two opposing bulkheads. This condition has been created at the end of the previous installation phase, the draining phase. Despite there being no changes in the pressures and forces acting on the bulkheads, the release phase is still being accounted for in the installation phases overview as it is a critical step before the reservoir can be operational. Therefore, the pressures on the inside and outside of the bulkhead are given in table 6.

Table 6 Pressure on the inside and outside of the bulkhead for the release phase

Pressure	Pressure on the outside of the bulkhead [kPa]	Pressure on the inside of the bulkhead [kPa]
At the start of the release phase	101,325	101,325
At the end of the release phase	101,325	101,325

Installation pressure profile

From the four individual installation phases described above, a pressure profile for the entire installation is created. This profile will be used to assess the stability of the proposed bulkhead designs in a dynamic simulation during a later stage of the project. Figure 10 shows the installation pressure profile on the inside and outside of the bulkhead, where important steps in the process are annotated in the graph.

A specific time for installation process on the x-axis cannot be given as it is dependent on many factors and is not constant for across all reservoir segments. Installation time for the final element in the HZMB island and tunnel project was approximately 18 hours from the moment the segment was lifted of the deck of the transportation barge to the moment the installation was completed. Although, it has to be taken into account that the segments in the HZM project are larger and more complex than the rigid reservoir segments (Lin et al., 2018). Hence, assuming an installation time of 10-16 hours per segment, depending on environmental conditions, should be a reasonable estimate.

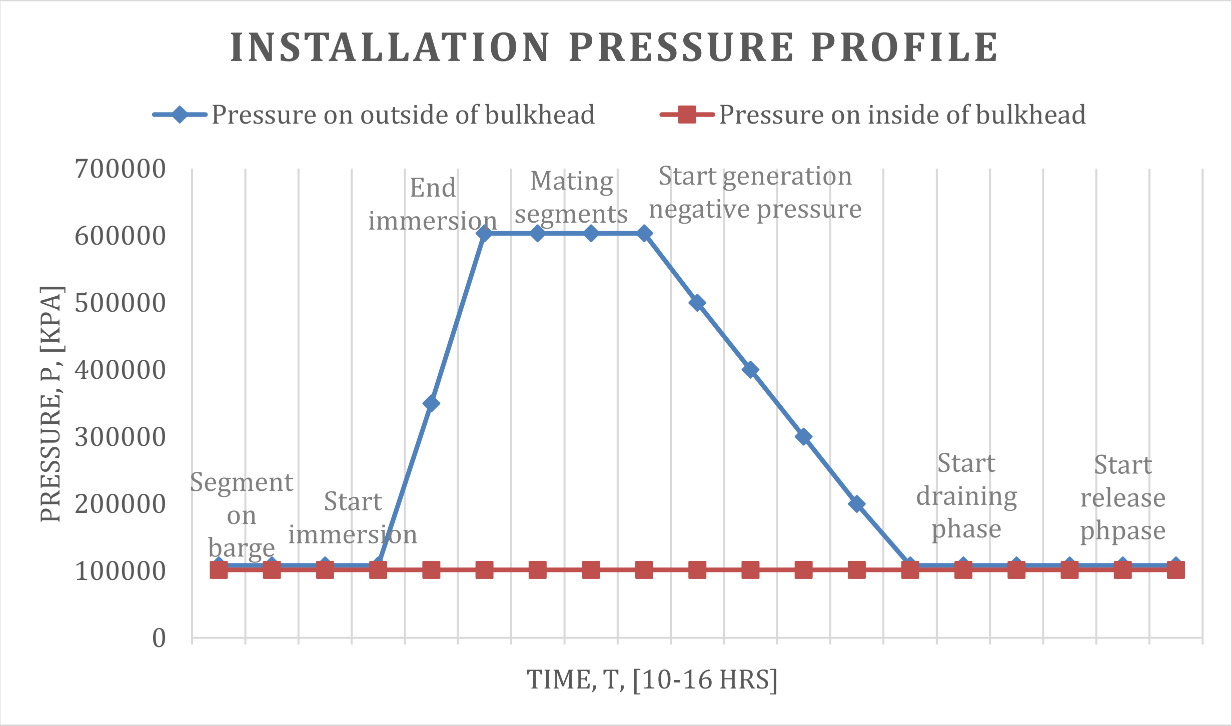

Figure 10 Graph showing external pressure on the reservoir segment during all installation phases, with time [Hrs] on the x-axis and external pressure [kPa] on the y-axis

What are possible material, shape and remote release system choices for the bulkhead designs?

Since the conceptual design phase has been completed in the previous, now the detailed design phase can commence. This section will focus on the first stages of the detailed design phase, which is creating concepts for the materials and shapes to be used such that the designed parts and assemblies geometrically meet the functional requirements set at the beginning of the project.

Permanent Bulkhead

A reservoir segment consists of a segment tube, two permanent bulkheads and four temporary bulkhead to create the watertight seal. The segment tube and the two permanent bulkheads will be made out of concrete as the will be poured as one piece.
Three different shapes are proposed for the permanent bulkhead: a flat circular disk, a perfectly sphere and a spherical bulkhead with a curvature of 12 meters. The 12 meter curvature was chosen based on literature where this curvature was also used for a similar roadway as the one in this project (Porathur et al., 2018).
In all permanent bulkhead designs, two circular holes with respective dimensions of 1500 mm and 300 mm each are made in the bulkhead to serve as water and air passages. The water passage dimension was determined from communications with Marijn van Rooij, as this dimension has already been used in other calculations for the ocean battery concept. The air passage dimension was chosen a factor of 5 smaller than the water to aid bulkhead stability. Since, density difference between water and air is approximately a factor 1000 this should not cause any problems for the reservoir ventilation during operation.
The bulkhead thickness of all designs was decided based on the force analyses conducted on the bulkhead concepts. However, both the force analyses and the bulkhead thickness will be elaborated on in the next sub-question.

Flat permanent bulkhead

As the name of the design suggests, the shape of this permanent bulkhead is a flat disk. Precise dimensions of the flat permanent bulkhead are given in figure 11. Because, the segment tube and the permanent bulkhead will be cast as one piece the diameter of the disk is the same as the inner diameter of the segment tube at 10,000 mm.

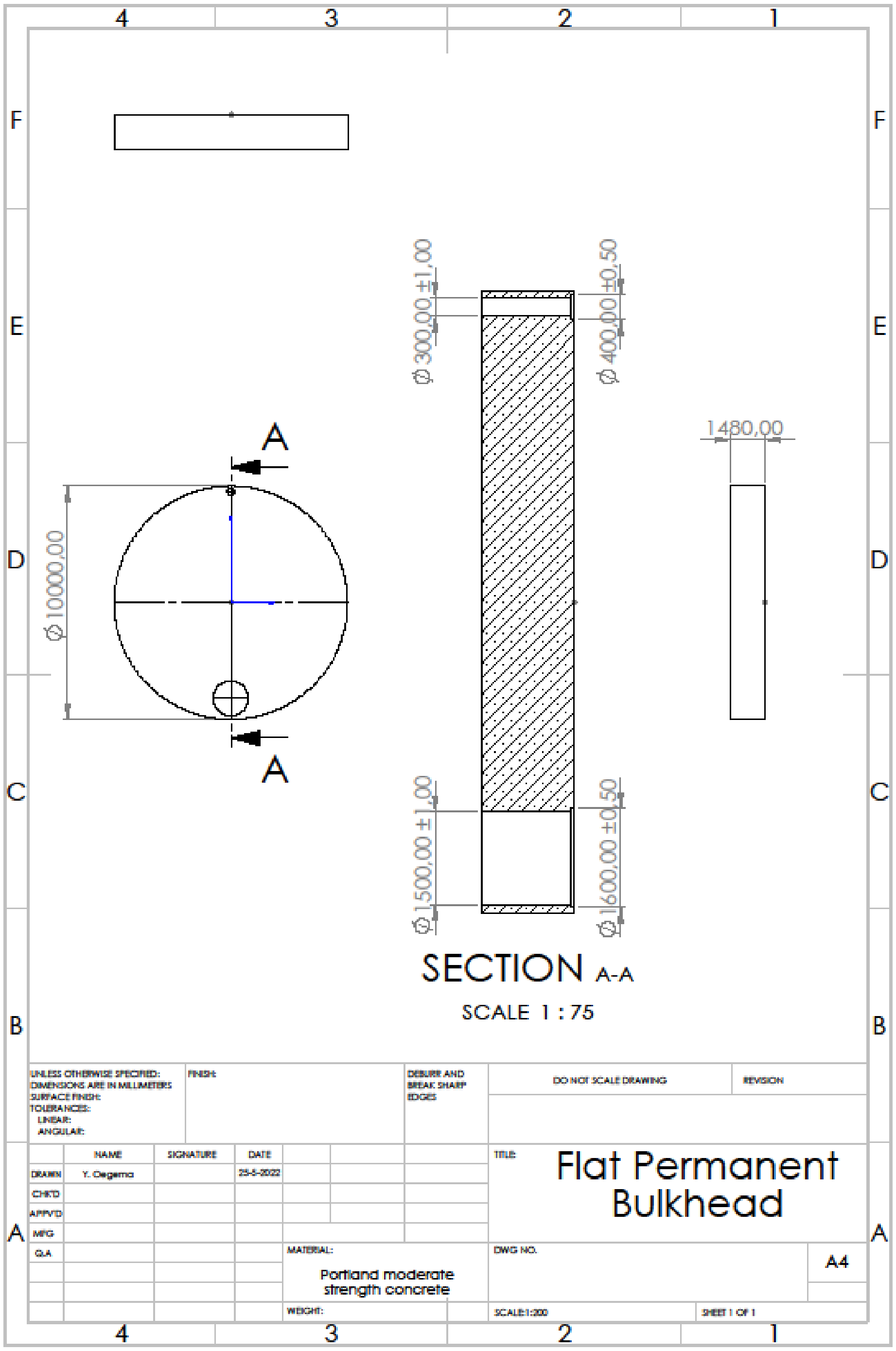

Figure 11 2D technical drawing for the flat permanent bulkhead, dimensions are in millimeters

5m curvature spherical permanent bulkhead

This permanent bulkhead design aims to capitalize on the ability of spherical structures to withstand pressure. For this design, a perfectly spherical geometry was chosen, meaning the radius of the sphere is the same as the inner radius of the segment tube at 5000 mm. Figure 12 below provides more details on the dimensions and shape of the bulkhead design.

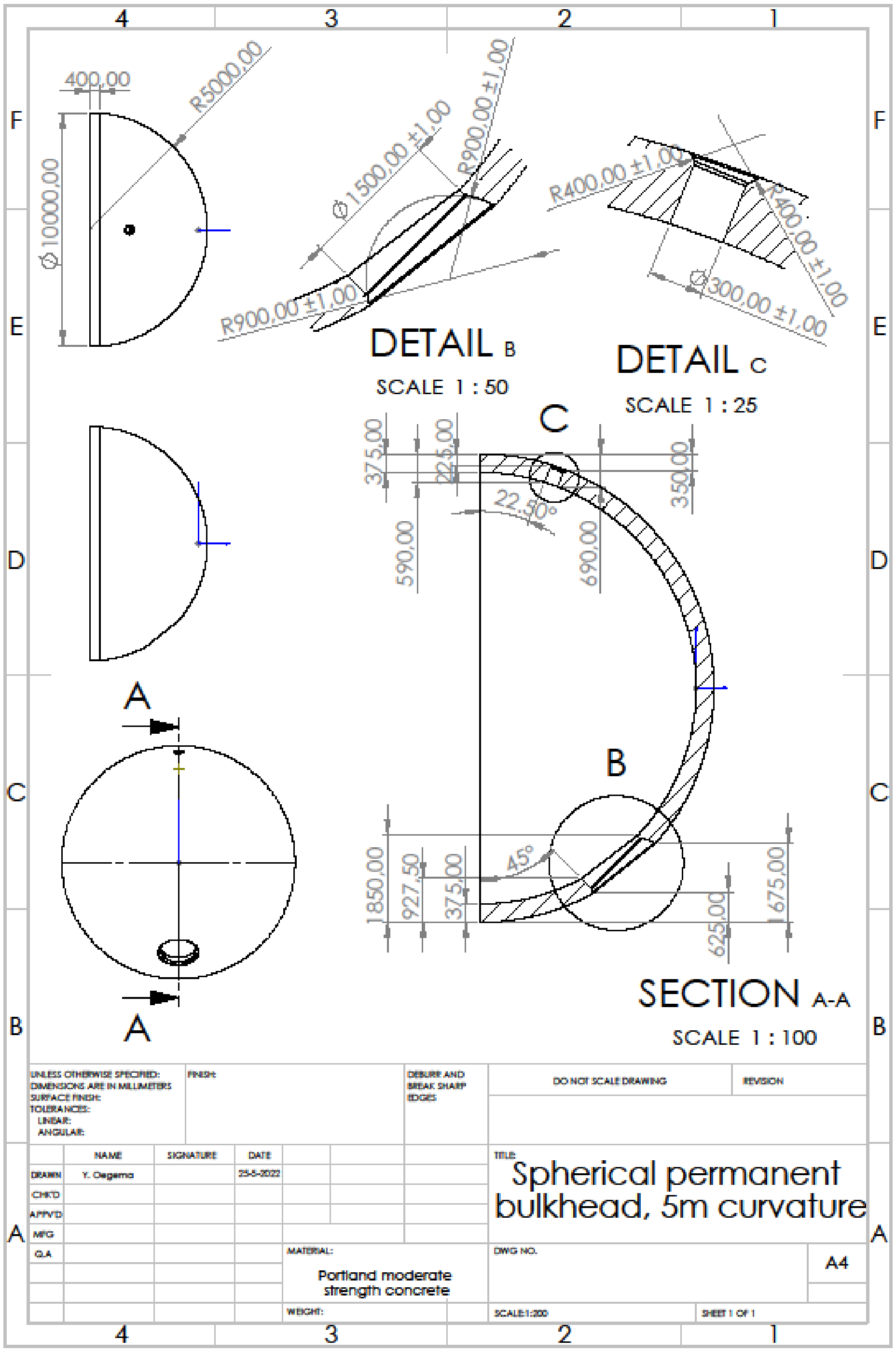

Figure 12 2D technical drawing for the 5m curvature spherical permanent bulkhead, dimensions are in millimeters

12 meter curvature permanent bulkhead

The curvature radius of this permanent bulkhead design was inspired by (Porathur et al., 2018) where a permanent bulkhead with an identical radius was used for a similar gallery dimension. A more comprehensive view of the dimensions and shapes of the design can be found in figures 13-15. In these figure, the permanent bulkhead shape is drawn for three different air and water passage designs that can house four different temporary bulkhead designs.

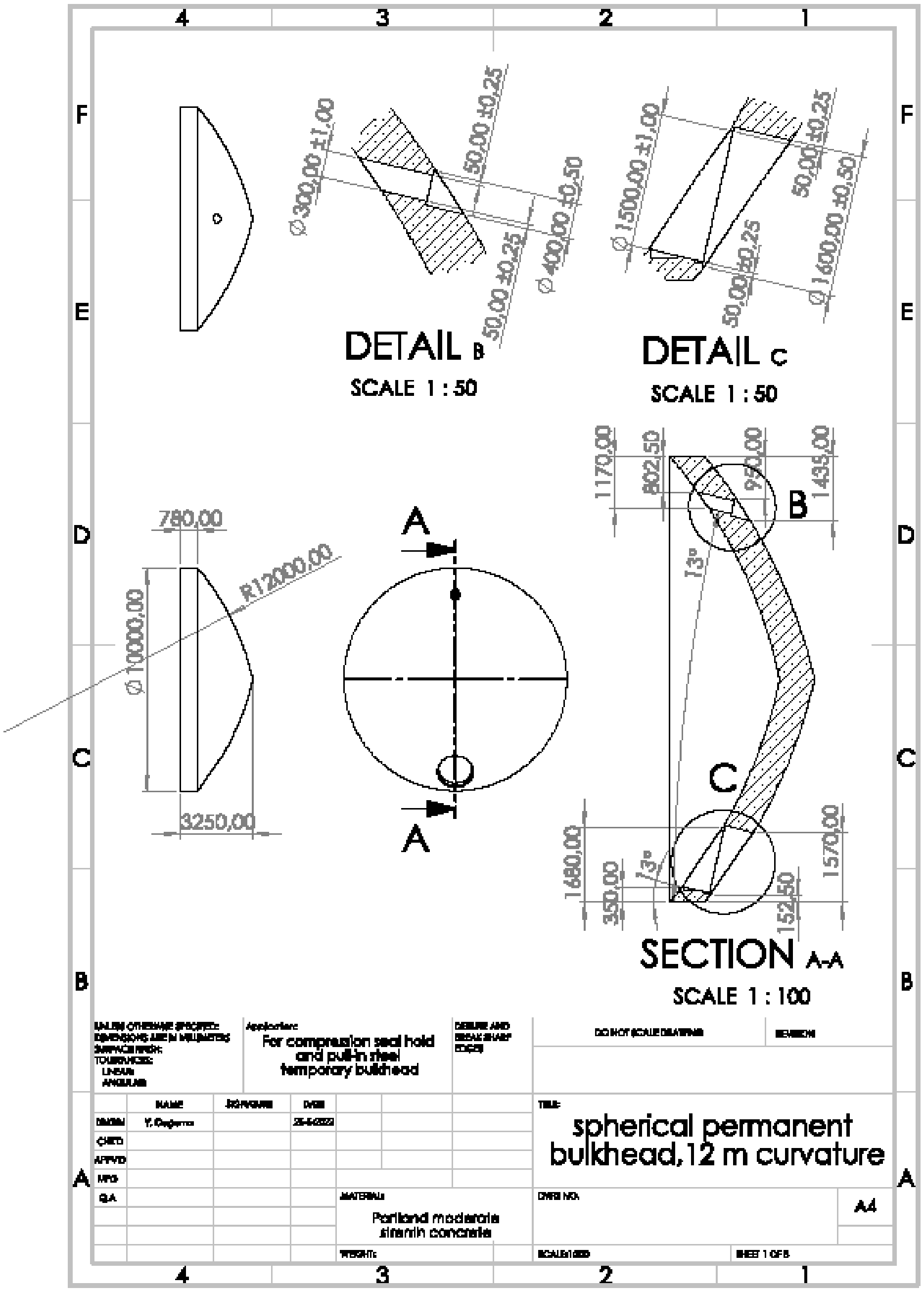

Figure 13 2D technical drawing of the 12m curvature spherical permanent bulkhead for the compression seal and pull-in steel temporary bulkhead, dimensions are in millimeters

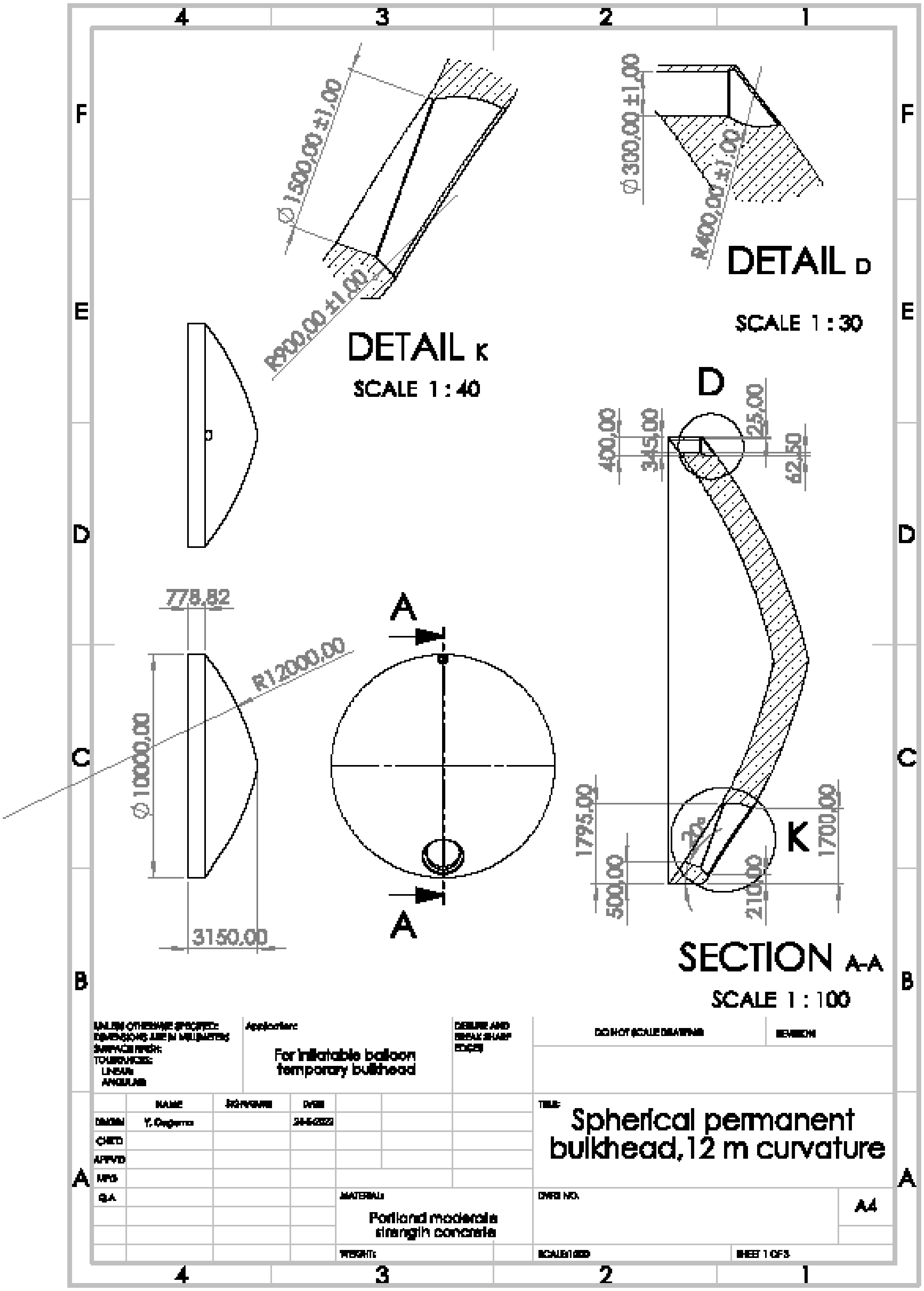

Figure 14 2D technical drawing of the 12 m curvature spherical permanent bulkhead for the inflatable balloon temporary bulkhead, dimensions are in millimeters

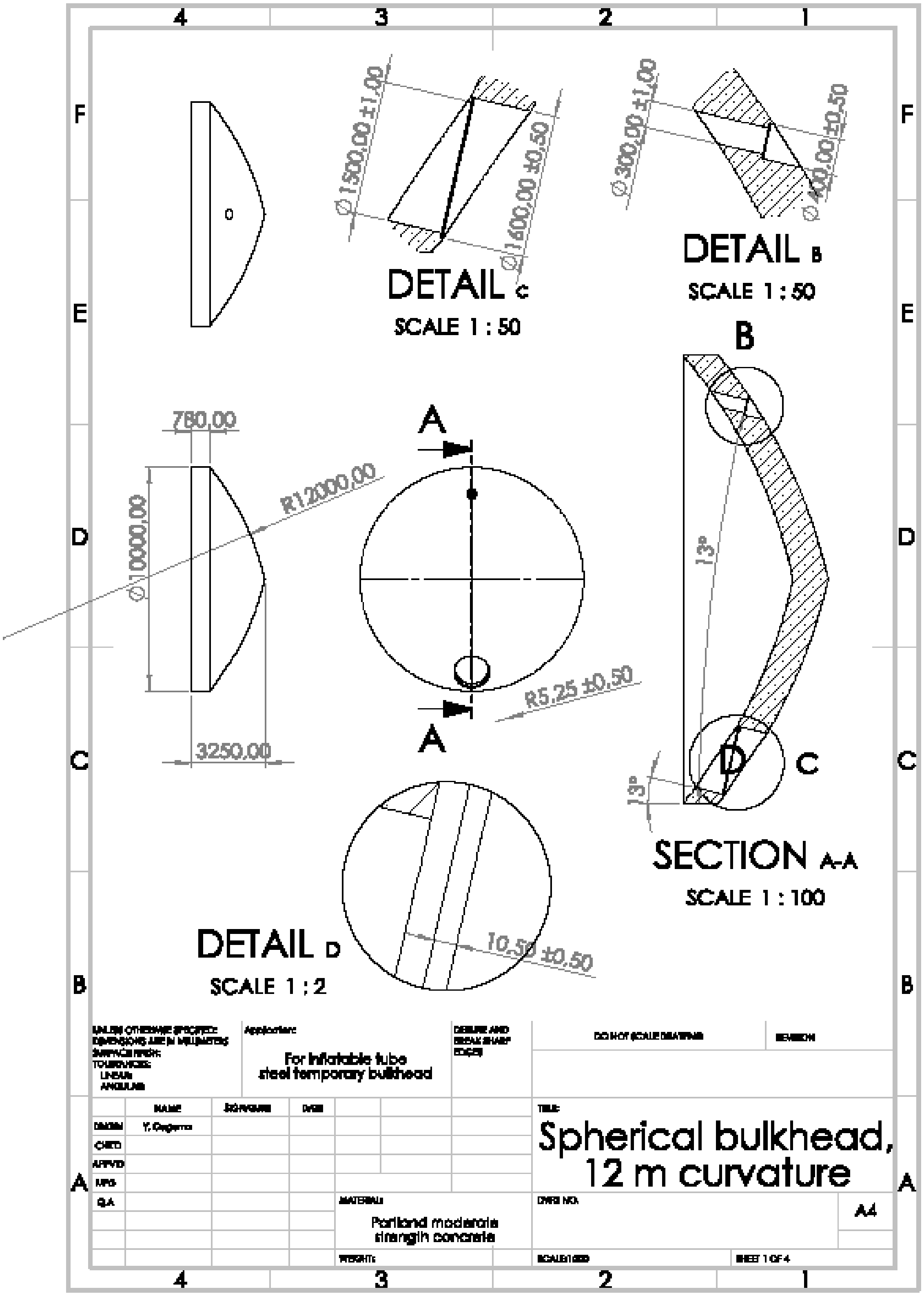

Figure 15 2D technical drawing of the 12 m curvature spherical permanent bulkhead for the inflatable tube steel temporary bulkhead, dimensions are in millimeters

Temporary Bulkhead

For the temporary bulkhead, four different design concepts have been developed for the water passage in the permanent bulkhead. The designs temporary bulkheads for the air passage will be developed after the simulations for the water passage temporary bulkhead designs are completed.

The first design is an inflatable balloon made from polyurethane. When inflated the balloon is wedged between the segment tube and the water/air passage in the bulkhead keeping it in place and sealing off the passage openings.

The three remaining designs feature a steel spherical plate with three different holding mechanisms. Two designs use friction to hold in the temporary bulkhead, through a rubber compression seal and an inflatable tube. The last temporary bulkhead has an attachment point for a cable. It can then be pulled into position with a (multi-turn) rotary actuator.

Inflatable balloon temporary bulkhead

This temporary bulkhead design consist of a spherical, polyurethane balloon with a radius of 900 mm and a wall thickness of 13.00 mm. The balloon can be inflated and deflated from the valve stem that has an outer diameter of 25.40 mm and an inner diameter of 13.00 mm. The inflating and deflating of the balloon will be managed via tubes running from a central distribution point to individual balloons.

Because, the polyurethane material of the balloon will provide a good seal against the concrete permanent no extra sealant or gasket material is needed. To counteract the external pressure jeopardizing the seal between the balloon and the permanent bulkhead, the internal pressure in the balloon will be the same as the maximum external pressure at 603.401 kPa.

Figure 16 provides an isometric view of the design model, while figure 17, on the next page, provides a technical drawing of the balloon temporary bulkhead.

A concave opening in the permanent bulkhead with an identical radius of 900 mm will house the balloon to ensure a good fit between the temporary and permanent bulkhead. To avoid cuts on the balloon surface, all sharp edges in the concave opening were filleted to create a round and smooth surface for the balloon to sit on. Furthermore, the balloon is also wedged against the inside wall of the segment tube to make sure it is securely in place for the installation.

The balloon can be inflated and deflated remotely from the immersion barge through the connection tube in the segment tube wall. The interaction of the balloon and the permanent bulkhead as well as the connection tube in the tube segment wall can be seen in figure 18.

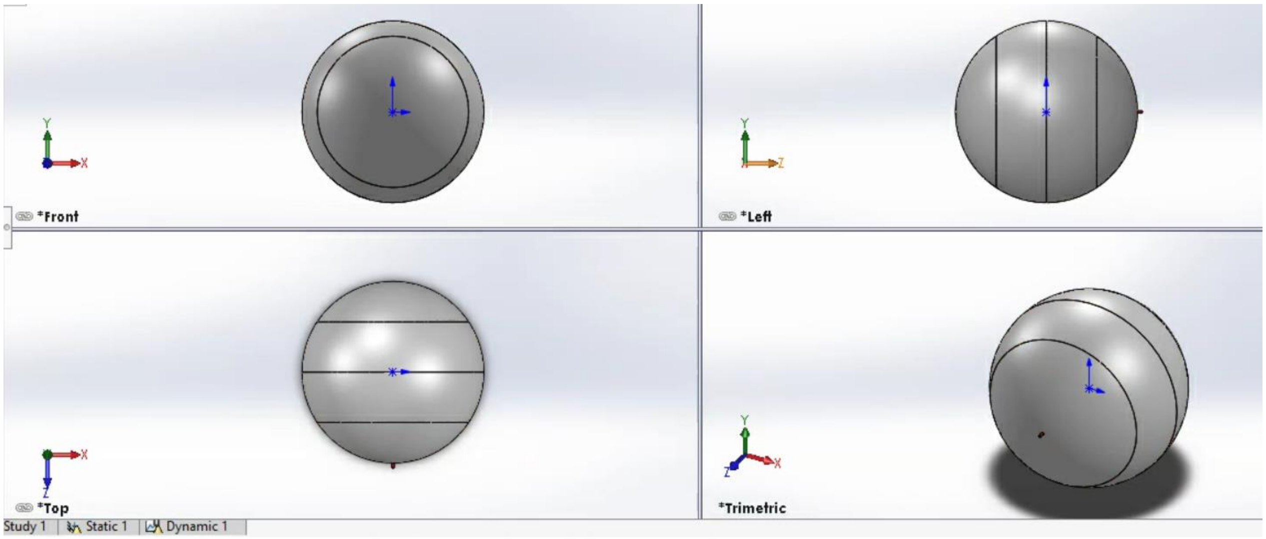

Figure 16 Isometric view of the water passage balloon temporary bulkhead

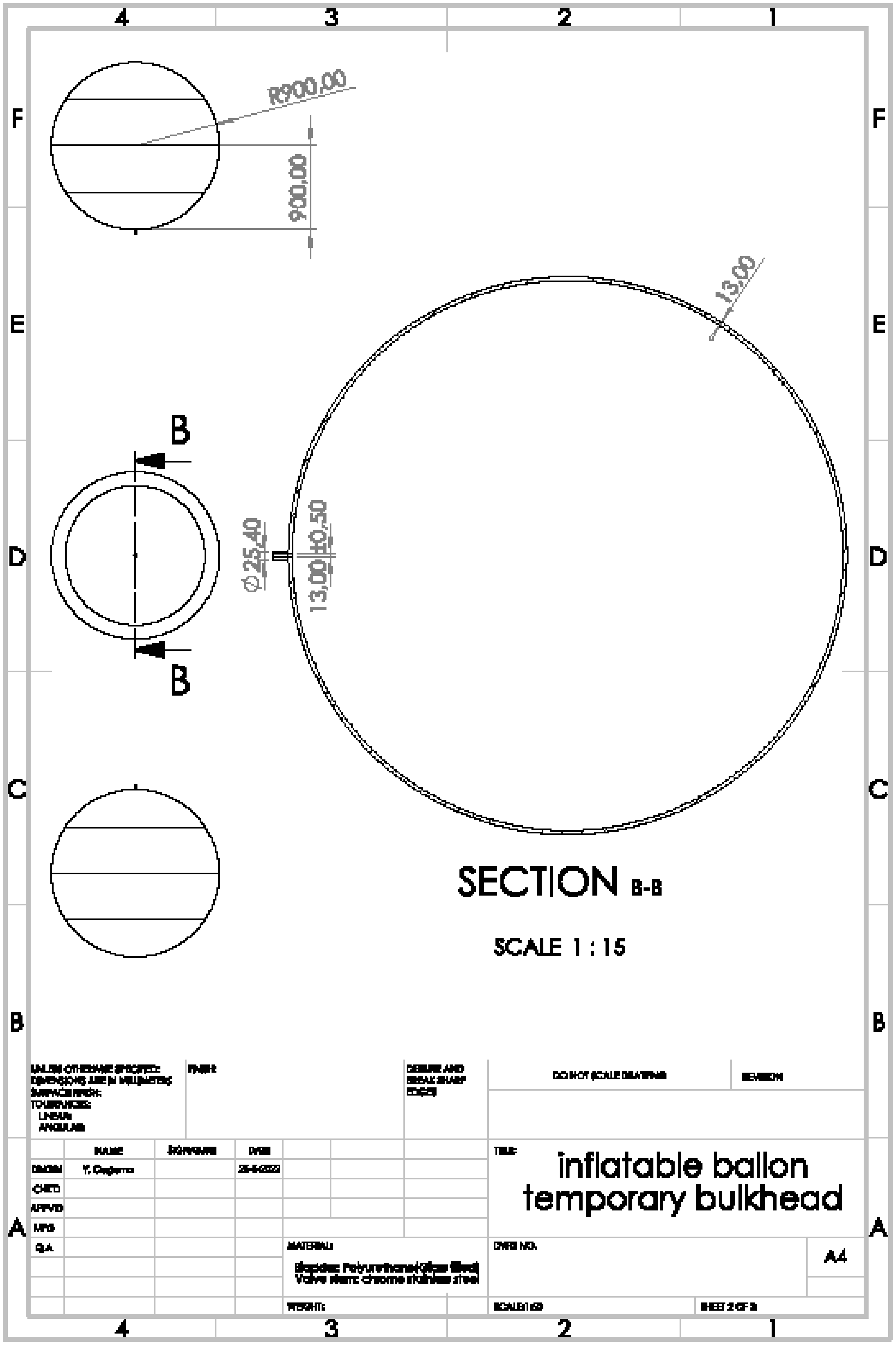

Figure 17 2D technical drawing of the water passage polyurethane balloon temporary bulkhead

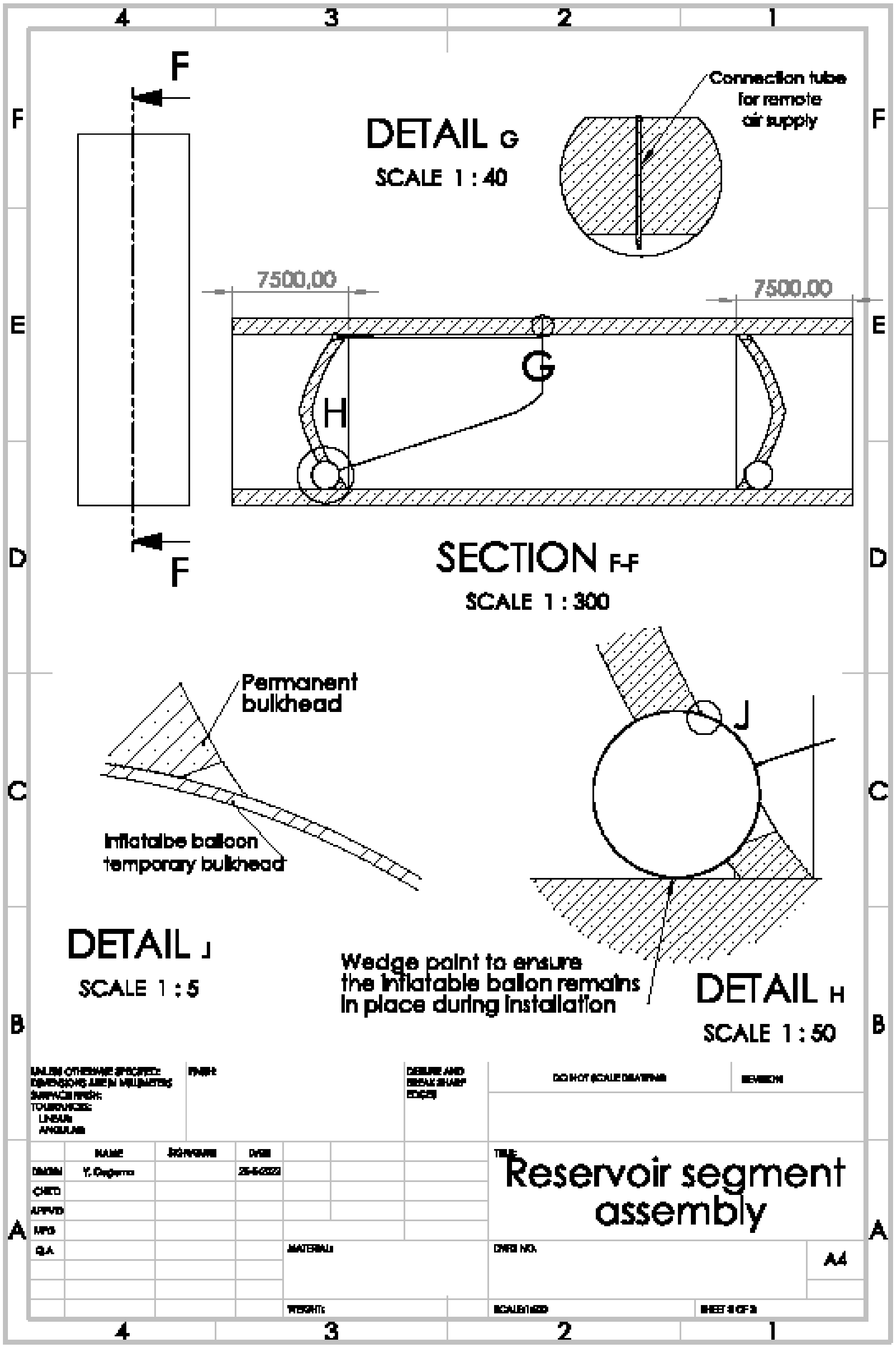

Figure 18 Assembly showing the interaction between the balloon temporary bulkhead and the permanent bulkhead

Pull-in steel temporary bulkhead

The steel temporary bulkheads are designed using the design recommendations from (Yao et al., 2007). Following their recommendation of a radius/thickness ratio of 143, a bulkhead thickness of 14 mm and a curvature radius of 2002 mm were determined for the pull-in steel temporary bulkhead. Figure 19 below shows an isometric view of the design concept.

A rubber gasket will be placed between the steel temporary bulkheads and the concrete permanent bulkhead to ensure a watertight seal is made. To this end, a 14 mm mating flange has been created on the backside of the steel temporary bulkhead to facilitate a good seal.

The remote control release mechanism is provided through a (multi-turn) rotary actuator. A connection hook for a cable has been created on the backside to enable the temporary bulkhead to be pulled in and released in a controlled manner.

Figures 20, 21 and 22 provide the dimensions of the pull-in steel temporary bulkhead, the rubber gasket and the interaction of those two parts with the permanent bulkhead respectively.

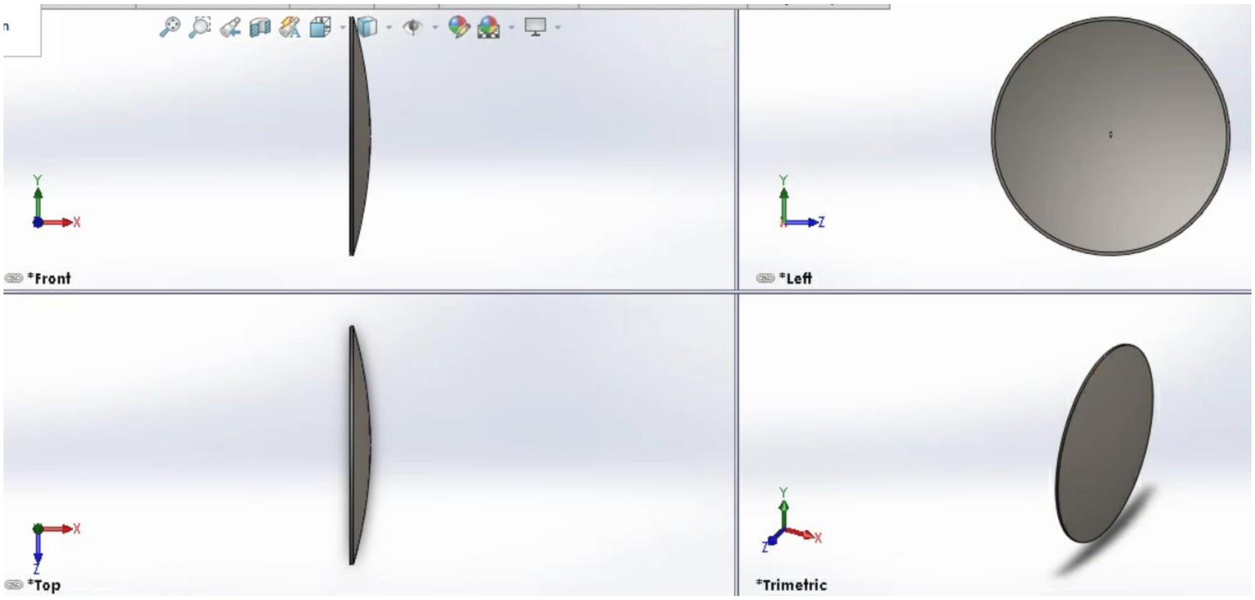

Figure 19 Isometric view of the water passage pull-in steel temporary bulkhead assembly

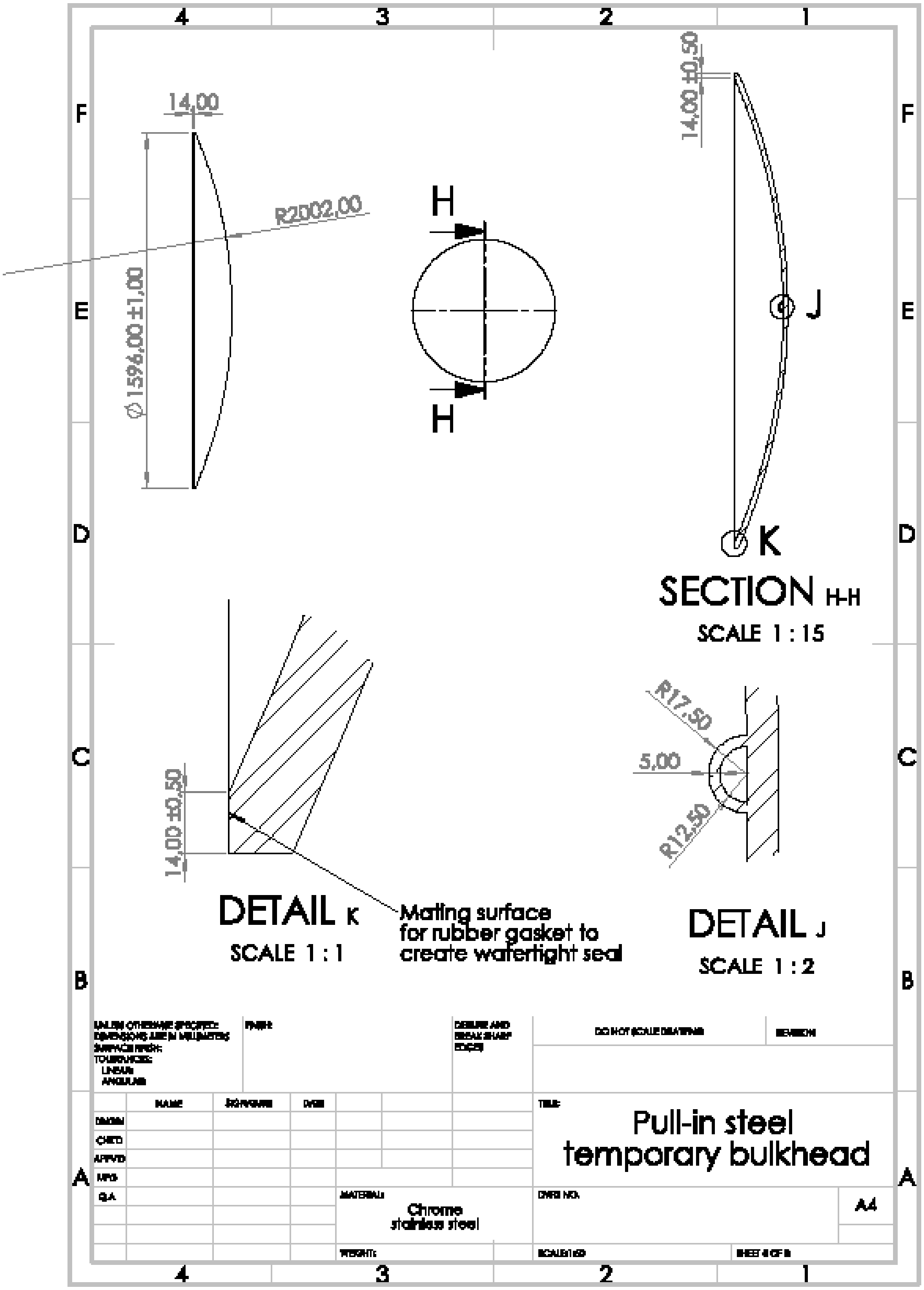

Figure 20 2D technical drawing of the water passage pull-in steel temporary bulkhead

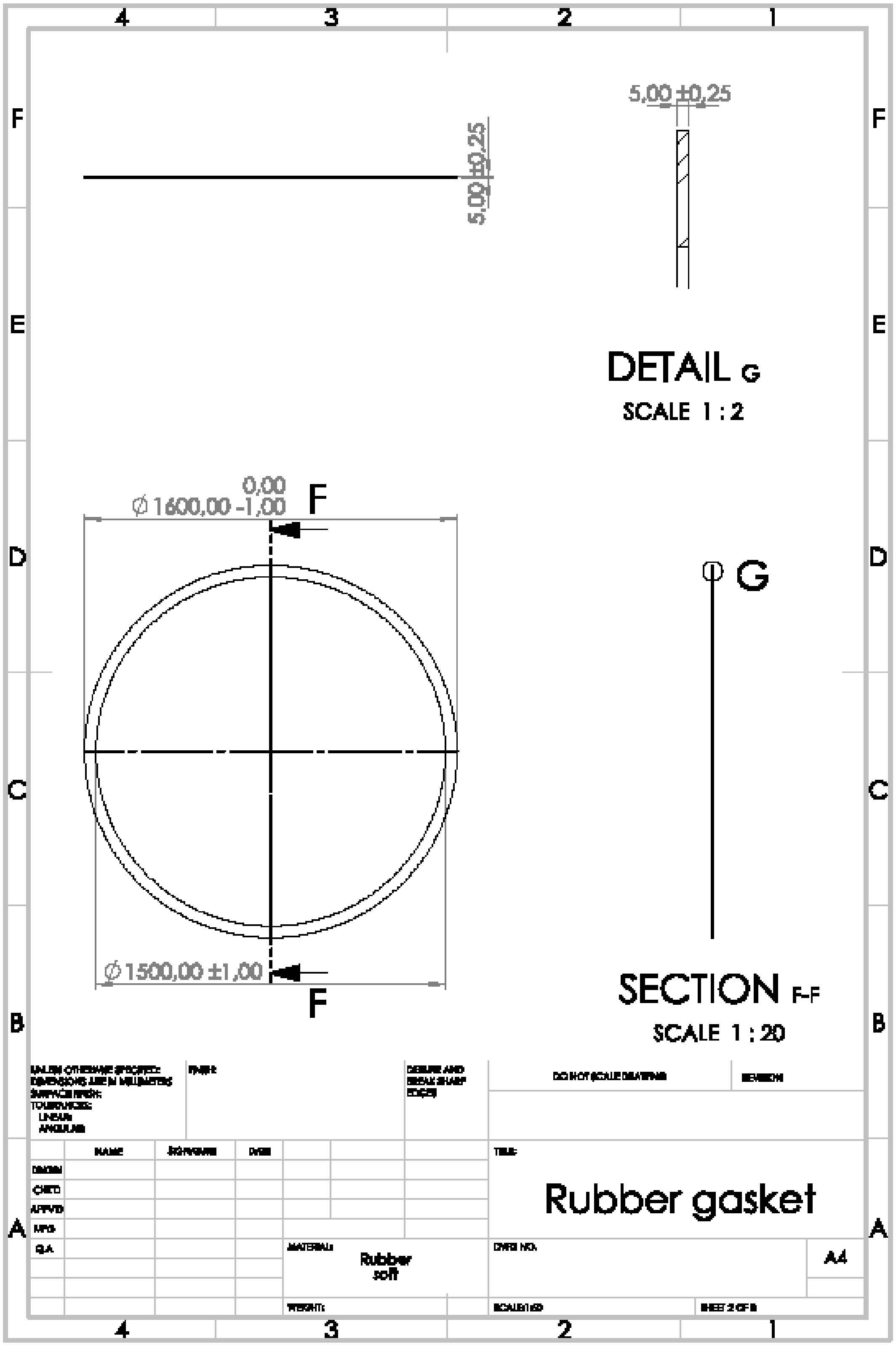

Figure 21 2D technical drawing of the rubber gasket that sits between the steel temporary bulkhead and the concrete permanent bulkhead in the water passage

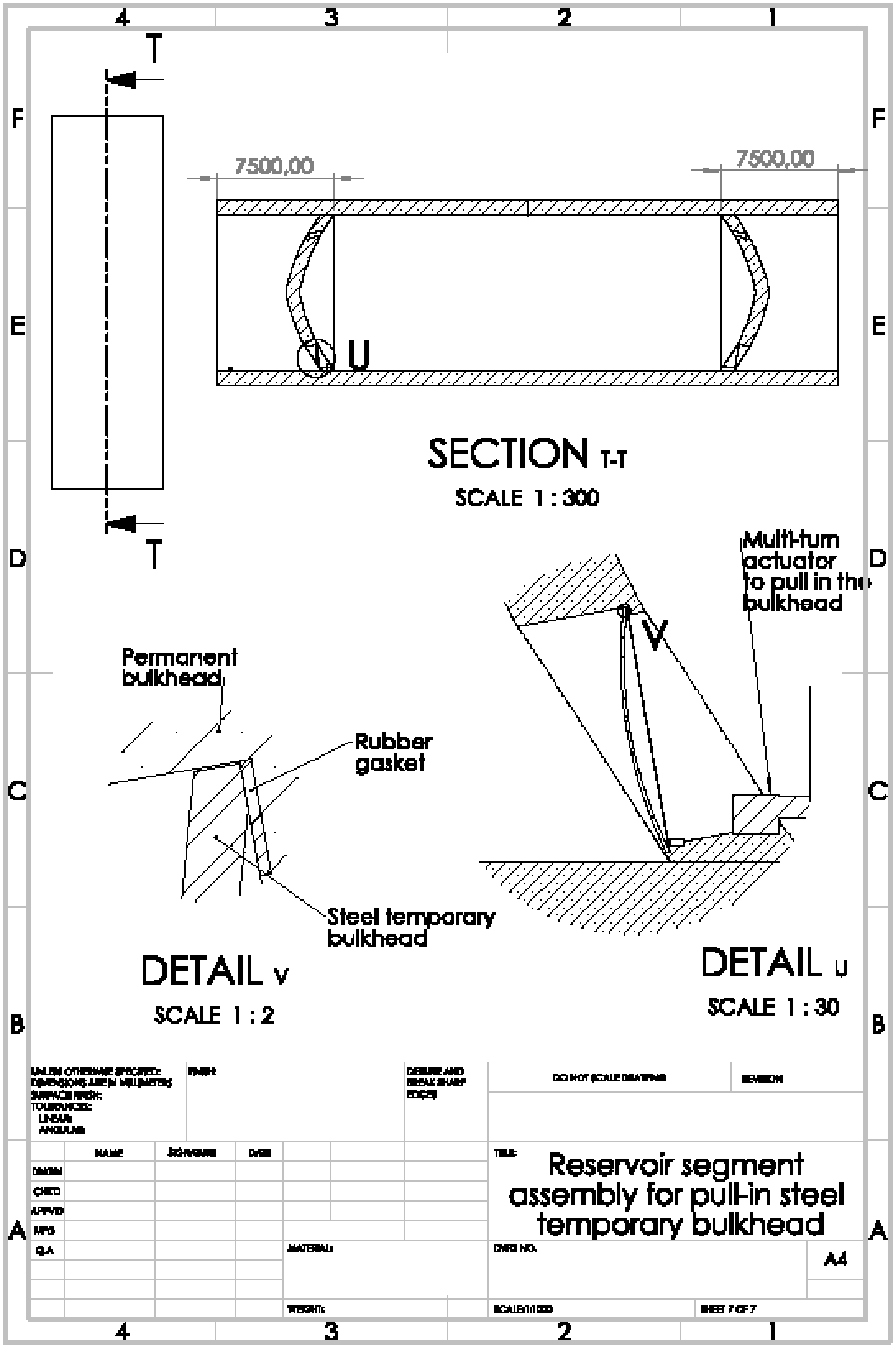

Figure 22 Assembly showing the interaction between the pull-in steel temporary bulkhead, the rubber gasket and the concrete permanent bulkhead

Compression seal temporary steel temporary bulkhead

Instead of using an actuator to hold the bulkhead in place, this bulkhead uses a square rubber seal to provide the necessary force. This is done through the friction force that is created between the rubber seal and the concrete permanent bulkhead a the seal is compressed. Since, this also places additional load on the temporary bulkhead the thickness of the bulkhead is increased from 14 mm to 20 mm to carry this additional load. Therefore, the curvature radius is also increased to 2860 mm to keep with the radius/thickness ratio of 143.
Similar to the pull-in steel temporary bulkhead, this temporary bulkhead also has mating flange on the backside to provide a good seal against the rubber gasket that is fitted between the temporary and permanent bulkhead. However for this design the mating flange is 20 mm instead of 14 mm. Figure 23 below, shows an isometric view of the temporary bulkhead assembly, that is the steel temporary bulkhead with the rubber sealing ring mounted on it.
The remote release mechanism for this design comes in the form a linear actuator the will push the bottom edge of the temporary bulkhead over the edge of the water or air passage opening. This will cause the bulkhead to fall out of the water or air passage opening due to gravity.
Dimensions of the compression seal steel bulkhead, the rubber compression seal and the interaction between these components and the permanent bulkhead can be found in figure 24, 25 and 26 respectively.

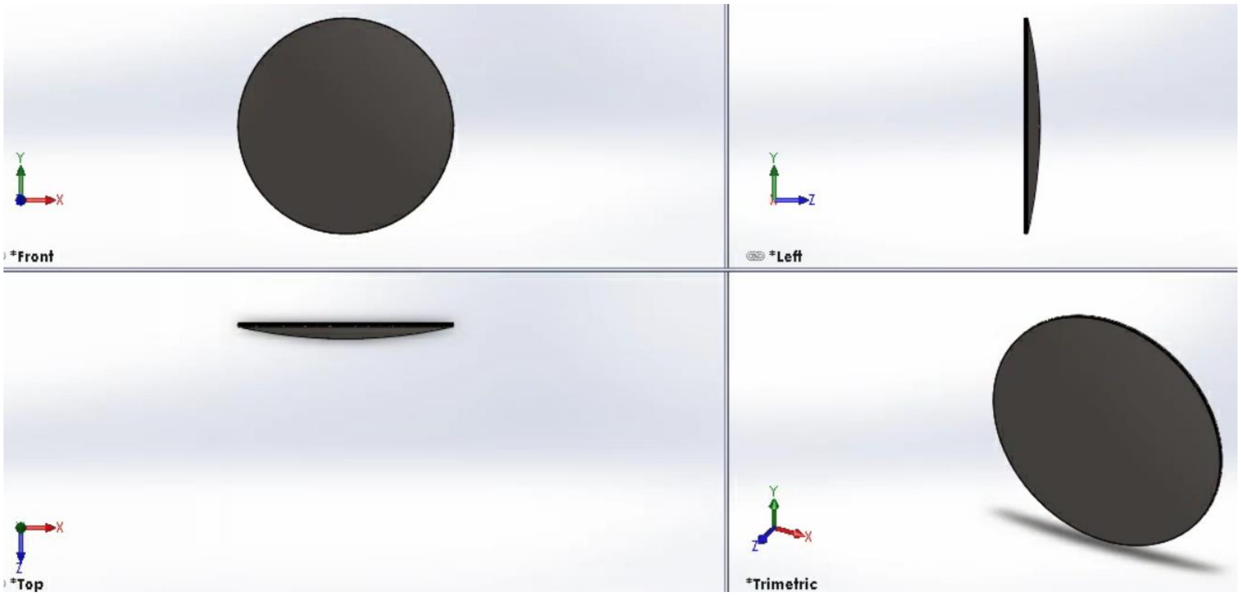

Figure 23 Isometric view of the water passage compression seal steel temporary bulkhead assembly

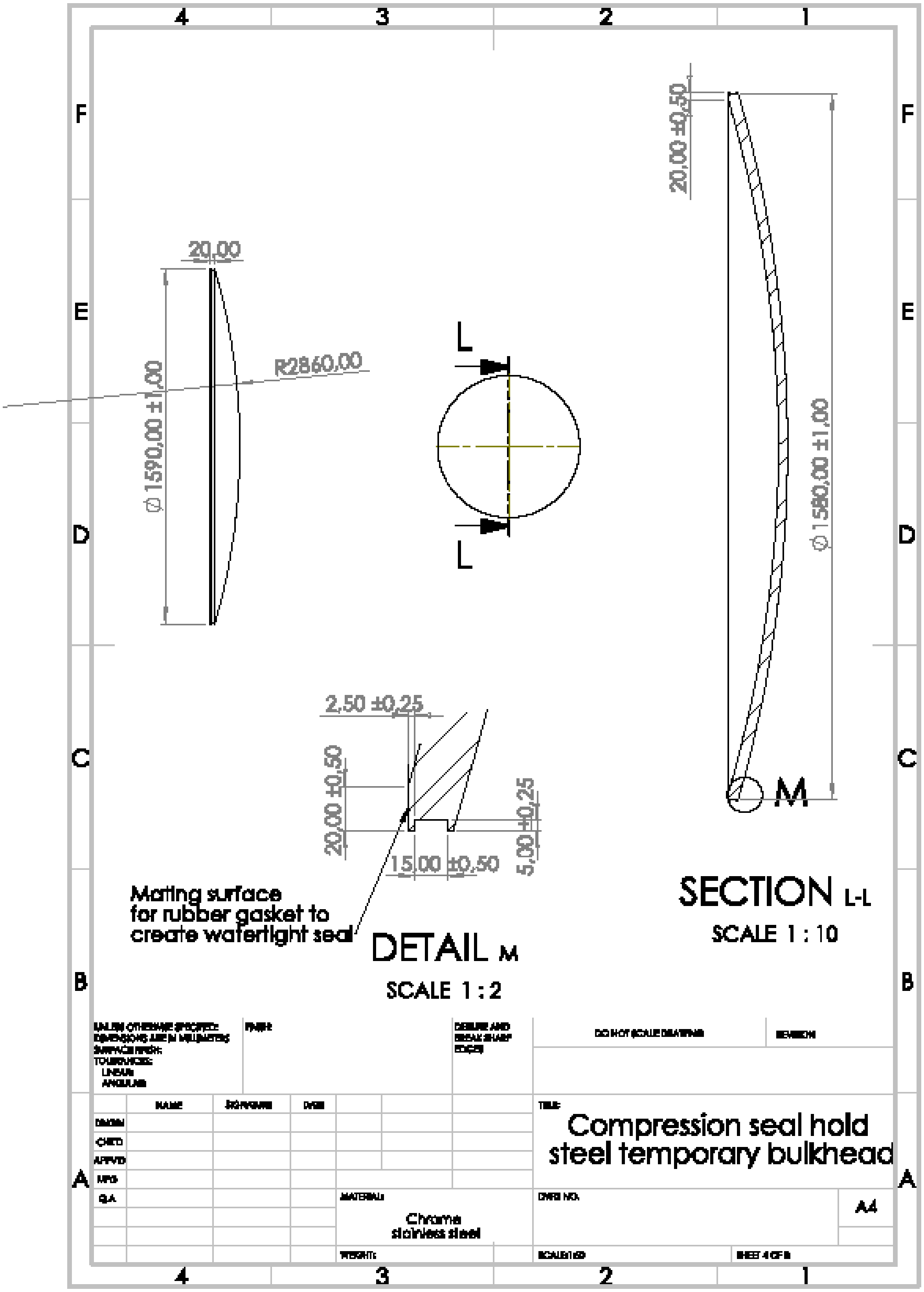

Figure 24 2D technical drawing of the water passage compression seal temporary steel bulkhead

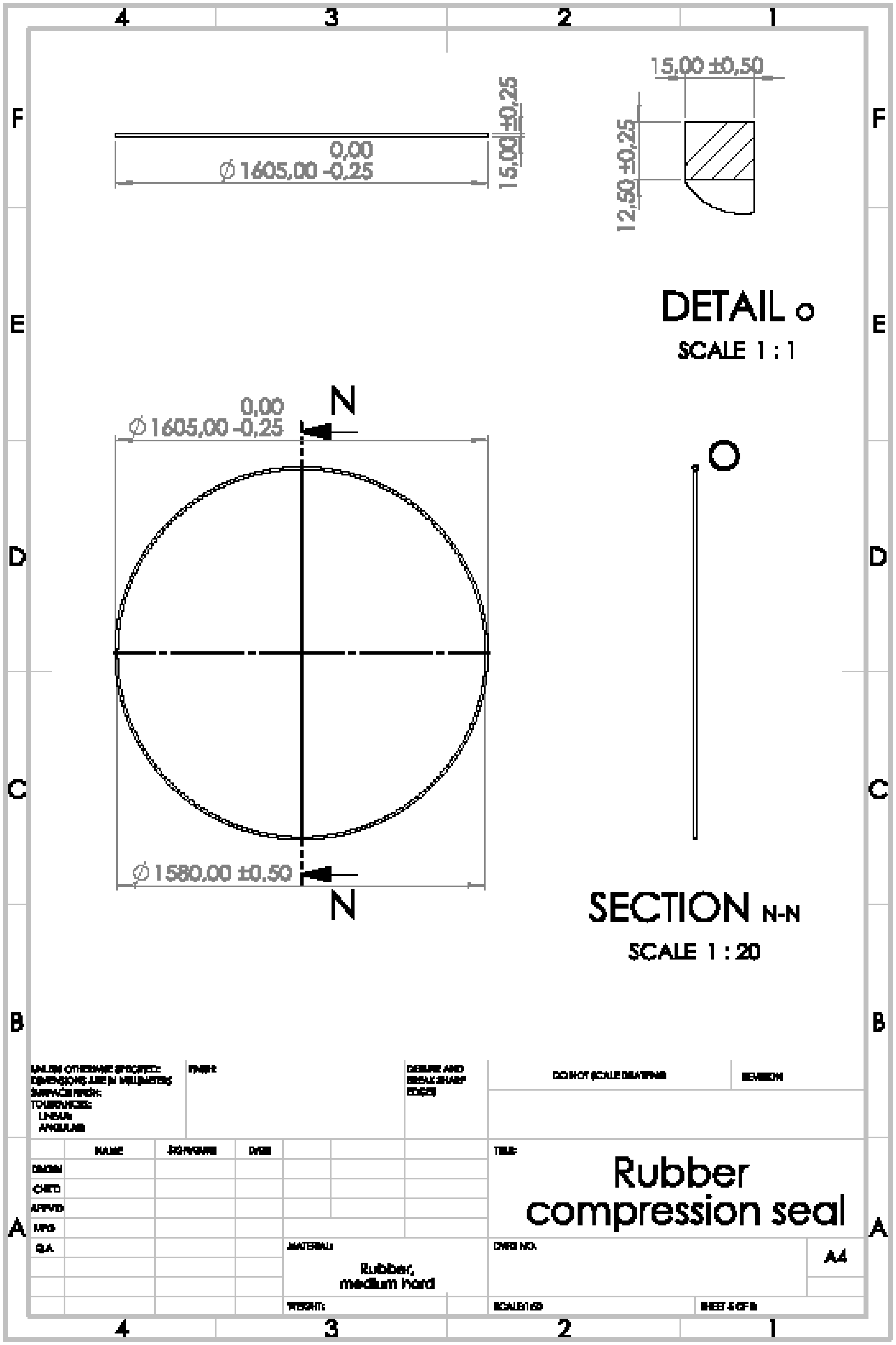

Figure 25 2D technical drawing for the water passage rubber compression seal

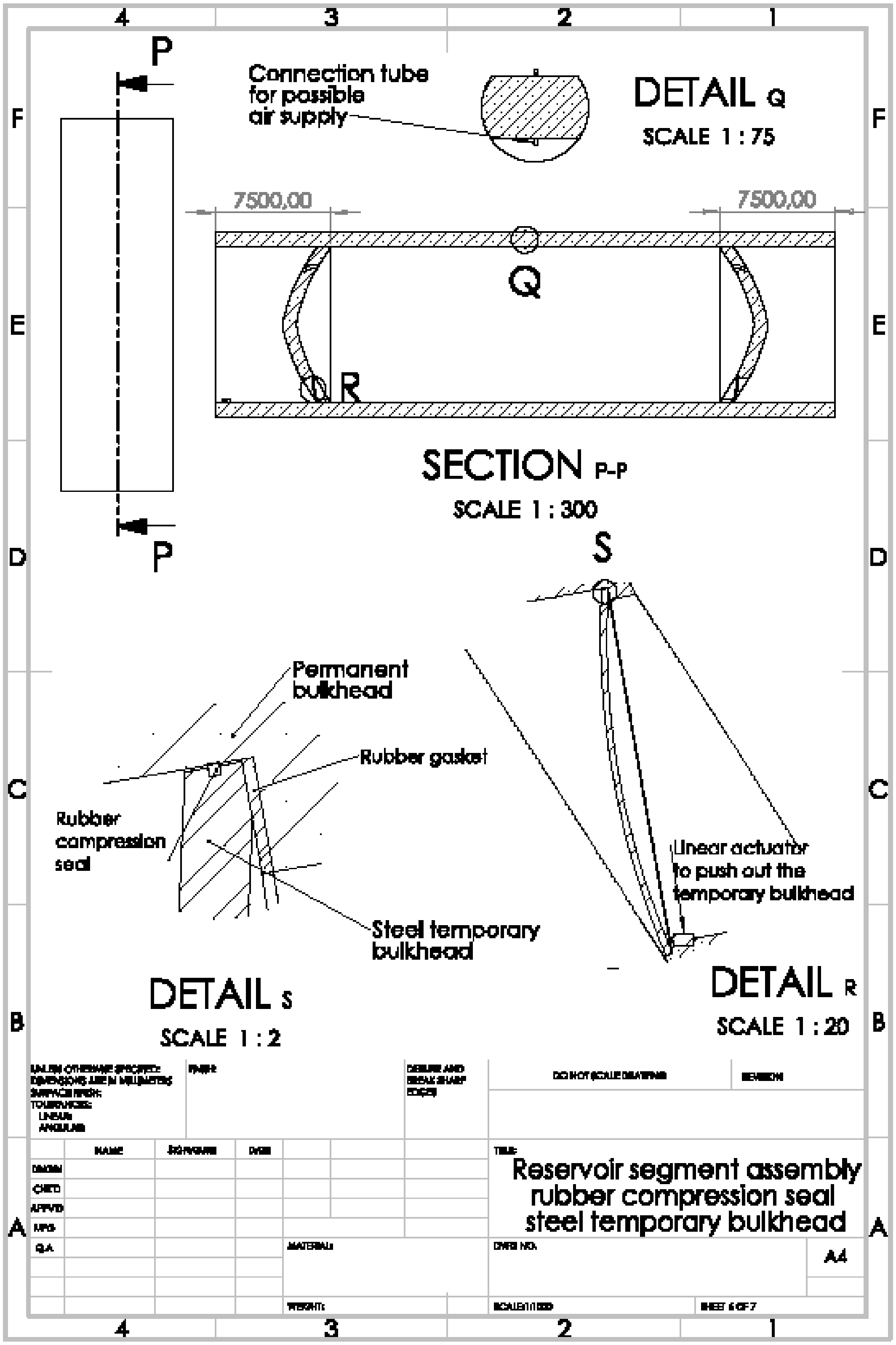

Figure 26 Assembly showing the interaction between the compression seal temporary bulkhead, the rubber compression seal, the rubber gasket and the permanent bulkhead

Inflatable tube steel temporary bulkhead

This temporary bulkhead design is a hybrid between the inflatable balloon temporary bulkhead and the steel temporary bulkhead. The force necessary to hold the temporary bulkhead into place will be provided by an inflatable tube, while the load bearing part will be handled by a steel temporary bulkhead similar to the previous design.

The thickness and radius of the steel bulkhead are 20 mm and 2860 mm respectively, identical to the compression seal temporary bulkhead. This is because the force exerted by the inflatable tube to hold the temporary bulkhead in place is similar to the force exerted by the rubber compression seal. On top of that, the inflatable tube sits in a groove in both the temporary and permanent bulkhead, which also assists in holding in the temporary bulkhead.

The inflatable tube can be inflated through fitting on the outside of the steel bulkhead after the temporary bulkhead assembly has been set in the right place in the water or air passage. Figure 27 shows the inflation fitting and tube running to the valve stem of the inflatable tube in light grey.

To release the bulkhead remotely, the inflatable tube can be deflated through a remotely activated valve after which the bulkhead will fall out of the water or air passage due to gravity.

Dimension shapes and interactions between the inflatable steel temporary bulkhead, the inflatable tube and the permanent bulkhead are given in figure 28, 29 and 30.

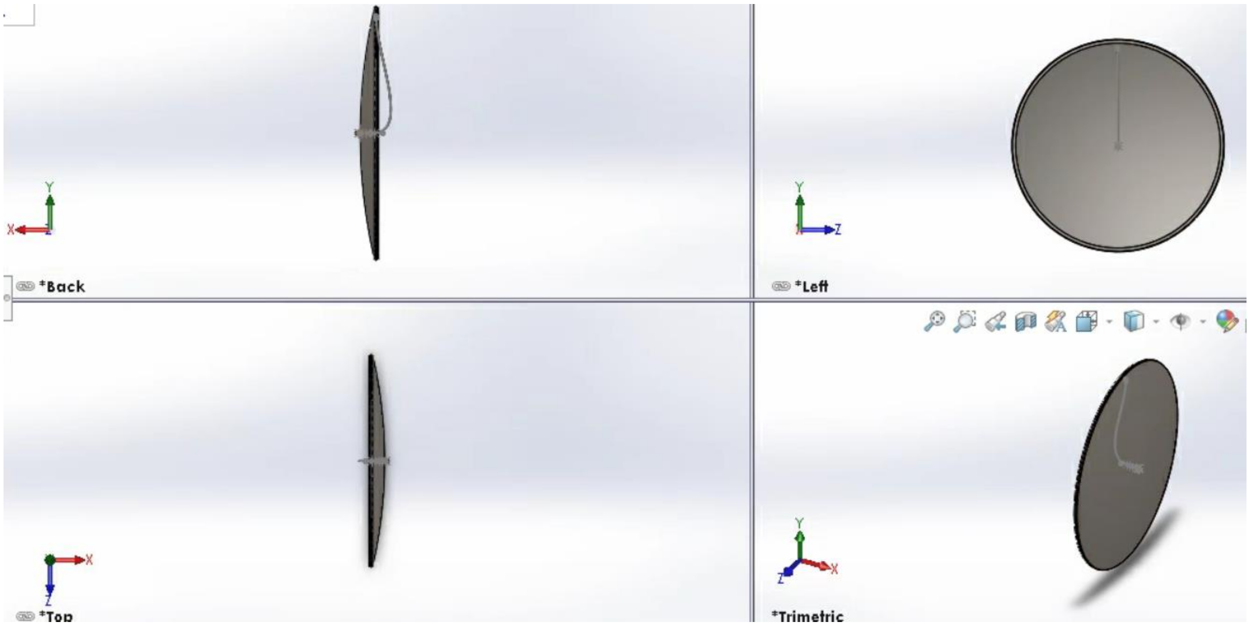

Figure 27 Isometric view of the water passage inflatable tube steel temporary bulkhead assembly

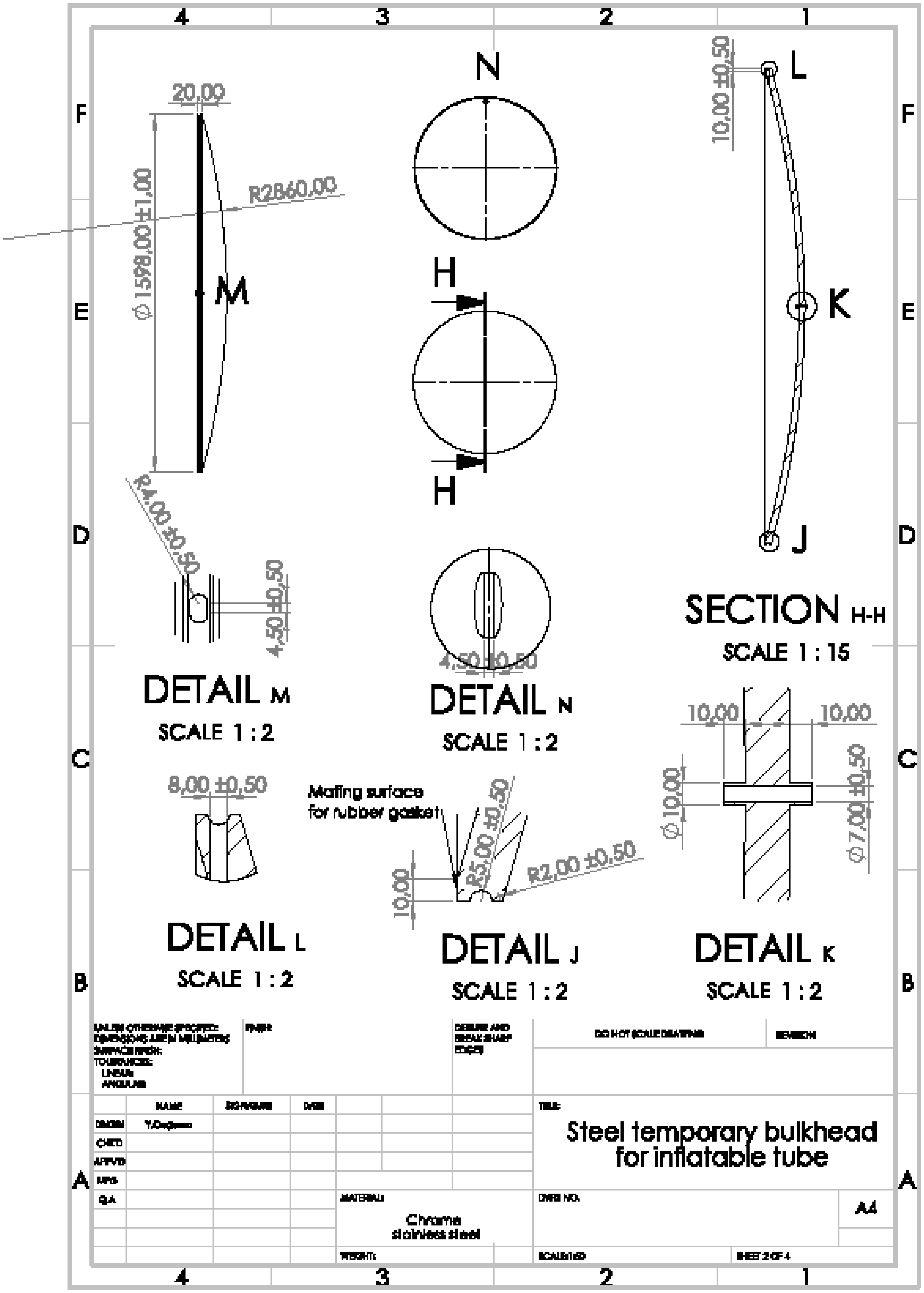

Figure 28 2D technical drawing for the water passage inflatable tube steel temporary bulkhead

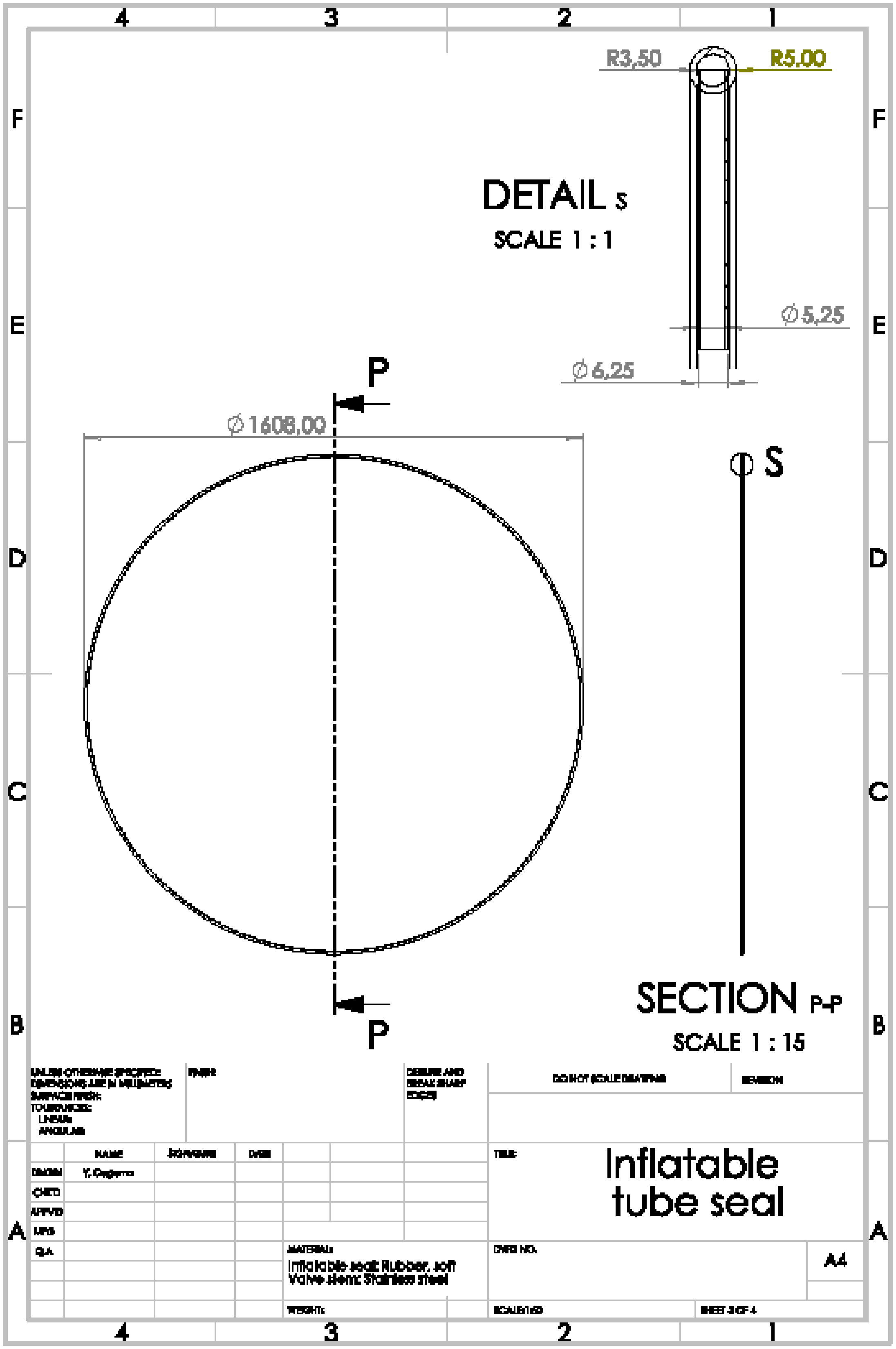

Figure 29 2D technical drawing for the water passage inflatable tube seal

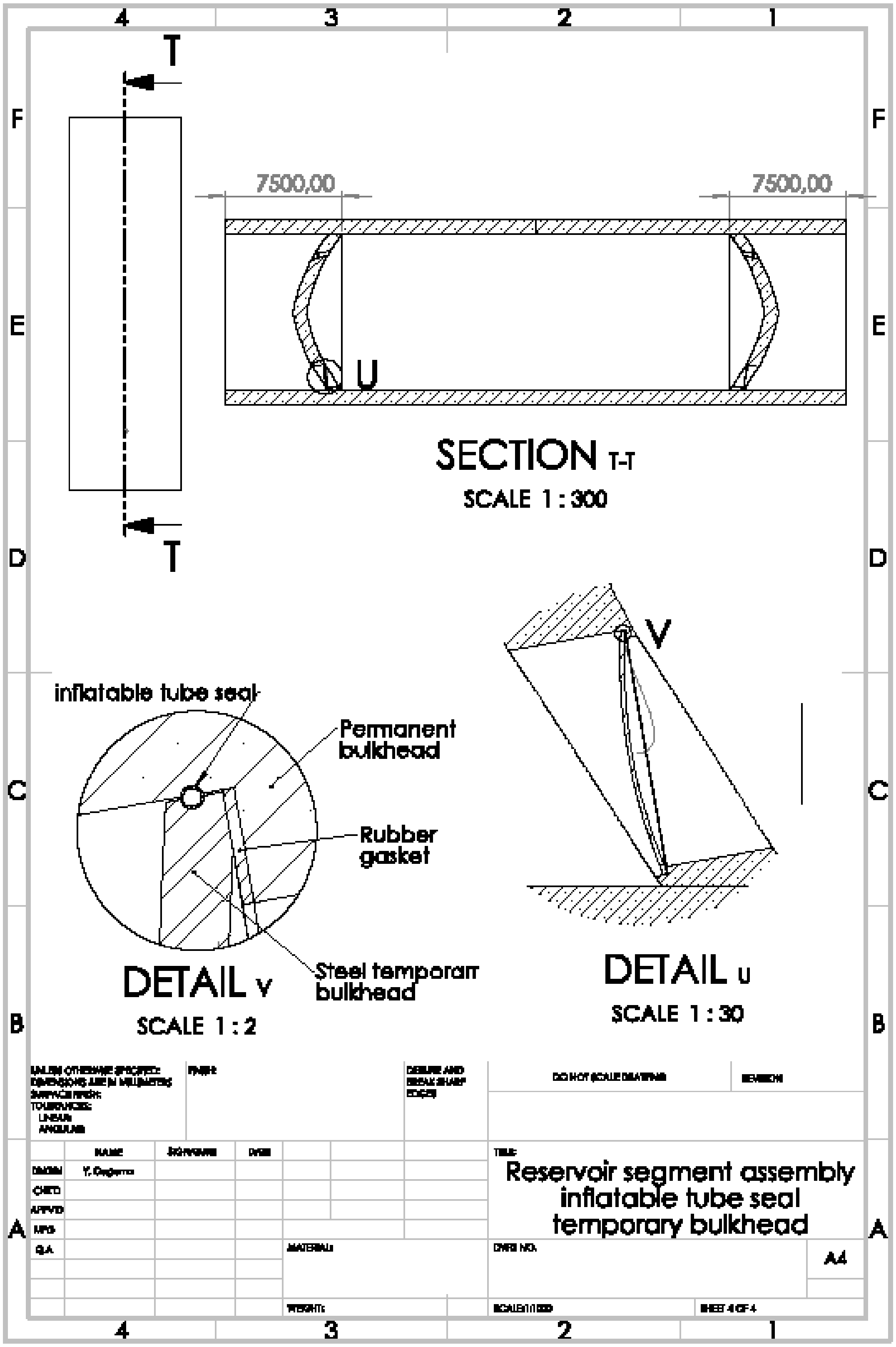

Figure 30 Assembly showing the interaction between the steel temporary bulkhead, the inflatable tube seal, the rubber gasket and the concrete permanent bulkhead

Remote control release mechanisms

The remote control release mechanisms have been briefly discussed per temporary bulkhead design. This subsection will provide additional insight into the remote release control release mechanism per temporary bulkhead.

Temporary bulkhead placement

As can be seen from permanent bulkhead technical drawings in figures 13, 14 and 15, the steel temporary bulkheads sit in the permanent bulkhead at a 13 degree negative slope. This angle was chosen as a compromise such that the temporary bulkhead would be relatively easily to hold in place during installation and would also relatively easily be removed from the air and water passages during the release phase.

The inflatable balloon is wedged between the inside wall of the segment tube and the permanent bulkhead to hold it into place during installation. The steel temporary bulkheads, on the other hand, are only held in by a multi-turn actuator, a rubber compression seal and an inflatable tube seal.

For the steel temporary bulkhead designs, it is important to know the gravitational forces acting on the temporary bulkhead to properly design the holding mechanisms. Moreover, the smaller temporary bulkheads to plug the air passages in the permanent bulkhead are lighter than the temporary bulkheads to plug the water passages. This also impacts the design of the holding and remote control release mechanisms for those designs. The gravitational forces on the temporary bulkheads can be expressed the following way:

$$F_z = -mg \tag{9}$$

$$F_{z,x} = sin\ (13) F_z \tag{10}$$

$$F_{z,y} = cos\ (13) F_z \tag{11}$$

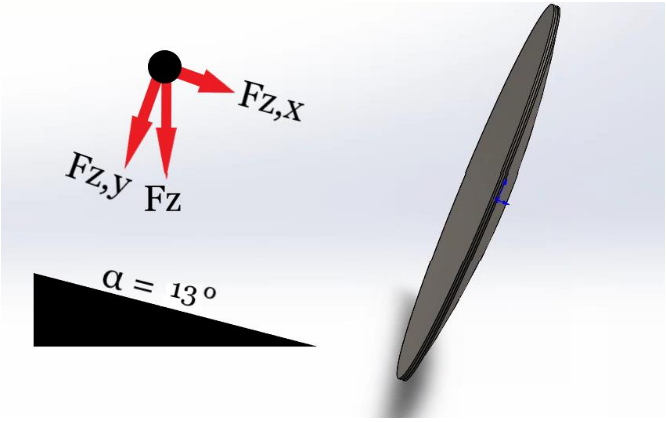

Figure 31 Force decomposition of the gravity load on the temporary steel bulkhead

Identical to the temporary bulkheads, the holding mechanisms are required to have a safety factor of 2. Meaning, the holding mechanisms for each design should have a minimum output force twice the gravitational force in the x-direction(Fz,x) to meet this criteria.
The calculated gravitational forces for the temporary bulkhead designs can be found in table 7 and 8. In this case, table 7 displays the forces for the water passage temporary bulkheads and table 8 displays the forces for the air passage temporary bulkheads.

Table 7 Analytical force calculation and decomposition of the gravitation force on the water passage steel temporary bulkheads

Water passage bulkheads	Pull-in steel temporary bulkhead	Compression seal steel temporary bulkhead	Inflatable tube steel temporary bulkhead
Mass	275.43 kg	365.5 kg	341.77 kg
Gravitational force (F_z)	2701.97 N	3585.56 N	3352.76 N
Gravitational force x-direction ($F_{z,x}$)	607.81 N	806.57 N	754.20 N
Gravitational force y-direction ($F_{z,y}$)	2632.72 N	3493.66 N	3266.83 N
Minimum holding mechanism force	1215.62 N	1613.14 N	1508.40 N

Table 8 Analytical force calculation and decomposition of the gravitation force on the air passage steel temporary bulkheads

Air passage bulkheads	Pull-in steel temporary bulkhead	Compression seal steel temporary bulkhead	Inflatable tube steel temporary bulkhead
Mass	4.93 kg	5.64 kg	14.83 kg
Gravitational force (F_z)	48.36 N	55.33 N	145.48 N
Gravitational force x-direction ($F_{z,x}$)	10.87 N	12.45 N	32.73 N
Gravitational force y-direction ($F_{z,y}$)	47.12 N	53.91 N	141.75 N
Minimum holding mechanism force	21.74 N	24.90 N	65.46 N

Energy source

In subsea valve control, the power, electric, hydraulic or pneumatic, is supplied to the actuators via cables and pipes from shore (Sotoodeh, 2020). This method can be adapted to the rigid reservoir by using a central power distribution point with a detachable connector on the outside of the reservoir segment. Of course, this connector also needs be detached remotely. To this end, a detachable remotely operated vehicle (ROV) connector, like the example in figure 32, can be used on the outside of the reservoir segment. However, that task could also be done manually by a diver.

The central distribution point then distributes compressed air to operate the remote control release mechanisms of the inflatable balloon temporary bulkhead, the pull-in steel temporary bulkhead and the compression seal steel temporary bulkhead.

On the other hand, the inflatable tube for the inflatable tube steel temporary bulkhead can be inflated from the outside when the reservoir segment is still above the water eliminating the need for a central power distribution point.

The actuators used in subsea valve control are very robust and expensive as they need to withstand the harsh environment of high external pressures and often salt water. Aside from expenses, having to use subsea actuators also significantly reduces the amount of actuator options available. Hence, in the assembly technical drawings, respectively figures 16, 20, 24 and 28, the permanent bulkheads are set back 7500 mm into the segment tubes to counteract this problem. When placing the permanent bulkhead at this point, the reservoir segments have a slight negative buoyancy once fully submerged, eliminating the need for ballast water inside the segment. Hence, the need for watertight actuators to facilitate the remote control release operations is no longer present, allowing the use of a wider range of conventional actuators instead of strictly subsea examples.

Figure 32 Heavy duty ROV connector (source: Morgrip subsea solutions)

Compression seal steel temporary bulkhead

The holding mechanism for this bulkhead design is not complex. Since, the outside diameter of the rubber holding ring is bigger than the cutout in the permanent bulkhead, the compressive and friction forces between the rubber ring and the permanent bulkhead will hold the temporary bulkhead in place. In order to remove the temporary bulkhead, the bulkhead has to be pushed or pulled out the air or water passage. However, as mentioned previously, the use of conventional actuators is more desirable than the use of subsea actuators. Hence, the option to pull out the bulkhead from the outside with a subsea actuator will not be considered further.

The remote control release mechanism that will be considered for this bulkhead is a linear actuator mounted on the inside of the bulkhead and can be seen in detail view ‘R’ of figure 27. The actuator will push the steel bulkhead over the lip of the opening in the permanent bulkhead causing the bulkhead to fall out of the opening due to gravity.

For the remote control release mechanism to work, the output of the linear actuator needs to exceed the clamping force of the rubber sealing rings. However, the clamping force to hold the temporary bulkheads in place is significantly smaller for the air passage temporary bulkhead than for the water passage temporary bulkhead. This means a significantly smaller linear actuator can be used to push out the air passage temporary bulkhead.

As can be seen from tables 7 and 8, the safety factor of 2 is used with regard to the holding mechanisms. This safety factor of 2 will also be used for the actuators used in the remote control release mechanisms. The factor of safety for the release mechanism is considered with regard to the output force of the holding mechanism. Hence, the output force of the pneumatic linear actuators should be at least 3226 N and 50 N for the water passage and air passage temporary bulkhead respectively.

Balloon temporary bulkhead

The remote control release mechanism for the balloon bulkhead is the most basic remote control release solution that was developed as only tubing from the central distribution point to the individual balloons is necessary. This tubing is needed anyway to first inflate the balloons such that the balloons are at the correct pressure for the installation. The remote release mechanism works by reversing the airflow through the central distribution point. This will result in the balloons deflating and releasing from the air and water passage in the permanent bulkhead, allowing the reservoir segment to be operational. Inflating and deflating the balloons can be done remotely via an air distribution manifold on the barge from which the reservoir segments are immersed. The tubing to inflate and deflate the balloons can be seen running through the reservoir segment in section view F-F of figure 18. However, the tubing in the figure purely illustrates the workings of the design, the actual tubing will need to have additional length so the balloons will not be obstructed in moving away from the permanent bulkheads.

Pull-in steel temporary bulkhead

The holding and remote control release mechanism for the pull-in steel temporary bulkhead will be executed by the same actuator. In particular, a pneumatic (multi-turn) rotary actuator will pull-in and let out the steel bulkhead plates by winding up and unwinding a cable attached to the temporary bulkheads.
Because, the multi-turn actuators is also the holding mechanism for this design, the holding force of the chosen actuators should large enough to fulfill the minimum safety factor requirement. Taking this into consideration, the output force of the multi-turn actuator should be at least 1216 N and 22 N for the water passage and air passage temporary bulkhead respectively.

Inflatable tube steel temporary bulkhead

The holding and remote control release mechanism of this design is a hybrid between the balloon temporary bulkhead and the compression seal steel temporary bulkhead. The holding mechanism relies partly on friction between the inflatable tube and the permanent bulkhead and partly on the interaction between the shape of the inflatable tube and the groove in the permanent bulkhead. Because of the latter, the pressure inside the inflatable tube can be lower than in the case of the balloon temporary bulkhead. That being said, the minimum output force for the inflatable tubes has to be 1509 N and 66 N for the water passage and air passage temporary bulkhead respectively.
The tube can be inflated through a valve stem on the outside of the steel bulkhead plates, eliminating the need of a central power distribution point. Furthermore, the release mechanism of this temporary bulkhead design does not need large actuators. Since, the temporary bulkheads will fall out due to gravity once the inflatable tube is deflated.
However, to deflate the tube remotely, an electric solenoid valve similar to the example in figure 33 is needed. Although this solenoid valve has to be powered electrically, this can be done by a very small battery limiting the risk of contaminating the fresh water in the rigid reservoir.
All the remote control release mechanisms for each temporary bulkhead design are summarized in table 9.

Figure 33 Electric solenoid valve (source: amazon.nl)

Table 9 Overview of remote control release mechanisms for the temporary bulkhead designs

	Inflatable balloon temporary bulkhead	Pull-in steel temporary bulkhead	Compression seal steel temporary bulkhead	Inflatable tube steel temporary bulkhead
Remote release mechanism	Deflating balloon by reversing airflow	Multi-turn rotary actuator	Linear actuator	Remotely activated valve
Central power distribution	Yes	Yes	Yes	No
Pneumatic option possible	Yes	Yes	Yes	No
Alternative	N/A	N/A	N/A	Small solenoid valve
Minimum actuator output force, water passage	N/A	1216 N	3226 N	N/A
Minimum actuator output force, Air passage	N/A	22 N	50 N	N/A
Example image	Figure 18, section view F-F	Figure 22, detail view U	Figure 26, detail view R	Figure 30, detail view U

Which of the possible design choices can withstand the hydrostatic forces at the chosen depth?

The first part of the detailed design phase has started in the previous section, in this section the second part of the detailed design phase will be elaborated on. In the second part of the detailed design phase, the designs developed in the previous section are loaded with the forces and pressures found in the conceptual design phase to see whether the design designs can withstand the load safely.

Permanent Bulkhead

Firstly, the three permanent bulkhead designs are tested against the pressure profile(figure 10) that was found in the conceptual design phase. From the reviewed literature it became apparent that the analytical equations for bulkhead thickness added little value as only one strength property is considered in analytical formulae. Hence an initial bulkhead thickness of 1 meter was taken and this thickness was increased or decreased to minimize bulkhead volume while still satisfying all assessment criteria.

Material

Because, the university (student) version of Solidworks does not have concrete materials as standard, a toolbox with concrete materials was sourced online (GrabCAD, 2016). For the simulations, the moderate strength option was chosen as a compromise between material costs and concrete strength. Table 10 displays the material properties for the moderate strength concrete.

Table 10 Material properties for the Portland moderate strength concrete used in the FEM simulations

Material property	Value	Unit
Elastic Modulus	2.3e+10	N/m^2
Poisson's Ratio	0.205	N/A
Shear Modulus	8000000	N/m^2
Mass Density	2100	kg/m^3
Tensile Strength	5000000	N/m^2
Compressive Strength	40000000	N/m^2
Yield Strength	25000000	N/m^2
Thermal Expansion Coefficient	1e-05	1/K
Thermal Conductivity	0.5	W/(mK)
Specific Heat	750	J/(kgK)
Material Damping Ratio	0.05	N/A

Assessment criteria

The reviewed literature on concrete bulkheads was in agreement that bulkhead failure starts with tensile crack forming and eventual complete failure happens through tensile and shear yielding. Tensile cracks form between 0.8-1 mm of bulkhead surface displacement, while complete failure starts when the bulkhead surface displaces more than 1 mm. Hence, the first assessment parameter is the bulkhead surface displacement. Which should be less than 1 mm during all installation phases.
The second and third assessment criteria are related, as they both describe more or less the same safety margin. It was decided to add both criteria to hopefully provide extra clarity with regard to the bulkhead stability. The maximum allowed Von Mises stress is 50% of the yield stress, or in other words a minimum safety factor of 2.
The final assessment criteria, bulkhead volume can also be seen as an optimization objective. Where the objective is to minimize bulkhead volume as this also minimizes material costs to construct the bulkhead. Table 11 summarizes the assessment criteria described above.

Table 11 Minimum and Maximum values for design parameters to assess the stability of the permanent bulkhead designs

Assessment parameter	Minimum/Maximum Value
Displacement/Deflection	Max. 1 mm
Von Mises stress	Max. 50% of yield stress
Factor of Safety	Min. 2
Bulkhead volume	Minimize

Simulation results

For the simulations, three reservoir segment assemblies were created by assembling the three permanent bulkhead designs inside a segment tube. These assemblies were tested using the Solidworks linear dynamic simulation tool following the pressure profile in figure 10. All outside faces were loaded according to the blue line in the pressure profile, which consist of pressures up to 603.401 kPa. The inside faces were loaded according to the red line in the pressure profile, which is atmospheric pressure of 101.325 kPa.
Figures 34, 35 and 36 provide the result models for the maximum stress, maximum displacement, minimal factor of safety from the dynamic simulation for the flat, the spherical 5m radius curvature and the spherical 12m radius curvature permanent bulkheads respectively. These result files were all from the simulation step in the dynamic simulation where the external pressure was at its highest point.
The results show that the stress and displacement as a result of the loading are more centralized for the flat permanent bulkhead, while they are spread out over almost the entire surface for the 5m radius curvature bulkhead. As expected, for the 12m radius curvature permanent bulkhead the stress and displacement is spread out more than for the flat permanent bulkhead, but less than for the 5m radius curvature permanent bulkhead.

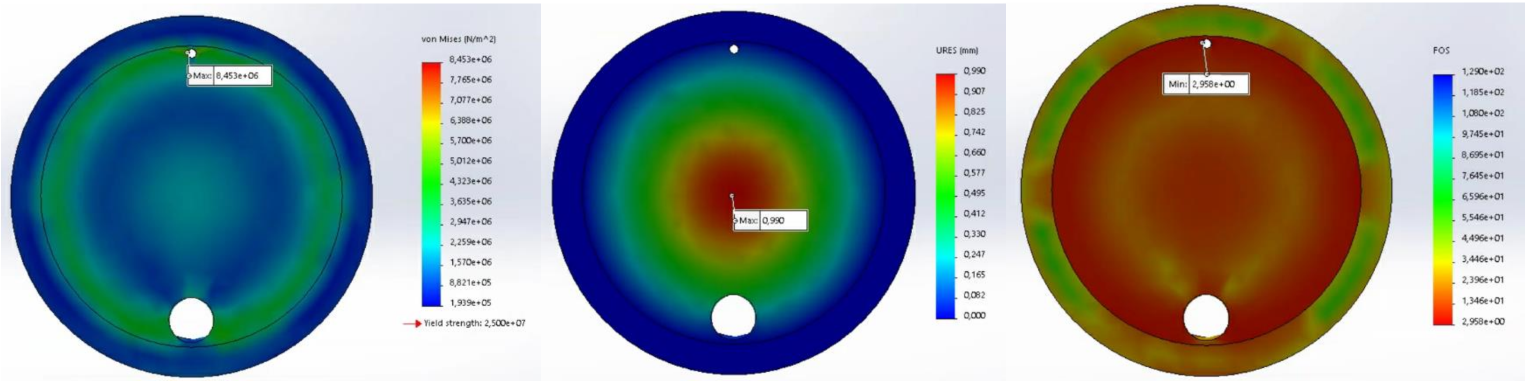

Figure 34 max. Von Mises stress, max. displacement and min. factor of safety results for the flat permanent bulkhead

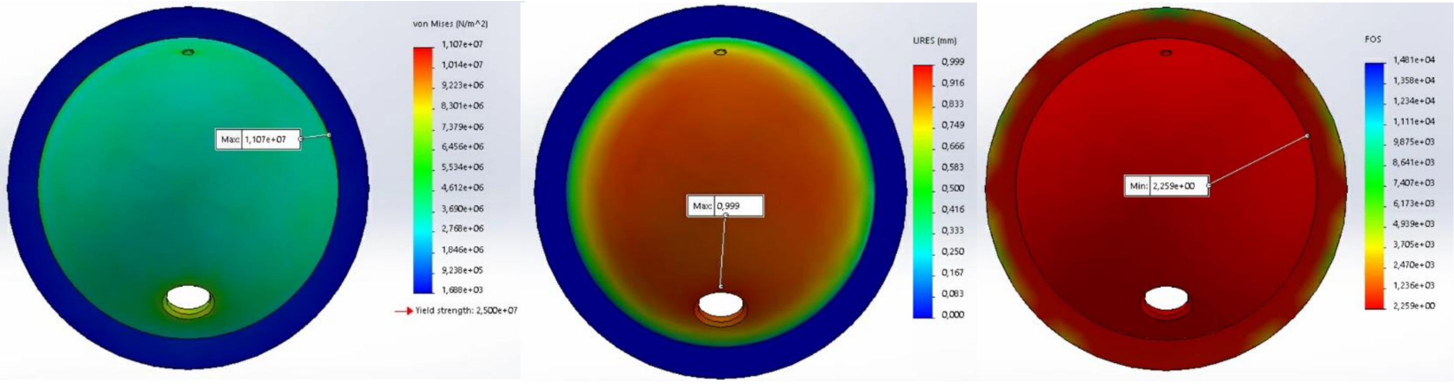

Figure 35 max. Von Mises stress, max. displacement and min. factor of safety results for the 5m radius curvature spherical permanent bulkhead

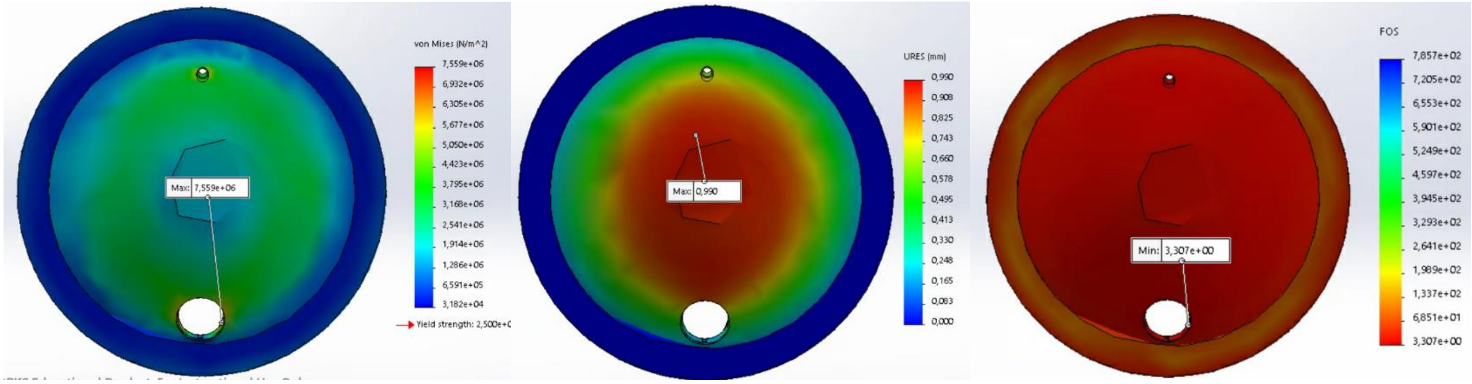

Figure 36 max. Von Mises stress, max. displacement and min. factor of safety results for the 12m radius curvature spherical permanent bulkhead

Table 12 provides an overview of resultant stress, displacement and safety factors for the assessment parameters. The bulkhead thickness, and thus the bulkhead volume, has been optimized such that the all the bulkhead designs meet the assessment criteria. Reducing the bulkhead thickness was stopped as soon as one of the assessment criteria could not be met when reducing the bulkhead thickness further. For all the bulkhead designs the maximum displacement(< 1 mm) of the bulkhead was the limiting factor as the safety factor for all the bulkheads remained above 2.
From the most right column of the table it becomes clear that the two spherical bulkhead designs are very close together with regard to bulkhead volume, 56.57 m^3 and 58.55 m^3 for the 5m curvature bulkhead and the 12m curvature bulkhead respectively. Whereas, the flat permanent bulkhead needs approximately twice as much volume, at 113.50 m^3, to meet the stability criteria. Because of the significant amount of necessary additional volume, the flat permanent bulkhead will not be considered as a suitable solution for the permanent bulkhead. Being that the volume of the two spherical bulkhead designs is so close together, both the designs will be regarded as possible solutions. However, the shape of the 5m spherical bulkhead will make the operation of some temporary bulkhead designs significantly more complicated or even impossible. Combined with the safety factor of the 12m spherical bulkhead being significantly higher, the 12m spherical bulkhead will be used for the development of the temporary bulkheads.

Table 12 Overview of the simulation results for the permanent bulkhead designs

Permanent bulkhead design	Max. Von Mises stress [Pa]	Percentage of yield stress [%]	Max. displacement [mm]	Min. Factor of Safety [N/A]	Bulkhead thickness [m]	Bulkhead volume [m^3]
Flat	8.453*10^6	33.8	0.990	2.958	1.480	113.50
Spherical, 5m curvature	1.107*10^7	48.8	0.999	2.259	0.375	56.57
Spherical, 12m curvature	7.559*10^6	30.2	0.990	3.307	0.780	58.55

Temporary Bulkhead

In this subsection, four temporary bulkhead designs are tested against the pressure profile(figure 10) that was found in the conceptual design phase. An initial thickness of 20 mm and curvature radius of 2860 mm was used for the steel temporary bulkheads, adopted from the reviewed literature (Yao et al., 2007).
The initial thickness for the balloon temporary bulkheads was obtained from the formula:

$$t = \frac{pr}{2\sigma_1} \tag{12}$$

Where t is the balloon wall thickness [m], p is the internal pressure [Pa], r is the radius of the balloon [m] and σ_1 is 0.5 σ_{yield}.
This provided an initial thickness of 8 mm for the balloon temporary bulkhead that will be used to plug the water passage in the permanent bulkhead. An initial thickness of 2 mm was found for the balloon temporary bulkhead that will be used to plug the air passage in the permanent bulkhead.
During the simulation process, all the temporary bulkhead thicknesses have been optimized such that they minimize material usage while also meeting the assessment requirements.

Material

Stainless steel

In the reviewed literature for steel bulkheads, 980 steel was used for the steel bulkhead plates (Yao et al., 2007). Initially, it was opted to use 1020 cold rolled steel for the steel bulkhead plates as the material library of the university (student) version of Solidworks did not have the exact matching material and the material properties for 980 and 1020 cold rolled steel are almost identical.
However, after reviewing the corrosion behavior of 1020 cold rolled steel, it was decided a stainless steel would be a more suitable choice to prevent contamination of the fresh water inside the reservoir during operation. Especially, considering the bulkhead plates remain submerged in water throughout the operational life of the Ocean Battery.
Hence, chrome stainless steel was used as the steel bulkhead plate material for the simulations. The material properties for this stainless steel can be found in table 13.

Table 13 Material properties for chrome stainless steel used in the FEM simulations

Material property	Value	Unit
Elastic Modulus	2e+11	N/m^2
Poisson's Ratio	0.28	N/A
Shear Modulus	7.7e+10	N/m^2
Mass Density	7800	kg/m^3
Tensile Strength	413613000	N/m^2
Yield Strength	172339000	N/m^2
Thermal Expansion Coefficient	1.1e-05	/K
Thermal Conductivity	18	W/(m·K)
Specific Heat	460	J/(kg·K)

Rubber

Multiple rubber parts for multiple different applications were developed during the course of the project. Hence, multiple different rubbers had to be used in the simulations to provide the correct hardness for each application.

This is mainly the case for the compression ring of the compression seal steel temporary bulkheads. Because, the compression force needs to be high enough to hold the bulkhead in place, yet as low as possible to reduce the force necessary to remove it. The medium hard rubber compound was found to provide these properties best out of the compounds.

For the inflatable tube and the rubber gaskets that sit in between the steel bulkhead plates and the concrete permanent bulkheads, high pliability of the material was the main criteria to ensure the gasket provides a good seal at all times. Hence, the soft rubber compound was chosen for these parts. A hard rubber compound was trailed for use with regard the balloon temporary bulkheads and the compression ring of the compression seal temporary bulkheads. However, in a later stage in the project it was decided other materials or material compounds were a better choice with regard to the function and environment of those parts.

The soft rubber material was sourced from the Solidworks material library. However, the material properties of medium hard were sourced from an online material online database (Matweb, 2022). The material properties for all the rubber compounds that were used in the FEM simulations have been combined into table 14.

Table 14 Material properties for the rubber used in the FEM simulations

Material properties Soft rubber	Value	Unit
Elastic Modulus	6100000	N/m^2
Poisson's Ratio	0.49	N/A
Shear Modulus	2900000	N/m^2
Mass Density	1000	kg/m^3
Tensile Strength	13787100	N/m^2
Yield Strength	9237370	N/m^2
Thermal Expansion Coefficient	0.00067	/K
Thermal Conductivity	0.14	W/(m·K)
Material properties medium hard rubber	**Value**	**Unit**
Elastic Modulus	12000000	N/m^2
Poisson's Ratio	0.49	N/A
Shear Modulus	3000000	N/m^2
Mass Density	1015	kg/m^3
Tensile Strength	16866200	N/m^2
Yield Strength	9876350	N/m^2
Thermal Expansion Coefficient	0.00065	/K
Thermal Conductivity	0.12	W/(m·K)

Polyurethane

The last material that was used is polyurethane, for the balloon temporary bulkheads. A polyurethane material was present in the material library, however the elastic modulus for this polyurethane sort was not specified. When this is the case the FEM analyses cannot run properly as they rely on the elastic modulus for the force calculations. To this end, the material properties for the polyurethane material were sourced from an online database and can be found in table 15. (Matweb, 2022). The polyurethane material was used for the balloon temporary bulkheads, as the significantly material strength increase over the hard rubber allowed the wall thickness of the balloons to be much less.

Table 15 Material properties for the polyurethane used in the FEM simulations

Material property	Value	Unit
Elastic Modulus	2580000000	N/m^2
Poisson's Ratio	0.41	N/A
Shear Modulus	20000000	N/m^2
Mass Density	1700	kg/m^3
Tensile Strength	64500000	N/m^2
Yield Strength	63600000	N/m^2
Thermal Conductivity	0.2256	W/(m·K)
Specific Heat	1386	J/(kg·K)

Assessment criteria

From literature, fewer assessment criteria have been found for the temporary bulkhead designs compared to the concrete permanent bulkheads. One assessment criteria found for the steel bulkheads states that the critical buckling stress should not exceed the yield strength of the chosen material. However, this already follows from the minimum safety factor of 2.
This means four parameters have been established to assess the viability of the temporary bulkhead designs, which can be found in table 16. Although the set of assessment parameters stems less from literature compared to the assessment parameters for the permanent bulkheads, it encompasses the necessary parameters to assess the stability of the temporary bulkheads.

Table 16 Minimum and Maximum values for design parameters to assess the stability of the temporary bulkhead designs

Assessment parameter	Minimum/Maximum Value
Holding mechanism factor of safety	Min. 2
Von Mises stress	Max. 50% of yield stress
Bulkhead factor of safety	Min. 2
Bulkhead volume	Minimize

Simulation results

To run the simulations, four reservoir segment assemblies were created by assembling the four temporary bulkheads inside the corresponding reservoir segment. These assemblies were tested using the Solidworks linear dynamic simulation tool following the pressure profile in figure 10. All outside faces were loaded according to the blue line in the pressure profile, which consist of pressures up to 603.401 kPa. The inside faces were loaded according to the red line in the pressure profile, which is atmospheric pressure of 101.325 kPa.

The boundary conditions of the model were considered per temporary bulkhead design and selected accordingly. For all assemblies the globally bonded option was selected as the boundary condition for the part connections, meaning that the parts used in the assembly are treated as bonded together during the simulations. Which is the case for most of the parts used in the assemblies. For parts in the assembly that displace significantly with respect to the rest of the assembly, i.e. interference fit or inflatable parts, local no-penetration boundary conditions were selected. This boundary condition allows selected parts to displace with respect to other parts of the assembly, however it does not allow parts to penetrate other parts of the assembly. Because parts are not able to penetrate one another, reaction forces are produced between different parts of the assembly. These reaction forces can be used to assess whether the strength of designed holding mechanisms meet the required safety factor of 2 with regard to the gravitational forces in the x-direction.

The air passage and water passage temporary bulkheads were both treated separately in the performed analyses to ensure accurate results. The results for the simulations of the water passage temporary bulkhead designs are summarized in table 17, on the next page. For the air passage temporary bulkheads, the simulation results have been summarized in table 18.

Water passage temporary bulkhead designs

The factor of safety for the holding mechanisms was determined based on the reaction forces between the temporary and permanent bulkheads using a simulation where all faces were loaded with atmospheric pressure. This was done to ensure the holding mechanisms provide a high enough output force to hold the temporary bulkheads in place while the reservoir segments are still above the water. It can be concluded that the holding mechanism factor of safety of the steel temporary bulkhead designs are close together with value between 2 and 2.18. On the other hand, the holding mechanism factor of safety for the balloon temporary bulkhead is significantly higher at 4.17.

Identical to the permanent bulkhead designs, the highest stresses for the temporary bulkheads were recorded when the external pressure was at its highest point. The results show that for this pressure only two out of four of the designs pass the assessment criteria that were set for the temporary bulkheads.

The compression seal steel temporary bulkhead shows a safety factor that is lower than 2, namely 1.729. And the inflatable tube steel temporary bulkhead shows a minimum factor of safety of 0.651.

Table 17 Overview of simulation results for the water passage temporary bulkhead designs

Temporary bulkhead design	Balloon	Pull-in steel	Compression seal steel	Inflatable tube steel
Holding mechanism output force [N]	9057.8	1215.62	1762.25	1546.3
Holding mechanism factor of safety	4.17	2*	2.18	2.05
Inflating pressure [kPa]	603,401	N/A	N/A	250
Max. Von Mises stress [kPa]	2.968*10^7	8.453*10^7	1.446*10^8	2.258*10^8
% of yield stress	46.66	47.06	57.84	153.61
Min. bulkhead factor of safety	2.143	2.125	1.729	0.651
Bulkhead thickness [mm]	13	14	20	20
Bulkhead volume [m^3]	0.13	0.035	0.047	0.044

*Since the (multi-turn) rotary actuator functions as both the holding and remote control release mechanism, an actuator can be selected such that the output force and factor of safety for the holding mechanism is as close as possible to 2.

With regard to the compression seal steel temporary bulkhead, the permanent bulkhead safety factor falls below the minimum allowed safety factor threshold due to the forces exerted on it by the compression seal temporary bulkhead.

This is caused by how the factor of safety analysis is approached. the Solidworks factor of safety analysis provides an analysis for all the bodies and parts contained in the simulation. Hence, the concrete reservoir segment itself is also considered. The factor of safety analysis found the minimum factor of safety was 1.729 for the 12m curvature concrete permanent bulkhead, caused by the deformation of the steel temporary bulkhead plate, which is flattened out during the immersion. As the bulkhead plate is flattened out, it transfers more force into compression seal, which in turn transfers a part of the force into the permanent bulkhead. This results in a tension load on the water passage in the permanent bulkhead. Which, is large enough to decrease the safety factor below the minimum of two. It has to be noted that the safety factor of compression seal steel temporary bulkhead remained above the minimum threshold. However, as a collective assembly the reservoir segment with the compression seal steel temporary bulkhead did not pass the assessment criteria and will thus not be considered an adequate solution.

Regarding the inflatable tube steel temporary bulkhead, the safety factor of 0.651 is far below the minimum threshold of 2. In this case, the lowest safety factor is for the inflatable tube itself at the when it is loaded with the highest external pressure of 603,401 kPa. Considering the safety factor is below 1, the inflatable tube will likely fail as a result of the external pressure.

However, it is debatable to what degree this influences the function of the temporary bulkhead. This is because, the bulkhead will be held in place by the hydrostatic pressure at that point in the installation and there is a rubber gasket behind the steel temporary bulkhead plate to provide the watertight seal between the temporary and permanent bulkhead. Furthermore, as the inflatable tube has likely failed, the steel temporary bulkhead will fall out of the water passage due to gravity once all the water is drained out at the end of the draining phase. Resembling the designed release mechanism. That being said, the control over the remote control release mechanism would be lost and introducing a reliance on chance for the temporary bulkhead design to operate well is bad practice.

Several design alteration were experimented with to increase the strength of the inflatable tube(e.g. varying the inflating pressure, using a stronger material, increasing the wall thickness of the inflatable tube) to find a combination that would meet all requirement. However, strengthening the inflatable tube presented similar problems of force transfer from the steel temporary bulkhead plate through the inflatable tube into the concrete permanent bulkhead as with the compression seal temporary bulkhead. Furthermore, the inflatable tube would probably become too stiff for the current remote control release mechanism design to operate properly.

The two temporary bulkhead designs that do meet all the assessment criteria, the balloon temporary bulkhead and the pull-in steel temporary bulkhead, are very different solutions made out of two very different materials. Even though, the safety factor for both temporary bulkheads is almost identical at 2.143 and 2.125 respectively, the stress experienced by the pull-in steel bulkhead is significantly higher than that of the balloon temporary bulkhead. Furthermore, there is a significant percentual difference in bulkhead thickness and volume between the two designs. Because reducing the bulkhead thickness further for the balloon and pull-in temporary bulkheads would cause the factor of safety to fall below 2, the safety factor could not be reduced further towards 2 than the achieved 2.1.

Air passage temporary bulkhead designs

The air passage temporary bulkheads were designed after the simulations for the water passage were completed. For reasons of reducing complexity and increasing robustness, it was decided that the same temporary bulkhead design will be used for the air and the water passage. Hence, only the balloon and pull-in steel temporary bulkheads were tested in the simulations to be used for the air passages. Technical drawings for the air passage temporary bulkheads and the rubber gasket that were used in the simulations can be found in appendix 1.
The simulation results for those temporary bulkheads are summarized in table 18.
From the table, it can be seen that both designs meet all the assessment criteria. Similar to the water passage bulkheads, the safety factor for both temporary bulkheads are very close together at 2.198 and 2.24. Although the realized safety factor of approximately 2.2 is higher than the minimum requirement, it could not be further reduced, since the safety factor for both designs fell below 2 when the bulkhead thickness was reduced further.
However, there is a significant difference between the factor of safety regarding the holding mechanisms. This is mainly caused by the balloon temporary bulkhead, as the holding mechanism factor of safety for this bulkhead far exceeds the minimum of 2. Although a factor of safety of 41 is far higher than necessary, it was kept at this value as no other factors of the design were compromised and it does not cause instability of the permanent bulkhead.

Table 18 Overview of simulation results for the air passage temporary bulkhead designs

Temporary bulkhead design	Balloon	Pull-in steel
Holding mechanism output force [N]	1361.4	21.74*
Holding mechanism factor of safety	41.06	2*
Inflating pressure [kPa]	603.401	N/A
Max. Von Mises stress [kPa]	2.893*10^7	7.695*10^7
% of yield stress	45.50	44.64
Min. factor of safety bulkhead	2.198	2.24
Bulkhead thickness [mm]	4	4
Bulkhead volume [m^3]	0.001	0.0006

*Since the (multi-turn) rotary actuator functions as both the holding and remote control release mechanism, an actuator can be selected such that the output force and factor of safety for the holding mechanism is as close as possible to 2.

What is the most cost-effective combination of material, shape and remote release mechanism?

Since, it has been established which designs for the permanent and temporary bulkhead designs can withstand the forces and pressures of the installation phase, a comparison can be made between the bulkhead designs that passed the assessment criteria.

Permanent bulkhead

Although all the designs for the permanent bulkhead met the assessment criteria, it has been established that the flat permanent bulkhead will not be considered as a solution to the permanent bulkhead problem. Apart from the fact that the extra concrete used would be a waste of material, this extra concrete would make the permanent bulkhead approximately two times more expensive per permanent bulkhead. A price could not be acquired for the Portland moderate strength concrete that was used in the simulations. However it is very similar to C40/50 concrete, which is more conventional in the Netherlands. Hence, the price per cubic meter for C40/50 concrete was used in the permanent bulkhead cost estimate. Table 19 provides an overview of the cost estimate comparison for the permanent bulkhead solutions.
Because the material and the material price for all the designs are the same, it is not difficult to see which design would be the most cost-effective. However, as both spherical permanent bulkhead are so close together, both spherical permanent bulkheads will be considered as a solution for the permanent bulkhead.

Table 19 Total cost estimate for the permanent bulkhead designs

Permanent Bulkhead design	Volume [m^3]	Material [N/A]	Material cost [€/m^3]	Total cost [€]
Flat	113.50	C40/50 concrete	135*	15.322,50
Spherical, 5m curvature	56.57	C40/50 concrete	135*	7.636,95
Spherical, 12m curvature	58.55	C40/50 concrete	135*	7.904,25

* Current price of C40/50 concrete(July 2022), obtained from direct communication with a concrete supplier.

Temporary bulkheads

With regard to the temporary bulkheads, two designs meet the assessment criteria for both the water passage and air passage temporary bulkheads. In table 20 and 21, a cost comparison is made for the water passage and air passage temporary bulkheads. Some cost assumptions had to made for the cost comparisons, these are displayed underneath the tables.
Additionally, it has to be noted that the comparison only takes into account material cost, as manufacturing cost for both temporary bulkheads are difficult to estimate accurately as they will vary per manufacturer. Furthermore, the cost of a detachable (ROV) connector and tubing inside the reservoir running from the central distribution point to the bulkheads were also not considered for the temporary bulkhead comparison. This choice was made because these costs are equal across the bulkhead designs.

Table 20 Total cost estimate for the water passage temporary bulkhead designs

Temporary bulkhead design	Balloon	Pull-in steel
Material [N/A]	Polyurethane	Stainless steel
Material cost [€/kg]	2,29*	3,74**
Volume [m^3]	0.13	0.035
Bulkhead mass [kg]	221.29	275.43
Material cost [€]	650,59	1030,11
Actuator	N/A	2500±1000***
Total cost [€]	650,59	3530,11

* Current polyurethane price per kg (https://exportv.ru/price-index/thermoplastic-polyurethane)
** Current stainless steel price per kg (https://steeltube.co.in/ss-304-price-per-kg/)
*** €2500 is an average price obtained from multiple price requests for an actuator that provides enough output force to meet the assessment criteria.

Table 21 Total cost estimate for the air passage temporary bulkhead designs

Temporary bulkhead design	Balloon	Pull-in steel
Material [N/A]	Polyurethane	Stainless steel
Material cost [€/kg]	2,29*	3,74**
Volume [m^3]	0.01	0.0006
Bulkhead mass [kg]	3.38	4.93
Material cost [€]	9,94	18,44
Actuator	N/A	1000 ± 500***
Total cost [€]	9,94	1018,44

* Current polyurethane price per kg (https://exportv.ru/price-index/thermoplastic-polyurethane)
** Current stainless steel price per kg (https://steeltube.co.in/ss-304-price-per-kg/)
*** €1000 is an average price obtained from multiple price requests for an actuator that provides enough output force to meet the assessment criteria.

For both the air and water passage, the balloon temporary bulkhead is the most cost-effective option. There are multiple reasons for this, the balloon temporary bulkhead has the lowest material cost per kilogram and the lowest mass for both the air and water passage bulkheads. Furthermore, the cost of an actuator for the remote control release mechanism does not have to be made in the case of the balloon temporary bulkhead. This leads to the balloon temporary bulkhead being significantly more cost-effective for both the air and water passage temporary bulkhead solutions.

Total cost per reservoir segment

Since the most cost-effective individual parts of the reservoir segment that meet all assessment criteria have been established, a total cost can be generated for the final design of a single reservoir segment. Table 22 summarizes the cost estimate for a reservoir segment per cost item, including a miscellaneous cost item of 5% of the other total cost. These miscellaneous costs are used to cover the cost of miscellaneous items such as tubing, fittings and the control panel to release the temporary bulkheads as well as any unforeseen costs that may arise. Furthermore, the 12m curvature permanent bulkhead was used for the cost estimate, since this design was used in the development and simulations for the temporary bulkheads.
From table 22, it can be concluded that the majority of the cost, 92.35%, of a reservoir segment stem from concrete reservoir tube structure itself. While, only 2.88% of the total cost come from the temporary bulkheads and parts needed to facilitate the remote control release mechanism.

Table 22 Total cost estimate for the final design of an individual reservoir segment

Cost item	Cost [€]	Quantity per segment		% of total cost
Segment tube	186.610,60*	1	186.610,60	85.14
Permanent bulkhead, 12m curvature	7.904,25	2	15.808,50	7.21
Balloon temporary bulkhead, water passage	650,59	2	1.301,18	0.59
Balloon temporary bulkhead air passage	9,94	2	19,88	0.009
ROV connector	5000 ± 1000**	1	5000 ± 1000	2.28
Miscellaneous (5% of other costs)	10.437,01	1	10.437,01	4.76
Total			219.177,17 ± 1000	

* Assuming a segment tube with in inside diameter of 10 m, a wall thickness of 1 m and thus an outside diameter of 12 m and a length of 40m. The segment tube required a concrete volume of 1382.3 m^3. When multiplied by the price of €135 per m^3 for C40/50 concrete. The segment tube itself will cost €186.610,60.
** Average price for an heavy duty ROV connector from multiple price requests that can withstand the necessary hydrostatic forces applicable to the project.

Result Validation

The internal validation of the designs is reached by comparing the final designs with the functional requirements set at the beginning of the project. This was done by creating a set of assessment criteria to assess the stability of the proposed temporary and permanent bulkhead designs. Furthermore, most designs were inspired by bulkhead design recommendations from proven published literature. Hence, the internal validation of the three permanent and two temporary bulkhead designs follows from the designs following available literature and meeting all the assessment criteria.

The external validation of the designs follows from being actually useful for the Ocean Grazer company. In order for the final design the be useful, it needs to be more cost-effective for the company than the current state of the art. That being said, a comparison of the final design with manual temporary bulkhead removal by divers/construction workers is not straightforward, as the attempt to receive pricing from offshore diving companies to perform such a task was unsuccessful. However, the validation of the final design can also be reached by demonstrating the design's novelty through reasoning.

Because, the lowest safety factor of the concrete reservoir segment design is 3.3 and divers/construction workers are not allowed to enter into the inside of the reservoir to remove the temporary bulkheads. An acceptable safety factor to allow divers/construction workers to work inside a submerged structure is between 8 and 15 (Porathur et al., 2018). Hence, divers would only be allowed to release the temporary bulkheads from a control box somewhere on the reservoir segment to release the temporary bulkheads remotely. However, with the current final design this can be done with a control panel above the water on the barge.

If divers would be used to release the temporary bulkheads in combination with the current final design, the cost for the temporary bulkheads cannot be removed. Since, divers are not allowed to go inside the reservoir, the temporary bulkheads cannot be taken out of the reservoir and are one-time-use. Meaning the cost has to be made for each individual reservoir segment, like in the current design. Only the ROV connector could be less costly by using a normal connector that divers could disconnect. However, the cost of a power supply connector cannot be fully removed as remote power from the barge is still be needed. Factoring in the additional costs of the offshore diving company, using divers to release the temporary bulkheads in combination with the current design adds complexity and probably also overall cost.

A second scenario where divers would be allowed to enter inside the reservoir also has to be considered. If divers could enter the rigid reservoir, it would be possible to re-use the same temporary bulkheads for multiple reservoir segments. Furthermore, the remote power supply is not needed in the scenario, eliminating the need for the (ROV) connector. This would reduce costs considerably. However, the safety factor of the rigid reservoir structure would need to be increased from 3.3 to 8 at a minimum for the divers to be allowed to enter the rigid reservoir. While it is difficult to estimate the cost of increasing the safety factor to a minimum of 8, this cost would be far higher than the expenses saved from reusing the temporary bulkheads and removing the ROV connector. Moreover, the costs of the offshore diving company to remove the temporary bulkheads have to be added on top of that.

Discussion

This research project has been a design study where completely new artifacts have been developed for use within the Ocean Battery rigid reservoir. To this end three permanent bulkhead designs and four temporary bulkhead designs were created.

Although all parts were developed separately from each other, the parts were assembled into assemblies to be tested as a whole during the simulations. This ensured the assembly as a whole passed the assessment criteria. However, more extensive simulation on individual parts could be done to further optimize the designs.

Analyzing the results of the permanent bulkhead simulations yielded some surprises. It was expected that the curved spherical bulkhead would perform better than the flat permanent bulkhead. The degree to which this was true was the most surprising. While the minimum bulkhead volume for the two spherical permanent bulkheads was similar, the flat permanent bulkhead needed almost twice the volume to remain stable.

The temporary bulkhead simulation results also differed from the initial expectations. After all the permanent bulkhead concepts to managed pass the assessment criteria, it was expected the same could be obtained for the temporary bulkhead concepts. However, the compression seal and inflatable tube steel temporary bulkheads could not be considered viable solutions after the safety factor for these temporary bulkhead designs remained lower than 2.

This left only the polyurethane balloon and the pull-in steel temporary bulkheads as viable solutions to the temporary bulkhead problem.

Although, it became apparent that an oversight was made when assembling the list of functional requirements after the simulations were finished. The effect of the bulkhead and remote control release mechanism materials on the fresh water inside the reservoir were not taken into account fully. It was already decided to use pneumatic actuators instead of electric or hydraulic examples and switch to stainless steel instead of normal steel for the temporary bulkheads to combat contamination of the fresh water inside the rigid reservoir.

However, even though stainless steel is far more resistant to corrosion than normal steel, it is not corrosion proof. Fresh water microbiological organisms form biofilms on stainless steel surfaces that over time will lead to stainless steel breakdown and cause the initiation of localized corrosion. This process can take place after as soon as 123 days (George et al., 2000). Meaning, the pull-in steel temporary bulkhead would not be a suitable long term solution as it will be submerged in water for longer than 123 days.

Luckily, the most cost effective temporary bulkhead solution, the polyurethane balloon, handles immersion in fresh water significantly better, as polyurethanes are generally environmentally friendly, non-toxic and non-flammable. Furthermore their hydrophobic nature makes them insoluble in water (Honarkar, 2018). Meaning the polyurethane balloons form little threat to contaminating the fresh water inside the rigid reservoir.

Limitations and future work

The cost comparison for the reservoir segment design against manual temporary bulkhead removal consists of the 12m spherical permanent bulkhead in combination with the balloon temporary bulkheads. The 12m spherical permanent bulkhead was used in the cost comparison as it was also used in the development and simulations of the temporary bulkheads.

However, the 5m spherical permanent bulkhead was the most cost effective design. It was not used for the development of the temporary bulkheads as it made the remote control release mechanisms for the steel temporary bulkhead significantly more complicated and expensive. That being said, the 5m spherical bulkhead is compatible with the balloon temporary bulkhead. Hence, future work could look into studying the stability of the 5m spherical permanent bulkhead in combination with the balloon temporary bulkheads for a potential further cost reduction.

Within the scope of the project the hydrostatic forces acting on the reservoir segment assemblies were assumed to be linear. To this end, a linear dynamical model was used to simulate the dynamical behavior of the hydrostatic forces acting on the assemblies. This does not take into account forces from waves and (underwater) currents which could have an impact on the bulkhead stability. Furthermore, the designs have been optimized to the research scope depth of 50 meters. Meaning that part thicknesses and safety factors are sufficient up to this depth. When exceeding 50 meters of depth, it should be evaluated for each part in the assembly which parts need to be redesigned to cope with the additional forces.

In addition, draining the cavity, that is created between opposing bulkhead when two segment are joined, was assumed to be done by pumping out the sea water. However, exploring other methods to drain out the water from the cavity could prove useful as pumping the water out of the cavity becomes significantly more difficult with increasing depth.

Conclusion

The main goal of the research came from the problem analysis, which led to the formulation of the problem statement. Ocean Grazer B.V. lacked a cost-effective solution to install the rigid reservoir segments for the Ocean Battery. Specifically, the goal was to design a permanent bulkhead and a temporary bulkhead with a remote control release mechanism to optimize the cost effectiveness of the rigid reservoir installation.

Initially, the deliverables consisted of the final designs of the permanent and temporary bulkheads with analytical and FEM strength calculations. However, only FEM simulations were performed after relevant literature found analytical calculations added little to no value as analytical equations only cover one material strength property. The FEM calculations were executed using the installation phase pressure profile in a linear dynamic simulation study.

The results of the permanent bulkhead simulations yielded three possible solutions that met the assessment criteria. The best performing permanent bulkhead out of the set of three was the 5m curvature spherical permanent bulkhead with an optimized bulkhead volume of 56.57 m^3. However, the 12m curvature spherical permanent bulkhead also performed well with an optimized bulkhead volume of 58.55 m^3. In addition the 12m spherical bulkhead also allowed for a wider range of temporary bulkheads and remote control release mechanisms to be developed. The volume difference of 7.74% between the two bulkheads translated over literally to the cost comparison as all permanent bulkheads used the same material.

The temporary bulkhead simulation results yielded two possible solutions that met all requirements, the polyurethane balloon and the pull-in stainless steel temporary bulkhead. The air and water passage temporary bulkheads were optimized in dedicated studies to ensure there was no interference between the air and water passage temporary bulkheads. The bulkhead thickness and volume for the air and water passage temporary bulkheads of both designs were optimized for their respective material choices. Although the pull-in steel bulkhead had the lowest bulkhead volume for both the air and water passage temporary bulkhead, the mass and material cost were the lowest for polyurethane bulkheads. Resulting in the polyurethane balloon temporary bulkheads being the most cost-effective temporary bulkhead designs.

The final designs are validated internally from the usage of multiple design element in final designs stemming from proven literature and from the final designs passing all the assessment criteria that originated from the functional requirements. They are externally validated by proofing the final design is more cost-effective than the current state of the art. Combining a cost comparison of the final designs with scenario building provided this proof of concepts assuring the novelty of the solution.

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Appendix

1. Technical drawings of the air passage temporary bulkheads

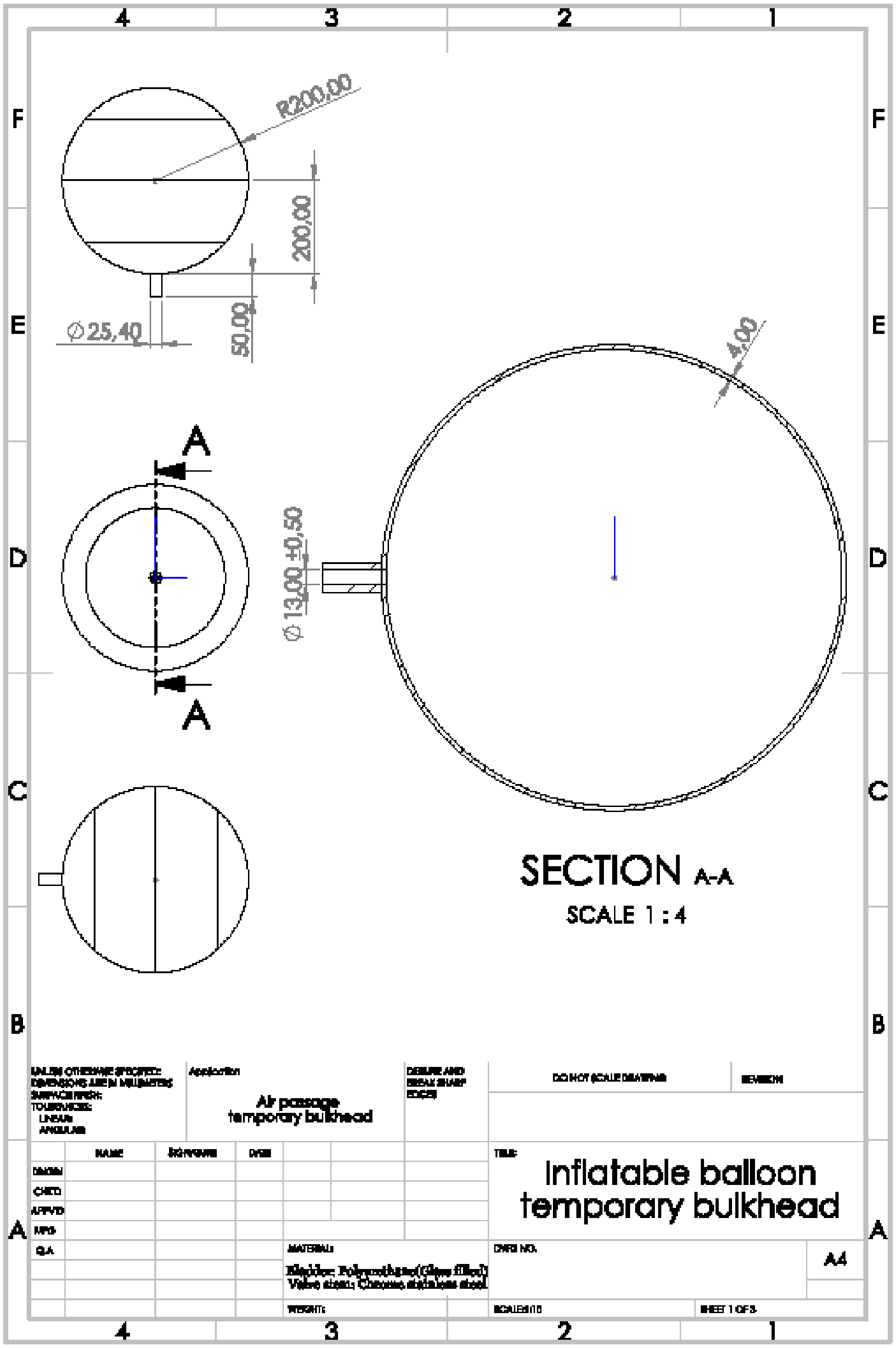


Figure 37 2D technical drawing of the air passage balloon temporary bulkhead

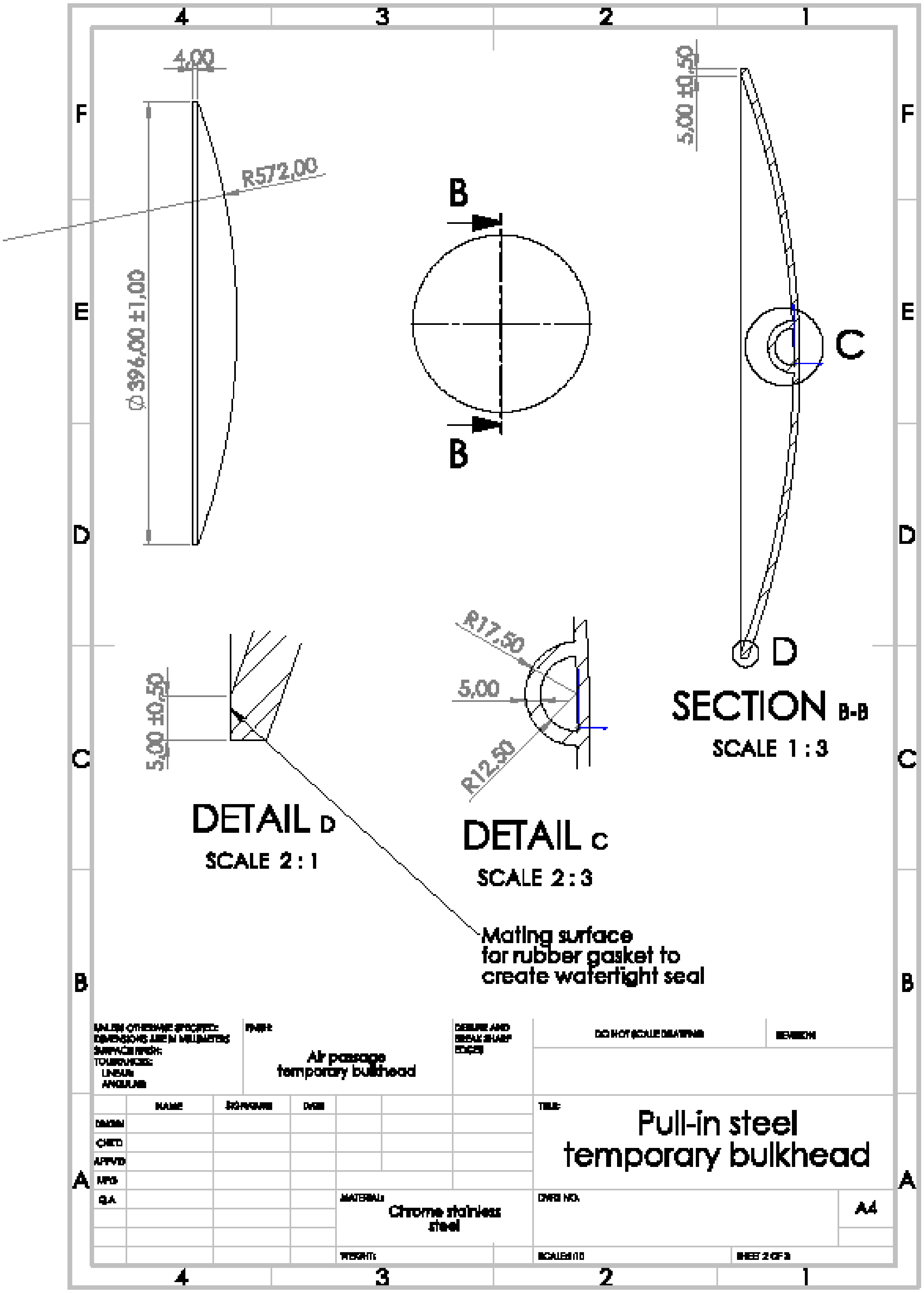


Figure 38 2D technical drawing of the air passage pull-in steel temporary bulkhead

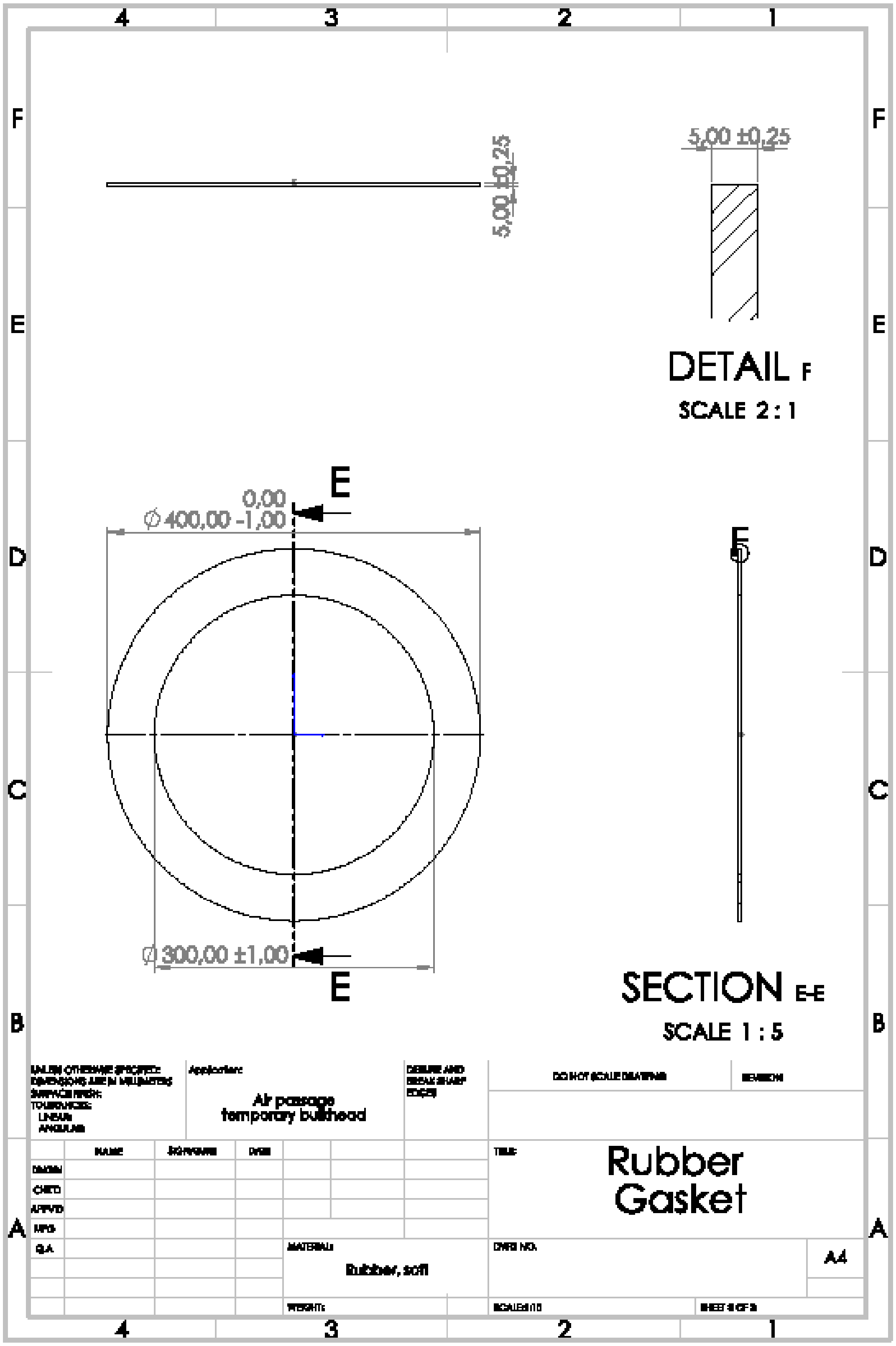
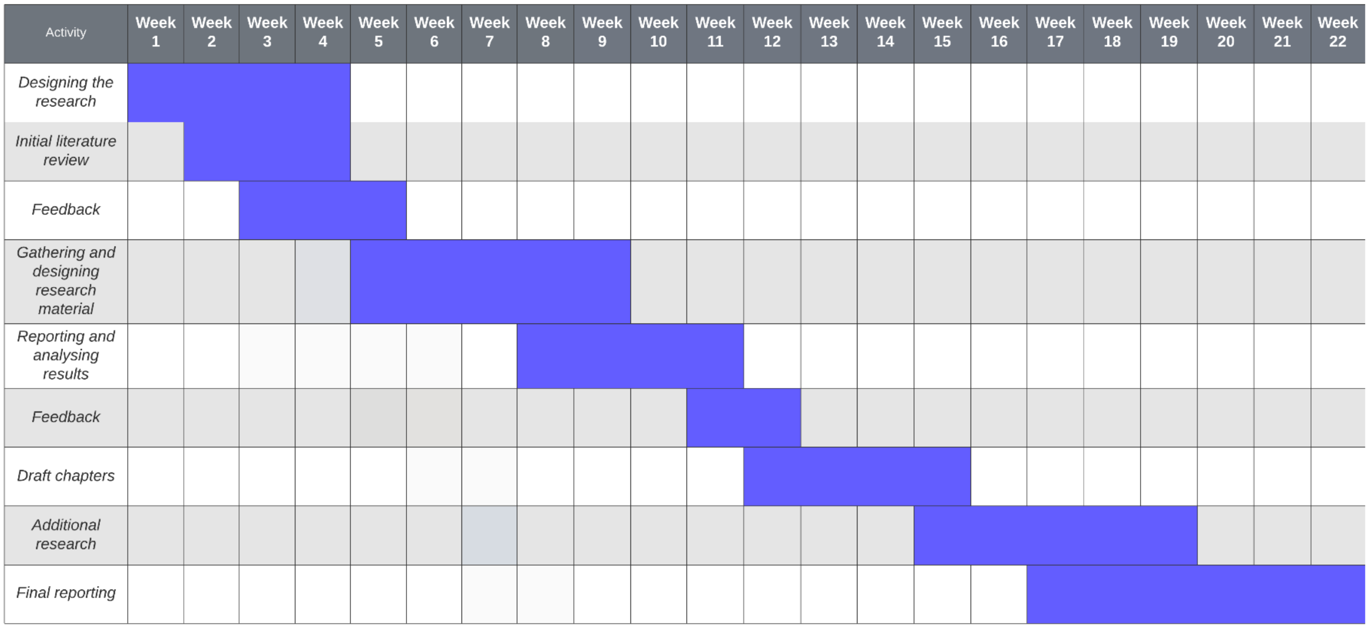


Figure 39 2D technical drawing of the air passage rubber gasket that sits between the steel temporary bulkhead and the concrete permanent bulkhead

2. Research planning

Reflecting upon the initial planning of the project, the time necessary to draft the intermediate chapters of the report was underestimated. Furthermore, the amount of time that could be allocated to the project in weeks 15-17 due to the author's sporting competitions was significantly less than imagined at the start of the project. Apart from those scheduling difficulties the planning was found to be realistic.



Activity	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	Week 7	Week 8	Week 9	Week 10	Week 11	Week 12	Week 13	Week 14	Week 15	Week 16	Week 17	Week 18	Week 19	Week 20	Week 21	Week 22
Designing the research	■	■	■	■																		
Initial literature review		■	■	■																		
Feedback			■	■	■																	
Gathering and designing research material					■	■	■	■	■													
Reporting and analysing results								■	■	■	■											
Feedback											■	■										
Draft chapters												■	■	■	■							
Additional research															■	■	■	■	■			
Final reporting																	■	■	■	■	■	■

Figure 40: Gantt chart showing the research planning.