Design of a standardized pressure-bleeding tool for subsea-intervention procedures

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Design of a standardized pressure equalization tool for subsea-intervention procedures

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Preface

This thesis is written at the department of Mechanical and Marine engineering at Western Norway University of Applied Sciences (WNUAS) to conclude a Bachelor of Science degree in General Mechanical Engineering. The project was issued by OSS, who provided supervision and input during the study and design process. The internal supervisor for the thesis was Associate Professor Arnstein Høyland.

During the writing of this thesis, we have received valuable guidance and assistance. We would therefore like to express our thanks to Associate Professor Arnstein Høyland for sharing his experience and knowledge. Thanks to our supervisors at OSS, Tonje Charlotte Stald and Nils Marius Sakserud for guiding us, introducing design ideas, and motivating us throughout the process. We would also like to express our gratitude to the rest of the OSS staff for providing help, interesting discussions, and thoughts on this project.

Abstract

A key part of the installation procedure of an OSS pump module is the seal-leakage test. To equalize the pressure of the pump process section with either the surroundings or the process piping, the reduction of pressure must be safe and controlled to keep the pressure level in the barrier-fluid circuit at the required level.

The suggested design for a standardized tool is based on a similar design for a different project. The principle of major loss in pipes provides the necessary pressure reduction to keep the rate of pressure drop within design limits.

The design is simple and can be modified to adapt to a range of design criteria. The method of calculation of pressure reduction can be automated using scripting, lowering the engineering costs to create a tool for a specific project.

The proposed design features a hot-stab, receptacle, ball-valve, pressure gauge and pressure equalization orifice in series. Evaluating the results gives a correlation between pressure drop, internal diameter and length of the pressure equalization orifice allowing for easy sizing given physical constraints.

An unsolved aspect of the design is cases where the target pressure is less than ambient pressure. A suggestion for further work to solve these cases is presented.

Sammendrag

En viktig del av installasjonsprosedyren til en OSS-pumpemodul er lekkasjetesten. For å stabilisere i pumpe prosess området med enten omgivelsene eller prosess rørledningen, må trykkreduksjonen være sikker og kontrollert for å holde trykk nivået i barriere-fluid systemet til det definerte nivået.

Det foreslåtte designet for et standardisert verktøy er basert på et likt design fra et annet prosjekt. Prinsippet for nedblødningshastigheten kommer fra friksjonstap i rør for å holde trykkendringsraten innenfor design kravene.

Designet er enkelt og kan tilpasses en rekke forskjellige designkriterier. Metoden for utregning kan automatiseres med scripting. Dette fører til reduserte kostander tilknyttet å lage et verktøy for et spesifikt prosjekt.

Designet er en seriekobling av hot-stab, receptacle, kuleventil, manometer og trykkutlignings-røret. Fra resultatene er det mulig å forme en sammenheng mellom trykkfall, innvendig diameter og rørlengde. Dette gjør det mulig å enkelt dimensjonere verktøyet med gitte design-krav.

Dokumentet utforsker også videre arbeid som ser på situasjoner hvor målet er å nå et trykk som er lavere enn omgivelsene.

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Nomenclature

Definitions

Parameter	Definition
BFIC	Barrier Fluid Internal Circuit
F. S	Fail Safe
HF SPV	High Flow Seal Protection Valve
ID	Inner Diameter
OD	Outer Diameter
OMM	Operation and maintenance manual
OSS	OSS
PEC	Pressure Equalization Circuit
PEO	Pressure Equalization Orifice
PET	Pressure Equalization Tool
PPS	Pump Process Section
SPV	Seal Protection Valve

Variables

*Units may vary depending on calculation. Table shows base unit.

Variable	Description	Unit	Variable	Description	Unit
$p_1(n)$	BFIC Pressure at current timestep	Pa	p_3	Ambient/Target pressure	Pa
$p_1(n+1)$	BFIC Pressure at next timestep	Pa	q_{PEO}	PEO Flowrate	m^3/s
$p_1(n-1)$	BFIC Pressure at previous timestep	Pa	q_{SPV}	SPV Flowrate	m^3/s
$\rho_1(n)$	BFIC Density at current timestep	kg/m^3	q_{HFSPV}	HF SPV Flowrate	m^3/s
$\rho_1(n+1)$	BFIC Density at next timestep	kg/m^3	kv	Kinematic viscosity	m^2/s
$K_1(n)$	BFIC Bulk-modulus	Pa	v	Velocity	m/s
m_1	BFIC Mass	kg	d	PEO piping internal diameter	m
$\dot{m}_1$	BFIC Mass flow rate	kg/s	l	PEO piping length	m
$p_2(n)$	PPS Pressure at current timestep	Pa	f	Friction factor	-
$p_2(n+1)$	PPS Pressure at next timestep	Pa	Re	Reynolds number	-
$p_2(n-1)$	PPS Pressure at previous timestep	Pa	ϵ	Roughness coefficient	m
$\rho_2(n)$	PPS Density at current timestep	kg/m^3	W_w	Weight in water	kg
$\rho_2(n+1)$	PPS Density at next timestep	kg/m^3	W_a	Actual weight	kg
$K_2(n)$	PPS Bulk-modulus	Pa	ρ_w	Density of sea water	kg/m^3
m_2	PPS Mass	kg	F_b	Buoyant force	N
$\dot{m}_2$	PPS Mass flowrate	kg/s	V	Volume of the model	mm^3
g	Acceleration due to gravity	m/s^2			

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1. Introduction

1.1 OneSubsea

OneSubsea (OSS) delivers integrated solutions, products and systems for the oil and gas market, and they have operations that cover the entire life cycle of the oil and gas fields worldwide. Today, they have more than 6,000 employees and operate in 23 different countries [1]. OSS has expertise in six different fields, Integrated Solutions, Production Systems, Process Systems, Control Systems, Swivel and Marine Systems, and Subsea Services [2]. Within Production Systems they offer solutions such as Subsea trees, manifolds, MARS systems, connection systems and wellheads. OSS's Process Systems delivers multiphase pumps, single-phase pumps, multiphase compressors, multiphase meters, and wet gas meters. In the field of control systems one can find products like multiphase pump controllers and multiphase flow controllers [3].

1.2 Background

1.2.1 Standardized pumping projects

OSS is transitioning to create standardized pump stations and pump modules for easier manufacturing and delivery of products for subsea use. For this project, the reference design parameters and criteria come from their proposed standard 10k project [4].

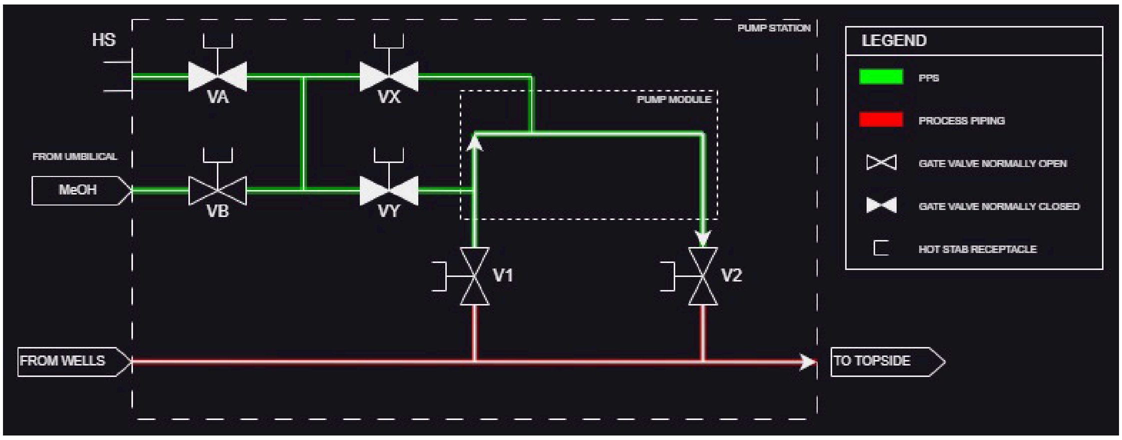


Figure 1: Simplified schematic of OSS Standard 10k pump schematic.

For a pumping project, the following modules and stations are deployed.

Pump station

The pump station is the base for the pump module. It includes instrumentation to monitor flow and condition of the process fluids through the process piping, as well as larger components such as coolers and flow mixers. The modular design of the pump station allows for efficient exchange and repair of pump modules [5, p. 8].

Multi-phase Pump

OSS uses Multiphase Pumps (MPP) in its subsea facilities to deliver oil and gas from reservoirs. The principle for the MPP is rotodynamic movement and helicoaxial or coaxial design of the shaft. The MPPs advantage is being able to transfer its mechanical energy to the fluid to keep fluids in several phases, such as liquid and gas, on the reservoir side at a low-pressure. This is important since there is both gas and liquid coming from a reservoir [6]. Heat transfer in the multiphase pump is carried out by the barrier fluid [5, p. 9], [6]. Heat transfer in the multiphase pump is carried out by the barrier fluid [5,

p. 9]. The barrier fluid also works as lubrication and contamination protection in the bearings and in the electric engine of the pump [5, p. 7].

1.2.2 Leak test and depressurization

After installation of the pump module onto the pump station, a leak test must be performed to test the seal in the connection between the pump module and the pump station. During this test, the internal process circuit of the pump module, also known as the Pump Process Section (PPS), is pressurized to a maximum of 1.1 x 10 000 psi, assumed to be 10 000 psi in this project as advised by OSS. After a completed test, the PPS must be depressurized to a pressure close to that of the process piping and this will be done through a Hot-Stab (HS) intervention point mounted on the pump module. The target pressure for this project is to have a pressure difference close to 0 psi.

A secondary system keeps seals in the pump module at constant overpressure to preserve them. This system is known as the Barrier Fluid Internal Circuit (BFIC). The valves regulating the flow of fluid out of the BFIC are known as the Seal Protection Valve (SPV), and High Flow Seal Protection Valve (HF SPV). To keep the pressure around the seals within a certain delta, the de-pressurization of the PPS must be done slowly and controlled. The flow capacity through the SPV and HF SPV determine the maximum drop in pressure per second the BFIC system can handle. The aim of this paper is to suggest a solution that can equalize the pressure in the PPS with the surroundings, in a slow and controlled manner.

Pressure equalization towards ambient pressure

When performing a leakage test the pump module will be isolated from the rest of the pump station, followed by being filled with methanol to the desired pressure. Figure 1 shows the isolated section in green. Methanol supplied through VB.

After a successful test, the pressure will be reduced to reach either the ambient pressure or the process pipeline pressure to secure a safe pressure difference before opening V1 and V2 to connect the PPS to the rest of the station.

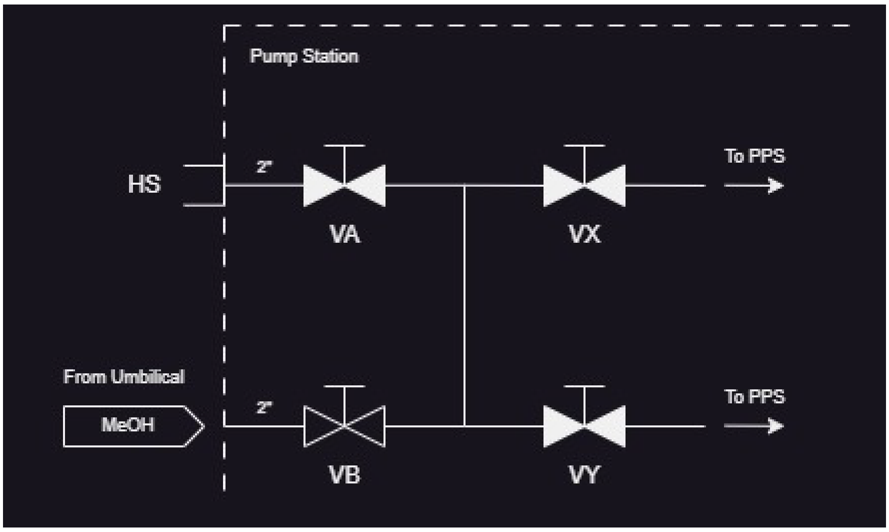


Figure 2: Simplified schematic of intervention valves.

The process of reducing or equalizing pressure occurs as follows. Refer to Figure 2. The valve VB is closed, stopping supply of methanol used in pressurization process. Attach a pressure equalization tool to intervention point HS. VA is then opened, and pressure is equalized to ambient- or process pressure.

1.3 Objective

The objective of this thesis is to design and create a standardized ROV-operable tool for subsea intervention. The tool should allow an operator to depressurize a pump module, while staying within a specified pressure delta between the pump process section and the barrier fluid internal circuit.

Sub-objectives:

- Evaluate subsea installations.
- Perform a concept study to find possible solutions.
- Calculate and specify design criteria.
- Create a concept design to fulfill design criteria.

2. Basis for design

2.1 Design method

The data for this design is highly quantitative. Calculations and data provide a concrete basis for the design. Although several of the formulas and models are theoretical, they have been formulated to ensure a conservative design.

To gather ideas and input on constraints and operational requirements, meetings with key OSS personnel have been conducted. This has ensured that the design is based on experience from other, similar projects.

OSS design process has been utilized for this design process. The design process is stagewise, with a 30% and a 60% design review. At these meetings, OSS personnel with relevant experience can provide insight and raise points for discussion. This raised new ideas and exposed flaws and factors that needed to be evaluated to create a better design.

2.2 Concept Study

Based on the objective, there are many ways to achieve it. This section evaluates potential solutions that could be suited to this task.

2.2.1 Throttle valve

The throttle valve primarily functions to regulate system pressure by operating at a lower level than the existing pressure within the system [7, p. 199]. It would potentially be possible to use one or more valves in a system to achieve a controlled pressure reduction.

A major issue with such a solution is that the greater throttling, the greater the speed of the fluid. At high speeds, the valve is no longer able to slow the fluid sufficiently. By Bernoulli's law, where energy is maintained between two points, the speed must increase if the pressure decreases [8]. In a throttle valve, the pressure drop will be greater in the area at the vena contracta, or throat, before it reaches slightly more pressure at the outlet when the tube expands again. If this pressure falls below the vapor pressure of the fluid, boiling and formation of steam bubbles will occur, also known as cavitation. The steam bubbles increase the volume of the fluid and slow down the speed as a result [9]. Then it will have no effect on the pressure difference between the points. In the case of gas, the throttling will work until it reaches the speed of sound of the fluid [10, pp. 1–3]. Shock waves occur that prevent further speed [9]. And the maximum mass flow rate is at the throat, which means that there will be no further change to the fluid in this region [11, pp. 678–679].

2.2.2 Labyrinth valve

The purpose of a labyrinth valve was to send the fluid through many different passages of reduced diameter. The fluid will then lose energy through collision with the walls and the various corridors [12]. These passages have been shown to have great pressure reducing capabilities as well as to regulate cavitation sufficiently [13, p. 1]. This valve can be seen as a mixture between the throttle valve concept and the actual pipe in the finished design. Production of this type of valve is likely expensive and complex to manufacture.

2.2.3 Tesla valve

The Tesla valve was invented by Nikola Tesla in 1920 [14]. It works by directing some of the flow of a fluid back to slow it down [15, p. 1] [16]. The main purpose of this valve is to prevent backflow, forcing the fluid to flow one direction as shown in Figure 3. In essence this is a self-regulating check-valve. For the purposes of the objective, since the valve will automatically slow itself down based on the flow of the fluid, it could be a simple way to slowly reduce pressure. The main difficulty with this design is calculation and analysis. This likely requires complex CFD analysis as there are no easy ways to calculate this type of flow. Regarding pressure reduction application, a tesla valve design would restrict the flow out of the pump module, resulting in a slow and steady drop in pressure.

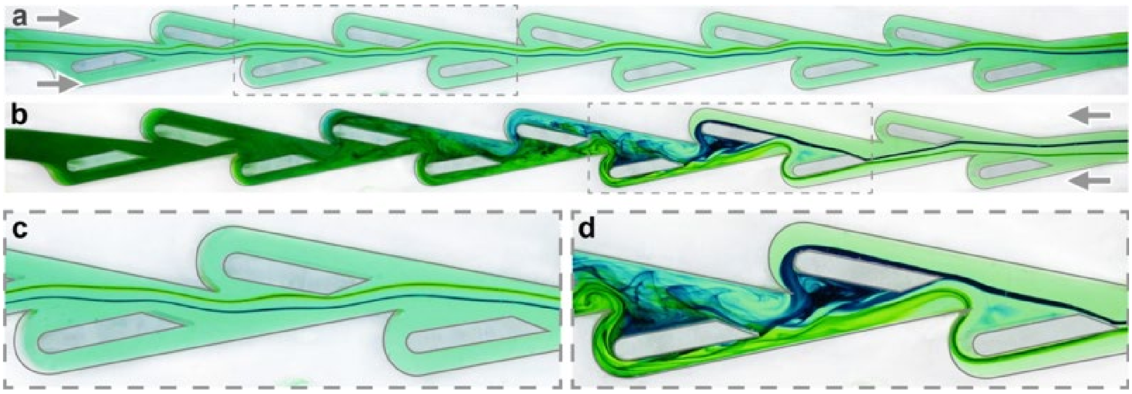


Figure 3: Flow characteristics of a fluid in a Tesla valve [17]. B and D show flow restriction.

2.2.4 The pre-pressurized tank

A surge tank is a pressure control device that is supposed to prevent pressure waves in systems that are exposed to sudden pressure changes [18, p. 1]. For the purposes of pressure reduction, the tank functions as an accumulator where the high pressure from the pumping station does not drop too quickly when opening the valve. This works by creating resistance in the flow that reduces pressure pulses [19]. The tank would then have to be used in combination with other valves.

An issue with this design is the number of extra components needed, valves for example. The tanks also take up a lot of space and must be emptied themselves after use. Extra valves also introduce extra operational steps, which is unwanted.

2.2.5 Frictional loss in pipes

In a long pipe, there will be losses due to friction around the pipe walls. The loss due to friction can be defined as major loss. In small diameter pipes these losses are quite large. At a given diameter the loss in pressure over the entire pipe is given by the length. This offers a high degree of flexibility to get the desired pressure drop.

A smaller factor for pressure drop is the pipe geometry. These are parts such as bends, fittings, connectors, or valves that add some type of resistance to flow. The effect of these parts is defined as minor losses. Although their contribution to the pressure drop is small compared to the major loss, with enough parts, they will play a part [20].

This solution has been evaluated by OSS for another project, though this was an integrated solution rather than a dedicated standardized tool [21].

Pressure equalization circuit concept

For the Anchor project, a pressure equalization circuit (PEC) was created to allow for equalization in a range of different cases. One of these, for the bleed-down procedure after leak-test, included a pressure equalization orifice (PEO). The PEC is an integrated circuit in the pump module and is specific to this project only. The PEO itself is detachable but is also designed for this specific project. The PEO is essentially a long pipe as evaluated in the previous section. This provides the slow bleed-down of the PPS [21].

2.2.6 Final concept

The final concept for this study is pipe pressure-drop from 2.2.5. The concept is simple, easy to calculate and has been well evaluated in the Anchor project. This provides a good basis for designing a standardized tool that can be adapted for any project.

Some of the concepts such as the tesla valve and labyrinth valve show promise but are very complex and difficult to evaluate. Both would likely require heavy CFD studies that would not be possible to achieve within our time-scope. Although CFD studies could be done for frictional losses as well, this is a lot simpler to do by hand and may not be necessary.

A system of throttling valves could work; however, this would likely require more operational steps to complete a bleed-down operation. Additionally, using throttling valves increases the likelihood of cavitation. Using valves in combination with a pre-pressurized tank could be done to alleviate some of these issues but adds complexity and size.

On this basis, the final concept will use the frictional losses in pipes to provide the desired pressure-drop.

Figure 4 shows a simple schematic of the tool. The components here are a hot-stab (HS) to connect to the intervention point, and the pressure equalization orifice (PEO) which provides the pressure-drop. The PEO is essentially one long pipe that is coiled in some manner. In the Anchor project the final length was around 60 m [22, p. 15]. The results for this project are expected to be similar.

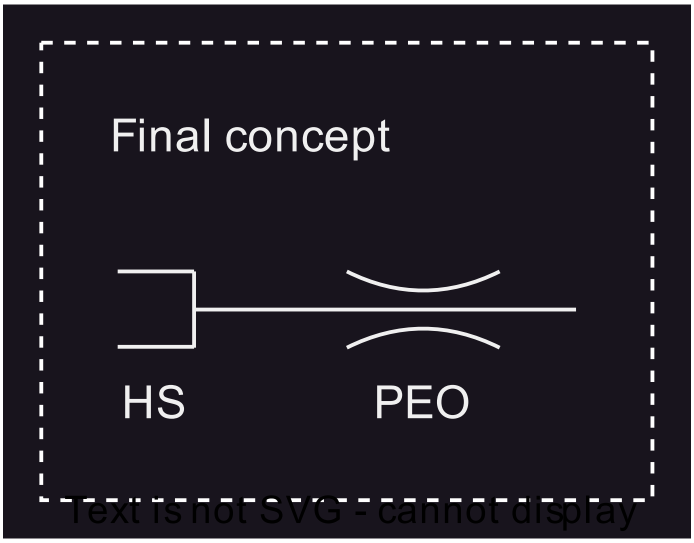


Figure 4: Pressure Equalization Tool.

2.3 Design criteria

2.3.1 Tool

The general requirements for the device are given in Table 1, while the operational design requirements are listed in Table 2. Many of the parameters here were defined in 30% and 60% review meetings, see Attachment G and Attachment H.

General

Parameter	Requirement
Design pressure	689.5 bara
Water depth	3048 m
Ambient temperature	4.4 °C
Ambient pressure	300 bara
Total weight, max	50 kg
Max pressure delta over seal, static (Barrier-Process)	160 bar
Max pressure delta over seal, static (Process-Barrier)	160 bar
PPS pressure, start / end	700 bara / 0 bara
PPS pressure delta, max	3.4 bara/s
PPS volume	2500 liters
BFIC volume	900 liters

Table 1: General design requirements

Operational design criteria

Parameter	Justification
Must easily be able to connect/disconnect from subsea intervention point	Ease of use.
Must be ROV operatable	Required to operate the tool subsea.
Should have few operational steps	To minimize complexity and difficulty during operation.
Should use hot stab for connection to intervention point	Industry standard, ROV operable and requires few steps to complete intervention
Must use a lockable hot stab.	To prevent a blowout due to high PPS pressure or accidental decoupling of hot stab.
Must have flexible pigtail/tubing between tool and pumping station.	Not possible to attach tool directly to intervention point using a stiff connection.

Table 2: Operational design requirements.

2.3.2 Components

Overview

A ROV panel with a pressure gauge and valve must be designed. The panel is necessary to provide shielding between the ROV and PEO. It also serves to support the components. The ROV panel must adhere to OSS standards for ROV access. The criteria are evaluated in OSS document [23].

Parameter	Value	Justification
Temperature	Constant at 4°C	Wholly submerged and open to surrounding seawater.
Material	Corrosion resistant Super Duplex	Will vary based on component. Standard.
Design pressure	700 bar	Maximum pressure the components must withstand.

Table 3: General component requirements

ROV and ROV panel

Parameter	Value	Justification
ROV intervention color code	ISO 13628-1 (RAL 2004 Orange).	For clear visibility of ROV operatable components.
Intervention point distance from grabber bars, horizontal max / min	500 mm / 1700 mm	The intervention points are operated directly by the ROV's manipulator. There must be a stabilization point that it can hold onto within reach.
Intervention point distance from grabber bars, vertical max.	500 mm	-
Distance between ROV access points, min.	300 mm center to center	Reduce risk of snagging adjacent access points. Not important for components that are not interacted with such as pressure gauges.
Distance from seabed to ROV access point, min.	2000 mm	ROV movement loosens debris from seabed if too close.
Intervention points must be free from obstruction.	-	ROV must be free to operate without getting the manipulator stuck or snagging exposed parts.
Tubes / cables located away from ROV manipulator.	-	Tubes, cables and/or other vulnerable parts must not be positioned close to the manipulators of the ROV. If this is not possible, the vulnerable parts must be protected with steel plates or the like
Must use appropriate ROV intervention handles.	-	D-handle for torque operation and Fishtail handle for push/pull operations.

Table 4: General requirements for ROV intervention point [23, p. 9].

A Remotely Operated Vehicle (ROV) is a subsea “robot” that allows an operator to perform operations on subsea installations. Figure 5 shows a Working Class ROV (WROV) and its manipulators. The manipulator that the ROV uses to hold on and stabilize itself is called a grabber arm. This manipulator is on the left-hand side, and it is important to place the grabber bar on the tool and the ROV panel correctly in relation to this. On the right side is the functional manipulator used to open the valve, attach the hot stab, and more. For torque operation a D-Handle is used and for push/pull operation a Fishtail-Handle is applied [23, pp. 5–7].

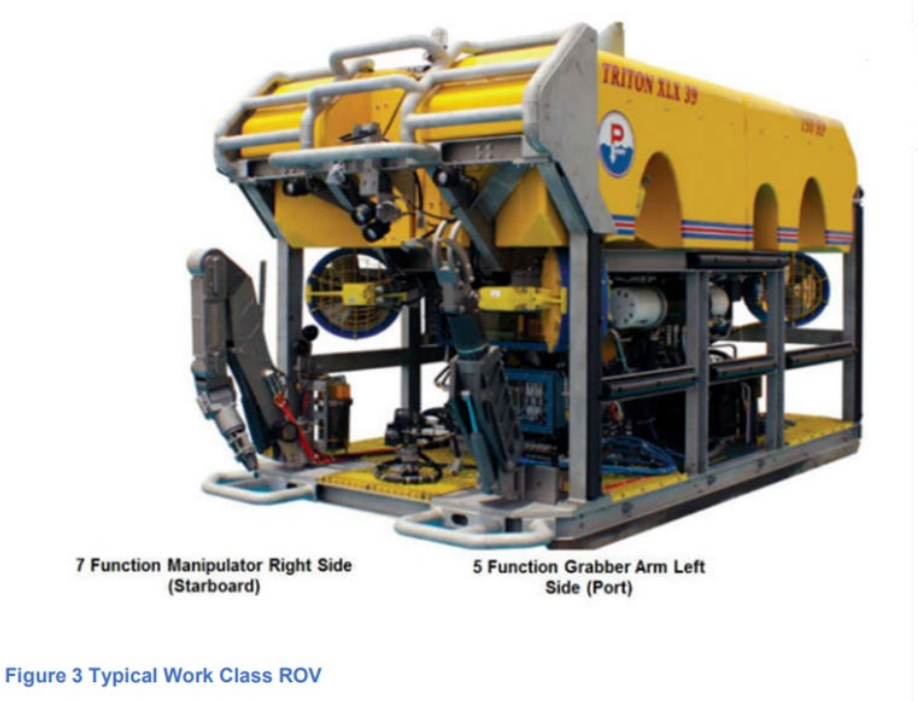


Figure 3 Typical Work Class ROV

Figure 5: WROV with manipulators, figure 3 in document [23, p. 7].

To safely manipulate the ROV interfaces such as valves, there are certain requirements to layout and dimensions of panels and equipment. Document OM-0562_B outlines the requirements. Factors that affect the space required are the height and width of the ROV, and elbow room for the manipulators [23, pp. 11–16]. The requirements relevant to this project are defined in Table 4.

Since the intervention is operated directly by the ROV’s manipulator, there must be a stabilization point that it can hold onto. This point is where the grabber bar will be placed.

The location of the intervention points plays an important role in relation to how much space or access the ROV must have for movement. Things that affect the space required are the height and width of the ROV, and elbow room for the manipulators [23, pp. 11–16].

ROV interventions must always be located at least 2000mm above the seabed to minimize disturbances caused by sand dust and the like on the seabed. The seabed is also muddy and will be an unstable location to land the ROV[23, p. 14] .

Valve

Parameter	Value	Justification
ID, max	6.35 mm / ¼ inch	Diameter of connecting tubing / piping with the pump module.
ROV bucket flange force requirements, damage / bending / axial	350 Nm / 1000 Nm / 2000 N	To ensure proper handling during operation.
Quick opening and closing of the valve.	-	This is to ensure minimal throttling of the fluid when opening. Ideally as close to instant as possible.
Must use a ROV handle	D-handle	Standard for torque operations.
Must be welded to the tool	-	Less chance of leakage compared to threaded fastening [24].
Valve position must be clearly legible	O = open and S = shut.	This is to give ROV operator good indication of what position the valve is in.

Table 5: Design requirements for valve [25] [23, pp. 18–19] [23, pp. 22–23].

It was clarified from the 60% design review meeting with engineers from OSS that the valve should be an open/close valve. That means fast opening and the least possible throttling. A ball valve is chosen here. The ball valve fulfills these requirements, rotating 90 degrees ensuring quick opening. The valve is also compatible with fluid in both gas and liquid state. A danger of opening or closing a valve is that tubes will be subjected to pressure pulses. This can cause harm to equipment [26, p. 7]. At the 60% review, pressure pulses were however, found to not be a problem.

The handle will be manually operated by a ROV. A D-handle will be utilized with an ROV bucket for this purpose. A welded connection between the valve and the rest of the piping is preferred. This provides a greater security against leakage over threaded fasteners [24]. This was confirmed by engineers at OSS as well.

The valve must be clearly marked with a reference point. O = open and S = shut. Intervention indicators must also be easy to read. For the placement of such indicators, one should consider that the ROV camera is placed at the top of the center on the front. Indicators should be placed to the left or above the interventions [23, pp. 18–19]. See Figure 6 below for a comparison between good and bad indicator marking.

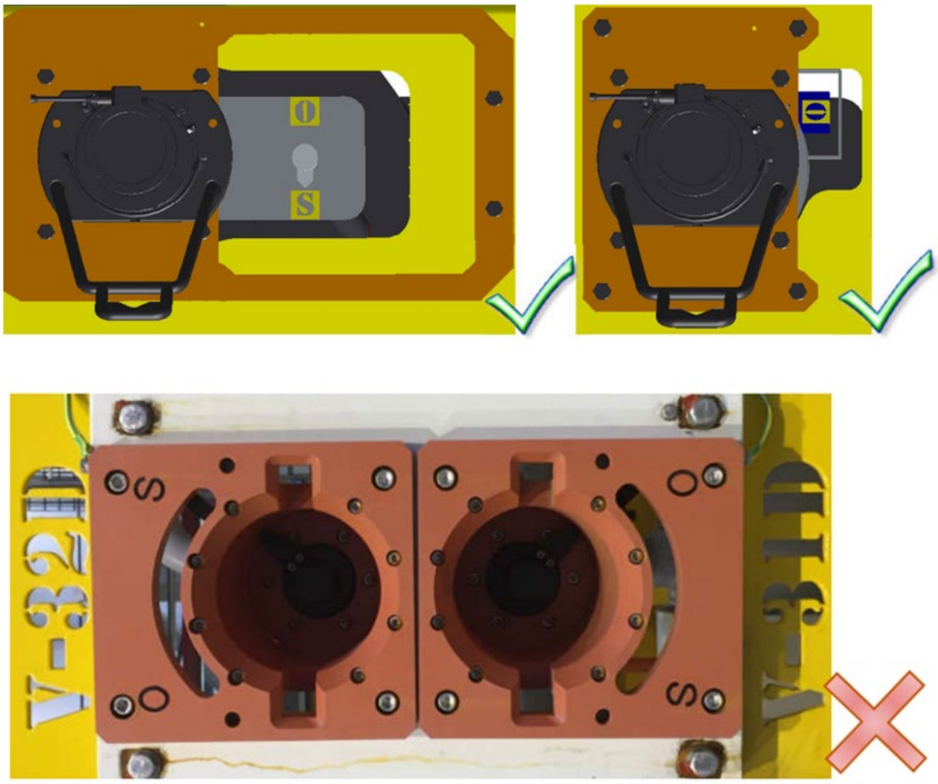


Figure 6: Examples of readable and unreadable valve indicators [23, p. 18].

It is important that cables and other equipment do not cover the intervention point. See Figure 7 as an example where a wire blocks access to intervention V22 in the bottom middle.

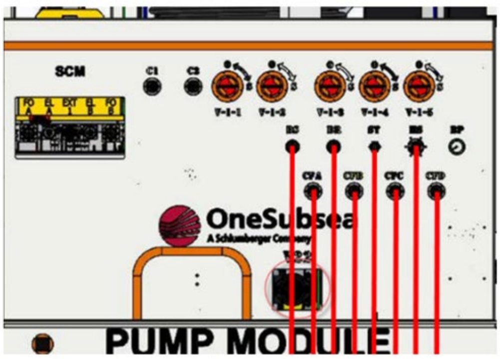


Figure 7: Blocked intervention, figure 30 in document [23, p. 22].

The valve in the ROV bucket must operate within ROV torque tools maximum torque. It is designed with a paddle handle so that the ROV torque manipulator can operate it. In other words, “D-Handle”. The inner diameter of the bucket must be a minimum of 150mm, but a smaller bucket may be considered later due to it being a bit large compared to the panel. See bucket and measurements below, only the image on the left is relevant here in Figure 8.

Figure 8: Picture to the left; ROV bucked with D-handle on panel [23, p. 23].

The paddle handle must have stoppers in the groove at 90-degree rotation. This is inserted so that it should not be possible to allow for overturning. The handle can also be used as a valve status indicator, O = open and S = shut, which is then clearly marked. Note that the direction must be clearly marked with an arrow.

Pressure gauge

Parameter	Value	Justification
Design pressure	700 bar	Maximum pressure the pressure gauge must be able to withstand.
Fluid temperature, internal / external	Assumed constant at 4°C	Wholly submerged and open to surrounding seawater.
Pressure gauge diameter	100 mm	To ensure that the ROV operator can easily interpret the measurements.
Connection to rest of piping	T-piece	Standard way of connecting the pressure gauge.
Should be filled with liquid, preferably glycerin	-	This is to dampen vibrations and shocks [27].
Material	Corrosion resistant	Necessary to ensure durability.

Table 6: Design requirements for the selection of pressure gauge [28].

A pressure gauge will be placed before the PEO so that the pressure and pressure drop during the bleed-down procedure can be monitored. This is important because the main aim of the device is to prevent a rapid pressure drop. The pressure gauge must be welded to the device in a T-piece, and it must be located before the ball valve. The actual pressure reading is done from the ROV panel. The pressure gauge must be of the analogue type as this does not depend on a battery to work. They are also good at resisting shock and vibration when the valve is opened quickly at high pressure [29]. The analogue pressure gauge is in the form of a Bourdon pressure gauge [28].

Grabber Bar

The design of the grabber bar which is best suited for the ROV's manipulator has been optimized by OSS presented in ISO 13628-8 and API 17H. It must withstand a minimum of 2.2kN in all directions. [23, p. 17].

Flexible pipe

Parameter	**Value**	**Justification**
Internal diameter, max	6.35 mm / ¼ inch	Given by the connected piping.
Must be compatible with subsea use.	ISO 13628-5 / API 17E	The pipe should meet the performance requirements of [30].
Must be flexible.	-	The tool cannot be attached to pump station by rigid connection.

Table 7: Design requirements for flexible pipe.

As part of the controlled pressure bleeding tool, there must be a flexible pipe that will connect the tool to the pump station.

Such flexible pipes often consist of a reinforcement for internal pressure in the pipe followed by a reinforcement for the tensile strength [31, p. 2]. More precisely, one can say that such a pipe consists of, from innermost to outermost [31, p. 2]:

- Inner flexible tube in stainless steel.
- Polymer barrier for the fluid.
- Protection tube against pressure in carbon steel.
- Anti wear tube.
- Protective tube for tensile strength.
- Outer polymer layer.

Hot stab and Receptacle

Parameter	Value
It should not be too heavy due to the wanted weight of de-pressurization tool to be maximum 50kg	The parts are ideally under 12kg. It is possible to find parts under this.
It must be in a material that is suitable for underwater use.	Mainly Super Duplex for corrosion resistance.
It must have a maximum ID of ¼", which is the same as the flexible pipe and the valve.	Maximum ID of ¼ inch.
It must be ensured that the hot stab does not detach from the receptacle.	J-lock locking mechanism.
It must withstand pressure above 700 bar.	Design pressure is 700 bar.
It must be pulled out and pushed in by the ROV.	The handle should then be in the form of a D-handle or a Fishtail handle.

Table 8: Hot stab and receptacle requirements.

To connect the pressure reduction device to the pump station, a connection in the form of a hot stab and then the associated receptacle is needed. These are subsea applications that are widely used. A hot stab is a hydraulic component whose purpose is to transport fluid from one point to another [32]. A distinction is made between "Live Hot Stab" and "Dummy Hot Stab". "Dummy Hot Stab" works as a plug, or a cork, which should be left in the receptacle without fluid being transported. In this device, a "Live Hot stab" will be used, which is used for transporting fluid [33].

To make the design and compatibility as good as possible, the de-pressurization tool will be equipped with the same hot stab and receptacle as the pump station. The design requirements are outlined in Table 8. It should follow the standard of API 17H. From API RP 17H it states that: ‘’API Recommended Practice 17H provides recommendations for development and design of remotely operated subsea tools and interfaces on subsea production systems to maximize the potential of standardizing equipment and design principles.’’ [34].

2.4 Formulas for sizing

2.4.1 Assumptions

Assumption	Applies to	Reasoning
$T = const$	$T_{ambient}$ T_{PEO}	Since the piping of the PEO is fully submerged and fully in contact with the seawater, we can assume that sufficient cooling is there such that $T_{PEO} = T_{ambient}$ at any given point.
$T = const$	T_{BFIC}	$T_{BFIC} = T_{ambient}$ due to submersion.
Smooth pipe	q_{PEO}	Conservative design. Any additional frictional losses due to pipe roughness provide a safety factor for calculations. Changing friction factor model would account for roughness.
Straight pipe	q_{PEO}	Conservative design. Additional frictional losses due to pipe geometry (Minor losses), provides a safety factor for calculations.
Interpolation in transition region	q_{PEO}	General models for the transition region do not exist.
100% Seawater	PPS	The mixture of the fluid in the PPS will be a combination of seawater and methanol. 100% seawater has been assumed for this model.
100% Oil	BFIC	The fluid in the BFIC is assumed to be 100% Castrol Brayco Micronic SPF-E oil.
$V_{sea} \gg V_{PPS}$	PPS	Sea-pressure assumed to be unaffected by the fluid from PPS.
$q_{PEO}(n) = const$	q_{PEO}	Constant flowrate through the PEO at each timestep.

Table 9: Assumptions for calculation.

2.4.2 Friction factor

The friction factor for a pipe is usually estimated using a moody diagram. For our purpose of iterative calculation, the friction factor can be modelled using an equation. The equation to be used varies based on the Reynolds number.

Figure 9 shows Moody diagram for friction factor at different values of Relative Roughness. Higher values of relative roughness give a flatter curve. The region of no data is the transition region $2300 < Re < 4000$. The region has a lot of variation based on the fluid properties and other factors. There is also high variability under the same conditions. This makes the friction factor difficult to predict. For the purposes of the design, linear interpolation is used to approximate the friction factor in this region.

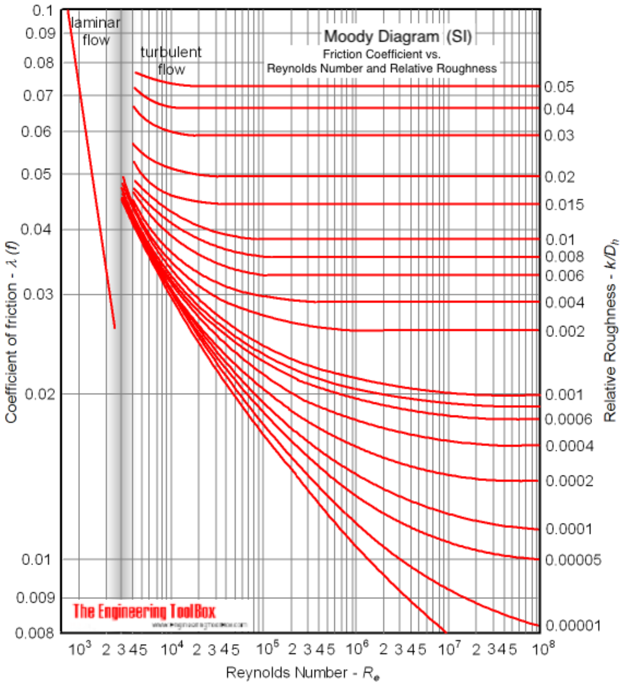


Figure 9: Moody friction factor diagram [35].

Model	**Formula**	**Region**
Laminar [36, p. 18]	**Eq. 1** $f_{la} = \frac{64}{Re}$	$Re \leq 2300$
Blasius [36, p. 18]	**Eq. 2** $f_{bl} = \frac{0.316}{Re^{0.25}}$	$Re \geq 4000$
Interpolation	**Eq. 3** $f_{tr} = f_{la}(Re) + \frac{(f_{bl}(Re) - f_{la}(Re)) \cdot (Re - 2300)}{4000 - 2300}$	$2300 < Re < 4000$

Table 10: Formulas for the friction factor for different Reynolds numbers.

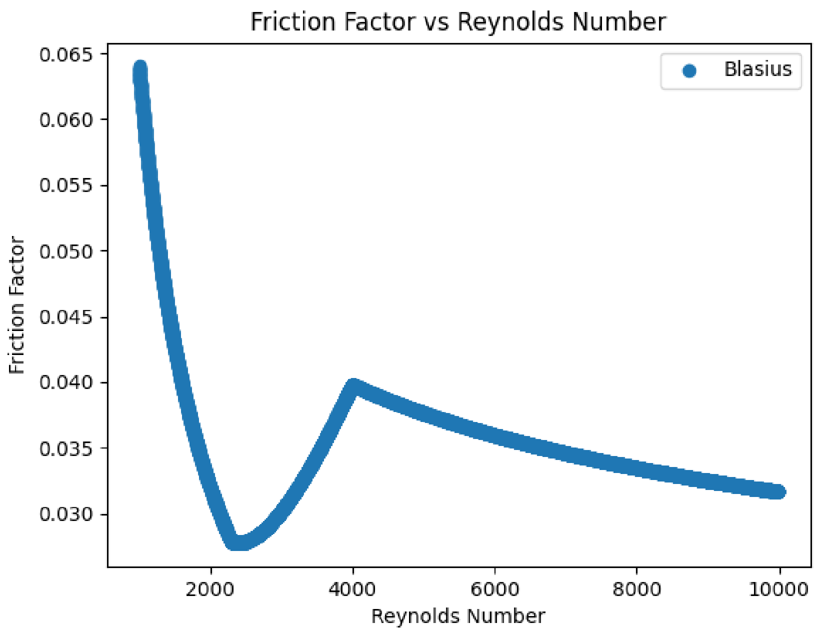


Figure 10: Final friction factor model for $10^3 < Re < 10^4$. Blasius + Interpolation.

Turbulent friction factor model

Model	**Formula**	$f_{max}(10^6)$	$f_{min}(4 \cdot 10^3)$
Blasius	**Eq. 4** $f = \frac{0.3164}{Re^{0.25}}$	0.0397	0.0099
Haaland	**Eq. 5** $f = \left(\frac{1}{-1.8\, log\left[\left(\frac{\epsilon}{3.7d}\right)^{1.11} + \frac{6.9}{Re}\right]}\right)$	0.0405	0.0137
Swamee-Jain	**Eq. 6** $f = \frac{0.25}{\left(log\left[\frac{\epsilon}{3.7d} + \frac{5.74}{Re^{0.9}}\right]\right)^2}$	0.0407	0.0139
Colebrook	**Eq. 7** $\frac{1}{\sqrt{f}} = -2\, log\left[\frac{2.51}{Re \cdot f^{0.5}} + \frac{\epsilon}{3.7d}\right]$	0.0400	0.0138

Table 11: Common friction factor models for turbulent flow.

In Table 11, $\epsilon = 0.001 \cdot 10^{-3}\ [m]$ and $d = 0.008\ [m]$.

Since the velocity is given by Eq. 18, increasing the friction factor reduces the velocity. Thus, a lower friction factor from the Blasius correlation ensures a conservative design. Figure 11 shows how the models in Table 11 vary for different Reynolds numbers.

At lower Reynolds numbers, the greatest difference between the values is 2.52%, which is acceptable. At higher Reynolds numbers the greatest difference between the values is 40%. To get an accurate value for the friction factor, taking material properties into account, Haaland, Swamee-Jain or Colebrook should be used.

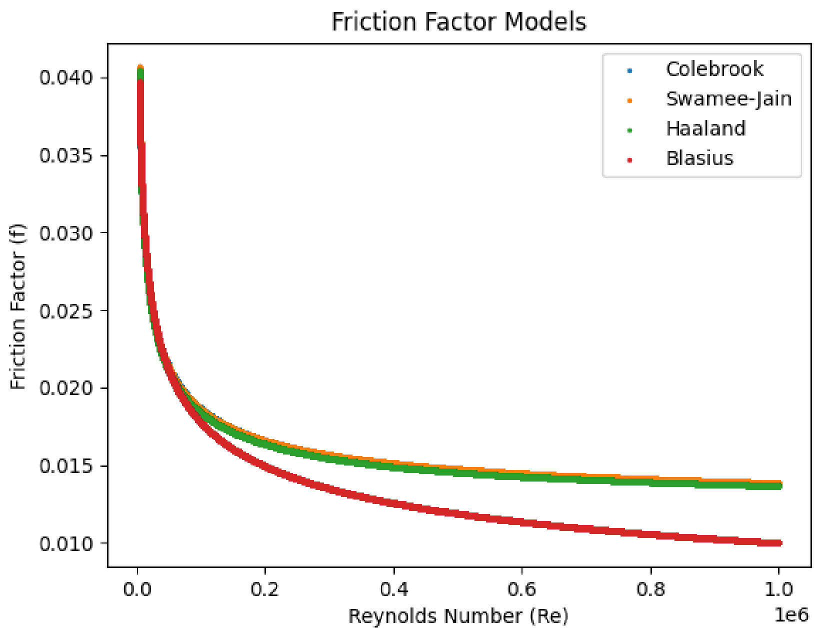


Figure 11: Friction factor models for $4 \cdot 10^3 < Re < 10^6$.

2.4.3 Pressure values

The values for the pressure of both the PPS and BFIC are calculated for each timestep using the following methods. A new density can be calculated by knowing the new mass based on how much mass is flowing out of the volume.

The bulk modulus defines how easily a volume of fluid can be changed when changing the pressure. Knowing the new density, the bulk modulus can be calculated. Eq. 9 defines the bulk modulus based on change in pressure and change in density [37].

The new pressure can now be calculated by rearranging the equation to solve for pressure at the next timestep. The derivation of Eq. 8 is outlined in Attachment F. The method was developed for a different OSS project [22].

Common formulas

$$\textbf{Eq. 8} \quad p_x(n+1) = p_x(n) - K_x(n) \cdot \left(1 - \frac{\rho_x(n+1)}{\rho_x(n)}\right) \; [Pa]$$

$$\textbf{Eq. 9} \quad K_x(n) = \frac{\big(p_x(n) - p_x(n-1)\big) \cdot \rho_x(n)}{\rho_x(n+1) - \rho_x(n)} \; [Pa]$$

$$\textbf{Eq. 10} \quad \rho_x(n+1) = \frac{m_x(n) + \dot{m}_x(n)}{V_x} \; \left[\frac{kg}{m^3}\right]$$

$x = 1$ for BFIC, $x = 2$ for PPS.

Mass transfer

$$\textbf{Eq. 11} \quad \dot{m}_1(n) = -\left(q_{SPV}(n) + q_{HFSPV}(n)\right) \cdot \rho_1(n) \; \left[\frac{kg}{s}\right]$$

$$\textbf{Eq. 12} \quad \dot{m}_2(n) = \dot{m}_1(n) - q_{PEO} \cdot \rho_2(n) \; \left[\frac{kg}{s}\right]$$

Method for calculation

1) Estimate mass transfer using Eq. 11 or Eq. 12
2) Calculate initial density for next timestep using Eq. 10
3) Calculate bulk modulus of elasticity for current timestep using Eq. 9
4) Calculate pressure for next timestep using Eq. 8
5) Determine density for current timestep using Eq. 21

2.4.4 Flowrate

The following definitions for the pressure drop will be used.

$$\textbf{Eq. 13} \quad \Delta p_{1,2} = p_1 - p_2$$

$$\textbf{Eq. 14} \quad \Delta p_{2,3} = p_2 - p_3$$

SPV

The test data forming the basis for Eq. 15 is provided in Attachment A and gathered from OSS [38, p. 11].

$$\textbf{Eq. 15} \quad q_{SPV} = \frac{(\Delta p_{1,2} - 61.32)}{0.611} \cdot \left(\frac{0.001}{60}\right) \; \left[\frac{m^3}{s}\right]$$

$\Delta p_{1,2}$ $[bar]$

The domain of the function is $\Delta p_{1,2} > 61.32$ as a negative flowrate is not possible. This means the setpoint for the SPV should be 61.32 bar. The maximum flowrate through the SPV has been set at a pressure drop of 75 bar [22] [38].

HFSPV

The test data forming the basis for Eq. 16 is provided in Attachment A and gathered from OSS [39, p. 18].

$$\textbf{Eq. 16} \quad q_{HFSPV} = \left(\frac{\Delta p_{1,2}}{68.246}\right)^{\frac{625}{19}} \cdot \left(\frac{0.001}{60}\right) \; \left[\frac{m^3}{s}\right]$$

$\Delta p_{1,2}$ $[bar]$

The setpoint of the HFSPV is 70 bar. The maximum flowrate through the HF SPV has been set at a pressure drop of 77 bar [22] [39].

SPV / HF SPV accuracy

From Attachment A the model created for the flow of the SPV is not very accurate. A linear model does not fit the data very well, as shown by $R^2 = 0.7849$. Using data from multiple SPV's would allow for a better model. For the purposes of the project however, the model is acceptable. As the flowrate of the SPV only affects the pressure-drop over time, for the criterion of a max delta of 50 $\left[\frac{psi}{s}\right]$ the model makes little difference.

The HF SPV model is very accurate, with $R^2 = 0.9841$.

PEO

For each timestep, the velocity is calculated iteratively until the delta between the last calculated velocity and the new velocity is in an acceptable range. The basis for this calculation is the principle of major head loss. The derivation of the formula is shown in Attachment C. The iterative process is there as the initial velocity after opening the valve to the PEO is unknown. The process works because the value of the friction factor is the only factor that changes for each calculation, meaning that after $x \rightarrow \infty$ number of runs, the difference between the last calculated velocity and the new velocity will be 0, yielding the correct velocity for the current conditions.

Eq. 17 $$Re = \frac{v \cdot d}{kv}$$

Eq. 18 $$v = \sqrt{2\frac{d \cdot \Delta p_{2,3}}{l \cdot f \cdot \rho_2}} \left[\frac{m}{s}\right]$$

$\Delta p_{2,3}$ $[Pa]$

Eq. 19 $$q_{PEO} = v \cdot \frac{\pi}{4} \cdot d^2 \left[\frac{m^3}{s}\right]$$

Steps for calculation of velocity and flowrate:

1. Guess the initial velocity.
2. Calculate Reynolds number using Eq. 17.
3. Calculate Friction coefficient based on Reynolds number using Eq. 1, Eq. 2 or Eq. 3.
4. Calculate a new velocity based on the friction factor using Eq. 18.
5. Repeat steps 1-4 until the new velocity is equal to the last velocity.
6. Calculate the flowrate based on Eq. 19.

Because the flowrate through the PEO is based on the pressure differential between PPS and ambient, the largest drop in pressure will be in the first timestep after opening. The velocity is on both sides of the equation and therefore depends only on $\Delta p_{2,3}$ since d, l and ρ_2 are constant. $\Delta p_{2,3}$ is largest in the first timestep and is gradually smaller.

2.4.5 Fluid density

Castrol SBF E

The density of the BFIC oil is calculated using the following relation based on (P, T) values. The data for the formula is gathered from OSS [40] and presented in Attachment D.

$$\textbf{Eq. 20} \quad \rho_1 = 0.0497 \cdot p_1 + 807.03 \left[\frac{kg}{m^3}\right]$$

p_1 $[bar]$

Seawater

The density of the seawater in the PPS is calculated using the following relation based on data from Safarov et al [41, p. 240]. The correlation is presented in Attachment E.

$$\textbf{Eq. 21} \quad \rho_2 = -0.0007p_2^2 + 0.5028p_2 + 1027.8 \left[\frac{kg}{m^3}\right]$$

p_2 $[MPa]$

2.4.6 Hoop stress

Knowing the internal diameter and the thickness of the pipe, the stress acting perpendicular to the cylinder walls can be evaluated through Eq. 22 [42].

$$\textbf{Eq. 22} \quad \sigma_h = \frac{pd}{2t} \ [MPa]$$

2.4.7 Pipe sizing and script

To iteratively calculate the reduction in pressure for every timestep for a range of different PEO-lengths and ID's, a Python script was created. The script is shown in Attachment K. The script calculates the pressure drop for every timestep and runs until either the optimization conditions are hit, or the pressure falls to the set value.

A sizing tool was already available for use from a previous OSS project [22]. This tool has been utilized for control to compare results from the script. The tool is based on the same method as outlined in this project.

The goal of creating a script is to efficiently calculate the required dimensions of the PEO, regardless of the initial conditions. Using the script, one can set the initial conditions, and target values such as time, maximum pressure delta, target pressure etc. Then running it will give values that can be used to calculate the ideal combination of length and internal diameter of the PEO.

Using OSS' tool for this would require manual calculation of a range of different diameters and lengths to find the ideal combination.

3. Pressure Equalization Tool

Figure 12 shows the schematic for the suggested PET. HS – Hot-Stab, V1 – Ball valve, PG – Pressure Gauge, PEO – Pressure Equalization Orifice. The inlet is HS and is connected via the flexible tubing to the pump module intervention point. The outlet is after the PEO and is open to the ocean.

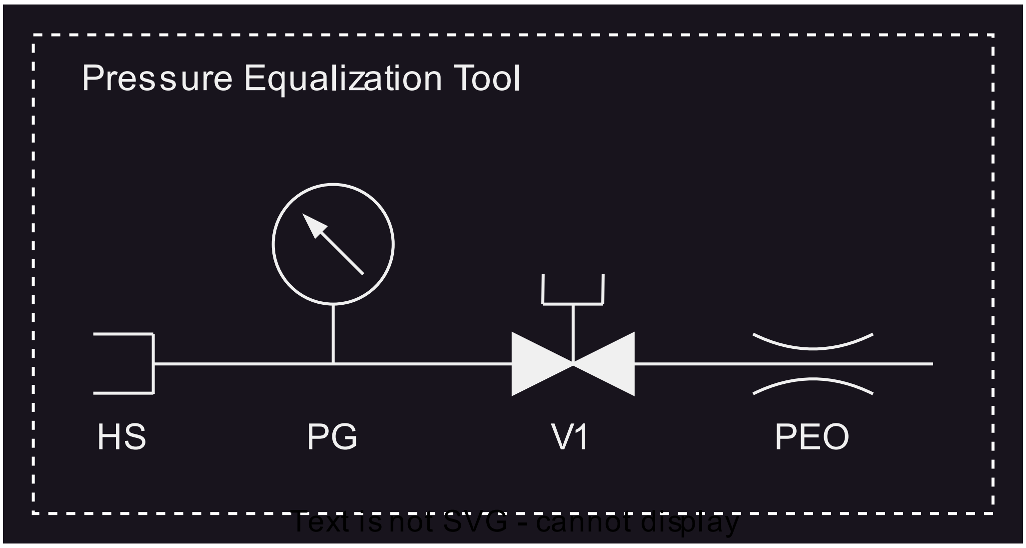


Figure 12: Pressure Equalization Tool.

3.1 PEO Sizing

The values given in Table 12 are used to calculate the PEO sizing tool.

Parameter	Value
$p_1(0)$	700 [bara] / 10152.6 [psia]
$\rho_1(0)$	839.8 [kg/m^3]
$K_1(0)$	1.9 [GPa]
V_1	0.9 [m^3]
$p_2(0)$	690 [bara] / 10007.6 [psia]
$\rho_2(0)$	1057.7 [kg/m^3]
$K_2(0)$	2.22 [GPa]
V_2	2.5 [m^3]
p_3	0 [bara]
SP_{SPV}	61.32 [bar]
SP_{HFSPV}	70 [bar]

Table 12: Input values for PEO sizing tool.

Using OSS' sizing tool yields the data in Attachment B for different values of ID and length of the PEO. The lengths have been chosen to come as close to 50 psia pressure delta in the first timestep as possible. The assumption being that the fall in pressure is the greatest in the first timestep, as explained in 2.4.4.

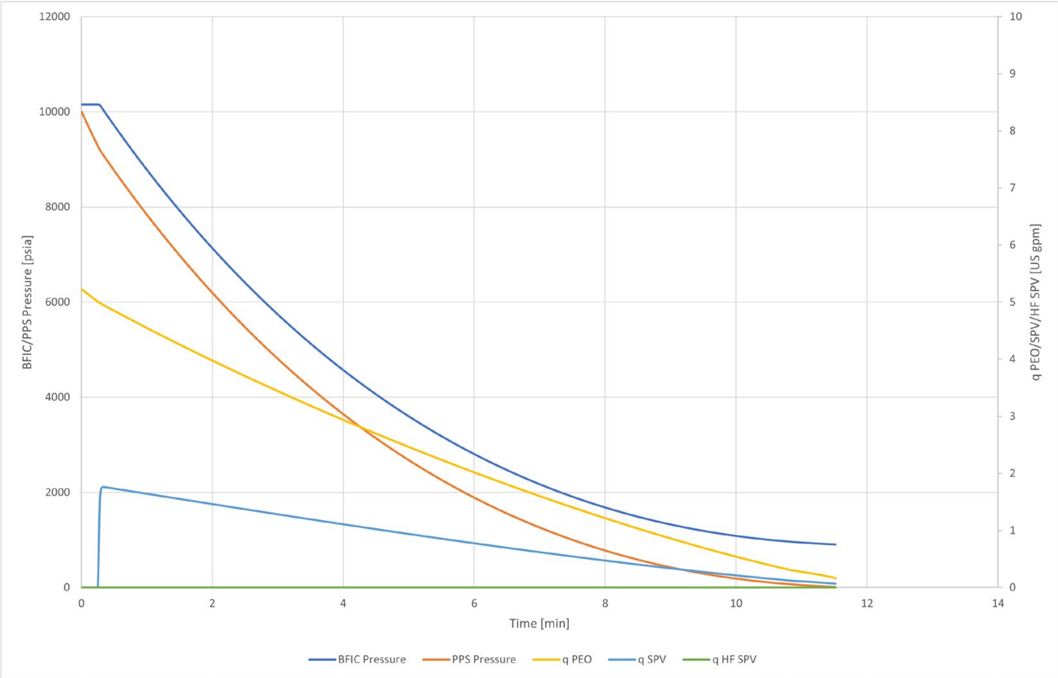


Figure 13: Bleed-down procedure at d=4mm, l=40m.

Figure 13 shows one calculation of the bleed-down procedure using initial conditions in Table 12 and internal diameter of 4 mm and length of 40 m. Keeping within the 50 psi/s limit shows the HF SPV never activates. This is good as there is some extra safety in it being able to activate.

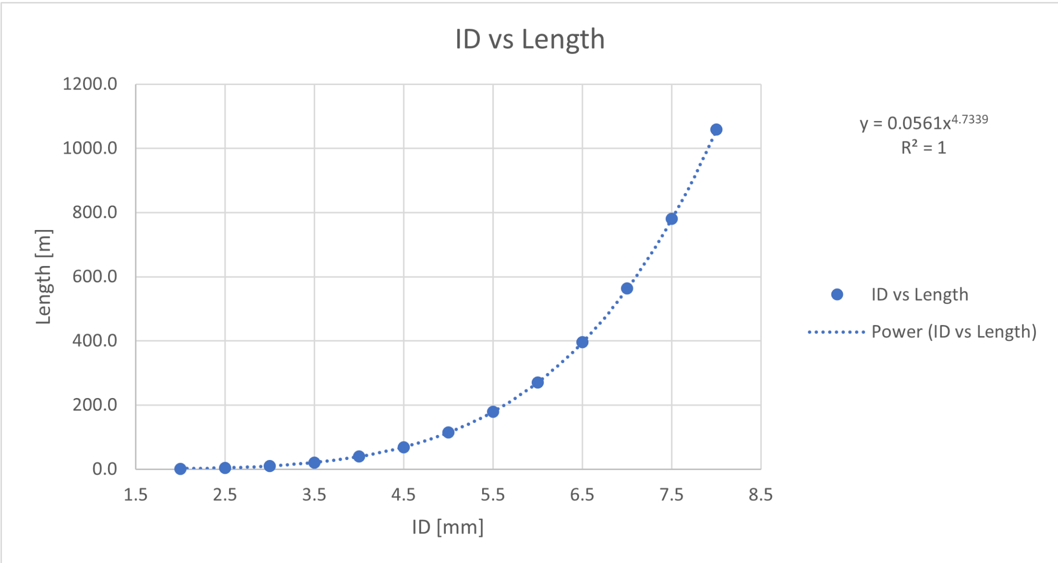


Figure 14: Correlation between ID and Length at $p_1 = 700$, $p_2 = 690$ initial conditions.

Figure 14 shows the plot of the data from Attachment B. Modelling the relationship between ID and Length to achieve $\Delta p_{2,max} = 50\ [psia]$ at initial conditions in Table 12 yields Eq. 23.

$$\textbf{Eq. 23}\quad l = 0.0561 \cdot d^{4.7339}$$

Looking at the model created in Figure 14, we see that the lower the diameter of the pipe is, the shorter the length of the pipe needs to be in order to achieve 50 psi/s. Already at a size of 4.5 mm, the pipe begins to approach 100 m of length to get the same result. Manufacture of the pipe itself might be easier but at the cost of a larger tool, added weight and material costs. Since the length of the pipe required increases exponentially, it is impractical to use any diameter larger than 4.5 mm.

The suggested maximum diameter of the pipe is therefore approximately 4 mm. This equates to a length of ~40 m. Comparing this to the results from the Anchor project, this is almost 20 m shorter pipe and at a higher ID. Anchors suggested pressure change per second was lower at approximately 30 psi/s which explains the higher diameter pipe and shorter length [22].

When designing the layout of the piping and fitting components in the tool, the calculated length/diameter of the pipe are suggested minimum/maximum. Keeping the length but lowering the diameter keeps it within spec. Keeping the diameter but extending the length does the same. This gives a certain amount of leeway when creating the tool.

One suggestion when designing the tool is to keep the diameter the same but extend the length. The length has smaller impact on the pressure change than the diameter. So, a small change in diameter has a large impact on length.

3.1.1 Final dimensions

The final selected size of the PEO is $d = 3.75\ [mm]$ and $l \approx 30\ [m]$. This is the maximum internal diameter and minimum length that the PEO can have to achieve the pressure delta.

Evaluating the hoop stress at an internal pressure of 700 bar yields stress of 525 MPa. For Super Duplex, UNS-S32760-F55, the yield strength is 620 MPa [43]. The pipe is therefore within spec. A factor that will aid the pipe to resist the stress due to the internal pressure is the ambient pressure. [43].

3.1.2 Script

PEO sizing data was solely gathered from OSS' sizing tool. The new script to replace it never yielded usable results. The main hypothesis is improper use of units for calculation. Another factor may have been improper implementation of the method. Consultation with OSS' staff yielded no discernible errors in the script, though this is no guarantee. It should be possible to create a working script using this reports method.

3.2 Pressure equalization tool

The final concept has its basis in the same principle as the tool created for a different OSS project. In terms of components, the tool is simple, consisting of 4 main parts.

In this design, the tool is connected to the pump module via the hot stab (HS). As per design requirements, a flexible tube connects between HS and the intervention point on the pump-module. V1 (Figure 12) is closed during the connection procedure to ensure secure connection and locking of the hot stab before opening V20 (Figure 1) on the pump-module.

Opening V1 allows the pressure to equalize by itself. Using the pressure gauge, the ROV operator can monitor the pressure in the PPS. Using V1, the ROV operator can stop the pressure equalization process when PPS pressure reaches a desired level.

3.2.1 Tool design

The design of the tool comes from the principle of a suitcase. The idea being that it is picked up and transported subsea, then you place it/hang it up subsea. The rectangular form allows for ample space to fit the tubing.

Other shapes could be possible to experiment with, however, this would likely add structural complexity. Using the rectangle as a basis also allows for easier routing and fitting of other components. For further work it may be beneficial to evaluate other form-factors for the tool.

Other forms of coiling could also be implemented; however, this would constitute a redesign of the structure. A circular coil was considered but a circular coil takes up more physical space than the current design.

With the current design, the size of the tool ends up being easily manageable during transport and operation. A requirement for safe storing and lifting of the tool is being able to land flat. The design works well in this regard, having a flat plane to land on.

3.2.2 Component selection

Hot stab

Parameter (hot stab)	**Value**
Standard.	ISO 13628 – 8 / API 17H type A.
Weight.	6 kg in air and 5 kg in water.
Test pressure.	1034 bar.
Pressure rating.	690 bar.
Handle.	D-handle, mechanically operated by ROV.
Number of ports.	1 port hot stab.
Safety measures.	J-Lock locking mechanism.
Material on the exterior.	Super Duplex.

Table 13: Hot stab parameters [44].

The choice will be a standard hot stab and receptacle that OSS uses. It is a standard ISO 13628-8 / API 17H type A. The hot stab is mechanically operated by the ROV using the D-handle. A J-Lock locking mechanism ensures that it does not come loose from the receptacle and at the same time gives a clear indication that it is attached correctly. These are the two horizontal protrusions on Figure 15. Most of the exterior is made of Super Duplex, apart from parts such as screws.

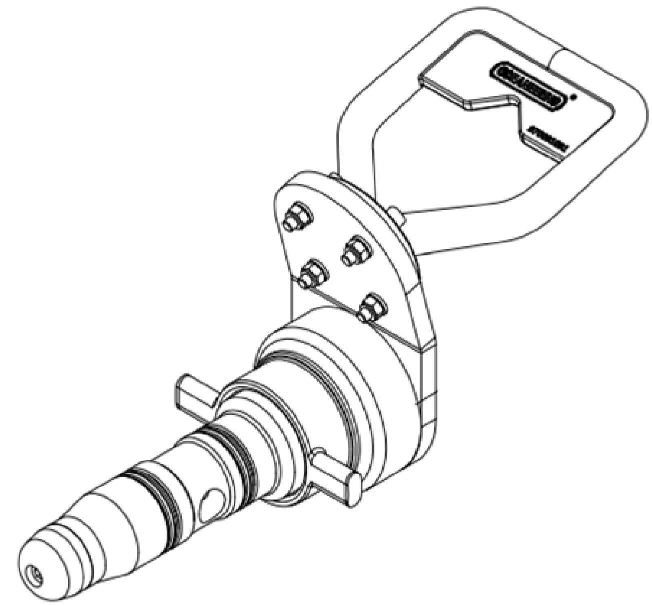


Figure 15: API 17H Type A Hot Stab. Hot Stab schematic [44].

Hot stab receptacle

Parameter (receptacle)	Value
Standard.	ISO 13628 – 8 / API 17H type A.
Weight.	11kg in air and 10kg in water.
Safety measures.	J-Lock fastening connection.
Material.	Super Duplex.

Table 14: Hot stab receptacle parameters [45].

The hot stab and receptacle are delivered as a pair. Figure 16 shows the receptacle.

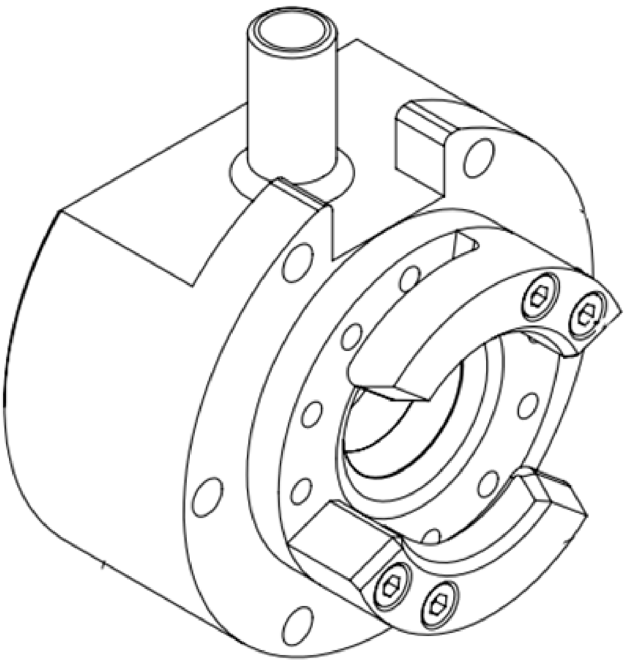


Figure 16: Receptacle with “J-lock”, from document [45]

Valve

Parameter	Value
Type of valve.	ROV operated ball valve with paddle handle form MRC Global.
Type of opening.	Open/close operation. 90° twist to fully open/close.
Weight.	8.5 kg
ID.	¼ inch
Damage torque.	160 Nm.
Operational torque.	100 Nm.
Test torque.	50 Nm.
ROV bucket flange maximum damage torque.	400 Nm.

Table 15: ROV operated ball valve parameters [46, p. 3].

The choice here is an ROV operated ball valve with paddle handle from MRC Global. This is a standard ball valve that OSS uses and a valve that meets the design criteria for this device. Parameters and values are taken from the document [46, p. 3]. Drawings of the valve with the ROV bucket are presented in [46, p. 3]. See Figure 17 and Figure 18 for reference.

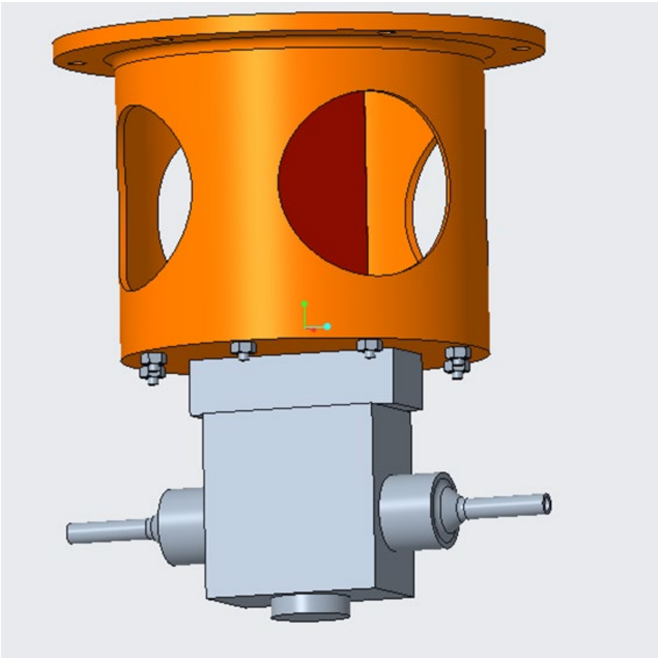


Figure 17: Ball valve with ROV bucket.

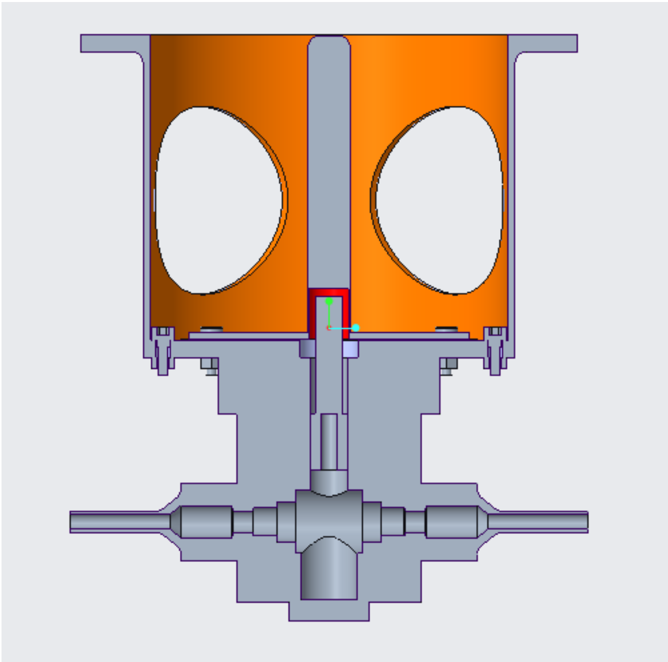


Figure 18: Section view of ball valve.

Pressure gauge

Parameter	Value
Reinforcement	Autoclave attachment
Accuracy.	Standard +/- 1.0% F.S. (up to 1600 bar).
Measuring ranges.	0-0.6 to 0-4000 bar.
Housing material.	Glass fiber reinforced polyester (GRP), black. Glass fiber content 25%. Oxygen index 34%.
Parts in contact with media.	AISI 316 up to 1600 bar for measuring element and AISI 316 for connection.
Gauge material.	AISI 304.
Display material.	Aluminum, black.
Dial material.	Aluminum, white with black writing.
Glass.	Non-reflective.
Overpressure load.	130% of F.S.
Degree of protection.	IP 68.
Liquid filling.	Glycerin.
Temperature resistance.	-20ºC to +70ºC ambient temperature. +100ºC maximum process temperature.
Weight.	1.1 kg.

Table 16: Technical specification for chosen gauge [47].

This pressure gauge is designed for subsea use. It measures relative pressure to ambient depth with automatic depth compensation. The glass is non-reflective for underwater reading. It is very well suited for salty and corrosive environments, and it is reinforced with an Autoclave attachment. Figure 19 shows a drawing of the pressure gauge with dimensions.

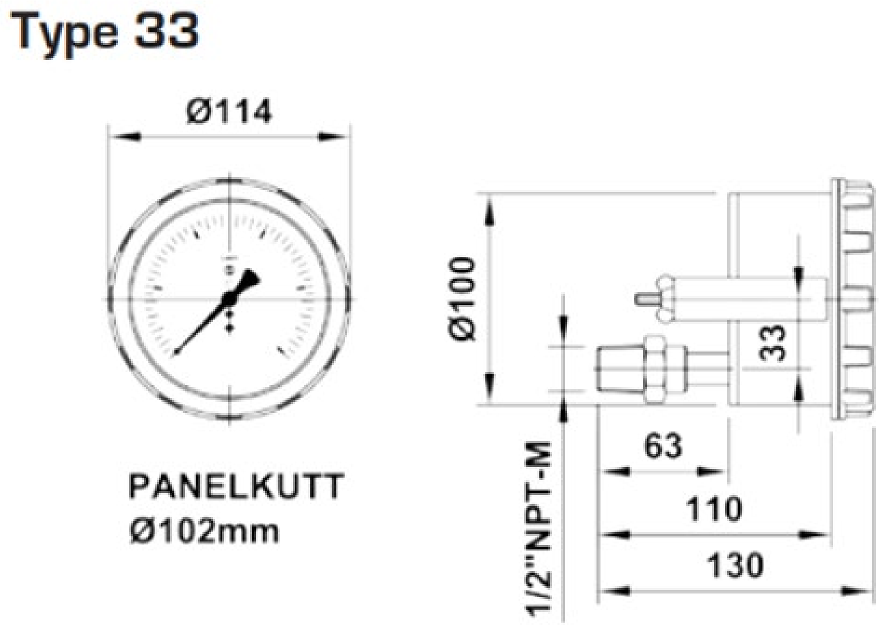


Figure 19: Type 33 pressure gauge [47].

Grabber bar

Parameter	Value
Diameter (solid).	20 mm solid bar.
Height.	300 mm.
Length.	250 mm.

Table 17: Design parameters for grabber bar from [23, p. 17].

OSS Processing has standardized Grabber Bars based on a 20mm diameter solid bar. The height of the handle is 300mm and the distance from the wall is 250mm. The distance is from the wall to the outermost part of the handle.

Flexible pipe

Parameter	Value
Performance requirements.	ISO 13628-5 / API 17E
ID.	¼ inch
OD.	0.520 inch
Maximum working pressure.	862 bar.
Damage pressure.	3447 bar.
Maximum bending radius.	5.9 inch
Specific weight.	0.31 kg/m.
Temperature range for operation.	-40ºC to 100ºC but note that the maximum temperature for water and methanol-based fluid is 70ºC.
Reinforcement.	Reinforcement against pressure is a high-strength wire in AISI 316/316Ti.

Table 18: Technical specifications for flexible pipes from [48].

3.2.3 Piping

Layout

For this design, using friction through a long pipe as the primary method for pressure loss, presents a challenge towards the pipe routing. Especially when it should fit inside a frame that is 0,7x 0.5x0.5 m and other components such as the valve and receptacle occupying space inside the tool.

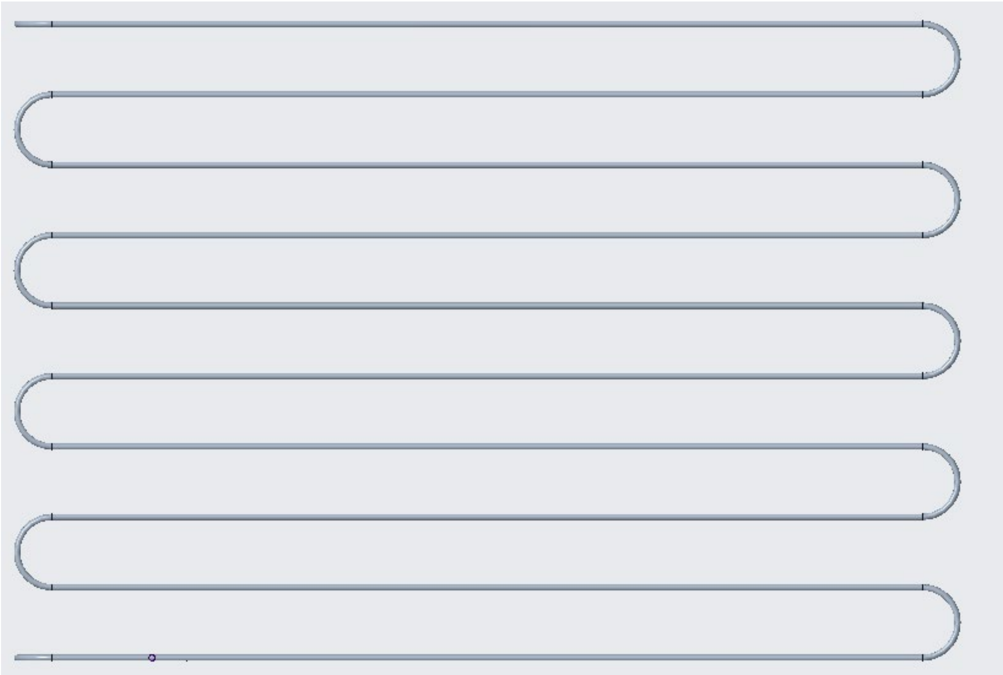


Figure 20: Visualization of the snake pattern.

To fit the piping inside the frame a snake pattern was decided, shown in Figure 20. This pattern uses the available space efficiently while also offering the designer flexibility to implement changes and exploit available space around other components.

An important factor to account for during the design of the layout is that the pipes cannot have a bend radius <5D. This is a manufacturing requirement given by OSS. Another factor is if the diameter isn't in the supporting qualifications from document [49], there must be conducted a new qualification of the given dimension. The diameter presented in 3.1.1 would therefore have to be qualified.

Material

As the designed device is to be used below sea level, the material for the orifice piping shall be corrosion resistant and have a yield strength able to withstand the hoop stress from 700 bar.

The chosen material was Super Duplex S32760, a stainless-steel alloy with high corrosion resistant capabilities and a yield strength above the minimum requirement, see 3.1.1. Other useful factors are its' few to none concerns with weldability and machinability[50].

3.2.4 Structure

Frame

To have a conservative design that can be resized depending on the requirements, the frame was chosen as a suitcase design where height, width and length can be easily adjusted, Figure 21. The cross sections selected were determined to be hollow pipes to save weight.

As these beams are hollow there will be air inside that could possibly cause complications during submersion, which will be prevented by drilling holes to fill them with water. To increase the lifetime of the tool, a corrosion resistant coating will be applied.

Between the pipes there will be buttwelds and fillet welds with NST E 7018 [51], a basic electrode for welding common unalloyed structural steels or a similar material, as this will be of similar strength or greater than the steel used in the frame.

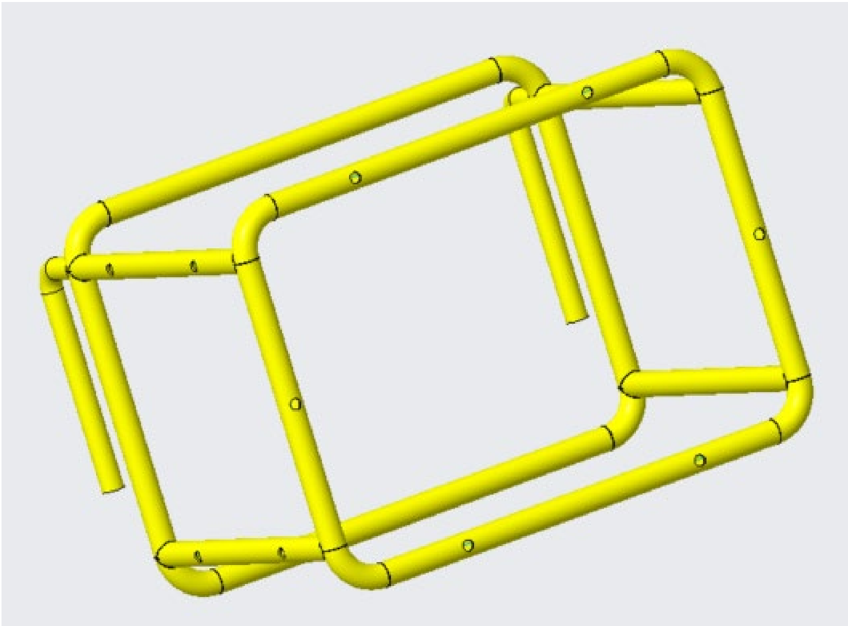


Figure 21: The designed "suitcase" frame.

Panels and padeyes

The panels are made of structural steel where Strenx 700 OME from SSAB could be a good selection considering its resilience towards corrosion and great weldability [52]. Another possibility is to coat them together with the frame, resulting in the possibility to use regular structural steel instead.

For lifting and moving the tool, three padeyes are to be attached. Having two located on one end and one at the other helps keeping the tool steady during lifting. The design is inspired by Offshore Engineering with the smallest size capable of handling a working load of 2mT. They are produced in S355 [53] and will be welded with the same material as the frame.

Assembly and buoyancy

A design proposition as shown in Figure 22 has a design weight of 61,8 kg as calculated in Creo. The different components are placed in a manner to be easily accessible for an ROV while also utilizing space efficiently, resulting in a compact tool.

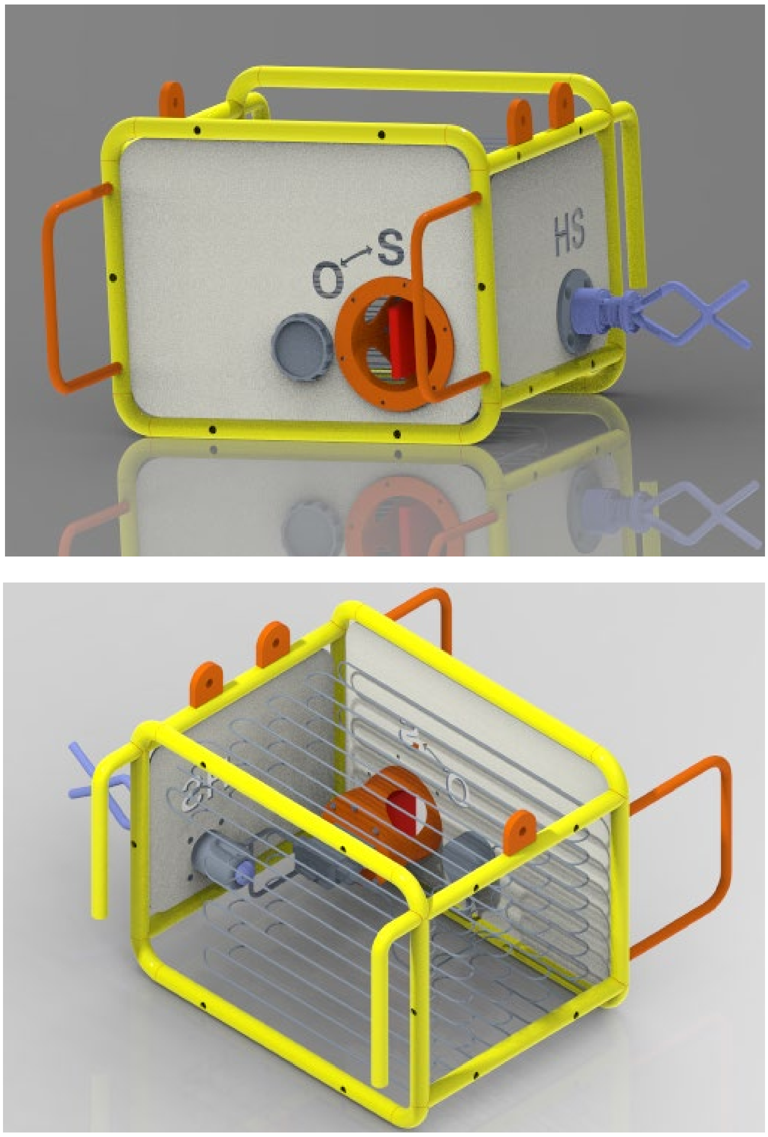


Figure 22: Design proposition made in Creo.

From Archimedes' principle, the weight of an object in water sujectet to a bouyant force can be expressed as:

$$\textbf{Eq. 24} \quad W_w = W_a - V_{model} * \rho_w$$

From Attachment J, applying Archimedes' principle, the designs' weight in water equals 54,1 kg, and considering there are more components in a final design it would probably transcend the desirable weight of 50 kg in water. In projects where this could become an issue, a buoyancy attachment could be a solution. Usually, this equipment is filled with a material that has a specific weight lower than the surrounding liquid, resulting in an upward buoyant force and reducing the weight in water. Commonly used are buoys filled with a syntactic foam.

4. Conclusion

The objective for this project was to create a standardized ROV-operable tool for subsea intervention. The final design falls within the specified requirements. At a weight of 54.1 kg and a size of 0.7x0.5x0.5 m the size of the tool falls within acceptable limits. The maximum pressure change at any point during the bleed-down procedure was approximately 50 psi falling within the specified maximum. Based on these results, the final design can be considered a good concept.

The tool is not yet standardized. Using this design, however, it will be possible to modify it to adapt to different conditions. If OSS creates a 5k or 7k standard, the tool can be modified to be delivered with such a project. Increasing or decreasing the height of the tool provides flexibility to manipulate the length of the pipe. Each layer of the pipe is about 6 m. In the current design one can remove the top 4 layers of piping, bringing the total length of the pipe down to ~21 m. This means there is a good amount of leeway to design around without redesigning and changing the entire tool.

Based on the results from our calculations, it will be possible to stay within the specified pressure difference between the PPS and the BFIC. Using the diagrams in 3.1, it is possible to find many combinations of length and internal diameter that fall within the specification. The results were only tested with one set of initial conditions for this project, and it may be interesting to test the same method on a range of initial conditions to evaluate if the method works for all of them. In theory, they should.

The concept study could be improved. The chosen concept was chosen partly due to its simplicity, but mostly due to the existing method for the Anchor project. There are possibly other solutions that are more effective or simpler. Tesla valves for example, could be interesting to evaluate further as it may be easier to manufacture than this tool. Because of the difficulty in evaluating some of these concepts, they landed outside the scope of the project.

The selected components are mostly standard for these types of applications. Testing of the actual tool would have to be done to prove the concept and whether they can handle the task in the designed configuration.

An aspect of the project that could have provided a better basis for designing a completed tool would have been a working script. This would allow for quick evaluation of dimensions for a range of initial conditions and variables and could be changed to optimize dimensions for the wanted results.

Due to simplifications and conservative design, the model does not provide an accurate representation of real-life behavior. This is intentional but will mean deviations when performing an intervention. Likely, the procedure will take longer time than expected. Testing will reveal how much difference there is. Alternatively, a more accurate model could be created to see the difference.

4.1 Further work

This section describes any factors or modifications that could be made to the tool.

4.1.1 Modular system

To modify the tool for a range of different conditions or applications, a modular design was suggested. The basis for the modularity is to add another hot stab to the PET. This allows for connection to other tooling or to the process pipeline.

Since the tool has been designed to flush directly to sea, it means that if $p_3 < p_{ambient}$, the tool will equalize pressure in the PPS such that $p_{2,final} = p_{ambient} > p_3$. A solution for this is to have a vacuum inside an attachable tank so that after 300 bar it will be possible to send the fluid to the third stage for further depressurization. It then becomes possible to bleed out the pumping station to the desired pressure. As a result, the tool can be used for multiple pumping stations at different pressures and create the desired pressure. Figure 23 shows a suggestion for how one could implement such a system.

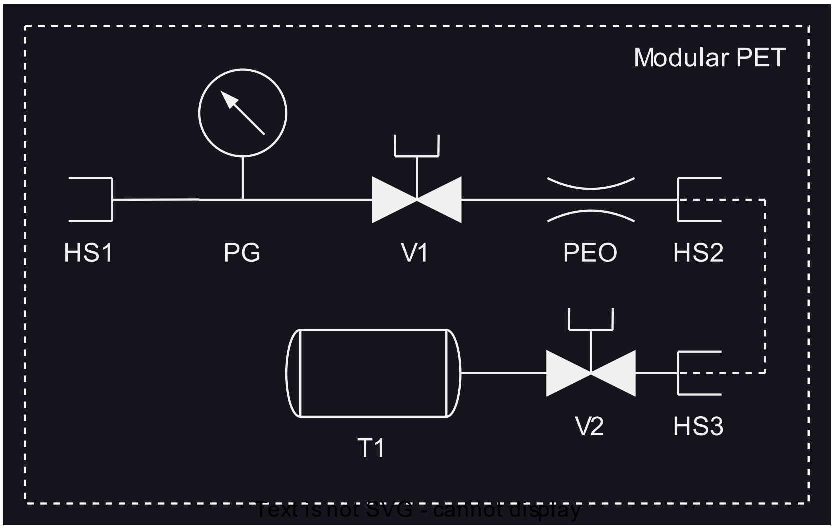


Figure 23: Modular PET design.

Other than a secondary tank, it is also possible to bleed the PPS fluid directly into the process piping. This eliminates the need to shut a valve at a desired pressure level and will automatically equalize the pressures between the two.

There are likely to be other possible applications using this modularity. Having a hot stab connection makes it easy to attach other tooling.

4.1.2 Operation and maintenance manual

To provide a guide on how to properly use the tool, an operation and maintenance manual (OMM) should be created. This provides a step-by-step guide on how to perform an intervention using this tool after the pump module leak test is performed.

The OMM should provide information on storage and transportation as well as maintenance after use. It should also provide steps for deployment and operation subsea.

4.1.3 Pump module attachment points

A constraint for this tool is the need to remain stationary during operation. After consultation with OSS personnel, the conclusion was that it was easiest to attach via some sort of hooks on the side of the station.

In the current design these have been added to the tool itself, but no attachment points have been designed on the actual station. To allow for intervention using a tool like this, the attachment must be incorporated into the standard 10k pumping system.

Considering already existing subsea stations, the attachment method must be evaluated individually with the available space. One option could be to design attachment points on the bottom of the device, provided it is possible to secure it on top of the pump module.

4.1.4 Submersion and air-fill

Due to the small diameter of the PEO, the tool will likely be filled with air during deployment. It will be difficult to flush all the air and fill it with seawater. Therefore, it would be important to consider the case of the PEO initially being filled with air and opening the valve to the PPS.

Another part of this problem is the compression when deploying the tool to depths. In this case the air will be compressed due to the ambient pressure.

What needs to be evaluated at this point is what amount of mass and volume of air is contained inside the PEO and whether this presents a problem when opening the PPS valve.

4.1.5 Fluid solution

For this model, the fluid has been assumed to be 100% standard seawater. The fluid solution will be partly methanol as this is used to pressurize the PPS for the leak test. To account for the fluid solution with seawater and methanol, a weighted average could be used to find the density of the fluid at each timestep.

$$\textbf{Eq. 25} \quad \rho_2(n) = A\rho_{SEAWATER} + B\rho_{METHANOL} \left[\frac{kg}{m^3}\right]$$

Where A and B represent the fluid proportion, $0 < A, B < 1$. The thermophysical properties of methanol would have to be known.

4.1.6 Effect of minor losses

The effect of minor losses has been neglected to ensure a conservative design. The velocity at each timestep is evaluated through major losses only. It may be beneficial to evaluate the effect of the minor losses to see the way the tool functions. To do this the geometry of the entire PEO must be evaluated, with all bends and straight sections. The effect of minor losses is far less than major losses but with sufficient bends there will be some effect.

4.1.7 Cavitation

Cavitation in different components, especially where there is a change in pipe diameter, should be evaluated. During meetings, this problem was discussed but concluded to be an unlikely issue due to high working pressures. It should nevertheless be evaluated. One way to do so is to check if the liquid pressure drops below the saturation pressure for the fluid at a given temperature[11, pp. 41–42].

4.1.8 Cost

Cost has not been evaluated in this project. It is however a significant factor in developing a standardized tool. To provide context for sizing the PEO and comparing different designs, cost is a major factor. It should therefore be evaluated when considering a final design for a tool.

5. References

[1] "OneSubsea." https://www.teknologiporten.no/en/arrangement/567/ (accessed May 13, 2023).
[2] "Who We Are." https://www.onesubsea.slb.com/who-we-are (accessed May 13, 2023).
[3] "OneSubsea Overview." OneSubsea, 2020. Accessed: May 13, 2023. [Online]. Available: https://www.onesubsea.slb.com/-/media/onesubsea/files/brochure/oss-overview-br.ashx
[4] "DRW-0008876 STANDARD 10kpsiMPP STATION." OneSubsea, 2021.
[5] "DOC-0121841_C - Barrier Fluid System Description." OneSubsea, Apr. 26, 2019.
[6] "Multiphase Subsea Pump." https://www.onesubsea.slb.com/powered-production/subsea-boosting-systems/multiphase-subsea-pump (accessed Feb. 28, 2023).
[7] K. Brautaset, *Innføring i oljehydraulikk*. Oslo: Universitetsforl., 1983. Accessed: May 05, 2023. [Online]. Available: https://urn.nb.no/URN:NBN:no-nb_digibok_2007090504010
[8] "What is Bernoulli's equation? (article) | Khan Academy." https://www.khanacademy.org/science/physics/fluids/fluid-dynamics/a/what-is-bernoullis-equation (accessed May 05, 2023).
[9] "Choked Flow in Control Valves," *isa.org*. https://www.isa.org/intech-home/2021/august-2021/departments/choked-flow-in-control-valves (accessed May 05, 2023).
[10] "Understanding Choked Flow of Gases." O'Keefe Controls Co. [Online]. Available: https://www.okeefecontrols.com/wp-content/uploads/Understanding-Choked-Flow-of-Gases-5.17.21.pdf
[11] Y. A. Cengel and J. M. Cimbala, *Fluid Mechanics - Fundamentals and Applications*, Fourth Edition in SI Units. Singapore, SINGAPORE: McGraw-Hill Education, 2020.
[12] "Labyrinth multi stage pressure reducing technology," *Xi'an Parri Control Technology Co.,Ltd*. https://www.xaparri.com/info/labyrinth-multi-stage-pressure-reducing-58228169.html (accessed May 05, 2023).
[13] R. Gan, B. Li, S. Liu, Z. Wu, Y. Peng, and G. Yang, "Multi structural parameter analysis based on the labyrinth valve design with high pressure drop and low noise," *Flow Meas. Instrum.*, vol. 89, p. 102301, Mar. 2023, doi: 10.1016/j.flowmeasinst.2022.102301.
[14] Nikola Tesla, *Nikola Tesla - Patent - US-01329559 - Valvular Conduit (1920-02-03)*. 1920. Accessed: May 05, 2023. [Online]. Available: http://archive.org/details/nikola-tesla-patent-us-01329559-valvular-conduit-1920-02-03
[15] F. Gong, X. Yang, X. Zhang, Z. Mao, W. Gao, and C. Wang, "The study of Tesla valve flow field on the net power of proton exchange membrane fuel cell," *Appl. Energy*, vol. 329, p. 120276, Jan. 2023, doi: 10.1016/j.apenergy.2022.120276.
[16] #author.fullName}, "Century-old water valve invented by Nikola Tesla could have modern use," *New Scientist*. https://www.newscientist.com/article/2277794-century-old-water-valve-invented-by-nikola-tesla-could-have-modern-use/ (accessed May 13, 2023).
[17] Q. M. N. Ristroph Joanna Abouezzi, Leif, *English: Neutrally buoyant dye are injected upstream at Reynolds number 200.* 2021. Accessed: May 21, 2023. [Online]. Available: https://commons.wikimedia.org/wiki/File:Nguyen_Tesla_flow_visualization.webp
[18] "Investigation of a new shock damper system efficiency in reducing water hammer excess pressure due to the sudden closure of a control valve." https://www-tandfonline-com.galanga.hvl.no/doi/epdf/10.1080/09715010.2018.1479665?needAccess=true&role=button (accessed May 05, 2023).
[19] "What is Water Hammer? All That You Need to Know!," *DFT® Inc*, Apr. 06, 2023. https://www.dft-valves.com/applications/water-hammer/ (accessed May 05, 2023).
[20] "Energy Equation - Pressure Loss vs. Head Loss." https://www.engineeringtoolbox.com/major-loss-ducts-tubes-d_459.html (accessed May 16, 2023).
[21] "DOC-0138489_G. Anchor Project MPP SYSTEM -FLOW ASSURANCE -Pressure Equalization Circuit Description." OneSubsea, Dec. 17, 2021.
[22] "DOC-0138895 MPP SYSTEM - INTERNAL - Pressure Equalization Circuit Dimensioning." OneSubsea, Apr. 06, 2020.
[23] "OM-0562_B - Design for ROV intervention." OneSubsea, Feb. 10, 2021.

[24] "Threaded Flange Explained - saVRee." https://savree.com/en/encyclopedia/threaded-flange#article (accessed May 13, 2023).

[25] cedricvialle, "Choosing the right valve," *Buying Guides DirectIndustry*, Nov. 30, 2018. https://guide.directindustry.com/choosing-the-right-valve/ (accessed Mar. 20, 2023).

[26] "handbok-ventilteknikk." Norsk Olje og Gass. Accessed: May 03, 2023. [Online]. Available: https://offshorenorge.no/globalassets/dokumenter/drift/hc-lekkasjer/handboker/handbok-ventilteknikk---03.04.2020.pdf

[27] "Glycerin pressure gauges: what they are and what they are used for." https://mundoriego.es/en/manometros-de-glicerina-que-son-y-para-que-sirven/ (accessed May 01, 2023).

[28] vincent, "Choosing the Right Pressure Gauge," *Buying Guides DirectIndustry*, Oct. 07, 2020. https://guide.directindustry.com/choosing-the-right-pressure-gauge/ (accessed Apr. 30, 2023).

[29] "What Is a Liquid Filled Pressure Gauge?," *Tameson.com*. https://tameson.com/pages/liquid-filled-pressure-gauge (accessed Apr. 30, 2023).

[30] "API Spec 17E." https://www.standard.no/nettbutikk/produktkatalogen/produktpresentasjon/?ProductID=538062 (accessed May 01, 2023).

[31] F. Cornacchia, T. Liu, Y. Bai, and N. Fantuzzi, "Tensile strength of the unbonded flexible pipes," *Compos. Struct.*, vol. 218, pp. 142–151, Jun. 2019, doi: 10.1016/j.compstruct.2019.03.028.

[32] C. Baughman, "Hot Stabs: Quick Couplings on Steroids," *Power & Motion*, Nov. 2015. https://www.powermotiontech.com/hydraulics/hydraulic-fluids/article/21884943/hot-stabs-quick-couplings-on-steroids (accessed May 01, 2023).

[33] "Microsoft Word - API 17H Hot Stab Data Sheet Rev7." Secc Oil and Gas Ltd. Accessed: May 01, 2023. [Online]. Available: https://secc-oilandgas.com/wp-content/uploads/2015/08/ISO-13628-8-Hot-Stab-and-Receptacle.pdf

[34] "API RP 17H - Remotely Operated Tools and Interfaces on Subsea Production Systems | GlobalSpec." https://standards.globalspec.com/std/13385742/api-rp-17h (accessed May 01, 2023).

[35] "Moody Diagram." https://www.engineeringtoolbox.com/moody-diagram-d_618.html (accessed Apr. 10, 2023).

[36] G. Pienta, *Pumps and Pump Systems II*. American Society of Plumbing Engineers (ASPE), 2015.

[37] "Bulk Modulus and Fluid Elasticity." https://www.engineeringtoolbox.com/bulk-modulus-elasticity-d_585.html (accessed May 21, 2023).

[38] "DOC-0137084 Prototype test report - SPV." OneSubsea, Feb. 09, 2021.

[39] "DOC-0137085 Prototype test report - HFSPV." OneSubsea, Oct. 08, 2021.

[40] "DOC-0137098 Barrier Fluid Properties." OneSubsea.

[41] J. Safarov, F. Millero, R. Feistel, A. Heintz, and E. Hassel, "Thermodynamic properties of standard seawater: extensions to high temperatures and pressures," *Ocean Sci.*, vol. 5, no. 3, pp. 235–246, Jul. 2009, doi: 10.5194/os-5-235-2009.

[42] "Stress in Thin-Walled Cylinders or Tubes." https://www.engineeringtoolbox.com/stress-thin-walled-tube-d_948.html (accessed May 16, 2023).

[43] "UNS S32760 (F55) Stainless Steel :: MakeItFrom.com." https://www.makeitfrom.com/material-properties/UNS-S32760-F55-Stainless-Steel (accessed May 16, 2023).

[44] "970140913 - Stab Hot 43mm 17H 10K 1 port w/J-lock." Sep. 28, 2017.

[45] "970321101 - Reseptacle 43mm w/J-lock, weld neck." May 31, 2017.

[46] "OSP-2000725542-MRB-005_01_001 code 1 - Manufacturing Record Book ITEM 00050." MRC Global, Jun. 14, 2021.

[47] "Type SS - Technical spesification for manometer." MRC Global, Jan. 20, 2021.

[48] "1/4'' 12,500 psi High pressure wire hose."

[49] BBO, "DOC-0100881/C - Cold Bending Procedure Specification." Mar. 27, 2023. [Online]. Available: https://nst.no/wp-content/uploads/2019/10/nst-e-7018-norsk-24082018.pdf

[50] "uns-s32760.pdf." Accessed: May 22, 2023. [Online]. Available: https://www.smithmetal.com/pdf/stainless/duplex/uns-s32760.pdf

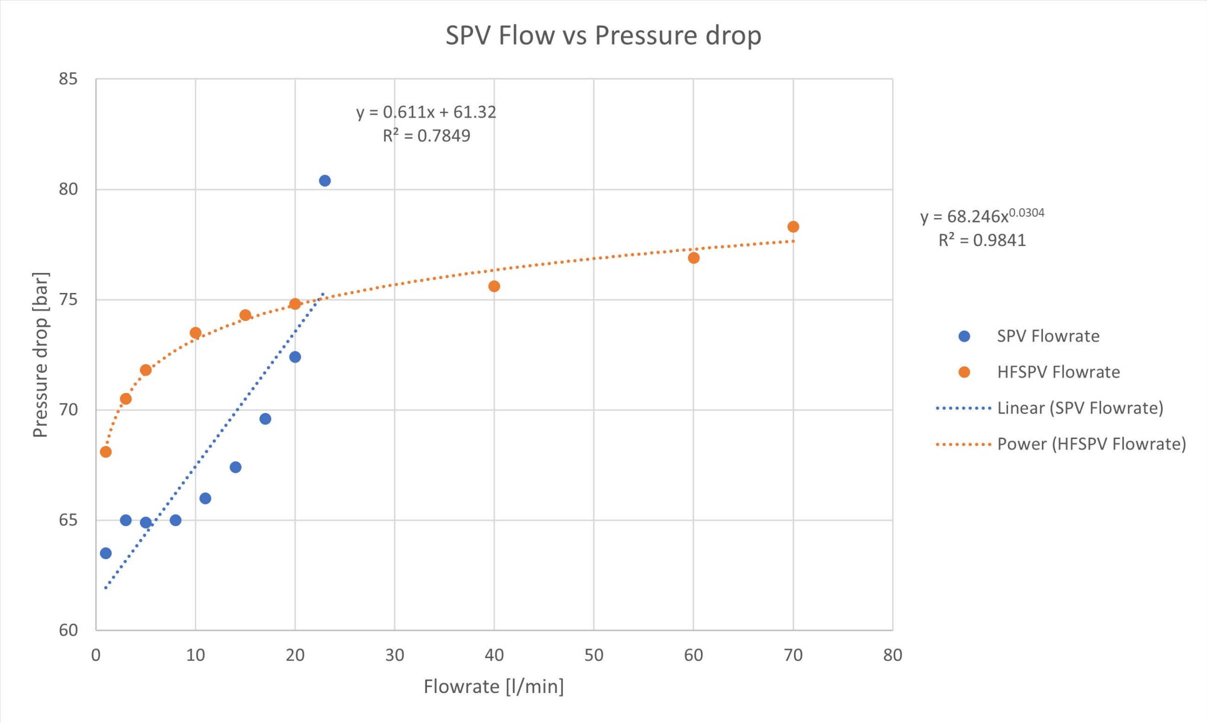
[51] "NST E 7018 - NST - Norsk Sveiseteknikk." https://nst.no/produkter/sveisetilsett/elektroder/ulegerte-elektroder/nst-e-7018/ (accessed May 12, 2023).

[52] "Strenx® 700 OME," *SSAB*. https://www.ssab.com/en/brands-and-products/strenx/product-offer/700/ome (accessed May 15, 2023).

[53] "Steel Steel padeye design | Standard padeye CAD drawing ready for cutting (dwg, dxf, pdf)),” Dec. 27, 2021. https://www.offshoreengineering.com/steel-padeye-design-standard-padeye-drawings-ready-for-plasma-cutting-autocad-dxf-pdf/ (accessed May 14, 2023).

6. Appendix

Attachment A Flowrate-Pressure drop for SPV and HF SPV



Attachment B PEO length and id data

ID [mm]	Length [m]	Time [min]	First step Δ [psia]	$p_{2,final}$ [psia]
2.0	1.5	11.67	49.3	14.3
2.5	4.3	11.62	49.4	14.0
3.0	10.1	11.52	49.8	13.9
3.5	21.0	11.48	49.8	14.1
4.0	40.0	11.52	49.5	14.4
4.5	69.0	11.42	49.9	13.7
5.0	114.0	11.40	49.9	14.3
5.5	179.0	11.38	49.9	14.0
6.0	270.0	11.35	50.0	14.5
6.5	396.0	11.36	49.9	14.3
7.0	563.0	11.36	49.9	14.2
7.5	780.0	11.35	49.9	14.5
8.0	1058.0	11.35	50.0	14.2

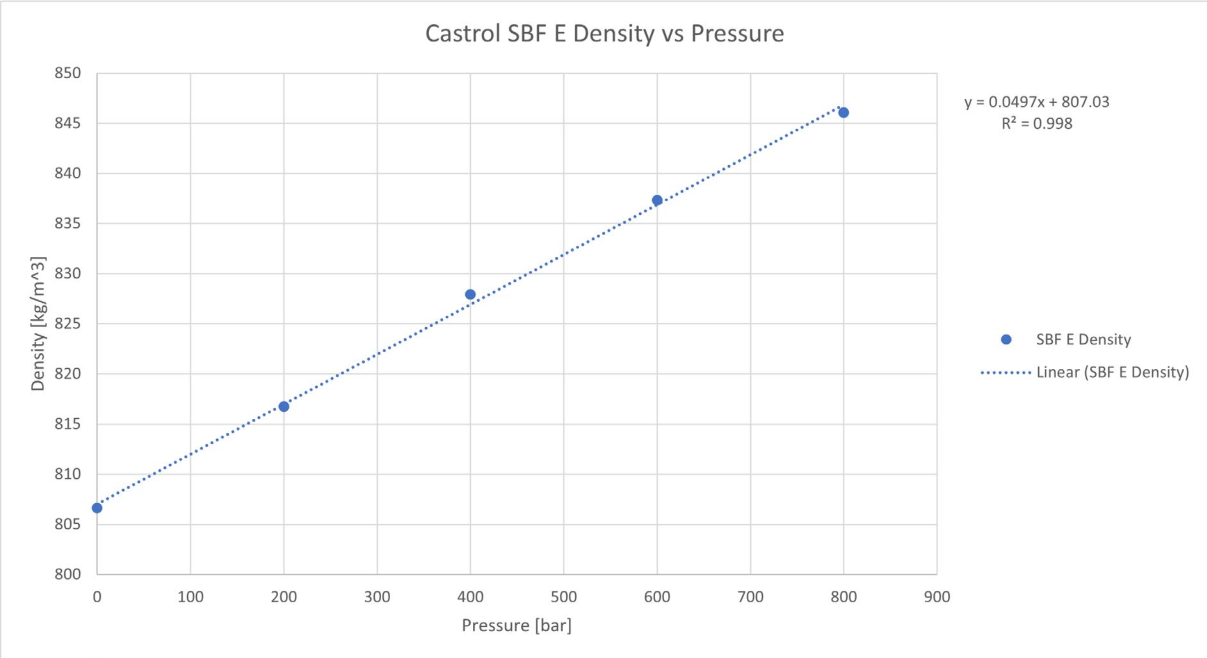
Attachment C Derivation of formula for velocity from major head loss

$$\Delta p = \frac{fl\rho v^2}{2d}$$

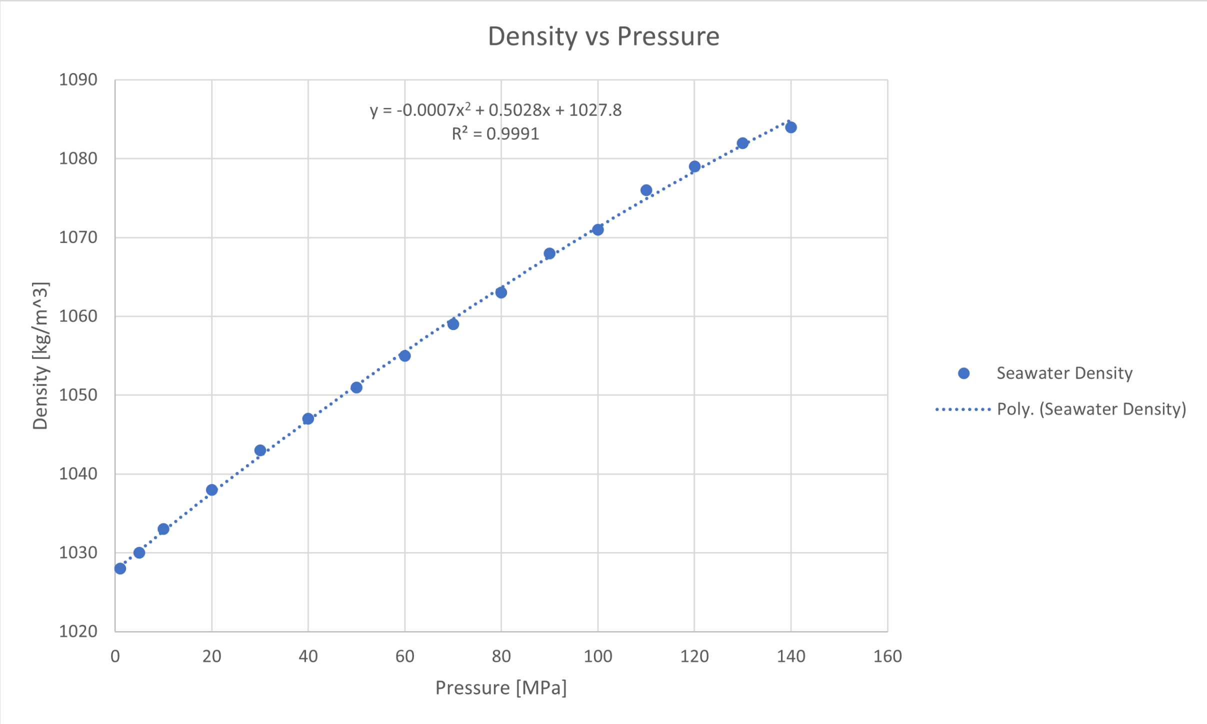
$$2d\Delta p = fl\rho v^2$$

$$v = \sqrt{\frac{2d\Delta p}{fl\rho}}$$

Attachment D Castrol Brayco Micronic SBF E – Density-Pressure Correlation



Attachment E Seawater Density-Pressure correlation



Attachment F Derivation of formula for pressure at next timestep

$$\delta p \cdot \rho(n) = K(n) \cdot \delta\rho$$

$$\big(p(n+1) - p(n)\big)\rho(n) = K(n)\big(\rho(n+1) - \rho(n)\big)$$

$$p(n+1) - p(n) = K(n)\left(\frac{\rho(n+1)}{\rho(n)} - \frac{\rho(n)}{\rho(n)}\right)$$

$$p(n+1) = p(n) + K(n)\left(\frac{\rho(n+1)}{\rho(n)} - 1\right)$$

Since $\rho(n+1) < \rho(n)$, $-1 \leq \left(\frac{\rho(n+1)}{\rho(n)} - 1\right) \leq 0$. Thus one can rewrite the equation as such:

$$p(n+1) = p(n) - K(n)\left(1 - \frac{\rho(n+1)}{\rho(n)}\right)$$

Attachment G 30% design review summary

MØTEREFERAT

1. Deltakere: Andreas Bjoerkhaug, Annbjoerg Tonstad Thomassen Werdal, Asbjoern Fauske, Benjamin Meisler, Bjørn Aalstad, Carl-Martin Carstensen, Christian Bogsnes, Henrik Haug, Kyrre Groenstoel, Nikolai Kaartveit, Nils Marius Sakserud, Oeyvind Reimers, Stig Kaare Kanstad, Thomas Skutle, Tonje Charlotte Stald, Tor Martin Vrangsund.

Referent: Benjamin Meisler

Dato: 08.03.2023

Sted: Teams/Møterom sone 2.1 i hjørnet

Bacheloroppgave – 30% design review

No.	Beskrivelse	Aksjon	Dato
1.	Verdier for pakninger: Maksimalt trykkdelta over pakning, statisk (barriere – prosess) - 160bar Maksimalt trykkdelta over pakning, statisk (prosess – barriere) – 200bar		
2.	Designet antas til å ikke måtte tåle prosess.		
3.	Ønskelig å senke trykket til flowline trykk/ 0bar, se på andre alternativer.		
4.	Maksvekt på 50 kg i vann er førende krav for totaldesignet.		
5.	Påkobling til pumpen på tåle reaksjonskreftene (fleksibel, slange).		
6.	Hotstab med låsemekanisme for å unngå uønsket release.		
7.	Lett tilgjengelighet, mulighet for utskift av komponenter.		
8.	Ved bruk av tank/akkumolator: Trykkes ned på vei opp fra vannet.		
9.	Plasseres i basket/stabil landing av toolet.		

Slutt på møtereferat

MØTEREFERAT

Vedlegg: [ingen] eller [1] etc.

Attachment H 60% design review summary

Scaffolding / stillas
stillas gjerder

Gjeiding på oppfestning

Lett i vann, installasjon (i basket)

Beregne trykktap i bends

Sensitivitetsanalyse, (10, 60, loostk

<u>Sprint</u>

Tur ná ut lik masse, derfor linear

Beskrive hvor for vi bruker de ulike delene

Ventil, åpne lukke raskt

<u>Slange</u>

Trommel, løs slange med holstab på begge sider

Tokt må fylles med vaske

Regne på massen 100% luft komprimert til ambient utgjør (worst case)

Feste tubing slik at den kan bevege seg

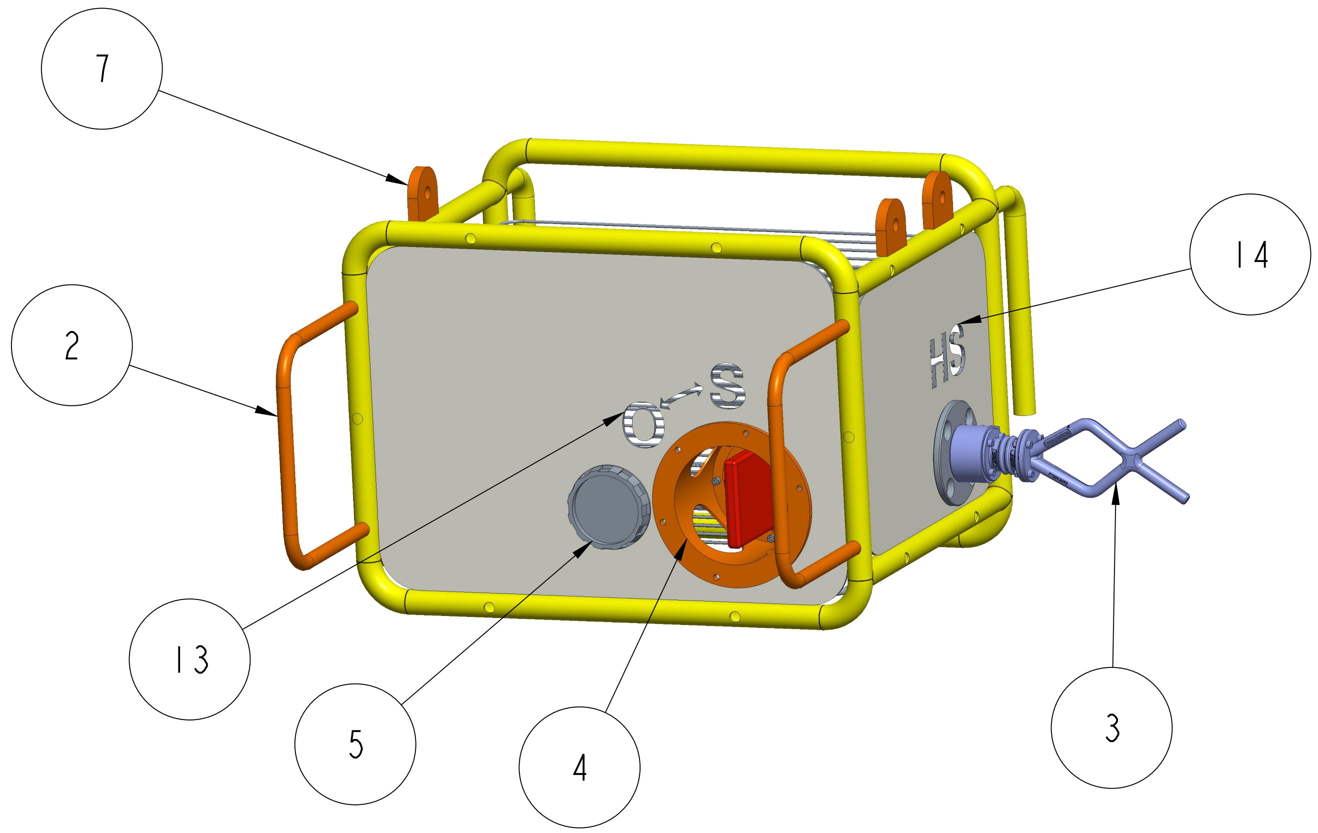
ITM-0294005

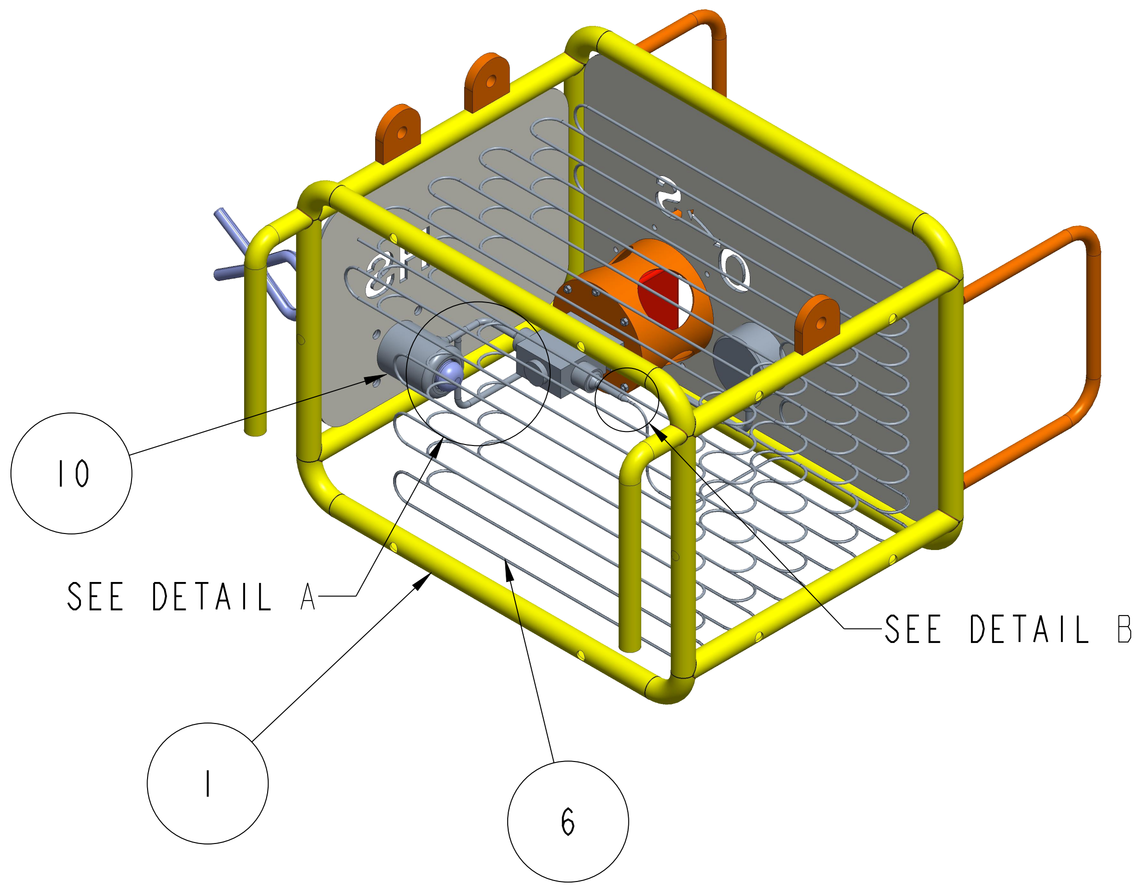
Bøyning på toppen/blåse

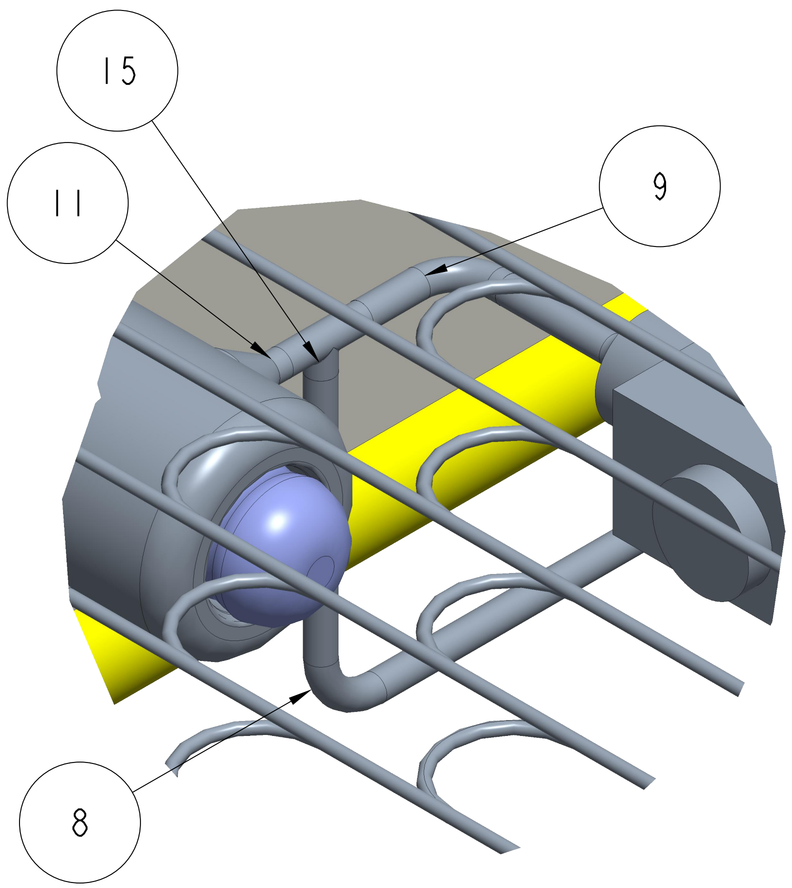
Reducer fra ventil til piping

Pigtail (Slange)

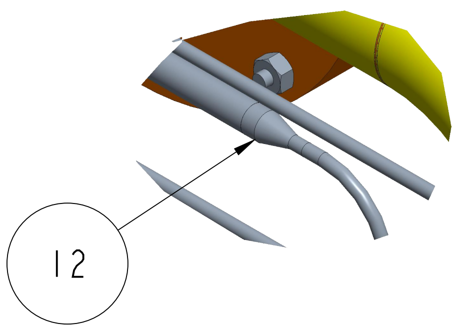
Attachment I CAD drawings of PET







DETAIL A
SCALE 1:2



DETAIL B
SCALE 1:2

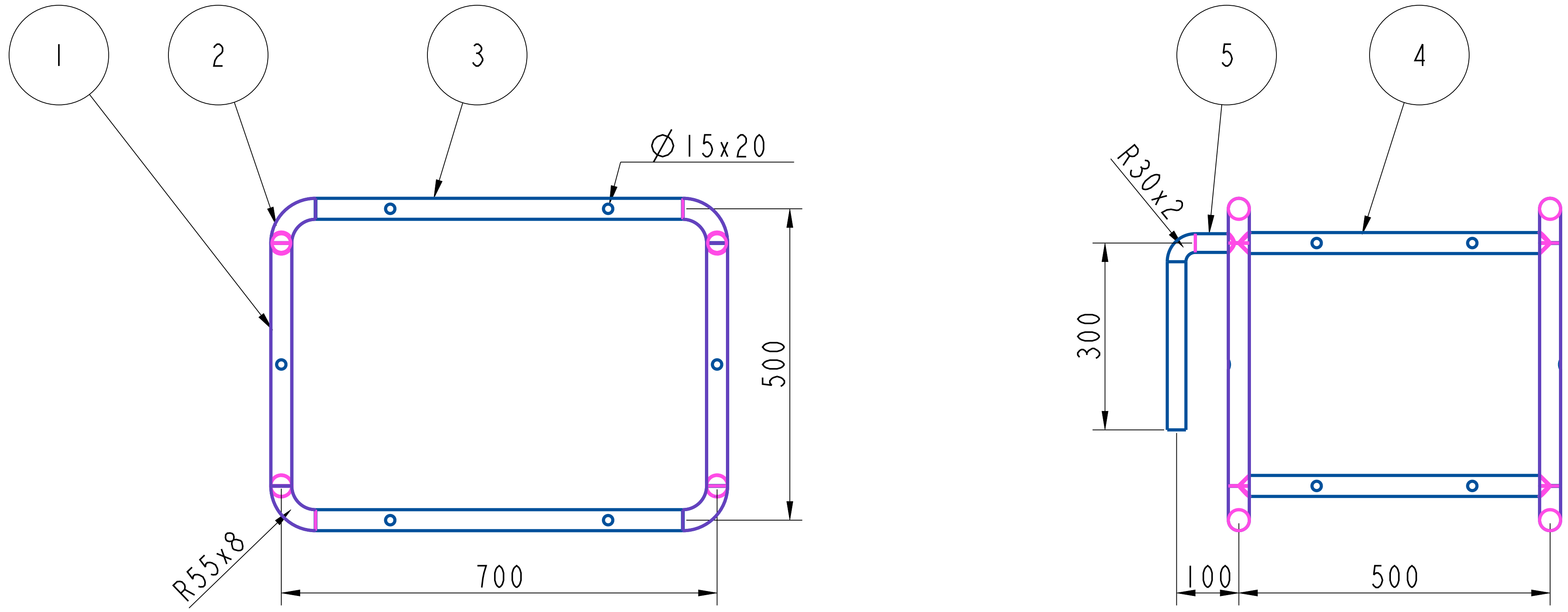
Pos	Ant	Artikell/Modell	Beskrivelse	Materiale	Dimensjon
15	1	SMALL_TEE		S32760	ISO 2768 f
14	1	ROV_PANEL_HOTSTAB		S355J	ISO 2768 m
13	1	ROV_PANEL		S355J	ISO 2768 m
12	1	REDUCER_SMALL		S32760	ISO 2768 f
11	1	REDUCER		S32760	ISO 2768 f
10	1	RECEPTACLE	Placeholder from OSS		
9	1	PIPE_VALVE		S32760	ISO 2768 f
8	1	PIPE_MANOMETER		S32760	ISO 2768 f
7	3	PADEYE		S355	ISO 2768 m
6	1	ORIFICE_TUBE		S32760	ISO 2768 f
5	1	MANOMETER_DUMMY	Placeholder		
4	1	ITM-0296886	Placeholder from OSS		
3	1	HOTSTAB_DUMMY	Placeholder from OSS		
2	2	GRABBER_BAR		S355J	ISO 2768 c
1	1	FRAME		S355J	ISO 2768 c

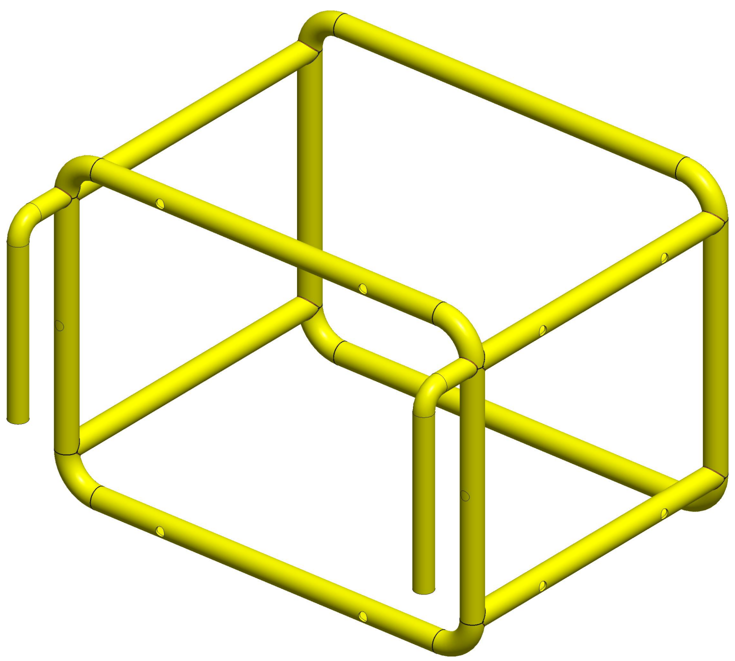
Konstr	Tegnet	Revisjon	Vekt	Skala	Format	Blad.nr
	Meisler		61.80 kg	1:10	A3	1(1)

Høgskulen på Vestlandet
IMM

Artikell/Modell: PRESSURE_REDUCTION_TOOL
Beskrivelse
Dato: 20-May-23
Tegning: PRESSURE_REDUCTION_TOOL

NAME	TYPE	SIZE	LENGTH
STEEL PIPE	DIN EN 10219	33.7x3.0	5920
ROUND STEEL	DIN 10060	30	664.6

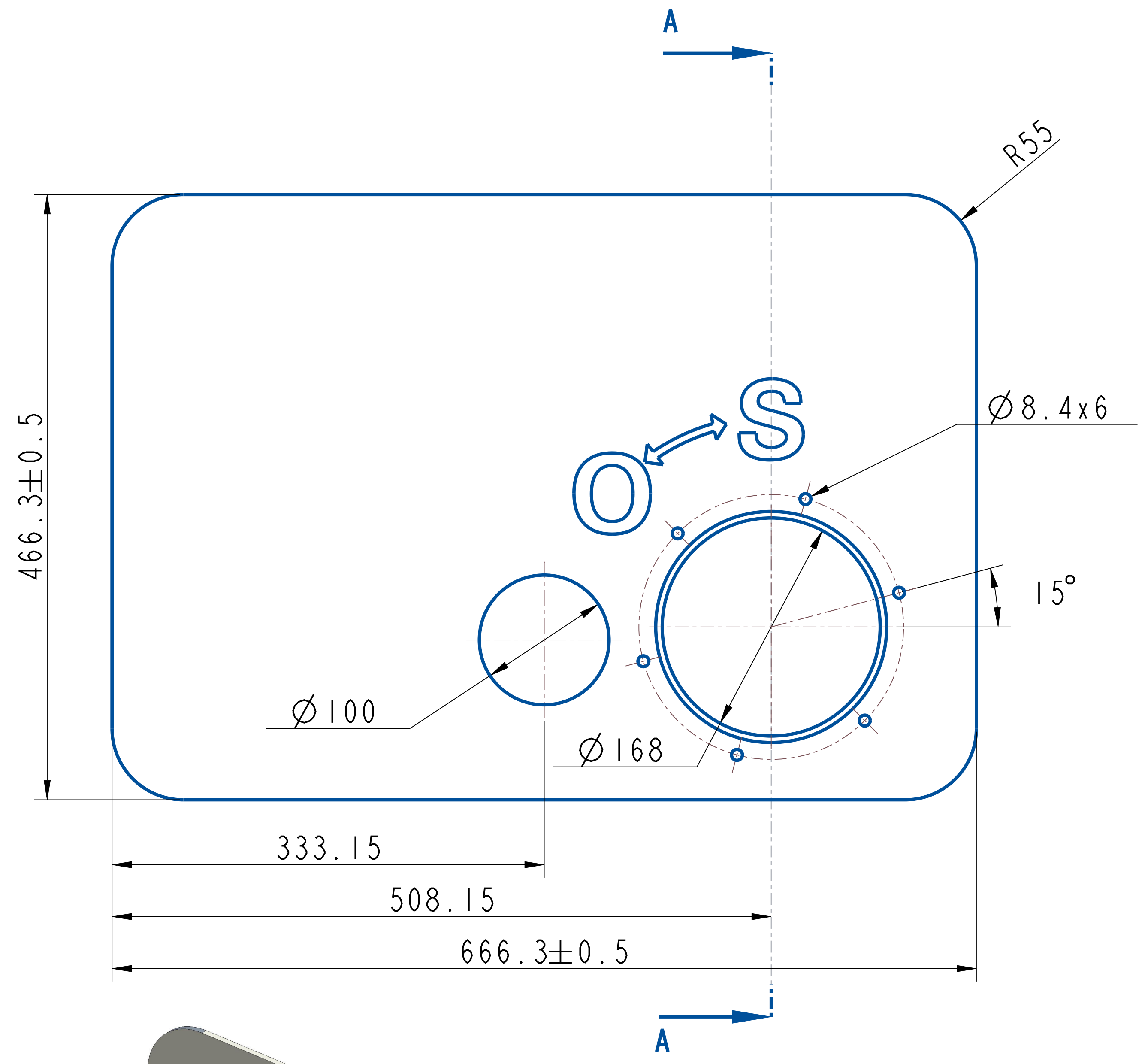


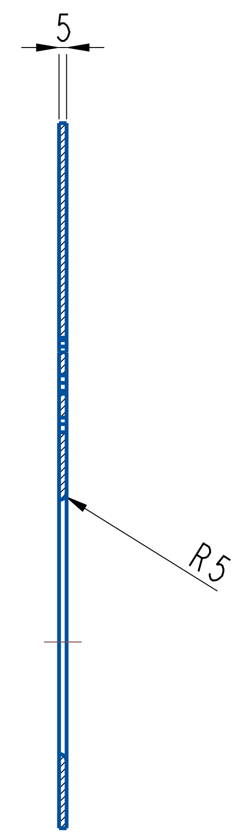


Pos	Ant	Artikell/Modell	Beskrivelse	Materiale	Dimensjon
5	2	ROUND STEEL		S355J	ISO 2768 c
4	4	STEEL PIPE		S355J	ISO 2768 c
3	4	STEEL PIPE		S355J	ISO 2768 c
2	8	STEEL PIPE		S355J	ISO 2768 c
1	4	STEEL PIPE		S355J	ISO 2768 c

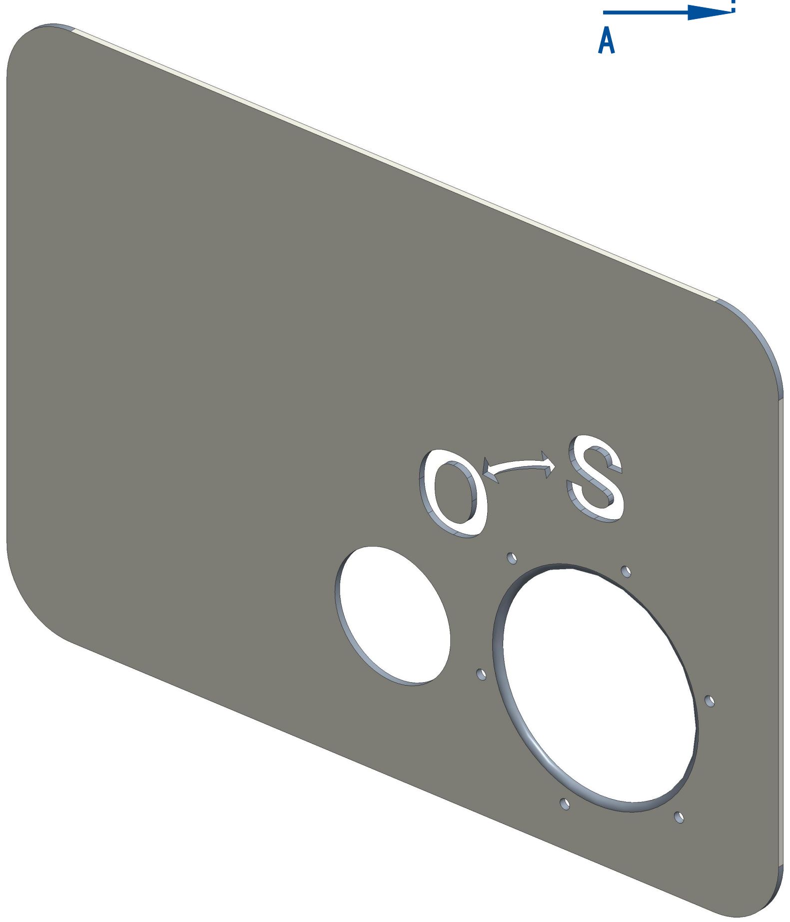
Konstr	Tegnet	Revisjon	Vekt	Skala	Format	Blad.nr
	Meisler		18.86 kg	1:10	A3	1(1)

Høgskulen på Vestlandet *IMM*	Artikell/Modell FRAME	Dato 20-May-23
	Beskrivelse	Tegning FRAME





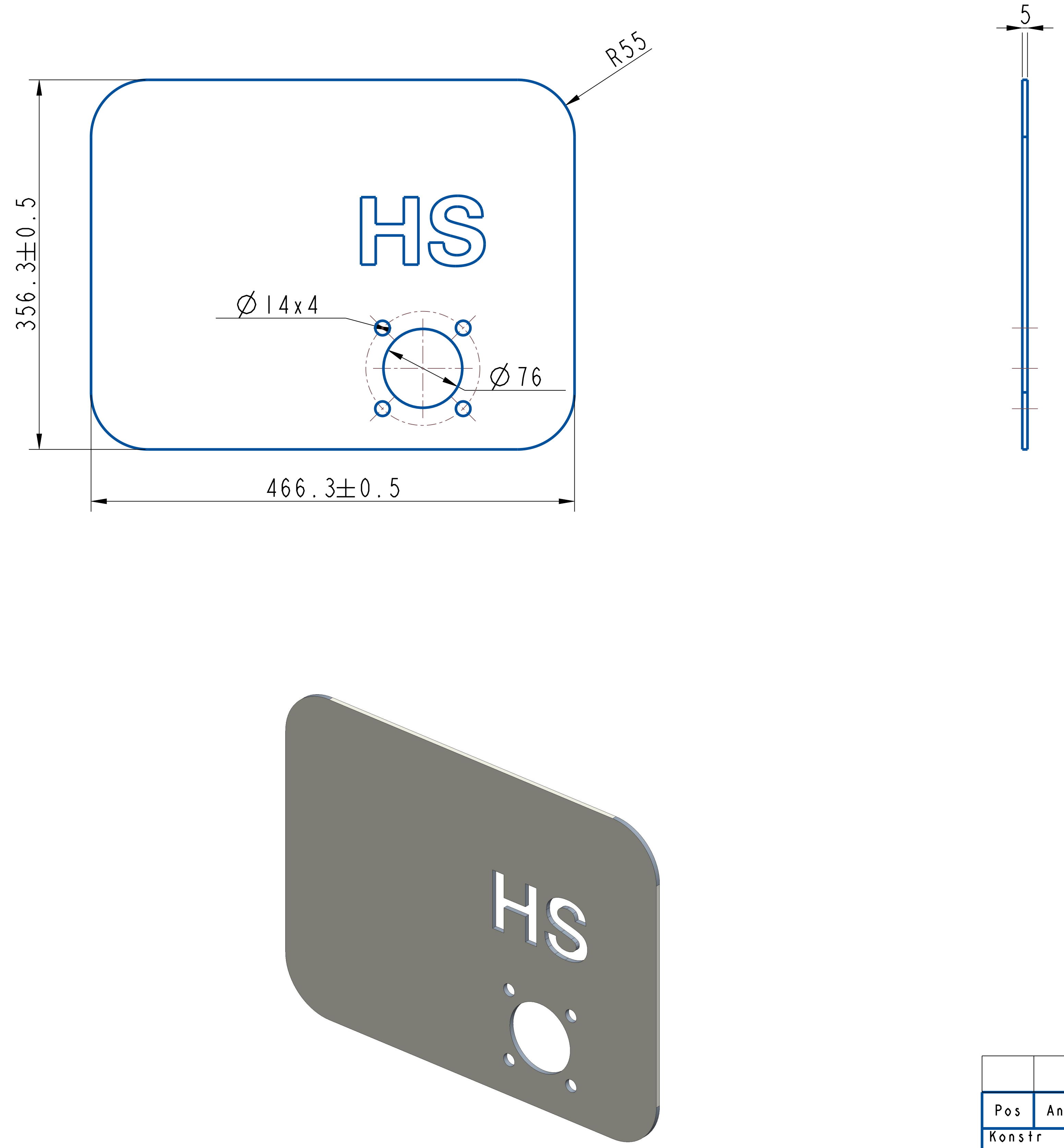
SECTION A-A



	1			S355J	ISO 2768 m
Pos	Ant	Artikell/Modell	Beskrivelse	Materiale	Dimensjon

Konstr	Tegnet	Revisjon	Vekt	Skala	Format	Blad.nr
	Meisler		10.21 kg	1:5	A3	1(1)

Høgskulen på Vestlandet *IMM*	Artikell/Modell ROV_PANEL	Dato 20-May-23
	Beskrivelse	Tegning ROV_PANEL



	1			S355J	ISO 2768 m
Pos	Ant	Artikell/Modell	Beskrivelse	Materiale	Dimensjon

Konstr	Tegnet	Revisjon	Vekt	Skala	Format	Blad.nr
	Meisler		5.77 kg	1:5	A3	1(1)

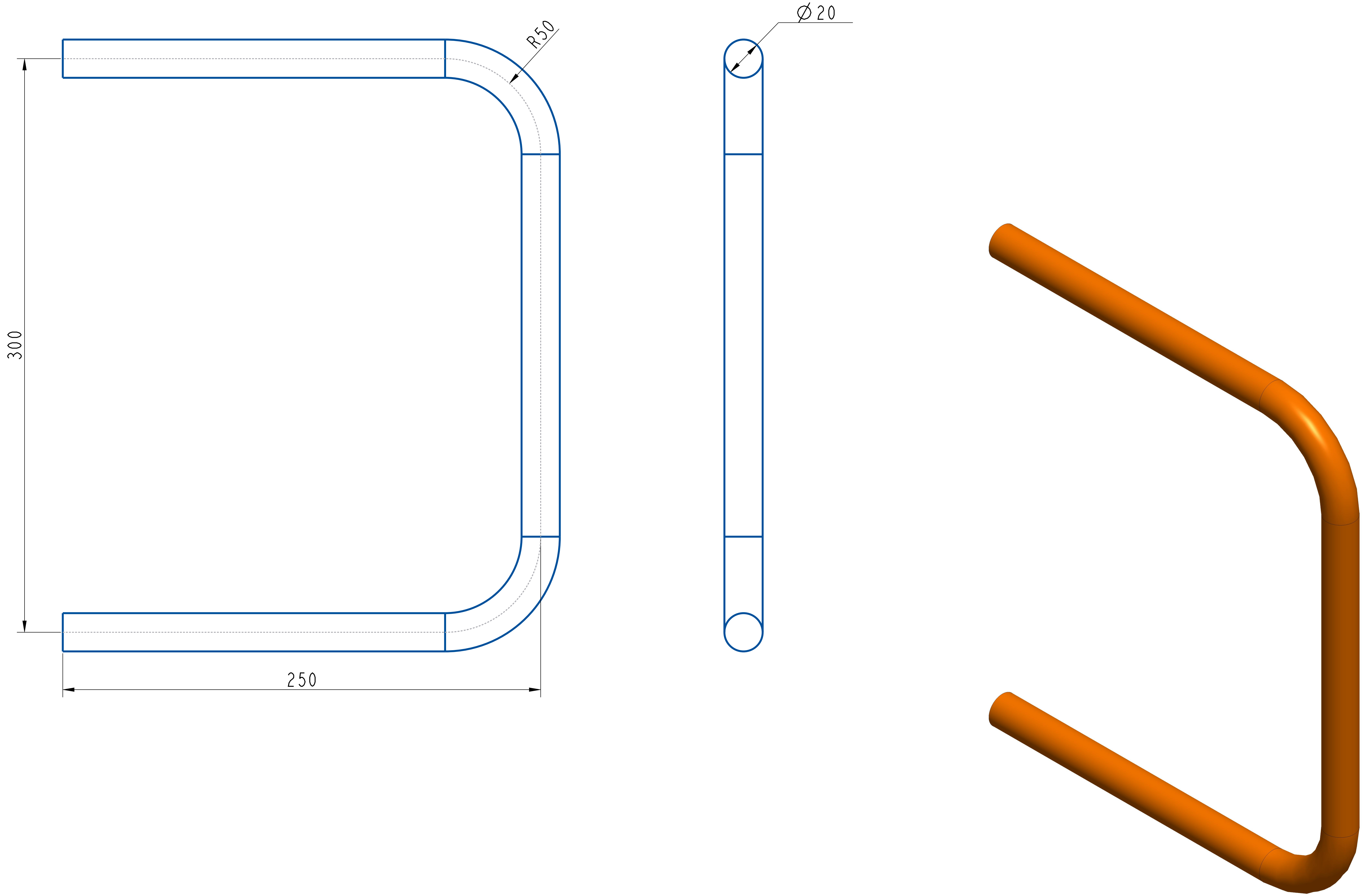
Høgskulen på Vestlandet
IMM

Artikell/Modell: ROV_PANEL_HOTSTAB

Beskrivelse:

Dato: 20-May-23

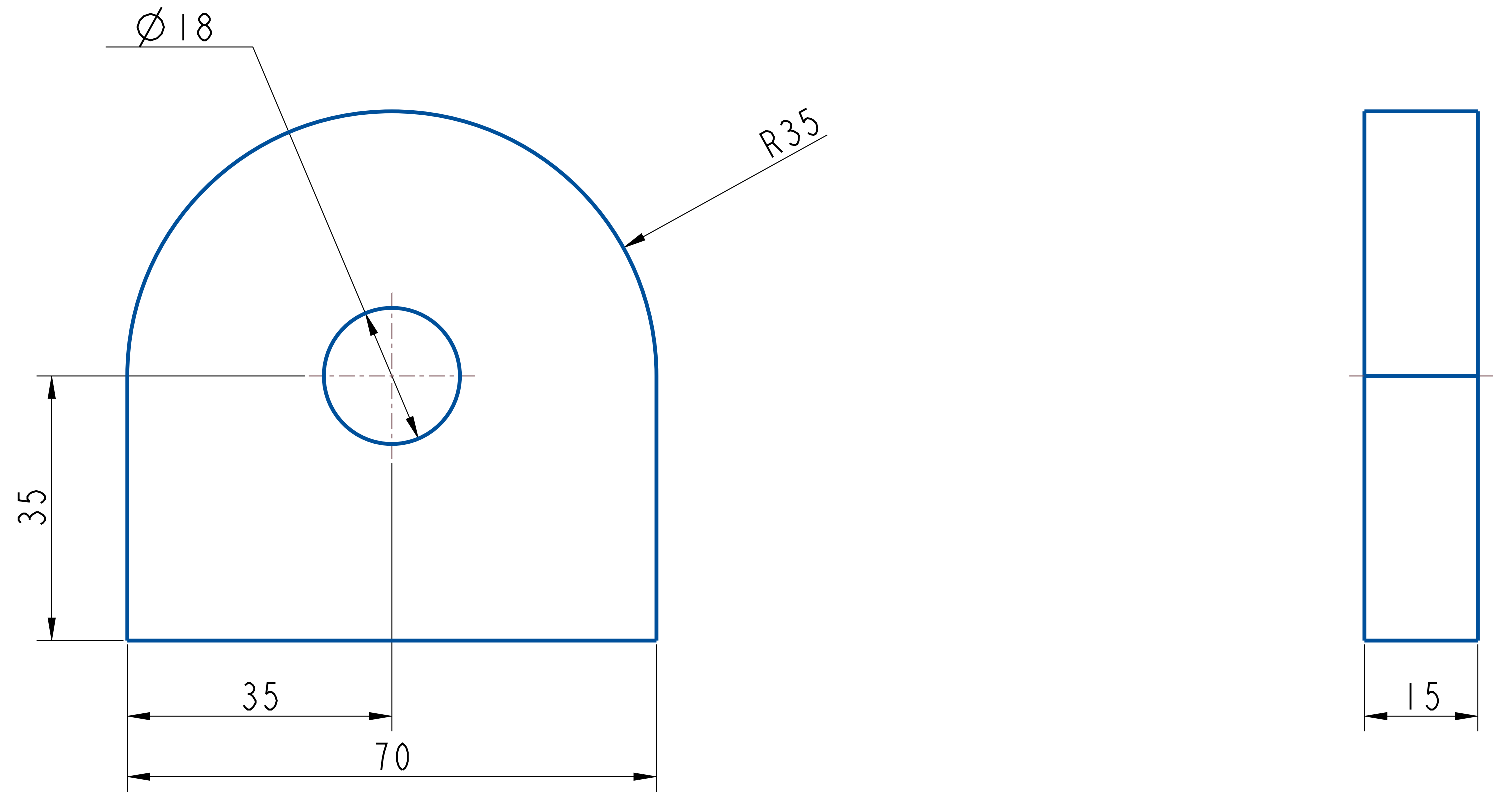
Tegning: ROV_PANEL_HOTSTAB

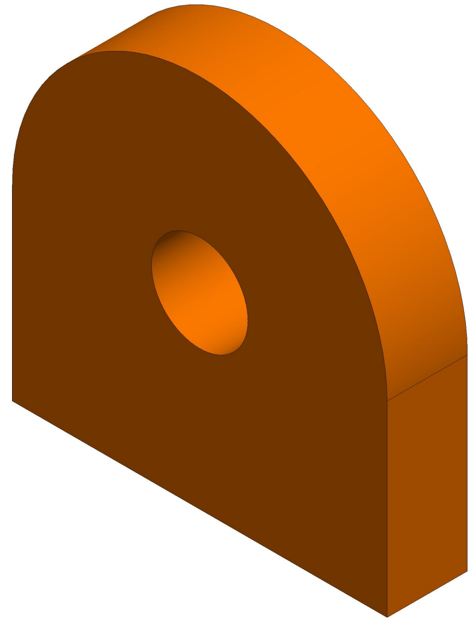


	2			S355J	ISO 2768 c
Pos	Ant	Artikell/Modell	Beskrivelse	Materiale	Dimensjon

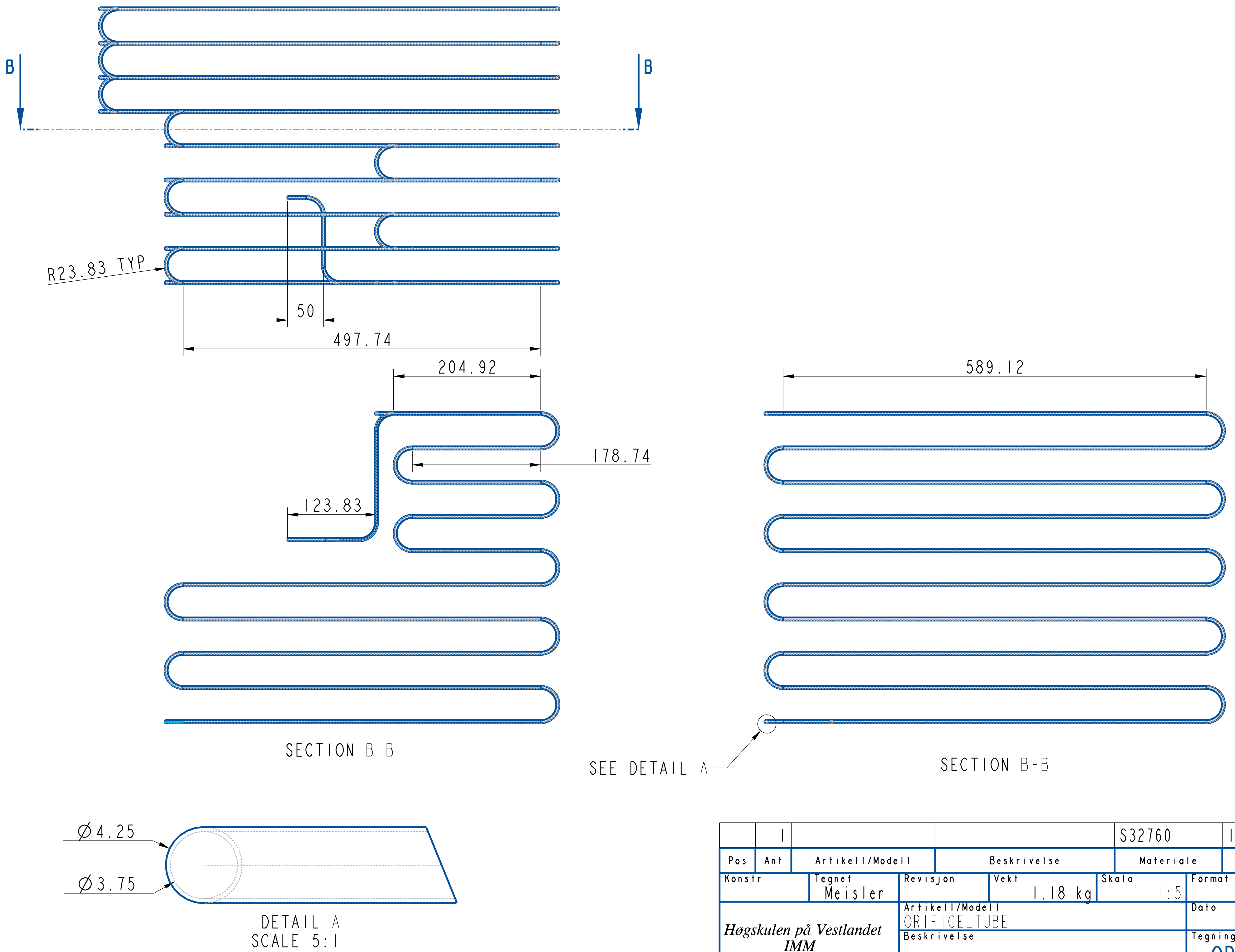
Konstr	Tegnet	Revisjon	Vekt	Skala	Format	Blad.nr
	Meisler		1.78 kg	1:2	A3	1(1)

Høgskulen på Vestlandet IMM	Artikell/Modell GRABBER_BAR	Dato 20-May-23
	Beskrivelse	Tegning GRABBER_BAR



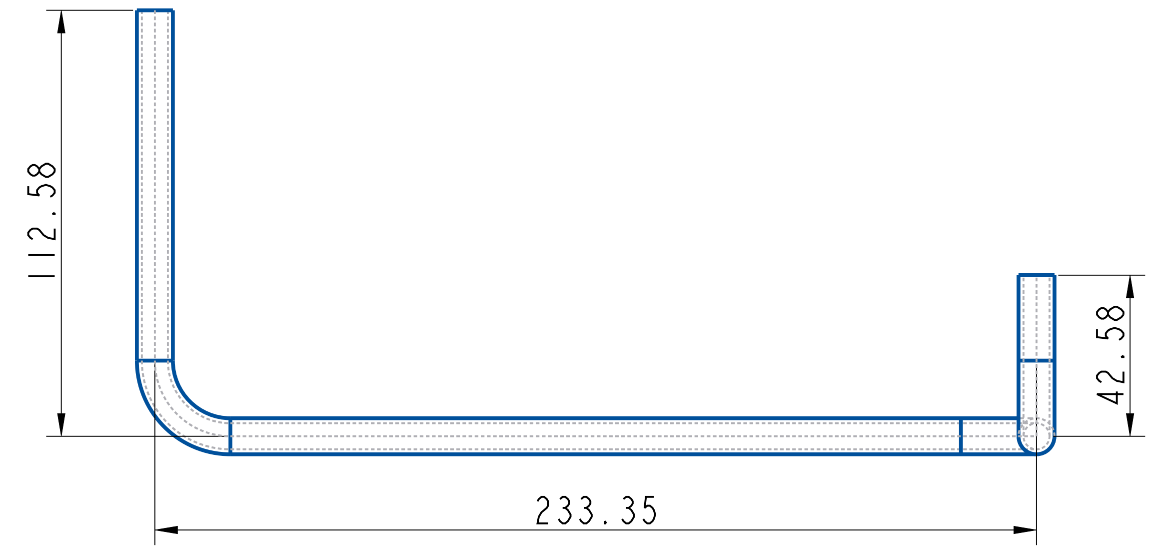


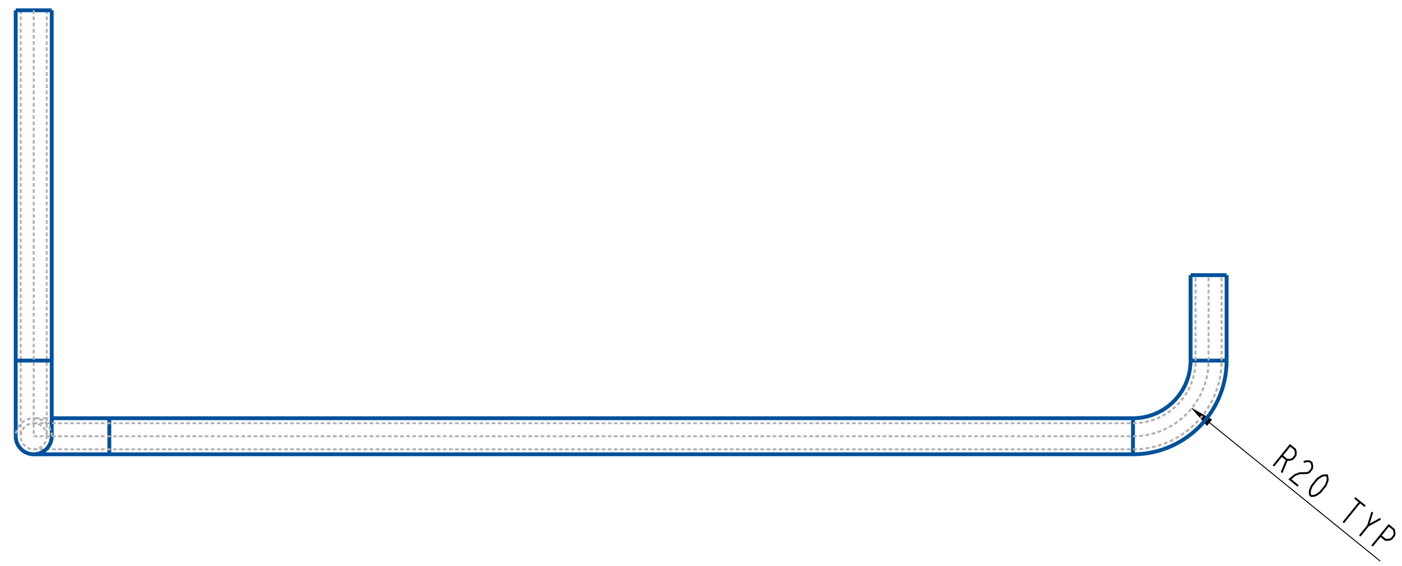
	3			S355	ISO 2768 m	
Pos	Ant	Artikell/Modell	Beskrivelse	Materiale	Dimensjon	
Konstr	Tegnet Meisler	Revisjon	Vekt 462.24 g	Skala 1:1	Format A3	Blad.nr 1(1)
Høgskulen på Vestlandet IMM		Artikell/Modell PADEYE			Dato 19-May-23	
		Beskrivelse			Tegning PADEYE	

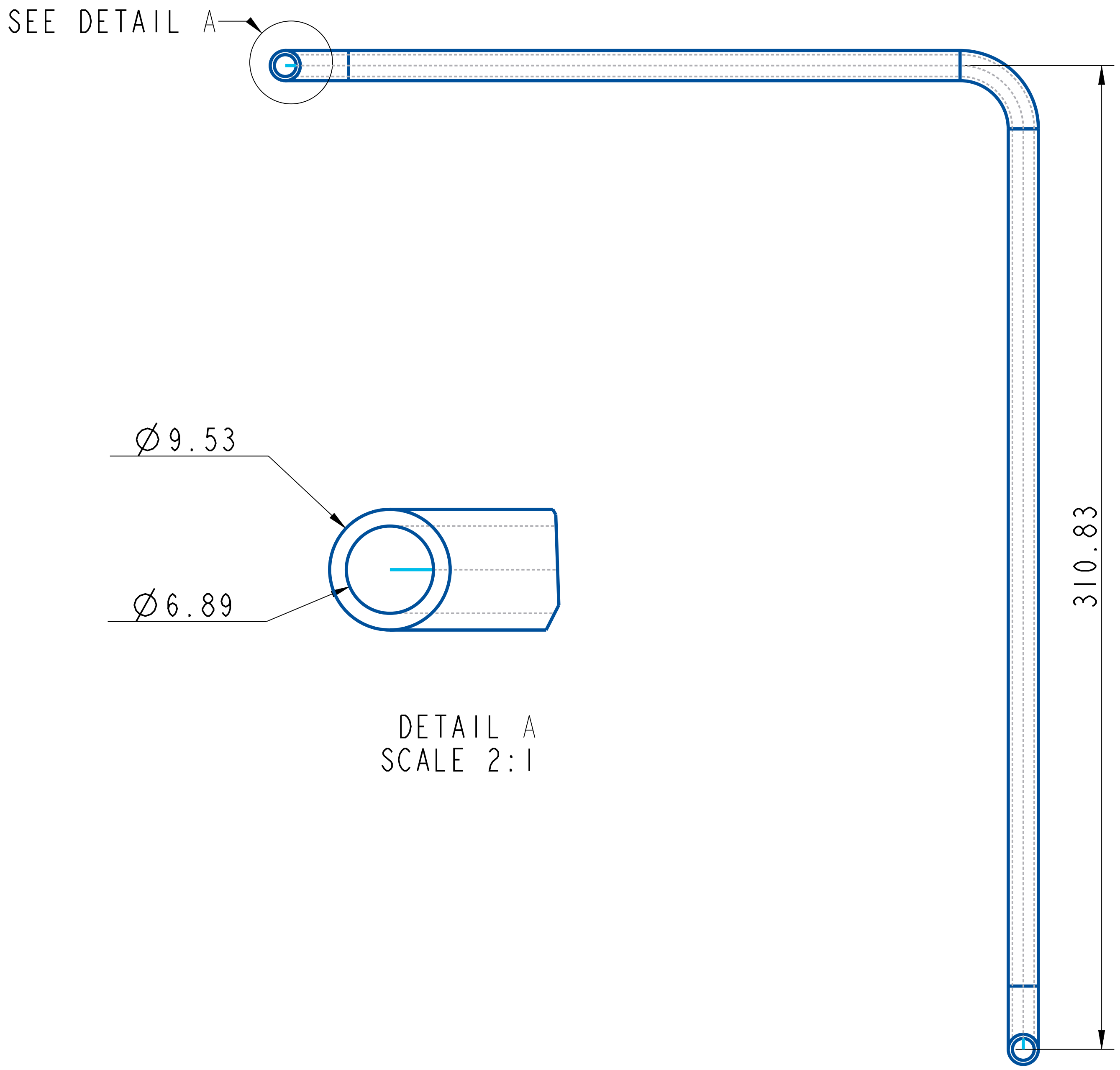


	1			S32760	ISO 2768 f
Pos	Ant	Artikell/Modell	Beskrivelse	Materiale	Dimensjon

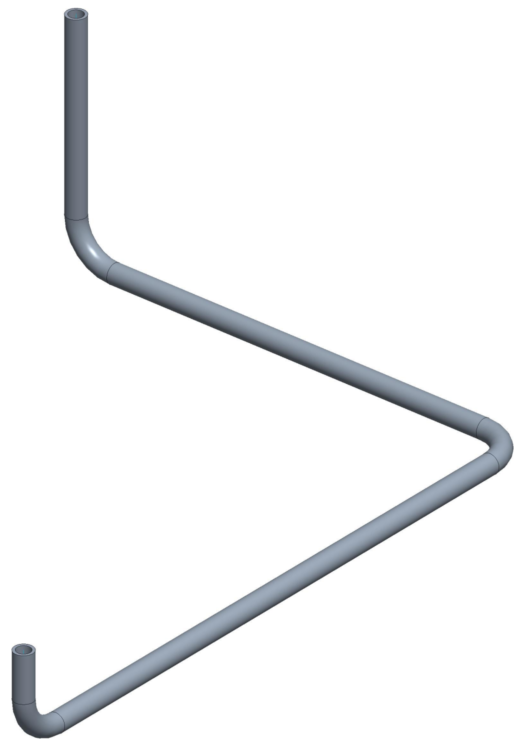
Konstr	Tegnet Meisler	Revisjon	Vekt 1.18 kg	Skala 1:5	Format A3	Blad.nr 1(1)
Høgskulen på Vestlandet IMM		Artikell/Modell ORIFICE_TUBE			Dato 20-May-23	
		Beskrivelse			Tegning ORIFICE_TUBE	





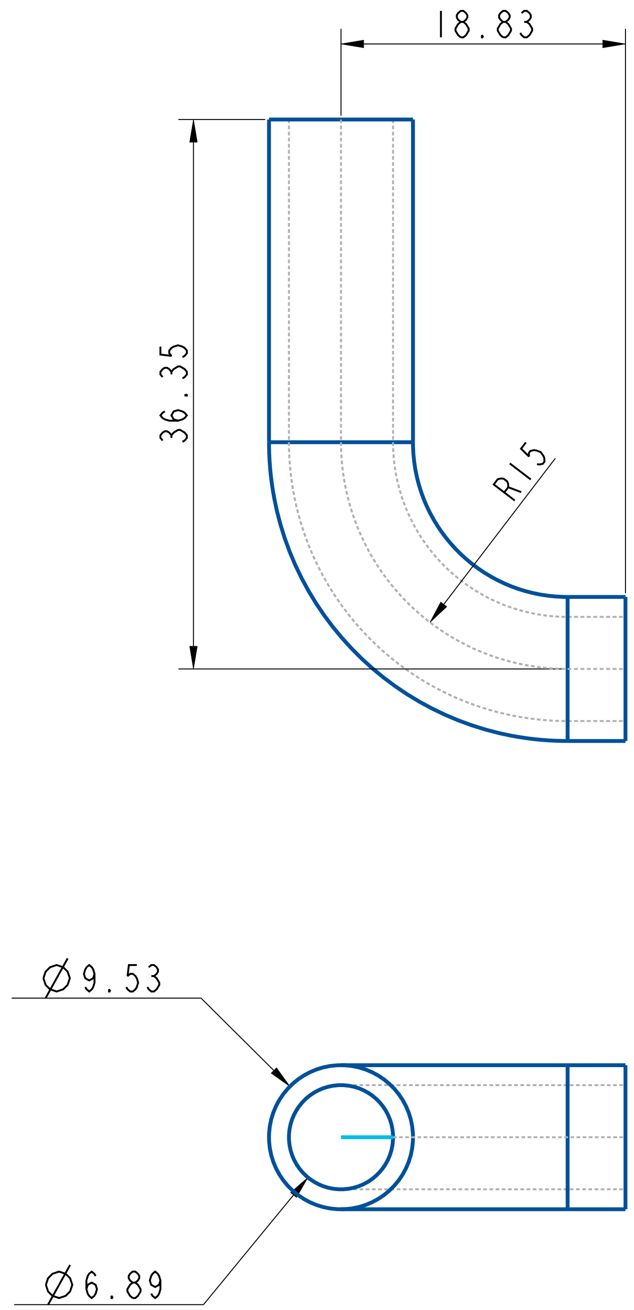


DETAIL A
SCALE 2:1



SCALE 33:100

	1			S32760		ISO 2768 f	
Pos	Ant	Artikell/Modell	Beskrivelse	Materiale		Dimensjon	
Konstr	Tegnet Meisler	Revisjon	Vekt 181.17 g	Skala 1:2		Format A3	Blad.nr 1(1)
Høgskulen på Vestlandet *IMM*		Artikell/Modell PIPE_MANOMETER				Dato 20-May-23	
		Beskrivelse				Tegning PIPE_MANOMETER	



Pos	Ant	Artikell/Modell	Beskrivelse	Materiale	Dimensjon
	1			S32760	ISO 2768 f

Konstr	Tegnet	Revisjon	Vekt	Skala	Format	Blad.nr
	Meisler		13.11 g	2:1	A3	1(1)

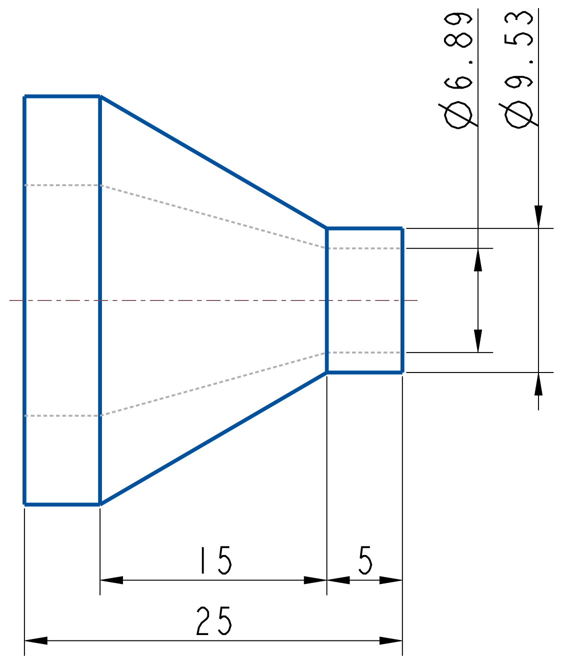
Høgskulen på Vestlandet
IMM

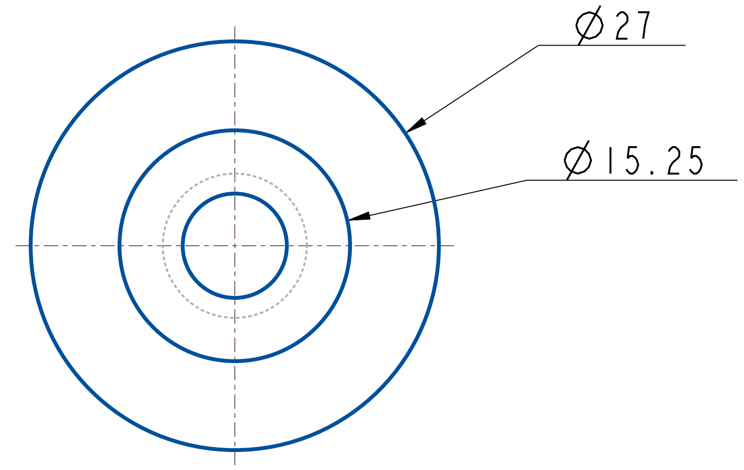
Artikell/Modell: PIPE_VALVE

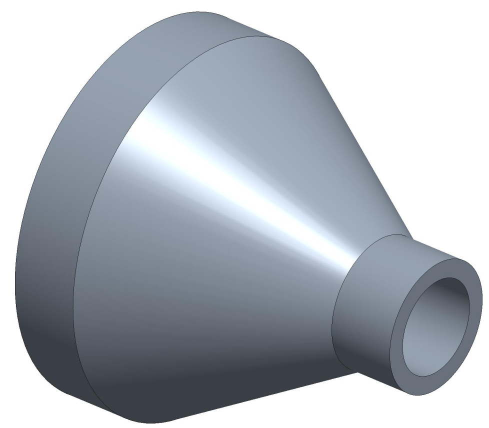
Beskrivelse:

Dato: 20-May-23

Tegning: PIPE_VALVE

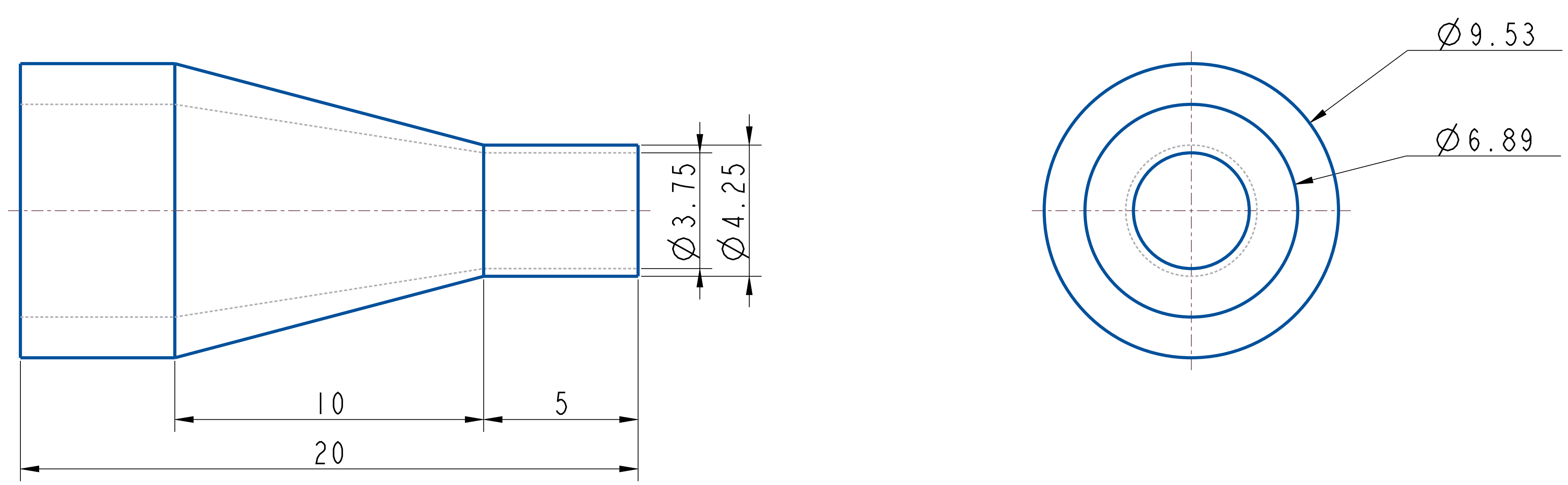


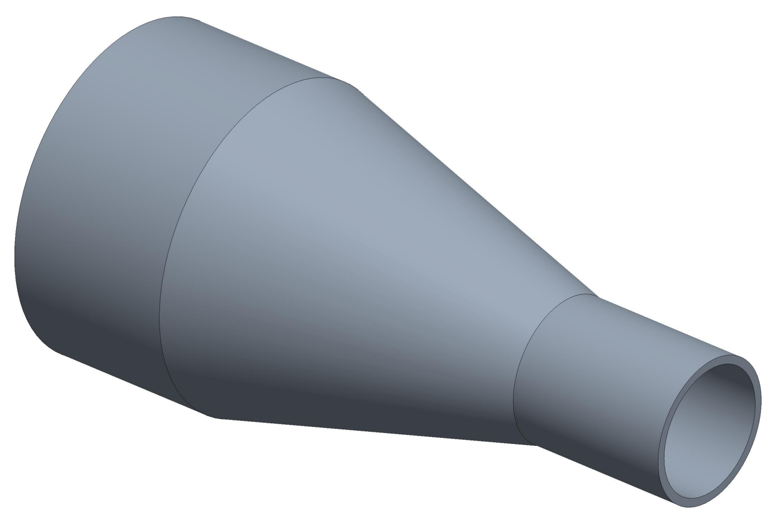




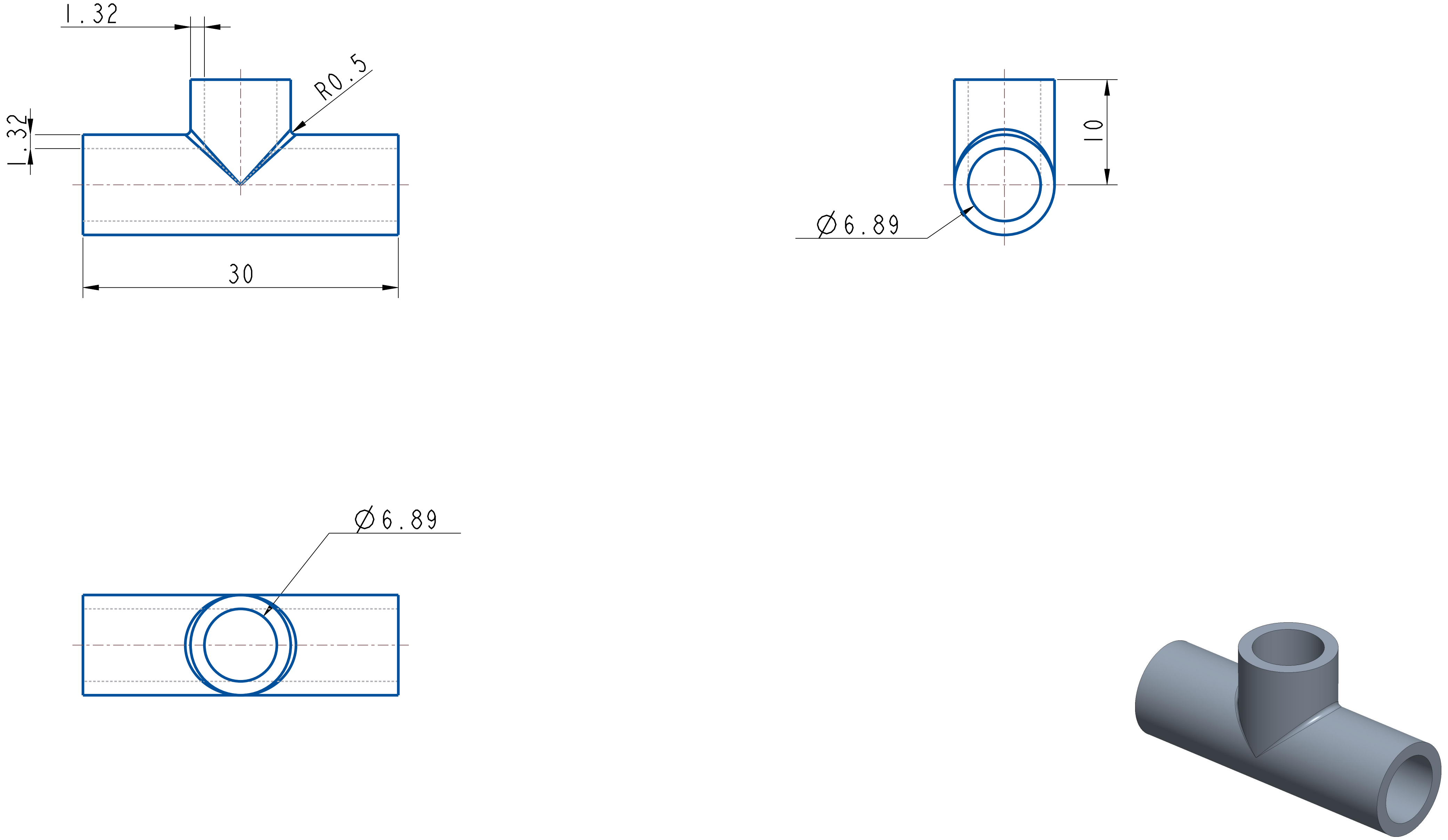
	1			S32760	ISO 2768 f
Pos	Ant	Artikell/Modell	Beskrivelse	Materiale	Dimensjon

Konstr	Tegnet Meisler	Revisjon	Vekt 38.22 g	Skala 2:1	Format A3	Blad.nr 1(1)
Høgskulen på Vestlandet IMM		Artikell/Modell REDUCER			Dato 20-May-23	
		Beskrivelse			Tegning REDUCER	





	1			S32760		ISO 2768 f	
Pos	Ant	Artikell/Modell	Beskrivelse	Materiale		Dimensjon	
Konstr	Tegnet Meisler	Revisjon	Vekt 2.75 g	Skala 5:1	Format A3	Blad.nr 1(1)	
Høgskulen på Vestlandet *IMM*		Artikell/Modell REDUCER_SMALL			Dato 20-May-23		
		Beskrivelse			Tegning REDUCER_SMALL		



Pos	Ant	Artikell/Modell	Beskrivelse	Materiale	Dimensjon
	1			S32760	ISO 2768 f

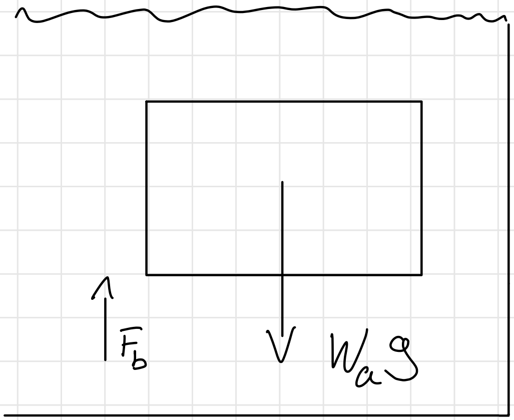
Konstr	Tegnet	Revisjon	Vekt	Skala	Format	Blad.nr
	Meisler		9.35 g	2:1	A3	1(1)

Høgskulen på Vestlandet
IMM

Artikell/Modell: SMALL_TEE
Beskrivelse:
Dato: 20-May-23
Tegning: SMALL_TEE

Attachment J Calculations for submerged weight

Weight in water caused by a buoyant force



$$F_b = V \rho_w g$$

$$W_w = W_a g - F_b$$

$$W_w = \frac{W_a g - V \rho_w g}{g}$$

$\rho_w = 1028\ kg/m^3$

where $S = 35‰$
and $T = 4°C$

$$W_w = 61{,}8\ kg - 7533951\ mm^3 \cdot 10^{-9} \frac{m^3}{mm^3} \cdot 1028\ kg/m^3$$

$$W_w \approx 54{,}1\ kg$$

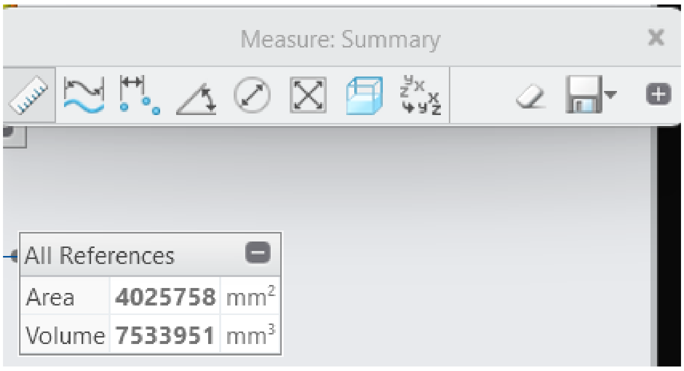


Figure 1: Volume from Creo model

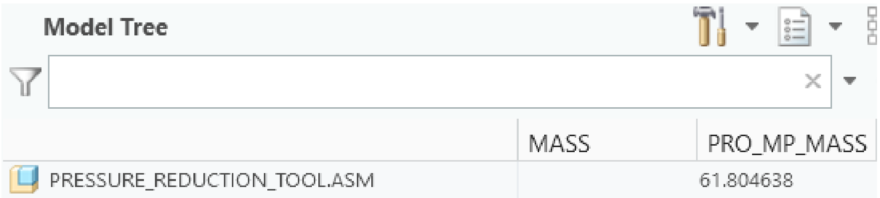


Figure 2: Weight from Creo model

Attachment K Unfinished script

The following headings define each Python file.

values.py

```
# Set modes

OPTIM_MODE = 0 # 0 = off, 1 = on

TEST_MODE = 1 # 0 = off, 1 = on


# Variables

P_TARGET = 0 # [bar]

TEST_ID = 0.00375 # [m]

TEST_LENGTH = 45 # [m]

INITIAL_VELOCITY = 0.002 # [m/s]


L_MAX = 80 # [m]

L_MIN = 10 # [m]

DL = 0.5 # [m]

TIME_UNIT = 'min' # 'min' or 's'


P_2_INIT = 690 # [bar] Initial pressure in PPS

V_2 = 2.5 # [m^3] Volume of PPS


P_1_INIT = 700 # [bar] Initial pressure in BFIC

V_1 = 0.9 # [m^3] Volume of BFIC


# Break conditions. Used for optimization

T_MAX = 400 # 'min' or 's' depending on unit set above

DP_23_MAX = 3.4 # [bar] Maximum change in pressure for each timestep

DP_12_MAX = 160 # [bar] Maxmimum difference in pressure between PPS and BFIC
```

main.py

```
import matplotlib.pyplot as plt

from density import castrol_density, seawater_density

from values import*

from worker import timestep_calc


# Conversion of units

p_target = P_TARGET * 10**5 # [Pa]


# Initial PPS values. Calculated at a tiny drop in pressure (1 Pa)

p_2_0 = P_2_INIT * 10**5 # [Pa]

rho_2_0 = seawater_density(p_2_0) # [kg/m^3]

k_2_0 = ((p_2_0 - 1) - p_2_0) * rho_2_0 / (seawater_density(p_2_0 - 1) - rho_2_0) # [Pa]

m_2_0 = rho_2_0 * V_2 # [kg]


# Initial BFIC values. Calculated at a tiny drop in pressure (1 Pa)

p_1_0 = P_1_INIT * 10**5 # [Pa]

rho_1_0 = castrol_density(p_1_0) # [kg/m^3]

k_1_0 = ((p_1_0 - 1) - p_1_0) * rho_1_0 / (castrol_density(p_1_0 - 1) - rho_1_0) # [Pa]

m_1_0 = rho_1_0 * V_1 # [kg]


# PEO values

peo_ids = [] # [m]


# Calculating time and pressuredrop for different PEO ids and lengths

if TEST_MODE == 1:

    time, p2_vals, p1_vals, q2_vals, q1_vals = timestep_calc(V_2, p_2_0, rho_2_0, k_2_0, m_2_0, V_1,
p_1_0, rho_1_0, k_1_0, m_1_0, p_target,
```

```
                                    TEST_ID,    TEST_LENGTH,    TIME_UNIT,    0,    0,    0,
INITIAL_VELOCITY, 0)

    # Plotting
    # Labels and titles
    label1 = 'PPS pressure'
    label2 = 'BFIC pressure'
    label3 = 'PPS flowrate'
    label4 = 'BFIC flowrate'
    title1 = 'Pressure in PPS and BFIC'
    title2 = 'Flowrate in PPS and BFIC'
    x_label = 'Time [' + TIME_UNIT + ']'
    y_label1 = 'Pressure [bar]'
    y_label2 = 'Flowrate [m^3/s]'

     # Create a figure and two subplots side by side
    fig, (ax1, ax2) = plt.subplots(1, 2, figsize=(15, 5))

    # Plot some data on the first subplot
    ax1.scatter(time, p2_vals, label=label1)
    ax1.scatter(time, p1_vals, label=label2)
    ax1.set_title(title1)
    ax1.set_xlabel(x_label)
    ax1.set_ylabel(y_label1)
    ax1.legend()

    # Plot some data on the second subplot
    ax2.plot(time, q2_vals, label=label3)
    ax2.plot(time, q1_vals, label=label4)
```

```
    ax2.set_title(title2)
    ax2.set_xlabel(x_label)
    ax2.set_ylabel(y_label2)
    ax2.legend()

    # Show the plot
    plt.show()
```

worker.py

```
from pressure import new_pressure, new_pressure_0
from flowrate import bfic_flow, peo_flow
from mass import bfic_dmass, pps_dmass
from density import seawater_density, castrol_density

def timestep_calc(pps_volume, initial_pps_pressure, initial_pps_density, initial_pps_bulk_modulus, initial_pps_mass,
                  bfic_volume, initial_bfic_pressure, initial_bfic_density, initial_bfic_bulk_modulus, initial_bfic_mass,
                  p_target, peo_id, peo_length, time_unit, time_break_condition, pressure_drop_break_condition,
                  maximum_delta_break_condition, initial_velocity, break_conditions_on_off):
    # Initial values
    velocity = initial_velocity
    t = 0

    # Lists for plotting
    timesteps = []
    pps_pressures = []
    bfic_pressures = []
```

```
peo_flowrates = []
bfic_flowrates = []

# Initializing
d = peo_id
l = peo_length

p_2_now = initial_pps_pressure # [Pa]
rho_2 = initial_pps_density # [kg/m^3]
m_2 = initial_pps_mass # [kg]
v_2 = pps_volume # [m^3]
k_2_0 = initial_pps_bulk_modulus # [Pa]

p_1_now = initial_bfic_pressure # [Pa]
rho_1 = initial_bfic_density # [kg/m^3]
m_1 = initial_bfic_mass # [kg]
v_1 = bfic_volume # [m^3]
k_1_0 = initial_bfic_bulk_modulus # [Pa]

# Calculation of values for t = 0
q_1 = bfic_flow(p_1_now - p_2_now) # [m^3/s]
q_2, velocity = peo_flow(velocity, d, p_2_now - p_target, l, rho_2) # [m^3/s]

dm_1 = bfic_dmass(q_1, rho_1) # [kg]
dm_2 = pps_dmass(dm_1, q_2, rho_2) # [kg]

if q_1 == 0:
    p_1_now, p_1_old = new_pressure_0(m_1, dm_1, v_1, p_1_now, rho_1, k_1_0) # [Pa]
```

```
else:
    p_1_now, p_1_old = new_pressure(m_1, dm_1, v_1, p_1_now, rho_1, k_1_0) # [Pa]
p_2_now, p_2_old = new_pressure_0(m_2, dm_2, v_2, p_2_now, rho_2, k_2_0) # [Pa]

rho_1 = castrol_density(p_1_now) # [kg/m^3]
rho_2 = seawater_density(p_2_now) # [kg/m^3]

# Calculating pressure in BFIC and PPS while PPS pressure is higher than target pressure
while True:

    # Pressure differences
    dp_12 = p_1_now - p_2_now # [Pa]
    dp_23 = p_2_now - p_target # [Pa]

    if dp_23 < 0:
        break

    # Flowrates
    q_1 = bfic_flow(dp_12) # [m^3/s]
    q_2, velocity = peo_flow(velocity, d, dp_23, l, rho_2) # [m^3/s]

    # Mass flow
    dm_1 = bfic_dmass(q_1, rho_1) # [kg]
    dm_2 = pps_dmass(dm_1, q_2, rho_2) # [kg]

    # Pressure
    if q_1 == 0:
        p_1_now, p_1_old = new_pressure_0(m_1, dm_1, v_1, p_1_now, rho_1, k_1_0) # [Pa]
```

```
        else:
            p_1_now, p_1_old = new_pressure(m_1, dm_1, v_1, p_1_now, p_1_old, rho_1) # [Pa]
        p_2_now, p_2_old = new_pressure(m_2, dm_2, v_2, p_2_now, p_2_old, rho_2) # [Pa]

        # Density
        rho_1 = castrol_density(p_1_now) # [kg/m^3]
        rho_2 = seawater_density(p_2_now) # [kg/m^3]

        # Appending values for plotting
        timesteps.append(t)
        pps_pressures.append(p_2_now)
        bfic_pressures.append(p_1_now)
        peo_flowrates.append(q_2)
        bfic_flowrates.append(q_1)

        # Incrementing timestep
        if time_unit == 'min':
            t += 0.01
        elif time_unit == 's':
            t += 1

    return timesteps, pps_pressures, bfic_pressures, peo_flowrates, bfic_flowrates
```

density.py

```
def castrol_density(p): # Input is Pa
    p = p / 10**5 # Pa to bar
    return 0.0497 * p + 807.03 # kg/m^3 p -> [bar]
```

```
def seawater_density(p): # Input is Pa
    p = p / 10**6 # Pa to MPa
    return -0.0007 * p**2 + 0.5028 * p + 1027.8 # kg/m^3 p -> [MPa]
```

flowrate.py

```
import numpy as np


def bfic_flow(dp): # Input is Pa
    dp /= 10**5 # Pa to bar


    spv_set = 60 # [bar]
    spv_dp_max = 75 # [bar]
    hfspv_set = 70 # [bar ]
    hfspv_dp_max = 77 # [bar]
    conversion = 0.001 / 60  # Converts l/min to m^3/s


    # SPV
    if spv_set < dp <= spv_dp_max:
        q_spv = (dp - 61.32) / 0.611
    elif dp > spv_dp_max:
        q_spv = (spv_dp_max - 61.32) / 0.611
    else:
        q_spv = 0


    # HFSPV
    if hfspv_set < dp <= hfspv_dp_max:
        q_hfspv = (dp / 68.246)**(625 / 19)
    elif dp > hfspv_dp_max:
```

```
        q_hfspv = (hfspv_dp_max / 68.246)**(625 / 19)
    else:
        q_hfspv = 0

    q_bfic = (q_spv + q_hfspv) * conversion

    return q_bfic # [m^3/s]

def peo_flow(velocity, id, dp, peo_length, pps_density): # Input is m/s, m, Pa, m, kg/m^3

    velocity_new = 0
    kv = 0.0000001
    delta_sensitivity = 0.0000000000001
    pi = np.pi

    while True:
        reynolds = (velocity * id) / kv
        friction_factor = friction_factor_calc(reynolds)

        square_root = (2 * dp * id) / (peo_length * friction_factor * pps_density)

        if (square_root) < 0:
            return 999
        else:
            velocity_new = np.sqrt(square_root)

        if abs(velocity_new - velocity) < delta_sensitivity:
            peo_flowrate = velocity_new * id**2 * (pi / 4)
```

```
            return peo_flowrate, velocity_new # [m^3/s]

        velocity = velocity_new

def friction_factor_calc(reynolds):

    # Calculates the friction factor based on the reynolds number
    if reynolds <= 2300: # Laminar flow
        friction_factor = 64 / reynolds
    elif reynolds >= 4000: # Turbulent flow
        friction_factor = 0.3164 / (reynolds**0.25)
    else: # Transition flow
        y0 = 64 / reynolds # Laminar flow
        y1 = 0.3164 / (reynolds**0.25)
        friction_factor = y0 + (((y1 - y0) * (reynolds - 2300)) / (4000 - 2300)) # Linear interpolation

    return friction_factor
```

pressure.py

```
def new_pressure(m, dm, v, p_now, p_old, rho_now):
    rho_new = (m + dm) / v
    k = (p_now - p_old) * rho_now / (rho_new - rho_now)
    p_new = p_now + k * (1 - rho_new / rho_now)
    return p_new, p_now

def new_pressure_0(m, dm, v, p_now, rho_now, k_0):
    rho_new = (m + dm) / v
    p_new = p_now + k_0 * (1 - rho_new / rho_now)
```

```
    return p_new, p_now
```

mass.py

```
def bfic_dmass(q_bfic, rho_1):
    return -q_bfic * rho_1


def pps_dmass(dm_1, q_peo, rho_2):
    return dm_1 - q_peo * rho_2
```