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Design of Compact Separator Laboratory

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Master Thesis

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In addition to oil and gas, oil wells also produce significant amounts of water. In the North Sea, this water — along with the hydrocarbons — is pumped to platform or on-shore facilities, where water is separated out before being discharged to sea or sometimes re-injected into a well. Pumping this water to the surface represents both a significant cost and has major environmental impact. If the water could be separated to sufficient purity on the seabed, it would both reduce operating expenses and the environmental impact.

A subsea separation facility needs to be compact due to limitations in vessels and equipment used to install subsea systems. These compact separators have complex and challenging dynamics, and handle transients and other non-ideal conditions too poorly to be used today. New control algorithms should solve or alleviate these problems. To aid with developing these algorithms, the Department of Production and Quality Engineering wishes to construct a small-scale compact separation laboratory.

In this Master's thesis, the students shall plan and design the compact separator laboratory. This laboratory should facilitate for research on relevant topics in compact subsea separation, include flexibility for future expansions, and seek to include state of the art equipment within separation technology. As part of this, the students shall

- Perform a literature review
- Design the laboratory facility
    - Choose key system parameters such as flow, temperature and pressure
    - Physical layout and design of key components, including material choices
    - Pick sensors and actuators, including support for auxiliary functions such as disturbance generators, pumps to move the fluid and others
    - Choose fluids to separate
    - Pick vendors and create a budget
- Take full consideration of HSE during design and construction, and create the necessary contingency plans

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Preface

This Master's thesis is the result of a design project carried out during the spring semester of 2016 at the Department of Production and Quality Engineering, Norwegian University of Science and Technology (NTNU).

The thesis came as a result of the Center of Innovation-Driven Research (SFI) SUBPRO (Subsea Production and Processing), which is a cooperation between the Norwegian University of Science and Technology and several companies in the oil and gas industry. The partners in SUBPRO expressed an interest in the concept of compact subsea separation, and a problem description was formulated through dialog between the students, Associate Professor Christian Holden and PhD Candidate Sveinung Johan Ohrem.

The thesis has been developed through continuous dialog with industry professionals, equipment suppliers, SUBPRO partners and academical staff. These oral sources have contributed with a significant amount of input to finalize the design of the laboratory, as well as highlighting technology which is relevant for the industry. To distinguish between information given by oral sources and written sources, oral sources are marked in the text as roman letters in brackets while written sources are marked as numbers in brackets. Some of the supplied information is considered to be confidential by the equipment suppliers, and will for that reason not be presented in this report.

The thesis is written for the Department of Production and Quality Engineering, but can hopefully be of interest for the oil and gas business in general. Basic knowledge about oil and gas and subsea processing is assumed known, however, the thesis aims to explain most of the fundamental aspects that are important for the complete understanding.

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SINTEF, especially Espen Krogh and Tor Erling Unander, for taking interest in our project and a potential cooperation when Phase 1 of the laboratory is constructed.

We would also like to thank all the equipment suppliers for their patience through several changes of the design, and for their genuine interest in identifying the best fitted equipment and solutions.

We deeply appreciate the fact that all of you have set aside both time and interest to assist us with your knowledge and experience in your otherwise busy schedule. Thank you.

O.N.

Emil Yde Aasen
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Summary

Most of the easily accessible offshore oil and gas resources have been developed. As a result of this, subsea production and processing has over the last decade been regarded as the future of the offshore oil and gas industry. Operators are moving into more complex environments and remote locations. The increased water depths and lower temperatures implies that the existing subsea technology is in constant need of innovation.

Through the Center of Innovation-Driven Research (SFI) SUBPRO (Subsea Production and Processing), which is a cooperation between NTNU and several companies in the oil and gas industry, the industry partners expressed an interest in compact separation technology, especially hydrocyclones and Compact Flotation Units (CFUs). Since the large vessels used in conventional subsea separation technology are limited by both hydrostatic pressure and installation complexity, compact separation technology is considered a necessity for operating at greater water depths. Because of their limited volume and short residence time, compact separators are sensitive towards flow irregularities. Flow irregularities are changes in pressure and flow rate that occurs naturally in a well stream, or during start up and shut down of a well. These irregularities can potentially have a negative impact on separation efficiency. Avoiding or suppressing the effects of these flow irregularities is some of the current challenges in compact separation design.

This Master's thesis describes the design of a compact separator laboratory that will facilitate research on novel control algorithms. The design is based on a multi-stage hydrocyclone system, with three hydrocyclones in series. The laboratory focuses on produced water treatment, and aims to meet the governmental regulations for disposal of produced water to the sea. By developing new aspects in control theory, the control algorithms aim to solve the problems related to flow irregularities in compact separation. As a result, the design includes several fast acting control valves, pressure- and temperature transmitters, and flow meters to provide a continuous real time overview of the system. Oil-in-Water (OiW) sensors are included to monitor the OiW concentration, and act as an input to the control system. Low shear control valves are also included in order to compare the impact on separation efficiency with conventional control valves.

The compact separator laboratory is designed and constructed through four individual phases. An additional phase, containing a feeding– and reservoir system, has also been designed. The phases are implemented based on the experience and requirements of the previous phase/phases. The last of the four phases focuses on future solutions, and is not implemented in the budget.

The main focus of this thesis is the specific design of Phase 1, but in order to account for future expansions and increased flexibility, Phase 2, 3 and 4 are included in the design. Technical future proofing is applied in the design of Phase 1 to ease the implementation of the later phases. Phase 1 will be connected to a Cameron feeding system, with both a gravity separator and oil- and water pumps. Phase 1 is designed with EX certified components to allow testing with crude oils, which increases the credibility of the results. The additional phase, a reservoir and a feeding pump system, are designed in detail to allow fast implementation if the Cameron feeding system proves to be disadvantageous for the separation results.

The total budget for the design, construction and operation of the compact separator laboratory is NOK 3,000,000. The proposed design is within the budget and has an economical safety factor of 1.50 %. The health, environment and safety aspects has influenced the entire

design process, and all chosen process equipment has a safety factor of 1.6 with respect to operating pressure. A NTNU standard risk assessment have been conducted.

Sammendrag

I løpet av det siste tiåret har undervannsproduksjon blitt ansett for å være fremtiden for olje- og gassindustrien. Dette kommer som en følge av at de mest tilgjengelige olje- og gassressursene har blitt utvunnet, og som en direkte konsekvens av dette er operatører tvunget til å utforske stadig mer avsidesliggende områder med tilhørende dypere havdyp og lavere temperaturer. Dette fører til et konstant behov for teknologisk innovasjon innenfor undervannsproduksjon av olje og gass.

Gjennom SUBPRO, Senter for Forskningsdrevet Innovasjon (SFI), som er et samarbeid mellom NTNU og flere sentrale aktører i olje- og gassindustrien, har industrien gitt uttrykk for en interesse rundt kompakte separasjonsløsninger. Spesielt hydrosykloner og kompakte flotasjonsenheter (CFU) har vært av særskilt interesse. Tradisjonelle separasjonskonsepter har, som følge av deres vekt og størrelse, begrensende installasjonsmuligheter på store havdyp. Kompakt separasjonsteknologi er derfor en forutsetning for å kunne produsere på slike havdyp. Samtidig er kompakte separasjonsløsninger begrenset av deres små volum og relativt korte oppholdstider. Dette gjør dem spesielt sensitive ovenfor uregelmessigheter i trykk og flyt, som potensielt kan redusere separasjonseffektiviteten. Disse uregelmessighetene kan oppstå naturlig i brønnstrømmen, og under oppstart og nedstenging av brønnen. En av de nåværende utfordringene i kompakte separasjonssystemer er derfor å unngå eller redusere disse uregelmessighetene.

Denne masteroppgaven beskriver designet av et kompakt separasjonslaboratorium som skal fasilitere for forskning på nye kontrollalgoritmer. Designet er basert på et flertrinns hydrosyklon system, der tre hydrosykloner er plassert i serie. Laboratoriet fokuserer på rensing av produsert vann, og ønsker å imøtekomme det statlige regelverket for utslipp av produsert vann til sjøs. Gjennom nyvinning og innovasjon, sikter kontroll algoritmene på å løse problemene innenfor kompaktseparasjon relatert til trykk– og strømningsuregelmessigheter. Designet inkluderer derfor en rekke kontrollventiler med lav responstid, trykk– og temperaturtransmittere, og flytmetere for å levere kontinuerlig oversikt av systemet i sanntid. Olje-i-vann sensorer er inkludert for å måle konsentrasjonen av olje i vann, i tillegg til å generere input til kontrollsystemet. Lavskjærsventiler er også inkludert for å måle deres innvirkning på separasjonseffektiviteten, sammenlignet med tradisjonelle kontrollventiler.

Det kompakte separasjonslaboratoriet er designet og konstruert gjennom fire individuelle faser. Designet inkluderer også en tilleggs fase bestående av et forings– og reservoarsystem. Fasene blir implementert basert på erfaringer og behov som har blitt avdekket i de forgående fasene. Den siste fasen fokuserer på implementering av fremtidige løsninger, og er derfor ikke inkludert i budsjettet.

Et detaljert design av Fase 1 har vært hovedfokuset i denne oppgaven. Samtidig har oppgaven prøvd å ta høyde for fremtidige utvidelser ved å inkludere teknisk fleksibilitet i designet, i tillegg til å designe utkast for Fase 2, 3 og 4. Teknisk fleksibilitet i Fase 1 er en forutsetning for å forenkle implementeringen av de senere fasene. Fase 1 vil bli koblet til Cameron sitt foringssystem, bestående av en gravitasjonsseparator, en oljepumpe og en vannpumpe. For å ha muligheten til å gjøre eksperimenter med ulike typer råolje, er alle komponenter i Fase 1 EX-sertifisert. Dette vil øke troverdigheten til resultatene. Tilleggs fasen, med forings– og reservoarsystem, er designet i detalj for å kunne implementeres dersom det skulle vise seg å være mindre fordelaktig å benytte Camerons foringssystem med tanke på separasjonsresultatet.

Design, konstruksjon og drift av kompakt separasjonslaboratoriet har et totalt budsjett på NOK 3,000,000. Det foreslåtte designet er innenfor budsjettrammen og har en økonomisk

sikkerhetsfaktor på 1.50 %. Helse, miljø og sikkerhet har vært et gjennomgående tema for hele designprosessen, og med hensyn på operasjonstrykk har alle komponenter blitt valgt med en sikkerhetsfaktor på 1.6. En standard NTNU risikoanalyse har blitt utarbeidet.

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Abbreviations

BPD	Barrels per Day.
CP	Centrifugal Pump.
dP	Differential Pressure
ERT	Electrical Resistivity Tomography.
FS	Flow split.
FUA	Focused Ultrasonic Acoustics.
GVF	Gas Volume Fraction.
HAZOP	Hazard and Operability Study.
HDPE	High Density Poly Ethylene.
HSE	Health Safety and Environment.
ISE	Internal Swirl Element.
LIF	Laser Induced UV Fluorescence.
NORSOK	The NORSOK standards are developed by the Norwegian petroleum industry to ensure adequate safety, value adding and cost effectiveness for petroleum industry developments and operations.
NTNU	Norwegian University of Science and Technology.
OiW	Oil-in-Water.
PCP	Progressive Cavity Pump.
PDR	Pressure Drop Ratio.
PN	Pressure Number.
PPM	Parts Per Million.
PWT	Produced Water Treatment.
SCC	Stress Corrosion Cracking.
SCH	Pipe schedule - wall thickness of pipes.
Skid	Metal frame.
SUBPRO	Subsea Production and Processing.
UV	Ultraviolet.
VSD	Variable Speed Drive.
ViPA	Visual Process Analyser.
WC	Water Cut.
WiO	Water-in-Oil.

Nomenclature

$a_c(r)$	Centrifugal acceleration [m/s^2].
C_i	Oil concentration inlet [%].
C_u	Oil concentration underflow [%].
D	Diameter of the large conical section [m].
D_1	Diameter of the vortex cavity [m].
D_i	Diameter of the inlet [m].
D_o	Diameter of the oil outlet [m].
D_u	Diameter of the cylindrical tail tube [m].
d	Diameter of the droplet [μm].
d_{50}	Cut size. The diameter of the particles that has a 50 % probability of being separated in the hydrocyclone [μm].
d_{max}	The maximum droplet size that can exist at equilibrium considering the coalescence rate and dispersion rate [μm].
F_B	The inwardly acting centrifugal buoyancy force [N].
F_C	The outwardly acting centrifugal force [N].
F_D	The inwardly acting drag force [N].
F_s	Flow split [%].
g	Gravitational constant [m/s^2].
L	Length of hydrocyclone [m].
L_o	Length of the oil outlet [m].
L_1	Length of the vortex cavity [m].
L_2	Length of the fine conical section [m].
L_3	Length of the cylindrical tail tube [m].
P_{PDR}	Pressure drop ratio [-].
P_i	Pressure inlet [bar].
P_o	Pressure overflow [bar].
P_u	Pressure underflow [bar].
Q	Volumetric flow rate [m^3/h].
Q_i	Volumetric flow rate inlet [m^3/h].
Q_o	Volumetric flow rate overflow [m^3/h].
Q_u	Volumetric flow rate underflow [m^3/h].
Q_{min}	Minimum volumetric flow rate [m^3/h].
Q_{max}	Maximum volumetric flow rate [m^3/h].
r	Orbit radius of the droplet [m].
r_d	Radius of the droplet [m].
t_r	Retention time [s].

u_r	Radial velocity [m/s].
u_θ	Tangential velocity [m/s]
α	Cone angle [°].
β	Fine cone angle [°].
ϵ	The separation efficiency in a hydrocyclone [%].
μ	Viscosity [cSt].
ρ	Density of the continuous phase [kg/m^3].
ρ_d	Density of the dispersed phase [kg/m^3].
ρ_o	Oil density [kg/m^3].
ρ_w	Water density [kg/m^3].
σ	Surface tension [N/m].

Chapter 1

Introduction

This Master's thesis constitutes a subproject of the Center of Innovation-Driven Research (SFI) SUBPRO (Subsea Production and Processing). SUBPRO is a cooperation between the Norwegian University of Science and several companies in the oil and gas industry, and aims to accelerate the level of innovation by combining highly relevant research groups at NTNU with the unique subsea competence and experience provided by the industry [1]. The SUBPRO homepage states the following [1]:

> "*Subsea production and processing technology is a key enabler for exploitation of Norwegian and international oil and gas resources. Norwegian oil companies and foreign oil companies with basis in Norway, with the strong support of Norwegian-based suppliers and manufacturing companies, have been in the forefront of developing subsea fields. However, new subsea solutions are needed to increase the recovery factor of existing fields on the Norwegian Continental Shelf, to reduce the cost of subsea installations and to allow development of new more demanding fields, such as in the Northern areas and the Barents sea.*"

According to [2], subsea processing is a key enabler for development of more remote field areas, and the benefits from applying this technology increases with both production rate, step-out distance and water depth. Subsea installations normally involves a larger cost than topside developments in shallow waters, and as a result conventional platforms have been preferred in fields with easily accessible resources. However, given the fact that most of the easily accessible resources have been developed, the oil and gas industry are currently forced to focus on deeper, colder, and more remote locations in order to maintain or increase their level of production. For these locations, subsea processing is the preferred technology both with regards to operational safety, total cost and production potential. [2]

The separation process is summarized as the heart of the offshore production system [3], and for a subsea processing system the benefits are maximized with the implementation of subsea compact separation technology [2]. This is mainly because conventional separation equipment consists of large vessels which constitutes a great part of the total size and weight of the overall processing system. The massive dimensions in size and weight, makes subsea installation of these vessels problematic at water depths greater than approximately 300 meter. This is because larger vessels need an increase in wall thickness corresponding to the water depth in order to withstand the hydrostatic pressure. Compact subsea separation technology is therefore considered to be an important part of subsea processing as operators move into more complex environments and increased water depths. However, because of their limited volume and short residence time, compact subsea separators are sensitive to flow irregularities. As a result, the development of compact designs and process control which are robust towards flow irregularities are of great interest for the oil and gas industry. [3]

As a part of the SUBPRO focus, combined with the industry's interest in compact subsea separation, this Master's project aims to develop a state of the art design of a compact separation laboratory. The design will serve as a foundation for the later construction of the laboratory and the implementation of novel system control algorithms. The laboratory will focus on produced water treatment, which is the last step in a liquid–liquid separation process.

With regards to references, this paper consists of both written and oral sources of information. The written sources can be found in the bibliography and are marked with Arabic numbers inside square brackets throughout the paper, while the oral sources can be found in Appendix A and are marked with roman numbers inside square brackets throughout the paper. This must not be confused with equation references, which are placed inside parentheses. The paper aims to shorten the gap between academia and the industry, and continuous dialog with different professionals with operational experience have been an important tool.

1.1 Background

As stated by [4], the environmental challenges facing the oil and gas industry will continue to increase in the future. This comes as a result of the Paris Agreement determined at the COP21 meeting in December 2015 [5], and the fact that more sensitive production areas are being opened for exploration and production [4]. A typical oil and/or gas reservoir will have several parameters that change during the course of production life, such as reservoir pressure, gas volume fraction (GVC) and water cut (WC) [3].

A large number of operative fields are now moving into the later phases of production, and this involves an increased water cut and decreased pressure in the reservoir [6]. Transporting the produced water back to the topside platform for further processing involves large operational costs, and these costs increase along with the increasing water cuts in the well stream. Over the past 10 years, subsea technology has therefore had an increased focus on subsea separation in order to re-inject the produced water directly into a well or to dispose it directly into the sea [6]. Because of the Paris Agreement, produced water treatment is an even more important aspect of future subsea separation and will be a focus area in compact subsea separator system design. As a result, this project will reflect this focus and aim to comply with the OSPAR convention. The OSPAR convention is further explained in Section 2.5.2.

The first subsea test separator was installed outside Abu Dhabi in the Zakum project as early as 1969 [6], however, it is the developments over the last decade with the installation of the Troll Pilot on the Statoil operated Troll field, the Tordis semi-compact separator on the Statoil operated Gullfaks C, and the worlds first deep water separator Marlim SSAO at the Petrobras operated Marlim field, that have made the greatest impacts [7].

The Marlim SSAO is the first subsea separator to utilize deoiling hydrocyclones. Two hydrocyclones are placed in series downstream of a pipe separator and a desander for the purpose of polishing the oil-in-water (OiW) content to a concentration level of 100 ppm, which is the maximum allowable oil concentration to be pumped into the injection well [8]. Higher OiW concentrations, could potentially clog the pores in the reservoir, which would decrease the production rate and the economical potential. An OiW concentration of 100 ppm is still more than 3 times higher than the allowed value in the OSPAR convention.

Regarding conventional separation equipment, mainly consisting of large vessels in different configurations, one of the major disadvantages has been the lack of flexibility related to modifying the equipment capacity, size and robustness, as the reservoir parameters change through the production life. As a result, expansions and retrofitting of existing separation equipment is often costly and complex. Inline separation equipment offers new degrees of freedom, and can be installed both in series and in parallel with existing equipment to increase capacity and performance [3].

One of the major drawbacks with hydrocyclones, is the sensitivity towards flow irregularities [9]. For conventional separation equipment, the large vessels act as a buffer against variations in operational pressure, flow rate, and oil phase concentrations, enabling it to uphold steady state conditions and separation efficiency. Flow transients appear naturally in the well stream, in pipelines, and during start up and shut down of a valve. As a result of being compact designs, hydrocyclones have limited size, and can not act as a buffer towards flow irregularities. Thus, dynamical changes in pressure, flow rates and oil concentrations will result in a significant decrease in the separation efficiency, and high energy pressure variations could also potentially damage the equipment [9]. Because of this, a solution that could avoid flow irregularities in compact separation systems is of great interest for the industry.

Laboratory setups using hydrocyclones have been previously built, for example by Kvaerner in 1999 [XI] and recently by the University of Aalbord, campus Esbjerg [V]. This project will focus on designing a laboratory that allows for further research and implementation of novel control algorithms. The control algorithms will be developed as a part of a PhD at the Department of Production and Quality Engineering at NTNU, and will aim to avoid the occurrence of flow transient in the compact separator laboratory.

1.2 Problem Description

As a result of the current focus in the oil and gas industry and the relevance of developing new designs for compact separation to cope with the increasingly complex production environment in subsea production systems, the following problem formulation has been developed:

In this Master's thesis, the students shall plan and design the compact separator laboratory. This laboratory should facilitate for research on relevant topics in compact subsea separation, include flexibility for future expansions, and seek to include state of the art equipment within separation technology.

With regards to audience, the paper is written for the Department of Production and Quality Engineering, but can hopefully be of interest for the oil and gas industry in general.

1.3 Objectives

The main objectives of this Master's thesis are

1. Perform a literature review.
2. Design the laboratory facility.
    (a) Choose key system parameters such as flow, temperature and pressure.

    (b) Physical layout and design of key components, including material choices.
    (c) Pick sensors and actuators, including support for auxiliary functions such as disturbance generators, pumps to move the fluid and others.
    (d) Choose fluids to separate.
    (e) Pick vendors and create a budget.

3. Take full consideration of HSE during design and construction, and create the necessary contingency plans.

1.4 Limitations

The proposed design described in this Master's thesis comes as a result of continuous consultation with several professionals in the oil and gas industry, input and guidance from equipment suppliers, and the authors' insight in academia and relevant research on the subject of compact separation. Final design decisions have been taken in consultation with Associate Professor Christan Holden [V] and PhD Candidate Sveinung Johan Ohrem [XIII], and quality assurance have been conducted by the different partners in SUBPRO. Knowing this, the design is still limited by the choices of the authors, and the insight they have acquired in the literature review. For that reason, it is important to underline that this design focuses on the produced water treatment aspect of a separation process, as well as other peripheral technology that is relevant for this process.

The design is also limited by the economical boundaries set by SUBPRO. The compact separation laboratory have been awarded with NOK 3,000,000, which is an absolute limit with respect to cost. The budget might be expanded with future allocations, but at the current time this limit is finite. Given the cost of some of the sensors implemented in the design, this economical boundary has limited the design to some extent, even though it is a considerable amount of money for research purposes.

1.5 Approach

This Master's thesis has combined a qualitative and a quantitative approach in order to develop a design that aims to satisfy the previously stated objectives. The qualitative approach has been utilized to identify the functionality that the compact separation laboratory would include, while a qualitative approach has been further utilized to specify and scale down this functionality to the extent that it is able to facilitate for the relevant research in the best way.

The design process has been supervised by Associate Professor Christian Holden [V], and given the fact that Mr. Holden is the person responsible for the future operation and maintenance of the laboratory, he has had the final word when major design decisions has been made. In relation to the main objectives of this paper, the following approach has been used:

1. *Perform a literature review:* As described in Chapter 3, the industry partners in SUBPRO had already expressed their interest in compact separation and hydrocyclones before the start of this project. For that reason, the literature review was focused on the subject of hydrocyclone separation, but was at a later point expanded to include Compact Flotation Units (CFU) as a result of the shift in interest from the SUBPRO industry partners. The

literature review also focuses on other relevant components and equipment that will be included in order to make the compact separation laboratory operational.

2. *Design the laboratory facility:* Each of the sub objectives in this objective was addressed after the qualitative assessment of the design had been conducted. The hydrocyclones were the dimensioning equipment with regards to flow, pressure and temperature, and sensors and actuators was chosen on the basis of designing a system that would be optimized for the future implementation of control algorithms. Materials were chosen in order to avoid corrosion, and withstand operational pressure and temperature. Fluids were originally chosen to avoid EX-certification of the laboratory, however, with the potential cooperation with SINTEF, the EX-certified equipment would still need to be implemented. With respect to ordering parts, contact with the suppliers have been established. The ordering of the parts have, based on consultation with Mr. Holden [V], been postponed until Fall 2016. The system parameters have been changed throughout the design process as a consequence of continuous input from suppliers and professionals in the industry.

3. *Take full consideration of HSE during design and construction, and create the necessary contingency plans:* Safety has been addressed in every aspect of the design. In the qualitative part of the design process, the NTNU safety factor of minimum 1.6 has been included in all process equipment. The design has continuously been discussed with industry professionals to ensure both the safety and the functionality of the design. The conformity assessment for pressurized equipment, set by DSB [10], acts as a quality check for Norwegian suppliers, and has been a great guideline for the design process. A risk assessment has also been conducted according to NTNU standards. See Chapter 7 and Appendix H for further information. At some point a Hazard and Operability Analysis (HAZOP) study of the laboratory was also considered, but based on the consultation with Mr. Holden [V], this part of the HSE aspect will be more relevant when the laboratory has been constructed.

1.6 Structure of the Thesis

This Master's thesis is organized in such a manner that it enables the reader to follow the design process from start to finish without refering to previous chapters to understand the content of the information. Thus, separate chapters and sections should be seen in context with the paper as a whole, and are not meant to be independent pieces of information.

The rest of this Master's thesis is organized as follows. Chapter 2 is a literature review which explains the basic concepts of compact separation, as well as other technologies that would be relevant to implement in the laboratory design. Examples are OiW sensors, pumps, and valves. Future concepts, which are technology and equipment that could be of interest to implement in the future, are also introduced briefly. In addition, it also includes some of the legal aspects that must be considered when developing the design.

Chapter 3, The Evolution of the Design, represents the method of this thesis. It enables the reader to follow the design process from the start on January 15th 2016, until the end on June 10th 2016. All changes in design, budget and implemented equipment are explained, and the impact of cooperation with different industry partners have also been clearly highlighted.

Chapter 4, Final Design, represents the results of this thesis. It summarizes the results of the design process explained in Chapter 3, The Evolution of the Design. It is recommended to read Chapter 3 to understand the full context of the final design.

Chapter 5, Proposed Equipment, lists the proposed equipment for the compact separator laboratory. Each part of the equipment is categorized in its installation phase, and relevant info such as equipment parameters and supplier status is listed.

Chapter 6, Budget, presents an overview of the budget in this project. The detailed budget is not listed, due to confidential offers from the suppliers. However, the budget is broken down into equipment categories and phases. This level of detail offers to some extent insight in the economical distribution between the phases.

Chapter 7, Health, Safety and Environment (HSE), presents how safety has been included in the design, as well as the different assessments and guidelines that have been used to meet NTNU safety standards.

Chapter 8, Conclusion and Recommendations, concludes the thesis based on the objectives stated in Chapter 1. Recommendations for the scope of future work is also included in this Chapter.

Chapter 2

Literature Review

2.1 Hydrocyclones

Hydrocyclones have been used in the industry for separation purposes since the 1940s, and the first patent can be traced back to the 19th century [11]. Hydrocyclone separation concepts are still under development, and are currently being used to separate solid–liquid, gas–liquid and liquid–liquid mixtures. For the liquid–liquid case, both dewatering and deoiling hydrocyclones have been utilized in the oil industry. Dewatering hydrocyclones are present when the multiphase fluids have low water cuts, to separate the water from the oil, and deoiling hydrocyclones are present in the opposite case, to separate the oil from the water. There are more challenges to liquid-liquid separation than for example separation of solids from either gas or liquid, both performed by hydrocyclones. This is because of the relatively small density difference, high volume fractions of the dispersed phase, poor coalescence and the danger of emulsion formation [12].

State of the art in the oil industry is to implement the hydrocyclone downstream of a three-phase bulk separator. Due to the continuous production flow, the residence time of oil and water in the three-phase bulk separator will be limited. This will cause the water outlet to contain oil droplets and a deoiling hydrocyclone can be used to further separate the remaining oil from the water. This separation process could be completed with several stages of deoiling hydrocyclones installed in series [XIV].

On topside developments the hydrocyclones have emerged as a practical and successful solution for produced water treatment and other applications, mostly due to its compactness, and the absence of moving parts and chemical additives [13]. As a result of the large flow rates present in the industry, a hydrocyclone will contain multiple hydrocyclone liners placed in parallel inside the vessel. This is due to the fact that one hydrocyclone liner is only capable of processing low flow rates. The amount of hydrocyclone liners inside the vessel depends on the flow rate in the system, and the scaling of the vessel is easily done by increasing or decreasing the number of hydrocyclone liners [XIV].

The centrifugal force which drives the separation process, is greater with a small hydrocyclone liner diameter, hence it is better to increase the number of liners instead of the diameter. This is further explained in Section 2.1.1. Compared to traditional gravity-based separators, the hydrocyclone vessel have superior qualitative performance. The magnitude of the gravity field in a gravity-based separator is 1 g compared to 2000–3000 g in a single hydrocyclone liner [9]. The hydrocyclone has a higher volumetric capacity, has simple and reliable operation, and represents a relatively low cost and has small maintenance requirements. In addition, a hydrocyclone setup will be easier to expand at a later time, and can therefore be modified to a required change in capacity. As a result, a hydrocyclone setup will be favorable because the water production will increase as the field ages due to changes in the reservoir conditions. [9],[14]

One of the major disadvantages of hydrocyclones, compared to gravity-based separators, are the sensitivity towards transient and oscillating flow. According to [15], transient flow derives mainly from riser induced slugging flow, however terrain induced slugging and hydrodynamic slugs may also represent problems on the same scale [XIII]. Since hydrocyclones have no buffer volume to harmonize flow irregularities, this may cause severe problems. Poor maintenance and insufficient operational control may also result in decreased separation efficiency [9].

2.1.1 Principle

A typical deoiling hydrocyclone liner contains four main parts as seen in Figure 2.1. The four main parts are the cylindrical chamber, two conical pipe sections and a long cylindrical underflow pipe. This will typical be 15 times longer than the first chamber's diameter [16].

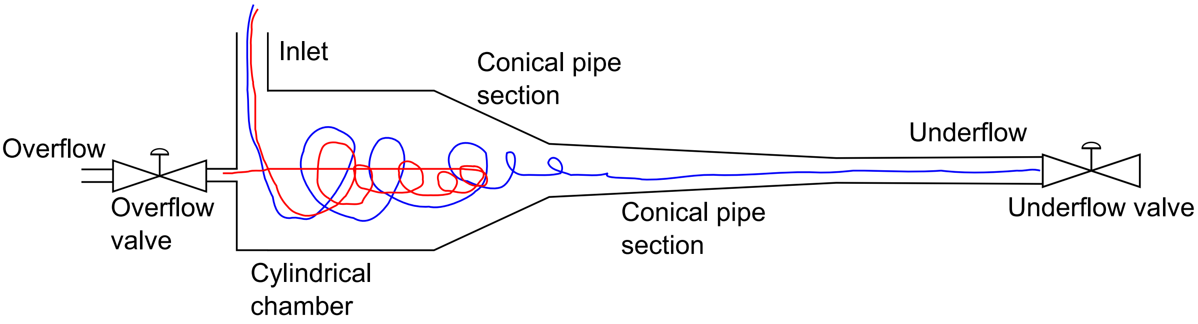


Figure 2.1: Typical deoiling hydrocyclone liner, where the blue line represents the water flow and the red line represents the oil flow [XIII].

The fluid enters the cylindrical chamber through a tangential inlet, which results in a vortex in the stationary body. The fluid is accelerated centrifugally and the separation occurs in the radial direction. The densest fluid (water) will migrate to the outer wall, while the less dense fluid (oil) moves towards the center [11],[16].

In a deoiling hydrocyclone the centrifugal acceleration is the driving force of the separation and is expressed by [17]

$$a_c(r) = \frac{u_\theta^2(r)}{r} \tag{2.1}$$

where u_θ is the tangential velocity of the fluid and r is the orbit radius of the droplet. By reducing the orbit radius r, the centrifugal acceleration is increased, and as a result the overall separation is increased. As explained in Section 2.1, this is one of the main reasons why several hydrocyclone liners are placed in parallel with a small hydrocyclone liner diameter.

The fluid droplets are subject to two opposing forces, the outwardly acting centrifugal force and the inwardly acting force which is a combination of drag and buoyancy forces, as seen in Figure 2.2.

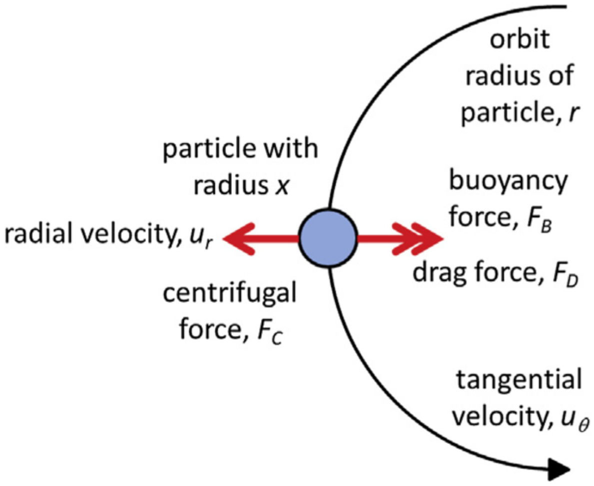


Figure 2.2: Force balance on a particle (droplet) in a hydrocyclone [11].

The following Equations (2.2), (2.3), (2.4) and (2.5) are given in [11]. The inwardly acting centrifugal buoyancy force, F_B, is

$$F_B = \frac{\pi d^3 \rho_o u_\theta^2}{6r} \tag{2.2}$$

where d is the droplet diameter, ρ_o is the oil density, u_θ is the tangential velocity and r is the orbit radius of the droplet. The inwardly acting drag force, F_D, is

$$F_D = 3\pi d \mu u_r \tag{2.3}$$

where d is the droplet diameter, μ is the viscosity and u_r is the radial velocity. The outwardly acting centrifugal force, F_C, is

$$F_C = \frac{\pi d^3 \rho_w u_\theta^2}{6r} \tag{2.4}$$

where d is the droplet diameter, ρ_w is the water density, u_θ is the tangential velocity and r is the orbit radius of the droplet. At equilibrium, the centrifugal force in the hydrocyclone is equal to the drag force and the buoyancy forces acting on the droplet

$$F_C - F_B - F_D = 0 \tag{2.5}$$

As described in [17], if Stokes law is assumed valid, which implicates laminar flow around the droplet, the radial velocity of the droplet, u_r, can be expressed by

$$u_r = \frac{2r_d^2(\rho_d - \rho)}{9\mu}\frac{u_\theta^2}{r} \tag{2.6}$$

where r_d is the radius of the droplet, μ is the viscosity of the emulsion, ρ_d and ρ is the density of the dispersed and continuous phases respectively and u_θ is the tangential velocity.

As the fluid moves to the underflow outlet, the decrease in cross-sectional area of the cyclone will increase the fluid angular velocity and the centrifugal force. Combined with the difference in density and the drag force, this effect will cause the oil, which in the oil-water case will be the slower settling particles, to move to the center of the hydrocyclone. In the center the oil is caught by reverse flow and separated through the overflow outlet. The phenomenon of reverse flow is explained by [14] in the following way:

> "*With high swirl intensity at the inlet region, the pressure is high near the wall region and very low toward the center-line, in the core region. As a result of the pressure gradient profile across the diameter, which decreases with downstream position, the pressure at the downstream end of the core is greater than the upstream, causing flow reversal.*"

This means that the narrowing profile of the hydrocyclone cross-sectional area is the main contributor to the pressure distribution of the hydrocyclone, and the inclination of this profile will thereby determine where the phenomenon of reverse flow occurs. [18]

2.1.2 Definition of performance parameters

The separation efficiency in a hydrocyclone is defined by [9] and [15] as

$$\epsilon \triangleq 1 - \frac{C_u}{C_i} \tag{2.7}$$

where C_u is the concentration of oil in the water leaving the underflow and C_i is the concentration of oil in the water entering the hydrocyclone inlet. As explained by [9] and [15], the separation efficiency can be affected by the inlet flow rate. The centrifugal forces will be weak when the flow rate is low, and hence only little or zero oil-water separation occurs. With large flow rates the result is a separation efficiency breakdown. The reason for this is either high turbulence and/or lack of the pressure gradient moving the oil-core through the overflow. Figure 2.3 is an illustration of the increase and the breakdown of the separation efficiency. The optimized flow rate is placed in the efficiency plateau between the minimum and maximum volumetric flow rates, Q_{min} and Q_{max}.

The separation efficiency is also influenced by the flow split (split ratio). The flow split is defined by [9], [15] and [14] as

$$F_s = \frac{Q_o}{Q_i} \tag{2.8}$$

where Q_o is the volumetric flow rate leaving the overflow, and Q_i is the volumetric flow rate entering the hydrocyclone inlet. As seen in Figure 2.4, an increase in flow split will result in an increase in separation efficiency. This implies the importance of keeping the flow split constant, in order to maintain the desired separation efficiency during the hydrocyclone operation [9],[15].

It is claimed by [15], that the separation efficiency becomes constant above a flow split of 2 %. As explained previously, slugs and transient flow may disturb this flow split and result in a decrease in the separation efficiency. It is discovered from several authors [9],[15] and [14], that the flow split is approximated to be proportional with the pressure drop ratio (PDR). PDR is defined by [9] and [15] as

$$P_{PDR} = \frac{dP_o}{dP_u} = \frac{P_i - P_o}{P_i - P_u} \tag{2.9}$$

where dP_o is the pressure difference between the inlet and the overflow and dP_u is the pressure difference between the inlet and the underflow.

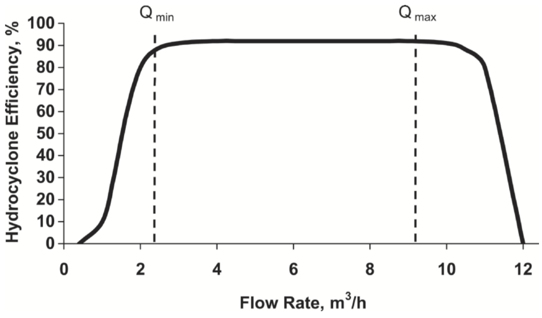


Figure 2.3: Hydrocyclone efficiency vs. flow rate [9].

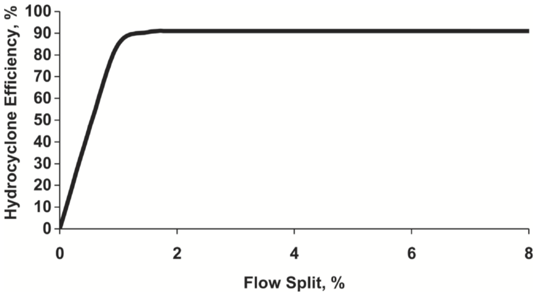


Figure 2.4: Hydrocyclone efficiency vs. flow split [9].

2.1.3 Geometry

Even though the hydrocyclone is, as previously mentioned, a simple structure, small changes in the geometric parameters of the hydrocyclone may affect the separation efficiency. Figure 2.5, shows a structural sketch of a standard liquid-liquid hydrocyclone [19], where the cone angle, $\alpha = 20°$, the fine cone angle, $\beta = 1.5°$, the length of the vortex cavity, $L_1 = D$, and the diameter of the vortex cavity, $D_1 = 2D = 4D_u$. In [19], the effects of changing L_1, the length of the fine conical section, L_2, and the performance parameters flow rate and the flow split, were investigated.

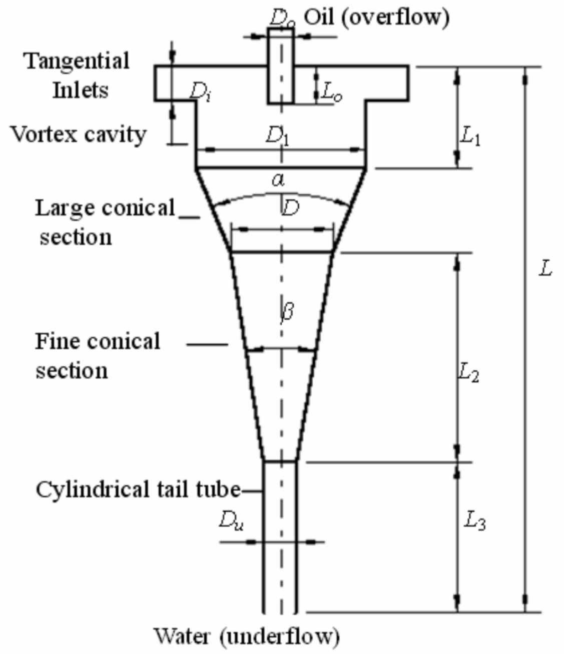


Figure 2.5: Structural sketch of a standard liquid-liquid hydrocyclone [19].

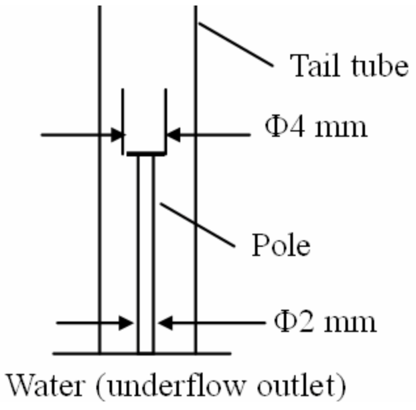


Figure 2.6: A pole at the underflow outlet [19].

The results showed that it is difficult to design one overall hydrocyclone to be used for different conditions. Because of this the hydrocyclone should be designed for its application. The optimized flow rate range for a hydrocyclone only exists for a specific application. There will also exist an ideal flow split for improving the separation results. The results also indicates that a hydrocyclone with a longer fine conical section, L_2, can reduce the pressure drop over the hydrocyclone and improve the separation efficiency. [19]

It was also found that to increase both the pressure drop and the separator efficiency by about 10 %, a pole could be added to the underflow outlet, as shown in Figure 2.6. This will improve the axial upward force and decrease the possibility of oil mixing with the underflow. [19]

There exist many different configurations for the feed inlet of hydrocyclones, as seen in Figure 2.7. The feed inlet will typically be circular or rectangular and vary in size depending on the flow rate. The rectangular design is often preferred over the circular one, because it will bring the particles closer to the wall when exiting the feed inlet [20]. The design of the feed inlet is important. Modification of it is seen as a simple approach to both control the cut size, d_{50}, and to improve the performance of the hydrocyclone. The cut size, d_{50}, is the diameter of the droplets that have 50 % probability of being separated in the hydrocyclone. Droplets larger than the cut size has a greater probability of being separated, and droplets smaller than the cut size has a smaller probability of being separated. [11]

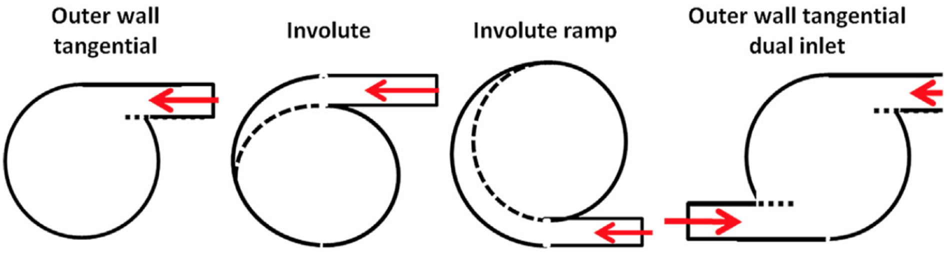


Figure 2.7: Feed inlet configurations in hydrocyclones [11].

One of the results from [21] is that an application of two inlets will improve the separation efficiency compared to one inlet. The reason for this is a reduction of fluid forces in the changeover between the feed inlet and the cylindrical chamber within the top volume part, which results in better vortex creation. The University of Aalborg, Campus Esbjerg designed their own hydrocyclone to be applied for experiments. Based on the information above, they chose to construct the hydrocyclone with two inlets [16].

2.1.4 Material of construction

The vessel housing, is most commonly constructed in metal, while the material selection for the hydrocyclone liners should be designed according to the application. For hydrocyclone liners in general, natural gum rubber is a common choice due to its low cost, high resistance to wear, and ease of handling. However, this material selection will not be suitable in conditions where temperatures may exceed approximately 60°C or in aggressive chemical environments, where the fluid may contain oil. Elastomers, such as neoprene or urethane, may perform better under such circumstances. In the case of highly abrasive fluids, ceramic materials such as silicon carbide or nickel-based steel alloys such as nihard, can be used. [11]

For the design in this thesis, which aims to separate fluids containing various concentrations of oil and water, a material which can withstand the required pressure, temperature and a corrosive environment should be applied. The standard within the oil and gas industry is to use a stainless steel alloy, with different specifications based on the operational environment of the system [XIV].

In [15] and [16], the hydrocyclone has been designed mainly for experimental purposes, and as a result, the material differs from the traditional industry materials. The hydrocyclone is constructed from poly-methyl methacrylate (PMMA) and is polished to make the hydrocyclone see-through. The hydrocyclone applied in State Key Laboratory of Environmental Aquatic Chemistry, [13], was also designed for experimental purposes, and glass was the chosen material. For the design in this thesis, the specific material selection is explained in Section 3.6.2.

2.1.5 Control

The residence time in a hydrocyclone is only a few ss [9]. It is essential to achieve precise operation through a highly responsive control system in order to obtain optimal conditions during this short residence time. According to [9], the main purpose of the control system is to satisfy the desired flow rate and flow split for the hydrocyclone.

Flow rate control

The main objective of flow rate control for a typical deoiling hydrocyclone application in the industry is to maintain a desired water level in an upstream three-phase bulk separator. If the flowrate through the hydrocyclone increases, the water level in the upstream bulk separator will decrease. Since the weir plate inside a gravity separator is designed for a constant water level, the hydrocyclone can be used to regulate flow irregularities at the inlet of the bulk separator. The objective is to keep the hydrocyclone flow rate between Q_{min} and Q_{max} as illustrated in Figure 2.3.

As seen in Figure 2.8, a hydrocyclone is characterized by a specific relationship between flow rate and the inlet to underflow pressure drop dP_u (dP_{water} in Figure 2.8). The inlet to underflow pressure drop corresponding to Q_{min} and Q_{max} are boundary values in flow rate control to match the optimized range of efficiency.[9]

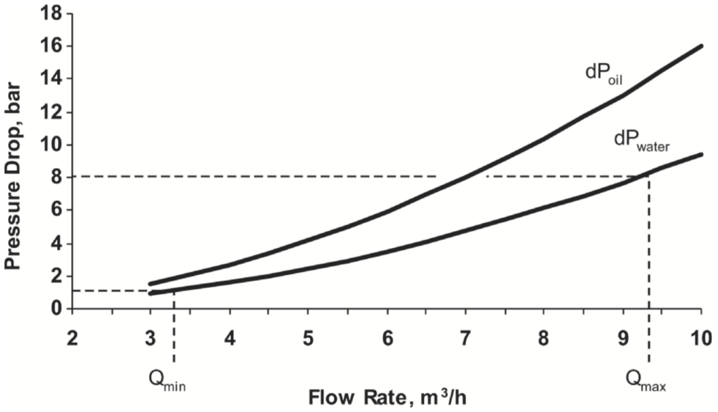


Figure 2.8: Hydrocyclone differential pressures. A specific relationship between flow rate and the inlet to underflow pressure drop dP_{water} (dP_u) [9].

Flow split control (PDR control)

If a certain flow split is constant as flow rate varies, the hydrocyclone efficiency is properly maintained [9]. Since the PDR and the flow split have a proportional correlation [22], PDR can be used as a control variable to maintain the desired separation efficiency. The PDR control strategy is the most widely used control solution in hydrocyclone applications. PDR control can be optimized if the PDR dynamics, under operating conditions are known. Information regarding the PDR dynamics is gained by knowing the operational flow rates and pressures, as they provide information on the PDR and flow split at different points of operation. [15]

According to [9] and [15], it is suggested that the PDR in a deoiling application is kept in the range between 1.7 and 2, depending on the design, and corresponding to a flow split of a few percent. This means that dP_o needs to be 1.7–2 times larger than dP_u, which ensures that a sufficient flow exits at the overflow outlet. If PDR $<$ 1.7 the oil core will backflow and mix with the underflow outlet. This scenario will lead to poor separation in the hydrocyclone.

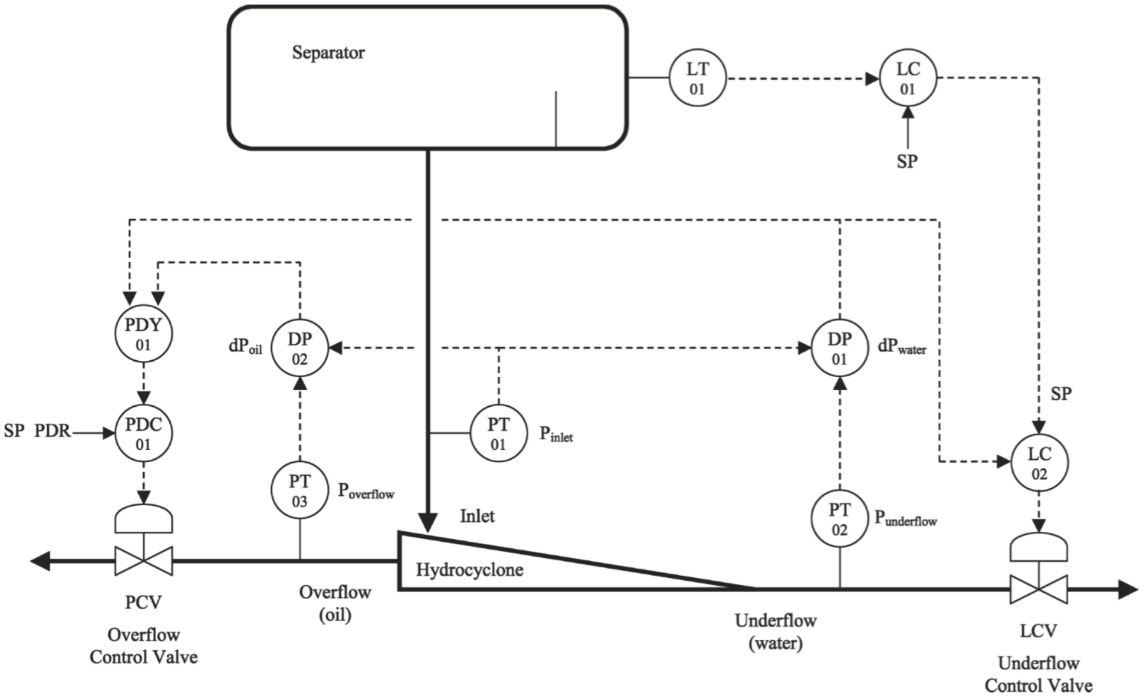


Figure 2.9: Typical hydrocyclone control scheme [9].

Figure 2.9 is an illustration of a typical hydrocyclone control scheme. To control the flow rate, the underflow control valve (LCV) controls the underflow by opening when the flow rate increases or closing when the flow rate decreases. It is operated by two controllers (LC01 and LC02) arranged in cascade mode. The overflow control valve (PCV) controls the flow split. It is operated by the pressure differential controller PDC01. PCV maintains the desired PDR and hence the flow split, by opening to increase PDR or closing to decrease PDR. The rest of the components are calculation blocks and measurements instruments. [9]

2.1.6 Disturbance generator

The intention of hydrocyclone control is to sustain a high separation efficiency even with the influence of disturbances present in the system. Variations in the flow rate, operational pressure and start-up/shutdown scenarios are the dynamic disturbances that have to be considered in the hydrocyclone system. Other disturbances could also occur in a real system, but these have not been included in the scope. To reduce the influence of the disturbances, a hydrocyclone controller with a strong disturbance attenuation capability is needed. Alternatively, a system that reduces or eliminates oscillated flow before it enters the first hydrocyclone is necessary. [23]

In a normal operating environment, dynamic liquid disturbances, such as variations in flow rate and pressure, will be a natural phenomenon caused by slugs in the well stream or during start-up and shutdown. In a laboratory setup on the other hand, these disturbances will be limited and must be provoked or simulated by additional equipment or laboratory functionality.

In ExxonMobil's presentation at the MCE Deepwater Development conference in Madrid, Spain in April 2014 [24], a liquid disturbance generator is presented. This liquid slug generator is able to generate slugs at various sizes between 0.1 and 0.6 m^3/h, where both the number and the frequency of the slugs can be controlled. ExxonMobil have been asked to share the results and design of the slug generator for the implementation in this thesis and laboratory design, however this cooperation was not in the interest of ExxonMobil.

The disturbances can also be created by connecting a Variable Speed Drive (VSD) to the feeding pump, which allows for the pump frequency to be changed rapidly. This would change the flow rate and the corresponding pressure, and result in what the separation system will see as a disturbance.

2.2 Flow Meter

Several technologies to measure the flow rate in a specific application exist. On the basis of various produced water treatment articles [25], [15] and [22], the Coriolis mass flow technology is favoured in gas–liquid applications, while the electromagnetic technology is favoured in produced water with low oil content applications.

2.2.1 Coriolis mass flow meter

The working principal of the Coriolis mass flow meter is described by [26];

> *"Coriolis mass flow meters measure the force resulting from the acceleration caused by mass moving toward (or away from) a center of rotation."*

If the accelerated mass is sent through a pipe which is fastened in both ends, the pipe will bend due to the Coriolis force. In a Coriolis mass flow meter the fluid is separated into two equal pipes, which are vibrating at some frequency. The mass of the fluid will resist acceleration and deceleration, at the inlet and the outlet of the pipes respectively. By placing sensors and a transmitter at the inlet and outlet, the Coriolis mass flow meter will measure the amount of bends in the pipes, which is proportional to the mass flow rate of the fluid passing through, and the sensors and the transmitter generate a linear flow signal. The technology is thereby not affected by fluid density changes. It is also possible to perform a precise density measurement of liquids by measuring the resonance frequency of the pipes. [26]

This technology has high accuracy, it is reliable and requires low maintenance. It can be used to measure the mass flow of both liquids and gases. According to [26], it represent about 21 % of all flow meters sold. A Coriolis flow meter is used by Schlumberger in [25] to make accurate three-phase flow rate measurements. The University of Aalborg recommended using a Coriolis flowmeter, as they have had very good results with their model from Emerson.

2.2.2 Electromagnetic flow meter

Faraday's Law of Electromagnetic Induction is utilized in electromagnetic flow meters to determine the flow rate of a liquid in a pipe. This technology involves a magnetic field that is generated and routed into a conductive liquid. The liquid will cause a voltage signal to be sensed by electrodes placed around the pipe. If the velocity of the fluid increases, more voltage will be generated. Faraday's Law declares that the voltage generated is proportional to the velocity of the flowing liquid. An electronic transmitter processes the voltage signal and decides the flow rate. [27]

As claimed by [27], the electromagnetic flow meter represent about 23 % of all flow meters sold. They are intermediate in accuracy and very reliable, but the technology will not work on non-conductive fluids such as oil and gas. The electromagnetic flow meter is widely used in produced water treatment applications. It is used by Alborg University in [15], by Schlumberger in [25] and in [22] to measure the flow rate of a produced water stream.

2.3 Valves

A central part of controlling a multiphase system is having the correct valves. Valves are central components in process control, and, equally important, valves may function as a safety barrier. As a consequence, an important aspect of the design process is to choose the right valves among the range of different types.

The different types of valves are represented by letters in the design sketches in Chapter 3 as C (control valve), CH (choke valve), M (manual valve), MX (mix valve) ans S (safety valve) with numbers according to their placement.

2.3.1 Manual valves

Manual valves comes in several shapes, designs and sizes, but they all need to be operated by an operator. This is normally operated by hand with a handle on top of the valve. These valves are called shut-off valves, and are normally installed in pipe systems to make other components available for maintenance by running the flow in a bypass [28]. For shut-off valves it is important that the valve is full bore, which means it will not disturb the flow pattern when the valve is open [VI].

Ball valve

The ball valve is constructed as an outer casing with a hollow, perforated ball inside it. In open position the ball's hole is in line with the fluid flow, while turning the top handle 90 degrees, it will close the valve by positioning the hole perpendicular to the flow direction. Because of their reliability and durability they are often preferred when designing systems with shut-off valves.

When the valve is open, and the hole is in line with the fluid flow, it will not affect the flow pattern. A properly designed ball valve can therefore be considered to be full bore. [29],[28]

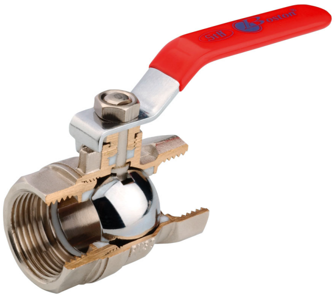


Figure 2.10: Typical design of a ball valve [29].

Gate valve

The gate valve is constructed as an opening that can be closed by a round or rectangular plate, and for that reason, considered to be a shut-off valve that either operates in open or closed position. The plate is typically lowered by turning a top wheel, and because of the flat design of the plate it has a great ability to cut through fluids when closing. The gate valve is also referred to as a knife valve, and is preferred in heavy oil operation in different parts of the petroleum industry. In fully open position, the gate valve will not be an obstruction in the flow, and is considered to be full bore. However, the ball valve is often preferred in shut-off systems due to their operational reliability. [30],[28]

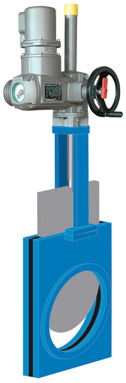


Figure 2.11: Typical design of a gate valve [30].

2.3.2 Control valves

Control valves are also referred to as regulating valves. They allow the operator to determine the direction and the amount of flow that is released by an additional actuator. To achieve desirable feedback control, the control valves should be as fast as possible, and preferably use less then 1 s to reach the desired position [V]. The reaction time of the valve depends on the operational speed of the actuator. Based on the experience from Aalborg University, pneumatic actuators are preferred [16]. Pneumatic actuators converts air pressure into linear or rotary motion to change a valves position. This results in fast working actuators.

Standard control valves will operate at a given percentage of open or closed, and this obstruction will contribute to oil droplet breakup [VI]. However, the company Mokveld have developed a low shear control valve that is able to control the flow without breaking the oil droplets using a so called Typhoon system. The Typhoon system is designed to reduce droplet break-up and emulsification of fluid phases, and this will result in significantly improvement of the efficiency in oil-water separation.

As shown in Appendix F, the stroke time of the valve, from open to closed, and from closed to open position, are both well below 1 s. Because of this, the low hear Typhoon valve is an interesting example of high end valves that could, if implemented, affect the separation results.

Check valve

Check valves, also called non-return valves, are valves that only allows fluid flow in one direction. These valves are therefore typically designed with two openings, one for the fluid to enter and one for the fluid to leave, and a spring loaded disc covering the opening. The valve requires a certain pressure to push back the spring and open the disc, and in the case of reverse flow the disc will close immediately. This design is shown in Figure 2.12. Because of the weight of the disc, the check valve produce a relatively high resistance to the flow in open position, and as a result, affect the flow pattern. For that reason, this valve should be avoided in pipes where the flow pattern and droplet size of the fluid is of great importance. [31],[28]

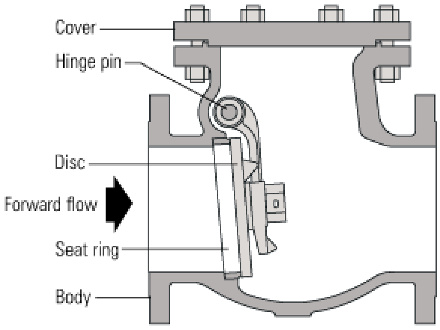


Figure 2.12: Typical design of a spring valve [31].

Choke valve

Choke valves are control valves which are able to relief the inlet pressure and regulate the outlet pressure in a pipeline by allowing the fluid to flow through a very small opening. The opening is set to a predetermined set pressure to protect for example pressure vessels and other equipment from being subjected to pressure above their design limits. [32]

Figure 2.13: Typical design of a choke valve [33].

Globe valve and needle valve

The globe valve and the needle valve are explained in the same sub section because of their similarity. Globe valves and needle valves are control valves which allow the operator to change the flow rate by rotating a threaded stem to adjust the rate. By rotating the stem, the plunger is raised or lowered into the seat, and this results in increasing or decreasing flow. Globe valves, as seen in Figure 2.15, are used in operations which require frequent flow rate changes. The main difference between globe vales and needle valves is the precision. Needle valves can be more finely tuned by utilizing a needle-shaped plunger, as seen in Figure 2.14. Needle valves can also provide positive shut-off, and hence, measurement instruments may be installed or removed safely. They can also be used to relieve pressure on the fluid. [34]

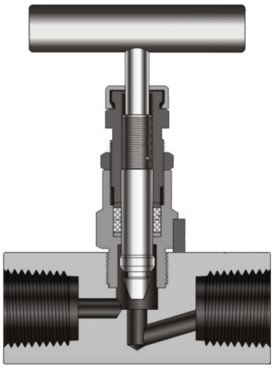


Figure 2.14: Typical design of a needle valve [34].

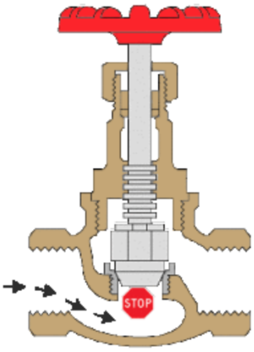


Figure 2.15: Typical design of a globe valve [34].

2.4 Pump Types

As one of the main purposes with the design of the laboratory is to reduce the OiW concentration in the produced water, every piece of equipment should be chosen to further support this purpose. As of January 1th 2007, the Oslo-Paris Convention decided to decrease the allowed level of oil spills from monthly production, resulting in a maximum concentration limit for dispersed oil of 30 ppm in produced water [35]. These regulations will be further explained in Section 2.5.2. In order to achieve this level of water purity through the separation in the hydrocyclone setup, the feeding pump plays a central role.

There are several types of pumps, where every design has its own benefits, drawbacks, and specific considerations. An important aspect of system design is therefore to be aware of available technology, and how the expected characteristics of the chosen design will affect the overall performance. Even though the objective of this project is to design a laboratory to emulate subsea separation, the pumps will be placed in a dry environment. This is mainly because the laboratory's main areas of interest are related to flow assurance and system control, not subsea pump design.

By using a dry environment for pump installation, the cost and complexity of the laboratory design is reduced, which allows for increased focus on flow- and control related components. This section will serve as an overview of the available pump types applicable for the laboratory design presented in this thesis.

2.4.1 Basic concepts

The main purpose of a pump is to transfer energy to the processed fluid and raise the pressure. Based on the principle of which the energy is transferred to the fluid, pumps can generally be divided into two groups; kinetic (also called dynamic) and displacement pumps. The relevant pumps within each category will be presented in Section 2.4.2 and 2.4.3.

Droplet breakup (dispersion) and coalescence are two crucial physical phenomenons in phase separation. Dispersion is well defined by [36]:

> *"Dispersion is the process where one phase in an immiscible system forms an unstable, heterogeneous state of two or more distinct phases dispersed in a continuous phase."*

Coalescence on the other hand is the opposite of dispersion, droplets are melting together. The maximum droplet size that can exist at equilibrium considering the coalescence rate and dispersion rate is expressed by [36]:

$$d_{max} = 432 \left(\frac{t_r}{\Delta P} \right)^{\frac{2}{5}} \left(\frac{\sigma}{\rho_w} \right)^{\frac{3}{5}} \tag{2.10}$$

where t_r is the retention time, ΔP is the pressure drop, σ is the surface tension and ρ_w is the water density. The equation implicates that the greater the pressure drop over a certain period of time, the smaller the maximum oil droplet diameter will be. This is because the increase in pressure also increases the shear forces that is applied on the fluid. Pumps, chokes, control valves and similar process equipment, generates large pressure drops over small distances, which will result in smaller oil droplets [VI]. Considering a hydrocyclone downstream of the pump, this will have a negative effect on the separation efficiency. As seen in (2.6), the droplet diameter is of great importance for centrifugal separation.

For this laboratory setup, two types of pumps have been considered. A kinetic pumpe type called a centrifugal pump, and a rotary displacement pump called a screw pump [36]. The screw pump described later in this paper is a progressive cavity pump (PCP).

2.4.2 Kinetic pumps – The centrifugal pump

The energy transfer principle of kinetic pumps is based on continuously increasing the velocity of the fluid to values greater than the operational value at the discharge side. This velocity difference causes a reduction in velocity within the pump, which further leads to a pressure increase. The centrifugal pump is one of the two types of kinetic pumps. The centrifugal pump are further divided into three subgroups, depending on orientation of the fluid when it enters and exits the pump. The three types are axial, radial and peripheral. The design of a typical centrifugal pump is shown in Figure 2.16. [36]

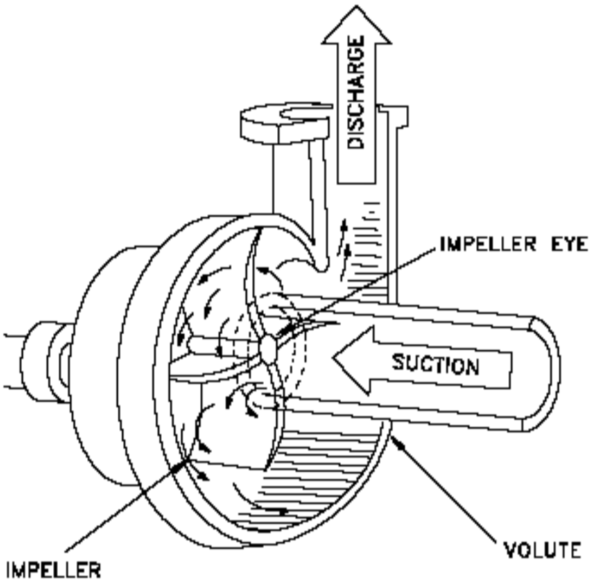


Figure 2.16: Schematic of a centrifugal pump [36].

The energy transfer principle of the pump influences greatly to shearing of the fluid. The centrifugal forces which increase the velocity of the fluid will at the same time cause shearing of the oil droplets. The risk of shearing and developing emulsions that will decrease pump efficiency and possibly damage it increases with the rotational speed of the pump [36]. However, a state of the art pump producer, claims to have developed a centrifugal pump that actually uses this principle as an advantage, and are actually able to increase the oil droplet size. This will be further discussed in Section 2.4.4.

2.4.3 Displacement pumps – The screw pump

As opposed to kinetic pumps, displacement pumps transfers energy periodically, by applying force to a number of closed volumes filled with fluid. Assuming incompressible fluids, this will generate an increase in pressure. Screw pumps are typically divided into single– or multiple rotor types. Single–screw pumps are more often called progressive cavity pumps, which is the pump type considered for this laboratory setup. Multiple–screw pumps are found in many different configurations, but the general function of the pump is to carry the fluid in an axial direction between two or more close clearance rotors. [36]

Compared to centrifugal pumps, screw pumps generate low amounts of shearing. In [36], the author has used several sources to conclude that the screw pump is the pump type that will apply the least amount of shearing forces to the fluid, and thereby also less dispersion and better downstream separation. The paper concludes that the progressive cavity pump is the best fitted subtype of screw pumps to deliver the desired pressure with the least amount of dispersion, while the centrifugal pump generate more shearing than other pump types..

2.4.4 Research and state of the art in technology

Research

As described in Section 2.1.1, the fluid particles in the hydrocyclone are subject to outwardly and inwardly acting forces. To achieve the best separation, the desired effect is to force the oil droplets towards the center of the hydrocyclone and the water phase towards the outer section. The inwardly acting forces on the oil droplets are drag and buoyancy, described by (2.2) and (2.3). The variables that affects the forces acting on the oil droplets are the density, the oil viscosity, and the droplet diameter. The oil viscosity and density are determined by the oil type, but the droplet diameter is a variable which is directly dependent of the equipment utilized in the separation system.

The break-up of oil droplets will reduce the efficiency of downstream produced water treatment equipment, such as the separation process in a hydrocyclon, and should therefore be avoided. The feeding pumps impact on oil droplets is also summarized by [37] which concludes;

> *"The separation device works much better when the oil droplets are larger. A progressive cavity pump will not change the oil droplets where a centrifugal pump will emulsify the oil and make the oil droplets very small and reduce the separation performance of the separator."*

This was also shown by an extensive study conducted by Conoco Inc as early as 1988 where five different pump types were tested, and one of the conclusions were [38];

> *"Of the pumps tested, progressive cavity pumps showed the least detrimental effects on oil droplets of the five kinds of tested (rank): (1) progressive cavity, (2) twin lobe, (3) sliding rotary vane, (4) centrifugal, and (5) twin screw pumps."*

According to [19], centrifugal and progressive cavity pumps influence on separation efficiency were compared through extensive testing in the Daqing oilfield. The results, which are shown in Figure 2.17, concluded that the progressive cavity pump was the ideal pump for hydrocyclones. This can be seen by the level of the oil-concentration in the underflow for the produced water compared to the centrifugal pump.

Given the amount of sources that verify the positive aspects of using a progressive cavity pump upstream of the hydrocyclone, this paper views this pump as the best option within the range of standard pumps types.

Recent research on the subject of reducing oil droplet break-up in pumps have, however, come up with results that are worth some attention. By using the vibration in centrifugal pumps, a pump supplier has recently shown that they are able to actually increase the oil droplet size during pumping. This is regarded as state of the art in pump technology.

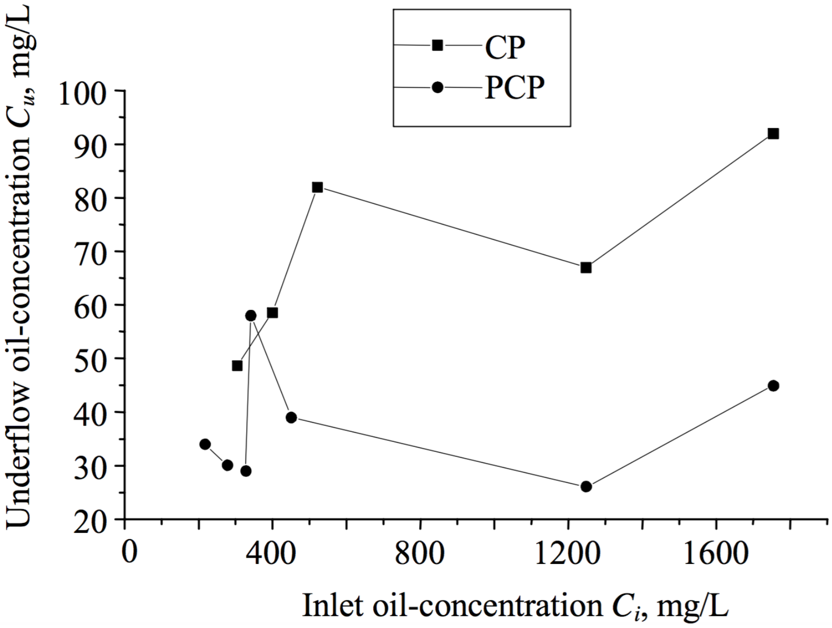


Figure 2.17: Test comparing the results from a progressive cavity pumps and a centrifugal pumps impact on the purity of a produced water system in the Daqing oilfield. A high oil concentration in the underflow is not desirable, and the figure shows that the progressive cavity pump gives generally much better separation results. [19].

State of the art technology – Coalescing pump

Even though the conventional centrifugal pumps are known to break up oil droplets in the process of pumping produced water, the Norwegian company Typhonix claims to have solved this problem in a way that actually increases the oil droplet size of the fluid during normal pump operation. By "using the turbulence in a centrifugal pump in a more constructive way" [39], Typhonix has done extensive testing to show that their pump design contribute to a substantial enlargement of the droplet size. Figure 2.18, shows a comparison of the three relevant pump types; centrifugal pump (normal), progressive cavity pump (also known as as eccentric screw pump), and the Typhonix prototype pump.

Typhonix delivers two types of pumps; a low shear pump and a coalescing pump. The low shear pump has been specifically designed to avoid oil droplet break-up. Both of the pumps are currently sold for commercial use. The purpose coalescing pumps purpose is to increase the oil droplet size, which leads to an increased separation efficiency. The coalescing pump does however require an oil droplet diameter of 5–15 μm. Typhonix has currently only tested their pump with an oil concentration up to 1 %, and are very interested in opportunities to test their pump at higher oil concentrations such as 1–5 %.

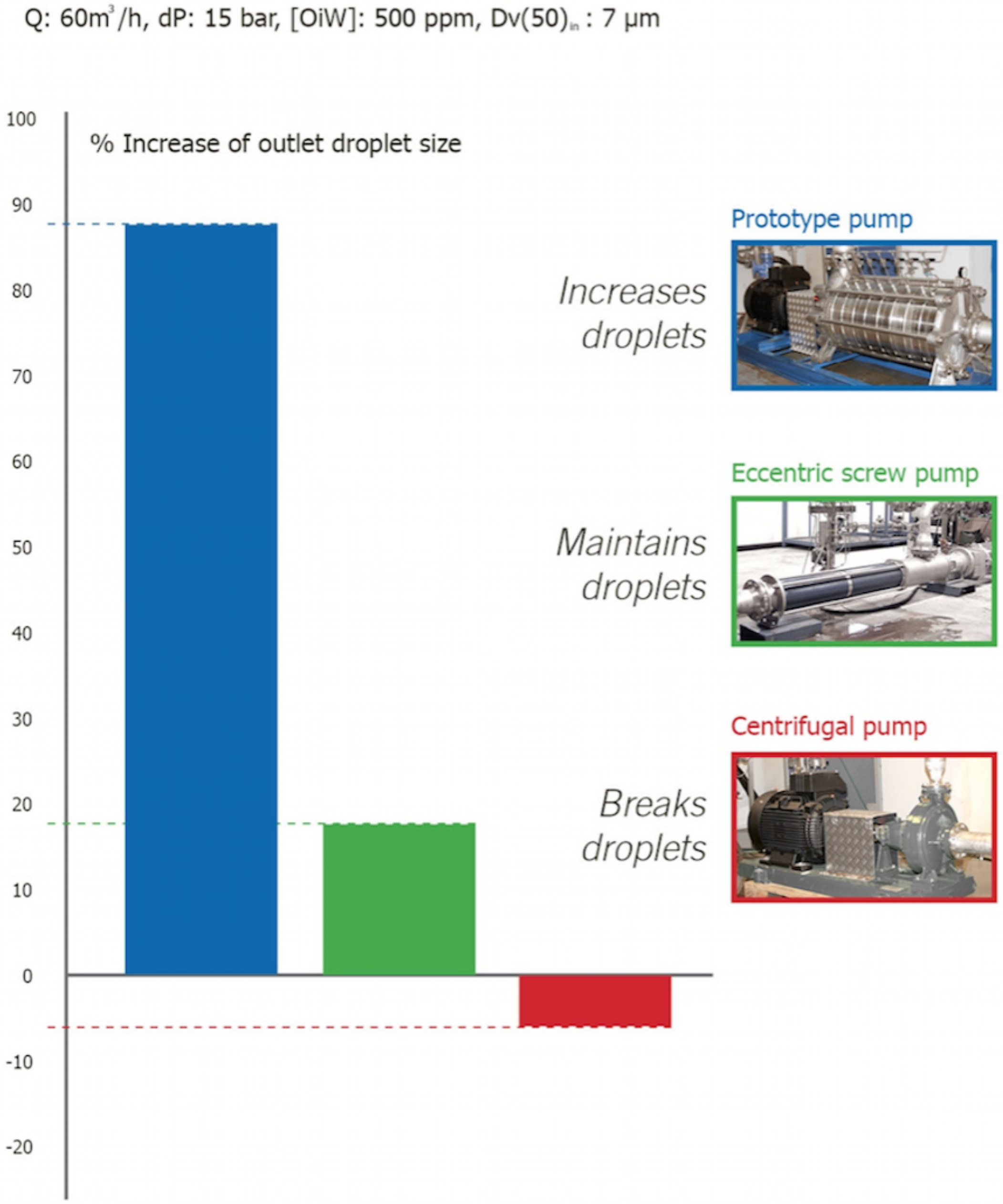


Figure 2.18: Comparison test between an eccentric screw pump (displacement pump), a centrifugal pump (kinetic pump) and a coalescing pump from Typhonix. The test indicates that the Typhonix pump has the largest increase in droplet size. [39]

2.5 Oil-in-Water Technology

The environmental impact is currently one of the main concerns for the oil and gas industry [40]. To meet the regulation of a dispersed oil concentration of 30 ppm in produced water, which is further explained in Section 2.5.2, it is important to have accurate and reliable sensors. The separation process in a hydrocyclone is very fast. According to [9], the residence time of a droplet is only a few ss, and because of this it will be desirable to have both an online upstream and a downstream OiW measurement, rather than performing batch-wise measurements.

There are several challenges regarding OiW measurement, which is further discussed in [35]. In recent years, the main challenge have been that it is not widely understood what oil in produced water actually is, and what the different sensors actually are measuring. Another issue is the placement of the OiW sensor. When placing the OiW sensor in a process it is essential to remember that oil and water are separated by the principle of gravitation in horizontal pipelines, and hence, the oil will tend to float on top of the water. It is of great importance to place the OiW sensors in turbulent flow areas, such as vertical pipelines, to achieve a homogeneous mixture of the fluids and correspondingly more accurate measurements. [IV]

Many technologies exist for making online OiW measurements. Laser Induced UV Fluorescence (LIF), as explained in Section 2.5.6, and Focused Ultrasonic Acoustics (FUA), as explained in Section 2.5.4, are considered the main technologies for online OiW measurements [35]. Manufacturers like Advanced Sensors [41] and ProAnalysis [42] applies LIF technology, while Mirmorax [43] applies the FUA technology. Other relevant technologies are image analysis manufactured by Jorin [44] and electrical resistivity tomography (ERT) manufactured by Industrial Tomography Systems [45].

By utilizing online OiW sensors the probe can be inserted directly into the produced water stream (in-line). Other OiW sensors are generally placed in a by-pass stream, which introduces a risk of non-representative sampling. Regarding maintenance, the in-line OiW sensors require a automatic self-cleaning system, or a system for insertion and extraction which enables manual cleaning. [46]

As stated by [40], most produced water treatment (PWT) systems are currently acting as non-feedback processes or passive feedback control systems, meaning that the outcome of treatment does not dynamically or actively influence the process. Recent developments of the online OiW sensors mentioned above, enables the oil and gas industry to operate PWT systems with feedback process-control in a closed-loop control system to constantly maintain the output at a predetermined set point. This will allow the operator to set parameters for the oil concentrations in overboard water at specific ppm values. Depending on the control algorithms, the closed-loop control system can adapt to the process conditions and/or employ water treatment equipment to maintain the set points. [40]

In the following sections, an explanation of what oil in produced water really is, oil-in-water regulations and the most relevant OiW technologies for making online measurements, are presented.

2.5.1 Oil in produced water

The total amount of hydrocarbons can be grouped into saturated and unsaturated aliphatic hydrocarbons, which absorbs infrared light, and aromatic hydrocarbons, which absorbs ultraviolet (UV) light. Oil in produced water is a general term, and is normally divided into dispersed and dissolved oil, as illustrated in Figure 2.19. Dispersed oil means small oil droplets in produced water (in the range of 0.5 to over 200 μm) [47], and contains both aliphatic and aromatic hydrocarbons. Dissolved oil, on the other hand, means oil in soluble form in produced water, and contains aromatic hydrocarbons, organic acids and phenols.

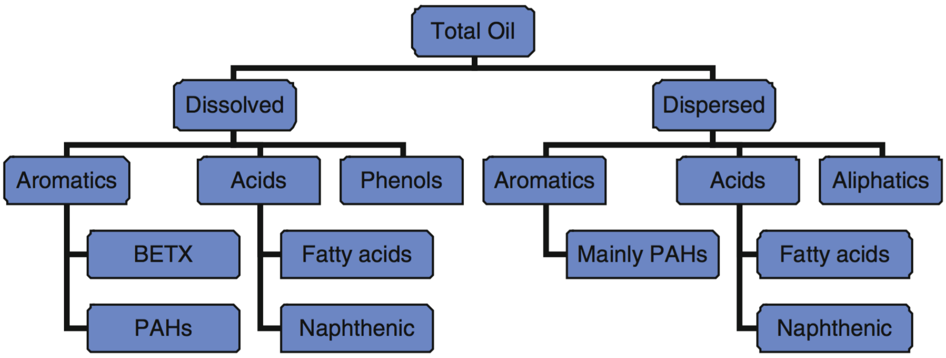


Figure 2.19: An overview of the total amount of hydrocarbons in oil [35].

Oil in produced water is a method-dependent parameter. This means that different methods of measuring the OiW concentration may give different results in the same sample. Without specifying the method used to determine the OiW concentration, the values reported can be misleading.

Further challenges involves sampling and calibration issues. Sampling is often not addressed by an analytical method and can lead to significant uncertainty in the final result. The measurement can only provide results as good as the representative sample. Calibration can produce different results. The results are also sensitive to the accuracy of calibration. Each produced water stream will be different, both in terms of concentration and the amount of aromatic and aliphatic hydrocarbons. Because of this, it is difficult to simulate a realistic "one fits all" produced water stream in a laboratory environment. [35]

2.5.2 Oil-in-water regulations

The main purpose of this compact separation laboratory is to research new control algorithms that enables separation of oil and water with such efficiency that the produced water reach the required level of purity. If the produced water reaches a level of purity that satisfies the governmental regulations it can be released to sea or injected. This leads to significant cost savings for the operator. The laboratory research aims to produce results that are relevant for the industry, and further could be translated into an offshore operational setup.

The level of purity, and how to interpret it, varies a bit depending on in which country the oil and gas operations are taking place. In Norway the disposal from petroleum facilities is governed by the Norwegian Petroleum Act, where the central international framework is set by the OSPAR convention [48]. With regards to disposal of produced water, the National Measurement System [49] summarize the OSPAR regulations in the following way:

> *"With regard to the discharge of oil in produced water in the UK, it was stipulated that the monthly average concentration of dispersed oil in produced water did not exceed the 40 mg/l during the period between permit issued on 31 December 2005, and did not exceed 30 mg/l after 1 January 2006. The maximum concentration of dispersed oil in the discharge should not exceed 100 mg/l."*

Even though the quotation reviews the UK, Norway is bound by the same regulations. The concept and measurement of dispersed oil is a complex term and is described in Section 2.5.1, but given that the oil content can be correctly measured, the specific wording of this regulation is of great importance for the design parameters of the laboratory. There has been some discussions regarding the measurement methods, as OiW sensors have only been able to measure dispersed oil, and not dissolved oil. Recent LIF technology is however able to measure both dispersed and dissolved hydrocarbons [46]. This might be of importance if the OSPAR regulation where to be updated with measurements of both dispersed and dissolved oil in the future.

As mentioned in Chapter 1, one of the major problems with compact separators is their vulnerability towards flow irregularities like slugs. Besides the fact that slugs have the kinetic energy to damage the equipment, they also represent a different flow regime than the system is originally designed for.

In the case of produced water treatment, an oil slug may increase the oil concentration in the produced water. The implementation of control systems might decrease the impact of slugs, but there is still a probability that they will drastically increase the oil concentration in the produced water over a short period of time. For that reason, an important design specification is how the limit for disposal is measured; as a maximum limit at every point in time, or a maximum limit accumulated over a longer period. The quote from the OSPAR regulations clearly states that the monthly average concentration of dispersed oil in produced water shall not exceed 30 ppm. This means that the maximum concentration can exceed 30 ppm at some point in time, as long as the monthly average does not exceed 30 ppm. The concentration can, however, not exceed 100 ppm at any point in time. These are important characteristics for the implementation of a slug control algorithm.

The oil concentration is also important if the produced water is to be re-injected into the reservoir. This is because if the oil concentration in the produced water is to high, it could plug the pores in the formation. Re-injecting large amounts of oil into the reservoir is also not desirable seen from a cost perspective, as some of the revenue is lost.

2.5.3 Electrical resistivity tomography

The principle of the electrical resistivity tomography (ERT) technique is to measure the resistivity from multiple electrodes around a pipe. From these measurements, a 2-D image of the oil droplets in the water can be created. The requirement for using this technique is that the phases in the fluid have different electrical resistance. Water and oil satisfies this criteria as the water has lower electrical resistance than hydrocarbon oil. [50]

Advantages of using ERT above other relevant tomography techniques, such as gamma-ray, is that ERT emits no radiation, it is non-intrusive, robust and cost-effective. The main drawback of the ERT–method compared to the gamma-ray method, is the lack of ability to send electrons in direct paths. There is a chance that the electric current will travel around droplets with high resistivity, by following the path of least resistance. The gamma-ray method is also capable of making faster measurements than the ERT–method. [50]

2.5.4 Focused ultrasonic acoustics

The focused ultrasonic acoustics measurement technique is based on individual acoustic echoes which are characterized by using signal processing. A highly engaged acoustic signal is transmitted directly into the produced water flow. Particles, such as oil droplets, solids and gas bubbles will reflect the acoustic energy and the reflected signals will contain specific information about the particle. An analyzer classifies the particle and calculates full size distribution based on a large number of measurements. Finally the size distribution is used to calculate the corresponding OiW concentration values. [35],[46]

2.5.5 Image analysis

The image analysis method is based on using a high resolution video microscope to investigate the OiW content of a sample stream. Several video images are captured in sequence and the particles on the images are counted and analysed by calculating their volume. A sample volume related to each of the images is determined by multiplying the image area by the focal depth, and further used to calculate the concentration of the particles. To distinguish the oil droplets from solids and gas bubbles, a shape factor is used. The shape factor is set to 1 for a sphere, and to be classified as an oil droplet, the shape factor has to be close to 1. Gas bubbles will also be spherical, but its optical property is very different from oil and can easily be excluded from the oil droplet calculation. [35],[46]

2.5.6 Laser induced uv fluorescence

The laser induced uv fluorescence (LIF) technology continuously measures the oil concentration in the water. The technique involves laser radiation to energize the aromatic hydrocarbons of the oil droplets with an optical wavelength. A sensitive, tuned detector, with a different wavelength measures the simulated fluorescence value of the energized oil droplets, and determines the amount of aromatic hydrocarbons. This can be related to the total amount of hydrocarbons. This technique relies on the ratio of aromatic hydrocarbons and the total amount of hydrocarbons remaining fairly constant. Because of this it is important to remember that the LIF technology will need a recalibration if the ratio of aromatic to aliphatic, or aromatic to total hydrocarbons is changed. This will occur in the industry when several oil streams from different fields are combined, and in the later phases of production from an oil field. [25],[41]

2.6 Future Concepts

Given the extensive design scope for the complete compact separation laboratory, the design and construction of the laboratory have been divided into phases. This will be further explained in Section 3.5.

This Master's thesis focuses mainly on the first phase of the laboratory design, which involves a basic setup of a produced water treatment process that will serve as a foundation for later expansions. Suggestions for future expansions have also been included in the later phases. For that reason, technology and equipment which is compatible with the basic setup in the first phase have been assessed.

The operation of hydrocyclones in series provide a potential for extremely efficient separation of oil and water, at relatively low oil concentrations. In order to be relevant, future concepts that are to be implemented in the later expansions must therefore add additional functionality or be able to further increase the separation efficiency of the laboratory. The different concepts and equipment in the following subsections can either be upstream or downstream of a hydrocyclone.

2.6.1 Air/gas injection

Based on the equations elaborated in Section 2.1.1, increasing the droplet diameter and decreasing the density would have a positive impact on the separation efficiency. At East China University of Science and Technology, they have made several experiments by utilizing air injection to further increase the separation efficiency of a deoiling hydrocyclone liner [51],[52].

Air is not the only medium that could be applied for injection. Gases like methane, nitrogen and sulfur hexafluoride are other alternatives. The principle behind gas injection, which is equal for air injection, is to attach or adhere oil droplets to gas bubbles. This can occur in different ways, as seen in Figure 2.20. The oil droplet can either spread around the gas bubble to form a perfect attachment, stay inside the gas bubble at the bottom, or adhere to the outer gas bubble surface to form a weak attachment. The spreading appearance, depends on the interfacial tensions acting at the contact surface between the fluid phases. The perfect attachment will both increase the oil droplet diameter and decrease the overall oil density, and hence increase the separation efficiency. [25]

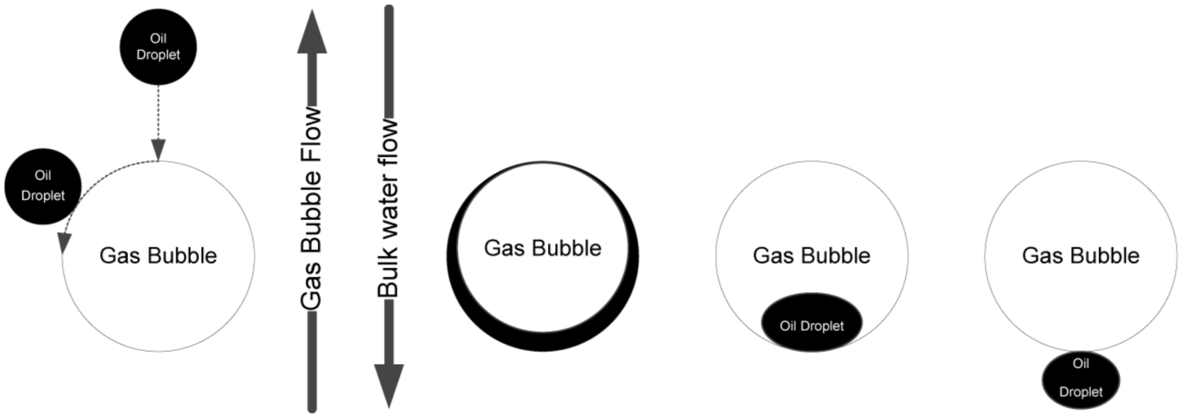


Figure 2.20: Gas bubble–oil droplet attachment. The gas flow and the liquid flow is sent in opposite directions, and the attachment process between the gas bubbles and the oil droplets can occur in three different ways. [25].

In [51], they have utilized air bubbles, which are injected directly into the produced water stream by a air-liquid pump before the hydrocyclone inlet. According to [51], the air bubbles will move faster than the oil droplets due to density differences and this will provide high probability for oil–air bubble attachments in the hydrocyclone. The results from their experiment confirmed that air injection will increase the separation efficiency. The improvement in efficiency reached a maximum when the air-liquid ratio is close to 1 %, which leads to an increase in the oil removal efficiency from 72 % (air-liquid ratio 0 %) to 85 % (air-liquid ratio 1 %). A further increase of the air-liquid ratio only caused performance deterioration. [51]

Air injection can be implemented in a number of ways, and a new experimental approach was carried out in [52]. A new type of hydrocyclone, called air-injected deoiling hydrocyclone

(AIDOH), was developed. This hydrocyclone was made by a micro-pore material, which allowed for the injection of micro-air bubbles into the hydrocyclone by a compressor to further increase the separation efficiency. The results from this experiment also confirmed that air injection will increase the separation efficiency. The results indicated that the pore diameter of the micro-pore material should be in the range 39–45 μm. [52]

2.6.2 Heaters

By increasing the fluid temperature, the water viscosity will drop. As a result of this, the separation efficiency will increase and is explained by Equation (2.6) in Section 2.1.1 and illustrated in Figure 2.21. As the viscosity, μ, drops, the radial velocity of the droplet, u_r, increases, which will increase the separation of the phases. This can be done by installing a heater system upstream of the hydrocyclone setup, or by utilizing waste heat in applications where it is available. Heating may also support the breakdown of strong emulsions, and hence allow better separation. [53]

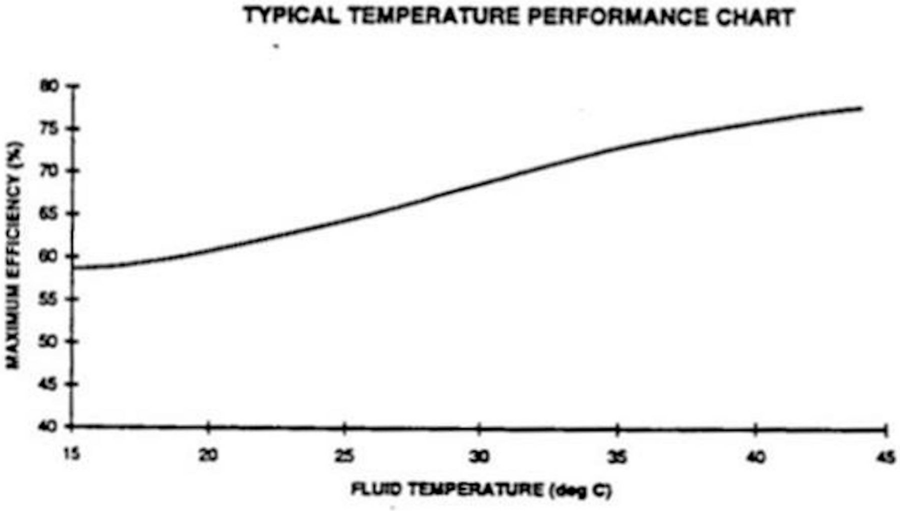


Figure 2.21: Typical temperature performance chart for a separation system with a heater. The figure clearly indicates that an increase in temperature leads to an increase in the maximum separation efficiency. [53].

2.7 Compact flotation unit (CFU)

There are several technologies that compete for a majority in the market of produced water treatment. Besides hydrocyclones, compact flotation units are one of the main technologies that are of great interest for the oil and gas industry. CFUs are already well-know, and is a well-proven technology for produced water treatment. It was first introduced to the oil and gas industry on the Norwegian Continental Shelf in 2001. A CFU utilizes both dissolved and induced gas flotation to remove oil droplets in the produced water. As explained in Section 2.6.1, the gas bubbles will increase the oil droplet diameter and thus improve the separation efficiency. [25]

According to [25], a CFU design by Schlumberger utilizes a gas mixer, to mix an external flotation gas with the bulk produced water flow, before a tangential inlet. The inlet is tangential to generate a swirling motion and to utilize centrifugal forces. The induced gas will create collisions between gas bubbles and oil droplets, and hence, the distance from the gas mixer to the CFU is an important part in the overall oil removal efficiency. Gas bubbles with attached oil droplets will rise to the liquid surface, and thereby form an oil layer and a gas pocket above it. The clean water will exit through the bottom of the vessel. This design solution is based on one injection inlet, but this could vary between different suppliers. [25]

A more innovative CFU design is the The Cameron TST-CFU. This is claimed by [54], to be the next generation CFU. The main difference between the Cameron TST-CFU and the above mentioned design by Schlumberger, is that the Cameron TST-CFU utilizes a static gas mixer installed near the bottom inside the vessel. The vessel consists further of special internals, a riser pipeline, distribution arms and inclined guide vanes. The mixing of gas and oil is introduced through several flotation stages within the vessel. The design is flexible and the number of flotation stages is dependent on the actual application. The produced water enters a inlet near the bottom of the vessel and flows upward. At the same time, gas bubbles are introduced to the produced water by the static gas mixer. These bubbles collide with the oil droplets in the riser pipeline. The gas bubbles and oil droplet mixture exits through the distribution arms horizontally in a radial-swirl pattern to properly release the liquid over the inclined guide vanes. Clean produced water exits through the bottom. [54]

According to [54], this next generation CFU is capable of handling high inlet oil concentrations and providing outlet OiW concentrations less than 10 ppm. The CFU technology have the potential to replace multiple produced water treatment technologies. [54]

The normal control variables of a CFU are the amount of flotation gas added and the amount of oil-reject withdrawn from the CFU. Normally, the CFU is operated manually, but Schlumberger have recently evolved the operation to be automatic. This is an absolute necessity in order for subsea operation, where there will be no operating personnel. The automatically operated CFU system reduces the OiW content, which could potentially allow for re-injection or disposal of the produced water in the same way as with hydrocyclones. [4]

A potentially interesting approach would be to implement a CFU in the laboratory setup, and compare the separation results from a system with hydrocyclones in series versus a CFU. This would be of great interest both during steady state conditions, and with the introduction of flow irregularities. [25]

2.7.1 Inline separation technology

In the last decades, Inline Separation Technology has been successfully introduced to several applications. The technology is applicable for gas-liquid, liquid-liquid and gas/liquid-solids separation. Inline technology is a compact separation solution, and achieves separation in pipe segments by the use of high centrifugal forces caused by cyclonic flow, except from the inline electrostatic coalescer further described in Section 2.7.1. The flow enters a stationary internal swirl element (ISE), as shown in Figure 2.22, to generate the cyclonic flow. The light phase migrates to the center and the heavy phase to the outer wall. This phenomenon is further explained in Section 2.1.1. The vanes, which are attached to the surface of the central body of the ISE and to the wall of the separator, generates the cyclonic flow. Both the axial velocity and the radius of the vanes contribute to increase the angular momentum. [3],[12],[55]

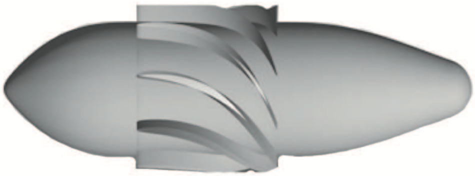


Figure 2.22: Internal Swirl Element [12],[55].

Inline gas-liquid separation

Inline gas-liquid separation is the most developed inline technology, and the portfolio includes the four separators phase-splitter, de-gasser, de-liquidiser and de-misterer, all based on the same principal. The inline phase-splitter, as seen in Figure 2.23, is the gas-liquid bulk separator. It is operating as a single stage separator, and is normally considered for applications with inlet gas volume fraction (GVF) ranging from 10 to 90 %. The inline de-gasser is normally used to separate gas from a liquid stream. It can be used for wide a range of inlet GVFs, typically from 0 to 60 %. It differs from a phase-splitter by utilizing a s separation stage. The inline de-liquidiser is the opposite solution to the de-gasser, separating liquid from a gas stream, also utilizing a s separation stage. It is normally considered for use at GVFs from 90 to 99.5 %. The last in the portfolio is the inline de-misterer. This contains small diameter demisting cyclones stacked in a pipe spool, and is used to remove small liquid droplets from a gas stream in a very compact manner. [3]

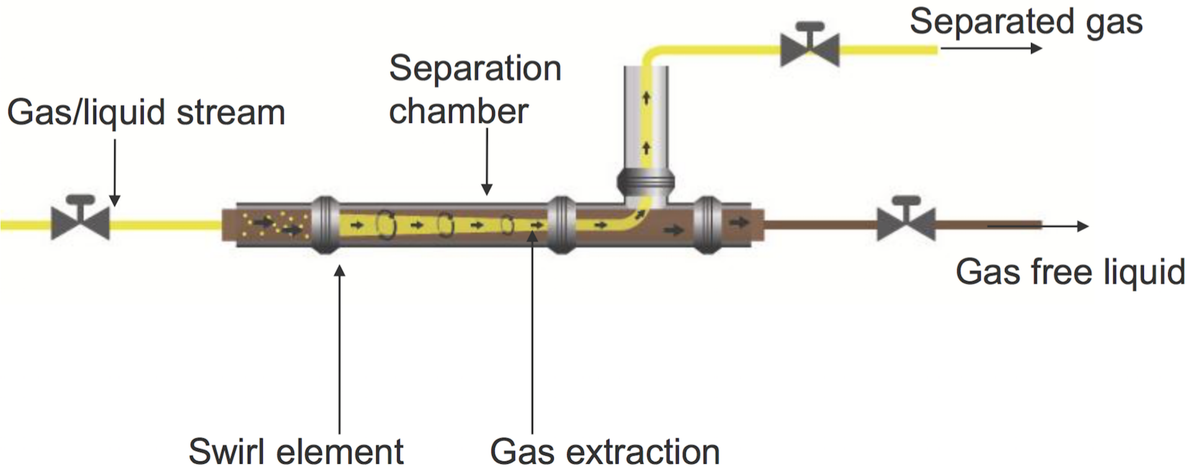


Figure 2.23: Illustration of an inline phase-splitter [56].

Inline electrostatic coalescer

The inline electrostatic coalescer utilizes electric fields to promote water-in-oil (WiO) droplet growth and emulsion breakdown to enable more effective oil-water separation. Previously, the electrostatic coalescers have been complex and large units with related operating challenges. As a result, the inline electrostatic coalescer has been developed for a more cost effective solution with a new high voltage power system and process design, resulting in higher efficiency, a more compact design and lower high voltage power consumption. Combined this allows for subsea installations. [3]

The inline electrostatic coalescer is designed to be fitted into a pipe spool and, as explained above, it increase the WiO droplets and break emulsions, which will allow for more efficient separation in a downstream separator. This is explained by (2.6) in Section 2.1.1. The downstream separator could for instance be a gravity separator, a pipe separator or a liquid-liquid hydrocyclone.

Separation with electrostatic coalescence has up until recently only been applied in topside processing systems, but inline technology has enabled a qualification of the technology for subsea applications. During the first quarter of 2015 ExxonMobil Upstream Research Company (EMURC) succeeded in developing and qualifying what [57] describes as *"an integrated, subsea compact separation system with electrocoalescence for ultra-deepwater applications"*. In the baseline trial, using a medium crude oil at 40 % water cut, the formed emulsions overwhelmed the pipe separator when separation was conducted without the electrocoalescer, leaving the end product with 30.5 % water cut. With the electrocoalescer integrated in the system the water cut of the end product after separation was 1.7 %. This example illustrates the importance of industry focus, and how seemingly advanced topside processing solutions can be integrated subsea as long as the industry partners see the value in such research. [6],[57]

2.8 Filtration Technology

The recent developments of accurate and reliable OiW sensors, mentioned in Section 2.5, the oil and gas industry will have the opportunity to operate produced water treatment (PWT) systems with feedback process-control and develop an effective and dependable closed-loop control system [40].

By investing in such OiW sensors, this will also be possible for the compact separator-lab. By operating the oil and water in a closed-loop system, some sort of filtration technology is an absolute necessity to ensure clean water returning to the water supply. Otherwise build-up of small oil droplets will occur that will degrade the system performance across time. [XIV]

Filtration is a mechanical or physical separation process to separate one phase from another by introducing a medium which only one phase can pass. Normally, the filters utilize one of the below mechanisms to separate the hydrocarbons from the produced water. [40]

2.8.1 Adsorption

This is a mechanical filtration process that will adhere the hydrocarbons to the surface of the filter media, and thereby create a film of hydrocarbons on the surface of the filter. According to [40], the most common adsorption filtration process in PWT are the nut shell filters.

2.8.2 Absorption

This is a physical filtration process where the hydrocarbon molecules are subjected to absorption in a volume by some bulk phase. According to [40], the most common absorption filters in PWT applications are activated carbon in granular or powder form.

2.8.3 Membrane

Like adsorption, membrane filtration is also a mechanical filtration process. Membrane filters are thin, film-like structures which acts as a selective barrier. The hydrocarbons in produced water are normally larger than 1 μm, and thereby a membrane filter with pores smaller than 1 μm will only allow the water to pass through and efficiently trap the hydrocarbons at the surface. To keep the membrane surface clean, a continuous scrubbing from gas bubbles and periodic backwash is necessary. [40]

2.9 Bulk Separation Concept from Department of Petroleum Engineering and Applied Geophysics

As described in Chapter 1, this paper is a part of the SUBPRO project, which is a cooperation between several industry partners and departments at NTNU. Each department has their own focus in the area of subsea technology, and are developing research within their field. One of these departments, the Department of Petroleum Engineering and Applied Geophysics, are currently working on developing new concepts for bulk separation of oil and gas. This concept should, if proven successful, be implemented in the future phases of the compact separation laboratory. This will likely result in an increase interest for the experimental results from the compact separation laboratory, and strengthen the cooperation between the different departments at NTNU in SUBPRO.

Chapter 3

Evolution of the Design

The SUBPRO project, an abbreviation for subsea production and processing, involves a cooperation between several industry partners and departments at NTNU. As a result, there are several interests and viewpoints to be accounted for. This laboratory design has therefore evolved as a result of continuous change. In order to understand how the final design was concluded, this chapter will act as a guide to the evolution of the design and why the specific decisions were made.

3.1 Foundation

SUBPRO's main intention is to become a leading international subsea research center that provides top quality candidates, knowledge and technology innovations [1]. In order to stay in the very front of technology development, SUBPRO aims to develop subsea solutions for current and future operational challenges. The industry partners clearly expressed an interest in the concept of compact subsea separation, and as a result it was decided that a laboratory should be built in order to test the relevant operational issues. For compact subsea separation, the current state-of-the-art includes hydrocyclones in different configurations, discussed in Section 2.1. Being a university, NTNU cooperates with several academical institutions around the world. One of these, the University of Aalborg Campus Esbjerg in Denmark, has already built a three-phase compact separation laboratory, and are using 2" pipes as the nominal diameter. Their setup includes both an upstream three-phase gravity separator and three different downstream hydrocyclones in parallel. At the very beginning of this semester Associate Professor Christian Holden [V] and PhD Candidate Sveinung Johan Ohrem [XIII] visited their facilities to get valuable inputs regarding the design and construction process. The information and experience which was gathered in Denmark served as the foundation for this project.

3.2 Start-Up Phase

There exist many different experimental setups of hydrocyclones. Some are more complex than others, but the basic idea is to either install a hydrocyclone downstream of a three-phase gravity separator, or to emulate the water outlet of an three-phase gravity separator by utilizing pumps and oil/water reservoirs. The University of Aalborg has the possibility to buy-pass almost every component, and thereby the opportunity to operate with several different laboratory setups. One of those is a simplified setup which involves an in-house designed transparent hydrocyclone liner, a positive displacement pump which feeds the fluid into the hydrocyclone, and a buffer tank containing the mixed fluid of oil and water, as seen in Figure 3.1, [15],[16],[23],[50].

One of the most important aspect of laboratory design is to build a setup which includes operational conditions as close to the industrial conditions as possible. Results acquired in a laboratory will be of less value if they can not be applied in an operational setting. Regarding hydrocyclones, the industrial approach is to stack multiple liners in parallel in order to handle a greater flow [15]. By scaling down the design to only involve one liner, important physical aspects within multiphase separation will still be maintained. A similar approach is applied in [13] and [14].

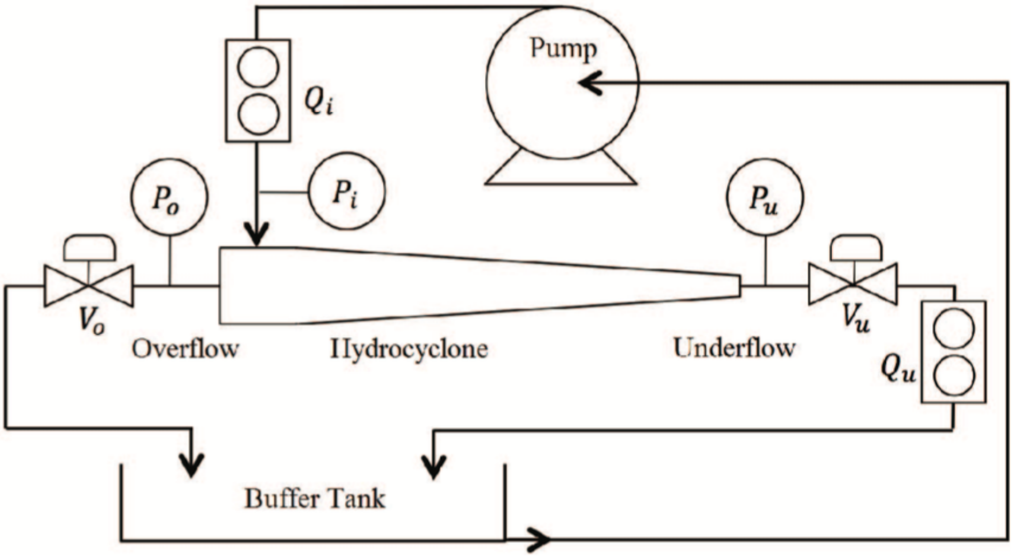


Figure 3.1: Example of a simplified hydrocyclone testing setup where the pump will generate a produced water stream [15].

The combined information from the visit at the University of Aalborg and the literature review conducted in Chapter 2 lead to the first design, illustrated in Figure 3.2. Gas was not implemented in the system at this point. The design was based on a water and an oil reservoir, two metering pumps capable of delivering the right amount of fluid with no pressure increase, a feeding pump to increase the pressure, one single hydrocyclone liner, pressure transmitters on the inlet, overflow and underflow to control the PDR, and a OiW sensor to measure the result. Since PDR control, as further explained in Section 2.1.5, is the most widely used control strategy to operate a hydrocyclone, this will be preferred in this thesis.

In the start-up phase the OiW sensor was identified as a key component for produced water treatment. An online OiW sensor will enable continuous monitoring of the separation result, and is therefore essential for the implementation of future control algorithms. As elaborated in Section 2.5, the recent developments of online OiW sensors enables produced water treatment systems to operate with feedback process-control in a closed-loop control system to constantly maintain the output at a predetermined set point. [40]

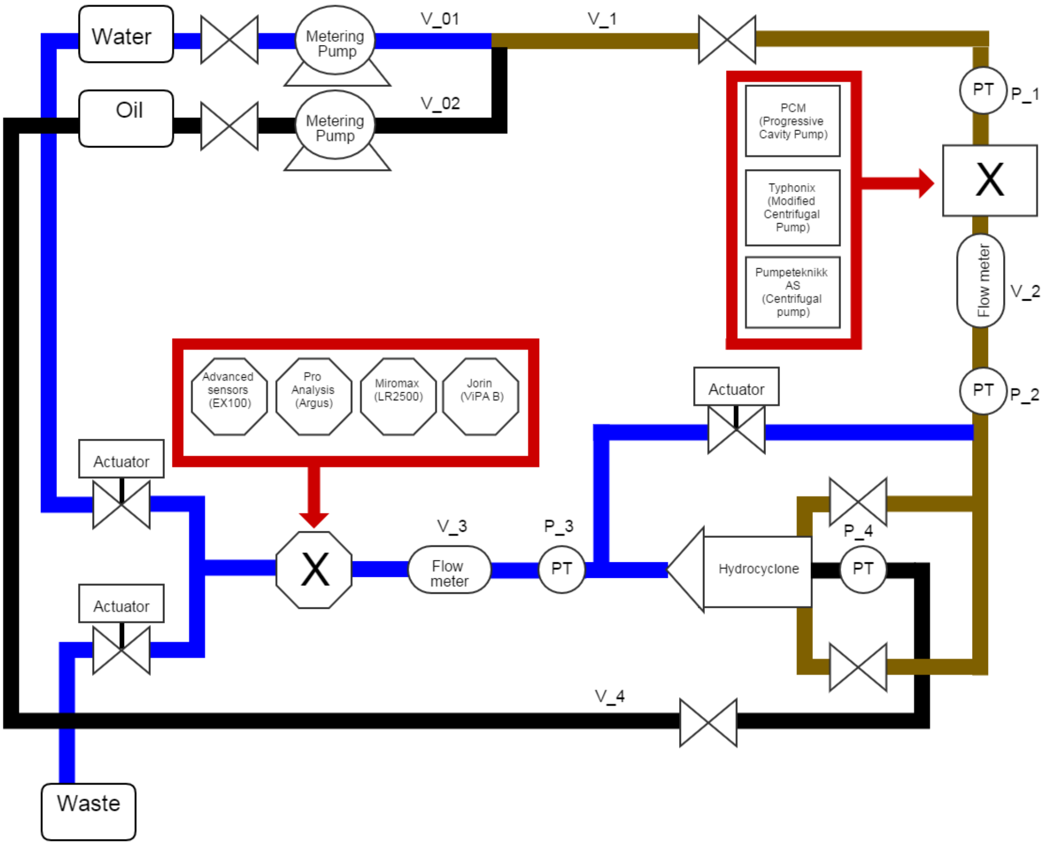


Figure 3.2: First draft of setup for compact separation laboratory. The blue line represents the water, the black line represents the oil, and the brown line represents a mixture of the two. Potential pumps and OiW sensors are placed inside red brackets.

During the start-up phase, contact with the different online OiW sensor suppliers has been established, and all the different technologies listed in Section 2.5 were assessed. Based on the fact that the residence time in a hydrocyclone is only a few seconds [9], the main concern for this equipment is to find the appropriate online OiW sensor which operates with a low response time. An equally important concern is that the technology is able to measure a synthetic model oil with a very low aromatic hydrocarbon content. This concern is further explained in Section 2.5.1 and 2.5.6.

At this very moment Statoil has an ongoing project to qualify different OiW technologies. Last year Statoil performed a topside laboratory test including three different technologies. Focused ultrasonic acoustics technology manufactured by Mirmorax [43], image analysis technology manufactured by Jorin [44] and LIF technology manufactured by ProAnalysis [42] were qualified. The conclusion from this test was that all three analyzers were capable of measuring oil concentrations up to 3000 ppm, they operated with high repeatability and accuracy within ± 20 % and the operation of the automatic cleaning systems were successful. The common disadvantage of the technologies was that they were highly dependent on droplet size distribution. Despite this disadvantage, all three technologies met the acceptance criteria and are ready for further field trials. In the near future Statoil is planning a topside offshore test and a subsea test. [58]

All the above mentioned OiW sensors qualified by Statoil were considered in this thesis. In addition, Advanced Sensors [41] which also utilizes LIF technology, and Industrial Tomography Systems [45] which utilizes Electrical Resistivity Tomography (ERT) technology were considered. These sensor options, except ERT, are shown inside the red bracket in Figure 3.1. The consideration is elaborated in Section 3.7.

3.3 First Adjustment

On February 4th 2016 a reference group meeting within the SUBPRO research project took place. The relevant industry partners and central parts of the administration at NTNU were present. One of the main topics up for discussion was the design and purpose of the compact separation laboratory. A/S Norske Shell informed that it would be interesting to expand the current design, with a setup with two or three hydrocyclones in series. The control aspect of this kind of setup is still not fully understood in the industry, especially since the coupling of control input between the hydrocyclones is very complex.

ExxonMobil investigated a two-stage produced water deoling system back in 2014 [47]. The preferred method for using a two-stage hydrocyclone system is for partial processing. Partial processing will be favorable in applications with high oil content in the produced water stream, e.g. 5 %. This is because a single stage hydrocyclone with limited separation efficiency not will be able to handle the high oil content. A two-stage hydrocyclone design consist of a first stage bulk hydrocyclone (HC1), which will reduce the oil content from 5 % down to 2000 ppm. A second stage water polishing hydrocyclone (HC2) is introduced to further reduce the oil content down to 30 ppm. [XIV]

Prior to the SUBPRO meeting on February 4th 2016 the process of evaluating equipment resulted in contact with Typhonix. Their technology are in the front end of pump development and have the potential to make a great impact on separation efficiency. Their coalescing pump, explained in Section 2.4.4, was therefore included in the design. Combined with the conclusions from the SUBPRO meeting the design was updated, and is shown in Figure 3.3. The Typhonix pump is placed in parallel with a conventional progressive cavity pump (PCP). This will allow for experiments that compare the impact on separation efficiency when using them as a feeding pump for the hydrocyclones. Sample points (SP) are included upstream and downstream of each hydrocyclone to compare with the results from the OiW sensors. Regarding the specific design of the hydrocyclones, it had not been decided if they were to be made in-house at NTNU or bought from an external supplier. As a result, the design was based on approximate values from articles [9] and [15], where the pressure was 10 bar and the flow rate 4 m^3/h. The dotted lines in Figure 3.3 connected to the control valves on the overflow and underflow is an illustration of how the PDR control strategy is set up. The main design parameters after the first adjustment are summarized in Table 3.1.

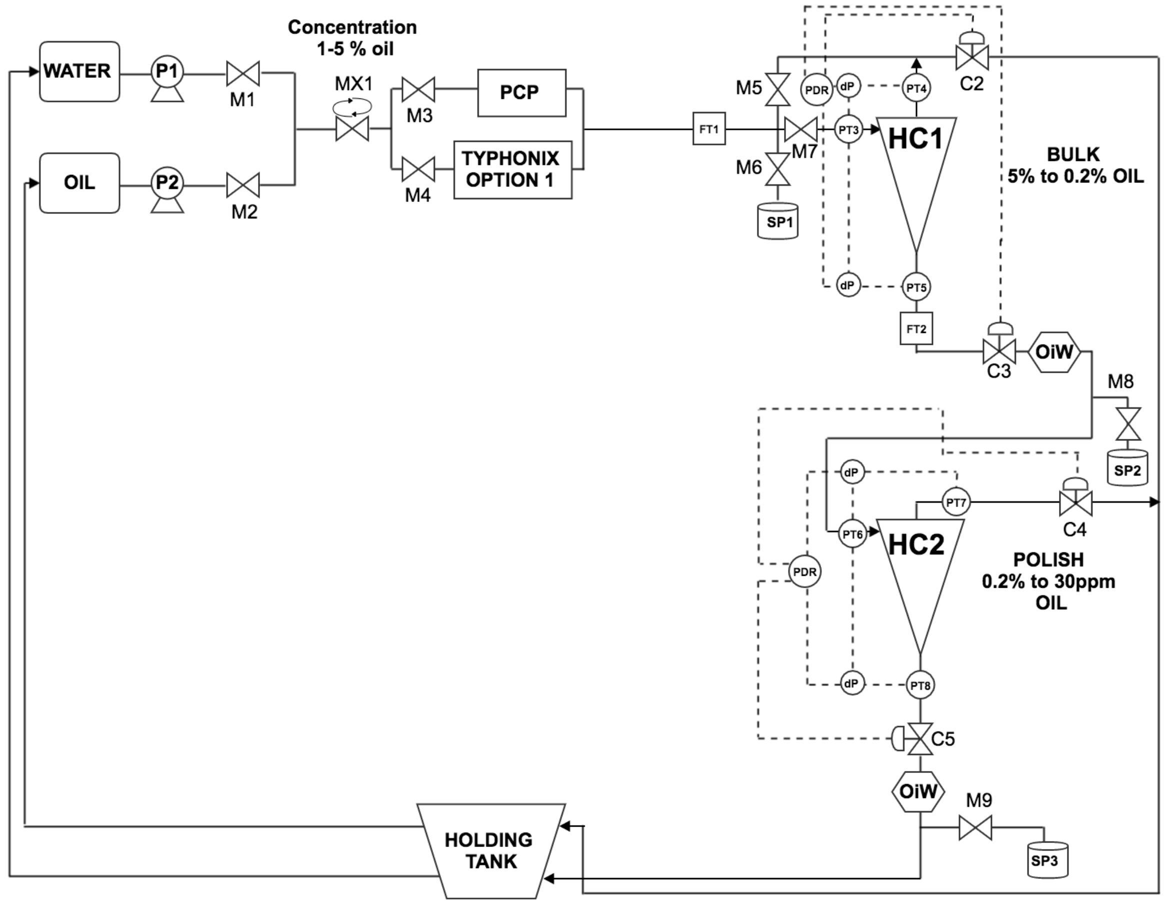


Figure 3.3: Design of two hydrocyclones in series. The dotted lines represents the PDR control. The oil exits through the top and the water through the bottom in both hydrocyclones.

Maximum Liquid Flow Rate	4 m^3/h
Maximum Operational Pressure	10 bar
Maximum Operational Temperature	Unknown
Material Selection	Unknown

Table 3.1: Design parameters after the first adjustment

3.4 Second Adjustment

3.4.1 Sponsored Hydrocyclone Liners

In the process of contacting equipment suppliers, the company eProcess Technologies offered to provide deoiler liners. The main point of contact has been Hank Rawlins [XIV], Technical Director at eProcess Technologies. Mr. Rawlins has informed that they are using the same liner in both the HC1 and HC2, however the oil reject port is modified. The HC2 may have an oil reject port of 2.0 mm and the HC1 between 2.5 and 4.0 mm depending on the oil stream treated. The optimal solution would be to implement control that enables the operator of the laboratory to change the oil reject ports from 1.5 to 4.0 mm depending on the test conditions.

As explained in Section 2.1.5, a hydrocyclone is characterized by a specific relationship between flow rate and the inlet to underflow pressure drop. eProcess provided a hydraulic capacity curve of their deoiler liners. On the basis of this curve, the operational flow rates could be specific. As seen in Figure 3.4, the minimum flow rate is 1.44 m^3/h and the maximum flow rate is 4.53 m^3/h. Based on the capacity curve the maximum operational pressure was increased to 30 bar considering the potential pressure drop when operating two hydrocyclone liners in series.

3.4.2 Potential Cooperation with Typhonix and visit

Due to a potential cooperation with Typhonix, the authors of this thesis, in addition to Associate Professor Christian Holden [V] and PhD Candidate Sveinung Johan Ohrem [XIII], were invited to their office in Bryne, outside Stavanger. The purpose of the visit was to discuss the implementation of Typhonix' low shear valves and coalescing pump, as well as a guided tour in their lab facilities. Due to their specific insight in reducing oil droplet breakup in separation processes, Typhonix were able to give specific advice regarding the overall design of the lab. Combined with their input, the design was updated with two different options for Phase 1. These options are shown in Figure 3.5 and 3.6.

As a part of the potential cooperation between NTNU and Typhonix, the design options shown in Figure 3.5 and 3.6 was sent to Typhonix for their assessment and approval. The authors of this thesis also included an assessment, based on their research, in the information that was sent to Typhonix. Both option A and B have a low shear typhoon valve in parallel with a conventional control valve between HC1 and HC2. This is to compare the impact of reduced oil droplet break-up through a Typhoon control valve, compared to the conventional valve. The main difference between the two options is the placement and types of pumps. One of the experiences from the visit at Typhonix, was the need for including a loop over the reservoir feeding pumps. This configuration in shown in Figure 3.5 and 3.6, and allows the pumps to adjust to the desired flow rate and pressure before entering the rest of the system.

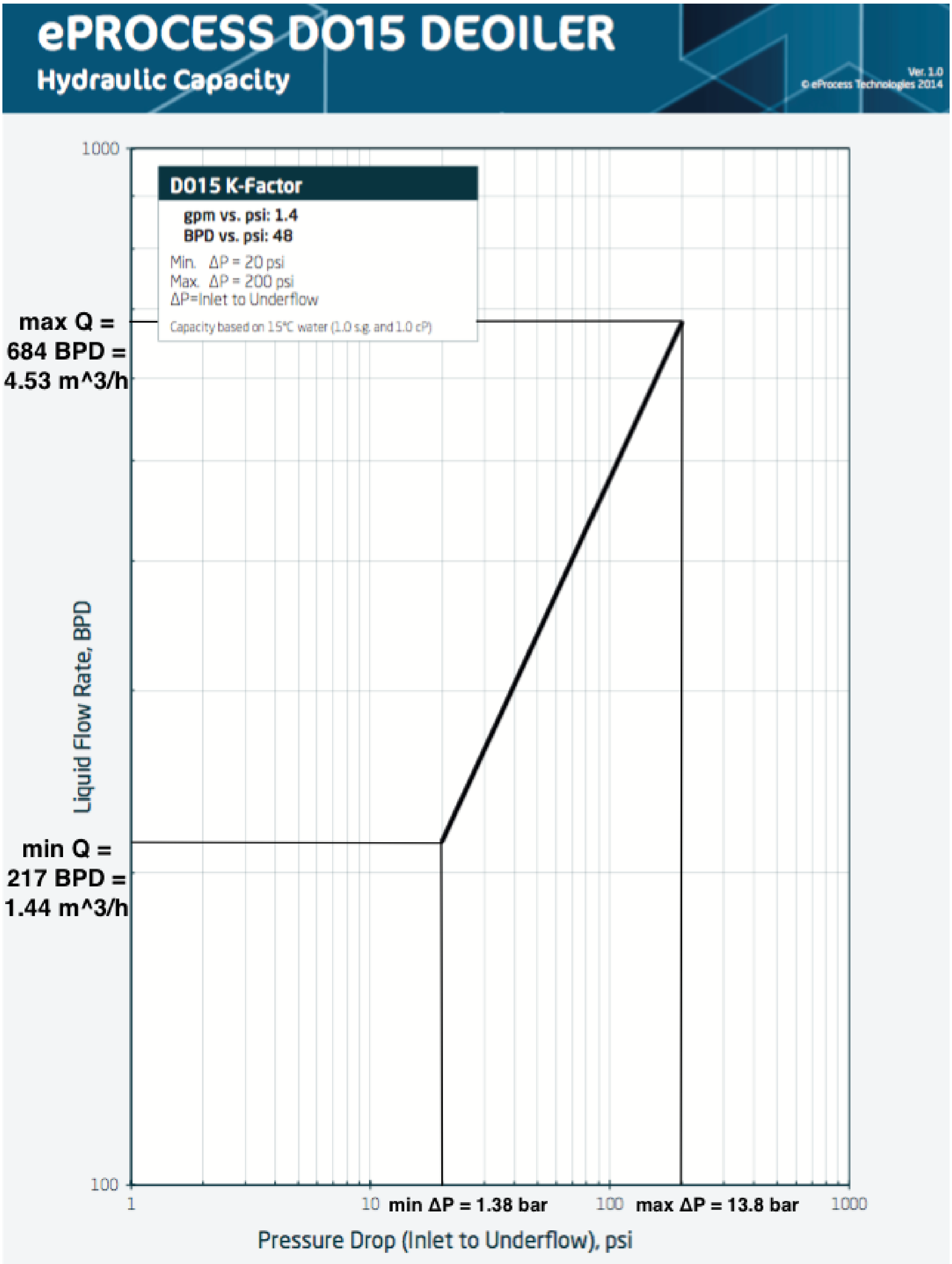


Figure 3.4: eProcess D015 Deoiler - Hydraulic Capacity. Shows the minimum and maximum flow rate and pressure drop for a hydrocyclone liner.

In Option A the reservoir pumps P1 and P2 will only generate the appropriate flow, and no pressure, while the feeding pumps in parallel will generate the desired pressure. The Typhonix coalescing pump and the progressive cavity pump are placed in parallel to compare the impact on later separation, as the Typhonix pump can increase the oil droplets size.

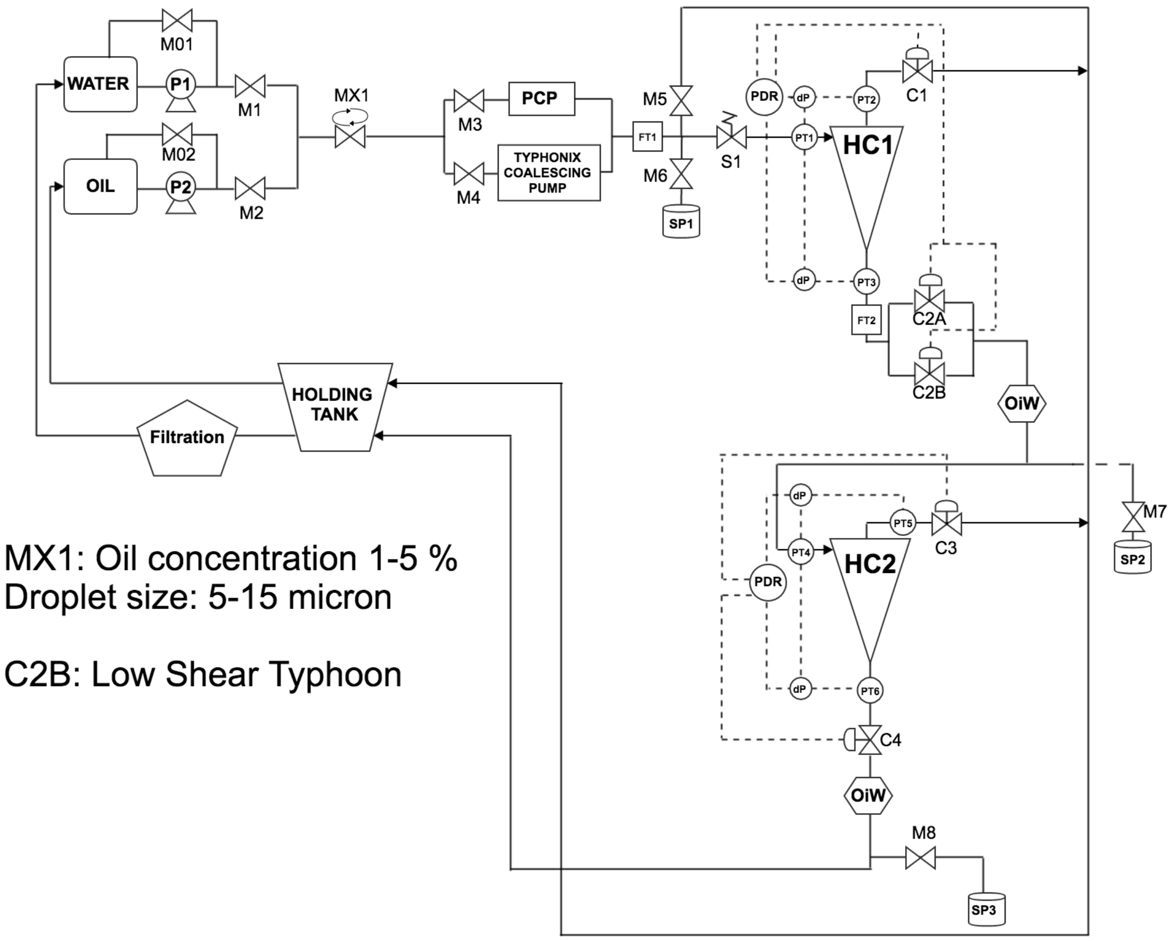
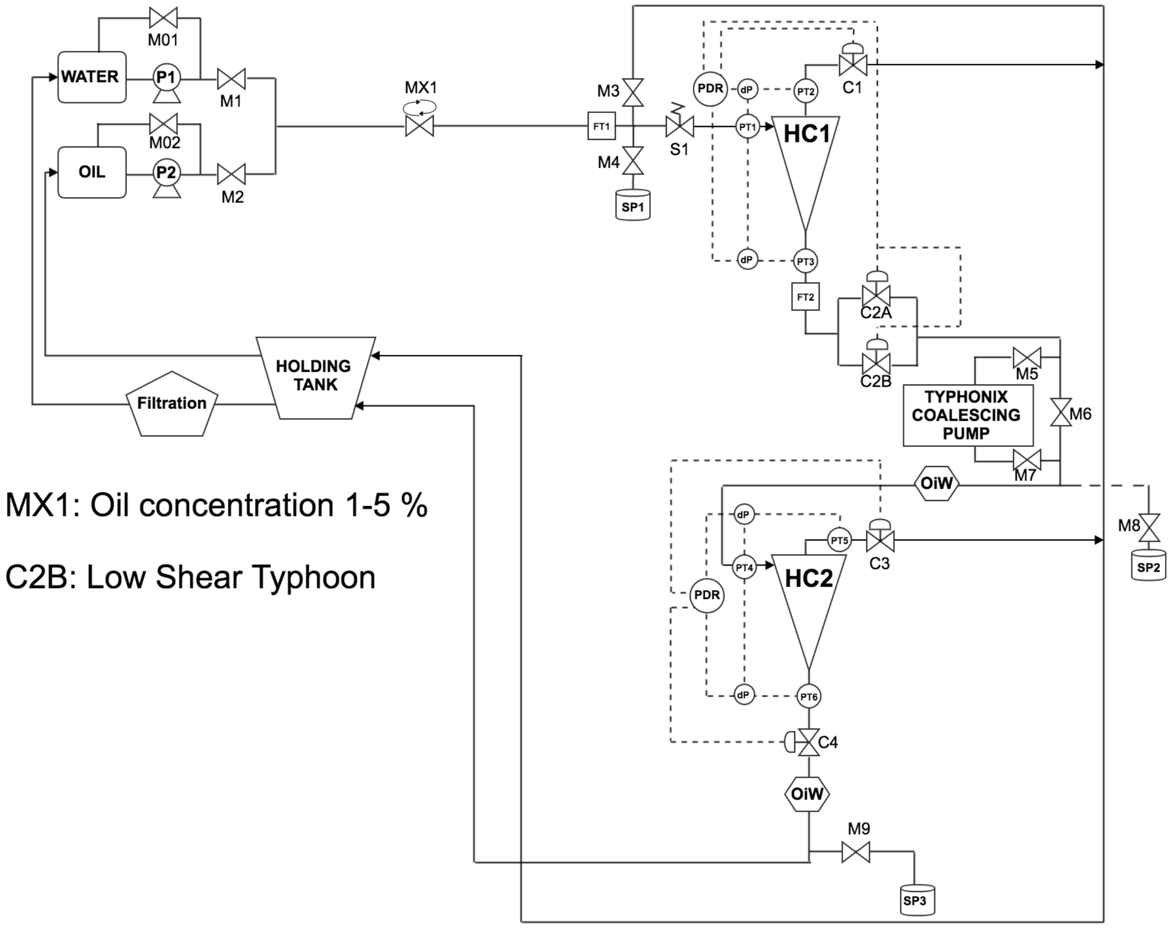


Figure 3.5: Phase 1 Option A. The Typhonix coalescing pump is used as a feeding pump and placed in parallel with a conventional progressive cavity pump. The low shear valve is placed in parallel with a conventional control valve to compare the impact on separation.

In Option B the reservoir pumps P1 and P2 generates both the desired flow rate and pressure, while the Typhonix coalescing pump is placed in a by-pass between HC1 and HC2. Since there will be an oil droplet break-up and a pressure decrease in HC1, the Typhonix pump is placed in a by-pass to compare the total separation result with and without a coalescing effect and the pressure increase between HC1 and HC2. Since Option B offers a more flexible and realistic design, the assessment recommended this. Summarized, Option B is more realistic because the oil and water feeding pumps will generate both the desired pressure and concentration directly to the hydrocyclone setup, while in Option A the feeding pumps would only deliver the concentrations and the Typhonix pump would generate the pressure. The main design parameters after the second adjustment are summarized in Table 3.2.



MX1: Oil concentration 1-5 %

C2B: Low Shear Typhoon

Figure 3.6: Phase 1 Option B. The Typhonix coalescing pump is placed in a by-pass between HC1 and HC2 to increase the oil droplet size and increase the pressure. The low shear valve is placed in parallel with a conventional control valve to compare the impact on separation.

Maximum Liquid Flow Rate	4.53 m^3/h
Maximum Operational Pressure	30 bar
Maximum Operational Temperature	Unknown
Material Selection	Unknown

Table 3.2: Design parameters after the second adjustment

3.5 Third Adjustment

In the SUBPRO reference group meeting mentioned in Section 3.3 the industry partners also expressed an interest in several concepts, in addition to hydrocyclones in series. Given the limited timeframe of this project, the need for several phases in the design and construction process was obvious. However, since the later phases of design and building would use the first phase as a foundation, the first phase needed to implement a flexibility for later expansions. This includes a possible increase in temperature ranges with the use of a compressor, all sensors, pipes and controls to be compatible with the implementation of gas in the system, and a setup based on by-passes that allows for the components to be tested individually and in series. The conclusion was to divide the total process into 4 phases; Phase 1, Phase 2, Phase 3 and Phase 4. The future phases are shown in Figures 3.7 to 3.9.

3.5.1 Phase 2

Phase 2, as seen in Figure 3.7, involves the implementation of air-injection to the produced water stream and a third-stage hydrocyclone (HC3). By operating with an air-liquid ratio of 1 %, this has the possibility to increase the separation efficiency. Experiments summarized in the paper [51] concludes that the oil removal efficiency was increased from 72 % to 85 % with an air-liquid ratio of 1 %. Further information about air-injection is found in Section 2.6.1.

eProcess have previously experimented by implementing HC3 after HC2 to further reduce the oil content from 30 ppm. Their results have shown that the oil droplet size is so small at this point in the separation cycle, that HC3 does not increase separation efficiency. An idea regarding this issue was to implement a Typhonix coalescing pump between HC2 and HC3 to increase the oil droplets and hence be able to further reduce the oil content from 30 ppm. However, when this idea was introduced to Trygve Husveg [VI], Technology Manager at Typhonix, it was rejected. The coalescing pump would not be able to increase the oil droplets due to the very low oil concentration. The coalescence effect is proportional to the oil concentration. Mr. Husveg proposed instead to implement a Typhonix low shear valve between HC2 and HC3, which might have a positive effect on the separation efficiency in HC3, and hence be able to further reduce the oil content below 30 ppm. The PDR control setup will be equally implemented for a three stage setup as for the two stage setup, as shown in Figure 3.3. For the continuation of this thesis the dotted lines will be removed from the schematics in order to simplify the overview of the design.

3.5.2 Phase 3

Phase 3 , as seen in Figure 3.8, will involve the implementation of a gravity separator. This has to be placed upstream of the hydrocyclone setup and will allow for an increase in the oil concentration. The implementation of a gravity separator also allows for cooperation between the different departments and research groups in SUBPRO. At the Department of Petroleum Engineering and Applied Geophysics new designs for bulk separation are currently being tested, and it might be relevant to include one of these concepts in Phase 3. By including a gravity separator or a similar concept for bulk separation, the implementation of gas in the system is also a possibility. Statoil, which is one of the industry partners in SUBPRO, has previously indicated that they are interested in sponsoring the laboratory setup with a phase–splitter. This should be implemented upstream of the gravity separator (or equivalent bulk separation).

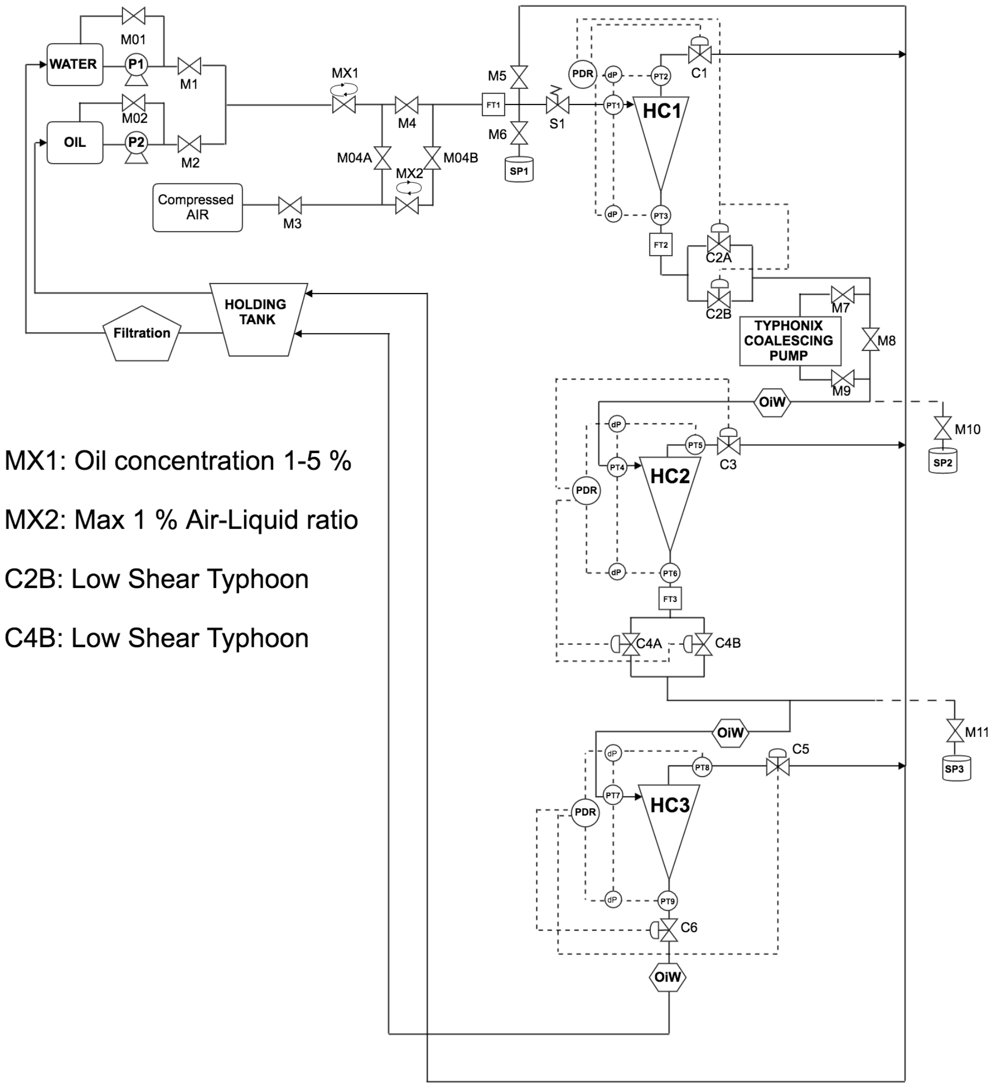
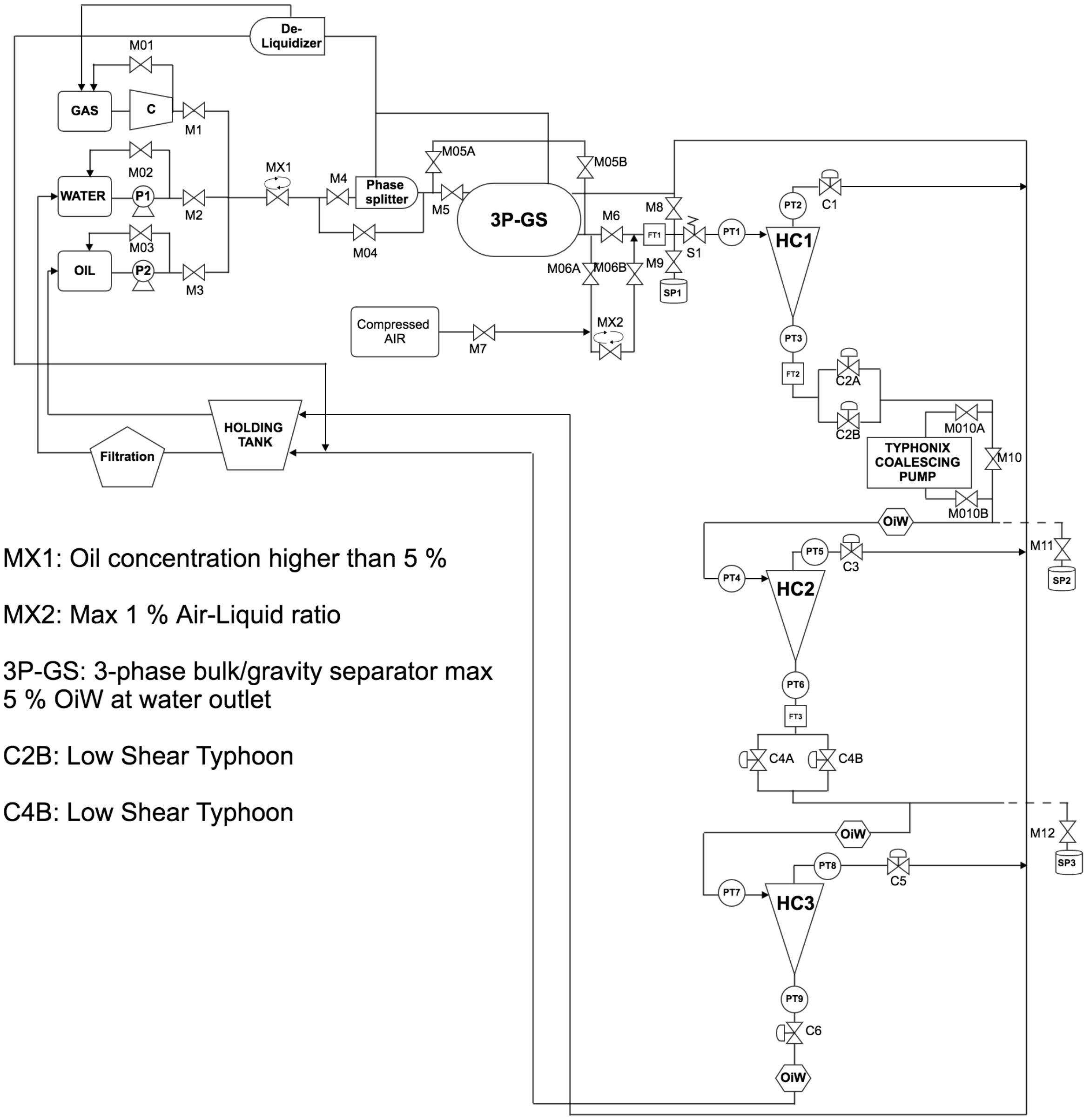


Figure 3.7: Phase 2. Implementation of air-injection and a third-stage hydrocyclone.

With the implementation of gas in the system, the laboratory will model a complete small scale compact separation facility.

It is important to choose the right gas type when implementing gas in the system. The laboratory setup is not EX certified, mainly due to cost constraints, as this would increase the cost substantially. Normally, methane or natural gas would be the the appropriate gases to model oil and gas separation. However, because of their explosive potential, especially under high pressures, these gases are not an option. Other gases, such as sulfur hexafluoride and nitrogen, have previously been applied in similar experiments because they do not include an explosion risk [59].



MX1: Oil concentration higher than 5 %

MX2: Max 1 % Air-Liquid ratio

3P-GS: 3-phase bulk/gravity separator max 5 % OiW at water outlet

C2B: Low Shear Typhoon

C4B: Low Shear Typhoon

Figure 3.8: Phase 3. Completing the small scale compact separation laboratory.

3.5.3 Phase 4

As mentioned previously, Phase 3 completes the compact separation laboratory. Thus, Phase 4, as seen in Figure 3.9, is used to implement future developments. Since new technology is constantly developing and the results from the future phases mentioned above are yet to be discovered, it is difficult to predict the precise scope of work for Phase 4, but process equipment like a Compact Flotation Unit (CFU), electrostatic coalescer, a heater and membrane filtration, might be alternatives to consider.

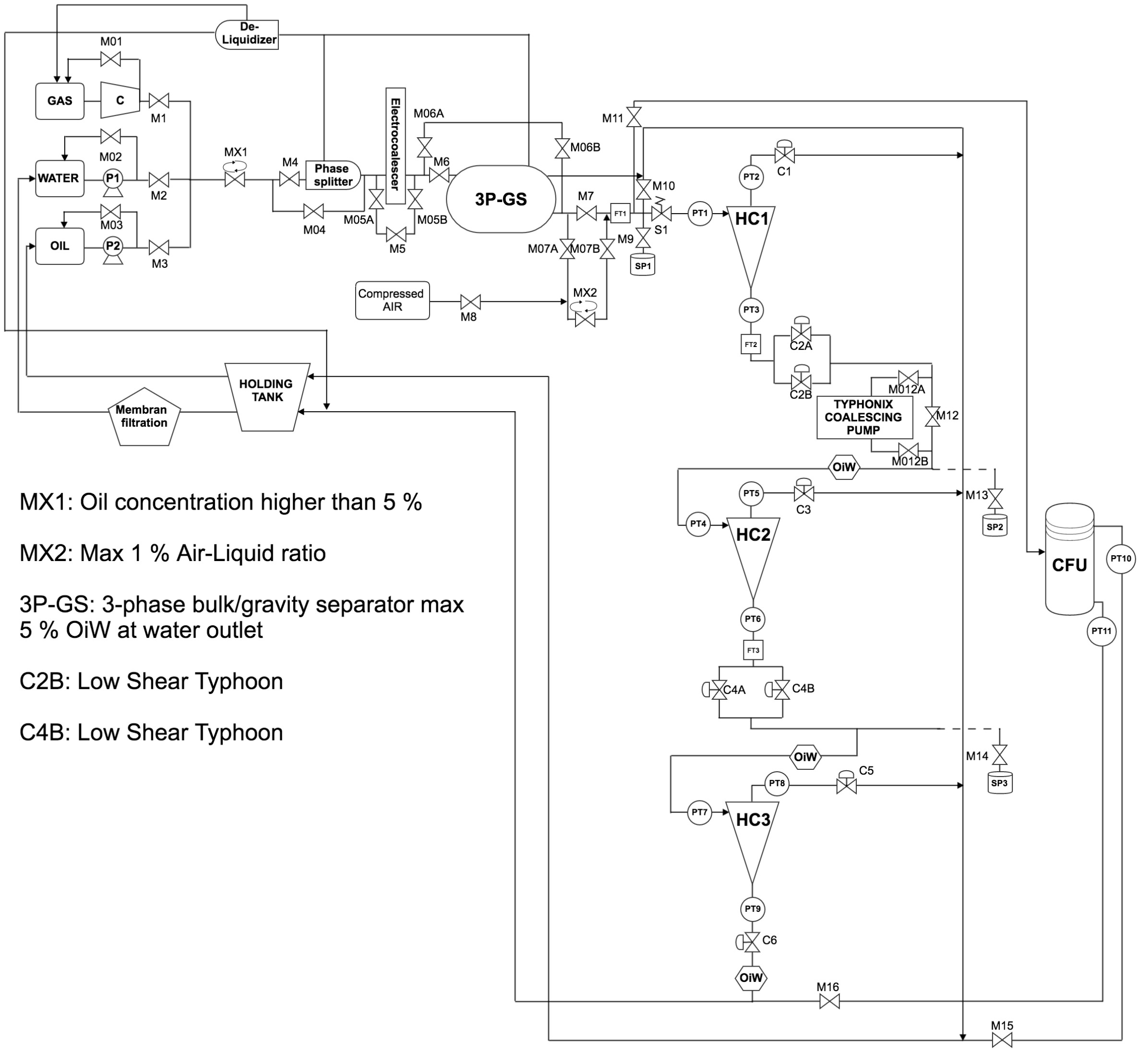


Figure 3.9: Phase 4. Implementation of future concepts.

3.6 Fourth Adjustment

The designs in Section 3.4 and 3.5 serve as a foundation for future design considerations. In order to finalize the design of Phase 1, and actually start the construction, there are a number of details that must be mapped out. As seen in Table 3.2, both the maximum operational temperature and the selected material must be determined. Besides the low shear Typhoon control valves from Mokveld and the coalescing pump from Typhonix, pumps, valves, and transmitters are generally "of-the-shelf equipment" as long as parameters like pressure, temperature and flow are determined. On the other hand, the reservoir system which includes the holding tank and the oil and water reservoirs for Phase 1, could be designed in a number of ways. These challenges together with the material selection were addressed in the fourth adjustment.

3.6.1 Reservoir system

Open vs. closed loop

In the design process for the reservoir system, the main challenge was to decide if the flow in the laboratory should be a closed or an open loop. With a potential maximum flow rate of 4.53 m^3/h (explained in Section 3.4), which equals 4530 liter through the system per hour, the system is dependent on a large water supply, and due to these large amounts of water a closed loop design is desirable.

Mr. Rawlins [XIV] pointed out that the main challenge with a closed loop is to ensure 0 ppm OiW returning to the water reservoir. It is therefore important to include some sort of oil removal system in the holding tank. The main purpose of such a system is to avoid the build-up of small oil droplets that will degrade the system performance over time. Mr. Rawlins informed that this has been their single biggest challenge, and even small concentrations of oil that get recycled back to the holding tank would create problems and degrade the overall separation results after just a few hours of testing.

As an example, the laboratory would have 100 % clean water the first time it runs, but since the oil and the water are dumped in the same holding tank, some of the reused water could be contaminated with oil. This depends on the separation and filtration process between the holding tank and the water reservoir. This accumulation of oil in the processed water could be avoided by designing the system as an open loop, as this would mean a continuous supply of 100 % clean water. This would, however, imply a great amount of waste water, which would mean a potentially challenging logistics chain in order to remove it safely, after processing. Water with an oil concentration of 30 ppm can be dumped in the Norwegian waste water network [XVI], a separate sewage system for industrial purposes, but since the system will be exposed to slugs there is a chance that the concentration of oil in the waste water is much higher than 30 ppm.

Another problem with the open loop design is the amount of water needed. The Department of Production and Quality Engineering share their workshop with the Department of Hydraulic and Environmental Engineering, and this department have installed large water reservoirs beneath the workshop. According to Geir Tesaker [XVI], engineer at the Department of Hydraulic and Environmental Engineering, these reservoirs contain 800 m^3 of water. A possible implementation of these reservoirs as a feeding system to the compact separation laboratory running in open loop has been discussed, but it was rejected because the compact separator laboratory could potentially empty the reservoirs in intensive periods of testing and experiments.

The Department of Hydraulic and Environmental Engineering did however approve that the compact separation laboratory used their water supply to refill the reservoir system when needed. See Appendix E for further details. As a result, the reservoir system has been designed to run in a closed loop, but with the possibility to add new water when a degradation of the results is detected.

Filtration technology in the reservoir system

Regarding the filtration process, an oil skimmer will be installed in the holding tank together with downstream filtration technology to perform a closed loop laboratory setup. There are several different types of oil skimmers on the marked. For this application a non-oleophilic belt oil skimmer, as seen in Figure 3.10, will be used. This machine is using a continuously rotating metal element which the oil adheres to because of the different surface tensions of oil and water. The oil skimmer will separate the bulk amount of oil accumulating on the liquid surface in the holding tank. The oil skimmer has the capacity to remove 150 l oil per hour [60]. [61],[62]

Figure 3.10: Non-oleophilic belt oil skimmer - Model Oil Grabber M8 [63].

Some filtration technologies are more advanced and expensive than others. Due to a strict budget, adsorption filtration will possibly be the most suited technology for this application. This is an affordable solution that utilizes filter media installed inside of a filtration tank. The hydrocarbons will adhere to the surface of the filter media and create a film of hydrocarbons on the surface of the filter. When the filter media has been saturated with oil, the filter media has to be replaced. The different filtration technologies are further explained in Section 2.8. [40]

Based on their operational experience from similar laboratory setups, Typhonix and Mr. Husveg [VI] was consulted regarding the filtration technology. Mr. Husveg informed that their filtration process was provided by Klart Vann AS [64]. Geir Kjærland [VIII], CEO at Klart Vann AS, proposed the exact same filtration solution for this application. The solution is based on the adsorption filtration technology and utilizes two equal metal filtration tanks. The first filtration tank contains a pre-filter, which normally filtrates particles in the range from 0.5

to 5 μm. This is to remove the most particulate contamination prior to the second filtration tank, which contains a hydrocarbon/emulsion filter. The hydrocarbon/emulsion filter filtrates particles greater than 0.3 μm. The exact equipment is listed in Section 5.8.1.

In a closed-loop setup, Mr. Husveg [VI] highlighted the importance of salt particles in the system. This will ensure a coalescing effect on the oil droplets, and is therefore important for the separation efficiency. When filtrating the hydrocarbons, the filtration technology will also remove the salt particles. This will have a huge impact on the coalescence in the system, and without the salt particles, the system will be more sensitive to shearing. This means the system will have an increased chance of oil droplet breakup, which will have a negative impact on the overall separation results. The solution will be to fill more salt in the recycled water when all the pre-salted water has been used. How much the water will need to be re-salted for each "run trough" will be based on trials and is a learning–by–doing process. It is important to be aware of the fact that a decreased salt concentration will lead to increased shear effects.

Tank design and layout

Optimizing the reservoir system have been an important aspect of the design process, both due to cost perspectives and the risks related to leaks. Fluids containing large amounts of oil should be contained in special containers with double walls in case of leaks, and pure oils should in addition be contained in steel containers to avoid any risk of fire. Several concepts were considered, but large tanks are expensive, as well as being sensitive to leaks. If a leak occurs the entire tank must be replaced. As a result, the reservoir system has been designed as a mix of larger and smaller tanks in order to easily be able to replace tanks in the case of leaks and at the same time comply with the need for double walled containers for fluids containing oil. The design of the reservoir system is shown in Figure 3.11.

The holding tank, which acts as a dump reservoir, will be a single walled container containing a maximum amount of 5000 l of water and oil. The amount of oil, 5 % at maximum, is considered to be low, and as a consequence the tank only needs a single wall [V]. This holding tank will serve as a gravity separator where oil will float to the top as a result of density differences, and the water will accumulate at the bottom. A submersible pump will be placed at the bottom of the holding tank, and deliver a maximum flow rate of 185 l/min to the filtration tank. Detailed info on the pump can be found in Section 5.8.4.

The water reservoir will be made up of five IBC tanks. The IBC tanks are made of high density polyethylene (HDPE), which is easily weldable [XVI]. This allows for parallel pipe connections between the tanks. The connections are made using 2" pipes with manual valves and flanges between the tanks. If a leakage should occur in one of the five tanks, the leakage can be isolated by closing the valves connected to the tank, allowing the tank to be replaced or repaired without further risk of spills. The pipe connections should be placed in the lower section of the IBC tank, as shown in Figure 3.12. This will allow all the tanks in the reservoir system to be filled up at the same time, instead of one tank at the time.

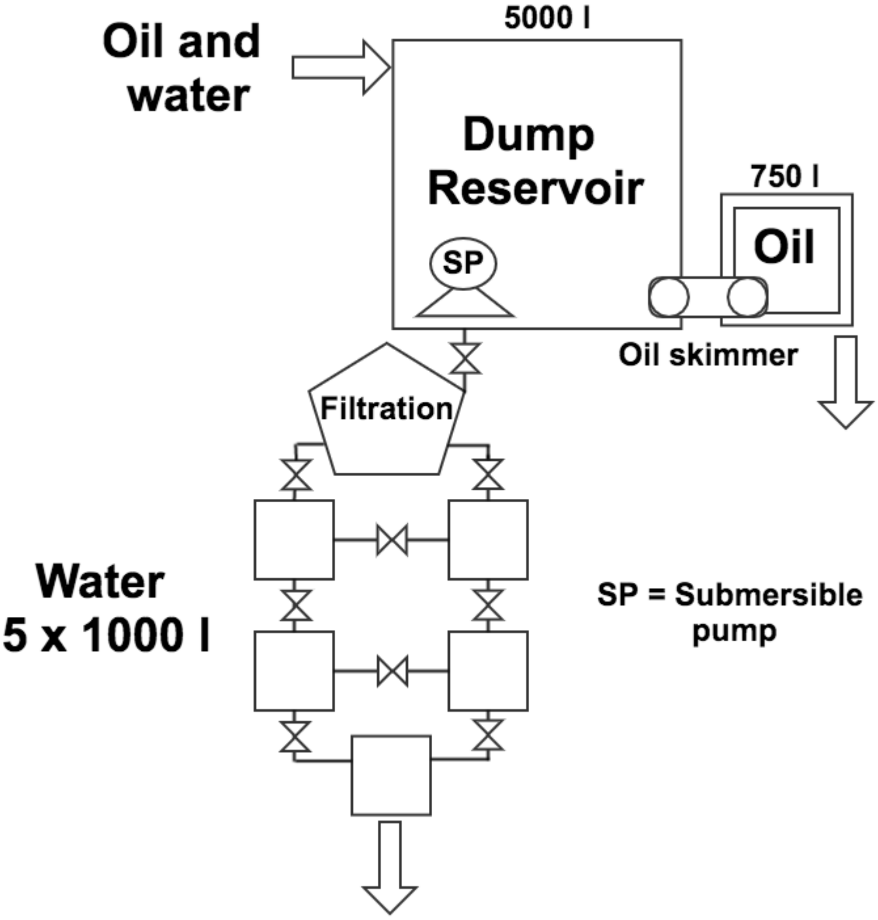


Figure 3.11: Sketch of the reservoir system. The oil and the water mixture are dumped in the dump reservoir, where the oil skimmer separates the oil accumulated on the surface, and a submersible pump feeds water to the filtration tank.

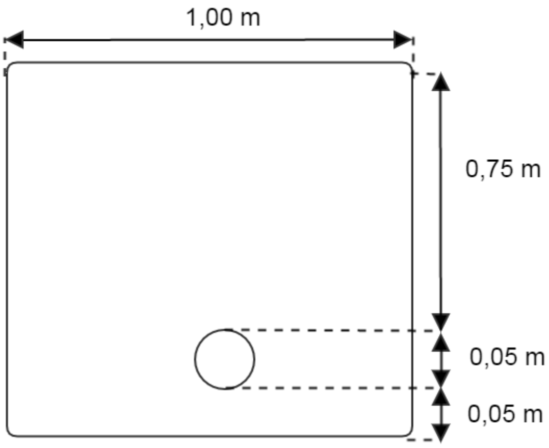


Figure 3.12: Sketch of IBC tank dimensions for reservoir system.

3.6.2 Material Selection

Regarding the the material selection, it has to be both corrosion- and wear resistant with respect to temperature, chloride-content and material compositions. In addition it must be able to withstand the operating pressure with a safety factor of 1.6 [V].

Galvanic corrosion is a major threat to the integrity of the piping system, and should be considered in the material selection process. In this application, galvanic corrosion will occur between two different metals (different electrode potential) when they are in direct electrical contact and are exposed to the same electrolyte. Water with low concentration of oil is an example of an electrolyte. The less noble metal in the coupling will act as a sacrificial anode and hence be exposed to corrosion. If the use of two different metals can not be avoided, a rule of thumb is to keep a favorable area ratio between the two metals, meaning that the area of the less noble metal has to be much greater than the area of the more noble metal. In this situation the galvanic corrosion on the less noble metal will be restricted and can normally be neglected. [65]

Critical galvanic corrosion is normally avoided by selecting metals with a potential difference less than 50 mV. However, there exist several measures which ensures galvanic corrosion is completely avoided. By separating the two metals with an insulating material, galvanic corrosion will be avoided. Galvanic corrosion can also be avoided by internal coating of the most noble metal. This is to keep a favorable area ratio, if a failure in the coating should occur. As mentioned above, the coating failure will have neglectable effect on galvanic corrosion because the area of the less noble metal is much greater than the more noble coating failure. According to [65], the NORSOK standards [66], recommends a minimum coating length of ten times the diameter to be applied. The preferred solution, however, is to use the same material for all the components in the system. [65]

It is obvious that the material should be some sort of stainless steel due to the combination of oil and water, with small amounts of salt (NaCl). AISI 316L and 22Cr DDS are stainless steel alloys commonly utilized in the oil and gas industry due to high resistance to corrosion [XI]. AISI 316L is an austenitic stainless steel with low strength. 22Cr DDS is a duplex stainless steel and provides higher strength and even higher corrosion resistance compared to AISI 316L, and a corresponding higher price per meter. [67]

Rune Kjeldsberg at Ahlsell [VII], proposed two different stainless steel alloys suited for the pipes for the laboratory. The first was ASTM 312 TP 316L, which is the same as AISI 316L. The second was ASTM A790 UNS S31803, which is the same as 22Cr DSS. Based on the fact that all components in the system, such as valves, pumps, transmitters and hydrocyclones normally will be manufactured in AISI 316L, as further elaborated in Chapter 5, the optimal solution is to choose pipes in the same material to avoid galvanic corrosion. This will allow the design to utilize "off-the-shelf" products, which will help reducing the overall cost.

By choosing AISI 316L as the piping material, the fluid temperature is restricted to a maximum of 50 °C to avoid stress corrosion cracking (SCC), as seen in Figure 3.13. SCC is cracking of the metal involving corrosion and tensile stress in the presence of a corrosive environment [65].

To be able to withstand the operational pressure with a safety factor of 1.6, the wall thickness and corresponding pipe strength of the pipes are important to specify. The wall thickness of pipes are expressed in schedules, referred to as pipe schedules. The pipe schedule is abbreviated as SCH and defined in the ASME standard [68]. The pipe schedule and allowable working pressure at 50 °C of ASTM 312 TP 316L are shown in Table 3.3. Based on the information

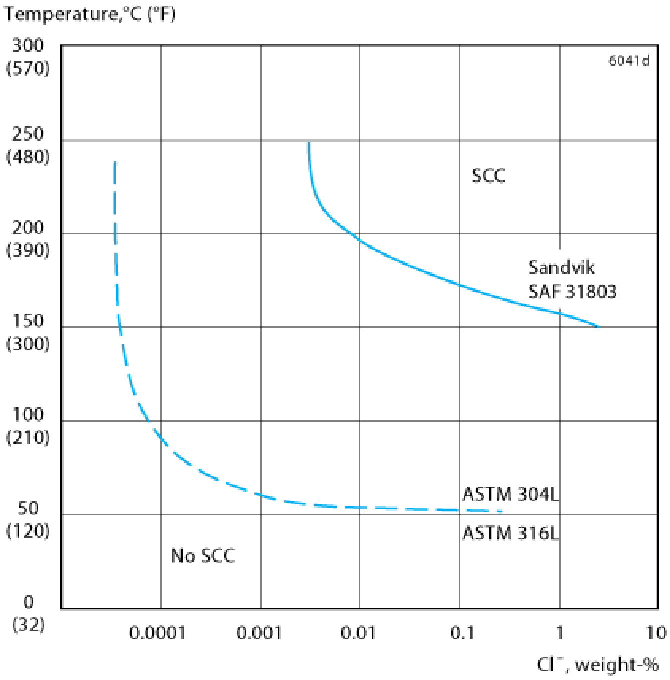


Figure 3.13: Resistance to stress corrosion cracking of ASTM 316L (AISI 316L) and SAF 31803 (22Cr DDS) in neutral chloride solutions with an oxygen content of about 8 ppm [67].

provided by the table, SCH 10 would be a sufficient solution for this application. This was suggested by Mr. Kjeldsberg at Ahlsell.

As mentioned in Section 3.1, the University of Aalborg Campus Esbjerg in Denmark have already built a similar compact separation laboratory, and are using 2" pipes as the nominal diameter. This will also be suited for this laboratory, and the decision have been consulted with Mr. Rawlins [XIV]. The design parameters after the fourth adjustment are summarized in Table 3.4.

Nominal Size (inches)	Schedule Number	Outside Diameter (mm)	Wall Thickness (mm)	Inside Diameter (mm)	Design Strength (bar) at 50 °C	Allowable Working Pressure (bar) at 50 °C
2	5	60.33	1.65	57.03	1150	56
2	10	60.33	2.77	54.79	1150	96
2	40	60.33	3.91	52.51	1150	138
2	80	60.33	5.54	49.25	1150	201

Table 3.3: Pipe schedule and allowable working pressure at 50 °C - ASTM 312 TP 316L [69].

Maximum Liquid Flow Rate	4.53 m^3/h
Maximum Operational Pressure	30 bar
Maximum Operational Temperature	50 °C
Material Selection	AISI 316L

Table 3.4: Design parameters after the fourth adjustment.

3.7 Fifth Adjustment

Along with the latest adjustments, continuous contact with the suppliers of OiW sensors enabled the selection of an OiW sensor to be determined. The different sensors and suppliers mentioned in Section 3.2 are evaluated in Section 3.7.1, and the conclusion is summarized in Section 3.7.3. Because of the dependency of aromatic hydrocarbon content in the oil for LIF technology, explained in Section 2.5.1 and 2.5.6, the specific model oil chosen for the laboratory was also of great importance. The process of choosing an appropriate model oil is explained in Section 3.7.4.

3.7.1 OiW sensor suppliers and offers

In order to choose the best suited OiW sensor for the laboratory, all the relevant suppliers have been consulted on their technology and asked to give a non binding offer. The summary of the relevant suppliers, in addition to the pros and cons relative to the design, are listed in the following subsections.

EX-100 – Advanced Sensors

The operational experiences with the EX-100 sensor vary depending on the source. In [40], the results confirmed that the EX-100 sensor can perform acceptable and reliable accuracy with no major operational issues. The sensor is also applied by Schlumberger in [25]. At the University in Aalborg, Denmark they have experienced difficulties with the sensor when trying to calibrate in the ranges 5–50 ppm [50]. The EX-100 sensor is shown in Figure 3.14.

The Norwegian distributor of the Advanced Sensors-series is Norsk Analyse AS [70]. On April 6th 2016, Morten Myhre Andersen and Jon Carlsen from Norsk Analyse AS, and Russell Hempsey [III] from Advanced Sensors, made a visit to the Department of Production and Quality Engineering. The agenda for the meeting was to discuss their offer, and discuss the implementation of their technology in our laboratory.

They informed that the response time of 1 s, as stated in their data sheet shown in Appendix D.1, could be modified to 480 ms. They also informed that the insertion/extraction tool in the offer would not be necessary in this application. In addition they informed that flow rate and droplet size variations would have minimal impact on the measurement readings. Regarding the issue of measuring a synthetic model oil with low aromatic hydrocarbon content, a sample of 30 ml Exxsol D140 (see Section 3.7.4) was sent to Mr. Hempsey for further analysis. A major disadvantage of the EX-100 sensor is that a maximum of two probes can be connected to one analyzer. This would increase the expansion cost if more than two probes are to be included in the future phases.

Supplier	**Advanced Sensors**
Norwegian distributor	Norsk Analyse AS
Technology	Laser Induced UV Fluorescence (LIF) LIF technology is explained in Section 2.5.6
Offer	Dual probe system: Price is confidential Automatic ultrasonic cleaning system: Included
Oil concentration range	0–3000 ppm
Response time	480 ms
Pros	Appropriate for feedback control Dispersed and dissolved hydrocarbons are detected In-line Self-cleaning system included in offer Salinity do not interfere with the measurements Various measurement ranges Not affected by 10–15 % gas content
Cons	Chemicals with aromatic content will affect the readings Maximum two probes connected to one analyzer Not able to measure the oil droplet size Recalibration for different types of oil Relative constant aromatic hydrocarbon content

Table 3.5: Summary of the Advanced Sensors EX-100, including pros and cons.

Figure 3.14: Advanced Sensors EX-100 [70].

Argus Oil in Water Monitor – ProAnalysis

Supplier	**ProAnalysis**
Technology	Laser Induced UV Fluorescence (LIF) LIF technology is explained in Section 2.5.6
Offer	Single probe system: Price is confidential Dual probe system: Price is confidential
Oil concentration range	0–3000 ppm
Response time	250 ms
Pros	Appropriate for feedback control Dispersed and dissolved hydrocarbons are detected In-line Maximum 14 probes connected to one analyzer Salinity do not interfere with the measurements Various measurement ranges Not affected by 10–15 % gas content
Cons	Chemicals with aromatic content will affect the readings Not able to measure the oil droplet size Recalibration for different types of oil Relative constant aromatic hydrocarbon content

Table 3.6: Summary of the Argus Oil in Water Monitor, including pros and cons.

The Argus Oil in Water Monitor, as seen in Figure 3.16, manufactured by ProAnalysis [42], is also based on the LIF technology. Thomas Friis-Eriksen [I], Chemist & Sales Engineer at ProAnalysis, have been the main point of contact, and have been very helpful in proposing optimized solutions for this application. Mr. Friis-Eriksen has informed that the response time of 1 s, as stated in their data sheet shown in Appendix D.4, will be modified to 250 ms in their upcoming Argus 2.0 Oil in Water Monitor. The Argus 2.0 will be commercialized during the third quarter of 2016 [42]. On a standard Argus OiW monitor, the measurement signal will update 1 time per second. It will make 10 measurements per second that are averaged before the measured value is updated. Argus 2.0 can make 20 measurements per second, and update the measurement value 4 times per second.

The occurrence of slugs or transient flow, will typically saturate the calibrated value, but the sensor has a reset time of 1 s. This means that the sensor will start operating normally 1 second after the flow irregularity has passed. Mr. Friis-Eriksen has also informed that flow rate and droplet size variations would have minimal impact on the measurement readings. ProAnalysis have performed operational tests with different industrial partners which indicates that the Argus Oil in Water Monitor is only slightly affected by changes in oil droplet size. The deviation was max 3.4 % with 0–700 ppm calibration, as seen in Figure 3.15.

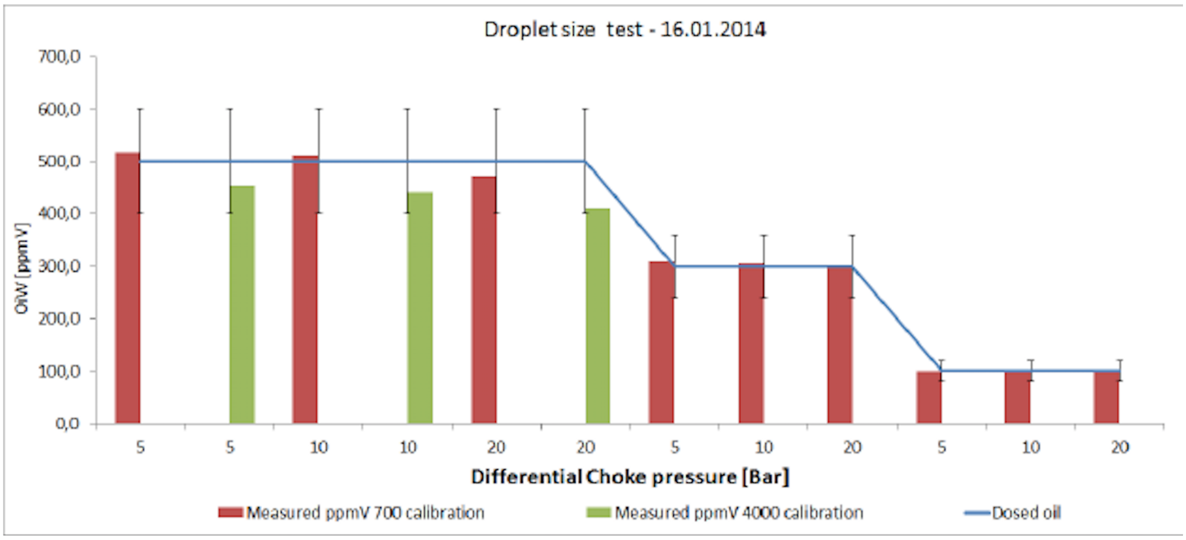


Figure 3.15: Results from an oil droplet size test performed by ProAnalysis. The red bars show measurements points with 0–700 ppm calibration, while the green bars with 0–4000 ppm calibration. The blue line is the dosed oil [42].

Regarding the issue of measuring a synthetic model oil with low aromatic hydrocarbon content, a sample of 30 ml Exxsol D140 (see Section 3.7.4) was sent to Mr. Friis-Eriksen for further analysis. A major advantage of the Argus Oil Water Monitor compared to the EX-100 sensor, is that it can include up to 14 probes per analyzer. This would save costs of implementing a third probe in a later phase of the separator laboratory, as explained in Section 3.8.

Figure 3.16: Argus Oil in Water Monitor [42].

3.7.2 Electrical resistivity tomography – Industrial Tomography Systems

Supplier	**Any electronics store (homemade)** **Industrial Tomography Systems**
Technology	Electrical Resistivity Tomography (ERT) ERT technology is explained in Section 2.5.3
Price/Offer	USD 20 (homemade)
Pros	Cost-effective (homemade) Non-intrusive Robust
Cons	Accuracy Reliability

Table 3.7: Summary of the Electrical Resistivity Tomography technology, including pros and cons.

An ERT sensor can be created and used as a cost-effective OiW measurement. At the University of Aalborg [50], they have constructing a homemade ERT sensor at a cost of less than USD 20. ERT requires direct electrical connection to a pipe, as seen in Figure 3.17, and thereby the use of a specific material, such as PMMA. [50]

Figure 3.17: Illustration of the homemade ERT sensor configuration in [50].

Compared to a homdemade ERT sensor, Industrial Tomography Systems [45] manufactures ERT sensors optimized for specific application. They are providing the sensor body and electrodes in various materials and the sensor can be installed in EX environments with ATEX standard. However, they are only providing complete packages and are offering an education and research package containing an ERT sensor, a data acquisition system, software, 12 months technical support and installation. They were not willing to provide a single ERT sensor, due to fact that they could only guarantee the performance of the sensor connected to one of their own instruments. In addition, they would not recommend a homemade ERT sensor combined with the PMMA material. This is because the material would possible not withstand the pressure in this application. Datasheet is found in Appendix D.2.

Because of the lack of operational references with this technology, and the fact that it is not involved in Statoil's ongoing qualifying project mentioned in Section 3.2, this technology has unfortunately been disregarded in the choice of an appropriate OiW sensor. However, given the fact that the cost of implementing an ERT sensor is much lower than other alternatives, ERT is an interesting OiW technology that is worth considering for future implementations. Mr. Holden [V] has informed that The Department of Production and Quality Engineering could realize a project in the future of constructing an ERT sensor.

Mirmorax Oil-in-water analyser LR2500 – Mirmorax

Supplier	**Mirmorax**
Technology	Focused Ultrasonic Acoustics (FUA) FUA technology is explained in Section 2.5.4
Offer	Single probe system: Price confidential Dual probe system: Price confidential
Oil concentration range	0–2.500 ppm
Response time	1.1–2 s
Pros	Able to measure the oil droplet size and the oil concentration simultaneously Auto calibration In-line Low sensitivity to deposits on the sensor surface Various measurement ranges
Cons	Dissolved hydrocarbons are not detected The measurements are affected by salinity above 350 g/l The presence of gas bubbles or solid particles above 5000 ppm can affect the measurements

Table 3.8: Summary of the Mirmorax Oil-in-water analyser LR2500, including pros and cons.

The Mirmorax Oil-in-water analyzer LR2500, as seen in Figure 3.18, is based on focused ultrasonic acoustics and are also is inserted directly into the produced water stream like the EX-100 sensor and the Argus Oil in Water Monitor.

On March 3th 2016, Eivind Gransæther [II] from Mirmorax made a visit to the Department of Production and Quality Engineering to discuss the relevance of their technology and their offer. Mr. Gransæther informed that the sensor uses an average of 1.1–2 s to make the cut to get more stable measurements. This could, however, be modified to about 1 s for faster measurements. By lowering the response time, it will not lower the accuracy, but increase the variance due to less cutting. This would result in more accurate real-time measurements. [II]

Mr. Gransæther also informed that a higher gas content than 5000 ppm in the system could lead to some of the measurements being incorrectly interpreted as sand or oil. As a quality assurance, Mirmorax have implemented a separate measurement that shows the percentage of gas related to the total measurements. Mirmorax is measuring the oil droplet size and the oil concentration continuously, and changes in the oil droplet size will therefore not affect the oil concentration measurements. This is an advantage during transient flow. [II]

The main advantage of the LR2500 compared to the LIF technology, is the capability to simultaneously measure both the oil concentration and the oil droplet size. In addition, the sensor performs auto calibration and self-diagnosing. Like the EX-100 and the Argus Oil in Water Monitor, it also operates with a built in flushing system to ensure a clean lens.

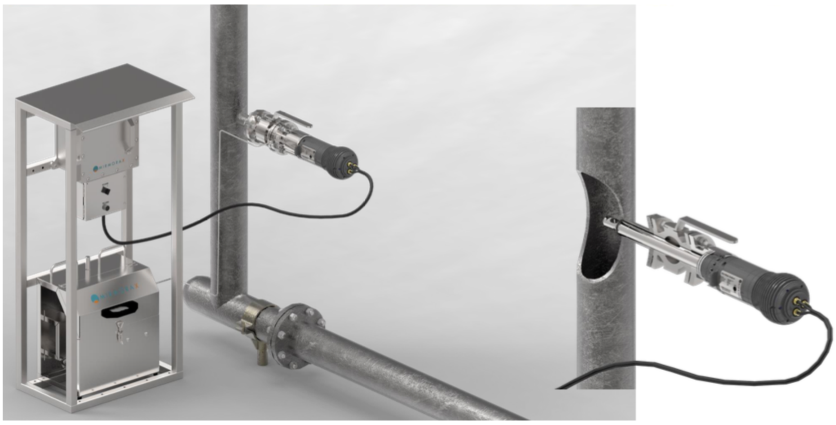


Figure 3.18: Mirmorax Oil-in-water analyser LR2500 [43].

ViPA B – Jorin

The ViPA B (Visual Process Analyser) is a compact and robust analyser that applies image analysis to measure the OiW concentration. It can be equally applied to a process line, a laboratory bench or as a portable field unit [44]. In recent years the image analysis technique has been popular for produced water treatment applications where the understanding of the oil droplet and solid particle size, size distribution and concentration has been important. A drawback with the image analysis method is that it operates as an indirect method, since it measures the particles and then calculates the concentration, which leads to a response time above 1 s. [44],[46]

Figure 3.19: ViPA B OiW sensor and related computer [44].

Supplier	**Jorin**
Technology	Image Analysis Image analysis technology is explained in Section 2.5.5
Offer	Single probe system: Price is confidential Dual probe system: Price is confidential
Oil concentration range	0–2.500 ppm
Response time	Above 1 s
Pros	Compact No need for calibration Portable Robust
Cons	Dissolved hydrocarbons are not detected Indirect method that leads to a response time above 1 s

Table 3.9: Summary of the ViPA B OiW sensor, including pros and cons.

3.7.3 Preferred OiW sensor

Based on the fact that online OiW sensors are extremely expensive and will represent a big part of the total budget, Arne Henriksen at Statoil [IV] was consulted about the choice of the most appropriate online OiW sensor for the laboratory. Mr. Henriksen has great experience with OiW sensor technology [46], and is part of the Statoil OiW sensor test project mentioned in Section 3.2.

Based on his previous experience, he is very optimistic concerning the image analysis technology. This is mainly because it is important to measure both the OiW concentration and the oil droplet size to optimize the hydrocyclone design. However, since the company eProcess have been willing to provide the hydrocyclone liners, the hydrocyclone design is not the main interest in this laboratory setup and the oil droplet size is of less importance. Image analysis technology will be less appropriate for feedback control, due to a response time above 1 s. Due to the focus on produced water treatment, and the implementation of a proper control systems to regulate slug generation, the response time is considered most important when evaluating the different sensor options. As a result, the sensor from Jorin was no longer considered for implementation, due to the fact that their response time is above 1 s. [IV]

LIF technology has in the recent years emerged as one of the main technologies for online OiW measurements and has provided accurate and reliable results. In addition, as mentioned in Section 2.5.2, the LIF technology is able to measure both dispersed and dissolved hydrocarbons [46]. This may be of importance if the OSPAR regulation where to be updated with measurements of both dispersed and dissolved hydrocarbons in the future. Based on the information provided by the suppliers, LIF technology operates with a lower response time compared to the other technologies mentioned above. Concerning the issue of the aromatic hydrocarbon content, a specific synthetic model oil will be implemented to keep the ratio relative constant.

Compared to measurements using focused ultrasonic acoustics, which could be affected by the presence of gas bubbles above 5000 ppm, LIF technology have proven operational quality in multiphase flow with a GVF of 10–15 %. This could be of importance for any later implementation of a phase-splitter and three-phase flow since a lower percentage of gas could be dissolved in the oil and water mixture downstream of the bulk separation. Additionally, as explained in Section 3.5.1, by operating with a gas-liquid ratio of 1 % (10,000 ppm), the separation efficiency in the hydrocyclones could potentially increase.

Mr. Henriksen also mentioned that the self-cleaning technology would not be necessary in the laboratory. This is because the application will only contain water with low concentrations of oil. This means that scaling with oil-film formation at the probe will not be a problem. A simple system to pull out the probe and flush it manually would be sufficient. [IV]

As mentioned in Section 3.3, sample points will be placed between each hydrocyclone stage in order to qualify the results. These sample points will act as a reference for the installed OiW sensors.

Based on the knowledge acquired from the different suppliers, technological and economical differences have been highlighted. These helped in the process of specifying which sensor technology that would be appropriate for the laboratory setup. Since NTNU is a governmental institution, it is bound by governmental regulations regarding larger purchases. These regulations imply the following [XV]:

- Total cost between 100.000 NOK and 500.000 NOK: Must be listed as a tender offer where at least three independent suppliers have the opportunity to place a bid.
- Total cost between 500.000 NOK and 1.7 million NOK: Must be listed as a tender offer in the Doffin database within Norway. The Doffin database is an overview of all the governmental procurements in Norway.
- Total cost above 1.7 million NOK: Must be listed as a tender offer in the Doffin database within Norway, and the Ted database within Europe. The Ted database is an overview of all the governmental procurements in Europe.

The OiW sensors are extremely expensive and will constitute between 700.000 and 1.2 million NOK (included VAT), and as a result, a tender offer must be listed in the Doffin database. The tender offer is based on a requirement specification which lists all the required technology an OiW sensor must have in order for a supplier to place a bid. The requirement specification has several categories with different priorities from A to C, where A is an absolute requirement and C is a "nice to have" requirement. The total price of the bid is also a deciding factor when a supplier is chosen. The requirement specification of this laboratory design can be read in further detail in Appendix C.

The procurement process is controlled by the Department of Procurement at NTNU, where Astrid Solberg [XV] has been the main point of contact. When the requirement specification is finished, the department control the rest of the process without the input from the designers of the laboratory.

3.7.4 Choice of Model Oil

In order to choose a safe and convenient oil suited for a laboratory setup, Dag Kvamsdal [XI] from Cameron was consulted. They are using the synthetic model oil Exxsol D140 in their already existing separator laboratory at the Department of Production and Quality Engineering. Exxsol D140 is a widely used industrial solvent, it is low in toxicity and it does not cause harmful health or environmental effects at levels typically found in the workplace or environment.

One potential problem when using a model oil is the fact that they are typically very low in aromatic hydrocarbon content. LIF technology, as described in Section 2.5.6, is dependent on the aromatic hydrocarbon content in order to measure the oil concentration. As a consequence, a sample of 30 ml has been sent to both ProAnalysis and Advanced Sensors to confirm that the LIF technology is able to make reliable measurements with such low aromatic hydrocarbon content.

Another issue by using a synthetic model oil, such as Exxsol D140, is the color. The model oils are usually colorless, and in order to be able to see the difference of the oil and the water, a powder could be added. The powder Oil Red O, manufactured by Alfa Aesar, is a powder which is insoluble in water, but soluble in ethanol:chloroform (1:1). As a result, this powder is suitable for use as dye, and only small amounts of this powder added to the water would color the oil red. [71]

The proposed suppliers to both Exxsol D140 and Oil Red O are shown in Section 5.3. The physical properties of Exxsol D140 are summarized in Table 3.10 and the complete data- and safety sheets are shown in Appendix G.

Physical Properties	**Exxsol D140**
Density	824 kg/m^3
Kinematic Viscosity	6.14 cSt
Vapor Pressure	$\leq 1.33\ 10^{-4}$ bar at 20 °C
Aromatic Content	$< 2\%$
Boiling Point Initial	275 °C
Boiling Point Final	315 °C
Flash Point	136 °C

Table 3.10: A summary of the physical properties of Exxsol D140 shown in Appendix G

3.8 Sixth Adjustment

After consulting Typhonix, Option B in Section 3.4 was chosen as the final design for the second adjustment. The specific parameters for the Typhonix coalescing pump, such as suction pressure, flow rate and differential pressure, could not be decided before the overall system parameters were final. This required more information from the hydrocyclone liner supplier eProcess, and will be described in Section 3.9.2.

A detailed design, combined with comprehensive contact with suppliers, allowed for an accurate budget. All four phases were included in the budget, with decreasing budget accuracy in the later phases. For more information concerning the equipment included in each phase, see Chapter 5. The overall budget overview is presented in Table 3.11.

Total cost phase 1+2+3+4	NOK 2,755,144
Available funds	NOK 3,000,000
Unforeseen cost/changes/modifications	NOK 244,856
Economical Safety Margin	8.16 %

Table 3.11: Budget overview for the current design after the fifth adjustment.

As mentioned, this budget estimate had decreasing accuracy for the development of the later phases. This is because the later phases involve great uncertainty concerning future design. Phase 1, as well as Phase 2 to some extent, was budgeted in detail, while Phase 3 and Phase 4 were less accurate.

As shown in Section 3.5, the knowledge of the system design for Phase 1 is a solid foundation for the later phases. This is true for both the technical design, as well as the budget. As seen in Table 3.11, the budget includes an economical safety margin of 8.16 %, which represents NOK 244,856.

This is a considerable amount, however the learnings from the design and budgeting of Phase 1 raised some concerns regarding the future phases. For the implementation of a bulk separator and a phase-splitter in Phase 3, the budget did not include any cost, since the bulk separator was to be developed by the Department of Petroleum Engineering and Applied Geophysics, and the phase splitter could be sponsored by Statoil. For Phase 4, NOK 140,000 is set aside for the implementation of future concepts such as a CFU. Summarized, the later phases had NOK 384,856 to implement gas in the system, include a bulk separator, a phase-splitter, and a CFU in addition to other future equipment of interest.

Given the experience from Phase 1, this would not be sufficient when the appropriate pipes, valves and sensors also had to be included in order to implement this equipment in the future phases. Combined with pipes and valves, the air-injection system in Phase 2, as shown in Figure 3.7, had an approximate cost of NOK 100,000. As a result, it was decided to move this implementation to Phase 3, where it could be combined with the implementation of gas in the system. Since the pressurized gas reservoir could be used as a supply, this eliminates the need for a separate air–injection pump, and therefore saves cost.

As described in Section 2.6.1, both air and gases like methane, nitrogen and sulfur hexafluride could be applied for injection. However, methane implies an explosion risk and air presents a risk of corrosion in the piping material.

Because of this, these alternatives will not be preferred options in this project [V] and air-injection will be referred as gas-injection in the rest of this thesis.

Equally important is the point that an implementation of a gas-injection pump would use a part of the budget in Phase 2, that might be needed in order to implement gas in the system in Phase 3. Simulating a three–phase system is of greater importance than the experimental setup of gas-injection, and as a result, this potential conflict of interests is avoided.

The cost savings of removing the gas-injection pump did, however, not have a great impact, since the major costs of the design are related to the OiW sensors. In order to increase budget flexibility for the implementation of equipment in Phase 3 and Phase 4, Phase 2 was re-designed with only two OiW sensors. This is shown in Figure 3.20.

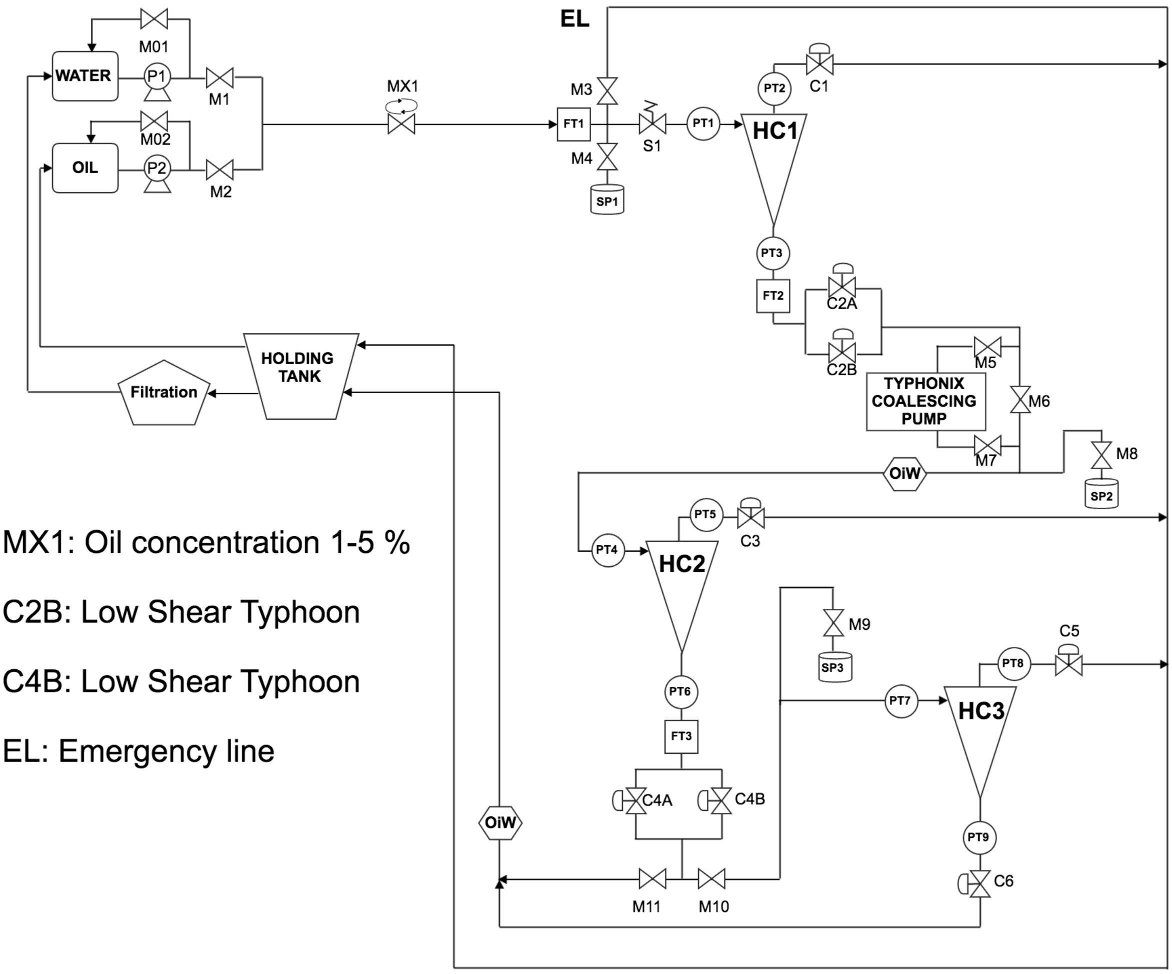


Figure 3.20: Phase 2 after the sixth adjustment. One OiW-sensor has been removed, and HC3 has been placed in a by-pass. Gas-injection has been moved to a later phase.

Comparing Figure 3.20 with Figure 3.7 in Section 3.5.1, HC3 have been included in a potential bypass after HC2. By doing this instead of the series design in Figure 3.7, one OiW sensor is eliminated but the system is still able to measure the OiW concentration after both HC2 and

HC3, however not at the same time. By closing valve M10 in Figure 3.20, the system is able to measure the separation impact after HC1 and HC2, and by using this as a reference when closing valve M11 and opening M10 the resulting separation impact after HC3 can easily be calculated.

A third OiW sensor could also be retrofitted into the system between HC2 and HC3 as a part of Phase 4 if SUBPRO have received additional funding, or the remains of the original budget allows it. As shown in Table 3.12, the removal of one OiW sensor and the gas-injection pump had a great combined impact on the budget.

Total cost phase 1+2+3+4	NOK 2,220,122
Available funds	NOK 3,000,000
Unforeseen cost/changes/modifications	NOK 779,887
Economical Safety Margin	26.00 %

Table 3.12: Budget overview for the design after the sixth adjustment.

With an economical safety margin of 26.00 %, which represents NOK 779,887, the implementation of gas, bulk separation, phase-splitter and a potential CFU is much more likely to succeed with the current budget. For Phase 3 the implementation of gas will now be combined with gas-injection. This is shown in Figure 3.21, where the gas is mixed in the two-phase liquid through a mixing valve MX2.

It is important to underline that the budget currently holds a lot of uncertainty. The cost of the Typhonix coalescing pump and the low shear Typhoon valve has not yet been included, due to the fact that Typhonix is still working on their offer. Other equipment related costs have also not been included in the budget at this point, because some of the suppliers are adjusting their offers due to continuous changes to the design. An example is the oil supply pumps, where the supplier is currently working on updating an offer. Nevertheless, the measures taken in the Sixth Adjustment to increase the safety factor will probably be necessary to complete the design within the budget.

3.9 Seventh Adjustment

3.9.1 Potential Cameron cooperation and laboratory Integration

The company Cameron has for several years had a test laboratory in the workshop connected to the Department of Production and Quality Engineering. This laboratory focuses on gas-liquid separation, and both knowledge and facilities connected to this laboratory could have great relevance for the compact separation laboratory project.

On March 29th 2016 it was arranged a meeting with Cameron regarding their already existing gas-liquid separator laboratory. Cameron and the department agreed on a future cooperation on the compact separation laboratory project. This agreement enables the department to re-use some of Cameron's equipment, involving feeding pumps, a gravity separator, instruments, piping and valves. By re-using this equipment, the total cost of the separator lab could be decreased. The disadvantages of applying Cameron's feeding pumps, are that they are not operated by variable speed drives. Both the pumps have a maximum operating pressure of 10 bar, with a flow rate from 4 to 25 m^3/h for the water pump and from 4 to 35 m^3/h for

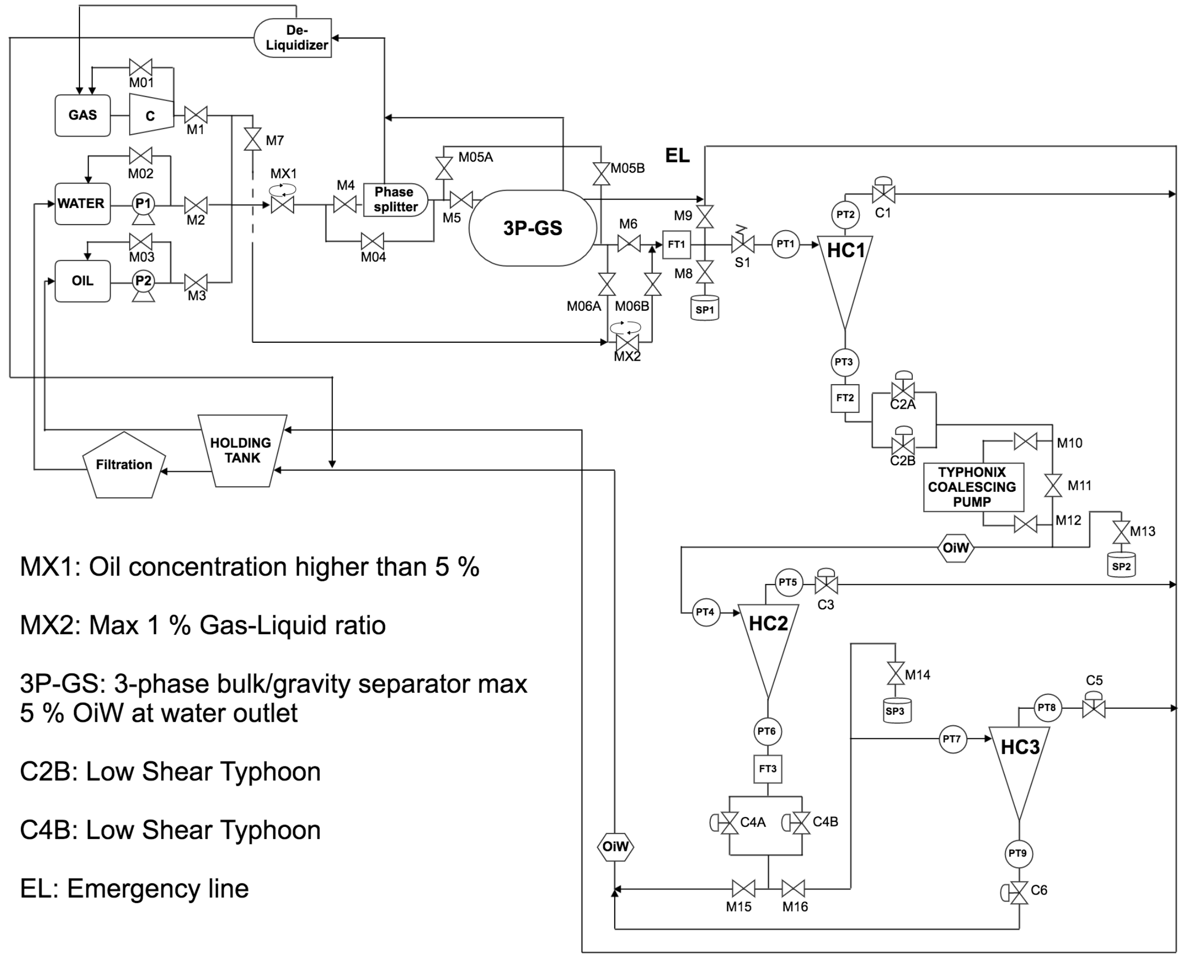


Figure 3.21: Phase 3 after the sixth adjustment. One OiW sensor has been removed, and HC3 has been placed in a by-pass. Gas injection is included in this phase.

the oil pump. Compared to the design parameters of the compact separator laboratory, this is a higher flow rate and a lower maximum pressure. Dag Kvamsdal [XI], CEO Gas Liquid Separation at Cameron, did however inform that the flow rate not will be a problem. He suggested a solution where the pumps flow rate is recirculated through a valve over the pump in order to achieve the desired, lower, flow rate. This solution will allow the pumps to operate down to a minimum flow of potentially 0 m^3/h. However the max operational pressure of 10 bar represents a problems with respect to completing the loop, but this issue will be addressed in Section 3.9.2.

In addition, Cameron recommended to construct the separator laboratory in several different skids. The reason for this was to simplify a potential relocation of the separator-lab. As a result, the design was divided in two parts, one involving the hydrocyclone setup and one involving the feeding pumps, as seen in Figures 3.22 and 3.23.

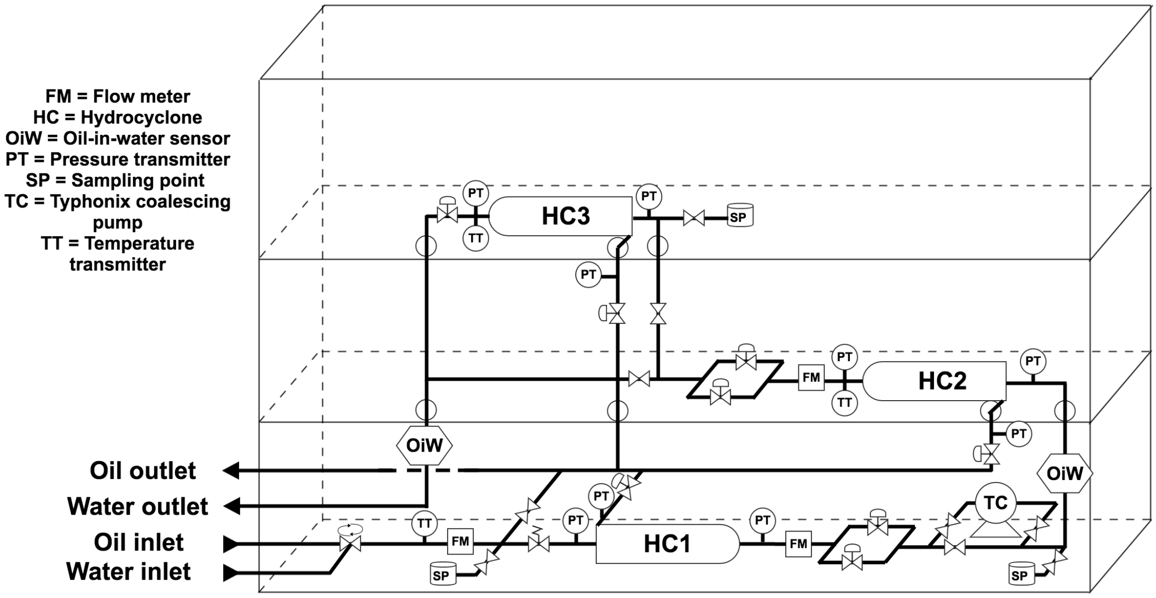


Figure 3.22: The first 3D sketch of the hydrocyclone skid.

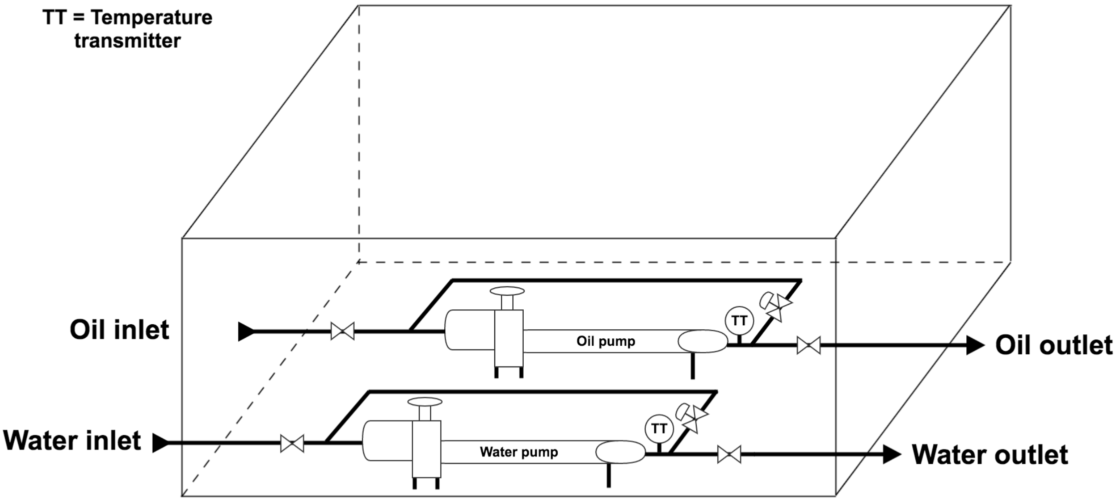


Figure 3.23: Sketch of the feeding pump skid. Control valves are placed in the recycle loops and temperature transmitters are placed downstream the pumps.

By constructing the separator laboratory in several skids, the technical flexibility is increased. Individual parts can be changed more easily, and the hydrocyclone skid shown in Figure 3.22 can be connected to different feeding systems. This allows the system to be tested with the feeding system in Cameron's lab. These learnings will come to great use for the construction and final design of the pump skid in Figure 3.23.

An additional aspect of connecting the hydrocyclone skid to the Cameron feeding system is the reservoir capacity of the system, and the ability to control the amount of polluted water that is re-injected in the system in closed loop. The gravity separator in Cameron's setup is 3000 l, which is smaller than the 5000 l in the designed reservoir system. This will further limit the time the hydrocyclone skid can be operated continuously before the water supply runs out.

In addition, the Cameron system does not have a filtration process downstream of the gravity separator. This could lead to polluted water with an unknown oil concentration returning to the water supply. This will cause build-up of small oil droplets that will degrade the system performance over time. Still, the Cameron system allows for testing of the hydrocyclone skid at a very low cost. This implementation will be further discussed in Section 3.12.

3.9.2 eProcess Input and Pressure Modifications

As a part of the continuous design changes, relevant industry partners are consulted to qualify the adjustments. The SUBPRO project group serves as a large base of knowledge, especially because of the "hands on" experience from the different industry partners, and this helps ensure the relevance of the adjustments.

When introducing the hydrocyclone skid to Mr. Rawlins at eProcess, his "hands on" experience were once again of great importance for the future proofing of the laboratory design. Summarized, the first of his inputs was that the start-up of the laboratory should include hydraulic tests (i.e. water only) to balance pressures, valves, flows, etc. before any oil is introduced. In this testing mode it will be beneficial to run everything manually. Regarding the control valves, they could be operated manually by a regulator, and a virtual switch could be made and operated through simulation programs such as LabView or Matlab [V].

Mr. Rawlins' second input was related to the capacity curve shown in Figure 3.24. The specific pressure drop over each hydrocyclone liner aligned in series is hard to predict in the design phase, but based on the fact that eProcess manufacture the liners, their experience served as a solid foundation for design parameters. In a two stage hydrocyclone setup, the first stage (HC1) will reduce the oil concentration from 5–10 % down to 2000–3000 ppm and operate at a 1-3 bar pressure drop. The second stage (HC2) will further reduce the oil concentration down to 30 ppm and operate at 5–7 bar pressure drop.

As seen in Figure 3.24, HC1 would need two hydrocyclone liners in parallel to provide sufficient flow rate to achieve the pressure drop in HC2. A potential third stage hydrocyclone (HC3) would run at the same conditions as HC2. This means that the hydrocyclone skid, as seen in Figure 3.25, would need two liners in parallel in HC1, one liner in HC2 and one liner in HC3 to operate a three-stage hydrocyclone setup.

This is because the liquid flow rate through HC2 and HC3 will be between 2.70 m^3/h and 3.21 m^3/h, while the liquid flow rate through a single liner in HC1 would be between 1.44 m^3/h and 2.10 m^3/h. It is an obvious necessity that two liners in parallel in HC1 is needed in order to deliver the appropriate liquid flow rate to HC2 and HC3. Two liners in parallel in HC1 results in a maximum liquid flow rate of 4.2 m^3/h through the system. Since the system must be designed to handle flow irregularities, which could imply an increase in the flow rate, the system is therefore designed to have a maximum flow of 5.0 m^3/h.

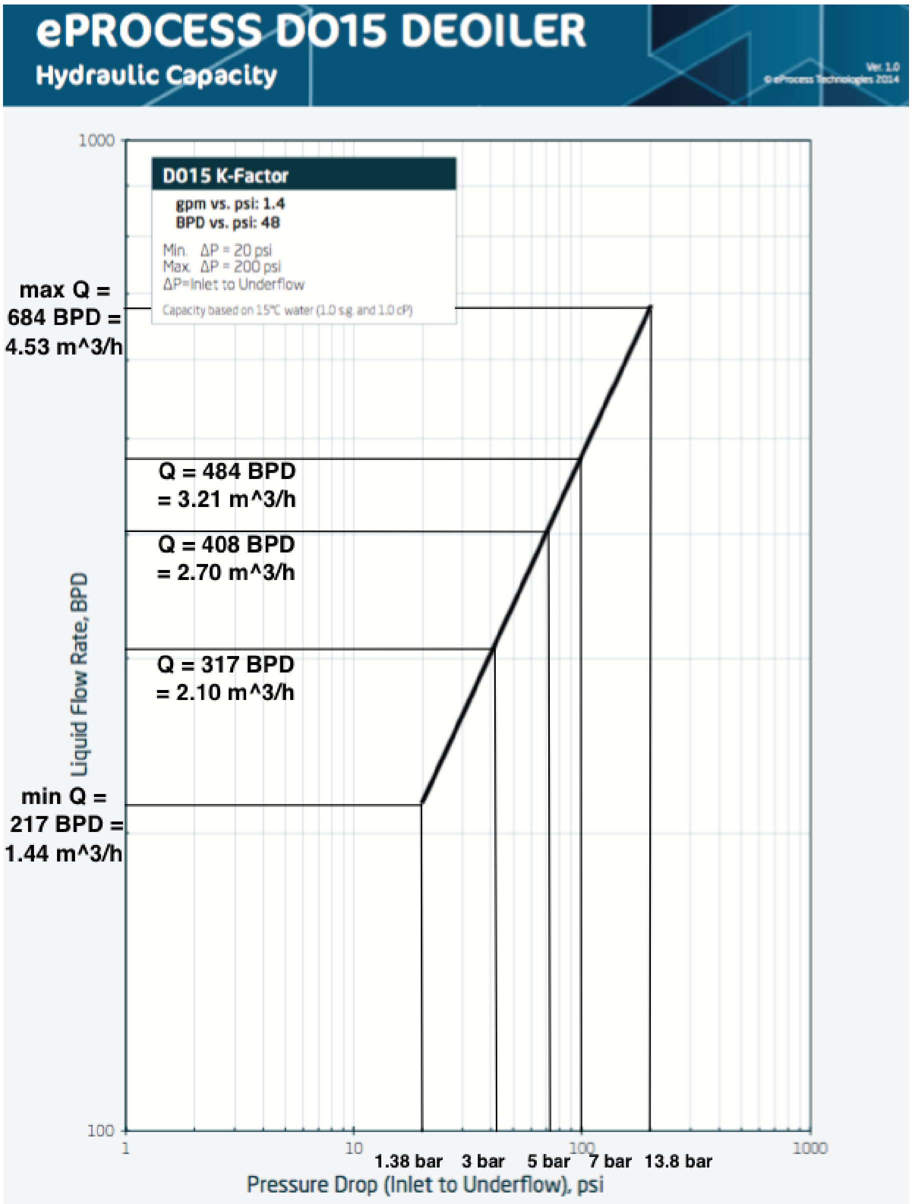


Figure 3.24: eProcess D015 Deoiler - Hydraulic Capacity - Modified to show the flow rate and corresponding pressure drop in HC1, HC2 and HC3.

One additional adjustment of the hydrocyclone skid that was made, was to move the second OiW sensor probe from the vertical pipeline down to the horizontal pipeline of the water outlet. The reason for this was that Mr. Hempsey [III] from Advanced Sensors, recommended to only place the OiW sensor probes in a vertical pipeline when the flow has an upward direction, which is the case for the first OiW sensor probe.

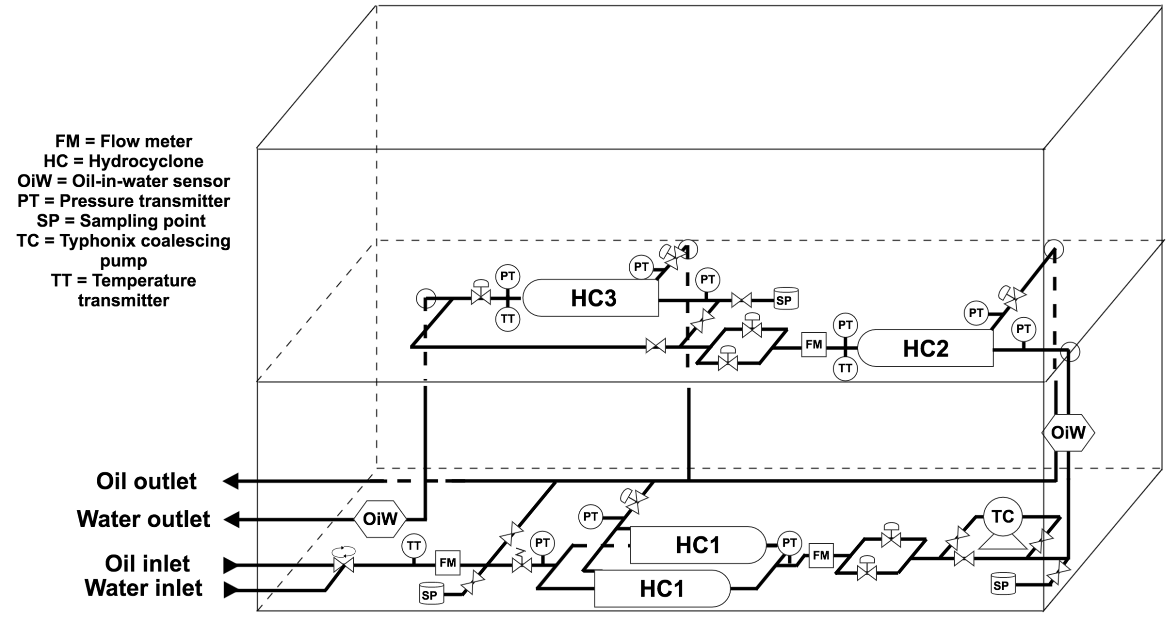


Figure 3.25: The second 3D sketch of the hydrocyclone skid with two liners in parallel in HC1. The number of floors have been reduced from three to two in order for higher flexibility.

eProcess' input regarding the pressure drop over each of the hydrocyclone stages also enabled the specification of the remaining system parameters to more specified. As described in Section 3.4, the maximum operational pressure of the laboratory has previously been designed to be 30 bar, but with the additional information from eProcess this could be made more accurate. A pressure drop of 1–3 bar in HC1, and a pressure drop of 5–7 bar in both HC2 and HC3 summarises to a total potential pressure drop of 17 bar.

Several other components such as valves, temperature- and pressure transmitters, OiW sensors and pipe bends, will also increase the total pressure drop in the system. This will however be minor pressure drop contributions compared to the pressure drop over the hydrocyclone liners. Combined the total pressure drop in the system could be close to 20 bar. A designed operational maximum pressure of 30 bar is unnecessarily high compared to 20 bar, especially when taking into consideration that a higher pressure requires pumps at a higher cost. At the same time, the system must be designed for future expansions as explained in Section 3.5.

A phase-splitter, gravity separator and more valves, could potentially increase the pressure drop. The Typhonix pump installed after HC1 will increase the pressure, but the system should be able to run all three stages of the hydrocyclones without the Typhonix pump, since the coalescing effect only works within given operational conditions, as explained in Section 2.4.4.

The laboratory design must also operate with a safety factor of 1.6 according to NTNU regulations [V], and for a 30 bar system this would imply a pressure grading of 48 bar on the pipes. Normal pipe classes are PN16 and PN40, designed for 16 and 40 bar respectively, and these are most often used as design standards [X]. Due to the fact that 25 bar is sufficient pressure to handle the pressure drop of future processing equipment, and that 25 bar with a safety factor of 1.6 is exactly 40 bar, the maximum operational pressure is therefore decreased to 25 bar. The main design parameters after the sixth adjustment are summarized in Table 3.13.

Maximum Liquid Flow Rate	5 m^3/h
Maximum Operational Pressure	25 bar
Maximum Operational Temperature	50 °C
Material Selection	AISI 316L

Table 3.13: Design parameters after the sixth adjustment.

The specified knowledge of the system parameters enabled Typhonix to work with their suppliers in developing a pump for the laboratory. The Typhonix coalescing pump normally operates at a liquid flow rate of 50 m^3/h, and thus, the entire design had to be scaled down [VI]. Based on a project lifetime of 10 years, and the need for VSD compatibility, Typhonix decided to rebuild a HZAR pump from the supplier Dickow to a coalescing pump. The maximum pump pressure for the HZAR pump is 40 bar, which allows a greater suction pressure range [VI]. The design parameters for the Typhonix pump are presented in Table 3.14

Design Flow Rate	5 m^3/h
Design dP	10 bar
Material	AISI 316L
Voltage	240 V, 50 Hz

Table 3.14: Typhonix coalescing pump parameters.

As discussed in Section 3.9.1, the max operational pressure of 10 bar in the Cameron feeding pump system will not be sufficient. This could be solved by using the Typhonix Coalescing pump as a booster pump between the hydrocyclone stages. With a 10 bar inlet pressure to the system, and a pressure drop of 1–3 bar in HC1, the suction pressure for the Typhonix pump could potentially be as low as 7 bar. The Typhonix pump is, however, designed to handle differences in suction pressure [VI], and as described in Table 3.14, the differential pressure of the Typonix pump is 10 bar, and potentially even 2 bar higher if the flow rate at the pump inlet is lower than the design flow rate [VI]. This means that the pressure at the pump outlet could be as high as 17 bar, which would be sufficient to achieve satisfying separation in HC2 and HC3.

By using the Typhonix coalescing pump as a booster pump this will enable the Cameron pumps to be used as a feeding system, and allow for extensive testing of the hydrocyclone skid without investing in additional feeding pumps in the first phase. The learnings from this testing should be used as a basis when evaluating the purchase of a potential pump feeding system with a higher operational maximum pressure in the later phases. This does, however, depend on the cost of implementing the Typhonix coalescing pump, and will be further discussed in Section 3.12.

3.10 Eight Adjustment

As described in Section 3.7.4, Exxsol D140 is the preferred oil type. Even though Exxsol D140 resembles the characteristics of crude oil in terms of liquid/liquid separation, it is a synthetic model oil which is not found naturally in oil and gas operations. This poses a future problem when the results from the experiments in the compact separation laboratory are to be presented for the oil and gas industry, as they usually would like to see experimental results using real operational fluids [X].

Exxsol D140 was chosen as the model oil because it did allowed the compact separation laboratory to be constructed without the need for an EX certification [XI]. Using a crude oil will, however, require EX certified equipment according to the ATEX directive [XI]. The equipment that is to be installed will be chosen according to the EX-classification of the area it is to be installed in. Table 3.15 shows an overview of the different EX-classifications.

European and IEC Zone Classification	**Definition of Zone**
Zone 0 (gases/vapors)	An area in which an explosive mixture is continuously present or for long periods.
Zone 1 (gases/vapors)	An area in which an explosive mixture is likely to occur in normal operation.
Zone 2 (gases/vapors)	An area in which an explosive mixture is not likely to occur in normal operation and if it occurs it will exist only for a short time.
Zone 20 (dusts)	An area in which an explosive mixture is continuously present or for long periods.
Zone 21 (dusts)	An area in which an explosive mixture is likely to occur in normal operation.
Zone 22 (dusts)	An area in which an explosive mixture is not likely to occur in normal operation and if it occurs it will exist only for a short time.

Table 3.15: EX Zone Classification [72]

To build the entire compact separation laboratory with an EX-classification would require increased funding, since NOK 3 million is not sufficient to buy equipment for all the development phases that are in line with the ATEX directive. However, by breaking the design up into separate skids, as explained in Section 3.9, this opened for an economical flexibility that allowed the hydrocyclone skid to be EX certified.

Based on the advice from Mr. Husveg [VI], contact was established with Espen Krogh [X] at the SINTEF Multiphase Flow Laboratory at Tiller, Trondheim. SINTEF has a large facility outside Trondheim, with several laboratories to develop flow assurance related research for the petroleum industry [73]. The SINTEF laboratories are built in different dimensions, and for different flow rates and pressure regimes. As a result, the authors of this thesis, in addition to Associate Professor Christian Holden [V] and PhD Candidate Sveinung Johan Ohrem [XIII], were invited to a meeting and a tour of their facilities at Tiller on April 18th 2016.

The meeting resulted in several inputs on the design of the compact separation laboratory. SINTEF's small scale loop, also called the hydrate laboratory, is able to do experiments with crude oils, and could be connected to the hydrocyclone skid. The parameters of SINTEF's small scale loop is compared to the design parameters of the compact separation laboratory in Table 3.16.

	SINTEF small scale loop	**Compact Separation Laboratory**
Max. Operating Pressure [bar]	100	25
Min. Operating Pressure [bar]	atm.	atm.
Temperature range [°C]	-10 to 50	10 to 50
Flow rate [m^3/h]	5	5
Pipe sizes [inch]	1 and 2	2
Oil Type	Any crude or model oil	Model oil

Table 3.16: SINTEF laboratory parameters compared to the compact separation laboratory parameters [73].

As seen in Table 3.16, the operational parameters of the SINTEF small scale loop and the compact separation design are fit for a future cooperation. The small scale loop has a higher maximum operating pressure, but this can be adjusted for the implementation with the hydrocyclone skid. The SINTEF small scale loop is EX–classified as Zone 1, so for the hydrocyclone skid to be allowed to connect, the equipment must be EX–classified as Zone 1. EX equipment is typically more expensive and will reduce the economical safety factor of the budget. However, if EX equipment can be installed within the budget constraints, experiments utilizing crude oil will increase the credibility of the results.

3.11 Ninth Adjustment

In Section 3.9 the Seventh Adjustment finalized the overall design lines, with two hydrocyclones in parallel in the first stage, one hydrocyclone in the second stage, one hydrocyclone placed in a by-pass in the third stage, and appropriate sensors and transmitters placed between the stages. The main design parameters such as pressure, flow rate, temperature, and dimensions are also set, and as a result, the next step of the design is optimization and details.

3.11.1 Vessel housing for hydrocyclone liners

The hydrocyclone liners, manufactured by eProcess, are delivered as simple liners without any attachment device or couplings. For the flow to enter the liners at the appropriate angle, and with the correct flow rate, the liners must be attached to the rest of the system in an appropriate way.

Based on the advice from eProcess, the hydrocyclone liners will be placed in a vessel housing, as shown in Figure 3.26. The normal industry procedure is to install a large number of liners in parallel inside the vessel housing, where the total number is based on the flow rate conditions.

The vessel housing holds the liners in place, and enables the implementation of a common inlet, oil reject chamber and water outlet chamber.

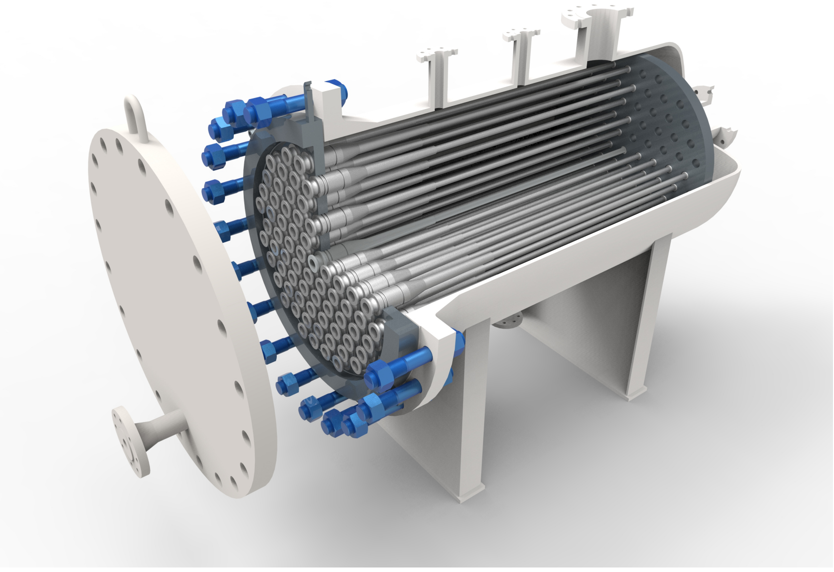


Figure 3.26: Illustration of a 36" diameter vessel housing containing 202 liners in parallel [XIV].

For the design in this project, the vessel housing will be scaled down. A 4" diameter vessel housing will be constructed to hold HC2 and HC3. The vessel housing will be built in three parts, and Victaulic Clamps Type 1007N [74] will be used to join the pieces together. The advantage of using victaulic clamps compared to weld the pieces together, is that it enables access to the hydrocyclone liners after installation for potential maintenance and inspection by simply drain the vessel housing and open the victaulic clamps. To hold the two liners in HC1, an equal vessel housing will be constructed with a 6" diameter. After consulting with Arild Saether, workshop manager at the Department of Production and Quality Engineering, the vessel housings could be constructed locally in the workshop. [XIV]

An alternative solution to installing the hydrocyclone liners in a vessel housing, would be to weld fittings directly onto the liner. This is, however, not recommended because it will be a permanent change and it could damage the liners if not done properly. [XIV]

Regarding the material selection of the vessel housings, the obvious solution would be to manufacture it in the same material as the hydrocyclone liners, for reasons explained in Section 3.6.2. According to eProcess, their liners are fabricated in duplex stainless steel (ASTM A790 UNS S31803). However, the hydrocyclone liners will be insulated by o-rings from the metal plates holding the liners in place inside the vessel housing, as seen in Figure 3.26. This is to totally seal the inlet flow from the water- and oil outlet flows. Because of this, the liners will not be in direct electrical contact with the vessel housings, and this allows the vessel housings to be created in the same material as the pipes, AISI 316L (ASTM 312 TP 316L).

Another argument is that the area ratio will be favorable between the two metals. The area of the the metal plate together with the vessel housing (less noble metal), will be much greater than the area of one hydrocyclone liner (more noble metal). In this situation galvanic corrosion on the less noble metal will be restricted and can normally be neglected [65].

To confirm the above mentioned arguments, Mr. Rawlins [XIV] was again consulted. He informed that AISI 316L is the correct material selection for the metal plates and the vessel housing.

In Table 3.13 in Section 3.9, the operational pressure is set to 25 bar. With a safety factor of 1.6, this will correspond to a 40 bar limit. As seen from Table 3.17 and 3.18, a sufficient solution will be to manufacture the 4" vessel housing in SCH10 and the 6" vessel housing in SCH40 to satisfy the 40 bar limit.

Nominal Size (inches)	Schedule Number	Maximum Joint Working Pressure (bar)	Maximum Permissible End Load (kN)
4	10	41.35	42.45
6	10	34.5	76.67
6	40	48.25	107.34

Table 3.17: Performance Victaulic Clamps Type 1007N [74] - 4" and 6" vessel housings

Nominal Size (inches)	Schedule Number	Outside Diameter (mm)	Wall Thickness (mm)	Inside Diameter (mm)	Design Strength (bar) at 50 °C	Allowable Working Pressure (bar) at 50 °C
4	10	114.3	3.05	108.2	1150	55
6	10	168.28	3.4	161.48	1150	41
6	40	168.28	7.11	154.06	1150	88

Table 3.18: Pipe schedules and allowable working pressure at 50 °C - ASTM 312 TP 316L [69] - 4" and 6" vessel housings

3.11.2 Valve Setup and Droplet Breakup

As presented in Section 2.1.1, the size of the oil droplets have a great impact on the separation efficiency in a hydrocyclone. This is the main reasons why low shear and coalescing equipment from Typhonix and Mokveld have been implemented in the design. It is important to consider potential droplet effects in valves, pipes and bends when optimizing the design. As mentioned in Section 2.3.2, the low shear Typhoon valve also has a stroke time that is sufficiently short for feedback control. Between HC1 and HC2, and HC2 and HC3 in the hydrocyclone skid, the separation result utilizing a low shear Typhoon valve will be compared to a regular control valve (explained in Section 3.4). Pipe bends could have an impact on the performance of the valves, and the positioning and layout of the two valves in parallel is thereby of importance. There are typically three options for the valve setup, option A, B or C, presented in Figure 3.27.

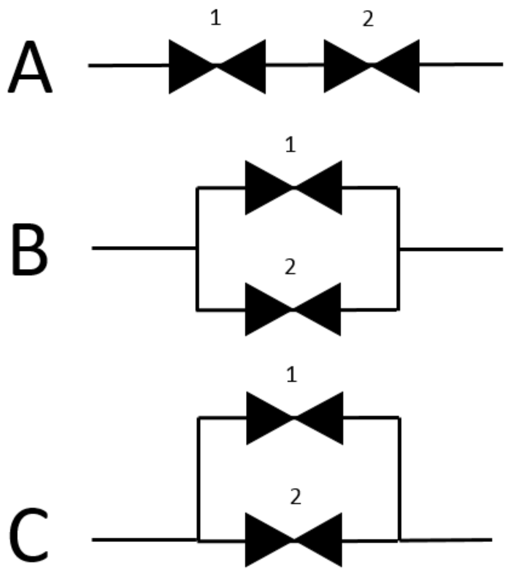


Figure 3.27: Three options for valve setup.

The cooperation with Typhonix have been beneficial in this optimization. Trygve Husveg's [VI] PhD thesis [75], also present the same conclusion as Section 2.1.1, regarding droplet breakup and separation.

> *"...a general rule of thumb is that the smaller the average size of the dispersed droplets the tighter the emulsion and the longer the residence time for phase separation."*

Mr. Husveg [VI] has great experience with separation and aspects leading to droplet breakup, and has therefore been consulted on this issue. Mr. Husveg informed that no control valves are normally full bore. This means that the first valve in option A will effect the inflow to the second valve, and hence this option is not recommended. Option B and C are practically equal. Option C would imply more optimal conditions for one of the valves, and this could lead to speculations when comparing the results. Thus, option B will be favourable due to symmetry. Due to the fact that the oil droplets in the water are small, and that turbulent flow in tees, elbows and bends are at least an order of magnitude less than in control valves, the piping in both option B and C will have no negative impact regarding droplet breakup. [VI] With the combined modification of the vessel housing and the valve setup fulfilled in the eight adjustment, the hydrocyclone skid are illustrated in Figure 3.28.

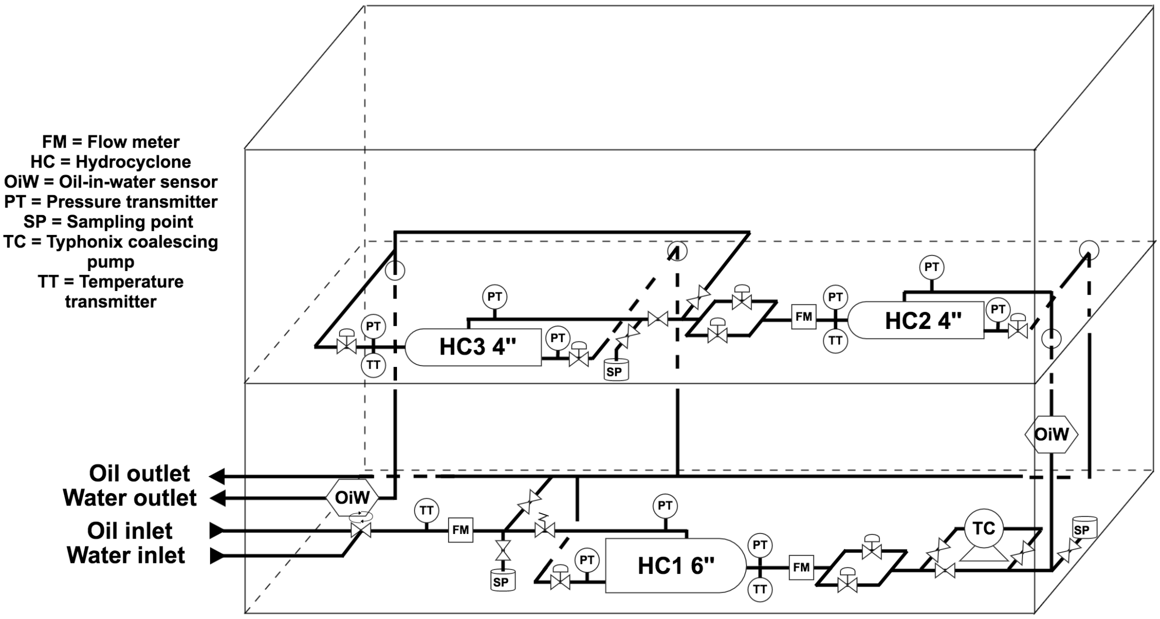


Figure 3.28: The third 3D sketch of the hydrocyclone skid. The modifications are vessel housings and valve setup.

3.12 Tenth Adjustment

3.12.1 First Specification of Typhonix Equipment

Low shear and coalescing equipment from Tyhponix and Mokveld have been considered in the design since the beginning, as described in Section 3.3. This technology is not standardized "of-the-shelf" equipment, especially not for the dimensions of this laboratory, and consequently represents an increase of both cost and complexity in the project scope in order to be installed. Cost estimates will not be included, as this is confidential information.

The equipment have specified operational envelopes in order to function as designed and achieve the desired low shear or coalescing effect. The low shear Typhoon valves must be at operated with the valve at 20 % opening, or more, in order to create a swirl effect that will induce the low shear effect. The flow rate must also be at a certain level.

As discussed in Section 3.4, the size of the oil droplets upstream of the pump are important with respect to the coalescing effect of the pump. As a result, a continuous dialog has been maintained with Typhonix through the different design modifications, to insure that the equipment is implemented in a way that is in the best interest of both NTNU and Typhonix.

At this point in the design process, the parameters, layout and equipment specifics where detailed enough for Tyhponix to give a cost estimate for the low shear Typhoon valve and the coalescing pump. An important note is that Typhonix is a relatively small, research based company, and hence, they have limited ability to sponsor this Master's project with money. The low shear Typhoon valve is also manufactured through the Dutch supplier Mokveld, and this also limits the flexibility with respect to sponsoring. For that reason, Typhonix have offered the equipment at cost price, which makes a great difference compared to normal price.

Typhonix would buy a specific centrifugal pump, and then rebuild it with their technology to operate as a coalescing pump.

As seen in Table 3.13, the system has been designed for 25 bar and based on the position of the pump, the inlet pressure would have to be 20 bar. An inlet pressure of 20 bar with a differential pressure of 10 bar requires double sealing in the pump, which drives the price up. For continuous pump operation with these parameters, the pump would need to be built in duplex steel, which further increases the price. However, due to the fact that the coalescing pump in this laboratory setup only would be operating for shorter periods (compared to continuous offshore operation), Mr Husveg [VI], with consultation from the pump manufacturer, agreed that AISI 316L would be sufficient. [VI]

The cost of this equipment was still higher than predicted in the budget, compared to standard control valves and pumps. As a result, with consultation from Mr. Husveg [VI], a new design option was developed with the intention of lowering the requirements for the pump and thereby lower the price. This design option is discussed in Section 3.12.2.

3.12.2 Second specification of Typhonix equipment

The main reason for the high price was the need for double sealing, which required the pump to follow offshore standards. By lowering the inlet pressure, the sealing could be reduced to a single sealing, which lowered the price. However, because of the total pressure drop over the hydrocyclones, as discussed in Section 3.9, lowering the inlet pressure of the pump will require the pump to work as a boosting pump to drive the separation in the hydrocyclone liners. This is illustrated in Figure 3.29.

This implementation would be fitted for integration with the Cameron feeding system, where the maximum pressure delivered to the hydrocyclone skid is 10 bar. By, designing the Typhonix pump for such a low inlet pressure, the sealing would not be designed for a pressure increase caused by a potential expansion in the later phases of development. This means that a coalescing pump would have to be by-passed in the later expansions of the lab.

In order to determine which part of the equipment to include in the final design, the relevance of the equipment related to subsea processing was essential. Because of her extensive knowledge and experience from the industry, technical coordinator in SUBPRO Gro Mogseth [XII] was consulted on the matter. Mrs. Mogseth highlighted the importance of using equipment which is relevant to subsea processing. Especially since there currently are no subsea control valves installed, except from the anti surge valve on the subsea gas compression project on Åsgard, on the Norwegian Continental Shelf [XII]. The anti surge valve in this project is delivered by Mokveld [76].

For the industry to view scientific results achieved in the laboratory as relevant for future subsea processing, the laboratory must have a design that is transferable to an installation on the seabed. As a result, the low shear Typhoon valve, is more likely to be installed subsea, than the coalecing pump, between the hydrocyclone stages. As a result of this, and due to a limited budget and large equipment costs, the low shear Typhoon valve is prioritized in Phase 1, and the coalescing pump is moved to Phase 4 as a possible future expansion. This is mainly because the authors of this thesis, in consultation with Mr. Holden [V] and Mrs. Mogseth [XII], views low shear control valves to be more relevant for subsea processing in the short term future. The updated phases are explained in Section 3.12.3.

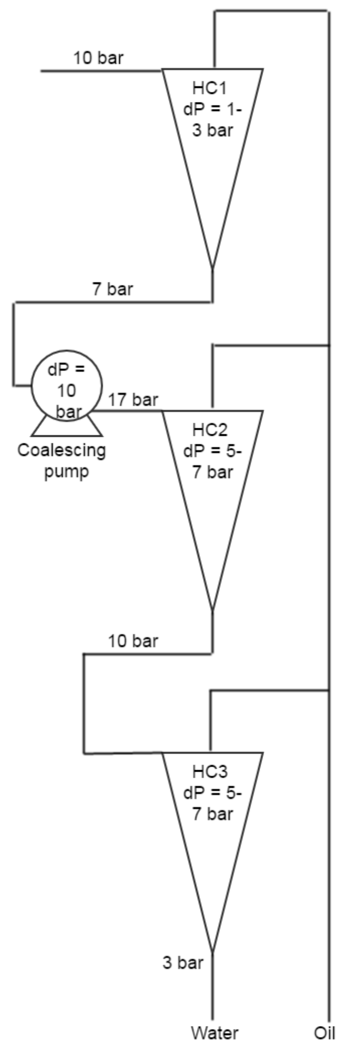


Figure 3.29: Alternative setup to decrease the inlet pressure for the Typhonix coalescing pump.

3.12.3 Change in phase setup and CFU implementation

Trough continuous contact with the industry partners in SUBRPO, the laboratory design aims to meet the interests of the industry. Since the reference group meeting on February 4th 2016, as described in Section 3.3, the industry partners have expressed an increasing interest in the implementation of a CFU in the laboratory setup. As a result of the typhoon valve being prioritized instead of the coalescing pump in Phase 1, and the increasing interest for an early implementation of a CFU, the phase setup have changed.

The implementation of the Cameron pump feeding system, described in Section 3.9, have also been clarified. This comes as a consequence not implementing the Typhonix coalescing pump in the series of hydrocyclones. Since the pump will not be implemented, the max pressure for Phase 1 will be 10 bar, delivered by the Cameron feeding system. This will only be sufficient pressure to drive the separation through HC1 and HC2, however, it will, contribute to a large amount of learning before possibly investing in a high pressure feeding system in Phase 3. The implementation of the reservoir system described in Section 3.6 has also been moved to Phase 3, to be implemented together with a potential high pressure feeding system.

Since the Tenth Adjustment is the last major adjustment to the design in this thesis, this serve as a foundation for the final design in Chapter 4.

Phase 1

Phase 1 has been expanded with one hydrocyclone, giving an initial setup with three hydrocyclones in series instead of implementing the third in Phase 2. The main reason for this change is that a later retrofit, where a third hydrocyclone would be installed in the pre–installed series of two, would be more costly than implementing the third hydrocyclone in Phase 1. The third hydrocyclone is placed in a by-pass.

Phase 1 will only involve the hydrocyclone skid. The Cameron pumps will be used as a feeding system, and the gravity separator will be used as a reservoir. This will limit the operational pressure to 10 bar and possibly degrade the separation results since the gravity separator will not be able to clean the water perfectly. It will, however, allow for extensive testing of the hydrocyclone skid.

Additionally, Mr. Rawlins [XIV] made some comments regarding the control valves on the oil reject lines in the hydrocyclone skid. Mr. Rawlins informed that the oil reject lines always will be at atmospheric pressure and questioned the relevance of installing control valves on the oil reject lines, since it theoretically not will be able to change the PDR.

As a result of this, Mr. Kvamsdal [XI] was also consulted. Mr. Kvamsdal agreed with Mr. Rawlins that the control valves would theoretically not be necessary. In addition, Mr. Kvamsdal mentioned that flashing could occur in the oil reject lines when operating near ambient pressure. Flashing occurs when the pressure of a fluid drops below its vapor pressure. The vapor pressure is an indication of the evaporation rate of a liquid. As a consequence, the fluid begins to change from a liquid to a gas [77]. In order to avoid flashing, Mr. Kvamsdal recommended to install the control valves.

However, as seen in Table 3.10 in Section 3.7.4, the vapor pressure of Exxsol D140 is $\leq 1.33\ 10^{-4}$ bar at 20 °C. Because of this, it is very unlikely that flashing will occur since the oil reject streams always will be at atmospheric pressure. Since flashing is a function of both temperature and pressure, the risk of flashing increase with temperature. This separation process is however approximated to 25 °C [I], and as a result this should not be a problem. [77]

Furthermore, a gravity separator or a similar bulk separation concept will be installed upstream of the hydrocyclone skid in a later phase. As explained in Section 2.1.5, the main objective of flow rate control for a typical deoiling hydrocyclone application in the industry is to maintain a desired water level in an upstream three-phase gravity separator.

The normal procedure of such setup is to use the underflow valve to control the water level in the gravity separator, and the oil reject valve to control the PDR. This is another argument to implement control valves on the oil reject lines in Phase 1. The reason why the underflow valve is used to control the water level in the gravity separator, is to avoid any disruption of the inlet flow to the hydrocyclone. By installing a control valve at the hydrocyclone inlet, in order to control the water level in the gravity separator, this will disrupt the inlet flow.

Budget constraints have great impact on design decisions, and as a consequence of high cost and the reasons mentioned above, consultation with Mr. Holden [V] and Mr. Ohrem [XIII] concluded to remove the overflow control valves in HC2 and HC3 in Phase 1.

However, a overflow control valve will be included in HC1, both because of the option to control the water level with the underflow control valve in a future upstream three-phase separator, and to add an additional degree of freedom to make the system less rigid with respect to system control [XIII]. This control valve is shown as C1 in Figure 3.30.

Since the underflow in HC1 will be equivalent to the inlet flow rate in HC2, the impact of the underflow control valve in HC1 will impact the separation process both in HC1 and HC2. This will also be the case for HC2 and HC3. For that reason, the system is highly coupled. Thus, the overflow control valve in HC1 will facilitate experiments to control the PDR. A overflow control valve in HC2 will be installed in Phase 3, if this control strategy is successful.

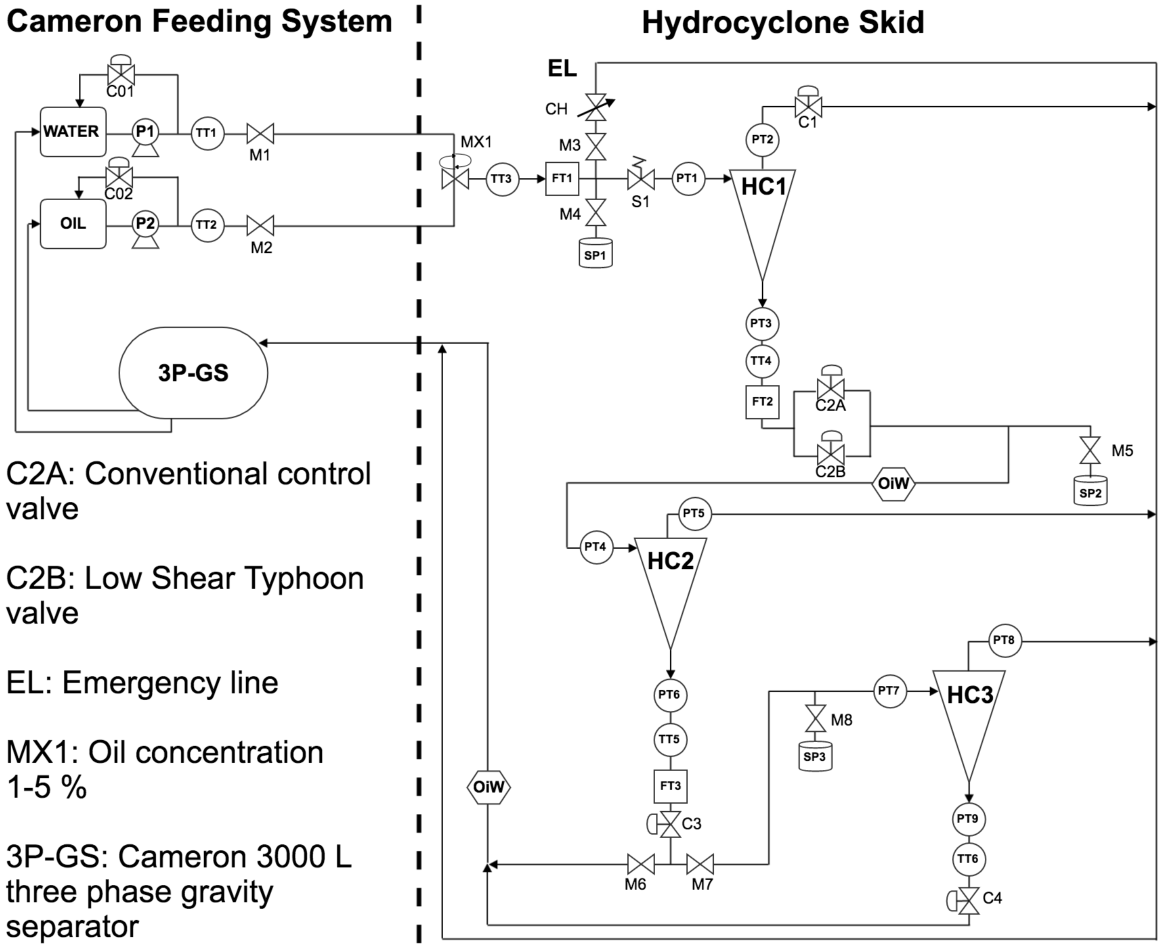


Figure 3.30: Phase 1. Hydrocyclone skid connected to Cameron's feeding system.

Additional modifications of the hydrocyclone skid in this adjustment was the implementation of a choke valve and sampling bombs, CH, SP1, SP2 and SP3 in Figure 3.30. Since the oil reject lines always will be at atmospheric pressure, a choke valve will be installed on the emergency line to ensure the same pressure when the pipes are combined.

Sampling bombs are pressure cylinders connected to the main line, which makes it possible to take samples from high pressure process lines. Sampling bombs will be installed on all sampling points. A schematic setup of a sampling bomb are shown in Figure 3.31.

The sampling point attached to the process line is marked as 1. The sample cylinder is first filled with liquid through the sampling point. According to Mr. Husveg [VI], in order to achieve a representative OiW sample it is important to avoid shear in valves. To take a representative sample without applying a large pressure drop, the inlet needle valve is first opened before the outlet needle valve is opened gently.

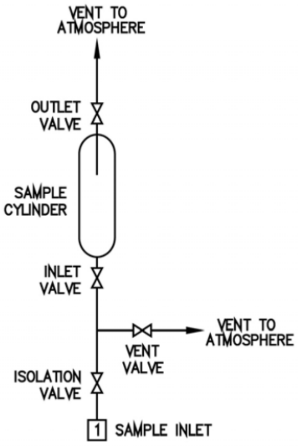


Figure 3.31: Schematic setup of a sampling bomb. The sampling point attached to the process line is marked as 1. The sample cylinder is first filled with liquid through the sampling point. To take a representative sample without applying a large pressure drop, the inlet needle valve is first opened before the outlet needle valve is opened gently [XI].

Phase 2

Based on the input from the industry partners in SUBPRO, the implementation of a CFU is expedited to Phase 2. This enables the laboratory to compare the separation results from the series of hydrocyclones with the results from the CFU. Both separation in hydrocyclones and CFU's are regarded to be "state of the art" within compact separation [XIV], and to compare these technologies with the same operational parameters in the presence of slugs and flow transients would be of great interest.

The implementation of a CFU also calls for the introduction of gas to the system. Gas implementation has therefore been moved from Phase 3 to Phase 2. The gas will be held in a pressurized tank at 10 bar, equivalent to the maximum operating pressure in the Cameron feeding system. This pressure can be further increased through compressor C1, which has a maximum differential pressure of 15 bar, resulting in a total pressure of 25 bar. A by-pass around compressor C1 will allow the gas reservoir to deliver a pressure of 10 bar to the system while the hydrocyclone skid is connected to the Cameron feeding system, and 25 bar to the system when a potential new feeding system is installed in Phase 3.

A settling tank is installed downstream of the CFU to separate the gas and the oil. The gas will go through compressor C2 and the oil will go to the holding tank. Compressor C2 has a maximum differential pressure of 10 bar, which is the same pressure as the pressurized gas reservoir. Gas injection, explained in Section 2.6.1, is also included in Phase 2, since this is a minor additional cost when gas already has to be implemented for the CFU.

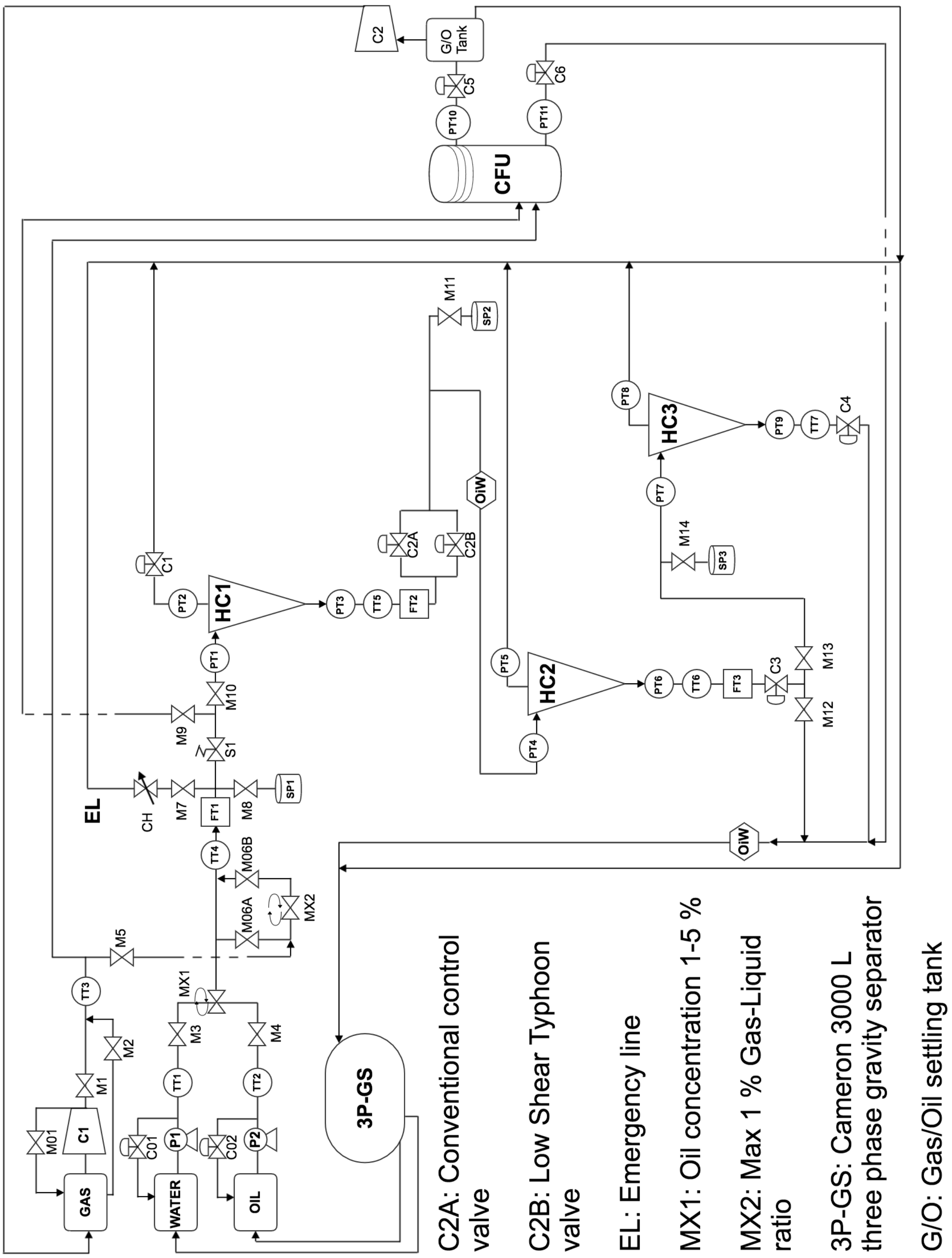


Figure 3.32: Phase 2. Hydrocyclone skid connected to Cameron's feeding system and implementation of CFU, gas reservoir and gas-injection.

Phase 3

In Phase 3 the plan is to procure in a new pump feeding system and reservoir system. This will increase the operational pressure to a maximum of 25 bar, which will allow for operation of the third hydrocyclone, HC3. A new reservoir system will, because of additional filtration technology, increase the purity of the recycled water. Using recycled water, without oil, will help to increase the repeatability of the research results and is important when working with oil concentrations at 30 ppm.

In addition to the feeding pumps and the reservoir system, Phase 3 aims to implement the bulk separation concept developed at the Department of Petroleum Engineering and Applied Geophysics. Depending on the developed concept, the phase-splitter and de-liquidizer setup, as shown in Figure 3.33, might be required. The phase-splitter will act as a bulk gas-liquid separator. The separated continuous gas stream will be sent through the de-liquidizer to further separate residual liquid droplets to ensure pure gas returning to the gas reservoir. The separated continuous liquid stream will be sent to the developed concept.

The implementation of the bulk concept will allow a higher oil concentration in the system, and the system in total will be a small scale model of a three–phase separation process. As mentioned in Section 3.12.3 a overflow control valve will be installed in HC2 if the previous experiments have proven successful. The overflow control valve is marked as C3 in Figure 3.33.

Phase 4

The Typhonix coalescing pump is now included in Phase 4 as a future implementation. This is mainly due to economical limitations, and the design considerations discussed in Section 3.12.2. A second low shear Typhoon control valve (C4B) is also proposed between HC2 and HC3 to further increase the separation efficiency. Phase 4 will be based on the interest for future concept in the oil and gas indstry, and input from the SUBPRO partners. The rest of the proposed future implementations, as shown in Figure 3.34, will be further described in Section 4.5.

3.12.4 Budget Changes and Safety Factor

The budget have had several small updates and changes since the Sixth Adjustment in Section 3.8. The cost of the low shear Typhoon valve has been included in Phase 1, the cost of gas compressors and pressure tanks for the implementation of the CFU have been included in Phase 2, and proposed pumps that are fit for the updated operational pressure of the system are included in Phase 3. The combination of EX-requirements and high pressures also made the control valves more expensive than initially anticipated.

This adds additional cost to the total budget and decreases the economical safety factor. The additional investment of upgrading the equipment to EX-certified as Zone 1, as described in Section 3.10, has also increased the overall cost. Because of the great uncertainty related to both the technical complexity and cost aspects, Phase 4 has not been included in the budget.

The budget overview for the tenth adjustment is shown in Table 3.19.

Total cost phase 1+2+3	NOK 2,955,135
Available funds	NOK 3,000,000
Unforeseen modifications	NOK 44,865
Economical safety margin	1.50 %

Table 3.19: Budget overview for the current design after the tenth adjustment.

As seen from the economical safety margin of 1.50 % in Table 3.19, Phase 4 will require additional funding in order to be implemented.

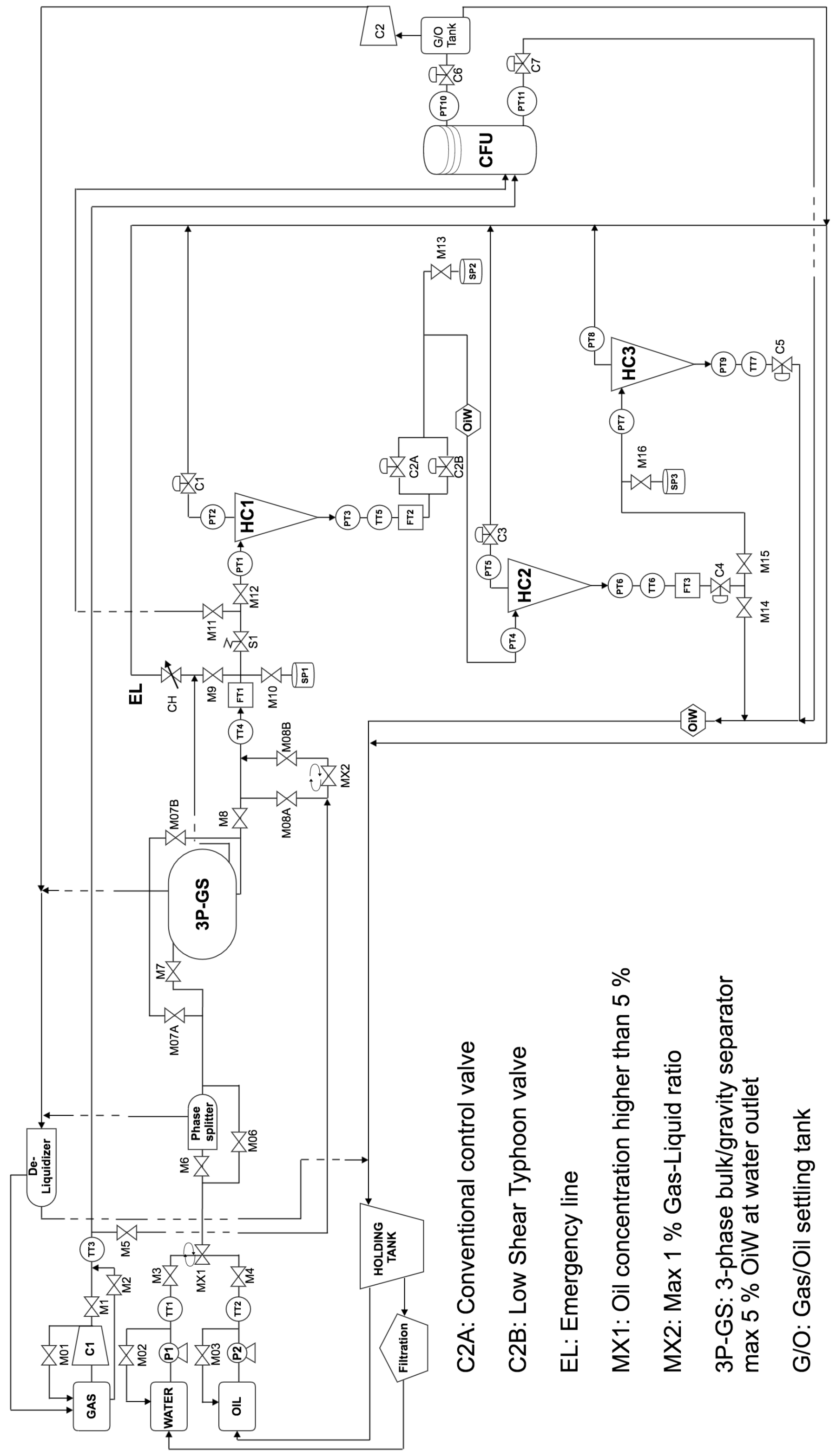


Figure 3.33: Phase 3. Implementation of a new feeding system, reservoir system, bulk separation, phase-splitter, de-liquidizer and a overflow control valve in HC2

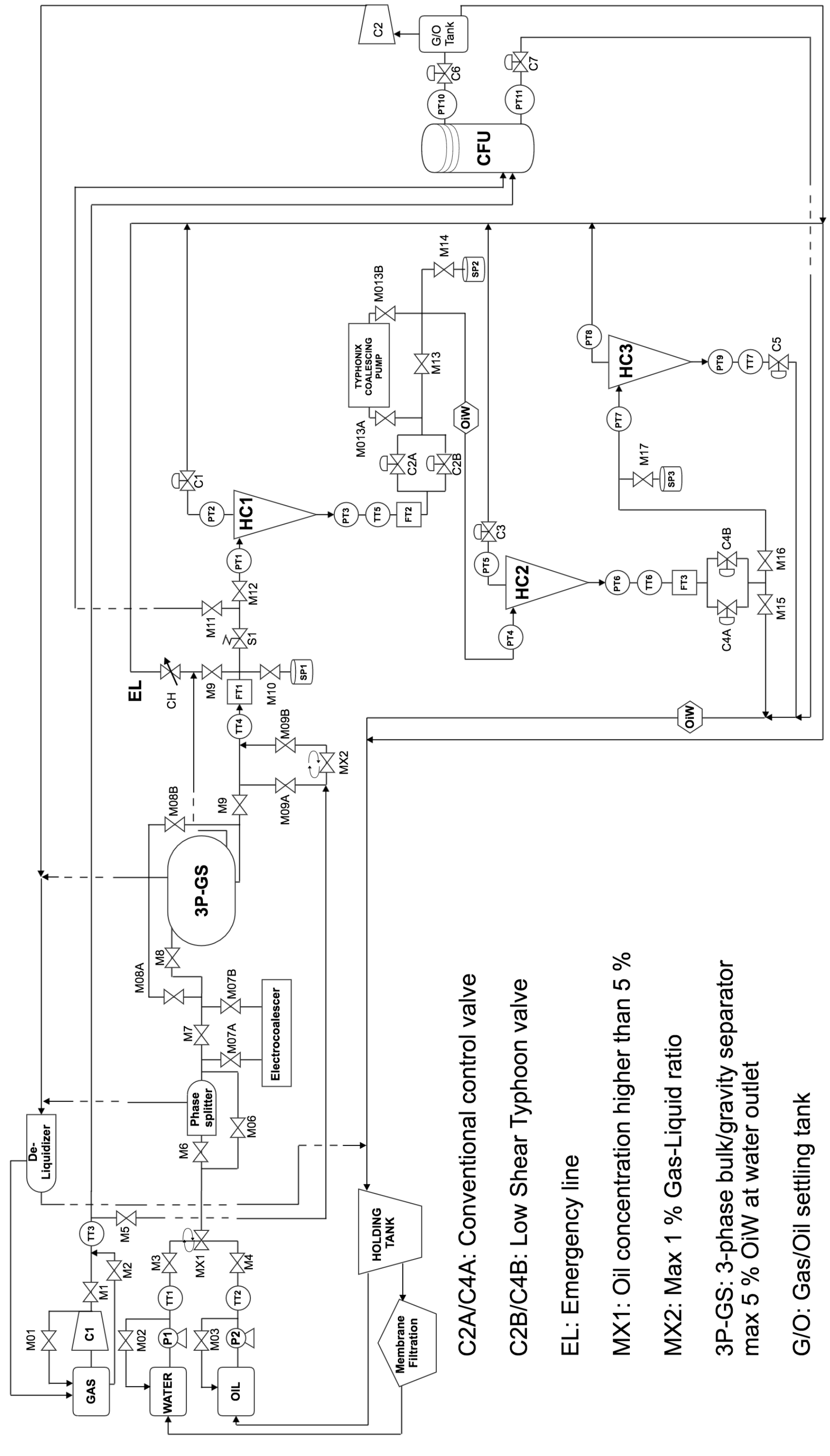


Figure 3.34: Phase 4. Implementation of future concepts. A Typhonix coalescing pump and a second low shear Typhoon valve are included.

Chapter 4

Final Design

The proposed compact separation laboratory at the Department of Production and Quality Engineering will expand gradually through four phases. In this thesis, both the first phase and future phases have been taken into account. However, the main focus in this thesis is the design of Phase 1, and to future proof this phase for later expansions. For that reason, the detail level of Phase 1 will be greater than the following phases. For maximum flexibility, the different phases has been designed with ample bypass systems and implemented flexibility to connect future modules and systems.

4.1 Phase 1

The final design of Phase 1, as shown in Figure 4.1, is a fundamental setup for a produced water treatment process, combined with several monitors and sensors which allows for the implementation of novel control algorithms. In order to assure the laboratory's relevance for the industry, several professionals with great industrial experience and knowledge of similar laboratory setups, like Hank Rawlins [XIV], Dag Kvamsdal [XI], Tryge Husveg [VI] and Arne Henriksen [IV], have been consulted in the process of optimizing the final design of this thesis.

The laboratory will be built on modular skids. The reason for this is to increase both flexibility and expandability, and simplify an eventual relocation of the laboratory. During Phase 1, the hydrocyclone skid, as illustrated in Figures 4.7 and 4.8, will be connected to the oil and water pumps in the Cameron laboratory. The Cameron pumps and gravity separator will serve as a feeding system to test the hydrocyclone skid. This will allow to test the overall system setup, especially control valves and sensors at different flow rates, pressures and oil concentrations to further optimize the performance of the system, before a potential investment decision concerning a new feeding pump system and reservoir system is taken. These learnings will come to great use for the future implementations of the later phases and corresponding equipment of the laboratory.

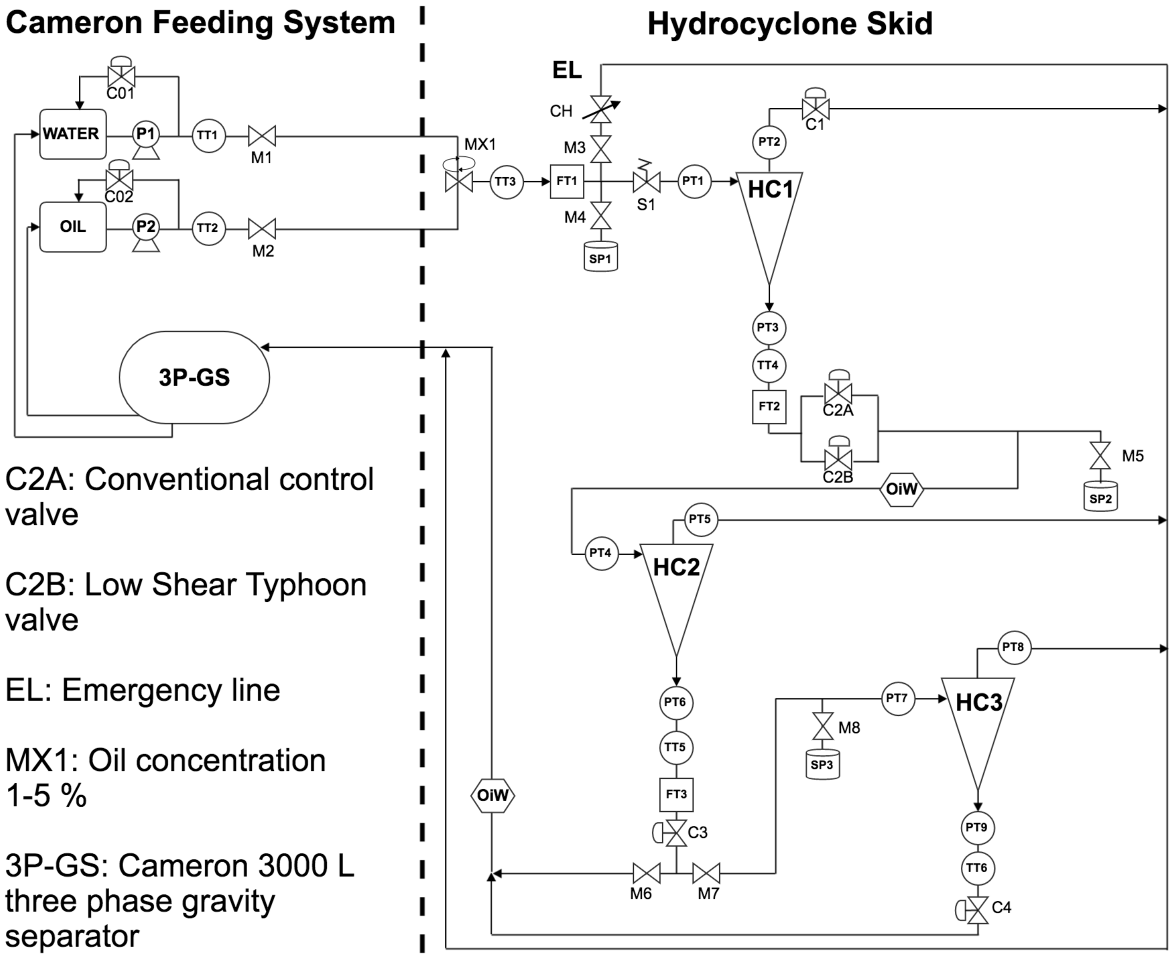


Figure 4.1: The final design of Phase 1. The Hydrocyclone skid connected to Cameron's feeding system.

Key components in Phase 1 are summarized in Table 4.1, the design parameters are summarized in Table 4.2 and administrative aspects are summarized in Table 4.3. The proposed equipment to be implemented in Phase 1 and the corresponding suppliers are listed in Chapter 5 and Appendix B respectively.

Component	**Purpose/explanation**
Cameron Feeding System	Oil and water supply from existing Cameron facilities
C01, C02, C2A, C3, C4	Standard pneumatic control valve
C2B	Low shear Typhoon control valve
CH	Choke valve to reduce the pressure
FT1	Coriolis flowmeter to measure density and flow rate
FT2/FT3	Magnetic flowmeter to measure flow rate
HC1	Reduce the oil content from ≤ 5 % to 2000 ppm
HC2	Reduce the oil content from 2000 ppm to 30 ppm
HC3	Further reduce the oil content below 30 ppm
M1, M2, M6, M7	Manual ball valve
M4, M5, M8	Manual needle valve for isolation of sampling bomb
M3	Manual ball valve as part of safety system
MX1	Mixing valve to ensure a homogeneous mix of oil and water
OiW	Oil-in-water sensor to measure the oil concentration in water (0 to 3000 ppm)
PT	Pressure transmitter to measure the differential pressure in order to calculate PDR
S	Safety system, pressure guard placed in this position
SP	Sampling point to enable batch-wise oil-in-water measurements
TT	Temperature transmitter to measure the temperature
3P-GS	Cameron Gravity Separator – accumulation of oil and water

Table 4.1: Key Components in the Final Design of Phase 1.

Design Parameters	
Max. liquid flow rate	5 m^3/h
Max. operational pressure	10 bar
Max. operational temperature	50 °C
Oil reservoir	Exxsol D140
Water reservoir	Freshwater + salt (up to 5 % NaCl)
3P-GS	3000 l
Material selection	AISI 316L
Wall thickness of pipes	SCH 10
Wall thickness of HC1	SCH 40
Wall thickness of HC2/HC3	SCH 10

Table 4.2: Design Parameters in the Final design of Phase 1.

Administrative Summary	
Total investment cost	NOK 1,974,123 (See Section 6.1)
Total space of HC skid	14 m^2
Startup date for construction	Fall 2016
Startup date for experiments	2017-01-01
Lifetime	7 years

Table 4.3: Administrative summary of Phase 1.

The input to the system will be generated by the Cameron feeding pumps both in normal and transient conditions. An illustration of Cameron's feeding pump system is shown in Figure 4.2. As explained in Section 3.9.1, these pumps do not have a VSD and both the water pump and the oil pump have a maximum operating pressure of 10 bar, with a flow rate of 4–25 m^3/h for the water pump and 4–35 m^3/h for the oil pump. Since the Cameron feeding pumps are positive displacement pumps, as described in 2.4.3, they will pump a closed volume independent of the back pressure until the operational pressure is reached. Thus, the pump flow rate will be recirculated through control valves (C01 and C02) over the pumps in order to achieve the correct flow rates required for the laboratory, before the manual valves (M1 and M2) are opened. This solution will allow the pumps to operate down to a minimum flow of potentially 0 m^3/h. [XI]

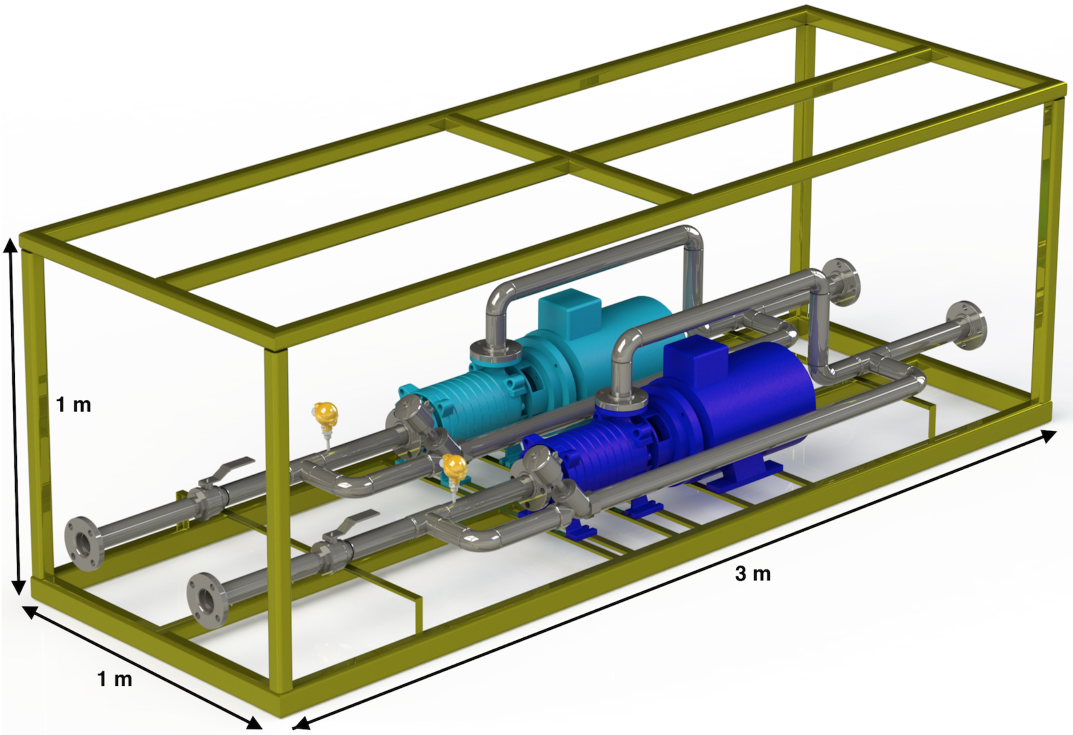


Figure 4.2: CAD model of Cameron's feeding pump system - The light blue pump illustrates the water feeding pump and the dark blue pump illustrates the oil feeding pump. Control valves are placed in the recycle loops and temperature transmitters are placed downstream the pumps.

As explained in Section 3.3, the preferred method for using a multi-stage hydrocyclone system is for partial processing. Partial processing will be favorable in applications with high oil content in the produced water stream because a single stage hydrocyclone system will not be able to handle the high oil content. The oil concentration delivered by the feeding system will thereby be between 1-5 %. A typical oil concentration from the water outlet from an upstream three phase gravity separator is, however, in the range of 500–1000 ppm [XI]. This could also be provided by the feeding system and then only utilize one hydrocyclone stage in the separation process.

The mix valve (MX1) will ensure a homogeneous mix of the oil and water phase when the two phases are combined in one pipe, as illustrated in Figure 4.5. Hydrocyclones installed in series of three stages will be used to further reduce the oil concentration down to the OSPAR regulation (explained in Section 2.5.2) of 30 ppm or less. The first stage (HC1) will consist of two hydrocyclone liners installed in parallel to reduce the oil content from 1–5 % down to about 2000 ppm. Then the second stage (HC2) will contain one hydrocyclone liner to further reduce the oil content from 2000 ppm down to 30 ppm before the oil and the water enters a joint holding tank (3P-GS). In a real system, the produced water could be dumped or re-injected, and the produced oil sent to a platform or onshore facility [47].

The purpose of the third stage (HC3) is to further reduce the oil content below 30 ppm during normal conditions and maintain 30 ppm during transients conditions. With respect to dimensions, HC3 will be equal to HC2, but HC3 will be installed in a buy-pass system in order to reduce the necessity of implementing a third OiW sensor probe between HC2 and HC3. As explained in Section 3.8, this probe is extremely expensive and will constitute a large part of the total budget. Regarding the maximum operational pressure of the Cameron feeding pumps of 10 bar and the potential pressure drop over HC1 (1–3 bar), HC2 (5–7 bar) and HC3 (5–7 bar), the realistic approach will be to only perform experiments with HC1 and HC2 in series during Phase 1. HC3 will need a higher operational pressure to be included in the experiments. A higher operational pressure will be possible in a later phase of the laboratory by investing in a new feeding pump system.

As explained in Section 3.7.3, the OiW sensor will be announced as a tender offer, which is based on the technical specification listed in the requirements specification in Appendix C. This requirement specification is the result of a thorough analysis of OiW technology, and is ready to be delivered to the Department of Procurement at NTNU without further modifications.

It is of great importance to place the OiW sensors in turbulent flow areas, such as vertical pipelines, to achieve a homogeneous mixture of the fluids and correspondingly more accurate measurements [IV]. This is further described in Section 2.5. Additionally, as explained in Section 3.9.2, it will be desirable to only place the OiW sensors in a vertical pipeline when the flow has an upward direction [III]. Based on this, the first OiW sensor is placed in a vertical pipeline, while the second OiW sensor is placed in a horizontal pipeline after a 90 ° bend. An illustration of the placement of the first and the second OiW sensors, are shown in Figures 4.3 and 4.4 respectively.

As elaborated in Section 3.12.3, sample points have been included between each of the hydrocyclone stages in order to qualify the results from the OiW sensors. Sampling bombs are pressure cylinders connected to the main line, which makes it possible to take samples from a high pressure process lines by utilizing needle valves. The first sampling bomb, SP1, is shown in Figure 4.5 and the second, SP2, is shown in Figures 4.3 and 4.6.

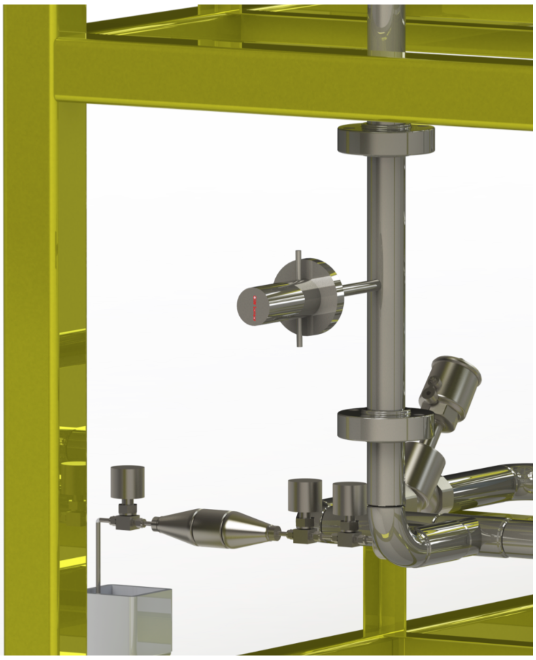


Figure 4.3: The first OiW sensor placed in a vertical pipeline.

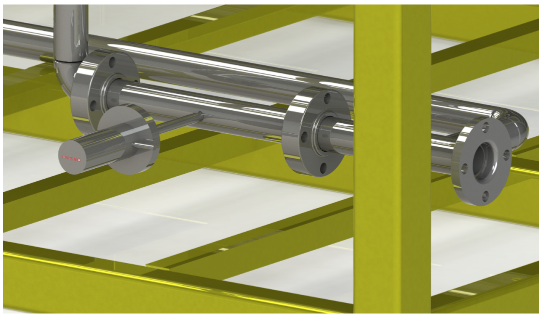


Figure 4.4: The second OiW sensor placed in a horizontal pipeline after a 90 ° bend.

As explained in Section 2.1.1, the separation efficiency increases with increasing droplet size. The conventional control valve (C2A) will reduce the oil droplet size, while the low shear Typhoon valve (C2B) will aim to maintain the oil droplet size. This is further explained in Section 3.11.2. Thus, the two control valves will be installed in parallel, as shown in Figure 4.6, between HC1 and HC2 to compare the effects of the different valves on the separation efficiency.

Prior HC1, the oil concentration will vary from 1-5 %. This range of OiW concentration is not possible to measure with the available online OiW sensor technology, which currently operates in the range from 0 to 3000 ppm. However, as explained in Section 2.2, in addition to measure the flow rate, the coriolis flowmeter has the possibility to perform a precise density measurement of liquids by measuring the resonance frequency of the pipes. By measuring the fluid density, the oil concentration can be calculated indirectly. To be able to measure the oil concentration prior HC1, the first flowmeter (FT1, as shown in Figure 4.5) will be a coriolis flow meter. The second and the third flowmeters (FT2, as shown in Figure 4.6, and FT3) will be magnetic flowmeters, due to the fact that these will only perform flow rate measurements of the water stream with a very low oil concentration between 30 and 2000 ppm.

As mentioned in the tenth adjustment of the Evolution of the Design in Section 3.12.3, there will be installed a overflow control valve (C1) in HC1 to experiment with the PDR control strategy and facilitate future installation of bulk separation. Control valves are installed downstream of each hydrocyclone stage to control the separation process by adjusting the pressure drop over each stage. The same type of control valves will also be installed over each of the feeding pumps in order to recirculate the flow and achieve the desired flow rate.

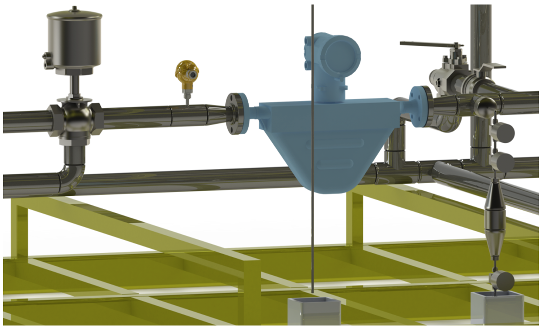


Figure 4.5: An illustration of how the mix valve combines the oil and the water flow into one pipe and ensures a homogeneous mix. The light blue component is a coriolis flow meter and the pressure cylinder is the first sampling bomb.

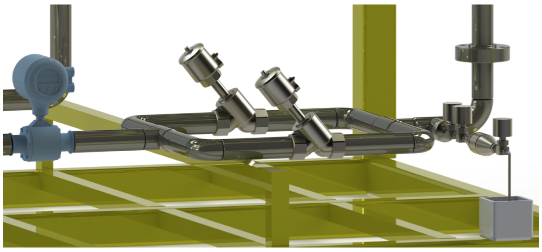


Figure 4.6: An illustration of how the two control valves (C2A and C2B) will be installed in parallel. The light blue component is a magnetic flow meter and the pressure cylinder is the second sampling bomb.

In order to calculate the PDR, differential pressure transmitters (PT) will be installed at inlet to underflow, and inlet to overflow, in all three hydrocyclone stages. Manometers will also be installed to ensure measurements in case of electrical errors. Temperature transmitters (TT) will be installed downstream of the feeding pumps, and upstream of HC1, HC2 and HC3 in order to measure the temperature of the fluid. As explained in Section 3.6.2, by choosing AISI 316L as the piping material, the temperature of the fluid should be restricted to a maximum of 50 °C to avoid stress corrosion cracking (SCC).

In order to maintain the safety aspect during operation of the laboratory an emergency line has been added. This is marked with EL in Figure 4.1. The purpose of the emergency line is to direct the flow directly to the dump reservoir if the pressure upstream of the hydrocyclones exceeds a maximum value. This value is set to 25 bar for the operational pressure of the later phases, which means that if the pressure upstream of the hydrocyclones exceeds 25 bar, the EL line will open and relieve the pressure. This solution is designed as a combination of a pressure guard, a magnet valve, and a shut-off valve. S1 in Figure 4.1, will represent a pressure guard which will send a signal to a magnet valve if the pressure limit is reached, which further will control the operation of a actuated valve M3. The EL line will then open, and the pressure upstream of the hydrocyclone setup will decrease. Since the oil reject lines always will be at atmospheric pressure, a choke valve (CH) will be installed on the emergency line (EL) to ensure the same pressure of a potential redirected flow.

The electrical system has not been given attention in this Master's thesis, and will be a subject for further work during the construction phase. All proposed equipment in Phase 1 are however based on 220–240 DC and a 4-20 mA output.

4.1.1 Crude oil and EX certification

As mentioned in Section 3.10, the compact separation laboratory aims to develop a future cooperation with SINTEF's small scale loop at Tiller, which will allow for the introduction of crude oils in the separation process. By performing experiments with crude oils, the credibility of the results will be increased with respect to the oil industry [VI].

This will, however, need the separation laboratory to be constructed EX-classified as Zone 1, as this is the EX-classification of SINTEF's facility. This involves additional technical specifications for all equipment, especially the electrical components. Phase 1 of the compact separation laboratory has been designed EX-classified as Zone 1, and for the later phases it should be considered if it will be necessary to build the later expansions EX-proof since it is mainly the HC-skid that will be transported to external locations.

4.1.2 Future transport of the hydrocyclone skid

The hydrocyclone skid has a length of 7 m, a width of 2 m, and a height of 2.1 m. A CAD model of the hydrocyclone skid is shown in Figure 4.7. The weight of the skid has not been accurately calculated, but is predicted to be between 1.5 and 2.0 tonnes. As a result of the overall dimensions and the weight, transportation of the hydrocyclone skid will be challenging.

For the linking of the hydrocyclone skid and the SINTEF small scale loop, described in Section 3.10, the hydrocyclone skid will have to be transported from the workshop at the Department of Production and Quality Engineering to SINTEF's office at Tiller. This represents a drive of approximately 10 km and must be done with a truck. Edgar Kaasboell [IX], Transport Manager at NTNU Operations, have been consulted on the matter and Mr. Kaasboell informed that the trucks max dimensions are 2.5 m in width and 6 m in length. As a result, the hydrocyclone skid have been split into two skids which are 3.5 m in length, shown in Figure 4.8.

This will allow the the hydrocyclone skid to be transported to the SINTEF laboratory without complications with respect to space limitations on the truck. A skid with a length of 3.5 m also has less risk of material deflection when lifted compared to a length of 7 m, and this will also simplify potential moving of the skid inside the workshop at the Department of Production and Quality Engineering.

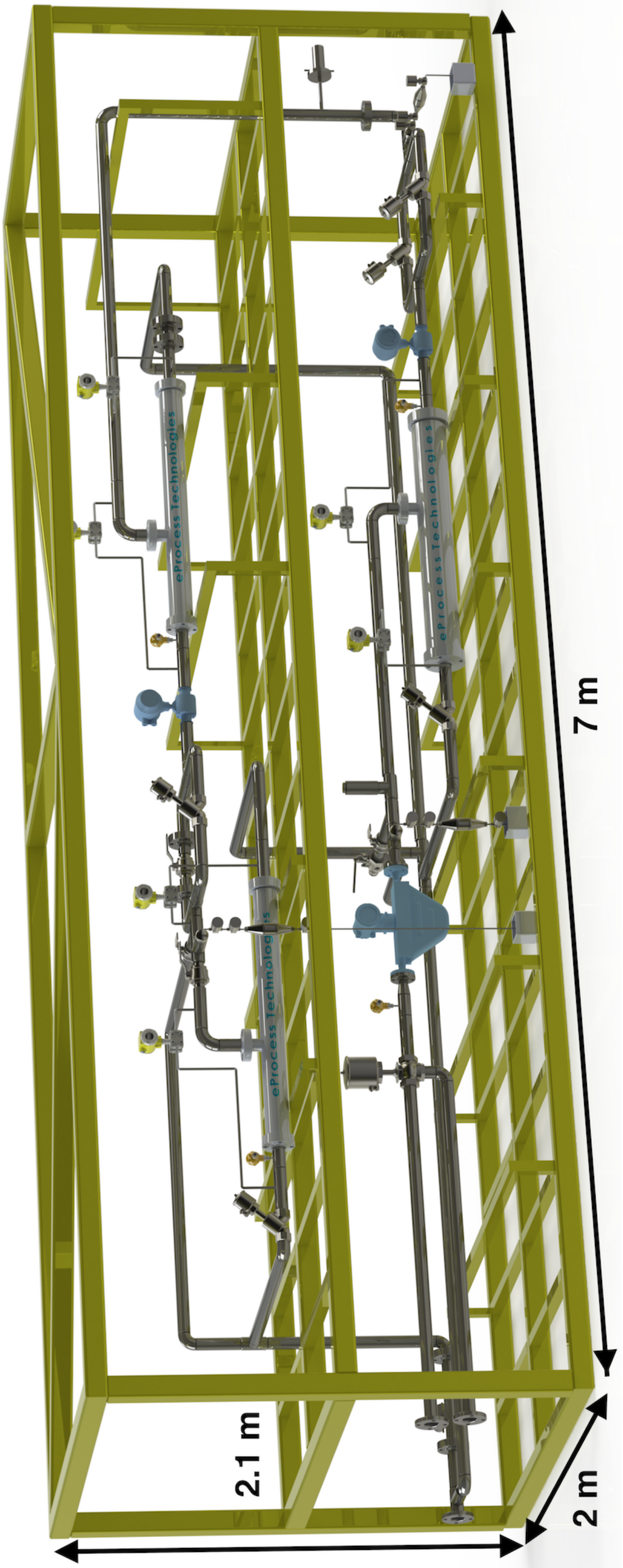


Figure 4.7: CAD model of the HC skid with a length of 7 m.

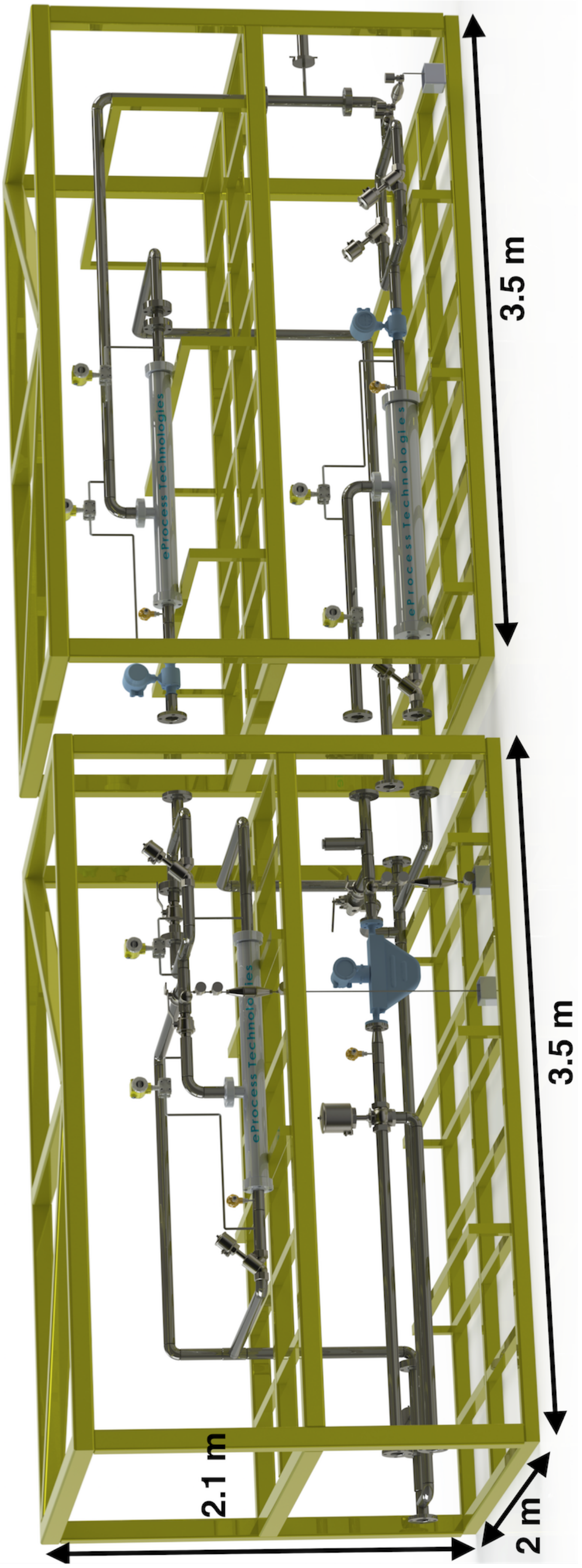


Figure 4.8: CAD model of the HC skid separated in two equal skids with a length of 3.5 m.

4.2 Reservoir System, Feeding Pump System and Project Management

The main challenge regarding the reservoir system has been to decide if it should be designed as a closed–loop or an open–loop system. The final result is based on a closed–loop system, for reasons explained in Section 3.6.1. To ensure clean water returning to the water reservoir an oil skimmer will be installed in combination with adsorption filtration technology. This is of great importance in order to avoid the build-up of small oil droplets that will degrade the system performance across time, when operating in closed-loop. A drawback with the filtration technology is the fact that it will also filtrate the salt particles from the system. This will have a huge impact on the coalescence in the system, and without the salt particles, the system will be more shear sensitive. As a consequence, it is of great importance to refill more salt in the recycled water after the filtration process to ensure a coalescing effect on the oil droplets.

After the filtration process, the clean water will be supplied to five equal 1000 l IBC containers. Each IBC container are installed with flanges and manual valves on both the inlet and outlet for easy replacement. There are several reasons for this solution. The main reason is to optimize the redundancy of the water supply system. If a leakage should occur in one of the IBC containers, the operator could simply remove or replace the IBC container and still be able to run the system with the other four IBC containers. Large tanks are in addition very expensive, and if a leakage should occur, the hole tank has to be replaced and the system has to be shut down until a new tank is installed. For that reason, five IBC containers will increase the flexibility of the water supply system. An illustrative CAD model of the reservoir system is shown in Figure 4.9.

By investing in a feeding pump system that could deliver an operational pressure of 25 bar, HC3 could be included in the experiments. The feeding pump system proposed in Section 5.9 will, in addition, be equipped with VSD. This enables the pump frequency to be changed rapidly to generate flow and pressure disturbances. This is further explained in Section 2.1.6. In order to be able to deliver an oil concentration between 1–5 % and a oil concentration up to 50 % for the later phases, both at a maximum operational pressure of 25 bar, the oil feeding system will consist of one small and one large oil pump installed in parallel. The reason for this, is that no single oil pump is able to deliver within the full spectre of the flow range, from 0.045 m^3/h to 3 m^3/h, at the operational pressure with sufficient accuracy. An illustrative CAD model of the proposed feeding pump system is shown in Figure 4.10. The purpose of the recycle lines over the pumps are to adjust the desired flow rates through the start up process.

It is important to highlight the importance of including VSD on the pumps, as these pumps should generate disturbances in flow rates and pressure. If VSD for some reason are not prioritized in the future investment, an additional disturbance generator must be bought or developed in order to generate flow transients.

Key components are summarized in Table 4.4 and administrative aspects are summarized in Table 4.5. The proposed equipment to the reservoir system and the feeding pump system and corresponding suppliers are found in Sections 5.8 and 5.9 respectively.

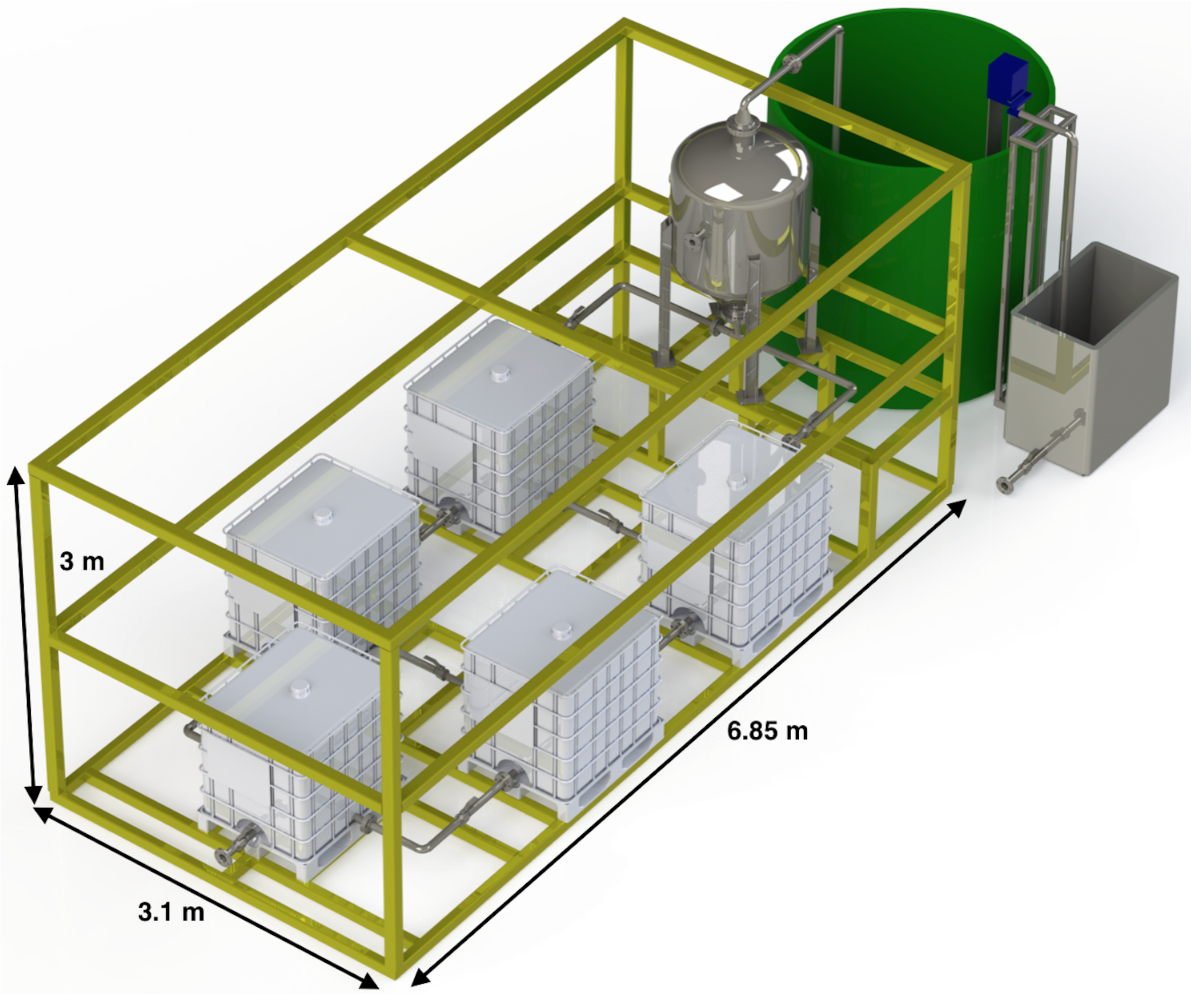


Figure 4.9: CAD model of the reservoir system. The 5000 l holding tank, the oil skimmer and the 720 l oil tank are placed upstream of the filtration tank, before clean water enter the five IBC containers.

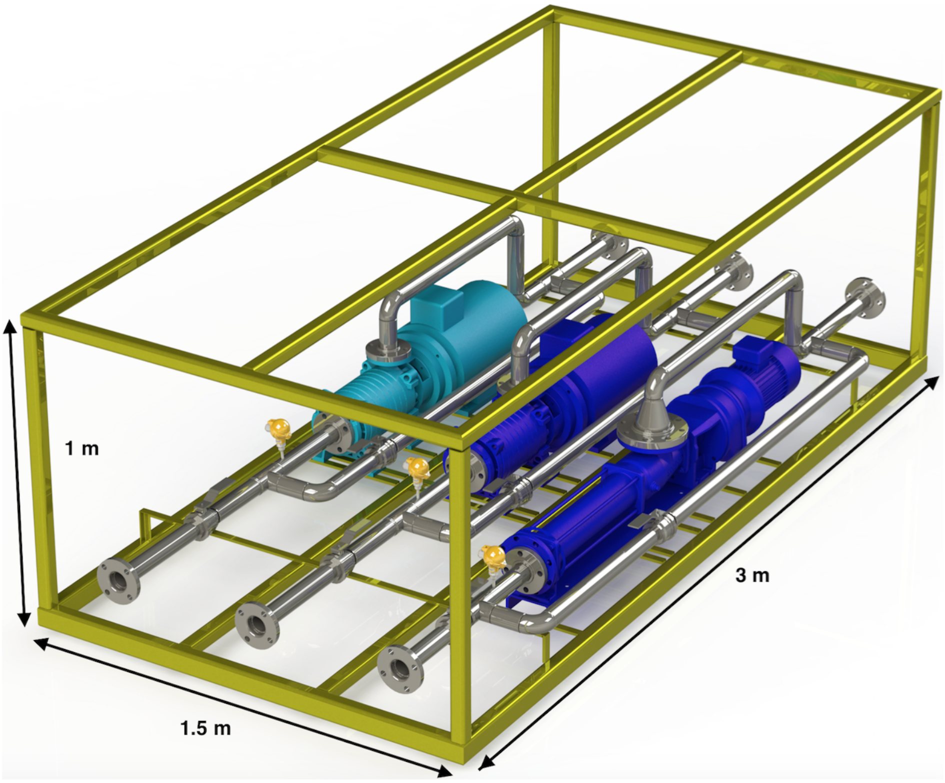


Figure 4.10: CAD model of the proposed feeding pump system - The light blue pump represents the water feeding pump, and the dark blue pumps represents the small and the big oil feeding pump respectively.

Component	**Purpose/explanation**
Filtration tank and filters	Avoid build-up of small oil droplets that will degrade the system performance across time
Flexitank V 5000 BT	5000 l Holding tank - Accumulation of oil and water
IBC container	Five equal 1000 l IBC containers to provide the water supply
Oil feeding pump 1	Delivers an oil flow rate between 0.53 to 3 m^3/h at 20 bar
Oil feeding pump 2	Delivers an oil flow rate between 0.045 to 0.53 m^3/h at 20 bar
Oil skimmer	Separates the bulk amount of oil accumulating on the liquid surface in the holding tank
PE Kombi	720 l Oil tank
Submersible pump	Pumps the water from the holding tank to the filtration tank
Water feeding pump	Delivers a water flow rate between 0 to 5 m^3/h at 20 bar

Table 4.4: Key Components of the reservoir system and the feeding pump system.

Administrative Summary	
Total investment cost	NOK 205,250 (See Section 6.2)
Total space of the reservoir system skid	22 m^2
Total space of the feeding pump skid	4.5 m^2

Table 4.5: Administrative summary of the reservoir system and the feeding pump system.

4.2.1 Project management

The potential implementation of a new feeding pump system and a new reservoir system should be seen in context with the learnings from Phase 1. As described in Section 4, the Cameron feeding system and gravity separator will be used to supply oil and water in Phase 1, and the operational experience from this setup will be a key in deciding when the reservoir system and feeding pump system should be implemented, as well as deciding which pumps that are fitted for the task.

The pumps listed in Section 5.9 are only suggestions, and a proper investment decision should only be made on the basis of the operational experience gained from Phase 1. There are a great deal of project management related to the implementation of both the feeding pumps and the reservoir system, as they could be implemented together in the same phase, or separately in different phases.

For that reason, this thesis does not advice which phase these systems should be implemented in, as this will be entirely based on the result from Phase 1. An example of this continuous project management process would be if the supply water from Cameron's gravity separator is so polluted with dispersed oil that the results are to degraded to use for further experiments. It would then be potentially interesting to implement the reservoir system before the start of Phase 2. An other example would be if the total pressure drop in Phase 1 is higher than predicted, which could lead to insufficient pressure to drive the separation in HC1 and HC2.

In the same way, it would then be potentially interesting to implement the feeding pump system before the start of Phase 2. Both the reservoir system and the feeding pump system could in several other scenarios also be implemented in Phase 2 and Phase 3, which all depends on the results from the previous phase. This project management process is illustrated in Figure 4.11.

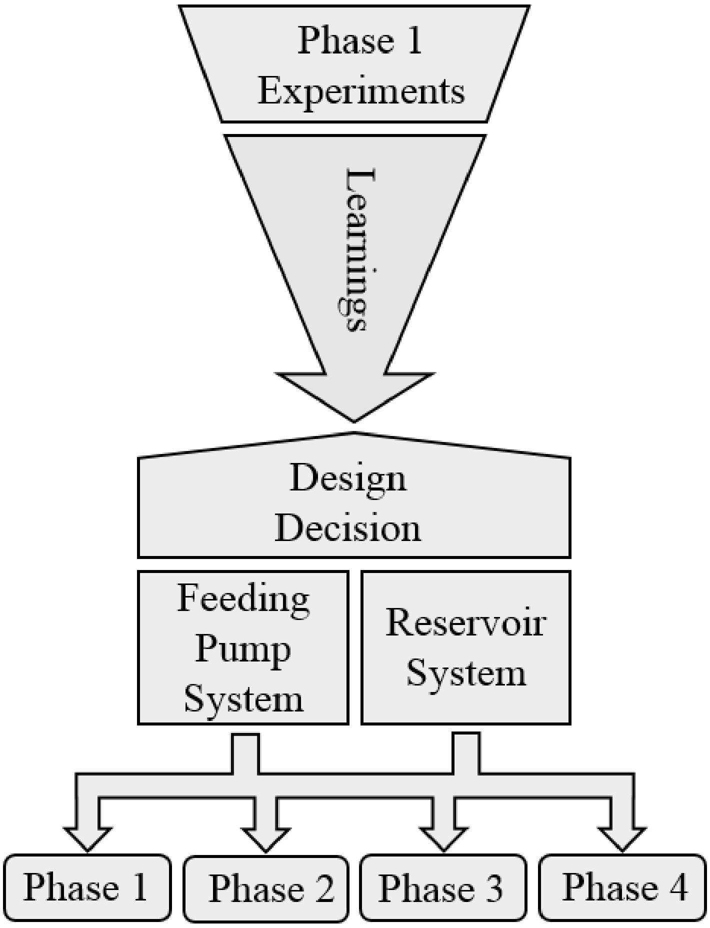


Figure 4.11: Illustration of the project management process that will be needed prior to the implementation of the feeding pump system and the reservoir system.

4.3 Phase 2

Phase 2, as shown in Figure 4.12, extends Phase 1 with a gas reservoir and a CFU in parallel to the hydrocyclone stages. As explained in Section 3.12.3, the industry partners in SUBPRO have expressed an increased interest in the implementation of a CFU during the course of this project. This is the main reason why the implementation of a CFU is suggested in Phase 2. This enables the laboratory to compare the separation efficiency between hydrocyclones in series and a CFU, based on equal conditions. Both of these technologies are generally considered state of the art in compact separation technology and produced water treatment [25],[22]. The CFU implemented in Figure 4.12, are based on the innovative CFU design mentioned in Section 2.7. According to [54], this is claimed to be the next generation CFU.

Due to the implementation of a gas reservoir, Phase 2 will have the opportunity to implement gas-injection to the inlet flow of the hydrocyclones. As elaborated in Section 2.6.1, several experiments conducted by the East China University of Science and Technology [51] have proven that operating with a gas-liquid ratio of maximum 1 % might increase the separation efficiency in hydrocyclones. In their experiments the oil removal efficiency increased from 72 % to 85 %.

In Phase 2, the gas reservoir will be a tank containing gas with a pressure of 10 bar. The suggested gas types are either air, SF_6 or N_2, and the decision of which gas to use should be taken during Phase 2. Compressor C1 has a maximum pressure of 10 bar, and compressor C2 has a maximum pressure of 15 bar. This will allow for a gas at a total of 25 bar to be delivered to the system. Gas at this high pressure will be necessary for Phase 3.

Key components to be implemented in Phase 2 are summarized in Table 4.6, the design parameters are equal to Phase 1 and administrative aspects are summarized in Table 4.7.

Component	**Purpose/explanation**
Compact Flotation Unit	Separates residual oil from produced water by flotation technology (gas bubbles)
Compressor	Increases the gas pressure
Gas-liquid mixing valve (MX2)	Dispenses the correct amount of gas in the produced water flow
Gas Reservoir	Gas supply for the implementation of a CFU and gas-injection for the hydrocyclone stages

Table 4.6: Key Components of Phase 2.

Administrative Summary	
Total investment cost	NOK 198,986 (See Section 6.3)
Total space of Phase 2 (estimate)	15 m^2

Table 4.7: Administrative summary of Phase 2.

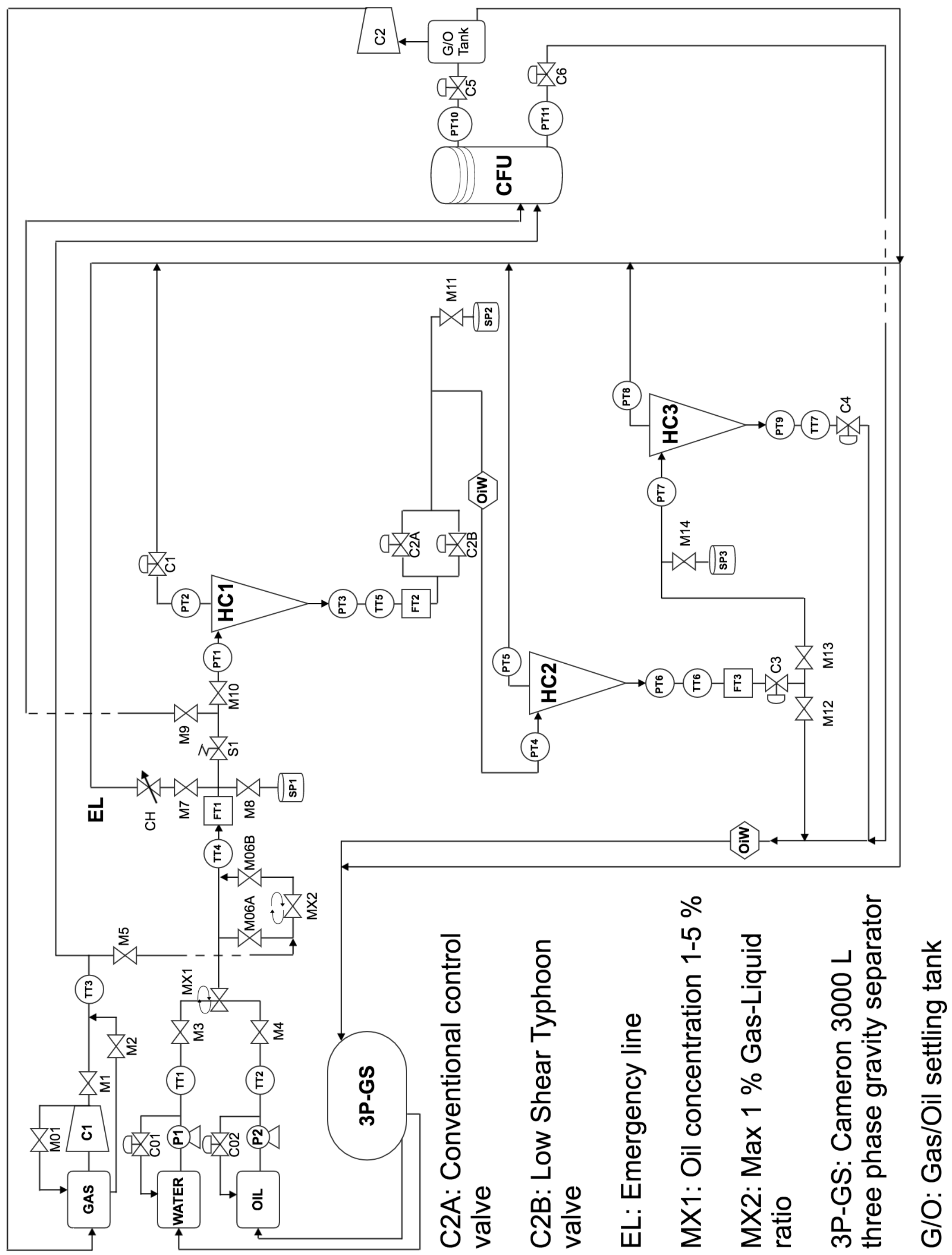


Figure 4.12: The Final design of Phase 2. Hydrocyclone skid connected to Cameron's feeding system and implementation of a gas reservoir, a CFU and gas-injection.

4.4 Phase 3

Phase 3, as shown in Figure 4.14, extends Phase 2 with the proposed reservoir- and feeding pump system elaborated in Section 4.2, a bulk separator, a de-liquidizer and a phase-splitter. The bulk separator will be placed upstream of the hydrocyclone setup, and will allow for an increase in the oil concentration.

The bulk separator may be a classical gravity separator, or a more novel design. As mentioned in Chapter 2.9, the Department of Petroleum Engineering and Applied Geophysics are currently working on developing new concepts for bulk separation of oil and gas. This concept should, if proven successful, be implemented in the compact separator lab as the bulk separator stage. As explained in Section 3.12.3, a second overflow control valve (C3) will be installed in HC2 if previous experiments of the PDR control strategy are proven successful. C3 will replace the pipe with flanges on both ends on the oil reject line in HC2, as illustrated in Figure 4.13.

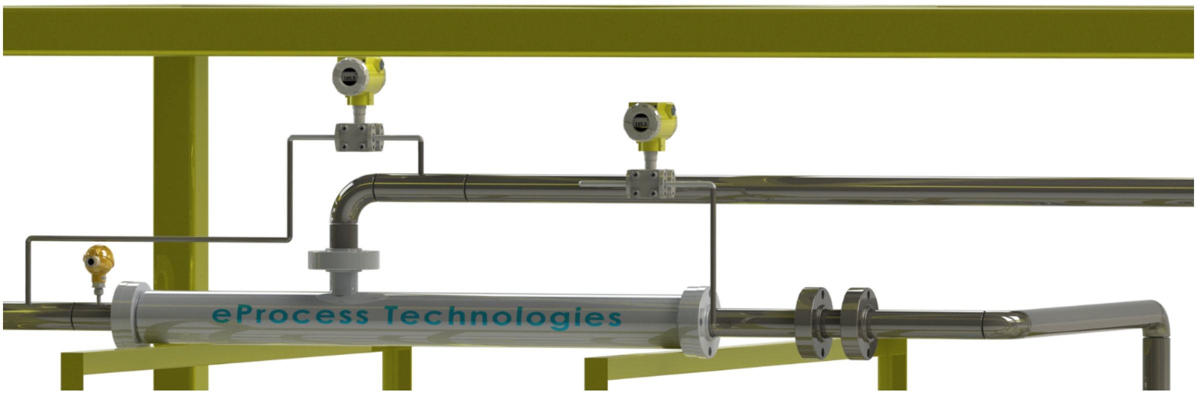


Figure 4.13: A pipe with flanges on both ends is installed on the oil reject line in HC2. This pipe can simply be replaced by C3.

Statoil has previously indicated that they are interested in sponsoring the laboratory with a phase-splitter. This will be implemented upstream of the bulk separator. The separated continuous gas stream will be sent through a de-liquidizer to further separate residual liquid droplets to ensure pure gas returning to the gas reservoir. The separated continuous liquid stream will be sent to the bulk separator.

With the completion of Phase 3, the laboratory will emulate the entire value chain for a produced water treatment subsystem of a small scale compact separation facility.

Key components to be implemented in Phase 3 are summarized in Table 4.8, the design parameters are summarized in Table 4.9 and administrative aspects are summarized in Table 4.10.

Component	Purpose/explanation
C3	Standard pneumatic control valve installed at the oil reject line in HC2
Feeding system from Section 4.2	Reservoir system, new feeding pump system and filtration technology
Three-phase bulk separator	Bulk separation of oil, water and gas
De-liquidizer	Separates liquid droplets from a gas stream
Phase-splitter	Bulk separation of liquid and gas at inlet gas volume fractions typically ranging from around 10 % to 90 %

Table 4.8: Key Components of Phase 3.

Design Parameters	
Max. liquid flow rate	5 m^3/h
Max. operational pressure	25 bar
Max. operational temperature	50 °C
Oil reservoir	Exxsol D140
Water reservoir	Freshwater + salt (up to 5 % NaCl)
Holding tank	5000 l
Oil tank	720 l
Material selection	AISI 316L
Wall thickness of pipes	SCH 10
Wall thickness of HC1	SCH 40
Wall thickness of HC2/HC3	SCH 10

Table 4.9: Design Parameters in the Final design of Phase 3

Administrative Summary	
Total investment cost	NOK 576,776 (See Section 6.4)
Total space of Phase 3 (estimate)	25 m^2

Table 4.10: Administrative summary of Phase 3.

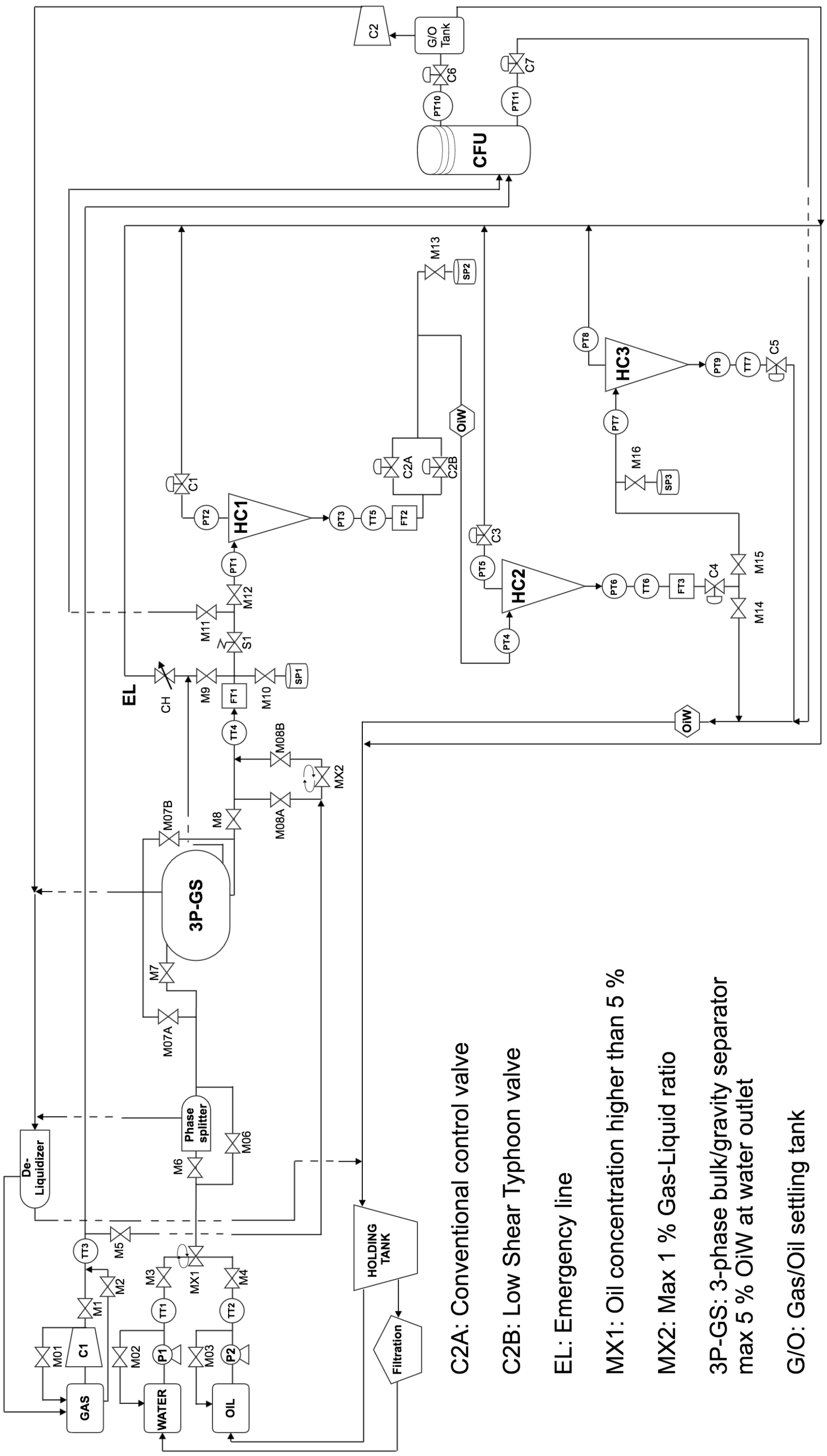


Figure 4.14: The Final design of Phase 3. Implementation of a new feeding pump system, a reservoir system, a bulk separator, a de-liquidizer, a phase-splitter and a second overflow control valve in HC2.

4.5 Phase 4

As mentioned in Section 4.4, Phase 3 completes the laboratory of a compact separation facility. Thus, Phase 4, as shown in Figure 4.16, is used to implement future developments. Since new technology is constantly developing it is hard to predict the precise scope of work for Phase 4, but process equipment like a Typhonix coalescing pump, a second low shear Typhoon control valve, a electrocoalescer, a heater or membrane filtration technology, might be alternatives to consider.

Considering the separation efficiency of the hydrocyclone setup, a Typhonix coalescing pump will be interesting to install between HC1 and HC2, as further explained in Section 3.4. A Typhonix coalescing pump has the ability to increase the oil droplet size within a given operational range (oil droplets size in the range of 5-15 μm), which will lead to a corresponding increase in the separation efficiency.

Since there will occur an oil droplet break-up and a pressure drop in HC1, the Typhonix coalescing pump could be installed in a by-pass to compare the total separation efficiency with and without a coalescing effect and pressure increase between HC1 and HC2. The potential pressure increase from implementing a Typhonix coalescing pump between HC1 and HC2 would also allow HC3 to be operated in the loop without investing in a new feeding pump system, as discussed in Chapter 3.12.2.

This will move the implementation of a Typhonix coalescing pump from Phase 4 to Phase 2, and as a consequence, involve an important project management process. In order to reach the right decision, the installation of the pump should also be seen in context with its relevance for a compact subsea separation facility. Because of the uncertainty regarding the implementation of the Typhonix coalescing pump, this equipment is not included in the CAD models of the hydrocyclone skid, as seen in Figures 4.7 and 4.8.

To further increase the separation efficiency, a second low shear Typhoon control valve (C4B) could be installed between HC2 and HC3 in parallel with a conventional control valve (C4A). As mentioned in Section 3.5, Mr. Husveg [VI] proposed to install a low shear Typhoon control valve between HC2 and HC3 since it might have a positive effect on the separation efficiency in order to further reduce the oil content below 30 ppm. As shown in Figure 4.15, a manual valve with flanges on both inlet and outlet is placed in parallel with the conventional control valve (C4A). The reason for this, is to have the opportunity to replace the manual valve with a low shear Typhoon control valve in the future. With extra funding, this implementation could be realized in an earlier phase.

An electrostatic coalescer will be interesting to implement in a buy-pass upstream of the bulk separator. The electrostatic coalescer could be included in the process if the liquid stream at the phase-splitter outlet is emulated to be oil continuous. The electrostatic coalescer uses electric fields to promote water-in-oil (WiO) droplet growth and emulsion breakdown to increase the separation efficiency in the bulk separator. The implementation of the remaining components proposed in Phase 4, a heater and membrane filtration, are described respectively in Section 2.6.2 and 2.8.

The future components proposed to be implemented in Phase 4 are summarized in Table 4.11, the design parameters are equal to Phase 3 and administrative aspects are summarized in Table 4.12.

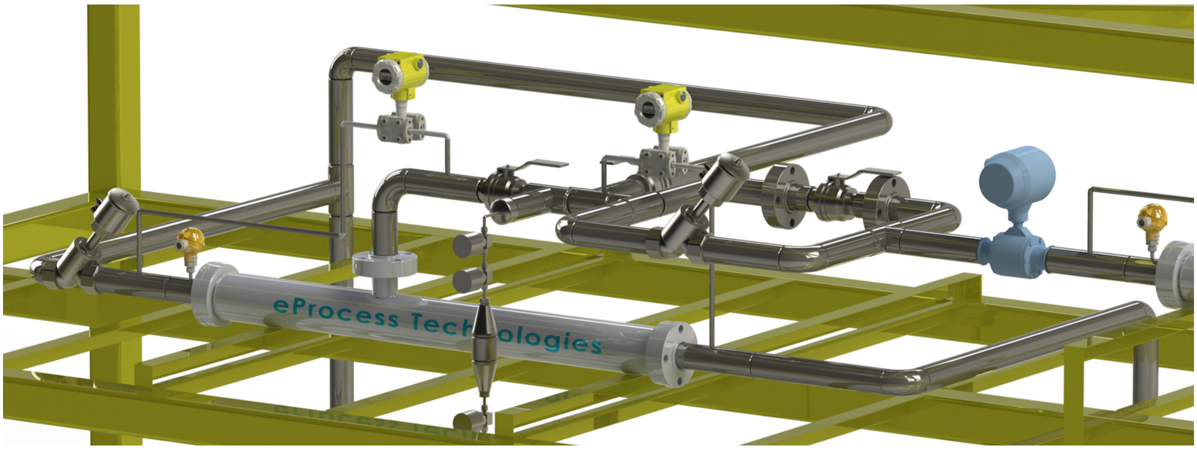


Figure 4.15: Illustration of a manual valve, with flanges on both inlet and outlet, placed in parallel with a conventional control valve. The Figure also illustrates HC3 installed in buy-pass.

Component	**Purpose/explanation**
C/C2A/C4A	Standard pneumatic control valve
C2B/C4B	Low shear Typhoon control valve
Electrostatic coalescer	Uses electric fields to promote water-in-oil droplet growth and emulsion breakdown to facilitate effective oil/water separation
Heater	Using heat to increase fluid temperature will decrease the water viscosity and thereby increase the separation efficiency
Membrane filtration	Filters placed downstream of the hydrocyclones will trap oil droplets and solids, ensuring water quality
Typhonix coalescing pump	These pumps can increase the oil droplet size and thus enhance separation efficiency. This would be placed between HC1 and HC2

Table 4.11: Key Components of Phase 4.

Administrative Summary	
Total investment cost	TBD
Total space of Phase 4 (estimate)	TBD m^2

Table 4.12: Administrative summary of Phase 4.

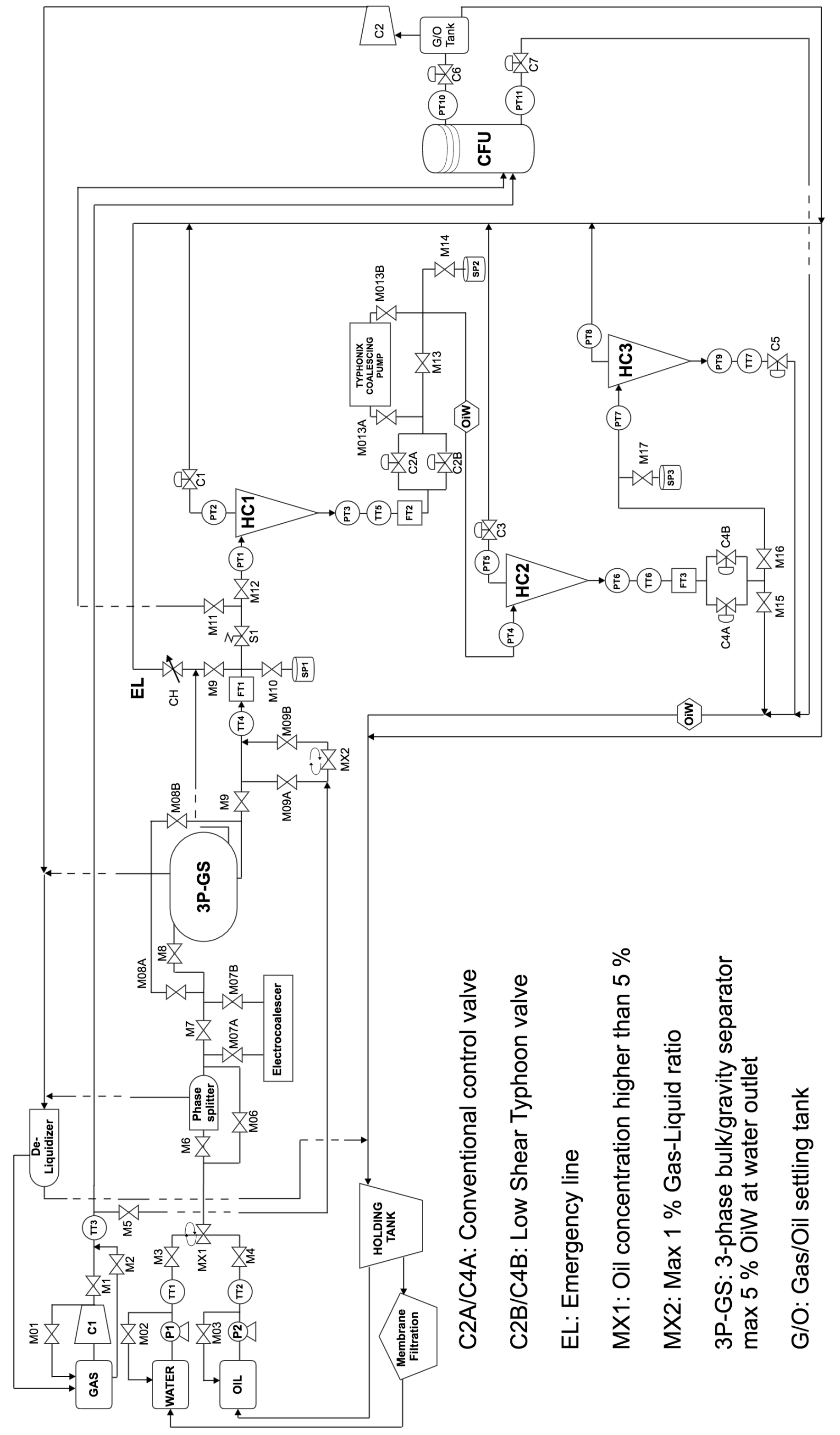


Figure 4.16: The Final design of Phase 4. Implementation of future concepts. A Typhonix coalescing pump and a second low shear Typhoon valve are included.

Chapter 5

Proposed Equipment

The final design involves a wide range of equipment and components, and besides the information found in Chapter 2 and 3, this Chapter summarizes the equipment for the compact separator design. Since Phase 2, 3 and 4 of the design are generally characterized by uncertainty with respect to technical details, only the components in Phase 1, the reservoir system and the pump feeding system have been included. The most important technical details of each component are listed, in addition to the suppliers.

Each of the equipments have been given a status equivalent to the design maturity of the component, in other words if the component is ready to be ordered or not. An overview of this status hierarchy is shown in Table 5.1.

Color	**Status**
Green	The equipment is ready to be ordered, and the technical details are checked according to the latest design updates. A supplier has delivered an offer on the equipment.
Yellow	The equipment is close to being ready for an order, but the technical details must be checked with the supplier and the latest design updates. A supplier may or may not have delivered an offer on the equipment.
Red	The equipment is not ready to be ordered, and should be discussed with the supplier according to the latest design updates and implementation in later phases.

Table 5.1: Status hierarchy.

All the suppliers, with relevant contact information, is listed in Appendix B. In the following subsections the equipment in Phase 1 are listed in alphabetic order.

5.1 Flowmeters

5.1.1 Coriolis flowmeter

The coriolis flowmeter Emerson F100S179CCAZNZZZZ in the F-series is manufactured and delivered by Emerson Process Management. The flowmeter will be placed upstream of HC1 and is able to measure both the flow rate and the fluid density at the inlet of the hydrocyclone. By measuring the fluid density, the oil concentration can be calculated indirectly. This calculation should be included in the control algorithm of the system. The flowmeter is delivered with a DN25 flange, and the pipe size must therefore be reduced to 1" before and after the flowmeter. A flowmeter with DN50 flanges, which fits 2" pipes, can be delivered at a higher cost and an increased lead time.

Status	Green
Model	Emerson F100S179CCAZNZZZZ
Supplier	Emerson Process Management
Material	AISI 316L
Density accuracy	2.0 kg/m^3
Mass flow accuracy	0.2 %
Pressure drop	0.04203
EX certified Zone 1	Yes

Table 5.2: Emerson coriolis flowmeter.

5.1.2 Magnetic flowmeter

The magnetic flowmeter Emerson 8705THA010CHM0K1B3Q4PD is manufactured and delivered by Emerson Process Management. There will be a total of two magnetic flowmeters, and the first will be placed between HC1 and HC2 and the second will be placed between HC2 and HC3. Both flowmeters will measure the flow rate and deliver information to help monitor and control the separation process. The flowmeters are delivered with DN25 flanges, and the pipe size must therefore be reduced to 1" before and after the flowmeter. Flowmeters with DN50 flanges, which fits 2" pipes, can be delivered at a higher cost and an increased lead time.

Status	Green
Model	Emerson 8705THA010CHM0K1B3Q4PD
Supplier	Emerson Process Management
Material	AISI 316L
Meter max flow	93.52 m^3/h
Meter min flow	0.08 m^3/h
EX certified Zone 1	Yes

Table 5.3: Emerson magnetic flowmeter.

5.2 Hydrocyclones

The deoiler DO15 hydrocyclone liners is manufactured and supplied by eProcess Technologies. The liners have been delivered to the Department of Production and Quality Engineering, and is ready for installation. In order to be installed, the hydrocyclone liners require a vessel housing which will be made in the department workshop. The Victaulic Clamps Type 1007 N can be bought from Victaulic [74]. Please see Section 3.11.1 for further information.

Status	Green – Delivered
Model	DO15
Supplier	eProcess Technologies
Flow rate	1.44 m^3/h – 4.53 m^3/h
Pressure drop range	1.38 bar – 13.8 bar
Material	ASTM A790 UNS S31803

Table 5.4: eProcess hydrocyclone liners.

5.3 Model oil and powder

The proposed synthetic model oil, Exxsol D140, is provided by Chemex, which has a Norwegian supplier based in Trondheim. The powder Oil Red O is manufactured by Alfa Aesar.

Status	Green
Model Oil	Exxsol D140
Supplier	Chemex
Powder	Oil Red O
Supplier	Alfa Aesar

Table 5.5: Model oil and powder.

5.4 OiW sensor

Which OiW sensor that will be installed depends on which supplier has the winning bid on the tender offer published in the Doffin database, as described in Section 3.7.3. The specific OiW sensor will have to fulfill the listed requirements in the requirement specification. This specification can be read in further detail in Appendix C. An important note is that most of the suppliers of OiW sensors have a lead time of 8–12 weeks from a order is placed until the sensor is delivered, and this should be taken into account in the construction process. As seen in Table 5.6, the status of the OiW sensor is listed as yellow. In this specific case, this means that the appropriate OiW technology have been selected, and the requirement specification is ready to be delivered to Astrid Solberg [XV] at the Department of Procurement to further determine which supplier who will manufacture the sensor.

For the installation of the OiW sensor it is especially important that the sensor is placed in a position where it will measure the flow as a homogeneous mix, since the sensor only typically will be placed 1" inside the pipe. As a result, the sensor must be placed after a bend, valve, or somewhere else where the flow will be turbulent and mixed.

Status	Yellow – Pending
Technical details	See Appendix C

Table 5.6: Proposed OiW Sensor.

5.5 Piping and steel frame - HC skid

The piping will be bought locally from the supplier Ahlsell. The piping will be manufactured in the material SCH 10 ASTM 312 TP 316L, which equals AISI 316 L, and is PN 40. The total pipe length and number of elbows, flanges and tees in Table 5.7 are based on the CAD model in Figure 4.8, and are only for the hydrocyclone skid in Phase 1. These numbers are the precise amount, and for the construction of the skid, it is recommended to invest in some additional meters of pipes in case of errors.

Status	Green
Supplier	Ahlsell
Material	SCH 10 ASTM 312 TP 316 L
Max Pressure	96 bar
Max temperature	50 °C
Total pipe length	31 m
Total short 90 ° elbows – radius 51 mm	23
Total long 90 ° elbows – radius 76 mm	5
Total number of tees	10
Total number of flanges	27
Price per meter	NOK 438

Table 5.7: Piping - HC skid.

The steel frame will also be bought locally from the steel supplier Smith Stål. The dimensions of the two equal steel frames of the HC skid are based on the CAD model in Figure 4.8.

Status	Green
Supplier	Smith Stål
Material	Carbon steel
Length	3.5 m
Width	2 m
Height	2.1 m

Table 5.8: Steel frame - HC skid.

5.6 Transmitters

5.6.1 Pressure transmitter

The pressure transmitter Apliens APR-2000 in the APR2000ALW-series is manufactured by Apliens and delivered by OEM Automatics. The transmitter is able to measure a differential pressure from 0 to 70 bar and is EX certified for operations in Zone 1.

Status	Green
Model	Apliens APR2000ALW
Supplier	OEM Automatics
Pressure range	0 – 70 bar
Output signal	4 – 20 mA
Supply voltage	12 – 55 V DC
EX certified Zone 1	Yes

Table 5.9: Apliens pressure transmitter.

The installation of the pressure transmitter can be done in a number of ways, but two of these have been recommended by OEM Automatics [28]. The first method is shown in Figure 5.1, where the pressure transmitter is delivered with two remote diaphragm seals. This requires two additional flanged connections in the pipe, and hence, this is an expensive alternative. The second method is to weld the capillary outlet directly to the pipe. This is the installation method with the lowest cost, and thereby the preferred method in this design due to a limited budget.

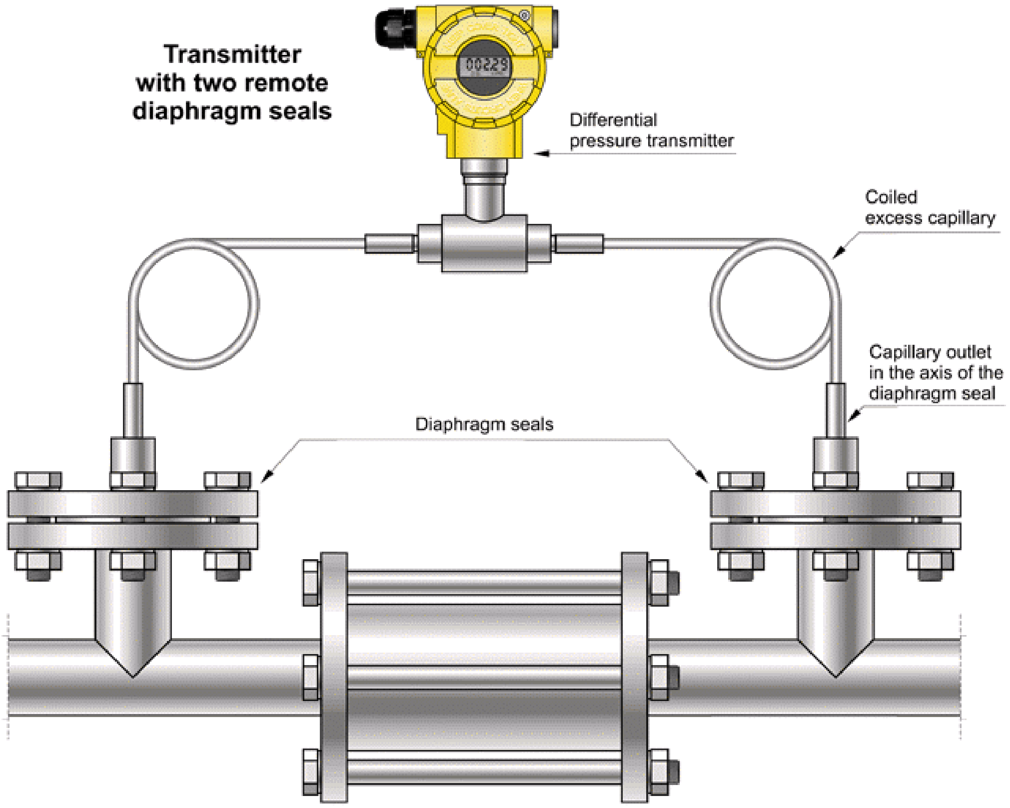


Figure 5.1: Installation of Apliens pressure transmitter [28].

5.6.2 Temperature transmitter

The pressure transmitter Apliens GB–00050050T in the CTGB1-series is manufactured by Apliens and delivered by OEM Automatics. The transmitter is able to measure a temperature from 0 to 75 °C and is EX certified for operations in Zone 1. The installation of the temperature transmitter should be done using the same method as for the pressure transmitters explained in Section 5.6.1, which means that the capillary outlet of the temperature transmitter should be welded directly to the pipe.

Status	Green
Model	Apliens GB–0050050T
Supplier	OEM Automatics
Temperature range	0 – 75 °C
Output signal	4 – 20 mA
Supply voltage	7.5 – 30 V DC
EX certified Zone 1	Yes

Table 5.10: Apliens temperature transmitter.

5.7 Valves

5.7.1 Ball valve

The Jun A3500 ball valve is manufactured by Jun and delivered by OEM Automatic. It will be installed in most positions where manual valves are needed. More specifically, this means valve M1, M2, M6 and M7 in Figure 4.1.

Status	Green
Model	Jun A3500
Supplier	OEM Automatic
Max pressure	69 bar
Material	AISI 316L
Dimension	2"
EX certified Zone 1	Yes

Table 5.11: Jun ball valve.

5.7.2 Mix valve

The mix valve Samson 3244 DN25PN40 1.4408 KVS10 is manufactured by Samson and delivered Matek. Based on calculations from the suppliers, the valve is delivered with 1" dimensions and must be installed with a reducer. 2" dimension valves could be delivered with an increase in price. It will be installed downstream of the feeding pumps and ensure a homogeneous multiphase flow of oil and water. This valve has a yellow status because an alternative solution would be to join the oil and water pipe together in a T-section. This would generate a turbulent flow where the two phases are mixed. The mix valve itself is ready to be ordered, but Mr. Holden [V] has the final word, as the mix valve represents a large cost in the budget.

Status	Yellow
Model	Samson 3244 DN25PN40
Supplier	Matek
Max pressure	40 bar
Material	AISI 316L
Output signal	4 – 20 mA
Dimension	1"
EX certified Zone 1	Yes

Table 5.12: Samson mix valve.

5.7.3 Control valve

The control valve Worcester V-Flow 20 is manufactured by Worcester and delivered by Sigum Fagerberg. It will be installed downstream of HC1, HC2 and HC3, as well as over each of the feeding pumps. The valve blend is adjustable in order to make assure efficient operation. This means that if the valve only performs effective control from 80 % to 90 % opening, the blend can be adjusted accordingly.

Status	Green
Model	Worcester V-Flow 20 DN 50
Supplier	Sigum Fagerberg
Max pressure	40 bar
Material	AISI 316L
Output signal	4 – 20 mA
Dimension	2"
EX certified Zone 1	Yes
Additional equipment	Delivered with pneumatic actuator and EX-certified positioner

Table 5.13: Worcester control valve.

The control valve Samson 3241 DN15PN40 1.4408 KVS1.6 is manufactured by Samson and delivered by Matek. It will be installed on the overflow line of HC1 in Phase 1, and possibly on the overflow line of HC2 in Phase 3, as described in Section 3.12.3. Based on calculations from the suppliers, the valve is delivered with 1" dimensions and must be installed with a reducer. 2" dimension valves could be delivered with an increase in price. This have been specifically delivered for small flow rates and pressures, as would be the case for the overflow line.

Status	Green
Model	Samson 3241 DN15PN40
Supplier	Matek
Max pressure	40 bar
Material	AISI 316L
Output signal	4 – 20 mA
Dimension	1"
EX certified Zone 1	Yes
Additional equipment	Delivered with pneumatic actuator and EX-certified positioner

Table 5.14: Samson control valve.

5.7.4 Safety valve

The safety valve is a combination of several components, all delivered by Sigum Fagerberg. The main valve, a FA4390 ball valve, will be placed on the EL line and will be closed in standby. A pressure guard, a Baumer ER2N L355, will be placed on the HC1 inlet, and if triggered, it will send a signal to a Namur IP65 magnet valve. The magnet valve will set the Gefa AP3 pneumatic actuator in an open position, and this will open the main valve and relief the pressure.

Status	Green
Model	FA4390 Ball valve
Model	Gefa AP3 pneumatic actuator
Model	Namur magnet valve IP65
Model	Baumer ER2N L355 Pressure guard
Supplier	Sigum Fagerberg
Max pressure	40 bar
Material	AISI 316L
Output signal	4 – 20 mA
Dimension	2"
EX certified Zone 1	Yes

Table 5.15: Worcester control valve.

5.7.5 Choke valve

The choke valve Samson 3241 DN15PN40 1.4408 KVS0.63 is manufactured by Samson and delivered by Matek. It will be installed on the emergency line EL, shown in Figure 4.1 to reduce the pressure at the main line to atmospheric pressure before the fluid enters the holding tank. The valve itself is very much alike the Samson control valve, but with a different valve seating, and therefore a different functionality.

Status	Green
Model	Samson 3241 DN15PN40
Supplier	Matek
Max pressure	40 bar
Material	AISI 316L
Output signal	4 – 20 mA
EX certified Zone 1	Yes
Additional equipment	Delivered with pneumatic actuator and EX-certified positioner

Table 5.16: Worcester control valve.

5.7.6 Sampling bombs

The sampling bomb system, also called sampling cylinders, are manufactured by Swagelok and delivered by Svafas. The system consists of a cylinder with a inlet valve, a vent valve, and an outlet valve. The sampling bomb system will be isolated from the main line by a Jun needle valve, manufactured by Jun and delivered by OEM Automatic. The sample outlet dimension is 1/4 ". The sampling bomb system is summarized in Table 5.17 and the needle valve is summarized in Table 5.18.

Status	Green
Model	Swagelok sampling bomb
Supplier	Svafas
Max pressure	124 bar
Material	AISI 316L
Volume	300 ml
Inlet dimension	1/4 "
EX certified Zone 1	Yes

Table 5.17: Swagelok sampling bomb.

Status	Green
Model	Jun N9300
Supplier	OEM Automatic
Max pressure	410 bar
Material	AISI 316L
Dimension	1/4 "
EX certified Zone 1	Yes

Table 5.18: Jun needle valve.

5.8 Reservoir System

In the following subsections the equipment in the reservoir system is listed in alphabetic order.

5.8.1 Filtration tank and filter patrons

The filtration solution is provided by Klart Vann AS [64]. As explained in Section 3.6.1, the solution contains two equal filtration tanks, as summarized in Table 5.19. The first filtration tank contains pre-filters, while the second filtration tank contains hydrocarbon/emulsion filters. The pre-filters are thread spun filtration patrons manufactured in polypropylene and summarized in Table 5.20. The hydrocarbon/emulsion filters are also manufactured in polypropylene, but in addition combined with patented MyClex-Technology, and summarized in Table 5.21

Status	Green
Model	4012055 7F0S3-316-2 inch
Supplier	Klart Vann AS
Capacity	35.64 m^3/h
Maximum differential pressure	10.3 bar at 149 °C
Material	AISI 316L
Number of patrons	7
Length of patrons	30 inches
Discount	25 %

Table 5.19: 4012055 7FOS3 - Filtration Tank [64].

Status	Green
Model	4012638 MS3O-PP-0.5
Supplier	Klart Vann AS
Capacity	0.36 m^3/h
Pressure drop clean patron	0.05 bar
Maximum temperature	60 °C
Material	Polypropylene (PP)
Diameter of patron	2.5 inches
Length of patron	30 inches
Filtration range	0.5 – 5 micron
Number of patrons per carton	15
Discount	40 %

Table 5.20: 4012638 MS3O-PP-0.5 Thread Spun - Filter Patron [64].

Status	Green
Model	4019963 30-HRM-5MY
Supplier	Klart Vann AS
Capacity	3.42 m^3/h
Pressure drop clean patron	0.07 bar
Maximum temperature	76 °C
Material	Polypropylene (PP) combined with MyCelx technology
Diameter of patron	2.75 inches
Length of patron	30 inches
Filtration range	$>$ 0.3 micron
Discount	40 %

Table 5.21: 4019963 30-HRM MyCelx - Filter Patron [64].

5.8.2 Oil skimmer

The oil skimmer Model Oil Grabber M8 is provided by QH-systems. The oil skimmer will separate the bulk amount of oil accumulating on the liquid surface in the holding tank. The metal element is 0.2 meter wide and operates with a capacity of removing 150 litre oil per hour.

Status	Green
Model	Model Oil Grabber M8
Supplier	QH Systems
Capacity	0.15 m^3/h

Table 5.22: Oil Skimmer - Model Oil Grabber M8.

5.8.3 Piping and steel frame - Reservoir system

The piping will be bought locally from the supplier Ahlsell. The piping will be manufactured in the material SCH 10 ASTM 312 TP 316L, which equals AISI 316 L, and is PN 40. The total pipe length and number of elbows, flanges and tees in Table 5.23 are based on the CAD model in Figure 4.9, and are only for the reservoir system in Phase 3. These numbers are therefore the precise amount, and for the construction, it is recommended to invest in some additional meters of pipes in case of errors.

Status	Green
Supplier	Ahlsell
Material	SCH 10 ASTM 312 TP 316 L
Max Pressure	96 bar
Max temperature	50 °C
Total pipe length	17 m
Total short 90 ° elbows – radius 51 mm	6
Total long 90 ° elbows – radius 76 mm	1
Total number of tees	1
Total number of flanges	38
Price per meter	NOK 438

Table 5.23: Piping - Reservoir system.

The steel frame will also be bought locally from the steel supplier Smith Stål. The dimensions of the steel frame of the reservoir system are based on the CAD model in Figure 4.9.

Status	Green
Supplier	Smith Stål
Material	Carbon steel
Length	6.85 m
Width	3.1 m
Height	3 m

Table 5.24: Steel frame - Reservoir system.

5.8.4 Submersible pump

The Tsurumi submersible pump is delivered by IKM testing and used to pump water from the dump reservoir into the IBC tanks. The pump will be submerged in the the dump reservoir. More information regarding the reservoir system can be found in Section 3.6.1.

Status	Green
Model	Tsurumi Pump LSC1.4S480W
Supplier	IKM Testing AS
Maximum Operational Pressure	1.1 bar
Maximum Operational Flow Rate	0.185 m^3/h
Normal Flow rate	0.038 m^3/h – 1 bar, 0.113 m^3/h – 0,6 bar, 0.17 m^3/h – 0.1 bar
Voltage Area	110/230 V 50 Hz 6.2/2.9 A

Table 5.25: Submersible pump - Tsurumi Pump LSC1.4S480W.

5.8.5 Tanks

The holding tank Flexitank V 5000 BT and the oil tank PE kombi 720 l are provided by Vera Tank AS [78]. The IBC tanks are provided by Witre [79].

Status	Green
Model	Flexitank V 5000 BT
Supplier	Vera Tank AS
Capacity	5000 l
Diameter and Height	2.12 m and 2.3 m
Weight	282 kg

Table 5.26: Holding Tank - Flexitank V 5000 BT [78].

Status	Green
Model	PE Kombi 720 l
Supplier	Vera Tank AS
Capacity	720 l
Length, Width and Height	1.1 m, 0.7 m and 1.2 m
Weight	68 kg

Table 5.27: Oil Tank - PE Kombi 720 l [78].

Status	Green
Model	IBC Container 1000 l
Supplier	Witre
Capacity	1000 l
Length and Width	1.2 m and 1 m

Table 5.28: IBC Container 1000 l [79].

5.9 Pump Feeding System

In order to be able to deliver a oil concentration between 1–5 %, and a oil concentration up to 50 % when the new feeding system is implemented, the oil pump feeding system had to include two pumps in parallel. This is because no single oil pump was able to deliver within the full spectre of the flow range, from 0.045 m^3/h to 3 m^3/h, at the operational pressure with sufficient accuracy. Both the oil feeding pumps and the water feeding pump have a status marked as red. The main reason for this is that the maximum operational pressure of the pumps is 20 bar, and not 25 bar as the system is designed for with PN 40 and a safety factor of 1.6. Since the installation of the new pump feeding system has been moved to a later phase, as described in Section 3.12, the pressure loss in the system at the future time must be taken into account when ordering the pumps. As it is unnecessary to use the suppliers time when the actual order might be several years in the future, the supplier Norsk Pumpeteknikk AS was not contacted for an additional offer on feeding pumps that can deliver a pressure of 25 bar. The pumps in Section 5.9.1, 5.9.2 and 5.9.4 will however serve as a good overview for cost and technical specifications.

In the following subsections the equipment in the pump feeding system is listed in alphabetic order.

5.9.1 Oil feeding pump 1

The first oil feeding pump is manufactured by Seepex and delivered by Norsk Pumpeteknikk AS. This is a progressive cavity, and could be used to deliver an oil flow rate in the large end of the flow range with the operational pressure of 20 bar.

Status	Red
Model	Seepx BN 5 - 12V
Supplier	Norsk Pumpeteknikk AS
Maximum Operational Pressure	20 bar
Maximum Operational Flow Rate	3 m^3/h
Normal Flow rate Capacity	0.53 m^3/h – 20 bar, 3 m^3/h – 20 bar
Voltage Area	400/690 V 50 Hz
Material	AISI 316L

Table 5.29: Oil Feeding Pump 1 - Seepx BN 5 - 12V.

5.9.2 Oil feeding pump 2

The second oil feeding pump is also manufactured by Seepex and delivered by Norsk Pumpeteknikk AS. This is a progressive cavity, and could be used to deliver an oil flow rate in the small end of the flow range with the operational pressure of 20 bar.

Status	Red
Model	Seepx BN 05 - 24
Supplier	Norsk Pumpeteknikk AS
Maximum Operational Pressure	20 bar
Maximum Operational Flow Rate	0.53 m^3/h
Normal Flow rate Capacity	0.045 m^3/h – 20 bar, 0.53 m^3/h – 20 bar
Voltage Area	230/400 V 50 Hz
Material	AISI 316L

Table 5.30: Oil Feeding Pump 2 - Seepx BN 05 - 24.

5.9.3 Piping and steel frame - Pump feeding system

The piping will be bought locally from the supplier Ahlsell. The piping will be manufactured in the material SCH 10 ASTM 312 TP 316L, which equals AISI 316 L, and is PN 40. The total pipe length and number of elbows, flanges and tees in Table 5.31 are based on the CAD model in Figure 4.10, and are only for the pump feeding system in Phase 3. These numbers are therefore the precise amount, and for the construction, it is recommended to invest in some additional meters of pipes in case of errors.

Status	Green
Supplier	Ahlsell
Material	SCH 10 ASTM 312 TP 316 L
Max Pressure	96 bar
Max temperature	50 °C
Total pipe length	12 m
Total short 90 ° elbows – radius 51 mm	15
Total number of tees	6
Total number of flanges	12
Price per meter	438 NOK

Table 5.31: Piping - Pump feeding system.

The steel frame will also be bought locally from the steel supplier Smith Stål. The dimensions of the steel frame of the pump feeding system are based on the CAD model in Figure 4.10.

Status	Green
Supplier	Smith Stål
Material	Carbon steel
Length	3 m
Width	1.5 m
Height	1 m

Table 5.32: Steel frame - Pump feeding system.

5.9.4 Water feeding pump

The water feeding pump is manufactured by Shanley Pump and Equipment [80] and delivered by Norsk Pumpeteknikk AS. This is a high-pressure multistage centrifugal booster pump which uses multistage design of multiple impellers to increase the pressure. [80]

Status	Red
Model	EDUR LBU 407 A142L / 11,0 KW
Supplier	Norsk Pumpeteknikk AS
Maximum Operational Pressure	20 bar
Maximum Operational Flow Rate	5 m^3/h
Voltage Area	230/400 V 50 Hz
Material	AISI 316L

Table 5.33: Water Feeding Pump - EDUR LBU 407 A142L.

Chapter 6

Budget

The objectives in Section 1.3 states the need for a detailed budget and vendor selection. The budget has been a continuous process since the start of the project, and have been updated several times as a consequence of changes to the the design or updated offers from vendors. As the vendors consider the individual offers to be confidential, the detailed budget will not be a part of this thesis. Instead, the different equipment in each phase will be presented in categories. The detailed budget has been given to Mr. Holden [V], and for that reason a more detailed budget insight could be given with his approval. Phase 4 is not included in the budget due to the uncertainty related to this phase. The vendors are listed in Chapter 5. All costs are listed in Norwegian kroner (NOK).

6.1 Budget Phase 1

The budget overview for Phase 1 is divided into five sub categories. Each of the sub categories contains the following.

Hydrocyclone: Hydrocyclone liners and vessel housing.
Instrumentation: OiW sensors, flowmeters, pressure transmitters and temperature transmitters.
Valves: Control valves, low shear valve, manual valves and sampling bombs.
Additional: Steel for frame, piping, welding operators and oil for operational use.
Shipping: Total shipping cost for the equipment.

Equipment	**Cost (no VAT)**	**VAT**	**Total cost**
Hydrocyclone	NOK 36,000	NOK 9,000	NOK 45,000
Instrumentation	NOK 943,371	NOK 236,430	NOK 1,183,801
Valves	NOK 510,799	NOK 127,700	NOK 638,499
Additional	NOK 77,129	NOK 19,282	NOK 96,412
Shipping	NOK 10,000	–	NOK 10,000
Total cost Phase 1			NOK 1,974,123

Table 6.1: Budget overview for the final design of Phase 1.

6.2 Budget Reservoir System

The budget overview for the Reservoir System is divided into two sub categories. Each of the sub categories contains the following.

Reservoir system: Tanks, drainage pumps, filters and valves.
Shipping: Total shipping cost for the equipment.

Equipment	**Cost (no VAT)**	**VAT**	**Total cost**
Reservoir system	NOK 155,840	NOK 38,960	NOK 194,800
Shipping	NOK 10,450	–	NOK 10,450
Total cost Reservoir System			NOK 205,250

Table 6.2: Budget overview for the final design of the Reservoir system.

6.3 Budget Phase 2

The budget overview for Phase 2 is divided into five sub categories. Each of the sub categories contains the following.

Main components: CFU, compressors and pressure tanks.
Instrumentation: Pressure transmitters, manometers and temperature transmitters.
Valves: Control valves and manual valves.
Additional: Piping and welding operators.
Shipping: Total shipping cost for the equipment.

Equipment	**Cost (no VAT)**	**VAT**	**Total cost**
Main components	NOK 58,887	NOK 12,222	NOK 71,109
Instrumentation	NOK 22,486	NOK 5,622	NOK 28,108
Valves	NOK 55,856	NOK 13,964	NOK 69,820
Additional	NOK 20,760	NOK 5,190	NOK 25,950
Shipping	NOK 4,000	–	NOK 4,000
Total cost Phase 2			NOK 198,986

Table 6.3: Budget overview for the proposed design of Phase 2.

6.4 Budget Phase 3

The budget overview for Phase 3 is divided into four sub categories. Instrumentation has not been included because of the uncertainty related to this phase. Each of the sub categories contains the following.

Main components: Feeding pumps, phase-splitter, de-liquidizer and gravity separator.
Valves: Control valves and manual valves.
Additional: Steel for frame, piping, welding operators and oil for operational use.
Shipping: Total shipping cost for the equipment.

Equipment	**Cost (no VAT)**	**VAT**	**Total cost**
Main components	NOK 356,590	NOK 76,648	NOK 433,238
Valves	NOK 38,197	NOK 9,549	NOK 47,746
Additional	NOK 64,633	NOK 16,158	NOK 80,792
Shipping	NOK 6,000	–	NOK 6,000
Total cost Phase 3			NOK 576,776

Table 6.4: Budget overview for the proposed design of Phase 3.

6.5 Budget Overview

The cost of each phase is summarized, and presented in Table 6.5. Rental costs will be sponsored by the Department of Production and Quality Engineering, thus not included in the budget.

Total cost of project	NOK 2,955,135
Available funds	NOK 3,000,000
Unforeseen modifications	NOK 44,865
Economical safety margin	1.50 %

Table 6.5: Budget overview for all phases combined.

Chapter 7

Health, Safety and Environment (HSE)

Safety has been addressed in every aspect of the design. From the start of the design process January 15th 2016, until the end June 10th 2016, safety has been an underlying policy for the entire design. This has been manifested through the NTNU safety factor of 1.6 [V], which has been included in all process equipment. The conformity assessment for pressurized equipment, set by DSB [10], has also been used as a guideline for the safety in general. This assessment includes a large set of guidelines and rules for pressurized vessels and pipes, and is regarded as the most relevant assessment for pressurized equipment in Norway, as DSB sets the national quality demands. According to §25 and §26 in "Regulation for pressurized equipment" an inspection of the pressurized equipment must be conducted by one of the following companies in order to acquire an official approval for operation of the laboratory.

- DNV GL AS
- Inspecta AS
- Teknologisk Institutt AS

However, based on §27 in the same document a dispensation can be given if the pressurized equipment is used in connection to operations with experimental interest. §27 states the following (Translated from Norwegian):

> "*The supervising authority may, when it is justified, allow for the usage and marketing of pressurised equipment described in §3 within Norway, independent of the provisions in §§25 and 26, and even if the procedures have not been applied, if the usage is of experimental interest.*"

Based on the fact that the compact separation laboratory is designed with the sole purpose of conducting experiments for the acceleration of innovation within subsea technology, an application for dispensation has been sent to DSB in order, in virtue of §27, to be exempted from a formal inspection and approval. The main reason for this is limited economical resources, since such an inspection would include a considerable cost. The continuous inspection of the design from professionals in the industry, as well as all the partners in SUBPRO, the design is considered safe [V]. However, if additional resources are awarded in close future, one of the priorities should be a formal inspection before the operation of the laboratory starts. The application, written in Norwegian, is included in Appendix E.

In accordance with NTNUs regulations for laboratory work, a comprehensive risk assessment has been conducted. This assessment is divided into two parts, one assessment for the construction of the laboratory and one assessment for the operation of the laboratory. All risks have been assessed and corrective actions have been suggested and assigned to responsible personnel, which in this case is mainly Mr. Holden [V]. This risk assessment is included in Appendix H. This assessment is, however, written in Norwegian, due to the NTNU standard.

Based on the input from Mrs. Mogseth [XII], a Hazard and Operability (HAZOP) study of the laboratory was considered. The HAZOP would analyse many of the same aspects as the risk assessment that has been conducted, but based on consultation with Mr. Holden [V] the HAZOP will be more relevant when the laboratory has been constructed. This is because the total HSE aspect can be analysed more thoroughly when the final location of the laboratory is decided, as surrounding equipment and installations may affect the HSE.

Chapter 8

Conclusion and Recommendations

Given the complex production challenges and environmental focus seen in the current oil and gas industry, produced water treatment (PWT) and compact separation technology are two of the key enablers for the further development of subsea technology. With respect to the number of currently operating installations, subsea separation technology still have a long way to go compared to other segments in subsea processing technology [6]. Given the fact that traditional gravity based separation designs are limited by their massive size and low flexibility, the oil and gas industry have expressed an interest for subsea compact separation.

The industry partners in SUBPRO are particularly interested in hydrocyclones, and the operational issues with transient flow related to this compact design. The Marlim SSAO is currently the only operating subsea separator utilizing deoiling hydrocyclones. Based on the current operational issues related to transient flow, the industry has identified a need for improved process control of a multi-stage hydrocyclone setup. The compact separation laboratory design in this Master's thesis comes as a consequence of this need.

8.1 Conclusion

This Master's thesis has aimed to design a compact separation laboratory which is able to facilitate research on novel control algorithms that could be implemented in future subsea installations. The compact separation laboratory will focus on PWT, and use a multi-stage hydrocyclone system for partial processing. Partial processing is favorable in applications with high oil content (1-5 %) in the produced water stream because a single stage hydrocyclone system will not be able to handle the high oil content.

The design has been divided in four phases, and this thesis has mainly focused on the detailed design of Phase 1. However, future proofing for the implementation of the future phases have been an important aspect of the thesis. In order to increase flexibility for each of the phases, both individually and combined, the phases are designed in modular skids. This allows for easy relocation, as well as increasing maintainability of each skid, due to a decreased internal technical dependency for the four phases combined. It also enables Phase 1 to be connected to the Cameron feeding system. This allows for overall testing of the system setup, before a potential investment decision concerning a new feeding system is taken.

Phase 1 has been divided in two sub skids, which simplifies transport of the skids to external locations. This is of interest because external laboratories may provide additional functionality that could be implemented or coupled with Phase 1. An example is SINTEF's laboratory facilities at Tiller, which will allow for testing with crude oils. This will increase the credibility of the future experimental results. In order to enable a potential cooperation with SINTEF's laboratory facilities, Phase 1 has been designed with EX certified components.

A key component in the design of Phase 1, both with respect to cost and the future implementation of novel control algorithms, is the OiW sensor. The OiW sensor will constantly measure the OiW content and allow for feed forward and adaptive control algorithms. Combined with low shear process equipment, this represents an innovative setup for a PWT process that have the potential to facilitate experiments that are of great interest for the oil and gas industry.

The design schematic of Phase 1 is shown in Figure 4.1, the 3D model is shown in Figure 4.8, the key components are summarized in Table 4.1 and the design parameters are summarized in Table 4.2.

The system is currently designed as a closed loop. If the closed loop proves to be a problem in Phase 1, a new feeding system should be taken into consideration. The Cameron feeding system provides no filtration technology, and this could be a potential problem with respect to build up of small oil droplets that will degrade the system performance over time. Another issue is the maximum operational pressure of 10 bar. This will have to be increased in order to include the third hydrocyclone stage in experiments. For that reason, a feeding system and a reservoir system have been designed, in order to facilitate for fast implementation if required. The feeding pumps of this system must be evaluated according to the learnings from Phase 1. The 3D models of the proposed feeding system is shown in Figures 4.9 and 4.10, and the key components are summarized in Table 4.4.

The main focus in Phase 2 of the laboratory is to introduce gas to the system and the implementation of a CFU installed in parallel with the hydrocyclone setup. This provides the opportunity to compare the separation results between several hydrocyclones in series and a CFU, which will be of great interest for the industry. The design schematic of Phase 2 is shown in Figure 4.12, the key components are summarized in Table 4.6 and the design parameters are equal to Phase 1.

Phase 3 will emulate the entire value chain for a PWT subsystem of a small scale compact separation facility. In Phase 3, a bulk separator concept developed at NTNU will be installed upstream of the hydrocyclone setup and the CFU. A phase-splitter will be installed upstream of the bulk separator and act as a bulk gas–liquid separator. Phase 3 will allow for an increased oil concentration. The design schematic of Phase 3 is shown in Figure 4.14, the key components in Phase 3 are summarized in Table 4.8 and the design parameters are summarized in Table 4.9.

Phase 4 will implement future concepts. The scope of this phase is hard to predict because new technology is constantly developed. A Typhonix coalescing pump will be interesting to install between HC1 and HC2. This pump has the ability to increase the oil droplet size within a given operational range. However, the installation of the pump should be seen in context with its relevance for a compact subsea separation facility. The design schematic of Phase 4 is shown in Figure 4.16, the key components in Phase 4 are summarized in Table 4.11 and the design parameters are equal to Phase 3.

The safety aspect has been involved in every part of the design process. An emergency line has been included in order to avoid pressure build up, and a safety factor of 1.6 is included in all process equipment. DSB guidelines have been followed, and a NTNU standardized risk assessment have been conducted. A HAZOP study should be carried out when the construction of the laboratory is finished.

The overall design is kept within the budget of NOK 3,000,000 with a safety margin of 1.50 %. Because of the uncertainty related to Phase 4, this phase has not been included in the budget. The total budget overview is shown in Table 6.5.

8.2 Discussion

This design has focused on a combination of innovation and relevance for the industry. Trough continuous contact with suppliers and operators the authors have tried to identify the current practises and state of the art solutions, as well as the potential next steps for subsea technology. OiW sensors and control valves are two examples of technology that is currently not included in subsea installations, but could be a part of future technology if the suppliers have an incentive to develop this functionality. The future experimental results from this laboratory could potentially be such an incentive, and is one of the reasons why the laboratory implements equipment which is currently not installed at the seabed. The relevance of this equipment is based on the authors best knowledge, consultation with industry professionals and input from Mr. Holden [V] and Mr .Ohrem [XIII].

Besides the technical aspect of the thesis, one of the main learnings have been the level of bureaucracy needed to develop the design. Requirements, guidelines and standards set by both NTNU and the industrial partners in SUBPRO have constituted additional work that is typically not reflected upon in this thesis. Examples of this work is a preliminary report that have been delivered to the industry partners, and the tender process for the OiW sensors. For the person that is to continue working on the construction of this laboratory, it is important to be aware that these processes might be tedious and should be initiated as early as possible.

The design has been based on 2" pipes. This was mainly due to the fact that the University of Aalborg Campus Esbjerg has used 2" pipes for their design. Except from slightly higher operational pressure and flow rate, the parameters for the compact separation laboratory are quite similar to the laboratory at the University of Aalborg, and the decision of using the same pipe dimensions was made at an early point in the design process. At a later point, some of the equipment suppliers pointed out that a 1.5" pipe dimension would have been sufficient. A smaller pipe dimension could potentially have made a small positive impact on the total cost of the laboratory design. However, the equipment suppliers did also point out that 2" pipes would not be a problem. This has been quality checked with Bernoulli calculations and consulted with Mr Rawlins [XIV].

The economical boundaries of this project, set by SUBPRO, have been challenging with respect to future proofing of the design. Especially since the development of the later phases depends on the results from Phase 1, it has been difficult to estimate the amount of resources that have to be assigned to these phases. To first invest in the construction of Phase 1, and save the remaining economical resources until the learnings from Phase 1 can be implemented in the project management of the later phases, acts as a safety barrier towards making poor equipment investments.

8.3 Recommendations for Further Work

Even though the design of the compact separator laboratory is completed in this Master's thesis, there is still a lot of work to be done before the laboratory is operational. The further work is divided into short-term, medium-term and long-term perspectives as elaborated below.

In this context short-term means the next steps of the process, and should be started as soon as possible. Medium term means within the next two years, and long term means within a period of 3 to 4 years.

Short-term

The first step is to start ordering equipment. As explained in Chapter 5, all equipment have been given a status, and contact information for the different suppliers are listed in Appendix B.

Regarding the purchase of an online OiW sensor, a tender offer must be listed in the Doffin database. The requirement specification is shown in Appendix C. A sample of 30 ml Exxsol D140 have be sent to both ProAnalysis and Advanced Sensors to confirm that the LIF technology is able to make reliable OiW measurements. This is, however, still not confirmed, and should be taken into account before the tender offer is sent to the Department of Procurement at NTNU.

The next step is to start the construction of the hydrocyclone skid. This has to be carefully planed and will be performed by future projects and Master's thesis', starting Fall 2016. In this Master's thesis a 3D model has been created, and it will be of great importance in the construction process. The electrical system will also be a subject for further work during the construction process. The construction of the vessel housing for the hydrocyclone liners have been discussed with the workshop at the Department of Production and Quality Engineering, and workshop manager Arild Saether have agreed to help. However, the application for dispensation, described in Section 7, must be approved before this construction can start.

When the construction and the electrical system of the hydrocyclone skid is completed, the next step will be to connect with the Cameron feeding system. This will allow testing of the overall system setup. In the testing process the laboratory should include hydraulic tests (i.e. water only) to balance pressures, valves, flows, etc. before any oil is introduced.

Medium-term

The experience and knowledge acquired from Phase 1 will serve as a foundation for updating and optimizing the design and construction of the future phases. This will also be performed by future project and Master's thesis'. The potential implementation of a CFU, a new feeding pump system and a new reservoir system should be seen in context with the learnings from Phase 1.

Long-term

The long-term perspective of future work is the completion of a small scale compact separation facility. To emulate the entire value chain for a PWT subsystem, a bulk separator concept will have to be installed upstream the hydrocyclone setup and the potential CFU. A Typhonix coalescing pump and a second low shear Typhoon control valve are equipments that will be interesting to include in the complete compact separator laboratory.

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Appendices

Appendix A

Oral Sources of Information

This thesis has had the privilege of receiving input from several professionals with extensive knowledge of the oil and gas industry, here listed in alphabetic order.

I Friis-Eriksen, Thomas [Chemist & Sales Engineer, ProAnalysis]

II Gransaether, Eivind [CEO, Mirmorax]

III Hempsey, Russel [Business Development Manager, Advanced Sensors]

IV Henriksen, Arne [Principal Researcher, Statoil]

V Holden, Christian [Associate Professor and Supervisor, Norwegian University of Science and Technology]

VI Husveg, Trygve [Technology Manager, Typhonix]

VII Kjeldsberg, Rune [Salesman, Industry and Construction, Ahlsell]

VIII Kjærland, Geir [CEO, Klart Vann AS]

IX Kaasboell, Edgar [Transport Manager, NTNU Operations]

X Krogh, Espen [Research Scientist, SINTEF]

XI Kvamsdal, Dag [CEO Gas Liquid Separation, Cameron]

XII Mogseth, Gro [Technical Coordinator SUBPRO, NTNU]

XIII Ohrem, Sveinung Johan [PhD Candidate, NTNU]

XIV Rawlins, Hank [Director, eProcess Technologies]

XV Solberg, Astrid [Advisor, Department of Procurements]

XVI Tesaker, Geir [Engineer, NTNU]

Appendix B

Equipment Suppliers

The following overview lists all the suppliers that have been contacted in this thesis.

Equipment	Company	Norwegian Distributor	Contact Person	Web Site	Contact Information
OiW Sensor	Advanced Sensors	Norsk Analyse AS	Morten Myhre Andersen	www.norskanalyse.no	morten.myhre.andersen@norskanalyse.no
	Jorin Limited	Jorin Limited	Nick Roth	www.jorin.co.uk	nick@jorin.co.uk
	Mirmorax	Mirmorax	Eivind Gransaether	www.mirmorax.com	mbl@mirmorax.com
	Industrial Tomography Systems	-	Ricardo Cardoso	www.itoms.com	ricardo.cardoso@itoms.com
	Pro Analysis	Pro Analysis	Thomas Eriksen	www.oilinwater.com	eriksen@proanalysis.com
Feeding Pump System	PCM	Pumpeteknikk AS	Andy Boot	www.pcm.eu	aboot@pcm.eu
	Pumpeteknikk	Pumpeteknikk AS	Joacim Elgaaen Kristiansen	www.pumpeteknikk.as	je@pumpeteknikk.as
Coalescing Pump	Typhonix	Typhonix	Trygve Husveg	www.typhonix.com	trygve.husveg@typhonix.com
Flow Meter	Emerson	Emerson	Jan-Inge Bjerkely	www.emerson.com	jan-inge.bjerkely@emerson.com
	Agar Corporation	-	Daniel Menghi	www.agarcorp.com	daniel.menghi@agarcorp.com
	Siemens	Siemens	Sean Roy Easter	www.buildingtechnologies.siemens.com	sean-roy.easter@siemens.com
Valves	OEM Automatic	OEM Automatic	Jan Kristian Jansen	www.oem.no	jankristian.jansen@oem.no
	Sigum Fagerberg	Sigum Fagerberg	Tommy Tinbod	www.sigumfagerberg.no	tti@sifag.no
	Øvre-Johnsen AS	Øvre-Johnsen AS	Ole M.R. Roeste	www.owre-johnsen.no	ole@owre-johnsen.no
	Matek-Samson Regulering AS	Matek-Samson Regulering AS	Eli-Marie Wold Sundt	www.matek.no	eli-marie@matek.no
	Hydex Systemhydraulikk	Hydex Systemhydraulikk	Stein Ove Haugnes	www.systemhydraulikk.no	steinove@hydex.no
Low Shear Valve	Mokveld	Typhonix	Trygve Husveg	www.typhonix.com	trygve.husveg@typhonix.com
Hydrocyclone	eProcess Technologies	-	Hank Rawlins	www.eprocess-int.com	h-rawlins@eprocess-tech.com
Pressure transmitters	OEM Automatic	OEM Automatic	Kjetil Gulliksrud	www.oem.no	kjetil.gulliksrud@oem.no
Temperature transmitters	OEM Automatic	OEM Automatic	Kjetil Gulliksrud	www.oem.no	kjetil.gulliksrud@oem.no
Oil Skimmer	QH System	-	Daniel Edlander	www.qh-system.se	daniel@qh-system.com
Pipes	Ahlsell	Ahlsell	Rune Kjeldsberg	www.ahlsell.no	rune.kjeldsberg@ahlsell.no
Steel for frame	Smith Staal	Smith Staal	-	www.smith.no	72 59 24 00
Water reservoir tanks	Witre	Witre	Ellen Andreassen	www.witre.no	ellen.andreassen@witre.no
Holding tank/oil tank	Vera Tank	Vera Tank	Hans Christian Trollsås	www.veratank.no	hct@veratank.no
Submersible water pump	IKM	IKM	Tom Idar Aabogen	www.ikm.com	tomidar.aabogen@ikm.no
Model oil Exxsol D140	Chemex	Chemex	Jan P. Petersen	www.chemex.dk	jpp@chemex.dk
Welding personell	M-Tech	M-Tech	-	www.m-tech.trondheim.no	72554020
Procurement Process	NTNU	NTNU	Astrid Solberg	www.svafas.no	astrid.solberg@ntnu.no
Swagelok sampling cylinder	Swagelok	Svafas	Ole Richard Bødkter	ole.richard.bodtker@svafas.no	ole.richard.bodtker@svafas.no

Appendix C

Buyer's Requirement Specification to an Online Oil-in-Water (OiW) Sensor

The following document is the requirement specification for the OiW tender offer. This must be delivered to the Department of Procurement.

Buyer’s requirement specification to an online oil-in-water (OiW) sensor

1 Purpose of the procurement

There exist many different technologies for making online OiW measurements, with related pros and cons. The objective of this procurement is to choose the most reliable and suitable online OiW sensor for the compact separation laboratory at the Department of Production and Quality Engineering at the Norwegian University of Science and Technology (NTNU). The purpose of the online OiW sensor is to measure the purity level of a simulated produced water stream, and utilize this measurement to achieve appropriate feedback control of several deoiling hydrocyclone liners in series.

The online OiW sensor to be acquired in this specification needs to operate as an in-line instrument, meaning that it can be inserted directly into the produced water stream. In addition it will need to have the possibility for an automatic self-cleaning system.

2 The content and scope of the procurement

The procurement is for for a monitoring system that is to be implemented in a compact separation setup, with online, real-time measurement of OiW concentration as its main task. The system aims to handle flow irregularities (slugs etc.) with dynamic control, and the OiW sensor is one of the key components to quality check the integration of the control system. As a result of the rapid dynamics in hydrocyclone separation, which results in a very short residence time, it is of great interest that the OiW sensor is capable to operate with a low sampling time. A low sampling time will be the main focus for a potential OiW sensor, however, it must also comply with the demands regarding in-line placement, automatic self-cleaning system, and an analyzer with the appropriate output.

The equipment shall be possible to operate by personnel within the buyer’s organization, including simple maintenance tasks, with simple training and normally without need of assistance from the supplier. In addition, the supplier shall have a customer support, for technical questions and maintenance services, available online and at site on request.

3 Requirements for documentation, information requirements etc.

Delivery will follow:

- Documentation from the producer:
    - Sensor units
    - Data processing and storage units
    - Operator stations/visual display
    - Internal communication
- User manual and technical procedures for operating the system, both software and hardware.
- Warranty in months from accepted delivery/system handover. (Minimum 9 month’s)

4 Training

The online OiW sensor shall be possible to operate by personnel within the buyer’s organization, including simple maintenance tasks, with simple training and normally without need of assistance from the supplier. Necessary familiarization and training on how to use the equipment and to maintain it should be quoted. In addition, the supplier shall have a customer support, for technical questions and maintenance services, available online and at site on request.

5 Table of requirements

The requirements in the table of requirements form the basis for the Supplier’s description of its solution specification. The Supplier must give an extensive description of all requirements so that the Parties will have a common understanding of what is to be delivered, or which can give the Buyer alternative perspectives to the requirements expressed in the Buyer’s requirements specification.

The different requirements have different priority.

Priority A =	Absolute requirements that must be fulfilled. Tenders that do not fulfill all the absolute requirements will be rejected.
Priority B =	Important requirements that should be fulfilled, but it is not an absolute requirement. Answers will be of great importance for the evaluation of the tender. The requirements are weighted higher than C-requirements.
Priority C =	Conditional requirements that should be fulfilled, but it is not an absolute requirement. Answers will be of importance for the evaluation of the tender. The requirements are weighted lower than B-requirements.

When filling out the table of requirements the Supplier shall mark an (X) in the column for yes, partly or no under "the Supplier's fulfillment". Reference to relevant documentation and any additional comments shall be made in the column "Comment". It is reminded that it is the duty of the Supplier to document that it fulfills the set requirements. Any missing documentation will result in the requirement being considered as not fulfilled.

Requirement no.	Priority	Description	The Supplier's fulfillment			Comment
			Yes	Partly	No	
1		**Online OiW sensor**				
1.1	A	In-line probe.				
1.1.1	B	Two probes connected to one analyzer.				
1.1.2	A	Online measurements.				
1.2	A	Automatic self-cleaning system.				
1.2.1	B	Possible to retrofit probe with automatic self-cleaning system.				
1.3	A	Oil Concentration Range [ppm] 0 – 3000.				
1.3.1	B	Must maintain an repeatability of +/-1 % with the given oil concentration range.				
1.4	A	Sampling time < 1 sec.				
1.4.1	B	Sampling time < 0.5 sec.				
1.4.2	B	Sampling time < 0.3 sec.				
1.4.3	B	Must maintain an accuracy of +/-1 % with the given sampling frequency.				
1.5	A	Needs to be able to make accurate measurements with model oils with low aromatic hydrocarbon content, < 2 %.				
1.6	A	Flow rate and droplet size variations needs to have minimal impact on the measurements.				
1.7	A	The OiW sensor will not be affected by low amounts of gas, 0 – 5 %.				
1.8	A	The OiW sensor will not be affected by low amounts of salt (NaCl) in water, 0.5 – 5 %.				
1.9	A	The OiW sensor must be EX-certified for operation in Zone 1				
2		**Interface details**				
2.1	A	Control unit connected to probe.				
2.1.1	A	Integrated OS in Control Unit.				
2.1.2	B	Possible to connect several probes to one control unit.				
2.1.2	A	User Software for remote control.				
2.1.3	B	Options for user to modify OS output.				

2.2	A	Serial communication: 4-20 mA/Modbus RS-485.				
2.3	A	Ethernet link for remote access.				
2.4	A	Power supply: 24 VDC / 220-240 VAC.				
2.5	A	The OiW sensor must be able to be calibrated to different types of oil.				
3		**Installation**				
3.1	B	Needs to be able to be installed in 2'' pipelines.				
3.2	A	Must be delivered as a complete "fit for purpose" solution. This means that the sensor must be ready for direct integration in the existing pipe setup, and deliver expected results after calibration.				
3.2.1	A	The OiW sensor must be able to be installed in the most beneficial placement to achieve homogeneous fluid flow.				
3.3	A	As an alternative to a normal purchase, the offer must include a rental agreement.				
4		**Materials**				
4.1	A	Both probe body and head needs to be in a corrosion resistant material suitable for our application (0.5 - 5 % salt in water, maximum 5 % oil and 0 - 1 % gas).				
4.1.1	A	Piping will be AISI 316L. The sensor must be in AISI 316L, or have a solution to avoid galvanic corrosion if the sensor is built in other material.				
5		**Operational conditions**				
5.1	A	Process temperature 20 - 50 °C.				
5.2	A	Operational pressure of 25 bar. With a safety factor of 1.6, it must withstand a pressure of 40 bar.				
5.3	A	Flow rate 2-5 m^3/h.				
6		**Additional equipment options**				
6.1	A	Additional probes/analyzers.				
6.2	A	Automatic self-cleaning system on all probes/analyzers.				
6.3	A	Spare parts and service kit.				

Appendix D

OiW Sensor Datasheets

In the following sections the datasheets for the different OiW suppliers are listed in alphabetic order.

D.1 Advanced Sensors

The following document shows the datasheet for Advanced Sensors OiW sensor EX–100.

Advanced sensors
by PAC

World's Best
Oil in Water
Analyzers

EX-100/1000

Side Stream Oil in Water Analyzer

Ultrasonics Fluorescence Spectroscopy

The EX-100 is a side stream Oil in Water analyzer that uses fluorescence to provide continuous accurate measurements of oil concentrations in water. Reliable real-time data enables operators to take accurate discharge measurements and to improve efficiency of separation processes enabling cost reductions.

In addition to the EX-100 features, the EX-1000 model offers spectral analysis.

Features

- Patented ultrasonic cleaning
- Laser Induced Fluorescence (LIF)
- Side stream format
- Periodic homogenisation of sample
- Sample point
- Various measurement ranges configurable (0-100ppb, 0-10ppm, 0-100ppm [...] up to 0-20,000ppm)
- Accuracy: ±1% and measurement repeatability 99%
- Remote management and diagnostics
- Easy to install (no sample conditioning)
- Multiple communications options - 4-20mA, HART, Modbus, Extended Ethernet or WiFi
- Optional integrated spectrometer

Benefits

- Easy to use
- Low Cost Of Ownership (COO) with zero routine maintenance
- No degradation of signal or recalibration
- Side stream format offers improved sample control
- Droplet size compensation with homogenized samples
- Sample point facilitates laboratory correlation
- Remote control and monitoring (ideal for un- manned locations and remote process monitoring)

Technical Specification

Measurement Performance

Measurement principle	Laser Induced Fluorescence (LIF)
Range	0-20,000ppm*
* User may select any desired measurement from 0-100ppb, 0-10ppm, 0-100ppm [...] Up to 0-20,000ppm	
Accuracy	±1% of measurement range
Repeatability	> 99%
Response time	< 1 Second, continuous results

Operating Conditions

Process temperature	0°C to 200°C
Process pressure	0-35 barg (180 barg optional)
Process flow	0-25 l/min (0-1,000l/min optional)
Operational ambient temperature	-20°C to 55°C
Cleaning	Ultrasonic (automatic)

Spectrometer Specification (1000 models only)

Emission wavelength range	400-1,100nm
Resolution	0.5nm

Utilities

Power supply	110 or 230 VAC (pre configured)
Power frequency	50 or 60 Hz
Power consumption	60W normal, 300W peak
Instrument air	5-8 barg (for pneumatic valve; electric valve option available)

Certification

Ingress protection	IP66
Enclosure material	Aluminium (SS 316L optional)
ATEX Exd II 2 G IIB T4, IECEX, USA and Canada Class 1 Div 1	Purged air not required
IMO MEPC 107 (49)	IMO Certified, ABS, US Coast Guard, BV

Weight & Dimensions

Weight (including stand, standard pneumatic Stainless Steel valve assembly, termination box and isolation switch)	Aluminium Enclosure: 93.55Kg Stainless Steel Enclosure: 141Kg
Dimensions	670W x 640D X 1112H mm (1120H mm for Stainless Steel enclosure)
Clear space	500mm front and rear

Communications

4-20 Ma	Passive
Ethernet	Standard
HART, Modbus, Wireless (WiFi), Extended Ethernet	Optional
Remote access	Standard
Internal data storage	>10 years
Security	Multiple level password protection

Additional Information

Flange fitting	1" ANSI RF standard (optional flange, sizes available)
Wetted parts	SS 316L (option of CR22, CR25, Monel, Inconel, Hastelloy, Titanium)
Sample take off point	Standard – integral to analyzer
Viewing window	Standard

Sample Conditioning

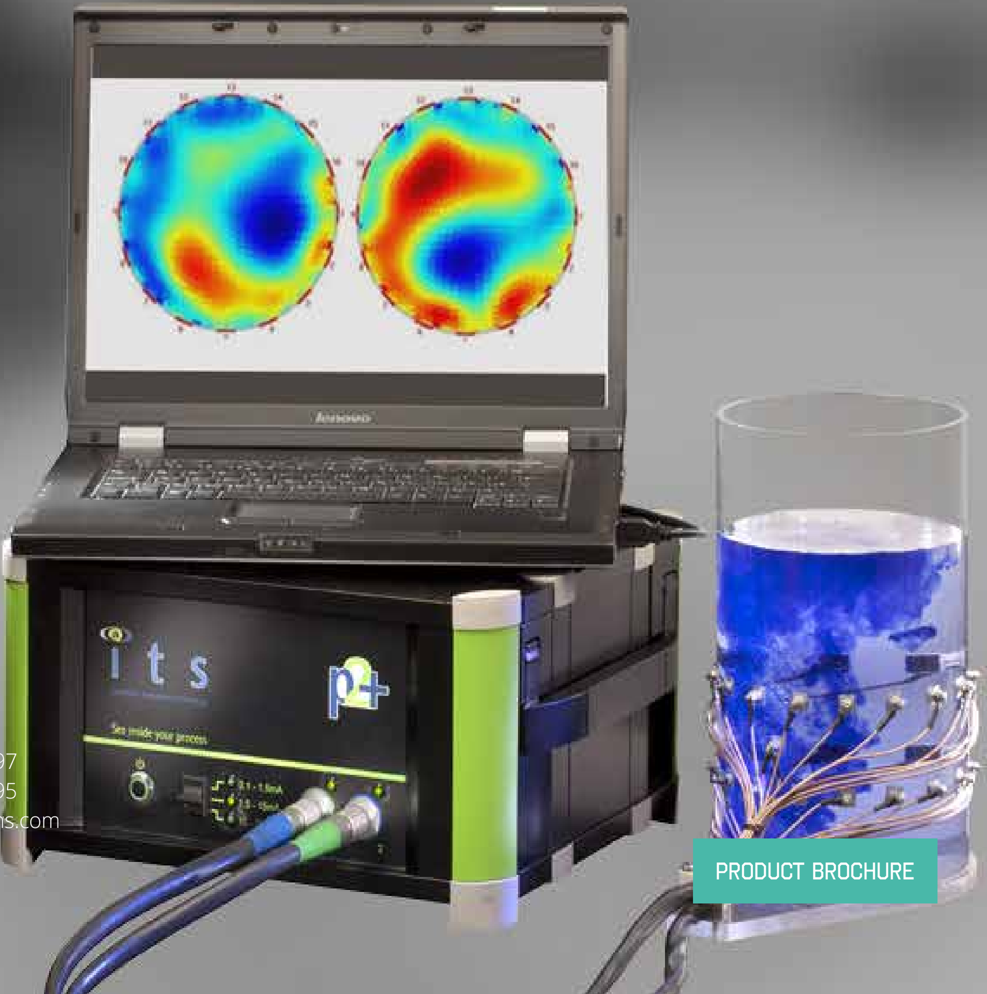
Homogenisation	Ultrasonic
Gas removal, solids removal, temp. conditioning, flow control	Not Required
Discrepancy for oil droplet size	Automatic Oil Droplet Size Compensation as standard

D.2 Industrial Tomography Systems

The following document shows the datasheet for Industrial Tomography Systems' OiW sensor.

SEE INSIDE YOUR PROCESS

RESEARCH & EDUCATION PACKAGES



INDUSTRIAL TOMOGRAPHY SYSTEMS PLC

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Registered in England No.04139271

PRODUCT BROCHURE

An affordable way to introduce tomography to your research

ITS' range of Research & Education Packages are specifically designed to meet the needs of R&D centers, universities and research institutions around the world.

Research & Education Packages from ITS allow for volumetric analysis of multiphase processes. Each package is tailored to the requirements of the user's field, meaning that package can be used for research into processes relating to petrochemicals, pharma, mining, and much more. The technology underpinning these packages is based on over 15 years' experience with tomography-based measurement solutions.

Electrical resistance tomography (ERT) technology works by applying a small current to an array of electrodes that are in contact with the process medium.

As this current propagates through the process volume, software uses complex algorithms to construct a conductivity map (or "tomogram"); a cross-sectional slice through the process. For non-aqueous processes, an alternative imaging technology is also available, based upon electrical capacitance tomography (ECT), which uses permittivity as the basis for measurements.

Tomography is extremely versatile, meaning that sensor arrays can be configured as vessels (see figure 1), probes, or as spool pieces pipelines for flowloops (see figure 2).

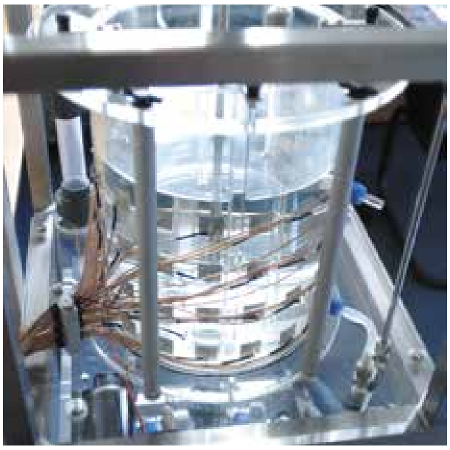

Figure 1 Lab-scale vessel sensor

Figure 2 Lab-scale sensor installed in a flow loop

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INNOVATIVE RESEARCH TOOL

The standard Research & Education Package is ideal for teaching and general laboratory at university level, with over 100 institutions around the world already using this tool as part of their process engineering research into in-line and batch processes; CFD and process model verification; unit processes such as hydrocyclones, static and driven mixers, packed columns; and multiphase flows.

Your chosen package will enable you to visualise multiphase processes as they progress and then export data to Matlab, Excel, and similar tools to analyse the resultant data; enabling you to add a new dimension to lab-based teaching.

PROCESS INFORMATION

Real time tomographic data gathered by the sensor included in the Research & Education Package is presented in 2D and 3D formats – showing processes as they evolve through contrasts in the electrical properties of materials – which can be automatically converted to phase concentrations. Data is collated on a mesh and statistical operators are used to provide process parameters such as mixing indices and regional changes in the process conditions.

All of this make the Research & Education Package a powerful teaching tool in the areas of standard unit processes, process modelling, and instrumentation.

KEY BENEFITS

- ✓ Package includes everything users need to get started with tomography
- ✓ Sensors are tailored to your research requirements
- ✓ Generate real-time data
- ✓ Adds a new dimension to your research
- ✓ Technology is proven across a range of industries, including pharma, oil & gas, and mining

PACKAGE INCLUDES

- → Lab-scale sensor, either as a probe, spool piece or vessel (see figure 1 on previous page)
- → Data acquisition system (see figure 3)
- → User-friendly Windows-based tomography software (see figure 4)
- → Optional technical support from ITS's team of specialist engineers

Figure 3 p2+ tomography instrument

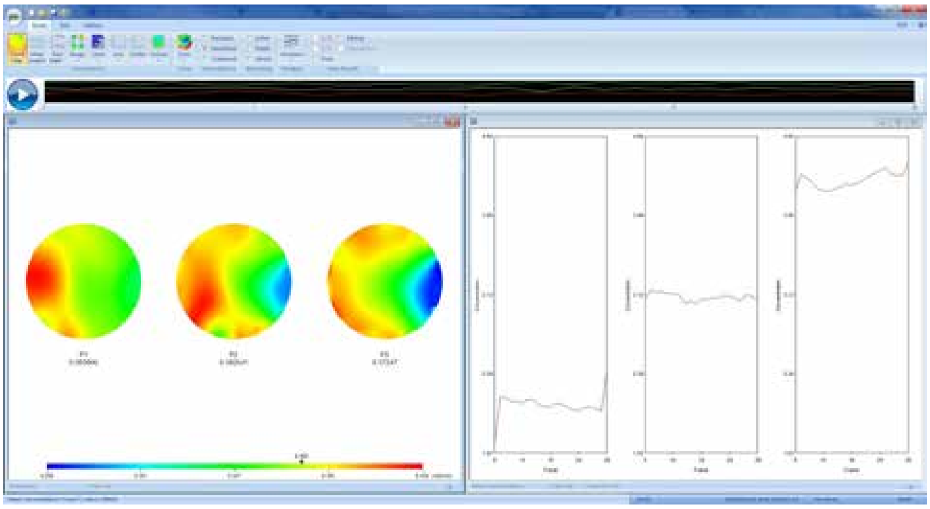


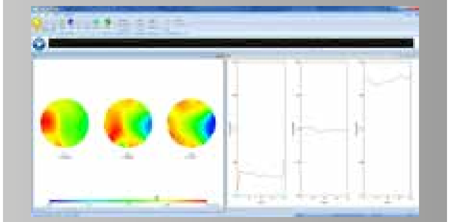
Figure 4 ITS Tomography Software

www.itoms.com

Research and Education Package: technical sheet

SYSTEM SPECIFICATION:

Research Package



Imaging	2D tomogram (concentration or conductivity) 3D vs. time / plane Zoned data (32 preset options)
Graphics	Conductivity, concentration, Mean resistivity, Radial / Axial conductivity, X-Y plots of multiple variables, individual pixel trace (up to 10 pixels)
Measurement rate	2 - 1,500 Hz
Conductivity range (ERT)	0.1 – 500mS/cm
Permittivity range (ECT)	0 – 7.5 relative permittivity
Statistics	Max, min, mean, std dev, mixing parameters, time averaging, pixel distribution
Raw data	Table, Graph
Data export format	CSV (for MatLab, Excel and other packages), AVI (for movies)
Algorithms	LBP, MSBP (standard) Tikhonov, Noser, Laplace, Landweber, 3D (offline)
Cross correlation (flow)	Aimflow
User interface	Windows-based

SENSOR SPECIFICATION:

Research Package

Vessel

Pipe

Probe

Sensor geometry	Pipe	Probe	Vessel
Sensor size (ERT)	5mm – 1.2m ID	5mm - 1m length	10mm - 8m ID
Sensor size (ECT)	5mm – 30cm ID	N/A	N/A
Number of planes (ERT)	1 - 2	1 - 8	1 - 8
Number of planes (ECT)	3	N/A	N/A
Electrodes per plane	ERT: 8, 16 or 32 ECT: 8, 12 or 24		
Operating pressure	Up to 200 bar		
Electrode material	316L, Hastelloy		
Sensor body	316L, Peek, PVDF, PTFE, PVDF, other materials by request		
Distance to instrument	ERT: 2.5m (longer available) ECT: 1m (max)		
Connectors	ERT: LEMO ECT: BNC		

INSTRUMENTATION SPECIFICATION:

Research Package

v5r ERT instrument

p2+ ERT instrument

m3c ECT instrument

ERT Instrument	p2+, v5r
ECT Instrument	m3c
Size	2-plane v5r / p2+: 340x300x160mm (W, D, H) 8-plane p2+ / m3c: 570x300x160mm (W, D, H)
Weight	2-plane v5r / p2+: 10kg 8-plane p2+ / m3c: 18kg
Power rating	100-250 Vac, 50/60 Hz, 2.5A
Power consumption	2-plane v5r / p2+ / m3c: 15W 8-plane p2+: 25W
Analog input (ERT)	4-20mA (for temp, flow, conductivity and other parameters)
Analog output (ERT)	4-20mA (for process control, data logging)
Outputs (ECT)	DDE
Digital output	USB
Additional interfaces	RS232, Ethernet
Installation	Desktop / workbench

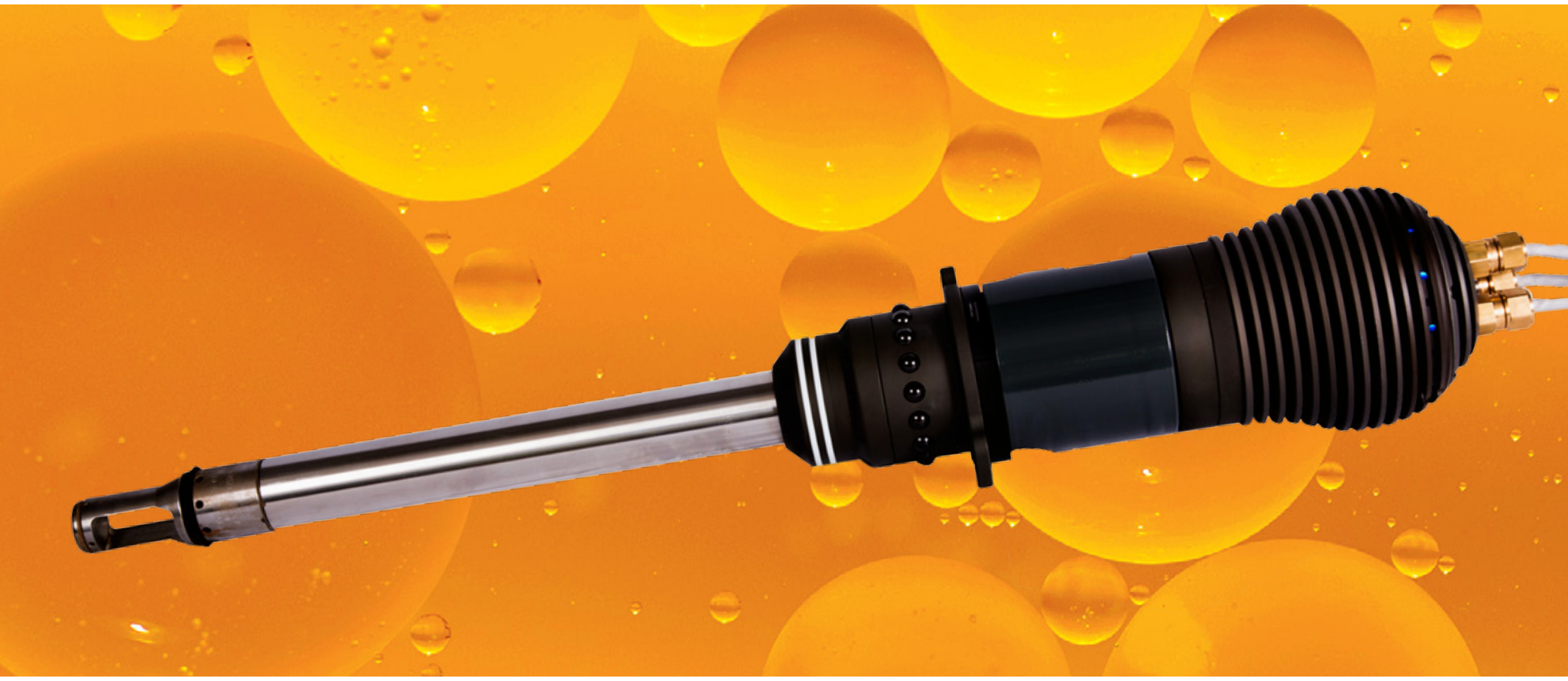
These specifications illustrate typical parameters for standard products. In practice ITS tomography systems can be supplied with technical variations to meet specific application requirements. Please use the above data with caution and check with our technical team as to a standard product's suitability for your application.

D.3 Mirmorax

The following document shows the datasheet for Mirmorax' OiW sensor LR2500.

MIRMORAX

Continuous in-line and online oil-in-water monitoring



OPERATING PRINCIPLE

The Mirmorax Oil-in-water analyzer is based on an ultrasonic measurement technique in which individual acoustic echoes are characterized using advanced signal processing.

A highly focused acoustic signal is transmitted directly into the produced water flow. The reflection and absorption of the signal provides a wide range of accurate measurements. In the focal region, individual solids, oil droplets and gas bubbles will reflect the acoustic energy and each reflected signal will hold particle specific information. Based on a large number of direct measurements, the monitor calculates full size distributions for oil and sand. The size distributions are used to calculate corresponding concentration values.

Important process information as salinity and temperature are measured and presented by the Oil-In-Water graphical user interface. The analyzer performs self-diagnosing and auto calibration.

MODEL FEATURES

The new Mirmorax Oil-in-water analyzer is 3rd generation ultrasonic analyzer. Model LR2500 is specially developed to manage the lower range, 0-2500 ppm of oil and particles with highest accuracy and at the same time deliver classification of particles and size distribution. This is especially suitable for discharge and water treatment applications, where knowledge on this is essential for reducing ppm levels and optimizing the separation process.

The analyzer has a built in flushing system to ensure clean lenses at all time.

DESIGN

The Mirmorax Oil-in-water analyzer consists of a Probe, which have an insertion design and a high performance signal processing and communication electronics, SPCE. The maximum length of communication and power cables between the probe and SPCE can be up to a 100 meters. The SPCE comes in both safe area (19” rack module) and an EX classification Zone 1 area version.

FACTS

Key features for the Mirmorax Oil-in-water analyzer are:

- Accurate and high resolution real-time measurements
- Simultaneous detection of oil, particles and gas
- Provides full size distributions and concentration for oil and particles
- Temperature measurements of process water
- Salinity Measurements of the process water
- Flushing system for transducer and reflector lenses
- Local display with screen selection
- EX Area Electronics option
- Remotely control and data access
- Insertion design, “one size fits all”
- No need to shut down to be inserted or extracted
- Reliable and robust
- Low maintenance

MIRMORAX

Continuous in-line and online oil-in-water monitoring

SPECIFICATIONS

Primary output parameters:

- Size distributions [µm]
- Median particle diameter, D50 [µm]
- Mass – volume concentration [mg/l]
- Volume concentration [ppm]
- Mass concentration [ppm]
- Temperature of process flow [°C]
- Salinity of water [g/l]

SYSTEM PERFORMANCE AND CHARACTERISTICS

Concentration range:

Oil	0 – 2500 ppm*
Particles	0 – 1000 ppm*

Uncertainty:
< 1% relative

Operating pressure:
200 bar g

Operating temperature:
max. 90°C

Ambient temperature:
-20°C to +60°C

Salinity:
0 – 350g/l NaCl

Flow velocity:
max. 4 m/s

Particle size range:
> 2 – 3 micrometer

Reynolds no.:
< 5000

Temperature variation:
max. 5°C/minute

*Max. Concentration range dependent on particle size range

INTERFACE DETAILS – ELECTRICAL

Power supply:
24VDC

Power consumption:
Maximum 36W

Serial communication:
RS485/4-20mA/HART/Ethernet

Protocol:
Modbus RTU

INTERFACE DETAILS – MECHANICAL

Connection type to pipe:

- 2” 150 lbs. weldoflange (or spool piece)
- Suitable for any pipe size >3”

Probe:

- Materials: SS316
- Hazardous area classification: Zone 1
  II 2 G Ex d IIB T5/T4 Gb (ATEX & IECEx)
- Weather protection: IP66, IEC 60529
- Weight: 20 kg

Signal processing and communication electronics, SPCE

Safe area:

- 19” rack, height 4U
- Material: Aluminum
- Weight: 10 kg

Ex area:

- Material: SS316
- Weather protection: IP66
- Weight: 70 kg
- Hazardous area classification: Zone 1
  II 2 G Ex d IIB T5 (ATEX)

D.4 ProAnalysis

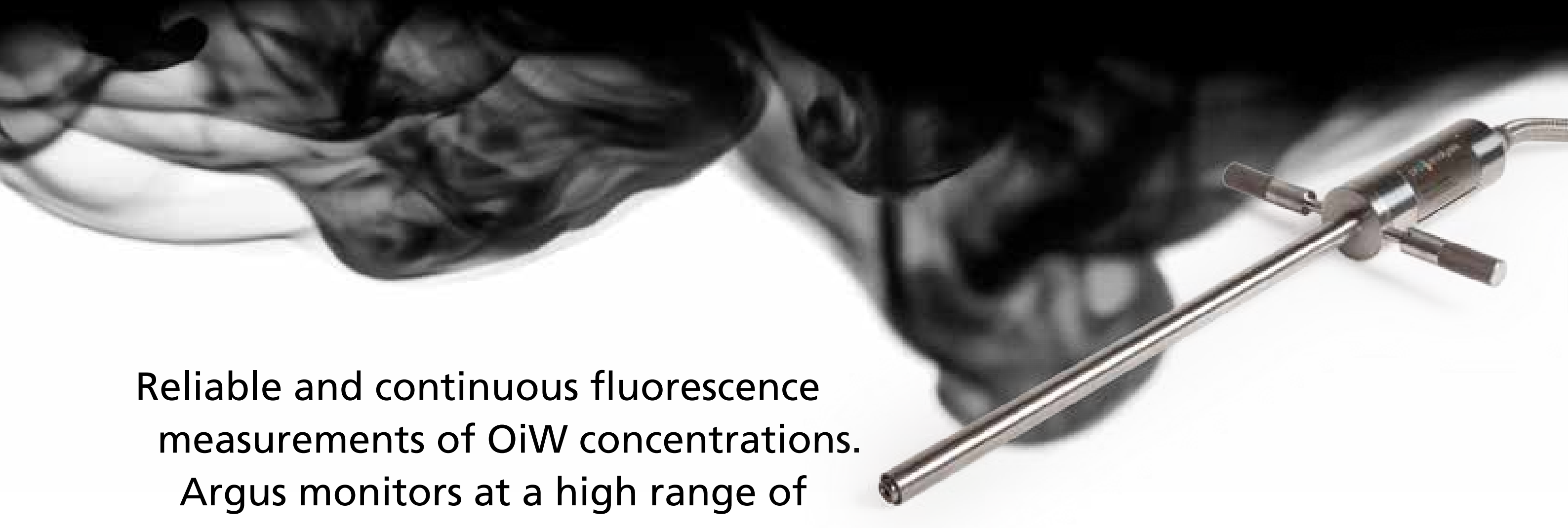
The following document shows the datasheet for ProAnalsysis' OiW sensor Argus.

pro analysis

ARGUS®

Spots every drop

Unique Oil in Water Monitoring



Reliable and continuous fluorescence measurements of OiW concentrations. Argus monitors at a high range of temperature and pressures, providing unique process performance information.

KEY FEATURES

- Very low maintenance
- Unique in-line probe design.
- Robust measurement principle: Laser Induced Fluorescence
- Retractable In-line probe. No bypass loop required
- Patented automatic ultrasound self-cleaning
- Remote monitoring of OiW (offshore or onshore), fully integrated with industry standard control systems

KEY BENEFITS

- Improves performance of produced water treatment systems
- Minimises OiW levels, achieving mandated HSE and operational targets for reductions in OiW
- Low maintenance.
- Replaces manual sampling and laboratory analysis.
- Prevents significant oil discharges. Immediate alarm when OiW levels exceed a defined limit
- Low installation costs

ONE CU – UP TO 14 PROBES.

With Argus OiW monitor, several in-line probes can be connected to the same control unit (CU). This means significant cost reductions. The CU can be located in hazardous - or safe area. One system can control up to 14 measurement points. (Maximum distance from control unit to measurement point: 200 meters). Configurating electronics in safe area reduces the total quantity of field equipment and simplifies access to the control unit.

proanalysis

ARGUS®


Spots every drop

MEASUREMENT

Measurement principle
Laser Induced fluorescence (LIF)
Sensor probe configuration
In-line
Number of measuring points per control unit 1 or 2
Number of measuring points per system 1 – 14
Measurement range oil in water
0 –3000 mg/l. Note 1
Measurement repeatability oil in water < ± 1 %. [Note 2]
Measurement range turbidity or optional
TSS - 0 – 1000 FNU or 0 – 100 mg/l
Sampling frequency
1 sample per second

OPERATIONAL CONDITIONS

Process temperature -
29 – 149 °C
Ambient temperature
-20 – 65 °C. [Note 3]
Design / operating pressure
0 – 50 barg. Tools for safe probe extraction under full process pressure are available
Pressure rating API 150 # - 600 #
Pipe dimension ≥ 3”
Flow velocity < 10 m/s

MAIN COMPONENTS

1. Control unit
   (electronics and communication)
2. In-line probe with retraction tool
3. Cable connection between
   probe and control unit

PROCESS CONNECTION

Probe installed directly into the process stream via a 2 inch flange retraction tool and isolation valve(s). Valve requirements: Full bore ball valve(s). Available standard dimensions and pressure classes:2” (DN50), 150# RF ANSI B16.5 (reg. flange dimensions)
Connection flange
2” 150/300/600# RF flange
(100 mm height)
Connection flange orientation
0 - 360°
Probe insertion length
Probe insertion is recommended within central 1/3 of pipe ID.
Required length for probe installation and maintenance
A free length of 1300-1600 mm measured backwards from flange surface on retraction tool should be available for probe installation and maintenance.
Standard material, probe and retraction tool wetted parts
22Cr Duplex (UNS S31803), titanium gr.5. [Note 4]
Weight, probe and retraction tool
typical 17-35 kg.

CERTIFICATION

Instrument is certified in accordance with
1. 97/23/EC Pressure Equipment Directive, module: A, A1 2. 94/9/EC ATEX, Ex de [ia] IIB T6 (Zone 1)
3. 2006/95/EC Low Voltage Directive
4. CSA / US certification pending

POWER SUPPLY

Supply voltage
220 – 240 VAC, 50/60 Hz, 16A
(110 VAC available on request)
Power consumption
100-200 W (average)

INSTRUMENT INTERFACE

Serial - Modbus RS-422 or RS-485 hardwired (standard). RS-485 can be delivered for fiber optic cable.
Ethernet
Ethernet hard wire (standard)
Ethernet for fiber optic cable
for distances above 100 meters
Analogue
(Exi) 4 - 20 mA, HART (optional)
Self-cleaning technology (Patented)
Ultrasonic cleaning
Cleaning intervals - Configurable

ACCESSORIES REQUIRED

2” RF Full bore isolation ball valve
(178 mm)

NOTES

1. Measurement range
   above 3000 mg/l on request
2. Repeatability measured
   on a stable fluorescent object
   for example Argus check
3. Ambient temperature
   over 40°C requires cooling
4. Other materials are available
   on request

FOR FURTHER INFORMATION ProAnalysis AS, Bredalsmarken 17, N-5006 Bergen, Norway
Telephone: (+47) 55 21 00 60 • Fax: (+47) 55 21 00 61 • E-mail: contact@proanalysis.no • Web: www.oilinwater.com

ARGUS®

Model code system

1 ENCLOSURE PROPERTIES

EX	Exde enclosure in SS316 for hazardous area
S19	Safe Area 19” Rack SWC Safe Area Wall Cabinet

2 NUMBER OF PROBES

1	Single probe system
2	Double probe system

3 RETRACTION TOOL

A	RT-C retraction tool (standard)
B	RT-Zc retraction tool
C	RT-H retraction tool

4 FIELD FIBER CABLE

XX	XX-meters cable for probe 1
YY	YY-meters cable for probe 2

5 PROBE, WETTED PARTS

A	Duplex (UNS S31803) and Titanium Gr.5. (standard)
B	Super duplex (UNS S32750) and Titanium Gr.5.
C	Stainless Steel 316L and Titanium Gr.5.

6 COMMUNICATION INTERFACE

1	4-20 mA, Ethernet and MODBUS RS 422/485 all hardwire (standard)
2	4-20 mA, Ethernet and HART all hardwire

7 LOCAL EX(I) DISPLAY

Y	Yes
N	No

8 AMBIENT TEMPERATURES

1	Below 40 Deg. C
2	Below 40 Deg. C

9 POWER SUPPLY

A	220/230 VAC, 50-60 Hz, 16A (standard)
B	110 VAC, 50-60 Hz, 16A

10 SAMPLE POINT IN PROBE SHIELD

0	No manual sample point (standard)
1	Manual sample point

11 DOCUMENTATION

A	Standard documentation
B	Standard documentation with client specific front page
C	Project specific documentation

The example in the heading will specify an OiW analyser with following: Control unit in SS316 Exd enclosure in field with one probe in Duplex/Titanium material connected.
RT-Zc retraction tool
25 meters of field fibre cable for probe 1 and 19 meters for probe 2.
Modbus Comm. Interface
Local Ex(i) display
Ambient Temperatures below 40 °C 220/230 VAC 50-60 Hz 16A circuit
No manual sample points
With standard documentation package

ARGUS	EX	2	2	25-19	A	1	Y	1	A	0	A
	①	②	③	④	⑤	⑥	⑦	⑧	⑨	⑩	⑪

FOR FURTHER INFORMATION ProAnalysis AS, Bredalsmarken 17, N-5006 Bergen, Norway
Telephone: (+47) 55 21 00 60 • Fax: (+47) 55 21 00 61 • E-mail: contact@proanalysis.no • Web: www.oilinwater.com

Appendix E

Legal Agreements

The following document is the application for dispensation delivered to DSB. This must be approved before the construction can start. The application is written in Norwegian, sincce DSB is a Norwegian company.

Søknad om dispensasjon i henhold til §27 i *Forskrift om trykkpåkjent utstyr*

Institutt for Produksjons- og Kvalitetsteknikk, NTNU

Førsteamanuensis Christian Holden

Laboratorieansvarlig førsteamanuensis Christian Holden ved Institutt for Produksjons- og Kvalitetsteknikk (IPK) ved Norges Teknisk-Naturvitenskapelige Universitet (NTNU) ønsker med dette å søke dispensasjon fra §§25 og 26 i Forskrift om trykkpåkjent utstyr basert på at §27 sier følgende om bruken av trykkpåkjent utstyr av eksperimentell interesse;

«Tilsynsmyndigheten kan, når det er berettiget, tillate at trykkpåkjent utstyr og enheter som omtalt i § 3 markedsføres og tas i bruk i Norge, uansett bestemmelsene i §§ 25 og 26, og selv om prosedyrene ikke har vært anvendt, dersom bruken har eksperimentell interesse.»

På Institutt for Produksjons- og kvalitetsteknikk på NTNU designes det for øyeblikket et kompakt separasjonslaboratorium som har til hensikt å separere olje og vann. Laboratoriet etterligner et typisk kompakt undervannsseparasjonsanlegg. Prosjektet er en del av SFI SUBPRO (Senter for forskningsdrevet innovasjon), der NTNU samarbeider med flere aktører fra industrien med den hensikt å bli et internasjonalt ledende senter for undervannsteknologi som produserer kandidater, forskning og teknologiske innovasjoner av topp kvalitet. Designet av separasjonslaboratoriet er planlagt ferdig juni 2016 og konstruksjonen skal igangsettes august 2016. Ved ferdigstilling vil laboratoriet fungere som utgangspunkt for videre forskning på avanserte styringsalgoritmer, hvis hensikt er å motvirke strømningsrelaterte irregulariteter i kompakte undervannsseparasjonssystemer. Laboratoriets hovedformål er derfor forskning, men det vil samtidig bli brukt i undervisning ved NTNU.

Laboratoriets design er vist i Figur 1.

<u>Systemet er designet med følgende parametere:</u>

Dimensjon: DN50

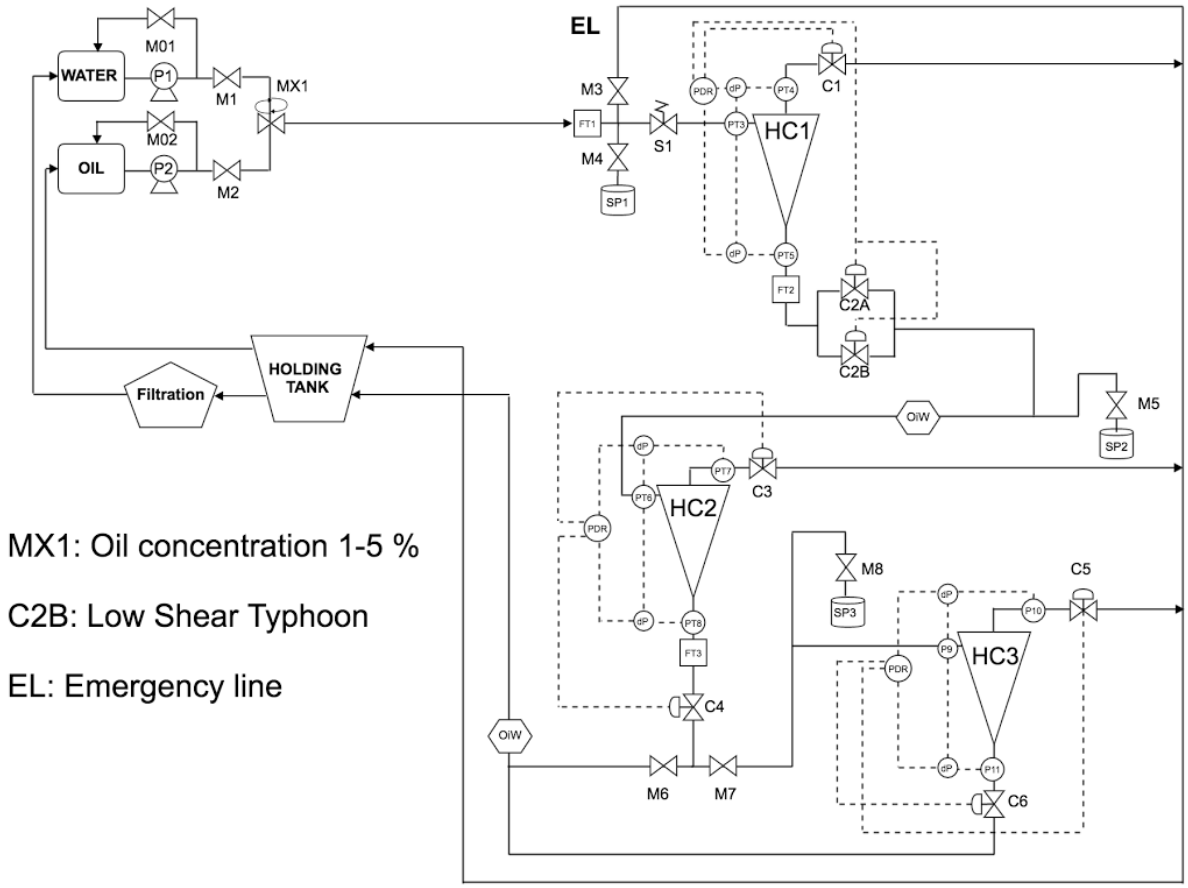
Temperatur: Inntil 50º Celsius

Flytrate: Inntil 5 m^3/h

Trykk: Operasjonelt trykk på inntil 25 bar. Systemet designes for et trykk på inntil 40 bar. Dette tilsvarer en sikkerhetsfaktor på 1,6.

Medium: Olje – Modellolje Exxsol D140. Konsentrasjon på inntil 5 %. Oljen har antennelsestemperatur på 140º Celsius. Se vedlagt datablad for oljen.

Vann – Saltvann med en saltkonsentrasjon på inntil 5 %. Vann vil utgjøre de resterende 95 % av mediet.



Figur 1 - Design av kompaktseparasjonslaboratorium

Funksjonalitet:

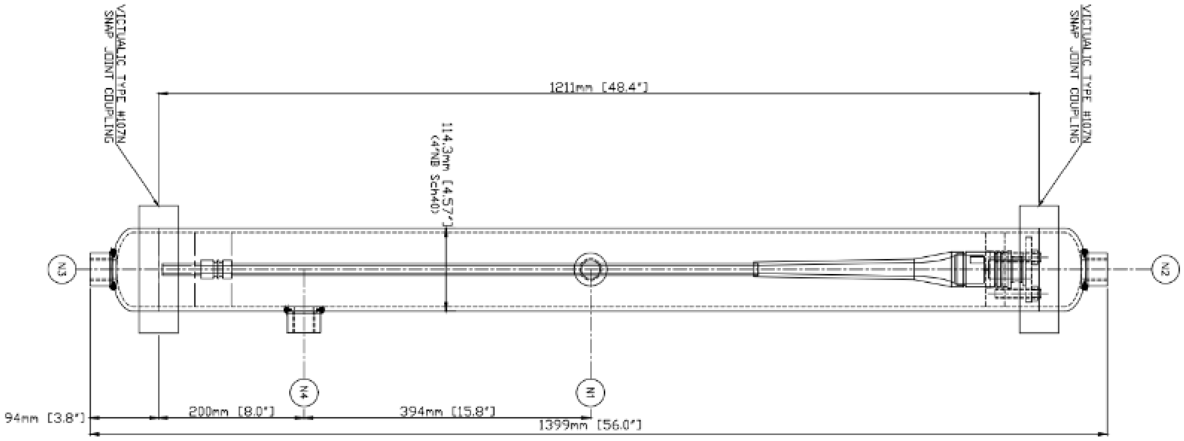
En flerfasestrøm med inntil 5% olje sendes inn på HC1 som består av to hydrosykloner, en type separator, i parallell. Olje og vann separeres slik at en vannløsning med en oljekonsentrasjon på 0,2 % sendes videre i systemet, mens oljen skilles ut gjennom kontrollventil C1. Vannløsningen med 0,2 % olje sendes gjennom et parallelt oppsett av kontrollventiler, C2A og C2B, der en av disse representerer et lavskjærsdesign som er banebrytende teknologi innenfor olje- og gassprosessering.

Mediet sendes videre til HC2 som består av en hydrosyklon, og oljekonsentrasjonen i vannet reduseres til 30 ppm. Etter dette er en tredje hydrosyklon, HC3, plassert i en «by-pass» slik at oljekonsentrasjonen ytterligere reduseres fra 30 ppm. Olje-i-vann sensorer plasseres mellom hydrosyklonene for å måle konsentrasjonen i sanntid. Dette skal videre benyttes til å utvikle styringsalgoritmer for systemet, med det formål å gjøre systemet som helhet mer robust mot strømningsrelaterte irregulariteter.

Trykkpåkjent utstyr:

Relatert til søknad om dispensasjon er enkelte komponenter i laboratoriet relevante å nevne. Først og fremst vil rørsystemet være designet for PN40, altså inntil 40 bar. Pumpe P1 og P2 i Figur 1 vil levere maksimalt 25 bar, som multiplisert med en sikkerhetsfaktor på 1,6 tilsvarer 40 bar. Pumpene har ikke kapasitet til å levere et trykk over 25 bar. Basert på input fra leverandører antar vi et trykktap på 1-3 bar over HC1 og 5-7 bar over både HC2 og HC3. Trykket ved utløpet av HC3 er derfor vesentlig lavere, og som en følge av dette har kontrollventil C6 fått trykklasse PN16. Resten av kontrollventilene er PN40. Dersom trykket på noe tidspunkt skulle overstige 25 bar vil sikkerhetsventil S1 stenge, og all væsken vil bli ført via EL-linjen (emergency Line) direkte til «holding»-tanken. EL-linjen har en strupeventil for å redusere trykket før væsken ankommer tanken.

Hydrosyklonene er omgitt av et trykkhus. Trykkhuset har et innløp til mediet plassert på midten, et avløp for vann og et for olje i hver sin ende. Når trykkhuset er fylt av væske, føres denne inn i hydrosyklonen gjennom radielle innløp i toppen av hydrosyklonen. Inngangsvinkelen til mediet vil gi et spirallignende strømningsmønster som på grunn av sentrifugalkrefter og forskjeller i tetthet mellom fasene fører til separasjon. Trykkhuset bygges for PN40, og er derfor sikret mot et innløpstrykk på 25 bar med en sikkerhetsfaktor på 1,6. Trykkhuset med hydrosyklon er avbildet i Figur 2.



Figur 2 - Trykkhus for hydrosyklon

1 Vedlegg – Exxsol D140 Safety

Appendix F

Mokveld Datasheet

The following datasheet shows the stroke time for the Mokveld Typhoon valve.

Stroke Model

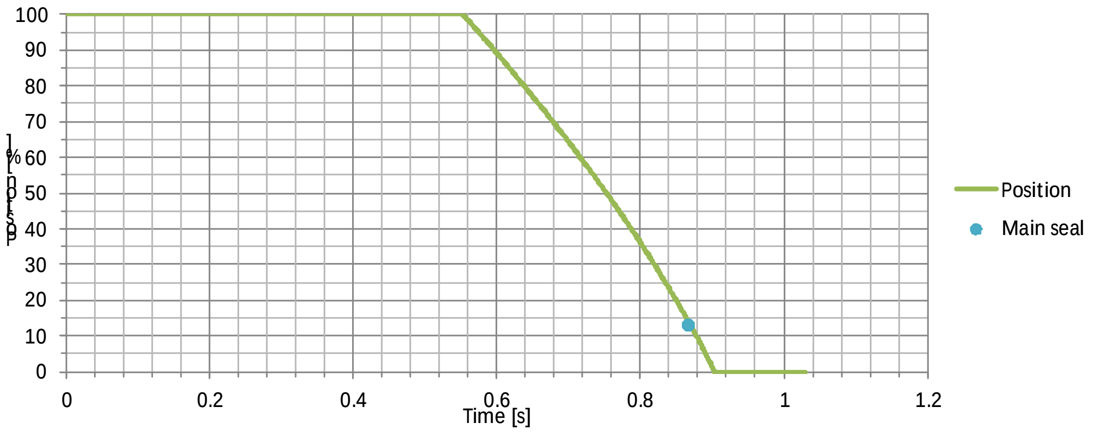
Print date: 14-04-16

DPL-202 V2.4.8 13-4-2016

Valve	RZD 2" S99 ANSI 300 Pressure: 52 bar
Actuator	M275 1-VS-2 (F1) Hydraulic block: Standard
Instrumentation	Control: ABB EDP300 Close: No instrument Open: No instrument Medium: Air Pressure: 1.1 bar

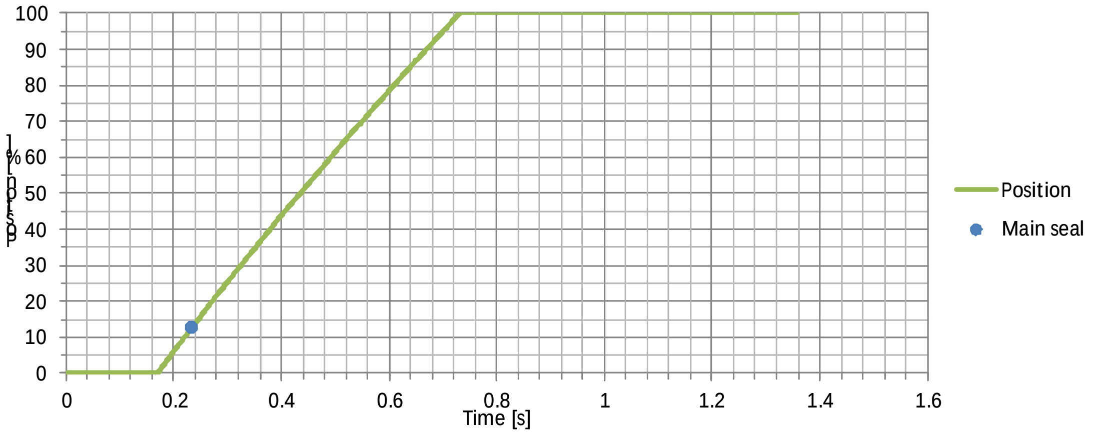
Stroke time CLOSE

Total: 0.9 s
Netto: 0.35 s



Stroke time OPEN

Total: 0.73 s
Netto: 0.56 s



Remarks

It is recommended to set ca. 0.33 bar higher pressure.

Appendix G

Synthetic model oil–Exxsol D140

The following documents shows the safety information and the datasheet for the synthetic model oil Exxsol D140.

Product Safety Summary

EXXSOL ™ D140 Fluid

This Product Safety Summary document is a high-level summary intended to provide the general public with an overview of product safety information on this chemical substance. It is not intended to provide emergency response, medical or treatment information, or to provide a discussion of all safety and health information. This document is not intended to replace the (Material) Safety Data Sheet. Warnings and handling precautions provided below are not intended to replace or supersede manufacturers' instructions and warning for their consumer products which may contain this chemical substance.

1. Chemical Identity

Exxsol™ D140 Fluid is produced from petroleum-based raw materials which are treated with hydrogen in the presence of a catalyst to produce a low odor, low aromatic hydrocarbon solvent. The major components include normal alkanes, isoalkanes, and cyclics.

For EU only: **EC no:** 919-029-3
Chemical Name: Hydrocarbons, C16-C20, n-alkanes, isoalkanes, cyclics, <2% aromatics

CAS No: 64742-46-7 **Chemical Name**: Distillates (petroleum), hydrotreated middle

2. Product Uses

Exxsol D140 Fluid is a solvent used in industrial, professional, and consumer applications such as manufacturing process solvent, metal working, and coatings. It is not sold directly to the public for general consumer uses; however this product may be an ingredient in consumer and commercial product applications such as metal working solvents and coatings.

3. Physical / Chemical Properties

Exxsol D140 Fluid can release vapors that readily form flammable mixtures. It should be handled only with adequate ventilation and in areas without any ignition source present (e.g. no open flames, static electricity sources, or unprotected light switches). The flash point for this product is ~140ºC / >284ºF.

4. Health Information

Exxsol D140 Fluid is generally recognized to have low acute and chronic toxicity. Aerosol concentrations above the oil mist exposure limit of 5 mg/m3 in the air can cause eye and lung irritation and may cause headaches, dizziness or drowsiness. Prolonged or repeated skin contact in an occupational setting may result in irritation and in these situations, the use of chemical resistant gloves is recommended. This product is not regarded as a mutagen or carcinogen, and there is low concern for reproductive, developmental, or nervous system toxic effects.

5. Additional Hazard Information

If accidentally swallowed, small amounts of liquid may be aspirated into the lungs during ingestion or from vomiting which may cause severe lung inflammation and lung edema (an accumulation of fluid in the lungs). This is a medical emergency which must be immediately and properly treated. Do not induce vomiting.

6. Food Contact Regulated Uses

This product is not claimed as compliant for food contact uses.

7. Environmental Information

Exxsol D140 Fluid biodegrades at a rapid rate and will not persist in the environment. It is not expected to cause short-term toxicity to fish or other aquatic organisms. Because of its low solubility in water and volatility (tendency to move from water to air) chronic aquatic toxicity is not expected. This product is expected to degrade rapidly in air. Measures should be taken to prevent its release to the atmosphere and minimize any exposure to the environment from manufacturing or use activities.

8. Exposure Potential

- **Workplace exposure** – This refers to potential exposure in a manufacturing facility or through evaporation in various industrial applications. Generally, exposure of personnel in manufacturing facilities is relatively low because the process, storage and handling operations are enclosed. The ExxonMobil recommended occupational exposure limit (OEL) for oil mist is 5 mg/m^3 per 8-hour work day.
- **Consumer use of products containing Exxsol D140 Fluid** – If exposure should occur, it is likely to be infrequent and of short duration depending on the products used and the conditions under which they are used. Exposure could occur through the use of cleaning agents or coatings formulations that contain this product. The best way to prevent exposure to vapors and oil mist is to work in well-ventilated areas, wear chemical resistant gloves, and follow good personal hygiene practices.
- **Environmental releases** – As a chemical manufacturer, we are committed to operating in an environmentally responsible manner everywhere we do business. Our efforts are guided by in-depth scientific understanding of the environmental impact of our operations, as well as by the social and economic needs of the communities in which we operate. Industrial spills or releases are rare; however a spill may pose a flammability issue. Our operational improvement targets and plans are based on driving incidents with real environmental impact to zero and delivering superior environmental performance.

9. Manufacture of Product

- **Capacity** – Publicly available sources report total global production capacity for this type of solvent product exceeded 1 billion pounds in 2005 (450 kT).
- **Process** – Exxsol D140 Fluid is produced from petroleum-based raw materials which are treated with hydrogen in the presence of a catalyst to produce a low aromatic, low odor solvent.

10. Risk Management

- **Workplace Risk Management** – When using this product, make sure that there is adequate ventilation. Always use chemical resistant gloves to protect your hands and skin and always wear eye protection such as chemical goggles. Do not eat, drink, or smoke where chemicals are handled, processed, or stored. Wash hands and skin following contact. If this product gets into your eyes, flush eyes thoroughly with tempered tap water. If irritation occurs, get medical assistance. Please refer to the (Material) Safety Data Sheet.

- **Consumer Risk Management** - This product is not sold directly to the public for general consumer uses. If exposure should occur, it is expected to be infrequent and of short duration. Always follow manufacturers' instructions, warnings and handling precautions when using their products.The best way to minimize exposure to vapors is to work in well-ventilated areas.

11. Federal/Science Agency Resources

(For EU: product specific search criteria should be used - see Section 1)

(For rest of the world CAS No. searches, enter 64742-46-7)

Organization for Economic Cooperation and Development (OECD) - ChemPortal web-based search tool

- http://www.echemportal.org/

U.S. Environmental Protection Agency - High Production Volume Information System (HPVIS)

- http://www.epa.gov/hpv/

European Chemical Substances Information System (ESIS)

- http://ecb.jrc.ec.europa.eu/home.php

European Chemical Agency (ECHA)

- http://apps.echa.europa.eu/registered/registered-sub.aspx

12. Regulatory Information

Regulations may exist that govern the manufacture, sale, transportation, use and/or disposal of this chemical and may vary by city, state, country or geographic region. Additional helpful information may be found by consulting the relevant ExxonMobil (Material) Safety Data Sheet at:

- http://www.msds.exxonmobil.com

13. Conclusion Statements

Exxsol D140 Fluid ...

- is a widely used industrial solvent, and may be an ingredient in consumer products.
- is low in toxicity; however it may cause lung damage if swallowed.
- does not cause adverse health or environmental effects at levels typically found in the workplace or environment.
- should be used only with good ventilation; avoid all ignition sources.

ExxonMobil Exxsol™ D140 Dearomatized Fluid

Category : Fluid

Material Notes:

Availability: Africa & Middle East and Europe Appearance: Clear/Transparent LiquidInformation provided by ExxonMobil

Order this product through the following link:
http://www.lookpolymers.com/polymer_ExxonMobil-Exxsol-D140-Dearomatized-Fluid.php

Physical Properties	Metric	English	Comments
Density	0.824 g/cc @Temperature 15.0 °C	0.0298 lb/in³ @Temperature 59.0 °F	ASTM D4052
Kinematic Viscosity	6.14 cSt	6.14 cSt	ASTM D445
Vapor Pressure	<= 0.000133 bar @Temperature 20.0 °C	<= 0.100 torr @Temperature 68.0 °F	ExxonMobil Method

Thermal Properties	Metric	English	Comments
Boiling Point	275 °C	527 °F	Initial; ASTM 1078
	315 °C	599 °F	Final; ASTM 1078
Flash Point	136 °C	276 °F	Method A; ASTM D93

Descriptive Properties	Value	Comments
Aniline Point	192°F	Method E, ASTM D611
Aromatic Content	0.006	UV, ExxonMobil Method

Contact Songhan Plastic Technology Co.,Ltd.

Website : www.lookpolymers.com
Email : sales@lookpolymers.com
Tel : +86 021-51131842
Mobile : +86 13061808058
Skype : lookpolymers
Address : United North Road 215,Fengxian District, Shanghai City,China

Appendix H

Risk Assessment

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

ID	6986	**Status**	**Dato**
Risikoområde	Risikovurdering: Helse, miljø og sikkerhet (HMS)	Opprettet	05.04.2016
Opprettet av	Andre Listou Ellefsen	Vurdering startet	05.04.2016
Ansvarlig	Christian Holden	Tiltak besluttet	06.04.2016
		Avsluttet	20.04.2016

Kompakt Separator Laboratorium

Gyldig i perioden:

4/5/2016 - 6/6/2025

Sted:

Institutt for produksjons- og kvalitetsteknikk

Mål / hensikt

Redusere risiko for eventuelle skader og ulykker i forbindelse med konstruksjon og bruk av separator laboratoriet.

Bakgrunn

Laboratoriet vil inkludere både brennbare fluider, gass og væske under trykk, roterende maskineri og elektriske komponenter, og vil derfor utgjøre en potensiell fare for personell og uvedkommende. Konstruksjonen av laboratoriet vil også involvere sikkerhetsmessige aspekter som løfting, sveising og klemfarer.

Beskrivelse og avgrensninger

Laboratoriet vil stå i verkstedet til IPK, nærmere bestemt ved østveggen av verkstedet. Senere vil riggen potensielt bli inkludert i det allerede eksisterende Cameron laboratoriet, og derfor være underlagt deres sikkerhetsrutiner. Tilgang til verkstedet er forbeholdt personell med sikkerhetskurs og laboratoriet vil kunne være tilgjengelig for klarert personell. Risikovurderingen omfatter derfor kun dette personellet, i tillegg til personell i umiddelbar nærhet og personell knyttet til konstruksjonen.

Forutsetninger, antakelser og forenklinger

Risikovurderingen forutsetter operatører med gjennomført opplæringskurs i bruk av laboratoriet, og at all konstruksjon blir utarbeidet av personell med de nødvendige faglige kvalitetene.

Vedlegg

[Ingen registreringer]

Referanser

[Ingen registreringer]

Oppsummering, resultat og endelig vurdering

I oppsummeringen presenteres en oversikt over farer og uønskede hendelser, samt resultat for det enkelte konsekvensområdet.

Farekilde: **Konstruksjon av laboratorium**

Uønsket hendelse: **Kuttskader fra utstyr og/eller materialer**

Konsekvensområde: Helse — Risiko før tiltak: 🟡 Risiko etter tiltak: 🟢

Risikoreduserende tiltak	Ansvarlig	Registrert	Frist	Status
Opplæring/kurs for utstyr tilknyttet konstruksjon av lab	Christian Holden	12.04.2016	15.08.2016	Til behandling

Uønsket hendelse: **Alvorlige kuttskader ved bruk av utstyr/maskiner**

Konsekvensområde: Helse — Risiko før tiltak: 🟡 Risiko etter tiltak: 🟡

Risikoreduserende tiltak	Ansvarlig	Registrert	Frist	Status
Opplæring/kurs for utstyr tilknyttet konstruksjon av lab	Christian Holden	12.04.2016	15.08.2016	Til behandling

Uønsket hendelse: **Ulykker ved bruk av løftekran**

Konsekvensområde: Helse — Risiko før tiltak: 🟡 Risiko etter tiltak: 🟡

Risikoreduserende tiltak	Ansvarlig	Registrert	Frist	Status
Opplæring/kurs for utstyr tilknyttet konstruksjon av lab	Christian Holden	12.04.2016	15.08.2016	Til behandling

Uønsket hendelse: **Klemskader**

Konsekvensområde: Helse — Risiko før tiltak: 🟡 Risiko etter tiltak: 🟢

Risikoreduserende tiltak	Ansvarlig	Registrert	Frist	Status
Opplæring/kurs for utstyr tilknyttet konstruksjon av lab	Christian Holden	12.04.2016	15.08.2016	Til behandling

Uønsket hendelse: **Belastningsskader som følge av tunge løft**

Konsekvensområde: Helse — Risiko før tiltak: 🟢 Risiko etter tiltak: 🟢

Risikoreduserende tiltak	Ansvarlig	Registrert	Frist	Status
Opplæring/kurs for utstyr tilknyttet konstruksjon av lab	Christian Holden	12.04.2016	15.08.2016	Til behandling

Farekilde: **Konstruksjon av laboratorium**

Uønsket hendelse: **Påkjørsel av truck**

Konsekvensområde: Helse — Risiko før tiltak: 🟡 Risiko etter tiltak: 🟢

Risikoreduserende tiltak	Ansvarlig	Registrert	Frist	Status
Opplæring/kurs for utstyr tilknyttet konstruksjon av lab	Christian Holden	12.04.2016	15.08.2016	Til behandling

Uønsket hendelse: **Øyeskader i forbindelse med sveising**

Konsekvensområde: Helse — Risiko før tiltak: 🟡 Risiko etter tiltak: 🟢

Risikoreduserende tiltak	Ansvarlig	Registrert	Frist	Status
Opplæring/kurs for utstyr tilknyttet konstruksjon av lab	Christian Holden	12.04.2016	15.08.2016	Til behandling

Uønsket hendelse: **Øyeskader ved små fremmedobjekter**

Konsekvensområde: Helse — Risiko før tiltak: 🟢 Risiko etter tiltak: 🟢

Risikoreduserende tiltak	Ansvarlig	Registrert	Frist	Status
Opplæring/kurs for utstyr tilknyttet konstruksjon av lab	Christian Holden	12.04.2016	15.08.2016	Til behandling

Uønsket hendelse: **Feil bruk av utstyr og maskiner**

Konsekvensområde: Materielle verdier — Risiko før tiltak: 🟢 Risiko etter tiltak: 🟢
Helse — Risiko før tiltak: 🟡 Risiko etter tiltak: 🟢

Risikoreduserende tiltak	Ansvarlig	Registrert	Frist	Status
Opplæring/kurs for utstyr tilknyttet konstruksjon av lab	Christian Holden	12.04.2016	15.08.2016	Til behandling

Uønsket hendelse: **Utløsning av brannalarm**

Konsekvensområde: Omdømme — Risiko før tiltak: 🟡 Risiko etter tiltak: 🟢

Risikoreduserende tiltak	Ansvarlig	Registrert	Frist	Status
Opplæring/kurs for utstyr tilknyttet konstruksjon av lab	Christian Holden	12.04.2016	15.08.2016	Til behandling

Farekilde: **Konstruksjon av laboratorium**

Uønsket hendelse: **Støt ved oppkobling av elektrisk utstyr**

Konsekvensområde:			
Helse	Risiko før tiltak: 🟡	Risiko etter tiltak: 🟢	

Risikoreduserende tiltak	**Ansvarlig**	**Registrert**	**Frist**	**Status**
Innleid kvalifisert personell	Christian Holden	12.04.2016	15.08.2016	Til behandling

Uønsket hendelse: **Brann**

Konsekvensområde:		
Helse	Risiko før tiltak: 🟡	Risiko etter tiltak: 🟢
Ytre miljø	Risiko før tiltak: 🟡	Risiko etter tiltak: 🟢
Materielle verdier	Risiko før tiltak: 🟡	Risiko etter tiltak: 🟡
Omdømme	Risiko før tiltak: 🟡	Risiko etter tiltak: 🟡

Risikoreduserende tiltak	**Ansvarlig**	**Registrert**	**Frist**	**Status**
Opplæring/kurs for utstyr tilknyttet konstruksjon av lab	Christian Holden	12.04.2016	15.08.2016	Til behandling

Uønsket hendelse: **Støyfare**

Konsekvensområde:		
Helse	Risiko før tiltak: 🟢	Risiko etter tiltak: ⚪
Ytre miljø	Risiko før tiltak: 🟢	Risiko etter tiltak: ⚪

Uønsket hendelse: **Sikkerhetskultur**

Konsekvensområde:		
Helse	Risiko før tiltak: 🟢	Risiko etter tiltak: 🟢
Omdømme	Risiko før tiltak: 🟢	Risiko etter tiltak: 🟢

Risikoreduserende tiltak	**Ansvarlig**	**Registrert**	**Frist**	**Status**
Opplæring/kurs for utstyr tilknyttet konstruksjon av lab	Christian Holden	12.04.2016	15.08.2016	Til behandling

Farekilde: **Bruk av laboratorium**

Uønsket hendelse: **Oljesøl**

Konsekvensområde:		
Helse	Risiko før tiltak: 🟢	Risiko etter tiltak: 🟢
Ytre miljø	Risiko før tiltak: 🟢	Risiko etter tiltak: 🟢
Materielle verdier	Risiko før tiltak: 🟡	Risiko etter tiltak: 🟢
Omdømme	Risiko før tiltak: 🟢	Risiko etter tiltak: 🟢

Risikoreduserende tiltak	**Ansvarlig**	**Registrert**	**Frist**	**Status**
Oljesølbarriere	Christian Holden	06.04.2016	19.12.2016	I arbeid
Ikke ATEX sertifiserte oljer	Andre Listou Ellefsen	06.04.2016	21.04.2016	Evaluert
Opplæring i bruk av rigg	Christian Holden	07.04.2016	16.12.2016	I arbeid

Uønsket hendelse: **Vannsøl**

Konsekvensområde:	Helse	Risiko før tiltak: 🟡	Risiko etter tiltak: 🟢
	Ytre miljø	Risiko før tiltak: 🟡	Risiko etter tiltak: 🟢
	Materielle verdier	Risiko før tiltak: 🟡	Risiko etter tiltak: 🟢
	Omdømme	Risiko før tiltak: 🟡	Risiko etter tiltak: 🟢

Risikoreduserende tiltak	**Ansvarlig**	**Registrert**	**Frist**	**Status**
Opplæring i bruk av rigg	Christian Holden	07.04.2016	16.12.2016	I arbeid

Uønsket hendelse: **Øyeskader**

Konsekvensområde:	Helse	Risiko før tiltak: 🟡	Risiko etter tiltak: 🟢

Risikoreduserende tiltak	**Ansvarlig**	**Registrert**	**Frist**	**Status**
Opplæring i bruk av rigg	Christian Holden	07.04.2016	16.12.2016	I arbeid

Uønsket hendelse: **Gass under trykk**

Konsekvensområde:	Helse	Risiko før tiltak: 🟡	Risiko etter tiltak: 🟢
	Materielle verdier	Risiko før tiltak: 🟡	Risiko etter tiltak: 🟡
	Omdømme	Risiko før tiltak: 🟡	Risiko etter tiltak: 🟢

Risikoreduserende tiltak	**Ansvarlig**	**Registrert**	**Frist**	**Status**
Opplæring i bruk av rigg	Christian Holden	07.04.2016	16.12.2016	I arbeid

Uønsket hendelse: **Væsker under trykk**

Konsekvensområde:	Helse	Risiko før tiltak: 🟢	Risiko etter tiltak: 🟢
	Materielle verdier	Risiko før tiltak: 🟡	Risiko etter tiltak: 🟢
	Omdømme	Risiko før tiltak: 🟡	Risiko etter tiltak: 🟢

Risikoreduserende tiltak	**Ansvarlig**	**Registrert**	**Frist**	**Status**
Opplæring i bruk av rigg	Christian Holden	07.04.2016	16.12.2016	I arbeid

Uønsket hendelse: **Skader på rigg**

Konsekvensområde:	Helse	Risiko før tiltak: 🟢	Risiko etter tiltak: 🟢
	Ytre miljø	Risiko før tiltak: 🟢	Risiko etter tiltak: 🟢
	Materielle verdier	Risiko før tiltak: 🟡	Risiko etter tiltak: 🟡
	Omdømme	Risiko før tiltak: 🟢	Risiko etter tiltak: 🟢

Risikoreduserende tiltak	**Ansvarlig**	**Registrert**	**Frist**	**Status**
Opplæring i bruk av rigg	Christian Holden	07.04.2016	16.12.2016	I arbeid

Farekilde: **Bruk av laboratorium**

Uønsket hendelse: **Feil bruk av rigg**

Konsekvensområde: Materielle verdier — Risiko før tiltak: 🟡 Risiko etter tiltak: 🟢

Risikoreduserende tiltak	Ansvarlig	Registrert	Frist	Status
Opplæring i bruk av rigg	Christian Holden	07.04.2016	16.12.2016	I arbeid

Uønsket hendelse: **Mangelfult vedlikehold**

Konsekvensområde: Materielle verdier — Risiko før tiltak: 🟢 Risiko etter tiltak: 🟢

Risikoreduserende tiltak	Ansvarlig	Registrert	Frist	Status
Opplæring i bruk av rigg	Christian Holden	07.04.2016	16.12.2016	I arbeid

Uønsket hendelse: **Brann**

Konsekvensområde:
Helse — Risiko før tiltak: 🟡 Risiko etter tiltak: 🟡
Ytre miljø — Risiko før tiltak: 🟡 Risiko etter tiltak: 🟡
Materielle verdier — Risiko før tiltak: 🟡 Risiko etter tiltak: 🟡
Omdømme — Risiko før tiltak: 🟡 Risiko etter tiltak: 🟡

Risikoreduserende tiltak	Ansvarlig	Registrert	Frist	Status
Ikke ATEX sertifiserte oljer	Andre Listou Ellefsen	06.04.2016	21.04.2016	Evaluert
Opplæring i bruk av rigg	Christian Holden	07.04.2016	16.12.2016	I arbeid

Endelig vurdering

De største gjenværende risikoene er knyttet til konstruksjonen av laboratoriet. Eksisterende tiltak vil til stor grad hindre disse, men avhenger av individuelle kvaliteter som sikkerhetskultur, erfaring og tilrettelegging for trygt arbeid.

Et annet stort faremoment er gass og væsker under trykk, men designet har tatt høyde for dette, og med tilstrekkelig sikkerhetskurs og opplæring i lab vil denne risikoen minimeres.

Laben bil også bli implementert i Cameron sitt lab-oppsett under drift, og vil derfor bli underlagt deres sikkerhetsrutiner. Dette vil bidra til et enda strengere sikkerhetsfokus som vil forbedre den generelle risikosituasjonen.

Totalt sett anser vi sjansen for større skader og ulykker som minimal, men sjansen for mindre overfladiske skader under konstruksjon som middels. Disse er imidlertidig så lite omfattende at de kan behandles med et enkelt førstehjelpsskrin.

Oversikt involverte enheter og personell

En risikovurdering kan gjelde for en, eller flere enheter i organisasjonen. Denne oversikten presenterer involverte enheter og personell for gjeldende risikovurdering.

Enhet /-er risikovurderingen omfatter

- Institutt for produksjons- og kvalitetsteknikk

Deltakere

Andre Listou Ellefsen
Emil Yde Aasen
Sveinung Johan Ohrem

Lesere

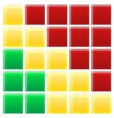
Øyvind Andersen
Øyvind Andersen
Øyvind Andersen
Øyvind Andersen
Gro Mogseth

Andre involverte/interessenter

Typhonix AS
eProcess Technologies
Cameron/Schlumberger
SUBPRO industripartnere

Følgende akseptkriterier er besluttet for risikoområdet Risikovurdering: Helse, miljø og sikkerhet (HMS):

Helse



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🟩	🟨	🟨	🟥	🟥
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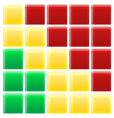
🟩	🟩	🟨	🟨	🟨

Materielle verdier



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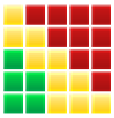
Omdømme



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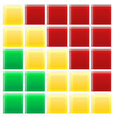
🟩	🟩	🟨	🟨	🟨

Ytre miljø



🟨	🟥	🟥	🟥	🟥
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🟩	🟨	🟨	🟥	🟥
🟩	🟩	🟨	🟨	🟥
🟩	🟩	🟨	🟨	🟨

Oversikt over eksisterende, relevante tiltak som er hensyntatt i risikovurderingen

I tabellen under presenteres eksisterende tiltak som er hensyntatt ved vurdering av sannsynlighet og konsekvens for aktuelle uønskede hendelser.

Farekilde	Uønsket hendelse	Tiltak hensyntatt ved vurdering
Konstruksjon av laboratorium	Kuttskader fra utstyr og/eller materialer	Førstehjelpsskrin
	Kuttskader fra utstyr og/eller materialer	Arbeidshansker
	Kuttskader fra utstyr og/eller materialer	Førstehjelpsskrin
	Alvorlige kuttskader ved bruk av utstyr/maskiner	Sykebåre
	Alvorlige kuttskader ved bruk av utstyr/maskiner	Førstehjelpsskrin
	Alvorlige kuttskader ved bruk av utstyr/maskiner	Arbeidshansker
	Alvorlige kuttskader ved bruk av utstyr/maskiner	Førstehjelpsskrin
	Ulykker ved bruk av løftekran	Sykebåre
	Ulykker ved bruk av løftekran	Vernesko
	Ulykker ved bruk av løftekran	Førstehjelpsskrin
	Ulykker ved bruk av løftekran	Hjelm
	Ulykker ved bruk av løftekran	Hjelm
	Ulykker ved bruk av løftekran	Sykebåre
	Klemskader	Vernesko
	Klemskader	Førstehjelpsskrin
	Klemskader	Førstehjelpsskrin
	Belastningsskader som følge av tunge løft	Sykebåre
	Belastningsskader som følge av tunge løft	Sykebåre
	Påkjørsel av truck	Sykebåre
	Påkjørsel av truck	Sykebåre
	Øyeskader i forbindelse med sveising	Førstehjelpsskrin
	Øyeskader i forbindelse med sveising	Sveisemaske
	Øyeskader i forbindelse med sveising	Sikkerhetskurs
	Øyeskader i forbindelse med sveising	Opplæring av verkstedet
	Øyeskader i forbindelse med sveising	Sveisemaske
	Øyeskader ved små fremmedobjekter	Vernebriller
	Øyeskader ved små fremmedobjekter	Førstehjelpsskrin
	Øyeskader ved små fremmedobjekter	Vernebriller
	Øyeskader ved små fremmedobjekter	Sikkerhetskurs
	Øyeskader ved små fremmedobjekter	Opplæring av verkstedet
	Feil bruk av utstyr og maskiner	Førstehjelpsskrin
	Feil bruk av utstyr og maskiner	Arbeidshansker
	Feil bruk av utstyr og maskiner	Sikkerhetskurs

Konstruksjon av laboratorium	Feil bruk av utstyr og maskiner	Opplæring i verksted
	Feil bruk av utstyr og maskiner	Sikkerhetskurs
	Feil bruk av utstyr og maskiner	Opplæring av verkstedet
	Utløsning av brannalarm	Opplæring i verksted
	Utløsning av brannalarm	Opplæring av verkstedet
	Støt ved oppkobling av elektrisk utstyr	Vernebriller
	Støt ved oppkobling av elektrisk utstyr	Førstehjelpsskrin
	Støt ved oppkobling av elektrisk utstyr	Arbeidshansker
	Støt ved oppkobling av elektrisk utstyr	Sikkerhetskurs
	Støt ved oppkobling av elektrisk utstyr	Opplæring i verksted
	Støt ved oppkobling av elektrisk utstyr	Vernebriller
	Støt ved oppkobling av elektrisk utstyr	Arbeidshansker
	Støt ved oppkobling av elektrisk utstyr	Sikkerhetskurs
	Brann	Brannslage
	Brann	Sykebåre
	Brann	Brannalarmklokke
	Brann	Førstehjelpsskrin
	Brann	Sikkerhetskurs
	Brann	Opplæring i verksted
	Brann	Brannslange
	Brann	Sikkerhetskurs
	Brann	Opplæring av verkstedet
	Brann	Brannalarm
	Støyfare	Sikkerhetskurs
	Støyfare	Opplæring i verksted
	Støyfare	Hørselvern
	Støyfare	Sikkerhetskurs
	Støyfare	Opplæring av verkstedet
	Sikkerhetskultur	Sikkerhetskurs
	Sikkerhetskultur	Opplæring i verksted
	Sikkerhetskultur	Sikkerhetskurs
	Sikkerhetskultur	Opplæring av verkstedet
Bruk av laboratorium	Oljesøl	Sluk/Avløp
	Oljesøl	Sikkerhetskurs
	Oljesøl	Opplæring i verksted
	Oljesøl	Oljesøl barriere
	Oljesøl	Avløp/sluk
	Oljesøl	Sikkerhetskurs
	Oljesøl	Opplæring av verkstedet

Bruk av laboratorium	Vannsøl	Sluk/Avløp
	Vannsøl	Sikkerhetskurs
	Vannsøl	Opplæring i verksted
	Vannsøl	Avløp/sluk
	Vannsøl	Sikkerhetskurs
	Vannsøl	Opplæring av verkstedet
	Øyeskader	Vernebriller
	Øyeskader	Førstehjelpsskrin
	Øyeskader	Sikkerhetskurs
	Øyeskader	Opplæring i verksted
	Øyeskader	Vernebriller
	Øyeskader	Førstehjelpsskrin
	Gass under trykk	Vernesko
	Gass under trykk	Vernebriller
	Gass under trykk	Førstehjelpsskrin
	Gass under trykk	Arbeidshansker
	Gass under trykk	Hjelm
	Gass under trykk	Sikkerhetskurs
	Gass under trykk	Opplæring i verksted
	Gass under trykk	Sikkerhetskurs
	Gass under trykk	Opplæring av verkstedet
	Væsker under trykk	Vernesko
	Væsker under trykk	Vernebriller
	Væsker under trykk	Førstehjelpsskrin
	Væsker under trykk	Arbeidshansker
	Væsker under trykk	Hjelm
	Væsker under trykk	Sikkerhetskurs
	Væsker under trykk	Opplæring i verksted
	Væsker under trykk	Sikkerhetskurs
	Væsker under trykk	Opplæring av verkstedet
	Skader på rigg	Sikkerhetskurs
	Skader på rigg	Opplæring i verksted
	Skader på rigg	Sikkerhetskurs
	Skader på rigg	Opplæring av verkstedet
	Feil bruk av rigg	Sikkerhetskurs
	Feil bruk av rigg	Opplæring i verksted
	Feil bruk av rigg	Sikkerhetskurs
	Feil bruk av rigg	Opplæring av verkstedet
	Mangelfult vedlikehold	Sikkerhetskurs

Bruk av laboratorium	Mangelfult vedlikehold	Opplæring i verksted
	Mangelfult vedlikehold	Sikkerhetskurs
	Mangelfult vedlikehold	Opplæring av verkstedet
	Brann	Brannslage
	Brann	Brannalarmklokke
	Brann	Førstehjelpsskrin
	Brann	Sikkerhetskurs
	Brann	Opplæring i verksted
	Brann	Brannslange
	Brann	Sikkerhetskurs
	Brann	Opplæring av verkstedet
	Brann	Brannalarm

Eksisterende og relevante tiltak med beskrivelse:

Vernesko

[Ingen registreringer]

Vernebriller

[Ingen registreringer]

Førstehjelpsskrin

[Ingen registreringer]

Avløp/sluk

[Ingen registreringer]

Brannslange

[Ingen registreringer]

Arbeidshansker

[Ingen registreringer]

Hjelm

[Ingen registreringer]

Sykebåre

[Ingen registreringer]

Sikkerhetskurs

[Ingen registreringer]

Opplæring av verkstedet

[Ingen registreringer]

Sveisemaske

[Ingen registreringer]

Brannalarm

[Ingen registreringer]

Flyttbart avsug

[Ingen registreringer]

Risikoanalyse med vurdering av sannsynlighet og konsekvens

I denne delen av rapporten presenteres detaljer dokumentasjon av de farer, uønskede hendelser og årsaker som er vurdert. Innledningsvis oppsummeres farer med tilhørende uønskede hendelser som er tatt med i vurderingen.

Følgende farer og uønskede hendelser er vurdert i denne risikovurderingen:

- **Konstruksjon av laboratorium**
    - Kuttskader fra utstyr og/eller materialer
    - Alvorlige kuttskader ved bruk av utstyr/maskiner
    - Ulykker ved bruk av løftekran
    - Klemskader
    - Belastningsskader som følge av tunge løft
    - Påkjørsel av truck
    - Øyeskader i forbindelse med sveising
    - Øyeskader ved små fremmedobjekter
    - Feil bruk av utstyr og maskiner
    - Utløsning av brannalarm
    - Støt ved oppkobling av elektrisk utstyr
    - Brann
    - Støyfare
    - Sikkerhetskultur
- **Bruk av laboratorium**
    - Oljesøl
    - Vannsøl
    - Øyeskader
    - Gass under trykk
    - Væsker under trykk
    - Skader på rigg
    - Feil bruk av rigg
    - Mangelfult vedlikehold
    - Brann

Oversikt over besluttede risikoreduserende tiltak med beskrivelse:

Oljesølbarriere

Planker eller lignende for å begrense omfang av oljesøl

Ikke ATEX sertifiserte oljer

Eliminerer fare for brann i olje

Opplæring i bruk av rigg

Opplæring i bruk av rigg inkluderer generell bruk, faremomenter, verneutstyr og bruk av sensitivt utstyr.

Opplæring/kurs for utstyr tilknyttet konstruksjon av lab

I tillegg til opplæring i verkstedet må det innføres egen opplæring som er tilknyttet konstruksjon av lab. Dette gjelder ulike relevante maskiner og utstyr.

Innleid kvalifisert personell

For sveising, oppkobling av elektrisk utstyr etc.

Konstruksjon av laboratorium (farekilde)

Konstruksjon av laboratorium/Kuttskader fra utstyr og/eller materialer (uønsket hendelse)

Sveiser og endestykker på materialer kan skape kutt på hender og kropp. Utstyr som kniver, avbitertang og sag kan også forårsake kutt av lignende art. Disse kuttskadene begrenser seg til overflate sår som kan behandles med enkel førstehjelp.

Årsak: Skarpe kanter på materialer

Beskrivelse:

Årsak: Bruk av utstyr uten hansker

Beskrivelse:

Samlet sannsynlighet vurdert for hendelsen: Ganske sannsynlig (4)

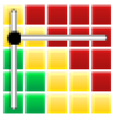
Kommentar til vurdering av sannsynlighet:

[Ingen registreringer]

Vurdering av risiko for følgende konsekvensområde: Helse

Vurdert sannsynlighet (felles for hendelsen): Ganske sannsynlig (4)

Vurdert konsekvens: Liten (1)



Kommentar til vurdering av konsekvens:

[Ingen registreringer]

Konstruksjon av laboratorium/Alvorlige kuttskader ved bruk av utstyr/maskiner (uønsket hendelse)

Utstyr som mekaniske sager, dreiebenker og freser kan føre til alvorlige kuttskader/ avkapp av kroppsdeler med alvorlige konsekvenser.

Samlet sannsynlighet vurdert for hendelsen: Lite sannsynlig (2)

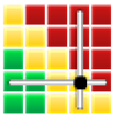
Kommentar til vurdering av sannsynlighet:

[Ingen registreringer]

Vurdering av risiko for følgende konsekvensområde: Helse

Vurdert sannsynlighet (felles for hendelsen): Lite sannsynlig (2)

Vurdert konsekvens: Svært stor (4)



Kommentar til vurdering av konsekvens:

[Ingen registreringer]

Konstruksjon av laboratorium/Ulykker ved bruk av løftekran (uønsket hendelse)

Det er påbudt med hjelm når løftekranen er i bruk. Dersom hengende last skulle falle av fra kran, kan dette medføre svært alvorlige skader og potensielt dødsulykker.

Samlet sannsynlighet vurdert for hendelsen: Svært lite sannsynlig (1)

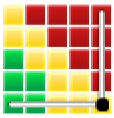
Kommentar til vurdering av sannsynlighet:

[Ingen registreringer]

Vurdering av risiko for følgende konsekvensområde: Helse

Vurdert sannsynlighet (felles for hendelsen): Svært lite sannsynlig (1)

Vurdert konsekvens: Katastrofal (5)



Kommentar til vurdering av konsekvens:

[Ingen registreringer]

Konstruksjon av laboratorium/Klemskader (uønsket hendelse)

Kan forekomme dersom objekter blir sluppet på bein eller kroppsdeler blir ligget mellom to tyngre objekter.

Samlet sannsynlighet vurdert for hendelsen: Sannsynlig (3)

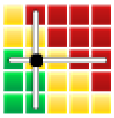
Kommentar til vurdering av sannsynlighet:

[Ingen registreringer]

Vurdering av risiko for følgende konsekvensområde: Helse

Vurdert sannsynlighet (felles for hendelsen): Sannsynlig (3)

Vurdert konsekvens: Middels (2)



Kommentar til vurdering av konsekvens:

[Ingen registreringer]

Konstruksjon av laboratorium/Belastningsskader som følge av tunge løft (uønsket hendelse)

Det vil være flere tunge objekter som skal installeres i konstruksjonen og løft av disse uten korrekt teknikk og utstyr kan medføre belastningsskader.

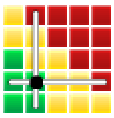
Samlet sannsynlighet vurdert for hendelsen:	Lite sannsynlig (2)

Kommentar til vurdering av sannsynlighet:

[Ingen registreringer]

Vurdering av risiko for følgende konsekvensområde: Helse

Vurdert sannsynlighet (felles for hendelsen):	Lite sannsynlig (2)
Vurdert konsekvens:	Middels (2)



Kommentar til vurdering av konsekvens:

[Ingen registreringer]

Konstruksjon av laboratorium/Påkjørsel av truck (uønsket hendelse)

Truck kjører på området og kan treffe personell som arbeider med konstruksjonen.

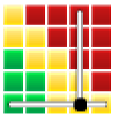
Samlet sannsynlighet vurdert for hendelsen:	Svært lite sannsynlig (1)

Kommentar til vurdering av sannsynlighet:

[Ingen registreringer]

Vurdering av risiko for følgende konsekvensområde: Helse

Vurdert sannsynlighet (felles for hendelsen):	Svært lite sannsynlig (1)
Vurdert konsekvens:	Svært stor (4)



Kommentar til vurdering av konsekvens:

[Ingen registreringer]

Konstruksjon av laboratorium/Øyeskader i forbindelse med sveising (uønsket hendelse)

Dersom hensiktsmessig utstyr ikke blir benyttet ved sveising kan dette medføre sveiseblindhet og andre øyeskader.

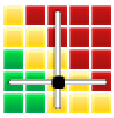
Samlet sannsynlighet vurdert for hendelsen:	Lite sannsynlig (2)

Kommentar til vurdering av sannsynlighet:

[Ingen registreringer]

Vurdering av risiko for følgende konsekvensområde: Helse

Vurdert sannsynlighet (felles for hendelsen):	Lite sannsynlig (2)
Vurdert konsekvens:	Stor (3)



Kommentar til vurdering av konsekvens:

[Ingen registreringer]

Konstruksjon av laboratorium/Øyeskader ved små fremmedobjekter (uønsket hendelse)

Spon fra fresing og dreiing kan treffe øyne og forårsake skader.

Samlet sannsynlighet vurdert for hendelsen: Svært lite sannsynlig (1)

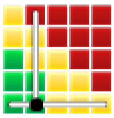
Kommentar til vurdering av sannsynlighet:

[Ingen registreringer]

Vurdering av risiko for følgende konsekvensområde: Helse

Vurdert sannsynlighet (felles for hendelsen): Svært lite sannsynlig (1)

Vurdert konsekvens: Middels (2)



Kommentar til vurdering av konsekvens:

[Ingen registreringer]

Konstruksjon av laboratorium/Feil bruk av utstyr og maskiner (uønsket hendelse)

Dersom operatør ikke har tilstrekkelig kjennskap/kursing til utstyr og maskinen han/hun bruker, kan dette føre til skader på både utstyr og personell.

Samlet sannsynlighet vurdert for hendelsen: Lite sannsynlig (2)

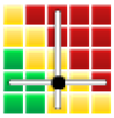
Kommentar til vurdering av sannsynlighet:

[Ingen registreringer]

Vurdering av risiko for følgende konsekvensområde: Helse

Vurdert sannsynlighet (felles for hendelsen): Lite sannsynlig (2)

Vurdert konsekvens: Stor (3)



Kommentar til vurdering av konsekvens:

[Ingen registreringer]

Konstruksjon av laboratorium/Utløsning av brannalarm (uønsket hendelse)

Dersom sveisearbeid eller annet arbeid blir iverksatt uten egnet avsug eller deaktivering av røyksensorer, kan dette medføre at brannalarm blir aktivert av røyk uten at det er tilløp til brann.

Samlet sannsynlighet vurdert for hendelsen: Lite sannsynlig (2)

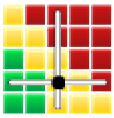
Kommentar til vurdering av sannsynlighet:

[Ingen registreringer]

Vurdering av risiko for følgende konsekvensområde: Omdømme

Vurdert sannsynlighet (felles for hendelsen): Lite sannsynlig (2)

Vurdert konsekvens: Stor (3)



Kommentar til vurdering av konsekvens:

[Ingen registreringer]

Konstruksjon av laboratorium/Støt ved oppkobling av elektrisk utstyr (uønsket hendelse)

Oppkobling av elektrisk utstyr som pumper, sensorer og ventiler medfører en risiko for kortslutninger og elektriske støt.

Samlet sannsynlighet vurdert for hendelsen: Svært lite sannsynlig (1)

Kommentar til vurdering av sannsynlighet:

[Ingen registreringer]

Vurdering av risiko for følgende konsekvensområde: Helse

Vurdert sannsynlighet (felles for hendelsen): Svært lite sannsynlig (1)

Vurdert konsekvens: Stor (3)

Kommentar til vurdering av konsekvens:

[Ingen registreringer]

Konstruksjon av laboratorium/Brann (uønsket hendelse)

Ved bruk av sveiseutstyr eller ved oppkobling av det elektriske anlegget kan det forekomme tilløp til brann.

Samlet sannsynlighet vurdert for hendelsen: Svært lite sannsynlig (1)

Kommentar til vurdering av sannsynlighet:

[Ingen registreringer]

Vurdering av risiko for følgende konsekvensområde: Helse

Vurdert sannsynlighet (felles for hendelsen): Svært lite sannsynlig (1)

Vurdert konsekvens: Stor (3)

Kommentar til vurdering av konsekvens:

[Ingen registreringer]

Konstruksjon av laboratorium/Støyfare (uønsket hendelse)

Støyfare fra enkelte maskiner og utstyr kan medføre skader på hørsel. Arbeid som foregår andre steder av verkstedet kan også medføre støy.

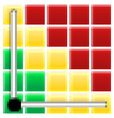
Samlet sannsynlighet vurdert for hendelsen: Svært lite sannsynlig (1)

Kommentar til vurdering av sannsynlighet:

[Ingen registreringer]

Vurdering av risiko for følgende konsekvensområde: Helse

Vurdert sannsynlighet (felles for hendelsen): Svært lite sannsynlig (1)



Vurdert konsekvens: Liten (1)

Kommentar til vurdering av konsekvens:

[Ingen registreringer]

Konstruksjon av laboratorium/Sikkerhetskultur (uønsket hendelse)

Dersom sikkerhetskulturen på verkstedet er dårlig, kan dette føre til mangelfull bruk av personlig verneutstyr og etterfølgelse av prosedyrer.

Samlet sannsynlighet vurdert for hendelsen: Svært lite sannsynlig (1)

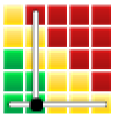
Kommentar til vurdering av sannsynlighet:

[Ingen registreringer]

Vurdering av risiko for følgende konsekvensområde: Helse

Vurdert sannsynlighet (felles for hendelsen): Svært lite sannsynlig (1)

Vurdert konsekvens: Middels (2)



Kommentar til vurdering av konsekvens:

[Ingen registreringer]

Bruk av laboratorium (farekilde)

Bruk av laboratorium/Oljesøl (uønsket hendelse)

Ved lekkasjer kan det forekommer oljesøl.

Samlet sannsynlighet vurdert for hendelsen: Lite sannsynlig (2)

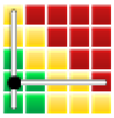
Kommentar til vurdering av sannsynlighet:

[Ingen registreringer]

Vurdering av risiko for følgende konsekvensområde: Helse

Vurdert sannsynlighet (felles for hendelsen): Lite sannsynlig (2)

Vurdert konsekvens: Liten (1)



Kommentar til vurdering av konsekvens:

[Ingen registreringer]

Bruk av laboratorium/Vannsøl (uønsket hendelse)

Ved lekkasjer kan det forekommer vannsøl.

Samlet sannsynlighet vurdert for hendelsen: Ganske sannsynlig (4)

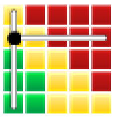
Kommentar til vurdering av sannsynlighet:

[Ingen registreringer]

Vurdering av risiko for følgende konsekvensområde: Helse

Vurdert sannsynlighet (felles for hendelsen): Ganske sannsynlig (4)

Vurdert konsekvens: Liten (1)



Kommentar til vurdering av konsekvens:

[Ingen registreringer]

Bruk av laboratorium/Øyeskader (uønsket hendelse)

Væsker ved lekkasjer og ulykker kan komme i kontakt med øyne.

Samlet sannsynlighet vurdert for hendelsen: Svært lite sannsynlig (1)

Kommentar til vurdering av sannsynlighet:

[Ingen registreringer]

Vurdering av risiko for følgende konsekvensområde: Helse

Vurdert sannsynlighet (felles for hendelsen): Svært lite sannsynlig (1)

Vurdert konsekvens: Stor (3)

Kommentar til vurdering av konsekvens:

[Ingen registreringer]

Bruk av laboratorium/Gass under trykk (uønsket hendelse)

Eksplosjoner kan forekomme dersom trykket i systemet er høyere enn dimensjonerte designverdier.

Samlet sannsynlighet vurdert for hendelsen: Svært lite sannsynlig (1)

Kommentar til vurdering av sannsynlighet:

[Ingen registreringer]

Vurdering av risiko for følgende konsekvensområde: Helse

Vurdert sannsynlighet (felles for hendelsen): Svært lite sannsynlig (1)

Vurdert konsekvens: Stor (3)

Kommentar til vurdering av konsekvens:

[Ingen registreringer]

Bruk av laboratorium/Væsker under trykk (uønsket hendelse)

Eksplosjoner kan forekomme dersom trykket i systemet er høyere enn dimensjonerte designverdier.

Samlet sannsynlighet vurdert for hendelsen: Svært lite sannsynlig (1)

Kommentar til vurdering av sannsynlighet:

[Ingen registreringer]

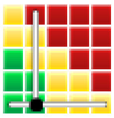
Vurdering av risiko for følgende konsekvensområde: Helse

Vurdert sannsynlighet (felles for hendelsen): Svært lite sannsynlig (1)

Vurdert konsekvens: Middels (2)

Kommentar til vurdering av konsekvens:

[Ingen registreringer]



Bruk av laboratorium/Skader på rigg (uønsket hendelse)

Dersom riggen ikke er forsvarlig sikret mot omgivelsene kan dette føre til at logistikkoperasjoner eller personell kommer i skade for å kollidere med riggen.

Samlet sannsynlighet vurdert for hendelsen: Svært lite sannsynlig (1)

Kommentar til vurdering av sannsynlighet:

[Ingen registreringer]

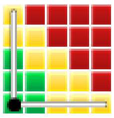
Vurdering av risiko for følgende konsekvensområde: Helse

Vurdert sannsynlighet (felles for hendelsen): Svært lite sannsynlig (1)

Vurdert konsekvens: Liten (1)

Kommentar til vurdering av konsekvens:

[Ingen registreringer]



Bruk av laboratorium/Feil bruk av rigg (uønsket hendelse)

Feil bruk av rigg kan føre til skader på enkelt komponenter, sensorer, og annet sensitivt utstyr.

Samlet sannsynlighet vurdert for hendelsen: Lite sannsynlig (2)

Kommentar til vurdering av sannsynlighet:

[Ingen registreringer]

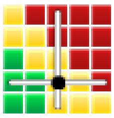
Vurdering av risiko for følgende konsekvensområde: Materielle verdier

Vurdert sannsynlighet (felles for hendelsen): Lite sannsynlig (2)

Vurdert konsekvens: Stor (3)

Kommentar til vurdering av konsekvens:

[Ingen registreringer]



Bruk av laboratorium/Mangelfult vedlikehold (uønsket hendelse)

Dårlige prosedyrer og rutiner for inspeksjon og vedlikehold av rigg kan medføre korrosjons- og erosjonsskader.

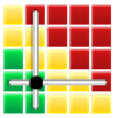
Samlet sannsynlighet vurdert for hendelsen: Lite sannsynlig (2)

Kommentar til vurdering av sannsynlighet:

[Ingen registreringer]

Vurdering av risiko for følgende konsekvensområde: Materielle verdier

Vurdert sannsynlighet (felles for hendelsen): Lite sannsynlig (2)



Vurdert konsekvens: Middels (2)

Kommentar til vurdering av konsekvens:

[Ingen registreringer]

Bruk av laboratorium/Brann (uønsket hendelse)

Dersom gnister forekommer fra det elektriske anlegget kan dette medføre brann.

Samlet sannsynlighet vurdert for hendelsen: Svært lite sannsynlig (1)

Kommentar til vurdering av sannsynlighet:

[Ingen registreringer]

Vurdering av risiko for følgende konsekvensområde: Helse

Vurdert sannsynlighet (felles for hendelsen): Svært lite sannsynlig (1)

Vurdert konsekvens: Stor (3)

Kommentar til vurdering av konsekvens:

[Ingen registreringer]

Oversikt over besluttede risikoreduserende tiltak:

Under presenteres en oversikt over risikoreduserende tiltak som skal bidra til å reduseres sannsynlighet og/eller konsekvens for uønskede hendelser.

- Oljesølbarriere
- Ikke ATEX sertifiserte oljer
- Opplæring i bruk av rigg
- Opplæring/kurs for utstyr tilknyttet konstruksjon av lab
- Innleid kvalifisert personell

Oversikt over besluttede risikoreduserende tiltak med beskrivelse:

Oljesølbarriere

Planker eller lignende for å begrense omfang av oljesøl

Tiltak besluttet av:	Andre Listou Ellefsen
Ansvarlig for gjennomføring:	Christian Holden
Frist for gjennomføring:	12/19/2016

Ikke ATEX sertifiserte oljer

Eliminerer fare for brann i olje

Tiltak besluttet av:	Andre Listou Ellefsen
Ansvarlig for gjennomføring:	Andre Listou Ellefsen
Frist for gjennomføring:	4/21/2016

Opplæring i bruk av rigg

Opplæring i bruk av rigg inkluderer generell bruk, faremomenter, verneutstyr og bruk av sensitivt utstyr.

Tiltak besluttet av:	Andre Listou Ellefsen
Ansvarlig for gjennomføring:	Christian Holden
Frist for gjennomføring:	12/16/2016

Opplæring/kurs for utstyr tilknyttet konstruksjon av lab

I tillegg til opplæring i verkstedet må det innføres egen opplæring som er tilknyttet konstruksjon av lab. Dette gjelder ulike relevante maskiner og utstyr.

Tiltak besluttet av:	Andre Listou Ellefsen
Ansvarlig for gjennomføring:	Christian Holden
Frist for gjennomføring:	8/15/2016

Innleid kvalifisert personell

For sveising, oppkobling av elektrisk utstyr etc.

Tiltak besluttet av:	Andre Listou Ellefsen
Ansvarlig for gjennomføring:	Christian Holden
Frist for gjennomføring:	8/15/2016

Farekilde: **Konstruksjon av laboratorium**

Uønsket hendelse: **Kuttskader fra utstyr og/eller materialer**

Opprinnelig sannsynlighet: Ganske sannsynlig (4)

Opprinnelig begrunnelse:

Revurdert sannsynlighet: Lite sannsynlig (2)

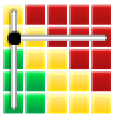
Revurdert begrunnelse:

Konsekvensvurderinger:

Konsekvensområde: Helse

Opprinnelig vurdering:

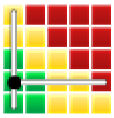
Konsekvens: Liten (1)



Begrunnelse:

Vurdering etter tiltak:

Konsekvens: Liten (1)



Begrunnelse:

Uønsket hendelse: **Alvorlige kuttskader ved bruk av utstyr/maskiner**

Opprinnelig sannsynlighet: Lite sannsynlig (2)

Opprinnelig begrunnelse:

Revurdert sannsynlighet: Svært lite sannsynlig (1)

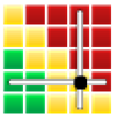
Revurdert begrunnelse:

Konsekvensvurderinger:

Konsekvensområde: Helse

Opprinnelig vurdering:

Konsekvens: Svært stor (4)



Begrunnelse:

Vurdering etter tiltak:

Konsekvens: Stor (3)

Begrunnelse:

Uønsket hendelse: **Ulykker ved bruk av løftekran**

Opprinnelig sannsynlighet: Svært lite sannsynlig (1)

Opprinnelig begrunnelse:

Revurdert sannsynlighet: Svært lite sannsynlig (1)

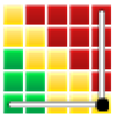
Revurdert begrunnelse:

Konsekvensvurderinger:

Konsekvensområde: Helse

Opprinnelig vurdering:

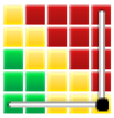
Konsekvens: Katastrofal (5)



Begrunnelse:

Vurdering etter tiltak:

Konsekvens: Katastrofal (5)



Begrunnelse:

Uønsket hendelse: **Klemskader**

Opprinnelig sannsynlighet: Sannsynlig (3)

Opprinnelig begrunnelse:

Revurdert sannsynlighet: Svært lite sannsynlig (1)

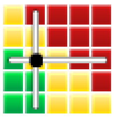
Revurdert begrunnelse:

Konsekvensvurderinger:

Konsekvensområde: Helse

Opprinnelig vurdering:

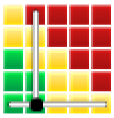
Konsekvens: Middels (2)



Begrunnelse:

Vurdering etter tiltak:

Konsekvens: Middels (2)



Begrunnelse:

Uønsket hendelse: **Belastningsskader som følge av tunge løft**

Opprinnelig sannsynlighet: Lite sannsynlig (2)

Opprinnelig begrunnelse:

Revurdert sannsynlighet: Lite sannsynlig (2)

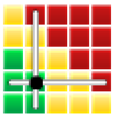
Revurdert begrunnelse:

Konsekvensvurderinger:

Konsekvensområde: Helse

Opprinnelig vurdering:

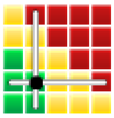
Konsekvens: Middels (2)



Begrunnelse:

Vurdering etter tiltak:

Konsekvens: Middels (2)



Begrunnelse:

Uønsket hendelse: **Påkjørsel av truck**

Opprinnelig sannsynlighet: Svært lite sannsynlig (1)

Opprinnelig begrunnelse:

Revurdert sannsynlighet: Svært lite sannsynlig (1)

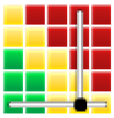
Revurdert begrunnelse:

Konsekvensvurderinger:

Konsekvensområde: Helse

Opprinnelig vurdering:

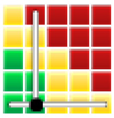
Konsekvens: Svært stor (4)



Begrunnelse:

Vurdering etter tiltak:

Konsekvens: Middels (2)



Begrunnelse:

Uønsket hendelse: **Øyeskader i forbindelse med sveising**

Opprinnelig sannsynlighet: Lite sannsynlig (2)

Opprinnelig begrunnelse:

Revurdert sannsynlighet: Svært lite sannsynlig (1)

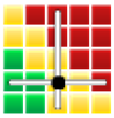
Revurdert begrunnelse:

Konsekvensvurderinger:

Konsekvensområde: Helse

Opprinnelig vurdering:

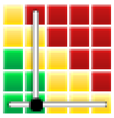
Konsekvens: Stor (3)



Begrunnelse:

Vurdering etter tiltak:

Konsekvens: Middels (2)



Begrunnelse:

Uønsket hendelse: **Øyeskader ved små fremmedobjekter**

Opprinnelig sannsynlighet: Svært lite sannsynlig (1)

Opprinnelig begrunnelse:

Revurdert sannsynlighet: Svært lite sannsynlig (1)

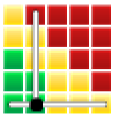
Revurdert begrunnelse:

Konsekvensvurderinger:

Konsekvensområde: Helse

Opprinnelig vurdering:

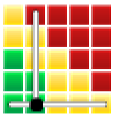
Konsekvens: Middels (2)



Begrunnelse:

Vurdering etter tiltak:

Konsekvens: Middels (2)



Begrunnelse:

Uønsket hendelse: **Feil bruk av utstyr og maskiner**

Opprinnelig sannsynlighet: Lite sannsynlig (2)

Opprinnelig begrunnelse:

Revurdert sannsynlighet: Lite sannsynlig (2)

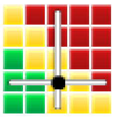
Revurdert begrunnelse:

Konsekvensvurderinger:

Konsekvensområde: Helse

Opprinnelig vurdering:

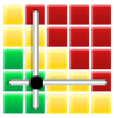
Konsekvens: Stor (3)



Begrunnelse:

Vurdering etter tiltak:

Konsekvens: Middels (2)

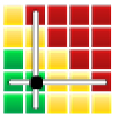


Begrunnelse:

Konsekvensområde: Materielle verdier

Opprinnelig vurdering:

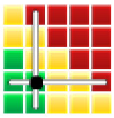
Konsekvens: Middels (2)



Begrunnelse:

Vurdering etter tiltak:

Konsekvens: Middels (2)



Begrunnelse:

Uønsket hendelse: **Utløsning av brannalarm**

Opprinnelig sannsynlighet: Lite sannsynlig (2)

Opprinnelig begrunnelse:

Revurdert sannsynlighet: Svært lite sannsynlig (1)

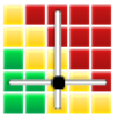
Revurdert begrunnelse:

Konsekvensvurderinger:

Konsekvensområde: Omdømme

Opprinnelig vurdering:

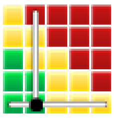
Konsekvens: Stor (3)



Begrunnelse:

Vurdering etter tiltak:

Konsekvens: Middels (2)



Begrunnelse:

Uønsket hendelse: **Støt ved oppkobling av elektrisk utstyr**

Opprinnelig sannsynlighet: Svært lite sannsynlig (1)

Opprinnelig begrunnelse:

Revurdert sannsynlighet: Svært lite sannsynlig (1)

Revurdert begrunnelse:

Konsekvensvurderinger:

Konsekvensområde: Helse

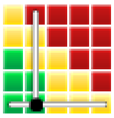
Opprinnelig vurdering:

Konsekvens: Stor (3)

Begrunnelse:

Vurdering etter tiltak:

Konsekvens: Middels (2)



Begrunnelse:

Uønsket hendelse: **Brann**

Opprinnelig sannsynlighet: Svært lite sannsynlig (1)

Opprinnelig begrunnelse:

Revurdert sannsynlighet: Svært lite sannsynlig (1)

Revurdert begrunnelse:

Konsekvensvurderinger:

Konsekvensområde: Helse

Opprinnelig vurdering:

Konsekvens: Stor (3)

Begrunnelse:

Vurdering etter tiltak:

Konsekvens: Middels (2)

Begrunnelse:

Konsekvensområde: Ytre miljø

Opprinnelig vurdering:

Konsekvens: Katastrofal (5)

Begrunnelse:

Vurdering etter tiltak:

Konsekvens: Middels (2)

Begrunnelse:

Konsekvensområde: Materielle verdier

Opprinnelig vurdering:

Konsekvens: Katastrofal (5)

Begrunnelse:

Vurdering etter tiltak:

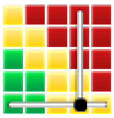
Konsekvens: Stor (3)

Begrunnelse:

Konsekvensområde: Omdømme

Opprinnelig vurdering:

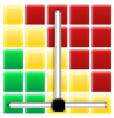
Konsekvens: Svært stor (4)



Begrunnelse:

Vurdering etter tiltak:

Konsekvens: Stor (3)



Begrunnelse:

Uønsket hendelse: **Sikkerhetskultur**

Opprinnelig sannsynlighet: Svært lite sannsynlig (1)

Opprinnelig begrunnelse:

Revurdert sannsynlighet: Svært lite sannsynlig (1)

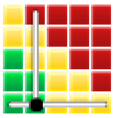
Revurdert begrunnelse:

Konsekvensvurderinger:

Konsekvensområde: Helse

Opprinnelig vurdering:

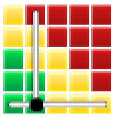
Konsekvens: Middels (2)



Begrunnelse:

Vurdering etter tiltak:

Konsekvens: Middels (2)

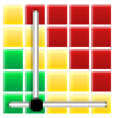


Begrunnelse:

Konsekvensområde: Omdømme

Opprinnelig vurdering:

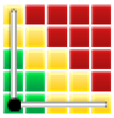
Konsekvens: Middels (2)



Begrunnelse:

Vurdering etter tiltak:

Konsekvens: Liten (1)



Begrunnelse:

Farekilde: **Bruk av laboratorium**

Uønsket hendelse: **Oljesøl**

Opprinnelig sannsynlighet: Lite sannsynlig (2)

Opprinnelig begrunnelse:

Revurdert sannsynlighet: Lite sannsynlig (2)

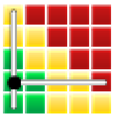
Revurdert begrunnelse:

Konsekvensvurderinger:

Konsekvensområde: Helse

Opprinnelig vurdering:

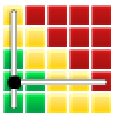
Konsekvens: Liten (1)



Begrunnelse:

Vurdering etter tiltak:

Konsekvens: Liten (1)

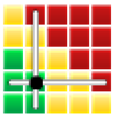


Begrunnelse:

Konsekvensområde: Ytre miljø

Opprinnelig vurdering:

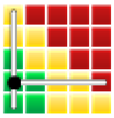
Konsekvens: Middels (2)



Begrunnelse:

Vurdering etter tiltak:

Konsekvens: Liten (1)

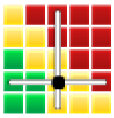


Begrunnelse:

Konsekvensområde: Materielle verdier

Opprinnelig vurdering:

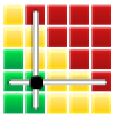
Konsekvens: Stor (3)



Begrunnelse:

Vurdering etter tiltak:

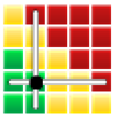
Konsekvens: Middels (2)



Begrunnelse:

Konsekvensområde: Omdømme

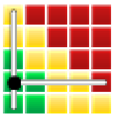
Opprinnelig vurdering:



Konsekvens: Middels (2)

Begrunnelse:

Vurdering etter tiltak:



Konsekvens: Liten (1)

Begrunnelse:

Uønsket hendelse: **Vannsøl**

Opprinnelig sannsynlighet: Ganske sannsynlig (4)

Opprinnelig begrunnelse:

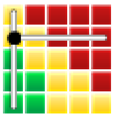
Revurdert sannsynlighet: Sannsynlig (3)

Revurdert begrunnelse:

Konsekvensvurderinger:

Konsekvensområde: Helse

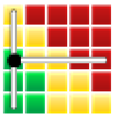
Opprinnelig vurdering:



Konsekvens: Liten (1)

Begrunnelse:

Vurdering etter tiltak:

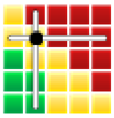


Konsekvens: Liten (1)

Begrunnelse:

Konsekvensområde: Ytre miljø

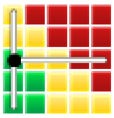
Opprinnelig vurdering:



Konsekvens: Middels (2)

Begrunnelse:

Vurdering etter tiltak:

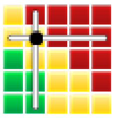


Konsekvens: Liten (1)

Begrunnelse:

Konsekvensområde: Materielle verdier

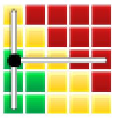
Opprinnelig vurdering:



Konsekvens: Middels (2)

Begrunnelse:

Vurdering etter tiltak:

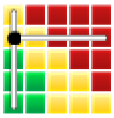


Konsekvens: Liten (1)

Begrunnelse:

Konsekvensområde: Omdømme

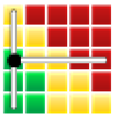
Opprinnelig vurdering:



Konsekvens: Liten (1)

Begrunnelse:

Vurdering etter tiltak:



Konsekvens: Liten (1)

Begrunnelse:

Uønsket hendelse: **Øyeskader**

Opprinnelig sannsynlighet: Svært lite sannsynlig (1)

Opprinnelig begrunnelse:

Revurdert sannsynlighet: Svært lite sannsynlig (1)

Revurdert begrunnelse:

Konsekvensvurderinger:

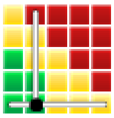
Konsekvensområde: Helse

Opprinnelig vurdering:

Konsekvens: Stor (3)

Begrunnelse:

Vurdering etter tiltak:



Konsekvens: Middels (2)

Begrunnelse:

Uønsket hendelse: **Gass under trykk**

Opprinnelig sannsynlighet: Svært lite sannsynlig (1)

Opprinnelig begrunnelse:

Revurdert sannsynlighet: Svært lite sannsynlig (1)

Revurdert begrunnelse:

Konsekvensvurderinger:

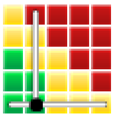
Konsekvensområde: Helse

Opprinnelig vurdering:

Konsekvens: Stor (3)

Begrunnelse:

Vurdering etter tiltak:

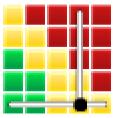


Konsekvens: Middels (2)

Begrunnelse:

Konsekvensområde: Materielle verdier

Opprinnelig vurdering:



Konsekvens: Svært stor (4)

Begrunnelse:

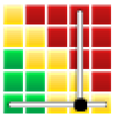
Vurdering etter tiltak:

Konsekvens: Stor (3)

Begrunnelse:

Konsekvensområde: Omdømme

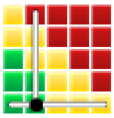
Opprinnelig vurdering:



Konsekvens: Svært stor (4)

Begrunnelse:

Vurdering etter tiltak:



Konsekvens: Middels (2)

Begrunnelse:

Uønsket hendelse: **Væsker under trykk**

Opprinnelig sannsynlighet: Svært lite sannsynlig (1)

Opprinnelig begrunnelse:

Revurdert sannsynlighet: Svært lite sannsynlig (1)

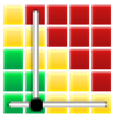
Revurdert begrunnelse:

Konsekvensvurderinger:

Konsekvensområde: Helse

Opprinnelig vurdering:

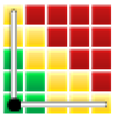
Konsekvens: Middels (2)



Begrunnelse:

Vurdering etter tiltak:

Konsekvens: Liten (1)

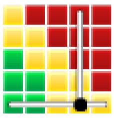


Begrunnelse:

Konsekvensområde: Materielle verdier

Opprinnelig vurdering:

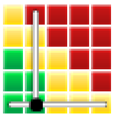
Konsekvens: Svært stor (4)



Begrunnelse:

Vurdering etter tiltak:

Konsekvens: Middels (2)

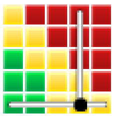


Begrunnelse:

Konsekvensområde: Omdømme

Opprinnelig vurdering:

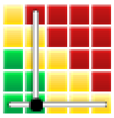
Konsekvens: Svært stor (4)



Begrunnelse:

Vurdering etter tiltak:

Konsekvens: Middels (2)



Begrunnelse:

Uønsket hendelse: **Skader på rigg**

Opprinnelig sannsynlighet: Svært lite sannsynlig (1)

Opprinnelig begrunnelse:

Revurdert sannsynlighet: Svært lite sannsynlig (1)

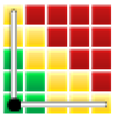
Revurdert begrunnelse:

Konsekvensvurderinger:

Konsekvensområde: Helse

Opprinnelig vurdering:

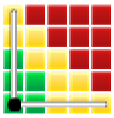
Konsekvens: Liten (1)



Begrunnelse:

Vurdering etter tiltak:

Konsekvens: Liten (1)

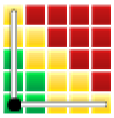


Begrunnelse:

Konsekvensområde: Ytre miljø

Opprinnelig vurdering:

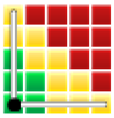
Konsekvens: Liten (1)



Begrunnelse:

Vurdering etter tiltak:

Konsekvens: Liten (1)

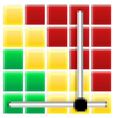


Begrunnelse:

Konsekvensområde: Materielle verdier

Opprinnelig vurdering:

Konsekvens: Svært stor (4)



Begrunnelse:

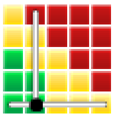
Vurdering etter tiltak:

Konsekvens: Stor (3)

Begrunnelse:

Konsekvensområde: Omdømme

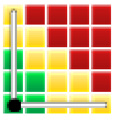
Opprinnelig vurdering:



Konsekvens: Middels (2)

Begrunnelse:

Vurdering etter tiltak:



Konsekvens: Liten (1)

Begrunnelse:

Uønsket hendelse: **Feil bruk av rigg**

Opprinnelig sannsynlighet: Lite sannsynlig (2)

Opprinnelig begrunnelse:

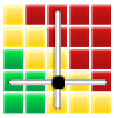
Revurdert sannsynlighet: Svært lite sannsynlig (1)

Revurdert begrunnelse:

Konsekvensvurderinger:

Konsekvensområde: Materielle verdier

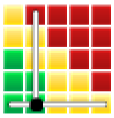
Opprinnelig vurdering:



Konsekvens: Stor (3)

Begrunnelse:

Vurdering etter tiltak:



Konsekvens: Middels (2)

Begrunnelse:

Uønsket hendelse: **Mangelfult vedlikehold**

Opprinnelig sannsynlighet: Lite sannsynlig (2)

Opprinnelig begrunnelse:

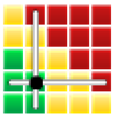
Revurdert sannsynlighet: Svært lite sannsynlig (1)

Revurdert begrunnelse:

Konsekvensvurderinger:

Konsekvensområde: Materielle verdier

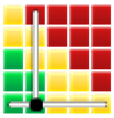
Opprinnelig vurdering:



Konsekvens: Middels (2)

Begrunnelse:

Vurdering etter tiltak:



Konsekvens: Middels (2)

Begrunnelse:

Uønsket hendelse: **Brann**

Opprinnelig sannsynlighet: Svært lite sannsynlig (1)

Opprinnelig begrunnelse:

Revurdert sannsynlighet: Svært lite sannsynlig (1)

Revurdert begrunnelse:

Konsekvensvurderinger:

Konsekvensområde: Helse

Opprinnelig vurdering:

Konsekvens: Stor (3)

Begrunnelse:

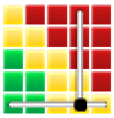
Vurdering etter tiltak:

Konsekvens: Stor (3)

Begrunnelse:

Konsekvensområde: Ytre miljø

Opprinnelig vurdering:



Konsekvens: Svært stor (4)

Begrunnelse:

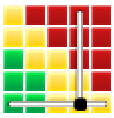
Vurdering etter tiltak:

Konsekvens: Stor (3)

Begrunnelse:

Konsekvensområde: Materielle verdier

Opprinnelig vurdering:



Konsekvens: Svært stor (4)

Begrunnelse:

Vurdering etter tiltak:

Konsekvens: Stor (3)

Begrunnelse:

Konsekvensområde: Omdømme

Opprinnelig vurdering:

Konsekvens: Stor (3)

Begrunnelse:

Vurdering etter tiltak:

Konsekvens: Stor (3)

Begrunnelse: