<table>
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<tr>
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Title of thesis: VRD Performance Testing Project

**Topic and scope of work, with activities:**
Due to seabed subsidence and ageing facilities, the Valhall field is to have a new integrated Production and Hotel (PH) facility installed to exploit the remaining reserves. The new PH facility comprises a fixed steel platform installed to the south side of one of the existing platforms and linked by two bridges. PH compromises a 180 bed Quarters module and 19 000 m$^3$/d (oil) and 4 MSm$^3$/d (gas) processing deck with utilities and flare structure. Part of the handover process from the Project team to Operation is assurance that the process and utility plant performs according to the design. To achieve this objective the project start up team needs to develop Plant Performance Test procedure that can be executed during the commissioning and early operation phases of the project. Along with that, the candidate will look closer into one of the systems, the seawater system, and follow the process of selecting the components in a system.

**Topic**
1) The candidate will give a description of the quality process with verification of the requirements that has been set according to the agreement/delivery of a technical system. This includes every effort from inspection, simulations and calculation to testing of components and systems. In this thesis there is chosen a seawater system. The quality process starts when selecting equipment and supplier and ends with handing over a complete system to production. Enlightened contents are quality assurance measures, different tests, visit to the construction area, accept criteria, relevant standards, reference literature etc.

2) The candidate will give a literature search to find relevant articles concerning the quality process of such systems. There will also be given a description of the seawater system chosen for VRD, including build-up and function. The description will include an identification of operation and maintenance.

3) The candidate will prepare a performance test/functioning test for the chosen system, and other essential systems in the VRD process module. The candidate should give suggestions to scope of quality assurance measures (f. ex. tests) that should be considered. Further on there should be explained why these tests are relevant and how the test should be carried through.

4) The candidate will prepare a performance test procedure of the following equipment.
- Export compressors
- Crude oil export pumps
- HP/LP flare knock-out drum pumps
- Firewater pumps
- Other utility pumps (e.g. cooling medium, jet water)

The candidate will hand in a detailed work plan to the institute, with a scheme over the disposal time the candidate has got for preparing the thesis.

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Abstract

This master thesis is written on the subject of BP Norway’s installation of a new field centre (PH), at Valhall. The project, called Valhall Re-Development (VRD), needed to outline procedures on how to verify performance of equipment installed into the process module at PH.

The purpose of developing these procedures is to make a program on how to verify that BP Norway, as the purchaser, receives the equipment and systems they have ordered. The aim of the performance test is to verify that the equipment guarantee points are capable of achieving rated production.

Systems that have been specified in the thesis include the seawater system, where a total system description has been given along with maintenance program, operational modus and performance tests.

Other systems that have been specified through the thesis are rotational equipment like firewater pumps, cooling medium pumps, oil booster pumps, oil export pumps and export compressors. For this equipment, a brief performance verification program is outlined to verify that the equipment is capable of meeting the designed criteria’s and the specifications BP Norway has set.

Along with the technical part that evolves around the process module at PH, the thesis also consists of a literary part that discusses the various aspects of designing a new system and what phases that has to be considered. This part describes the two parties involved in a trade and what the purchaser has to consider during the designing period. In this lies verification of quality assurance, design criteria’s, performance specifications, verification tests etc.

The second part of the thesis gives a well-designed program on how to verify the promised performance and how to locate faults and mismatches. The thesis also consists of a discussion part where different aspects of the thesis are represented. This includes problem approaches related to the procedures and aspects that could lead to gaps in the resulting part.
Preface

This thesis is concerned around BP Norway’s project VRD, a project of installing a new field centre at Valhall (PH). The thesis intention was to outline a program for testing the many items of equipment and systems at the new platform. Particular tests were to qualify assure the performance of the equipment, to be sure that BP Norway, as the purchaser, got the agreed product.

The thesis is written during the five first months of 2010, at VRD-project’s headquarter, Trim-Towers, at Sandnes. This location gave a close collaboration between the candidate and the Start-up team of the project. The candidate has also had close relation with the University of Stavanger, and with the candidate’s internal supervisor.

Through the VRD-project’s common document hub, ShareCat, the candidate has had full access to all the relevant documentation of the project. This involves documents from the system designers as well as subcontractors for the different equipments.
Acknowledgments
This thesis is written in cooperation with BP Norway, and is concerned around their project VRD. I therefore have to give my biggest gratitude to this company, which I also am a proud employer of.

In BP Norway, my closest superior during the thesis has been Graeme Neil, who is the Start-Up Manager for VRD, and the process engineer Charles Honner. I therefore wish to give these two men my highest gratitude for all the help and support I have received throughout the project.

I also wish to give my internal supervisor at University of Stavanger, Conrad Carstensen, the highest of appreciations for the help and support I have received throughout the thesis.

Most of all I want to thank my team leaders at Valhall, Arvid Stavland and Dag Adolfsen, who have organized my full-time job offshore in a way that has made it possible for me to graduate through the master degree.

Åsbjørn Enerstvedt
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VRD Plant Performance Testing Project

Definitions

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<tr>
<td>VRD</td>
<td>Valhall Re-Development</td>
</tr>
<tr>
<td>PH</td>
<td>Process and Hotel</td>
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<tr>
<td>LQ</td>
<td>Living Quarter</td>
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<tr>
<td>ESP</td>
<td>Electrical Submersible Pump</td>
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<tr>
<td>WP</td>
<td>Wellhead Platform</td>
</tr>
<tr>
<td>VFN</td>
<td>Valhall Flank North</td>
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<tr>
<td>UCP</td>
<td>Unit Control Panel</td>
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<tr>
<td>FAT</td>
<td>Factory Acceptance Test</td>
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<tr>
<td>LP</td>
<td>Low Pressure</td>
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<tr>
<td>mlc</td>
<td>meter liquid column</td>
</tr>
<tr>
<td>LAT</td>
<td>Lowest Astronomical Tide</td>
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<tr>
<td>IGBT</td>
<td>Insulated Gate Bipolar Transistors</td>
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<tr>
<td>PCS</td>
<td>Process Control System</td>
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<tr>
<td>PCP</td>
<td>Production &amp; Compressor Platform</td>
</tr>
<tr>
<td>PDO</td>
<td>Plan for Development and Operation</td>
</tr>
<tr>
<td>Bara</td>
<td>Absolute pressure over a perfect vacuum</td>
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<tr>
<td>Barg</td>
<td>Pressure over atmospheric pressure at sea level</td>
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<tr>
<td>HVAC</td>
<td>Heating, Ventilation and Air Conditioning</td>
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<td>PFS</td>
<td>Power From Shore</td>
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<tr>
<td>VSD</td>
<td>Variable Speed Drive</td>
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<tr>
<td>QP</td>
<td>Quarter Platform</td>
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<tr>
<td>IP</td>
<td>Injection Platform</td>
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<tr>
<td>DP</td>
<td>Drilling Platform</td>
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<tr>
<td>VFS</td>
<td>Valhall Flank South</td>
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<tr>
<td>CCP</td>
<td>Compressor Control Panel</td>
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<td>ASC</td>
<td>Anti-Surge Control</td>
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<td>HP</td>
<td>High Pressure</td>
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<tr>
<td>SPM</td>
<td>Shock Pulse Method</td>
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<tr>
<td>RMS</td>
<td>Root Mean Square</td>
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<tr>
<td>AHU</td>
<td>Air Handling Unit</td>
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<td>AHU</td>
<td>Air Handling Unit</td>
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Units

\[
A = \text{Area} \ [m^2] \\
Q = \text{Flow} \ [m^3/h], [m^3/s] \\
H_d = \text{Dynamic head} \ [mlc] \\
\rho = \text{Density} \ [kg/m^3] \\
\nu = \text{Kinematic viscosity} \ [m^2/s] \\
\Delta p = \text{Differential pressure} \ [Pa] \\
\varepsilon = \text{Friction factor} \ [-] \\
d = \text{Diameter} \ [m], [mm] \\
Re = \text{Reynolds number} \ [-] \\
R = \text{Universal gas constant} \ [8.314 \frac{kJ \cdot m}{kmol \cdot K}] \\
T = \text{Absolute temperature} \ [K] \\
n = \text{Polytropic exponent} \ [-] \\
C_v = \text{Flow coefficient} \ [-] \\
H_h = \text{Hydrostatic head} \ [mlc] \\
H_p = \text{Polytropic head} \ [kJ/kg] \\
g = \text{Gravity} \ [9.81 \, m/s^2] \\
p = \text{Pressure} \ [Pa], [kPa] \\
f = \text{Friction number} \ [-] \\
l = \text{Length} \ [m] \\
v = \text{Velocity} \ [m/s] \\
w = \text{Weight flow} \ [kg/h] \\
M = \text{Molar weight} \ [kg/kmol] \\
Z = \text{Compressibility factor} \ [-] \\
" = \text{Inch} \ [25.4 \, mm]
1 Introduction

In Scandinavian mythology Valhall is described as a majestic, enormous hall of celebration in the mighty castle of Åsgard, ruled over by the great god Odin. Valhall is also a name of one of the most significant oil and gas fields on the Norwegian shelf located in the southern corner, block 2/8.

The field has been producing oil and gas since the start-up in 1982. With three original platforms, one living quarter (QP), one drilling platform (DP) and one process and compressor platform (PCP), the field was first expanded in 1996 with one wellhead platform (WP).

The year of 2004 was a big year of expansion at Valhall, with three more platforms tied in to the original field centre, two un-manned flank platforms; flank south (VFN) and flank north (VFN), and one combined drilling and water injection platform (IP). Other tiebacks to the Valhall-complex are the un-manned Hod-field that was started up in the year of 1990.

The first estimates for the oil reservoir at Valhall was set to 247 million barrels of oil, by the end of 2004 the field had almost produced 600 million barrels of oil. With 450 million barrels still to go and an aging facility, the Valhall field needed to be upgraded. It was therefore decided to develop a new field centre that could process oil and gas until 2050. The main component would be a new combined process and living quarter platform (PH), which would phase out two of the existing platforms, PCP and QP, and in time DP.

The project, called VRD, started right after the decision was made in 2005. Big contracts were awarded to Wood Group, and their subsidiary company Mustang Engineering in Houston, for detail engineering of PH. Fabricom Stavanger would design the medications required to the existing Brownfield platforms whilst Aker Solutions would carry out the offshore construction. Heerema earned the contract for construction of the main deck, while SLP Engineering constructed the accommodation unit at their premises in Lowestoft, England. The new platform, PH, is planned to be installed in July 2010, and will start processing oil and gas in second quarter of 2011.

In relation to the new process module a lot of equipment is installed from many different suppliers. The main objective for this thesis is to quality assure that BP Norway, as the purchaser, is getting the products they have paid for and that they are working according to the specifications and guarantees. This means to outline a program on how to test the performance of systems and different equipment. The main systems selected for this thesis is the HP and LP seawater systems, where a total description will be given along with equipment data and operational modus.

The thesis will also describe the formatives on how to design a new system from the beginning to the end. Enlightened issues in this matter are selection of contracts, testing procedures, quality assurance, design documentation etc.
2 System Design & Project Execution

2.1 Development phases

In the petroleum industry there are many players and roles, some companies are running the production of an oil field while other companies just have partner interests. Other companies again have their specialization in service, by providing the oil companies with products and services. When an oil company has been awarded a field license and decides to develop it, they have to involve a lot of contractors and specialists to help them solve the mystery to a successful production system. The field development project consists of two main phases, called development planning and project execution.

The planning phase involves concept screening, feasibility studies and concept engineering. Concept screening takes care of the exploration part, while the feasibility studies are evolved around creating a PDO (Plan for Development and Operation) and getting it approved by the authorities and partners. When forming a PDO it is always focused on finding the best all round solution associated with commercial potential and safety, and environmental evaluations.

When the PDO is approved, which is part of the development planning, the conceptual engineering is started based on the recommendations of the PDO (Odland, 2000).

The conceptual engineering consists of:

- Final development concept (engineering basis)
- Operation and maintenance philosophy
- Safety and environmental programs
- Requirements to materials and standardization
- Master schedules and cost control estimates
- Procurement and contract philosophy

During the conceptual engineering phase the engineering basis, called Master Control Schedule, is being defined and held as a basis for technical changes in the project. Along with the Master Control Estimate, the technical concept of the project is being supported and activities and milestones are being defined.

To help out organizing schedules, resource plans, cost estimations and status reports, many projects implement a data tool called Work Breakdown Structure. This is a program that brakes down the scope of works in a hierarchy, with the work packages at the lowest level.

<table>
<thead>
<tr>
<th>Development Planning</th>
<th>Project Execution</th>
<th>Operation</th>
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<td>Exploration (screening)</td>
<td>Project development (feasibility)</td>
<td>Conceptual engineering</td>
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<td></td>
<td>Preparation for operation</td>
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| TABLE 2.1.1 PROJECT DEVELOPMENT PHASES |

The execution phase is where the detail engineering takes place, along with designing, procurement, fabrication and installation of the various systems.
2.2 Contractual Arrangements

When a company decides to invest in a particular development, there can be many parties involved. For most oil fields today this can be a difficult decision as there may be several oil companies having interests and also the government has to agree.

Procurement selection: Procurement is the acquisition of goods and/or services at the best possible total cost of ownership, in the right quantity and quality, at the right time, in the right place for the direct benefit or use of governments, corporations, or individuals, generally via a contract (Odland, 2000). This means that a company that wants to invest in an item of equipment or supply of service has to choose a contractor to supply the goods/services, unless the company is capable of producing the goods/services themselves. Procurement is normally dealt with through a contract, where the two parties have to agree on the terms and rights. A simple procurement deal could be just to buy single item of equipment, while complex procurements could involve finding long-term partners, or even 'co-destiny' suppliers that might fundamentally commit one organization to another.

When the operator of a new development finally gets the go ahead to invest, there are several types of contractual arrangements to choose between. This is especially true when developing an offshore field development project. Different contracts that has to be considered are:

E: Engineering, where an engineering contractor is hired. This contractor has got technical, scientific and mathematical skills, to acquire, apply, design and implement a system in a safe and desired way. This includes how the system is being shaped and what kind of equipment that is needed to make sure the system work as desired.

EP: Engineering and Procurement, where a contractor is hired to perform the engineering and procurement. The company now has responsibility to gather all the equipment that is needed through sub contractors. This could be components in a system, like pumps, compressors, valves, instrumentation etc.

EPC: Engineering, Procurement and Construction. Together with engineering and procurement, the contractor also has the responsibility for construction of the system. This includes the building and assembling of all the sub systems. The major operation in this phase is to assemble all the sub systems and instruments, and all the major fundamental structures.

EPCI: Engineering, Procurement, Construction and Installation. Includes every phase of the delivery of a technical system, even the installation part where the system is being hooked up against live systems at the site where it will be operated.

Turnkey: Everything above + Commissioning. In this contract the contractor handles everything including the commissioning phase of the system. This is where the system is being tested according to the requirements and objectives that the purchaser has set. After the commissioning phase the system is handed over to the client company’s Operations team and the purchaser has then received the complete product.

Other types of contracts might be put together by the joint venture-principles, where two or more companies are cooperating with each other. The key in these types of contracts is that the involved parties are benefiting from another by shearing the risk, costs and of course rewards.
2.3 Designing a system

The designer’s approach to design a system is basically the same as designing one single component or a subsystem (Misra, 2008). But it differentiates a bit according to the degree on which the task is being carried out. A system is normally being designed on behalf of a customer with desirable objectives and requirements. In a selection process on what types of components are to be chosen, there should always be an evaluation to document the selection of the best technology to the right cost. It is not desirable to install prototypes in new systems because these are products that are not being properly tested and could lead to a lot of problems in operation. However, any process system is unique and is designed from the specification where it is going to be operated. In that case, we might say that every system is in effect a prototype. The difference is that a process system is being designed after the “tailor made” method, where a total quality program is outlined to secure that the product and technology is accurate for the requirements. But, it is very important to separate between equipment prototype and process system prototype.

An example on how a particular item of equipment is designed is listed as follows (Misra, 2008):

1. Develop one or more design concepts that satisfy the design objectives.
2. Carry out feasibility analysis for the various design concepts. This is done by using methods like theoretical analysis and simulations, or by experimentation and testing in combination with personal experience.
3. Select one of the design concepts that meet all of the design objectives. Objectives in this matter are reliability, safety and other performance goals. In this process they have to look into the whole system, from the combination down to each single part in the system hierarchy.
5. Pass on the chosen design for procurement and fabrication of development hardware, to be used in the feasibility and evaluation testing of the hardware.
6. Prepare qualification test requirements, as well as production tests and inspection requirements.
7. Prepare the prototype, and work with the qualification testing and corrective design actions.
8. Prepare the final design of the prototype. This includes reviews of the original design objectives.
9. Review and approve/reject the uncertainties which is bound to the prototype.
10. When the objectives of design and other requirements are approved for manufacturing or fabrication or for the user’s disposition, the complete design is to be released.

When the designer has released his prototype there are still a few tasks to perform. Examples of such functions are design-configuration control and design-change control. Design-change control is a tool used for controlling the changes made in a product. This is a request that needs to come under direct control of the top management, because the difficulties this will bring if everyone changed the design into their own matter.

Design-configuration control is more related to control of requirements for each specific product and model type of hardware. In the process of executing the first two phases of the design, we find approaches like feasibility studies and preliminary system design. This is a process every product has to go through and which there are different ways of handling. The most common practice for a design is to do a feasibility study of all the designs.
Then engineers compare the different designs, and choose the best configuration for a further more in depth study. The engineers now have to see which of the designs that would be the best to optimize, which will be executed in the preliminary design by computers. An ideal process of a design would be to optimize every one of the chosen designs, and then select the one it would be best to proceed with. But because this is a much bigger, and more expensive operation, most companies choose the common practice for system design (Misra, 2008). When the right design is chosen for a system there are three phases of development that has to considered:

**Conceptual design** is the first phase where the life cycle of the system is being calculated and the foundation for the rest of the phases is being based. The conceptual design evolves from functional definition of the system, based on the requirements from the customer and other needs. This is also where the design criteria for the system are being established. The system design starts with identifying the user’s needs and requirements for a fully developed system configuration that is ready for production and delivery for subsequent use. In this process it is very useful to involve the customer into the design team, to solve out deficiencies in present design and to get more specific needs based on experience.

When the needs and requirements are highlighted it is time to identify some possible design approaches, this is done in terms of performance effectiveness, maintenance, logistic support and economical criteria. Based on the results, the best alternative is selected. System specifications are now developed, and a review of the conceptual design is to be undertaken.

**Preliminary system design** is a step further in the process, where it is being worked with the requirements obtained from the conceptual design phase and breaks it down to subsystem level requirements to develop a system configuration. It is also the phase where the specific requirements for hardware, software, manpower, facilities, logistic support and other related resources through a functional analysis are being identified. This analysis is also used to describe functional interfaces and to identify resources for hardware, software, people, facilities and data, including their interfaces. A system design review is then undertaken to ensure that the requirements are being met, along with the allocation process, the trade-off studies and the selected design approaches are being reviewed towards the initially set of requirements. All the deviations resulting from the review are being recorded and the appropriate necessary corrective measures are being initiated.

**Detail design and development** is based on the results from the review of the preliminary design phase, and evolves from the system specifications. These are specifications from appropriate design-dependent parameters, technical performance measures and associated design, to criteria for characteristics, subsystems and components. The design requirements are achieved through a requirements allocation process, which identifies the detailed performance and effectiveness parameters for each of the elements in the functional analysis. This could be parameters like input-output factors, metrics etc. A designer can now decide whether to meet the requirement of an item that is commercially available, or by modifying an already existing commercial item or design, develop and produce a totally new item to meet the specific requirements. The design is being evaluated through the fabrication phase of a prototype, or by using a physical working model. Before the firm design data is released to initiate production and fabrication, a new review is undertaken. A detail design review has objects to establish good “production baseline”, and verify the adequacy and producibility of the design. The design is now being re-evaluated.
through manufactory methods, schedules and cost, before the product is being “frozen” and sent to testing and for final evaluation.

Design evaluation of a system has the purpose of assessing the requirements of each level of the system hierarchy, in terms of hardware, software, facilities, people and data. The baseline is evaluated against the particular design configuration, and expectations like effectiveness, cost, time, frequency etc. are being assessed. The whole operation is done to meet the customer’s expectations and deliver a successful product.

2.4 Testing

During, and after, a design phase it is always desirable to test the system against the requirements. This is done to outline faults and errors in the system, as well as pleasing the authorities and the purchaser by showing the progress. Different tests are being outlined during the design and commissioning phase, all with certain mutuality lineaments. Along with the system there shall always be included a test plan with explanations and guidelines for which test to be carried out. The test plan consists of the following contents:

- The definition and schedule of all test equipment and details of organization, administration and control responsibilities.
- The conditions of test conditions including maintenance and logistic support.
- The description of test plans for each type of testing.
- A description of the formal test phase.
- The description of conditions and provisions for the retest phase. This phase is accomplished when the acceptance criteria from the other phases are reached, and the tests are not successful.
- The test documentation.

A test plan serves as a valuable reference and indicates what is to be accomplished, requirements for the test, schedules for the processing of equipment and material for test support, data collecting and reporting methods etc.

Different tests are outlined during the design phases, all to ensure quality assurance and that the design is progressing in the right direction and goal. In the qualification procedures for new technology relevant examples of tests are (DNV, 2001):

Basic tests, specified to test the material properties to establish the key parameters in the design. Also specified to be part of the quality assurance of supplied subsystems. Examples of basic tests are material properties, dimensional accuracy, contamination level of hydraulic fluids, electrical resistance etc.

Prototype tests are qualification tests of the components and assemblies to verify the functional requirements of a new type of design. These tests are often combined with measurements and numerical analysis to verify the functions. Prototype tests can be carried out in phases including laboratory tests and full service tests, such as in shallow/deep water and with hydrocarbons etc.

FAT (Factory Acceptance Test) is a verification test of the manufacturing and assembly of a system that already has been through a prototype test. This is a test that will outline that the performance of the new system meets the requirements, and is therefore a part of the quality control procedure (quality assurance). “The tests shall verify that the probability for manufacturing and assembly failures is acceptably low” (DNV, 2001).
Typical requirements of equipment, such as a centrifugal pump, could be pump performance
tests such as head versus flow, energy consumptions etc. Other parameters a FAT utilizes are
level of vibration, bearing temperatures, noise level, leakages etc.
These are some examples of many acceptances criteria the provider has to refer to. To help
out with this process, standards are made to help out both provider (when designing) and
purchaser (when accepting) in the project phase. Well-known standards are API, ISO and
NORSOK. A FAT is performed where it is most practical, normally at providers test-rig or at
installation site, in order to reduce damage probability or uncertainty in the product. This is a
test where the purchaser of the final product often is participating and witnesses.

Pre and post installation test is outlined during and after the system is being assembled and
installed at the facility site, this to confirm the correctness of the installation.

Pilot application represents the first use of the system, and includes start up, functional tests
and performance tests. These are advanced tests run to gain more experience of the system,
and check out critical operations and complexity associated with this. In this phase it is
desirable to test the performance of the equipment, to be sure that the purchaser is getting the
product he has paid for. Example of this could again be a centrifugal pump that is being tested
for performance according to head versus flow, energy consumptions etc. Also conditioning
monitoring parameters are desirable to check to verify that the pump is running according to
the set requirements. These tests are much like the tests outlined during the FAT.

A simpler guidance to which tests are to be performed during a design phase is the following
hierarchy:
- Material testing
- Component testing
- Sub-assembly testing
- Assembly testing

Another method, called accelerated tests, is used to reduce test time and cost, and is suitable
through building a theory model to simulate the desired tests. This method is depending on
that the uncertainties is localized and reduced to a minimum.

2.5 Final design documentation

Some of the most important actions of a design operation lie in the documentation. This is
written proof of how the system is being designed, including signatures and approvals.
The final design documentation usually includes:

- Specification: Performance requirements, specified environmental conditions, system
  performance goals and specified basic logistics requirements. Examples of this could
  be limits of CO₂ and NOₓ pollution to the air and maximum capacity of equipment
  (gas compressors, crude oil pumps etc).
- Drawings: Coordination drawings, correlation drawings, production drawings,
  procurement drawings and drawings of special test equipments. For drawings related
to a project it is in this context related to “as-built” P&ID’s and “red mark-up”
P&ID’s. The term "as-built" is equivalent to "as-is", and is showing the exact
condition of the system. “As-built” drawings can be documented either after or during
construction. After the construction phase of a system, a qualified technician collects accurate data to reconstruct the drawings back to “as-built”. During a project phase, when there are frequent changes in the “as-built” P&ID’s, the drawings often gets marked with red lines to indicate minor or major adjustments in the system. This is a temporary solution, called “red mark-up”, and is updated after the project phase, back to “as-built” P&ID’s.

- **Parameters**: Functional parameters with their tolerances, starting at the operational use and going backward towards the supplier. The tolerances are specified such as they may be adjusted after time, for example as a result of equipment degradation. The adjustment tolerances are therefore called “funnels of tolerance”, where the small end of the funnel is localized at the start, and the large end is pointing towards the future. Good examples of this could be frequency of condition monitoring samples, where the frequency of sampling in the start-up phase is very frequent and is decreasing after a time with stable conditions.

### 2.6 Phases of a project

**Mechanical completion, Installation and Commissioning:**
A technical system is normally manufactured by contractor, and then assembled and tested before it is handed over to the purchaser. Each system has to be commissioned, normally done by a commissioning team localized at the construction or installation site where the system is to be installed. The system has to go through a mechanical completion, installation and commissioning phase before it is ready for start-up. A commissioning manager leads this latter phase, and has the responsibility that every activity and objectives are being reached. The most important tasks are to assemble the systems and to functional test the components involved in the system.

Important tasks and activities in the mechanical completion, installation and commissioning phase are (ISS International, 2006):

- Visual inspections for complete and correct installation.
- Shaft alignment, where the rotational machinery is being balanced to reduce the vibration to a minimum.
- Lube oil flushing, simply flush the pipes to clean out eventual particles.
- Pressure/leak tests, to verify that the pipes, vessels and equipments are able to work with the desired pressure.
- Cabling, draw cables between instrumentation and equipment.
- Electrical commissioning, test the electrical system for function.
- Instrumentation commissioning, verify that the installed instrumentation is functioning.
- Loop testing.
- ESD Functioning test, test that the ESD system is working according to limits.
- Integration into existing site.
- As built P&ID’s, update the P&ID such that these are correct.
- Functional/integration tests.
- Off-line equipment test, testing of electronic equipment that is not in direct communication (or under the control of) the main process.
- Management of spares, decide and make a plan for what kind of spare parts that needs to be in stock.
• Certification, make sure that the correct certification has been completed and has the right signatures and stamps.

Start-up phase: Start-up is the point in a project where process fluids, such as hydrocarbons (if applicable), and conditions of the equipment are established with the intent of making a final product/products. The systems are now handed over to the Start-Up Team, led by the Start-Up Manager. This phase includes start-up of the systems and functional testing. Here are some of the most important tasks and responsibilities the Start-Up Manager has before handing over the system to the Operations Team. (ISS International, 2006):

• First year operability requirements. This means stock of parts that might break down during the first year of operation. Examples of typically spare parts relevant for a centrifugal pump could be a gasket, bearings, seals, lube oil etc.
• Start-up procedure. Describing the start-up for each of the systems.
• Plant line-up. Arrange the systems up ready for start-up.
• Mechanical run-in machinery monitoring.
• GC/calorimeter calibration (Only applicable for the petroleum industry, typically involved in gas compressors and metering systems).
• Equipment troubleshooting. To detect faults and errors.
• Control-loop tuning. Verify that every control functions are in place. Typical example of this could be the response of a regulation valve
• ESD wet tests / Blow-down tests (Only applicable for the petroleum industry, typically involved in oil and gas plants).
• Surge-line setting. (Only applicable for installation of centrifugal gas compressors)
• Minimum-flow system functional tests.
• Performance and functional tests as required.
• Support training of operations personnel.
• Plant optimizing and de-bottlenecking. Defining the operational settings for each of the systems, along with the total production.
• Certification.

Operational phase: At the end of a project the systems are handed over to the Operations team that will from this point on operate and maintain the systems in normal operational modus. Typical tasks and responsibilities the Operations team has to follow up we find (ISS International, 2006):

• Pre-operations plan. Outline procedures on how to operate the systems.
• Production reporting.
• Recruit Operation and Maintenance teams. Includes training courses and education of personnel.
• Maintenance routines.
• Accepting of project engineering data.
• Operations support and maintenance contracts.
• Brownfield permit system. Decide which strategy to choose, related to the maintenance activities.
• Provide staff for commissioning and start-up teams.
• Certification.
In Fig. 2.6.1 a simplified project chart is illustrated, containing every of the mentioned phases above along with their submissions and objectives. From the left the main phases are listed up, starting with construction and further on with commissioning, start-up and operation.
3 Seawater system PH

3.1 System description

The chosen seawater system for Valhall PH is split into two separate systems, each with their own working pressure. One LP (Low Pressure) seawater system to provide cooling medium for the cooling medium coolers, and one HP (High Pressure) seawater system to provide cooling medium to a few particular coolers, as well as keeping up the pressure on the firewater ring main, fresh water generation, service water etc.

The pumps for both of the systems are each mounted inside a caisson, which allows the systems to collect seawater at a depth of 50 m below LAT (Lowest Astronomical Tide). From this depth the seawater is transported to the platform by seawater lift pumps, namely two LP pumps and two HP pumps. The reason for this big depth is to ensure that the seawater contains as little organic pollution as possible, even in prolonged periods of the year (Carstensen, 2009).

3.1.1 LP System

In this description, reference is made to the following P&ID’s: PH-ME-P-0258-001, PH-ME-P-0259-001 & PH-ME-P-0264-001.

The LP system consists of two LP seawater lift pumps (84-PX-9101A/B), where both of the pumps are designed for 100 % system flow. This means that only one of the pumps is in service at a time, while the other one is in stand-by. The two pumps are identical and are designed to deliver a rated flow of 2400 m$^3$/h with a discharge pressure of 3,5 barg at the topside. However, the system is designed to handle pressure all the way up to 14 barg, which is the reason why the pumps are a little over dimensioned as will be illustrated in the pump characteristic.

The pumps are called Eureka Lineshaft Deepwell Pump, and are a vertical turbine product lubricated pump that is driven by a dry mounted electrical motor. This means that the flowing seawater is lubricating the bearings and the rotational parts. Each of the pumps is mounted in a caisson, which is injected with hypochlorite and copper to prevent bio fouling.

On the topside, each of the pumps are protected by a minimum-flow valve that will secure a minimum continues flow through each of the pumps. Each of the two pumps is also equipped with a vacuum breaker to help draining the stand-by pump of water. This vacuum breaker also acts as an air release trap during start-ups. The same piece of item is located at the highest point of the seawater distribution manifold.

The pumps are lifting the seawater to the topsides where the flow is first filtrated through a coarse filter (84-CA-9119) to separate out particle contaminants. The reason for this mechanical filtration is to avoid plugging of pipes and heat exchangers. The filter is designed for 100 % flow (2400 m$^3$/h).

After the seawater is filtered, the flow is distributed to the two cooling medium coolers (45-HB-9101A/B) where the seawater flow receives heat energy from the cooling medium system. These coolers are dimensioned for a flow of 2400 m$^3$/h each.

The temperature on the cooling medium system is controlled downstream the two coolers, where a temperature controller (84-TIC-93286A/B) is controlling the seawater flow through the coolers.

The LP seawater system is also provided with a flow controller (48-FIC-93294) downstream each of the two coolers. This is a controller that is active in a change over situations between the two coolers. The controller simply measures the total seawater flow through the two
coolers, and ensures that the total flow does not exceed 2400 m$^3$/h. If the seawater flow should increase over this value, the flow controller will override the temperature control valves and regulate these valves according to the flow. Downstream the coolers, the seawater is gathered and injected into the LP seawater dump caisson and back to the sea.

### 3.1.2 HP System

In this description, reference is made to the following P&ID’s: PH-ME-P-0259-002, PH-ME-P-0259-003, PH-ME-P-0259-004, PH-ME-P-0259-005 & PH-ME-P-0260-001. The HP seawater system is provided with two identical ESP’s (Electrical Submersible Pump) (84-PX-9102A/B), each designed for 100 % capacity (900 m$^3$/h) with a discharge pressure of 9,5 barg at the topside. The pumps are both submerged in a caisson, which is injected with copper and hypochlorite to prevent bio fouling. Each of the pumps is equipped with their own minimum-flow regulation to ensure that the pump always gets a minimum continues flow. They are also equipped with their own vacuum breaker to help drain the stand-by pump of water. This vacuum breaker also functions as an air release trap during start-ups. The seawater is sucked into the rotating impeller wheel through a suction strainer, and lifted to the surface through the pipe stack. At the topside the seawater flow is first filtered for particles in a coarse filter (84-CA-9129), which is a mechanical filter designed to handle 200 % of the system capacity (1800 m$^3$/h). After the filter, the seawater flow is distributed to the consumers.

The HP seawater system supplies to two types of consumers, essential and non-essential. The systems classified as essential are those critical for the safety of the PH installation. This system has small bore tubing communication with the firewater ring main, intended to maintain the pressure in the firewater ring main when the firewater pumps are in stand-by mode. In case of an emergency the firewater pumps will start, and there will be a reversed situation where the firewater system provides the flow to the essential users. Two check valves in series control this backflow, preventing the firewater from flowing into the non-essential consumers.

The essential users are:
- Pressure support of the firewater ring main.
- Cooling medium to the VSD (Variable Speed Drive) Cooler (60-HB-9126)
- Cooling medium to essential HVAC (Heating, Ventilation and Air Conditioning) coolers in the LQ
- Cooling medium to the emergency/essential generators on PH

The non-essential consumers are:
- Potable water makers
- Cooling medium to non-essential HVAC coolers in the LQ
- Cooling medium to PFS (Power From Shore) transformation coolers
- Electro chlorination generator
- Utility stations

After the many consumers, the non-essential and essential water is collected and dumped into the HP seawater dump caisson and back to the sea.
3.2 Equipment description

3.2.1 LP Pump
Reference for the following description is taken from Bjørge Eureka’s compendium, Eureka Seawater Lift Pumps. Technical literature regarding centrifugal pumps are found in Palgrave, 2003 and Girdhar and Moniz, 2005.

The pumps are provided by Bjørge, called Eureka Lineshaft Deepwell Pump, and are a vertical turbine product lubricated pump which is driven by a dry mounted electrical motor.

The pump is working after the principal of adding kinetic energy to the flowing medium by rotating an impeller wheel(s), and then convert the energy to static pressure in a diffuser. The diffuser increases the flowing area, which decreases the flowing speed. According to Bernoulli’s principals where the energy is constant, the static pressure will increase in the flowing medium. The pump unit and the shaft are placed inside a column riser, which is again mounted inside a protection caisson. The pump unit with line shaft and impellers has got a length of 45 m, while the caisson is 85 m deep.

To prevent bio fouling hypochlorite and copper are injected to the caisson. The pump unit consists of two impellers, each surrounded by pump bowls which function as diffusers. A strainer is mounted on the suction side of pump unit to prevent inflow of large marine organisms and other substances from the water. The shaft and the pump unit are supported by sleeve bearings between the two stages, lubricated by the flowing seawater. As already mentioned, the line shaft is mounted inside the riser column.

In the flange connections of the many riser column sections there are mounted journal bearings that is supporting the rotating shaft. These are also lubricated by the flowing water.

The axial forces from the impellers is to be taken by a deck head mounted thrust bearing, which is oil/grease lubricated.

The seawater flows into the inlet nozzle through the inlet strainer, and is lifted up the topside by the impeller wheels. At the topside, the seawater flows out of the column riser through a 90 degree discharge bend while the line shaft continues up to the electric motor, placed vertically above the column riser. To prevent an external seawater leakage in the point where the shaft leaves the riser column, it is installed with labyrinth seal.

![Fig. 3.2.1.1 Eureka Lineshaft Deepwell Pump]
Technical data:

<table>
<thead>
<tr>
<th>Performance diagram</th>
<th>Rated point</th>
</tr>
</thead>
<tbody>
<tr>
<td>Imp. diam: 514.2 mm</td>
<td>Flow [m³/h] 2400</td>
</tr>
<tr>
<td>Medium: Seawater</td>
<td>Head [m] 80.1</td>
</tr>
<tr>
<td>Speed: 1180 rpm</td>
<td>NPSHr [m] 7.9</td>
</tr>
<tr>
<td>Imp. stages: 2</td>
<td>Power [kW] 657.8</td>
</tr>
<tr>
<td>Temp: 14 deg C</td>
<td></td>
</tr>
</tbody>
</table>

Material selection:
As for the material chosen for the LP seawater lift pumps, 25 Cr. Duplex is used for most of the equipment. This includes line shaft, impellers, pump bowl, column pipes, sleeves and wear rings. Reasons for choosing 25 Cr. Duplex, also known as super duplex, is because this is a material with exceptional strength and high corrosion resistance.
Maintenance regimes vary between start-up and regular operation, because of run in phase and abnormal situation. However, in normal operation, the provider of the pump, Bjørge AS, is recommending the following maintenance program for the pump:

<table>
<thead>
<tr>
<th>Maintenance activity</th>
<th>Intervals</th>
</tr>
</thead>
<tbody>
<tr>
<td>Visual inspection when pump is running. Check for bearing temperature, vibration, lube oil supply etc.</td>
<td>Once a month.</td>
</tr>
<tr>
<td>Visual inspection when pump is stopped. Check for lube oil leakages.</td>
<td>Annually.</td>
</tr>
<tr>
<td>Check for vibration levels on pump and motor bearings. Motor bearings are equipped with SPM-nipple. Vibration level on pump to be checked on pump bearing house. Max level is 5 mm/s in RMS.</td>
<td>Once a month for the first 6 months in operation, every 3rd months after this.</td>
</tr>
<tr>
<td>Change oil in pump bearing. Pump bearing to be drained by unscrewing the drain plug at the end of the drainpipe. New oil to be filled trough the filling plug in the bearing cover. Ref doc no PH-26016-R-4800006. (Not in the appendices).</td>
<td>Annually. Plus every time repair work is done, that could have affects on the bearing or oil level.</td>
</tr>
<tr>
<td>Check the pump performance, and compare the data against the predicted performance curves given by Bjørge AS. Ref doc no PH-26016-R-4800015. (In the appendices).</td>
<td>Every 2-3 years.</td>
</tr>
<tr>
<td>Visual coupling inspection.</td>
<td>Every 2-3 years.</td>
</tr>
</tbody>
</table>

**TABLE 3.2.1.3 MAINTENANCE PROGRAM FOR LP SEAWATER LIFT PUMPS (84-PX-9101A/B)**
3.2.2 HP Pump

Reference to the following description is taken from Frank Mohn Flatøy’s compendium, Technical Description Electrical Submersible Pump. Technical literature regarding centrifugal pumps are found in Palgrave, 2003 and Girdhar and Moniz, 2005.

The HP seawater lift pumps are called ESP, and are an example of a centrifugal pump with an axial flow, provided by Frank Mohn. The pump is working after the principal of adding kinetic energy to the flowing medium by rotating an impeller wheel(s), and then convert the energy to static pressure in a diffuser. The diffuser increases the flowing area, which decreases the flowing speed. According to Bernoulli’s principals where the energy is constant, the static pressure will increase in the flowing medium.

The pump consists of four main parts:

- Pump/Motor unit with end suction.
- Pipe stack with internal electrical power transmission system (riser pipes).
- Top plate arrangement with electrical junction box.
- Oil circulation unit.

The electrical motor is submerged into the seawater where it is provided with electrical power and is rotating the pump head, consisting of one impeller wheel. This wheel takes in the seawater flow through an inlet strainer, before lifting the flow to the topside through the outer shell of the pump house and up the water pipe section of the pipe stack. The pump is connected to the topside via the pipe stack (47 m), mounted inside a 85 m long caisson. This pipe stack consists of one oil pipe section placed inside a water pipe section.

As mentioned before the water section is leading the seawater to the topside, while the oil pipe is leading non conductive oil down to the pump unit. Inside the oil pipe section it is located three copper conductors which is providing the electrical motor with power. Inside this section we also find a return line for the oil, leading the oil back to the topside. Reasons for supplying oil to the pump unit are:

- Lubricate the mechanical seals and the bearing system.
- Cool the electrical motor.
- Keep an overpressure in the oil pipe section, to avoid seawater inflow to the electrical conductors.
- Electrical insulation condition monitoring.

The pump/motor unit is supported through the pipe stack, with a roller bearing for radial support on the non-drive end, and a combined radial and thrust bearing on the drive end. The seal system protects the electrical motor against inflow of seawater, and consists of a mechanical seal riding on a sleeve. The spring, forcing the seal rings towards each other is placed inside the electrical motor casing, so that sealing plates are lubricated and cooled by the forced oil circulation system.
On the topside, the water section of the pipe stack is going out through a 90 degree bend, while the power conductor is going further up to the top plate arrangement where the junction box is located. In this box the electric power supply is placed, as well as the adapters for the pressure and return side of circulation oil.

The utility system associated with the pump, is the oil circulation unit. It consists of an atmospheric oil reservoir, a positive displacement pump to keep up the pressure on the circulation loop, an accumulator, a closed circulation loop and a pump to circulate the oil from the pressure side and back to the return side. The positive displacement pump is installed to compensate for the small loss of circulation oil through the mechanical seal.

Technical data:

<table>
<thead>
<tr>
<th>Performance diagram</th>
<th>Rated point</th>
</tr>
</thead>
<tbody>
<tr>
<td>Imp. diam: 575 mm</td>
<td>Flow [m³/h] 900</td>
</tr>
<tr>
<td>Speed: 1780 rpm</td>
<td>Head [mL] 132.1</td>
</tr>
<tr>
<td>Imp. stages: 1</td>
<td>NPSHr [mL] 14.5</td>
</tr>
<tr>
<td>Temp: 14 deg C</td>
<td>Power [kW] 435</td>
</tr>
</tbody>
</table>

![Table 3.2.2.1 Performance diagram 84-PX-9102A/B](table.png)

![Table 3.2.2.2 Rated point 84-PX-9102A/B](table.png)

![Fig. 3.2.2.2 Pump characteristic 84-PX-9102A/B](fig.png)
Material selection:
As for the material chosen for the HP seawater lift pumps, 25 Cr. Duplex is used for most of the equipment. This includes pump/motor casing, impeller and pipe stack with sleeves, studs and nuts. The shaft between the motor and the impeller is made of 32CrNiMo6, while the caisson is made of carbon steel.
Reasons for choosing 25 Cr. Duplex, also called super duplex, for the seawater system is that this is a material with exceptional strength and high corrosion resistance.

Maintenance:
Maintenance regimes vary between start-up and regular operation, because of run in phase and abnormal situation.
However, in normal operation, the provider of the pump, Frank Mohn, is recommending the following maintenance program for the pump:

<table>
<thead>
<tr>
<th>Maintenance activity</th>
<th>Intervals</th>
</tr>
</thead>
<tbody>
<tr>
<td>Check for functionality of air release trap.</td>
<td>Annually.</td>
</tr>
<tr>
<td>Check the ambient conditions (air circulation, humidity) and seal integrity of the process connections. Also check cable connectors and cover screws, functional reliability of the voltage supply, the grounds and the lightening protection.</td>
<td>Annually.</td>
</tr>
<tr>
<td>Check the pump performance, and compare the data against the predicted performance curves given by Frank Mohn. Ref doc no PH-14034-R-4710023. (In the appendices)</td>
<td>Annually.</td>
</tr>
<tr>
<td>Perform particle counting and water analysis of circulation oil.</td>
<td>Once a month.</td>
</tr>
<tr>
<td>Take full oil analysis. The oil is to be replaced if the viscosity or if the oxidation stabilizing elements are below minimum limits.</td>
<td>Annually, and after major overhaul and maintenance.</td>
</tr>
<tr>
<td>Drain the oil circulation tank for condensation of water.</td>
<td>Once a month.</td>
</tr>
<tr>
<td>Change oil filter elements.</td>
<td>Once a year in operation, or if the</td>
</tr>
<tr>
<td>Task</td>
<td>Frequency</td>
</tr>
<tr>
<td>----------------------------------------------------</td>
<td>--------------------------------</td>
</tr>
<tr>
<td>Measure the consummation of circulation oil. This</td>
<td>Continually.</td>
</tr>
<tr>
<td>to give a figure of the mechanical seal leakage.</td>
<td></td>
</tr>
<tr>
<td>Change the air breather.</td>
<td>If air breather with silica gel is installed, change when the color changes. If water block breather is installed, change annually.</td>
</tr>
<tr>
<td>Check pre-charge pressure on the accumulator.</td>
<td>Annually.</td>
</tr>
<tr>
<td>Major maintenance, requiring retrieval of the</td>
<td>Every 5th year, 40 000 running hours or upon failures.</td>
</tr>
<tr>
<td>electric submerged pump and full inspection with</td>
<td></td>
</tr>
<tr>
<td>replacement. This is a program the service engineer from Frank Mohn is called out to do.</td>
<td></td>
</tr>
</tbody>
</table>

**TABLE 3.2.2.3 MAINTENANCE PROGRAM FOR HP SEAWATER LIFT PUMPS (84-PX-9102A/B)**
3.2.3 Seawater Coarse Filter

The seawater coarse filters for both the LP and HP seawater systems are provided by GFSA. The filters consist of a large number of standing wedge wire filters, which are open at both ends. A housing made of titanium surrounds the filter assembly. Each of the wedge wire filters has got a filter mesh, designed to filter out every particle above 500 \( \mu \text{m} \) \((5 \times 10^{-4} \text{ m})\). The normal flow through the filter is guided into the filter from both ends, and then forced to flow through the wedge wire filter on the way out. By this, the particle contaminants will end up in the inner face of the filter elements.

The filters are designed to provide their own backflushing sequence. This regeneration sequence consists of an electrical motor that rotates a backflushing-arm assembly and a control valve that opens a dump line to the seawater dump caissons.

The backflushing-arm assembly is designed in the way that the wedge wire filter is closed off and sealed at both ends, the assembly now opens a path to the drain system in sequence with opening the control valve. Because of the differential pressure, the already filtrated water will now be forced into the dirty wedge wire filter, with a high velocity going in the opposite direction of the normal path. The wedge wire filter is now being backflushed, and the particle lying in the inner face of the filter elements are being flushed away.

This regeneration operation can be controlled by a timer or by a differential pressure measure over the filter, as well as manually.

![Fig. 3.2.3.1 Normal Filtration Phase](image1)

![Fig. 3.2.3.2 Backflushing Phase](image2)
3.2.4 Electro Chlorination Generator

The electro chlorinator generator is supplied to prevent bio fouling on the seawater lift pumps and associated piping systems and filter. The purpose of this generator is to take a small amount of the seawater flow and use this to generate sodium hypochlorite and free copper ions, which are later injected to the seawater caissons.

The process of making sodium hypochlorite and copper ions is done in two different electrolysis processes, which are designed to dose a seawater flow of 4200 m$^3$/h.

First the seawater flow is split in two, regulating 25 m$^3$/h through the copper-adding vessel and 0.6 m$^3$/h through the electro chlorination cell.

The copper-adding vessel consists of one copper anode to which an alternating current is applied. The copper anode will function as a positive pole (anode) and the surrounding vessel will function as a negative pole (cathode), resulting in oxidation of the copper element. The copper ions will therefore be released into the seawater flow. This means that the copper anode is consumed over time, and has to be replaced.

The reaction will be:

$$\text{Cu}_2 \rightarrow 2\text{Cu}^+ + 2\text{e}^-$$

The electro chlorination cell consists of one anode chamber, where the positive electrode is located, and one cathode chamber where the negative electrode is located. The electro chlorination panel now puts a direct current through the electrolyte, sending electrons through the seawater, from the anode to the cathode. By this process, the molecules in the seawater attempt to reach their original elements. Two reactions will occur; the anode will attract the negative charged ions while the cathode will attract the positive charged ions. At the cathode, the ions are receiving electrons while the ions are giving off electrons at the anode.

At the anode:

$$2\text{Cl}^- \rightarrow \text{Cl}_2 + 2\text{e}^-$$

At the cathode:

$$2\text{Na}^+ + 2\text{H}_2\text{O} \rightarrow 2\text{Na}^+ + 2\text{OH}^- + \text{H}_2 + 2\text{e}^-$$

The elements resulting from the electrolysis is now separated in the two chambers, but is soon to be mixed together again and new chemical reactions will occur.

The total reaction will then be:

$$\text{Cl}_2 + 2\text{Na}^+ + 2\text{OH}^- \rightarrow 2\text{NaOCl} + \text{H}_2\text{O}$$

This is the reaction where the sodium hypochlorite is being made. This is then mixed in with the rest of the seawater not participating in the reaction, and is later injected to the seawater caissons along with the flow coming from the copper-adding vessel.
3.3 Potential Root Causes

3.3.1 Water hammer (Surge)
A common problem encountered in seawater systems is surge, or water hammer. This is a phenomenon that occurs due to a sudden change in the liquid velocity. Water hammer usually occurs when a transfer system is quickly started, stopped or is forced to make a rapid change in direction (Sharp and Sharp, 1996). A typical system which is exposed to this, such as a seawater system, often consists of quick closing valves, lots of vertical pipe runs and large pumps with high flow rate. The danger with this phenomenon is extremely high pressure peaks, up to as much as 5 times the system working pressure, which can result in blown diaphragms, ruptured discs, seals and gaskets, as well as burst pipes.

Water is an incompressible medium meaning that every input of energy is transmitted instantly. When a sudden change occurs in a system, as a force like a quick opening valve or a pump start, the energy becomes dynamic and will result in a high velocity change in the medium. This sudden change in velocity will result in a high acoustic sound in the system, causing a pressure spike. This acoustic sound will rapidly accelerate to the speed of sound (in liquid), causing the pressure spike (Webb, Gould and Hardie, 1978).

A way to prevent water hammering is to install a pulsation dampener. This is a tank that is connected to the water system, which is equipped with a gas volume on top to be compressed when the water pressure increases. Gas is a compressible medium and will therefore decrease in volume when the water pressure increases. Another way to prevent water hammer is install actuators that are acting with slow movements, such that valves are not suddenly closing or opening.

3.3.2 Pulsation
Much like surge, a phenomenon called pulsation also exists. Pulsation occurs in a system that produces pulses with high amplitude, typically displacement pumps. This high amplitude pulse occurs when liquid is being accelerated and decelerated (velocity change), as a result of starting/stopping pumps and quick operating of valves. The uncontrolled energy results in pressure spikes.

The common pump used for seawater systems are therefore centrifugal pumps that are normally producing non-damaging high frequency but low-amplitude pulses, but also here it might appear (Sharp and Sharp, 1996).

3.3.3 Vibration
The technical literature in this section is taken from; Eisenmann and Eisenmann, 2005; Hongyun and Hanwei, 2009, where vibration is briefly described.
Historically, vibration has caused a lot of problems for an operational seawater system. One reason for this is that the main drivers for such systems often are pumps of the kind with a dry mounted electrical motor, converting energy down to a submersible impeller wheel via a long shaft. With an incorrect balancing of the pump shaft the shaft will start vibrating, and increase the mechanical wear on the bearings that stabilize the shaft and the rotor. To help us deal with equipment breakdown caused by vibration it is desirable to install vibration sensors to stop minor failures to escalate.

The vibratory motion is measured by finding the amplitude of the dynamic signal. Meaning that large amplitudes are directly related to high level of vibration, again related to a mechanical problem. In general, the amplitude of vibration relates to the size of the vibratory
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Amplitude could be defined from a sine wave in the time domain, such in Fig. 3.3.3.

In this diagram three different types of amplitude measurements are identified. The total magnitude is represented by the peak-to-peak value of the amplitude, and measures from the lowest portion of the dynamic signal (bottom peak) to the highest portion of the signal (top peak). Peak-to-peak amplitude therefore equals to the total signal height, and is an indication of the highest speed achieved.

The zero to peak value represents the middle of the dynamic signal to the highest portion of the signal. For simple voltage signal, the relationship between peak to peak and zero-to-peak could be expressed as:

\[
\text{Amp}_{\text{peak to peak}} = 2 \times \text{Amp}_{\text{zero to peak}}
\]

RMS (Root Mean Square) is another measure of the amplitude, and is lower than the zero to peak value. For a pure sine wave, the actual amplitude value reduction from zero to peak equals to \(2^{0.5}/2\), which gives the numerical value of 0.7071.

This gives these relations to the other amplitude measurements in a voltage signal:

\[
\text{Amp}_{\text{rms}} = 0.7071 \times \text{Amp}_{\text{zero to peak}}
\]

\[
\text{Amp}_{\text{rms}} = 0.3536 \times \text{Amp}_{\text{peak to peak}}
\]

RMS amplitude is an indication of the amount of vibration energy in the machine. The unit used to express RMS is given in mm/s.

There are three different methods of measuring vibration motion:

- **Displacement sensors**, used to measure internal clearances between bearing and shaft, as well as shaft motions. This distance is measured in peak-to-peak difference in the amplitude, means the distance between the positive and negative peak, also known as the magnitude. These are non-contacting transducers that are mounted on a reasonable stationary mechanical structure, observing static and dynamic displacement of the moving machinery.

  A typically probe used for measuring displacement is the proximity probe.

  The unit for displacement is in ISO standards expressed in \(\mu\text{m} (10^{-6}\text{ m})\), while it is measured in mils (1\(\times\)6 inch) in the API standards.

- **Acceleration sensors** measure the acceleration of the amplitude by detecting changes in the force resulting from vibration. The most common acceleration transducer is the Piezoelectric Accelerometer, which is a fully contacting probe that is mounted directly on the mechanical element (e.g., bearing housing). The probe consists of a piezoelectric material that produces an electrical charge when being squeezed. This charge is proportional to the force, meaning
that it will increase with increasing motions and vibration. Since the mass is constant, the electrical charge will also be proportional to the acceleration.

*Velocity sensors* measure the velocity of the amplitude from zero to peak-point. The most used transducer is the Velomitor, which is working after the same principles as the accelerometer. Only difference is that Velomitor measures the speed instead of acceleration.

As for the pumps chosen for the LP and HP seawater systems at PH, vertically suspended centrifugal pumps are selected. For these kinds of pumps it is very important to design it according to API 610, where the pumps are designed with balancing degree. Meaning that the vibration is in relation to the speed of the pump. Also an important issue while selecting pump is to choose a pump with minimum robustness that can handle the environment the pump is set to operate in.

In appendix D, the vibration limits for vertically suspended centrifugal pumps is found. This table is taken from the API 610, standard for centrifugal pumps, and gives vibration limits in peak-to-peak and RMS inside the preferred operating area. The table also shows allowable increase in vibration at flows outside the preferred operating region, inside the allowable operating region.
4 Performance Test of the Seawater Systems

BP, as one of the biggest energy companies’ world wide, has many internal objectives and requirements to follow. These are rules outlined through the company’s strategy and goals. In BP’s internal goals, some key success factors that related to the start-up phase of a facility are found.

Key success factors:

- BP Operations accountable and lead the start-up of facilities. Means that BP run their own start-up strategy, lead by internal personnel that is familiar with BP’s requirements.
- Commissioning manager appointed to project in Define. Meaning that the company needs to define the Commissioning Manager of the project.
- Start-Up Manager appointed and small, dedicated Start-Up Team initiated in define.
- Use of start-up execution manual. Means that the project needs to follow BP’s “tailor-made” manuals on how to execute a start-up of a facility.
- Rigorous Go/No-go process. This is a common process in BP, means that the company’s management needs to approve the phase changes of a project.

There is also outlined a few internal requirements related to a plant performance test.

Plant performance testing:

a. If plant performance tests are required only for internal BP requirements, commissioning and operating authorities shall jointly prepare plant performance test procedures to check that design complies with equipment guarantee points for systems that are critical in achieving rated production.

b. Operating authority should complete performance test procedures within 6 months of start-up.

c. If successful plant performance test form part of contractual delivery by an external design contractor, design engineering contractor should prepare plant performance test procedures based on project SoR.

d. If plant performance is satisfactory, results shall be provided to plant manager for information.

e. If plant performance is unsatisfactory, under BP direction, contractor shall investigate root cause of problem and solve technical issues.

4.1 LP Seawater System

Before the LP seawater system is ready to be tested, the commissioning phase has to be verified and completed. The commissioning phase includes pressure/leak tests as well as functionality tests of the different equipment to be sure that the system will be able to operate after design criteria.

When looking at the whole system, the interfaces also have to be considered along with the subsystems and the start-up sequence. These are systems like electrical- and hydraulic power, PCS (Process Control System), instrument air etc.

Other recommended checks required before start-up, include the line up and general equipment status. It is recommended to go over the entire system, and follow the normal flow path through the system to check that all valves are in correct position for start-up. Use the following P&ID’s for going through the system: PH-ME-P-0258-001, PH-ME-P-0259-001 & PH-ME-P-0264-001.
Critical equipment for this system is the vacuum breakers/air release traps and pressure relief valves. Locate these devices and verify that they’re correctly installed and NOT blocked.

- 84-PH-S-1000, Air release trap at LP Seawater Lift Pump A.
- 84-PH-S-1001, Air release trap at LP Seawater Lift Pump B.
- 84-PH-S-1011, Air release trap at LP Seawater manifold.
- 84-PH-S-1004, Air release trap downstream Cooling Medium Coolers, placed at the cellar deck.
- 84-PSV-93224A, Relief valve upstream LP Coarse Filter.
- 84-PSV-93291A, Relief valve downstream Cooling Medium Cooler A.
- 84-PSV-93291B, Relief valve downstream Cooling Medium Cooler B.

Before starting with the functionality and performance tests on the different equipment involved in the LP distribution system, there are some main components that have to work.

- Review the flow regulation loop (84-FIC-93294), downstream the cooling medium coolers and record the tuning parameters. The maximum flow through both of the two coolers should not exceed 2400 m$^3$/h. (Table 6.1)
- Record the tuning parameters for the temperature regulation at the cooling medium coolers, 84-TIC-93286A/B. (Table 6.2/6.3)

When this is verified it is desirable to test each of the main components in the LP seawater distribution systems, starting with the main drivers.

4.1.1 LP Seawater Lift Pumps (84-PX-9101A/B)

The purpose of these tests is to gather pump performance and conditioning monitoring data. Recommended tests for the LP seawater lift pumps:

- Functionality test
- Performance test to verify the pump curves
- Verification of bearing temperatures, winding temperatures and vibration

**Method:**
Since the minimum-flow valve is dimensioned to handle flow up to 1030 m$^3$/h (Appendix C), it is recommended to use this line to verify the first two points of the pump characteristic. This is even if the seawater distribution system is in service or not. If the seawater system is in service, it is desirable to start testing the stand-by pump, and then operate both of the pumps simultaneously before changeover and stopping the pump in duty mode to verify the whole length of the pump characteristic of the stand-by pump. The provider of the pump used 1027 kg/m$^3$ as the seawater density, which is also recommended to use in this test.

**Pre-phase:**
References relevant for the tests are P&ID’s: PH-ME-P-0258-001, PH-ME-P-0107-004 & PH-ME-P-0107-005.

Before the tests are ready to be executed, it is desirable to verify that the instruments used during the tests are in good shape and that correct alarm settings are given. To be sure the data is correct, it is recommended to calibrate the most critical instruments. Local indicators can also be accepted as reference.

Critical instruments are:

- 84-FT-93207A/B. Alarm limits: L=770 m$^3$/h
- 84-PT-93207A/B. Alarm limits: H=6,8 barg, L=2,8 barg
It is also necessary to verify that the pumps are supplied with electrical power and that the PCS is updated and in service. Instruments necessary for the conditioning monitoring of the pump and the electrical motor needs to be verified correctly installed along with instrumentation and alarm settings.

Following instruments needs to be verified:
- 84-FI-93201A/B. Alarm limits: L=5,5 m$^3$/h
- 84-YI-95500A/B. Alarm limits: HH=7,1 mm/s, H=4,5 mm/s
- 84-YI-95501A/B. Alarm limits: HH=7,1 mm/s, H=4,5 mm/s
- 84-YI-95510A/B. Alarm limits: HH=8 mm/s, H=5 mm/s
- 84-YI-95511A/B. Alarm limits: HH=8 mm/s, H=5 mm/s
- 84-TI-95500A/B. Alarm limits: HH=120°C, H=110°C
- 84-TI-95502A/B. Alarm limits: HH=145°C, H=135°C
- 84-TI-95505A/B. Alarm limits: HH=145°C, H=135°C
- 84-TI-95508A/B. Alarm limits: HH=145°C, H=135°C
- 84-TI-95511A/B. Alarm limits: HH=120°C, H=110°C

**General Procedure:**

Use Table 6.4/6.5 to record the data.

- Measure the distance between the cellar deck and the sea level to be sure of the suction pressure of the pump. This is used in the head calculations later. The total length from the submerged pump to the cellar deck is 44,7 m. The distance from the cellar deck to the discharge level is 0,3 m.
- Start testing the stand-by pump. (If the system is in service, if not it’s optional).
- Record the relevant XV open/close times and leave the valves in auto.
- Record the tuning parameters of the minimum-flow valve (84-FIC-93207A/B) and leave the flow regulation in auto. Verify that the set point is put to 1400-1500 m$^3$/h.
- Verify that the lube oil levels are acceptable.
- Start the stand-by pump using the start-up sequence and let it run for 2 hrs to stabilize winding temperatures at the motor, if not recently started.
- Use the minimum-flow valve on manual to regulate the flow. It is recommended to start verifying the left hand side of the pump characteristic. Start by closing the outlet valve (84-XV-93212A/B). Operate the minimum-flow regulation in manual and decrease the flow to 770 m$^3$/h, verify that the low-flow alarm activates. Record the flow and outlet pressure at this point, which will be the first of six desirable points.
- Other desirable recordings are the speed, temperatures and vibrations.
- Visually go over the system to localize abnormal vibrations or leakages. This should be repeated for every flow.
- Make 5 more recordings of flow, outlet pressure, temperatures and vibrations. For flow above 1050 m$^3$/h the outlet valve (84-XV-93212A/B) needs to be opened, meaning that the distribution system needs to be available. Operate the minimum-flow regulation in manual to help reaching the desirable points. Desirable recordings of the flow: 1030, 1600, 2100, 2400, 3100 m$^3$/h.
- It is recommended to stop the parallel pump when the total flow though the system exceeds 2400 m$^3$/h.
- 2400 m$^3$/h represent the rated point of the pump; at this point the differential head should be between 78,5 – 84 mle (meter liquid column), while the power should not exceed 684 kW. This is according to API 610 (appendices E).
3100 m³/h represents the maximum flow through the pump. However, this flow is above the max capacity of the seawater coarse filter, it is therefore recommended to operate the minimum-flow valve in manual again to achieve the highest flow through the pump.

After the test, the results should be plotted into the original pump characteristic (Fig. 3.2.1.2).

Approximate Duration:
The different tests of one single pump are estimated to take around 3 hrs. This time however, could be reduced if some of the desirable data has been collected during the offshore commissioning phase. These tests can be carried out at any time, also after the system is put in service.

4.1.2 LP Seawater Lift Pump Changeover and Trip Test
The objective for these tests is to verify that changeover between the two pumps is possible when the seawater system is online. The test is desirable to carry out when one of the pumps is in operation. The test requires start-up of the second pump and a simultaneous operation for a while. It is also desirable to test the trip function of each of the pumps at low flow. However, at the writing moment the trip limit is not specified yet. This is something that needs to be implemented before start-up.

General Procedure:
- Verify that the trip limit at low flow is set on both of the pumps.
- Verify that one of the pump is in operation, refer to this pump as the duty pump.
  - Record the flow through the pump: ______ m³/h.
- Start the stand-by pump.
- Let the two pumps run simultaneously for a few minutes.
- Duty pump: Verify that the minimum-flow regulation is in auto, and close the outlet valve (84-XV-93212A/B).
  - Put the minimum-flow regulation in manual, and decrease the flow by closing the minimum-flow valve. It is desirable to decrease the flow to the trip level of the pump.
  - Put the minimum flow-regulation back to auto.
- Record the flow through the stand-by pump: ______ m³/h.
- Start the duty pump again.
- Let the two pumps run simultaneously for a few minutes.
- Stand-by pump: Verify that the minimum-flow regulation is in auto, and close the outlet valve (84-XV-93212A/B).
  - Put the minimum-flow regulation in manual, and decrease the discharge flow by operating the minimum-flow valve. It is desirable to decrease the flow to the trip level of the pump.
  - Put the minimum-flow regulation back to auto.
- When the pressure and flow has stabilized again, the system can be put into normal operation.

Approximate Duration:
The pump changeover and trip test is estimated to take ½ hr, but is depending on what is done during the commissioning phase. The test is able to carry out at any time after the commissioning phase of the system.
4.1.3 LP Seawater Coarse Filter

The purpose of these tests is to verify that the LP seawater coarse filter is properly installed and is functioning after design. It is also desirable to verify the functionality of critical instruments installed in the package.

Before the LP seawater coarse filter is ready to be tested for functionality, it is necessary to have the LP seawater distribution system in operation to have actual flow through the filter. Desirable tests to carry out are:

- Functionality test of the backflushing sequence
- Verification of essential instrumentation

References relevant for the tests are P&ID: PH-ME-P-0259-001.

General procedure for functionality test of LP seawater coarse filter:

- Verify that the motor (84-CA-9119-M01) is supplied with electrical power, and that the PCS is updated with operational functions.
- Verify that the drain valve (84-XV-93229A) is supplied with electrical power and is acting on demand from the PCS.
- Verify that the differential pressure instrument (84-PDC-93221) is properly installed and is communicating with the PCS.
  Also check that the correct alarm limit is implemented, set at 0.5 barg.
- Put the pressure differential controller (84-PDC-93221) in auto, along with the drain valve (84-XV-93229A).
- Verify that the backflushing sequence is being activated at the set point (0.5 barg), by waiting for the differential pressure to increase or by manipulating the differential pressure from the PCS.

General procedure for verification of essential instrumentation:

- Verify that the following instruments are properly installed and that the PCS is updated with alarm limits.
  - 84-TI-93225.
  - 84-AI-93223. Alarm limits: L=0.2 ppm.
  - 84-PI-93223. Alarm limits: L=2.5 barg.
- Verify that 84-PI-93224, is properly installed and that the PSD is updated with trip limit, LL=2.0 barg. This trip will activate PSD 1 after 60 seconds.
  - Temporarily override the output signal to avoid PSD 1. Block the transmitter and drain it. Verify that the low-low alarm activates. Put the system back to original status.

Approximate Duration:
The different tests corresponding to the LP seawater coarse filter is estimated to take ½ hr, and is suitable to be carried out when ever the LP seawater distribution system is in service.
4.1.4 Final tuning of LP seawater distribution system

When the different tests around the LP seawater distribution system are finished, it is time to do the final tuning around the regulation loops at the cooling medium coolers (45-HB-9101A/B). This involves the flow regulation (84-FIC-93294) and the temperature regulation (84-TIC-93286A/B).

To do this, the LP seawater distribution system has to be in service along with the cooling medium system. Make sure that one of the two coolers is being tuned at a time. Record the final settings in Table 6.1/6.2/6.3.

4.2 HP Seawater System

Before the HP seawater system is ready to be tested, the commissioning phase has to be verified and completed. When looking at the whole system, the interfaces also have to be considered along with the subsystems and the start-up sequence. These are systems like electrical- and hydraulic power, PCS, instrument air etc.

Other devices that it is preferable to check before start-up are the line up of valves and equipment. It is recommended to go over the entire system, and follow the normal flow path through the system to check that all valves are in the correct position for start-up.

Use the following P&ID’s for going through the system: PH-ME-P-0259-002, PH-ME-P-0259-003, PH-ME-P-0259-004, PH-ME-P-0259-005, PH-ME-P-0260-001 & PH-LP-P-4353-001.

Critical equipment for this system is the vacuum breakers/air release traps and pressure relief valves. Locate these devices and verify that they’re correctly installed and NOT blocked / isolated.

- 84-PH-S-1002, Air release trap at HP Seawater Lift Pump A.
- 84-PH-S-1003, Air release trap at HP Seawater Lift Pump B.
- 84-PH-S-8002, Air release trap upstream IGBT Heat Exchangers.
- 84-PH-S-8003, Air release trap upstream AHU Cooling Coil.
- 84-PH-S-8004, Air release trap downstream AHU Cooling Coil.
- 84-PH-S-8005, Air release trap downstream IGBT Heat Exchangers.
- 84-PSV-93494A, Relief valve upstream HP Coarse Filter.
- 84-PSV-93487 / 84-PSV-93488, Relief valve on the essential users.
- 84-PSV-93237, Relief valve on Emergency Generator Cooler A.
- 84-PSV-93238, Relief valve on Emergency Generator Cooler B.

Before starting with the functionality and performance tests on the different equipment involved in the HP distribution system, there are some main components that have to work.

- Review the temperature regulation loop (84-TIC-93233), downstream the VSD cooler and record the tuning parameters. (Table 6.6)
- Review the temperature regulation loop (84-TIC-91771A/B), downstream the AHU cooling coils and record the tuning parameters. (Table 6.7/6.8)

When this is verified it is desirable to test each of the main components in the HP seawater distribution systems, starting with the main drivers.
The HP seawater lift pumps are to be tested after the commissioning phase and initial start-up is completed. This includes start-up of the oil circulation unit, and that the electrical motor is mounted and verified ready for test.

Recommended tests for the HP seawater lift pumps:
- Functionality test of the oil circulation unit
- Functionality test of the pump and electrical motor
- Performance test to verify the pump curves

**Method:**
If the seawater system is in service, it is desirable to start testing the stand-by pump and operate both of the pumps simultaneously before changeover and stopping the pump in duty mode, to verify the whole length of the pump characteristic of the stand-by pump. The minimum-flow valve is dimensioned to handle flow up to 380 m³/h, which is right above the minimum continuous flow through the pump at 360 m³/h. It is therefore recommended to use this line to verify the first point of the pump characteristic, even if the seawater system is in service or not. The provider of the pump used 1030 kg/m³ as the seawater density, which is also recommended to use in this test.

**Pre-phase:**
References relevant for the tests are P&ID’s: PH-ME-P-0104-006, PH-ME-P-0259-002, PH-ME-P-0259-003, PH-ME-P-0259-004, PH-ME-P-0259-005, PH-ME-P-0260-001 & PH-LP-P-4353-001.

Before the tests are ready to be executed, it is desirable to verify that the instruments used during the tests are in good shape and suitable for reading the preferred data. To be sure the data is correct, it is therefore recommended to calibrate the most critical instruments. Local indicators can also be accepted as reference.

Critical instruments are:
- 84-FT-93477A/B. L=396 m³/h.
- 84-PT-93477A/B. H=12,3 barg, L=8,2 barg.
- 84-TT-93477A/B.

It is also necessary to verify that the main motor, and the pressurizing and circulation pumps for the oil circulation unit are supplied with electrical power. The PCS needs to be verified updated and functionality tested.

**General Procedure Oil Circulation Unit:**
- Check that the following instruments are properly installed and that the PCS is updated with alarm limits:
  - 84-PI-95555A/B. HH=24 barg, H=22 barg, L=12,1 barg, LL=10,1 barg.
  - 84-PIC-95556A/B. Start=16,4 barg, Stop=14,4 barg.
  - 84-FI-95554A/B. L=80 l/min, LL=40 l/min.
  - 84-TI-95553A/B. HH=70°C, H=65°C.
  - 84-PDI-95556A/B. H=2,5 barg.
  - 84-LI-95551A/B. H=82,9 %, L=51,2 %, LL=39,6 %.
- Verify that the circulation oil level is acceptable.
- Review the circulation system and line it up for operation.
- Start the pressurizing pump (84-PS-9101A/B).
When the pressure has stabilized, start the circulation pump (84-PG-9102A/B).
- Review the system visually, and look for leakages.
- Use the PCS to make trends of the instruments mentioned in the first point. This to verify that the conditions are acceptable before start-up of the submersed pump.

**General Procedure Pump/Electrical Motor:**
Use Table 6.9/6.10 to record the data.
- Measure the distance between the cellar deck and the sea level to be sure of the suction pressure of the pump. This is used in the head calculations later. The total length from the submerged pump to the cellar deck is 45.5 m. The distance from the cellar deck to the discharge level is 1.1 m.
- Start testing the stand-by pump. (If the system is in service, if not it’s optional).
- Measure and record the relevant XV open/close times and leave the valves in auto.
- Record the tuning parameters of the minimum-flow valve (84-FIC-93477A/B) and leave the flow regulation in auto. Verify that the set point is put to 440 m³/h.
- Start the stand-by pump using the start-up sequence and let it run for 15-20 min to stabilize temperatures, if not recently started.
- Use the minimum-flow valve to regulate the flow. It is recommended to start verifying the left hand side of the pump characteristic. Reduce the flow to the minimum by closing the outlet valve (84-XV-93482A/B). Operate the minimum-flow regulation in manual and decrease the flow to 380 m³/h, verify that the low-flow alarm activates. Record the flow and outlet pressure at this point, which will be the first of six desirable points.
- Visually go over the system to locate abnormal vibrations or leakages. This should be repeated for every flow.
- For flow above 380 m³/h the outlet valve (84-XV-93482A/B) needs to be opened, which means the distribution system needs to be available. Operate the minimum-flow regulation in manual to help reach the desirable points. Desirable recordings are 380, 650, 800, 900, 1050 m³/h.
  - It is recommended to stop the parallel pump when the total flow through the system exceeds 900 m³/h.
  - 900 m³/h also represent the rated point of the pump; at this point the differential head should be between 129.5 – 139 mlc, while the power should not exceed 452 kW. This is according to API 610 (appendices E).

After the test, the results should be plotted into the original pump characteristic (Fig. 3.2.2.3).

**Approximate Duration:**
The different tests of one single pump are estimated to take around 1-2 hrs. This time however, could be reduced if some of the desirable data has been collected during the offshore commissioning phase. These tests can be carried out at any time, also after the system is put in service.
4.2.2 HP Seawater Lift Pump Changeover and Trip Test

The objective for this test is to verify that changeover between the two pumps is possible when the seawater system is in service. The test is desirable to carry out when one of the pumps is in operation. The test requires start-up of the second pump and simultaneous operation for a while. It is also desirable to test the trip function at low flow for each of the pumps. However, at the writing moment the trip limit is not specified yet. This is something that needs to be implemented before start-up.

**General Procedure:**
- Verify that the trip limit at low flow is set on both of the pumps.
- Verify that one of the pump is in operation, refer to this pump as the duty pump.
  - Record the flow through the pump: ______ m³/h.
- Start the stand-by pump.
- Let the two pumps run simultaneously for a few minutes.
- Duty pump: Verify that the minimum-flow regulation is in auto, and close the outlet valve (84-XV-93482A/B).
  - Put the minimum-flow regulation in manual, and decrease the flow by closing the minimum-flow valve. It is desirable to decrease the flow to trip level of the pump.
  - Put the minimum-flow regulation back to auto.
- Record the flow through the stand-by pump: ______ m³/h.
- Start the duty pump again.
- Let the two pumps run simultaneously for a few minutes.
- Stand-by pump: Verify that the minimum-flow regulation is in auto, and close the outlet valve (84-XV-93482A/B).
  - Put the minimum-flow regulation in manual, and decrease the discharge flow by closing the minimum-flow valve. It is desirable to decrease the flow to the trip level of the pump.
  - Put the minimum-flow regulation back to auto.
- When the pressure and flow has stabilized again, the system can be put into normal operation.

**Approximate Duration:**
The pump changeover and trip test is estimated to take ½ hr, but is depending on what is done during the commissioning phase. The test is able to carry out at any time after the commissioning phase of the system.

4.2.3 HP Seawater Coarse Filter

The purpose of these tests is to verify that the HP seawater coarse filter is properly installed and is functioning after design. It is also desirable to verify the functionality of critical instruments installed in the package.

Before the HP seawater coarse filter is ready to be tested for functionality, it is necessary to have the HP seawater distribution system in operation to have actual flow through the filter. Desirable tests to carry out are:
- Functionality test of the backflushing sequence
- Verification of essential instrumentation
General Procedure, Functionality Test:

- Verify that the motor (84-CA-9129-M01) is supplied with electrical power, and that the PCS is updated with operational functions.
- Verify that the drain valve (84-XV-93499A) is supplied with electrical power and is acting on demand from the PCS.
- Verify that the differential pressure instrument (84-PDC-93491) is properly installed and is communicating with the PCS. Also check that the correct alarm limit is implemented, set at 0.5 barg.
- Put the pressure differential controller (84-PDC-93491) in auto, along with the drain valve (84-XV-93499A).
- Verify that the backflushing sequence is being activated at the set point (0.5 barg), by waiting for the differential pressure to increase or by manipulating the differential pressure in PCS.

General Procedure, Verification of Essential Instrumentation:

- Verify that the following instruments are properly installed and that the PCS is updated with alarm limits.
  - 84-TI-93495.
  - 84-AI-93493. L=0.2 ppm.
  - 84-PI-93493. L=7.5 bar.
- Verify that 84-PI-93494, is properly installed and that the PSD is updated with trip limit, LL=6.0 bar. This trip will activate PSD 1 after 60 seconds.
  - Temporarily override the output signal to avoid PSD 1. Block the transmitter and drain it. Verify that the low-low alarm activates. Put the system back to original status.

Approximate Duration:
The different tests corresponding to the HP seawater coarse filter is estimated to take ½ hr.

4.2.4 Electro Chlorination Generation

The electro chlorination generation consists of two vessels, the electro chlorination cell and the copper-adding vessel. The purpose of this test is to line these two vessels up in parallel and adjust the flow running through the package. Also the instrumentation and trip function will be function tested. The HP seawater distribution system needs to be in service before starting these tests.

Desirable tests to carry out are:
- Capacity test
- Functionality test

Reference relevant for the test is P&ID: PH-ME-P-0260-001.

General Procedure:

- Verify that 84-PSV-96072 is correctly mounted and is set at 10 barg.
- Verify that the UCP (Unit Control Panel) is correctly mounted and supplied with electrical power.
- Check 84-PCV-96073 for functionality, should be set at 7.5 barg.
Verify that the following instruments are properly installed and that the PCS is updated with alarm limits:

- 84-PI-96071. L=6.5 barg.
- 84-FI-96069. LL=22 m³/h.
- 84-FI-96070. LL=0.48 m³/h.
- 84-II-96062. L=15 A.
- 84-EI-96063. H=120 V.
- 84-II-96064. L=5 A.
- 84-EI-96065. H=13 V.

Line the system up ready for operation.

Verify that the control valves for hypochlorite to the seawater lift pumps in operation are open (84-XV-93472A/B and 84-XV-93202A/B).

Adjust the flow through the electro chlorinator cell (84-CX-9107) by regulating the outlet valve, 84-V-94004. The flow should be left at 25 m³/h.

Adjust the flow through the copper-adding vessel (84-VX-9108) by regulating the outlet valve, 84-V-94006. The flow should be set at 0.6 m³/h.

Activate the electro chlorinator generator with 84-HS-96061.

Adjust the current at the UCP according to the analyzers, 84-AI-93223 on the LP seawater distribution system and 84-AI-93493 on the HP seawater distribution system.

Distribute the hypochlorite to the two systems by regulating on the valves upstream 84-XV-93202A/B (LP system) and 84-XV-93472A/B (HP system). The flow should be set to 18.5 l/h at the LP system and 7 l/h in the HP system.

Make the same adjustments for the stand-by pumps.

Approximate Duration:
The test should take about 1 hr to complete, including correct flow adjustment.

4.2.5 Final tuning of HP seawater distribution system

When the different tests around the HP seawater distribution system are finished, it is time to do the final tuning around the temperature regulation loops. This involves the temperature regulation at the VSD cooler (84-TIC-93233) and at the AHU cooling coils (84-TIC-91771A/B). To do this, the HP seawater distribution system has to be in service along with the coolers and containing utility systems. Record the final settings in Table 6.6/6.7/6.8.
5 Performance Test Rotational Equipment

5.1 Cooling Medium Pumps (45-PA-9106A/B)

Before the test is ready to be executed it needs to be verified that the commissioning phase is completed and the LP seawater system is in operation, as well as the cooling medium system is ready for operation. The recycle line is designed to handle a maximum flow of 680 m$^3$/h, which is also the minimum continuous flow through the pump. The first point to be verified on the flow will therefore be just above 680 m$^3$/h.

Reference relevant for the test is P&ID: PH-ME-P-0263-001.

General Procedure

Use Table 6.11/6.12 to record the data.

- Take a density sample of the medium and send to lab for analysis.
- Start testing the stand-by pump. (If the system is in service, if not it’s optional).
- Measure and record the relevant XV open/close times and leave the valves in auto.
- Record the tuning parameters of the minimum-flow valve (45-FIC-93267A/B) and leave the flow regulation in auto.
- Start the stand-by pump using the start-up sequence and let it run for 15–20 min to stabilize temperatures, if not recently started.
- Use the minimum-flow valve to regulate the flow. It is recommended to start verifying the left hand side of the pump characteristic. Start reducing the flow towards the minimum continuous flow, by regulating the manual outlet valve 45-V-91245/6. The first desirable point will be at 700 m$^3$/h, verify that the low-flow alarm activates. Record the flow, pressures and temperatures at this point, which will be the first of six points.
- Visually go over the system to look for abnormal vibrations or leakages. This should be repeated for every flow.
- Slowly operate the manual outlet valve again, and increase the flow through the pump. Operate the minimum-flow regulation in manual to help reaching the desirable points. Use the table and record the parameters. Desirable recordings are 1000, 1200, 1550, 1750, 2000 m$^3$/h. It is recommended to stop the parallel pump when the total flow through the system exceeds 1550 m$^3$/h. 1550 m$^3$/h represent the rated point of the pump; at this point the differential head should be between 73,5 – 79 mlc, while the power should not exceed 213 kW. This is according to API 610 (appendices E).

After the test, the results should be plotted into the original pump characteristic (appendix K).

Approximate Duration:
The different tests of one single pump are estimated to take around 1-2 hrs. This time however, could be reduced if some of the desirable data has been collected during the offshore commissioning phase. These tests can be carried out at any time, also after the system is put in service.
5.2 Firewater Pumps (48-XD-9107A/B)

Before the test is ready to be executed it needs to be verified that the commissioning phase is completed. A manual dump valve will adjust the firewater flow while the outlet valve of the pump will be closed. The provider of the pump used 1026 kg/m$^3$ as the seawater density, which is also recommendable to use in this test. It is desirable to test one of the two pumps at a time, means that only one firewater pump is stand-by in an emergency situation. Therefore the test has to be well coordinated along with other critical operations at the platform. References relevant for the test are P&ID’s: PH-ME-P-0290-001 & PH-ME-P-0291-001.

General Procedure

Use Table 6.13/6.14 to record the data.

- Measure the distance between the cellar deck and the sea level to be sure of the suction pressure of the pump. This is used in the head calculations later. The total length from the submerged pump to the cellar deck is 49.5 m. The distance from the cellar deck to the discharge level is 1.3 m.
- Start testing one of the pumps, while the other one is in auto-mode.
- Verify that the start-mode selector is switched to auto and press the “TEST START” button. Let it run for 2 hrs to stabilize temperatures. It is recommended to start verifying the right hand side of the pump characteristic.
- Start by opening the manual dump valve a few percent (48-HV-93544A/B), close the outlet valve (48-HV-93547A/B) before opening the dump valve entirely. Record the flow, pressures and temperatures at this point, which will be the first of six desirable points. The approximated flow through the pump at this time should be around 2300 m$^3$/h. This flow represent the rated point of the pump; at this point the differential head should be between 173.5 – 182 mlc. This is according to API 610 (appendix E).
- Visually go over the system to look for abnormal vibrations or leakages. This should be repeated for every flow.
- Slowly operate the manually dump valve towards closed to adjust the flow through the pump. Use the table and record the parameters. Desirable recordings are 2100, 1750, 1550, 1200, 1000 m$^3$/h.
- Stop the pump by switching the start-mode selector to manual, and press the “STOP Diesel Engine” button.
- Close the manual dump valve (48-HV-93544A/B).
- Open the outlet valve (48-HV-93547A/B).
- Switch the start-mode selector back to auto, and acknowledge alarms.

After the test, the results should be plotted into the original pump characteristic (appendix L).

Approximate Duration:
The different tests of one single pump are estimated to take around 3 hrs. This time however, could be reduced if some of the desirable data has been collected during the offshore commissioning phase. These tests can be carried out at any time, also after the system is put in service.
5.3 Oil Booster Pumps (11-PA-9101A/B)

Before the test is ready to be executed it needs to be verified that the commissioning phase is completed and the oil train is in operation. The recycle line is designed to handle a maximum flow of 320 m$^3$/h, which is also the minimum continuous flow through the pump. The first point to be verified on the flow will therefore be just above 320 m$^3$/h. Use the metering station for export oil to verify the density of the oil.

References relevant for the test are P&ID: PH-ME-P-0132-001.

General Procedure

Use Table 6.15/6.16 to record the data.

- Start testing the stand-by pump.
- Measure and record the relevant XV open/close times and leave the valves in auto.
- Record the tuning parameters of the minimum-flow valve (11-FIC-92347A/B) and leave the flow regulation in auto.
- Start the stand-by pump using the start-up sequence and let it run for 15-20 min to stabilize temperatures, if not recently started.
- Use the minimum-flow valve to regulate the flow. It is recommended to start verifying the left hand side of the pump characteristic. Start reducing the flow towards the minimum continuous flow, by regulating the outlet valve 11-V-90245/9. The first desirable point will be at 340 m$^3$/h, verify that the low-flow alarm activates. Record the flow, pressures, speed and temperatures at this point, which will be the first of six points.
- Visually go over the system to look for abnormal vibrations or leakages. This should be repeated for every flow.
- Slowly operate the outlet valve to increase the flow through the pump. Operate the minimum-flow regulation in manual to help reaching the desirable points. Use the table and record the parameters. Desirable recordings are 450, 550, 790, 900, 950 m$^3$/h. It is recommended to stop the parallel pump when the total flow though the system exceeds 790 m$^3$/h. 790 m$^3$/h represent the rated point of the pump; at this point the differential head should be between 79 – 84,5 mle, while the power should not exceed 182 kW. This is according to API 610 (appendices E).

Approximate Duration:

The different tests of one single pump are estimated to take around 1-2 hrs. This time however, could be reduced if some of the desirable data has been collected during the offshore commissioning phase. These tests can be carried out at any time, also after the system is put in service.
5.4 Oil Export Pumps (11-PA-9102A/B)

Before the test is ready to be executed it needs to be verified that the commissioning phase is completed and the oil train is in operation. The recycle line is designed to handle a maximum flow of 360 m$^3$/h, which is also the minimum continuous flow through the pump. The first point to be verified on the flow will therefore be just above 360 m$^3$/h. Use the metering station for export oil to verify the density of the oil.

References relevant for the test are P&ID: PH-ME-P-0133-001.

General Procedure

Use Table 6.17/6.18 to record the data.

- Start testing the stand-by pump.
- Measure and record the relevant XV open/close times and leave the valves in auto.
- Record the tuning parameters of the minimum-flow valve (11-FIC-92367A/B) and leave the flow-regulation in auto.
- Start the 2nd Booster Pump. This to make sure the export pumps got enough NPSH.
- Start the stand-by pump using the start-up sequence and let it run for 15-20 min to stabilize temperatures, if not recently started.
- Use the minimum-flow valve to regulate the flow. It is recommended to start verifying the left hand side of the pump characteristic. Start reducing the flow towards the minimum continuous flow, by regulating 11-LIC-92264. The first desirable point will be at 380 m$^3$/h, verify that the low-flow alarm activates. Record the flow, pressures and temperatures at this point, which will be the first of six points.
- Visually go over the system to look for abnormal vibrations or leakages. This should be repeated for every flow.
- Slowly operate 11-LIC-92264, and increase the flow through the pump. Operate the minimum-flow regulation in manual to help reaching the desirable points. NB! Do not forget to observe the oil level in the 2nd oil separator during this operation, and keep the level inside the boundaries. Use the table and record the parameters. Desirable recordings are 500, 650, 795, 900, 1050 m$^3$/h. It is recommended to stop the parallel pump when the total flow though the system exceeds 795 m$^3$/h. 795 m$^3$/h represent the rated point of the pump; at this point the differential head should be between 789 – 821 mlc, while the power should not exceed 1872 kW. This is according to API 610 (appendices E).

After the test, the results should be plotted into the original pump characteristic (appendix N).

Approximate Duration:
The different tests of one single pump are estimated to take around 1-2 hrs. This time however, could be reduced if some of the desirable data has been collected during the offshore commissioning phase. These tests can be carried out at any time, also after the system is in put in service.
5.5 1st Stage Gas Compressor (23-KA-9101)

Technical literature used to define the performance test of the centrifugal compressors is taken from; Ford, 2007.

Before the test is ready to be executed it needs to be verified that the commissioning phase is completed and the surge line is properly implemented. The recycle line is designed to handle a flow up to 54 000 m$^3$/h with a differential pressure of 7,4 bar, which means that the recycle line can almost handle the maximum flow of the compressor. However, by running gas on recycle this will affect the molecular weight (i.e. become leaner), it is therefore recommended to let the compressor operate under normal conditions as far as possible.

Since there is not installed any sampler for measuring molecular weight, there is a problem related to the sampling operation. For a centrifugal compressor it is recommended to take three different gas samples related to the anti-surge valve position. However, since the amount of gas that is being produced at Valhall is significantly below the designed capacity of the new compressors, it is assumed that the anti-surge valve position may never be entirely closed. With this information it is only required two gas samples during the test.

The sampling operation, however, is a critical operation where the operator has to couple a sample bottle up to a high-pressure hydrocarbon system. It is therefore important to be aware of the hazard this can lead to, and that the operation has to be well planned. The sample will be sent to shore to be analyzed.

References relevant for the test are P&ID’s: PH-ME-P-0151-001, PH-ME-P-0152-001, PH-ME-P-0153-001 & PH-ME-P-0160-001.

General Procedure

Use Table 6.19 to record the data.

- Record the relevant XV open/close times. NB! This has to be collected during offshore commissioning, or in a start-up sequence.
- Record the final ASC (Anti-Surge Control) tuning parameters (23-FIC-92543).
- Start the compressor using the start-up sequence and bring the compressor up to load.
- Ensure that the compressor suction temperature (23-TI-92533) and pressure (23-PI-92532) are in normal operating range (approximately 40°C and 3,5 barg).
- Ensure the compressor discharge cooler (23-TIC-92604) is operating in the normal operating range.
- Put the anti-surge valve (23-FIC-92543) into manual, and slowly increase the output signal to 100 % (fully opened). The first desirable flow recording is at 58 000 m$^3$/h (around 187 t/h), locate this parameter at the CCP (Compressor Control Panel) if not available in PCS.
- Visually go over the compressor to verify that everything is working according to design.
- Take a gas sample for molar weight analysis. It is recommended to use the isokinetic sample valve (23-AE-92527-S2), located downstream 1st stage suction scrubber.
- Record the following data:
  - The speed, only relevant to record it once since it is fixed speed
  - The flow
  - The recycle valve position
  - The inlet and outlet temperature
  - The inlet and outlet pressure
  - Bearing temperatures
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- Vibrations
  - Operate the anti-surge valve towards zero, and make 5 more recordings of the parameters listed above. NB! Confirm that ASC will automatically switch back to auto-mode on detection of surge.
  - Desirable flow recordings are 56 000, 53 000, 50 000, 45 000, 40 000 m³/h. It is desirable to take a gas sample when the recycle flow is at minimum.
  - 53 000 m³/h represent the rated point of the compressor; at this point the differential head should be between 142 – 149 kj/kg, while the power should not exceed 10,08 MW (API 617, 2002).
  - To operate the compressor at lower flow, it may be desirable to close the outlet valve (23-ESDV-92551A) to obtain high pressure and low flow. But, make sure the compressor does not reach the region of surge and that the hot-gas recycle valve (23-FV-92542) is held closed. Visually go over the compressor for each flow recording.

Approximate Duration
The performance test of the 1st stage gas compressor should take about 3-4 hrs. However if data is collected during offshore commissioning, particularly during the set up of the anti-surge controller, then this time may be reduced. This test can be carried out at any stage after the compressor is available by operating it on recycle.

5.6 2nd Stage Gas Compressor (23-KA-9102)
Before the test is ready to be executed it needs to be verified that the commissioning phase is completed and the surge line is properly implemented. The recycle line is designed to handle a flow up to 18 650 m³/h with a differential pressure of 20,9 bar, which means that the recycle line can almost handle the maximum flow of the compressor.
It is recommended to take two gas samples during the test, all related to the anti-surge valve position. The sampling operation, however, is a critical operation where the operator has to couple a sample bottle up to a high-pressure hydrocarbon system. It is therefore important to be aware of the hazard this can lead to, and that the operation has to be well planed. The sample will be sent to shore for analyzing.
References relevant for the test are P&ID’s: PH-ME-P-0160-001, PH-ME-P-0161-001, PH-ME-P-0162-001, PH-ME-P-0170-001 & PH-ME-P-0170-002.

General Procedure
Use Table 6.20 to record the data.
- Record the relevant XV open/close times. NB! This has to be collected during offshore commissioning, or in a start-up sequence.
- Record the final ASC tuning parameters (23-FIC-92643).
- Start the compressor using the start-up sequence and bring the compressor up to load.
- Ensure that the compressor suction temperature (23-TI-92633) and pressure (23-PI-92632) are in normal operating range (approximately 24°C and 11 barg).
- Ensure the compressor discharge cooler (24-TIC-92774) is operating in the normal operating range.
- Put the anti-surge valve (23-FIC-92643) into manual, and slowly increase the output signal to 100 % (fully opened). The first desirable flow recording is at 20 000 m³/h (around 220 t/h), locate this parameter at the CCP if not available in PCS.
Visually go over the compressor to verify that everything is working according to design.

Take a gas sample for molar weight analysis. It is recommended to use the isokinetic sample valve (23-AE-92627-S2), located downstream 2\textsuperscript{nd} stage suction scrubber.

Record the following data:
- The speed, only relevant to record it once since it is fixed speed
- The flow
- The recycle valve position
- The inlet and outlet temperature
- The inlet and outlet pressure
- Bearing temperatures
- Vibrations

Operate the anti-surge valve towards zero, and make 5 more recordings of the parameters listed above. NB! Confirm that ASC will automatically switch back to auto-mode on detection of surge.

Desirable flow recordings are 19 500, 18 700, 17 200, 16 000, 14 000 m\textsuperscript{3}/h.
It is desirable to take a gas sample when the recycle flow is at minimum.
17 200 m\textsuperscript{3}/h represent the rated point of the compressor; at this point the differential head should be between 133 – 140 kj/kg, while the power should not exceed 10,00 MW (API 617, 2002).

To operate the compressor at lower flow, it may be desirable to close the outlet valve (23-ESDV-92651A) to obtain high pressure and low flow. But, make sure the compressor does not reach the region of surge and that the hot-gas recycle valve (23-FV-92642) is held closed. Visually go over the compressor for each flow recording.

Approximate Duration
The performance test of the 2\textsuperscript{nd} stage gas compressor should take about 3-4 hrs. However if data is collected during offshore commissioning, particularly during the set up of the anti-surge controller, then this time may be reduced. This test can be carried out at any stage after the compressor is available by operating it on recycle.

5.7 3\textsuperscript{rd} Stage Gas Compressor (23-KA-9103)
Before the test is ready to be executed it needs to be verified that the commissioning phase is completed and the surge line is properly implemented. The recycle line is designed to handle a flow up to 9 160 m\textsuperscript{3}/h with a differential pressure of 32,3 bar, which means that the recycle line can almost handle the maximum flow of the compressor.
It is recommended to take two different samples during the test, all related to the anti-surge valve position. The sampling operation, however, is a critical operation where the operator has to couple a sample bottle up to a high-pressure hydrocarbon system. It is therefore important to be aware of the hazard this can lead to, and that the operation has to be well planed. The sample will be sent to shore for analyzing.
References relevant for the test are P&ID’s: PH-ME-P-0170-003, PH-ME-P-0171-001, PH-ME-P-0172-001 & PH-ME-P-0180-001.
General Procedure

Use Table 6.21 to record the data.

- Record the relevant XV open/close times. NB! This has to be collected during offshore commissioning, or in a start-up sequence.
- Record the final ASC tuning parameters (24-FIC-92743).
- Start the compressor using the start-up sequence and bring the compressor up to load.
- Ensure that the compressor suction temperature (23-TI-92733) and pressure (23-PI-92732) are in normal operating range (approximately 18°C and 33 barg).
- Ensure the compressor discharge cooler (23-TIC-92704) is operating in the normal operating range.
- Put the anti-surge valve (24-FIC-92743) into manual, and slowly increase the output signal to 100% (fully opened). The first desirable flow recording is at 10 500 m$^3$/h (around 420 t/h), locate this parameter at the CCP if not available in PCS.
- Visually go over the compressor to verify that everything is working according to design.
- Take a gas sample for molar weight analysis. It is recommended to use the isokinetic sample valve (23-AE-92727-S2), located downstream 3$^{rd}$ stage suction scrubber.
- Record the following data:
  - The speed, only relevant to record it once since it is fixed speed
  - The flow
  - The recycle valve position
  - The inlet and outlet temperature
  - The inlet and outlet pressure
  - Bearing temperatures
  - Vibrations
- Operate the anti-surge valve towards zero, and make 5 more recordings of the parameters listed above. NB! Confirm that ASC will automatically switch back to auto-mode on detection of surge.

Desirable flow recordings are 10 000, 9 150, 8 150, 7 300, 6 300 m$^3$/h.

It is desirable to take a gas sample when the recycle flow is at minimum. 8 150 m$^3$/h represent the rated point of the compressor; at this point the differential head should be between 68 – 71,5 kJ/kg, while the power should not exceed 8 560 kW (API 617, 2002).

To operate the compressor at lower flow, it may be desirable to close the outlet valve (24-ESDV-92751A) to obtain high pressure and low flow. But, make sure the compressor does not reach the region of surge and that the hot-gas recycle valve (23-FV-92742) is held closed. Visually go over the compressor for each flow recording.

Approximate Duration

The performance test of the 3$^{rd}$ stage gas compressor should take about 3-4 hrs. However if data is collected during offshore commissioning, particularly during the set up of the anti-surge controller, then this time may be reduced. This test can be carried out at any stage after the compressor is available by operating it on recycle.
5.8 4th Stage Gas Compressor (27-KA-9104)

Before the test is ready to be executed it needs to be verified that the commissioning phase is completed and the surge line is properly implemented. The recycle line is designed to handle a flow up to 3 500 m$^3$/h with a differential pressure of 67.3 bar, which means that the recycle line can almost handle the maximum flow of the compressor. However, by running gas on recycle this will affect the molecular weight (i.e. become leaner), it is therefore recommended to let the compressor operate under normal conditions as far as possible.

References relevant for the test are P&ID’s: PH-ME-P-0195-004, PH-ME-P-0195-005, PH-ME-P-0199-001 & PH-ME-P-0205-002.

General Procedure

Use Table 6.22 to record the data.

- Record the relevant XV open/close times. NB! This has to be done when the compressor is stopped, or in a start-up sequence.
- Record the final ASC tuning parameters (27-FIC-92943).
- Start the compressor using the start-up sequence and bring the compressor up to load.
- Ensure that the compressor suction temperature (27-TI-92933) and pressure (23-PI-92932) are in normal operating range (approximately 16°C and 47 barg).
- Ensure the compressor discharge cooler (27-TIC-93004) is operating in the normal operating range.
- Put the anti-surge valve (27-FIC-92943) into manual, and slowly increase the output signal to 100 % (fully opened). The first desirable flow recording is at 4 200 m$^3$/h (around 167 t/h), locate this parameter at the CCP if not available in PCS. Visually go over the compressor to verify that everything is working according to design.

Record the following data:

- The speed, only relevant to record it once since it is fixed speed
- The flow
- The recycle valve position
- The inlet and outlet temperature
- The inlet and outlet pressure
- The molar weight
- Bearing temperatures
- Vibrations

- Operate the anti-surge valve towards zero, and make 5 more recordings of the parameters listed above. NB! Confirm that ASC will automatically switch back to auto-mode on detection of surge.

Desirable flow recordings are 3 800, 3 500, 3 050, 2 700, 2 400 m$^3$/h. 3 050 m$^3$/h represent the rated point of the compressor; at this point the differential head should be between 127 – 133.5 kJ/kg, while the power should not exceed 6 750 kW (API 617, 2002).

To operate the compressor at lower flow, it may be desirable to close the outlet valve (27-ESDV-93019A) to obtain high pressure and low flow. But, make sure the compressor does not reach the region of surge and that the hot-gas recycle valve (27-FV-92942) is held closed. Visually go over the compressor for each flow recording.
Approximate Duration

The performance test of the 4th stage gas compressor should take about 3-4 hrs. However if data is collected during offshore commissioning, particularly during the set up of the anti-surge controller, then this time may be reduced. This test can be carried out at any stage after the compressor is available by operating it on recycle.
6 Calculation

For the rotational equipment it is desirable to verify that the characteristic is the same as it was during the FAT. This is done in order to verify that the purchaser gets the product he paid for. The characteristic is verified through head versus flow, and is plotted against the curves given from the manufacture. For units related to the following calculations please check Units at page 7.

Centrifugal pumps:
For centrifugal pumps, the formula used to calculate total dynamic head is given by:

\[ H_d = \frac{p_o - p_i}{\rho \cdot g} + \frac{v_o^2 - v_i^2}{2 \cdot g} \]  

(GPSA, 2004)

Where \( v_i \) and \( v_o \) expresses the inlet and outlet velocity, measured in m/s.
In relation, most flow versus head characteristics is given in m³/h of flow.

Example:
\( Q = 2400m³/h \)
\( p_i = 1,27bar(g) = 127000Pa \)
\( p_o = 9,29bar(g) = 929000Pa \)
\( \rho = 1030kg/m³ \)
\( g = 9,81m/s² \)

First the liquid velocity in and out of the pump flanges needs to be calculated.

\[ d_i = 35" = \frac{35 \cdot 25,4}{1000} = 0,889m \]
\[ d_o = 18" = \frac{18 \cdot 25,4}{1000} = 0,4572m \]

\[ A_i = \frac{\pi \cdot d_i^2}{4} = \frac{\pi \cdot (0,889)^2}{4} = 0,621m² \]
\[ A_o = \frac{\pi \cdot d_o^2}{4} = \frac{\pi \cdot (0,4572)^2}{4} = 0,164m² \]

\[ Q = \frac{2400m³}{h} = \frac{2400}{3600} = 0,667m³/s \]

\[ v_i = \frac{Q}{A_i} = \frac{0,667m³/s}{0,621m²} = 1,07m/s \]
\[ v_o = \frac{Q}{A_o} = \frac{0,667m³/s}{0,164m²} = 4,07m/s \]

The total dynamic head of the pump is then calculated, and in relation to the flow, plotted and compared with the characteristic given by the provider of the centrifugal pump:

\[ H_d = \frac{929000Pa - 127000Pa}{1030kg/m³ \cdot 9,81m/s²} + \frac{(4,07m/s)^2 - (1,07m/s)^2}{2 \cdot 9,81m/s²} = 80,16m \]
Centrifugal compressors:

For centrifugal gas compressors, the formula used to calculate flow and polytrophic head is given by:

\[ Q = \frac{w \cdot R \cdot T_i \cdot Z_i}{M \cdot p_i} \]  

\[ H_p = \frac{Z_{avg} \cdot R \cdot T_i}{M \cdot (n-1)} \left[ \left( \frac{p_o}{p_i} \right)^{\frac{n}{n-1}} - 1 \right] \]  

Where:

\[ Z_{avg} = \frac{Z_i + Z_o}{2} \]

\[ T_o = \left( \frac{p_o}{p_i} \right)^{\frac{(n-1)}{n}} \]

The volumetric flow is then calculated:

\[ Q = \frac{150000 \, \text{kg} / \text{h}}{8.314 \cdot 288.15 \, \text{K} \cdot 0.983}{22.572 \, \text{kg} / \text{kmol} \cdot 336 \, \text{kPa}} = 46576 \, \text{m}^3 / \text{h} \]

The polytrophic head is then calculated, and in relation to the flow, plotted and compared with the characteristic given by the provider of the centrifugal compressor:

\[ H_p = \frac{0.958 \cdot 8.314 \cdot 288.15 \, \text{K} \cdot 0.983}{22.572 \, \text{kg} / \text{kmol} \cdot 0.267} \left[ \left( \frac{1075 \, \text{kPa}}{336 \, \text{kPa}} \right)^{0.267} - 1 \right] = 138.7 \, \text{kJ} / \text{kg} \]
7 Discussion

When the objectives for the submission were first introduced there were a few discussions relating to the contents of the thesis. This was resolved in a tidy way, where the involved parties introduced their opinion on what the report should contain. It was in this process where it was selected to have main focus on one particular system, the seawater system. Along with this system it was decided to describe a verification program for other chosen rotational items of equipment. Afterthoughts and discussions has revealed that this might have been solved out in a better and more effectively way. This is particularly relevant to the performance verification program of the many items of rotational equipment, where it has been suggested that a more effectively way would be to describe the method of one centrifugal pump and one centrifugal compressor instead of describing all the rotational equipment along with tag numbers and specific data. The reason for this is that Chapter 5, performance test rotational equipment, might seem a bit repetitive, especially as it contains a large number of equipment items. It was, however, during the project accepted to avoid some of the rotational equipment mentioned in the submission of the thesis, this was equipment like the HP/LP knock-out drum pumps and jet water pumps. The reason for this decision was that these pumps were deemed less critical and of a more minor scale and size, compared with the larger pumps and compressors.

During the thesis, some aspects have been highlighted as possible root causes for potential errors and gaps in the performance testing results. These are summarized below. Relating to the submersed pumps, such as firewater, LP and HP seawater lift, there has been revealed a problem of measuring the suction pressure. The reason for this issue is that the pumps are submersed into the seawater beneath the platform and therefore not equipped with pressure gauges at the suction side. This problem is solved by finding the exact length of the pump unit from the submerged rotational impeller and up to the outlet flange. By measuring the differential level from the sea level to the outlet flange, the submersed length of the pump can be determined. This depth is used to calculate the inlet pressure to the pumps. However, this method could lead to a few errors, especially if the sea is upset and large waves are introduced.

Another parameter that might lead to errors or mismatches when calculating the performance of equipment is the density of the medium running through it. Density is a parameter that changes marginally with temperature deviations. It was therefore decided for majority of equipment to measure the density during the performance test to be sure. However, because the changes are relatively low, the same value as used for the factory acceptances test shall be used for all the equipment involving seawater. In other rotational equipment the density is measured, either by analyzing a sample in the lab or by an online sampling station.

The main problem relating to the gas compressors is associated with the molar weight of the gas running through them. The P&ID’s revealed that only the 4th stage had installed gas chromatograph to sample the molar weight. As stated in the report, the gas that is forced to flow through the recycle loop of the compressor shall get progressively leaner over time. This implies the molar weight shall reduce proportionally with closure of the anti-surge valve position. This would have given a mismatch according to the head calculation if a simulated value for the molar weight had been used. First it was suggested to take three gas samples for each of the compressor stages, everyone at different anti-surge valve position. But, since one of the samples was recommended to be taken when the anti-surge valve is closed, something
that is very hard to achieve because of the small amount of produced gas at Valhall, it was decided to only take two gas samples for each of the compressor stages. This will give a more realistic molar weight and hence picture of the gas compressor performance. However, this method introduces a high risk relating to the sampling operation, where the sampling bottles need to be connected to high-pressure hydrocarbon systems. It is stated that due care needs to be exercised when performing this operation.

A problem has also occurred when defining the inlet and outlet compressibility factors for the compressors. To define the exact compressibility factors a comprehensive calculation needs to be carried out. A much less comprehensive way to define this value is to use pre-made compressibility charts of natural gases (with leaner molar weight than 40 kg/kmol). The problem is first that the charts do not include every single molar weight, and second that the exact molar weight is hard to define. By interpolating between two nearby charts, the suspected compressibility factors are found. This might lead to some mismatches in the calculation part. The charts are attached to this report.

Another issue related to this thesis and the literature, is the use of sources found in the VRD-project’s internal database, ShareCat, where each equipment supplier deposits important information relating to their product. This is a database that only project personnel can access, and could therefore lead to some misinterpretation for external personnel not having this access. By attaching all the relevant literature, the report can be read and understood by external personnel. There will also be engaged an internal BP employee to assist the evaluation part of the report.

At the time of writing this document there has been discussion in the VRD-project regarding the alarm settings in the new process modules. When searching the documentation given by the many providers, a lot of vendor recommended alarm limits were found. But, when studying the alarm limits set by the responsible personnel in the VRD-project, there was found a mismatch between the settings. This is particularly relevant to vibration and temperature limits, where it is observed that the VRD-project has specified more conservative alarm and trip limits compared to vendor recommendation. This report refers to the alarm settings given by the project, due to this conservatism. As the alarm settings are likely to change (through a managed change process) throughout start-up, the “final” limits have not been specified. Where relevant the test sheets identify this uncertainty, reminding the executing personnel that these limits were not decided at the time of writing.

Hence although there are uncertainties and potential errors relating to the performance testing results, the submitted verification program still is suitable for defining whether the equipment is performing according to the guarantee point or not. But following this procedure it is hoped that the VRD project and ultimately BP Norway Valhall asset will obtain some valuable information regarding the performance of some key equipment.
8 Conclusion

The objective for this master thesis was to outline a program on how to test the performance of chosen equipment on the new field centre (PH) at Valhall. The system that was decided to review in detail was the seawater system, and in particular the LP and HP seawater systems. Along with these systems it was decided to outline a less comprehensive performance verification program for other rotational equipment. The method selected for the verification was to record some of the conditioning monitoring parameters, such as suction and discharge pressure, and thereby calculate the head of the rotational equipment. In relation to the flow through the equipment, the head versus flow points can be plotted against the original characteristic given by the provider. By use of this method, the performance of the equipment can be measured and reviewed for acceptability. The aim of the performance test is to verify that the design complies with the equipment guarantee points and is therefore capable of achieving rated production. The candidate recommends the submitted program as a tool to verify the performance of the tested equipment.
References


Frank Mohn Flatøy (2006), *Technical Description Electrical Submersible Pump*. Compendium


Eisenmann, R.C. and Eisenmann R.C. Jr. (2005), *Machinery Malfunctions Diagnosis and Correction*. Prentice Hall, New Jersey, USA.


## Test Sheets

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<tr>
<td>Date and time</td>
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<tr>
<td>Flowrate (84-FIC-93207A) [m³/h]</td>
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<tr>
<td>Distance from cellar deck to sea level [m]</td>
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<tr>
<td>Discharge pressure (84-PI-93207A)[Barg]</td>
</tr>
<tr>
<td>Discharge temp. (84-TI-93207A) [°C]</td>
</tr>
<tr>
<td>Power (84-PX-9101A) [kW]</td>
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<tr>
<td>Speed (84-NI-95500A) [rpm]</td>
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<tr>
<td>Min flow position (84-FV-93207A) [%]</td>
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<tr>
<td>Tuning parameters (84-FIC-93207A)</td>
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<tr>
<td>Vib. DE motor (84-YI-95501A) [mm/s]</td>
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<td>Vib. Shaft (84-YI-95510A) [mm/s]</td>
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<td>Vib. Shaft (84-YI-95511A) [mm/s]</td>
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<td>Temp. windings (84-TI-95502A) [°C]</td>
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<tr>
<td>Temp. windings (84-TI-95505A) [°C]</td>
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<td>Temp. windings (84-TI-95508A) [°C]</td>
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<tr>
<td>Open / Close time (84-XV-93212A) [s]</td>
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**Table 6.4 LP Seawater Lift Pump A**

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<td>-</td>
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<td>-</td>
<td>-</td>
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<td>-</td>
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<td>-</td>
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<td>-</td>
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<td>-</td>
<td>-</td>
<td>-</td>
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<tr>
<td>Power (84-PX-9101B) [kW]</td>
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<td>-</td>
<td>730</td>
<td>-</td>
<td>-</td>
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<td>4.5</td>
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**Table 6.5 LP Seawater Lift Pump B**
### Table 6.6 Tuning Parameters 84-FIC-93233

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### Table 6.7 Tuning Parameters 84-TIC-91771A

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### Table 6.9 HP Seawater Lift Pump A (84-PX-9102A)

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<th>4</th>
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<td>Integr.</td>
<td>Derv.</td>
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<tr>
<td>Open / Close time (84-XV-93212A) [s]</td>
<td>5</td>
<td>-</td>
<td>14</td>
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<td>Closing</td>
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<td>Open / Close time (84-XV-93202A) [s]</td>
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<td>-</td>
<td>4</td>
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<td>Closing</td>
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### Table 6.10 HP Seawater Lift Pump B (84-PX-9102B)

<table>
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<th>Norm</th>
<th>Alarm</th>
<th>Max</th>
<th>1</th>
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<th>3</th>
<th>4</th>
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<tbody>
<tr>
<td>Flowrate (84-FIC-93477B) [m³/h]</td>
<td>900</td>
<td>-</td>
<td>1050</td>
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<tr>
<td>Distance from cellar deck to sea level [m]</td>
<td>32</td>
<td>-</td>
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<tr>
<td>Discharge pressure (84-PI-93477B)[Barg]</td>
<td>9.7</td>
<td>12.3</td>
<td>14</td>
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<tr>
<td>Discharge temp. (84-TI-93477B) [°C]</td>
<td>6</td>
<td>-</td>
<td>50</td>
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<tr>
<td>Power (84-PX-9102B) [kW]</td>
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<td>-</td>
<td>500</td>
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<tr>
<td>Min flow position (84-FV-93477B) [%]</td>
<td>0</td>
<td>-</td>
<td>100</td>
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<tr>
<td>Tuning parameters (84-FIC-93477B)</td>
<td>-</td>
<td>-</td>
<td>Gain</td>
<td>Integr.</td>
<td>Derv.</td>
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<tr>
<td>Open / Close time (84-XV-93212B) [s]</td>
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<td>-</td>
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<td>Closing</td>
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<tr>
<td>Open / Close time (84-XV-93202B) [s]</td>
<td>2</td>
<td>-</td>
<td>4</td>
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<td>Closing</td>
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### Cooling Medium Circulation Pump A (45-PA-9106A)

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<td>Flowrate (45-FIC-93267A) [m³/h]</td>
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<td>2040</td>
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<tr>
<td>Density [kg/m³]</td>
<td>1003</td>
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<td>-</td>
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<td>Suction pressure (45-PI-93264A) [Barg]</td>
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<tr>
<td>Suction temperature (45-TI-93262A) [°C]</td>
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<td>127</td>
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<tr>
<td>Discharge pressure (45-PI-93267A) [Barg]</td>
<td>11.5</td>
<td>13.7</td>
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<tr>
<td>Discharge temp. (45-TI-93267A) [°C]</td>
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<td>60</td>
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<tr>
<td>Power (45-PA-9106A) [kW]</td>
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<td>Min flow position (45-FV-93267A) [%]</td>
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<td>Tuning parameters (45-FIC-93267A)</td>
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<td>-</td>
<td>Gain</td>
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<td>Open / Close time (45-XV-93272A) [s]</td>
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<td>32</td>
<td>Opening</td>
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<tr>
<td>Open / Close time (45-XV-93267A) [s]</td>
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<td>20</td>
<td>Opening</td>
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### Cooling Medium Circulation Pump B (45-PA-9106B)

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<tr>
<td>Suction pressure (45-PI-93264B) [Barg]</td>
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<td>Suction temp. (45-TI-93262B) [°C]</td>
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<td>127</td>
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<tr>
<td>Discharge pressure (45-PI-93267B) [Barg]</td>
<td>11.5</td>
<td>13.7</td>
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</tr>
<tr>
<td>Discharge temp. (45-TI-93267B) [°C]</td>
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<td>60</td>
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<tr>
<td>Power (45-PA-9106B) [kW]</td>
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<td>450</td>
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<tr>
<td>Min flow position (45-FV-93267B) [%]</td>
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<td>-</td>
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<tr>
<td>Tuning parameters (45-FIC-93267B)</td>
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<td>-</td>
<td>Gain</td>
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<tr>
<td>Open / Close time (45-XV-93272B) [s]</td>
<td>8</td>
<td>32</td>
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<tr>
<td>Open / Close time (45-XV-93267B) [s]</td>
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<td>Opening</td>
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### Firewater Pump A (48-XD-9107A)

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<td>Flowrate (48-FI-93544A) [m³/h]</td>
<td>2300</td>
<td>3425</td>
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<tr>
<td>Distance from cellar deck to sea level [m]</td>
<td>35</td>
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<tr>
<td>Interstage pressure (48-PI-93543A) [Barg]</td>
<td>2.98</td>
<td>4.93</td>
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<tr>
<td>Discharge pressure (48-PI-93544A) [Barg]</td>
<td>14.0</td>
<td>16.2</td>
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<tr>
<td>Speed engine (48-SI-95400A) [rpm]</td>
<td>1850</td>
<td>2070</td>
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### Firewater Pump B (48-XD-9107B)

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<td>Flowrate (48-FI-93544B) [m³/h]</td>
<td>2300</td>
<td>3425</td>
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<tr>
<td>Distance from cellar deck to sea level [m]</td>
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<tr>
<td>Interstage pressure (48-PI-93543B) [Barg]</td>
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<td>4.93</td>
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<tr>
<td>Discharge pressure (48-PI-93544B) [Barg]</td>
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<td>16.2</td>
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<tr>
<td>Speed engine (48-SI-95400B) [rpm]</td>
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<td>2070</td>
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### Oil Booster Pump A (11-PA-9101A)

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<th>3</th>
<th>4</th>
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<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flowrate (11-FIC-92347A-01) [m³/h]</td>
<td>790</td>
<td>950</td>
<td>960</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Oil density at metering station [kg/m³]</td>
<td>0,786</td>
<td>-</td>
<td>-</td>
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<td></td>
<td></td>
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<tr>
<td>Suction pressure (11-PI-92344A) [Barg]</td>
<td>1,8</td>
<td>-</td>
<td>-</td>
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<td></td>
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<tr>
<td>Suction temperature (11-TI-92342A) [°C]</td>
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<td>-</td>
<td>-</td>
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<tr>
<td>Discharge pressure (11-PI-92347A)[Barg]</td>
<td>8</td>
<td>9,2</td>
<td>-</td>
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<tr>
<td>Discharge temp. (11-TI-92347A) [°C]</td>
<td>60</td>
<td>70</td>
<td>-</td>
<td></td>
<td></td>
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<tr>
<td>Power engine [kW]</td>
<td>173</td>
<td>-</td>
<td>200</td>
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<tr>
<td>Min flow position (11-FV-92347A) [%]</td>
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<td>-</td>
<td>100</td>
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<tr>
<td>Tuning parameters (11-FIC-92347A)</td>
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<td>-</td>
<td>Gain</td>
<td>Integr.</td>
<td>Derv.</td>
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<tr>
<td>Open / Close time (11-ESDV-92352A) [s]</td>
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<td>-</td>
<td>28</td>
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<td>Closing</td>
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<tr>
<td>Open / Close time (11-ESDV-92349A) [s]</td>
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<td>-</td>
<td>16</td>
<td>Opening</td>
<td>Closing</td>
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**Table 6.15 Oil Booster Pump A**

### Oil Booster Pump B (11-PA-9101B)

<table>
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<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
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</thead>
<tbody>
<tr>
<td>Flowrate (11-FIC-92347B-01) [m³/h]</td>
<td>790</td>
<td>950</td>
<td>960</td>
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<td></td>
<td></td>
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</tr>
<tr>
<td>Oil density at metering station [kg/m³]</td>
<td>0,786</td>
<td>-</td>
<td>-</td>
<td></td>
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<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Suction pressure (11-PI-92344B) [Barg]</td>
<td>1,8</td>
<td>-</td>
<td>-</td>
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<tr>
<td>Suction temperature (11-TI-92342B) [°C]</td>
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<td></td>
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<tr>
<td>Discharge pressure (11-PI-92347B)[Barg]</td>
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<td>9,2</td>
<td>-</td>
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<tr>
<td>Discharge temp. (11-TI-92347B) [°C]</td>
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<td>70</td>
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<tr>
<td>Power engine [kW]</td>
<td>173</td>
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<td>200</td>
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<td>Min flow position (11-FV-92347B) [%]</td>
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<td>Tuning parameters (11-FIC-92347B)</td>
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<td>Gain</td>
<td>Integr.</td>
<td>Derv.</td>
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<td>Open / Close time (11-ESDV-92352B) [s]</td>
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<td>Closing</td>
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<td>Closing</td>
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**Table 6.16 Oil Booster Pump B**

### Oil Export Pump A (11-PA-9102A)

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<th>4</th>
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<th>6</th>
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<tr>
<td>Oil density at metering station [kg/m³]</td>
<td>0,786</td>
<td>-</td>
<td>-</td>
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<td></td>
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<td>Suction pressure (11-PI-92364A) [Barg]</td>
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<td>Integr.</td>
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<td>-</td>
<td>Gain</td>
<td>Integr.</td>
<td>Derv.</td>
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<td>Open / Close time (11-XV-92372A) [s]</td>
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<td>Closing</td>
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<td>16</td>
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**Table 6.17 Oil Export Pump A**
### VRD Plant Performance Testing Project

#### Oil Export Pump B (11-PA-9102B)

<table>
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<th>-</th>
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<th>Alarm</th>
<th>Max</th>
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<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flowrate (11-FIC-92367B-01) [m³/h]</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>790</td>
<td>-</td>
<td>1070</td>
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<tr>
<td>Oil density at metering station [kg/m³]</td>
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**Table 6.18 Oil Export Pump B**

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**Table 6.19 1st Stage Gas Compressor**
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*Table 6.20 2nd Stage Gas Compressor*
### 3rd Stage Gas Compressor (23-KA-9103)

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<td>FIC tuning param. (24-FIC-92743)</td>
<td>-</td>
<td>-</td>
<td>Gain</td>
<td>Integr.</td>
<td>Derv.</td>
<td></td>
</tr>
<tr>
<td>Vib. DE (23-YI-96305-01) [µm]</td>
<td>30</td>
<td>57</td>
<td>82</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vib. DE (23-YI-96305-02) [µm]</td>
<td>30</td>
<td>57</td>
<td>82</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vib. NDE (23-YI-96306-01) [µm]</td>
<td>30</td>
<td>57</td>
<td>82</td>
<td></td>
<td></td>
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<tr>
<td>Vib. NDE (23-YI-96306-02) [µm]</td>
<td>30</td>
<td>57</td>
<td>82</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vib. NDE (23-ZI-96307) [µm]</td>
<td>+0.2</td>
<td>+0.5</td>
<td>+0.75</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Temp. DE (23-TI-96301-01) [°C]</td>
<td>50</td>
<td>60</td>
<td>65</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Temp. DE (23-TI-96301-03) [°C]</td>
<td>50</td>
<td>60</td>
<td>65</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Temp. NDE (23-TI-96302-01) [°C]</td>
<td>50</td>
<td>60</td>
<td>65</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Temp. NDE (23-TI-96302-03) [°C]</td>
<td>50</td>
<td>60</td>
<td>65</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Temp. NDE (23-TI-96303-01) [°C]</td>
<td>50</td>
<td>70</td>
<td>85</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Temp. NDE (23-TI-96304-01) [°C]</td>
<td>50</td>
<td>70</td>
<td>85</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Open/Close time (24-ESDV-92939A)</td>
<td>8</td>
<td>-</td>
<td>32</td>
<td>Opening</td>
<td>Closing</td>
<td></td>
</tr>
<tr>
<td>Open/Close time (24-ESDV-92939B)</td>
<td>3</td>
<td>-</td>
<td>6</td>
<td>Opening</td>
<td>Closing</td>
<td></td>
</tr>
<tr>
<td>Open/Close time (25-XV-92861A)</td>
<td>7</td>
<td>-</td>
<td>24</td>
<td>Opening</td>
<td>Closing</td>
<td></td>
</tr>
<tr>
<td>Open/Close time (25-XV-92861B)</td>
<td>3</td>
<td>-</td>
<td>6</td>
<td>Opening</td>
<td>Closing</td>
<td></td>
</tr>
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</table>

**Table 6.21 3rd Stage Gas Compressor**
<table>
<thead>
<tr>
<th>Date and time</th>
<th>-</th>
<th>-</th>
<th>-</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flowrate (27-FI-92933) [10^3 m³/h]</td>
<td>30,5</td>
<td>-</td>
<td>42,3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Molar weig. (27-AI-93022) [kg/kmol]</td>
<td>18,39</td>
<td>-</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inlet pressure (27-PI-92932) [Barg]</td>
<td>47,5</td>
<td>55</td>
<td>58,2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Outlet pressure (27-PI-92940) [Barg]</td>
<td>105</td>
<td>130</td>
<td>135</td>
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<td></td>
<td></td>
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<tr>
<td>Inlet temperature (27-TI-92933) [°C]</td>
<td>16,1</td>
<td>25</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Outlet temp. (27-TI-92938) [°C]</td>
<td>100</td>
<td>120</td>
<td>125</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Power engine [MW]</td>
<td>6,3</td>
<td>-</td>
<td>11,0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Speed engine (27-NI-96444) [rpm]</td>
<td>1784</td>
<td>-</td>
<td>1802</td>
<td></td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td>Recycle position (27-ZT-92943) [%]</td>
<td>20</td>
<td>-</td>
<td>100</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FIC tuning param. (27-FIC-92943)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Gain</td>
<td>Integr.</td>
<td>Derv.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vib. DE (27-YI-96405-01) [µm]</td>
<td>30</td>
<td>57</td>
<td>72</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vib. DE (27-YI-96405-02) [µm]</td>
<td>30</td>
<td>57</td>
<td>72</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vib. NDE (27-YI-96406-01) [µm]</td>
<td>30</td>
<td>57</td>
<td>72</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vib. NDE (27-YI-96406-02) [µm]</td>
<td>30</td>
<td>57</td>
<td>72</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vib. NDE (27-ZI-96407) [µm]</td>
<td>+0,2</td>
<td>+0,5</td>
<td>+0,75</td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Temp. DE (27-TI-96401-01) [°C]</td>
<td>50</td>
<td>60</td>
<td>65</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Temp. DE (27-TI-96401-03) [°C]</td>
<td>50</td>
<td>60</td>
<td>65</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Temp. NDE (27-TI-96402-01) [°C]</td>
<td>50</td>
<td>60</td>
<td>65</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Temp. NDE (27-TI-96402-03) [°C]</td>
<td>50</td>
<td>60</td>
<td>65</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Temp. NDE (27-TI-96403-01) [°C]</td>
<td>50</td>
<td>70</td>
<td>85</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Temp. NDE (27-TI-96404-01) [°C]</td>
<td>50</td>
<td>70</td>
<td>85</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Open/Close time (27-ESDV-92876A)</td>
<td>7</td>
<td>-</td>
<td>28</td>
<td>Opening</td>
<td>Closing</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Open/Close time (27-ESDV-92876B)</td>
<td>3</td>
<td>-</td>
<td>6</td>
<td>Opening</td>
<td>Closing</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Open/Close time (27-ESDV-93019A)</td>
<td>6</td>
<td>-</td>
<td>24</td>
<td>Opening</td>
<td>Closing</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Open/Close time (27-ESDV-93019B)</td>
<td>3</td>
<td>-</td>
<td>6</td>
<td>Opening</td>
<td>Closing</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**TABLE 6.22 4th STAGE GAS COMPRESSOR**
Appendix A. Relative roughness and friction factors
Appendix B. Moody diagram
Appendix C:
This is an example of how to calculate pressure loss in a pipe. In this example it is made references to appendix A and B. For units related to the following calculations, please check Units at page 7.

According to the data sheet from the flow valve, the following data is stated:
- The valve has got 10” inlet/outlet size with 8” nominal port size.
- The port area of the valve is \( A_p = 0.03243 \text{ m}^2 \).
- The valve has got a \( C_v = 924 \) at 100% opening.
- The valve has an equal percentage characteristic.

According to the pump data:
- The pump head is tested to be, \( H = 105 \text{ lmc} \), with a flow of 1000 \( \text{m}^3/\text{h} \).
- The minimum submerged length of the pump is 10 m.
- The vertical length from the seawater level to the cellar deck is 35 m.
- The vertical length from the cellar deck to the flow valve is 0.8 m.

The piping characteristic of the seawater flow, going through the flow valve, starts going through the inlet strainer upstream of the pump. On the discharge side of the pump, seawater is flowing horizontally for 4 m, then turns 90° vertically in a tee and takes the last turn upstream the flow valve through a 90° bend.

Downstream the flow valve, the pipe is going vertically upwards for 10 m before turning around and gets dumped to the seawater caisson, which contains atmospheric pressure.

Density of seawater = 1027 kg / \( \text{m}^3 \)

Kinematic viscosity seawater at 5°C = 1.519 \( \cdot 10^{-6} \text{ m}^2 \cdot \text{s}^{-1} \)

Maximum differential pressure over the pump at 1000 m\(^3/\text{h}\):
\[
H_1 = 105 \text{lmc} = 105 \text{m} \cdot 1027 \text{kg} / \text{m}^3 \cdot 9.81 \text{m} / \text{s}^2 = 1057861 \text{Pa}
\]

The maximum static pressure upstream the flow valve:
\[
H_2 = 35 \text{m} + 0.8 \text{m} = 35.8 \text{m} \Rightarrow 35.8 \cdot 1027 \text{kg} / \text{m}^3 \cdot 9.81 = 360680 \text{Pa}
\]

Pressure loss in pipe, assuming flow of 1000 m\(^3/\text{h}\):
\[
\Delta p = f \cdot \frac{l}{d} \cdot \frac{v^2 \cdot \rho}{2}
\]

(Bird, 2007)

\[
\text{Re} = \frac{v \cdot d}{v}, \text{ Re } \geq 2600 \text{ (Turbulence), Re } \leq 2599 \text{ (Laminar)}
\]

(Bird, 2007)

\[
\text{Laminar} : f = \frac{64}{\text{Re}} = \frac{64 \cdot v}{v \cdot d}
\]

\[
\text{Turbulence} : f = \text{Moodydiagram}
\]
\[ \Delta p_1 (\text{strainer}) : \]
\[ d_1 = 24'' = 0.6096m \Rightarrow v_1 = \frac{Q}{A_1} = \frac{1000m^3 / h}{3600s} = \frac{0.278m^3 / s}{0.2919m^2} = 0.952m / s \quad (\text{McCabe}, 1993) \]
\[ \text{Re} = \frac{0.952m / s \cdot 0.6096m}{1.519 \cdot 10^{-6} m^2 / s^{-1}} = 388053 \Rightarrow \text{Turbulence} \]
\[ \text{Relative roughness} = \frac{\varepsilon}{d} = \frac{0.05}{609.6mm} = 8.2 \cdot 10^{-5} \]

Moody diagram \( \Rightarrow f_1 = 0.022 \)

Equivalent length of the strainer is found from Nergaard, 2009, and is given as:
\[ \frac{l}{d} = 170 \Rightarrow l_1 = 0.6096m \cdot 170 = 103.6m \]
\[ \Delta p_1 = f_1 \cdot \frac{l_1}{d_1} \cdot \frac{v_1^2 \cdot \rho}{2} = 0.022 \cdot \frac{103.6m}{0.6096} \cdot \frac{(0.952m / s)^2 \cdot 1027kg / m^3}{2} = 1740Pa \]

\[ \Delta p_2 (18'' \text{pipe}) : \]
\[ d_2 = 18'' = 0.4572m \Rightarrow v_2 = \frac{Q}{A_2} = \frac{0.278m^3 / s}{\pi \cdot (0.4572m)^2} = 1.693m / s \]
\[ \text{Re} = \frac{v_2 \cdot d_2}{\nu} = \frac{1.693m / s \cdot 0.4572m}{1.519 \cdot 10^{-6} m^2 / s^{-1}} = 509571 \Rightarrow \text{Turbulence} \]
\[ \text{Relative roughness} = \frac{\varepsilon}{d} = \frac{0.05}{457.2mm} = 1.09 \cdot 10^{-4} \]

Moody diagram \( \Rightarrow f_2 = 0.0215 \)
\[ l_2 = 4m \]
\[ \Delta p_2 = f_2 \cdot \frac{l_2}{d_2} \cdot \frac{v_2^2 \cdot \rho}{2} = 0.0215 \cdot \frac{4m}{0.4572m} \cdot \frac{(1.693m / s)^2 \cdot 1027kg / m^3}{2} = 177Pa \]

\[ \Delta p_3 (12'' \text{Tee} + 90^\circ \text{bend}) : \]
\[ d_3 = 12'' = 0.3048m \Rightarrow v_3 = \frac{Q}{A_3} = \frac{0.278m^3 / s}{\pi \cdot (0.3048m)^2} = 3.81m / s \]
\[ \text{Re} = \frac{3.81m / s \cdot 0.3048m}{1.519 \cdot 10^{-6} m^2 / s^{-1}} = 764508 \Rightarrow \text{Turbulence} \]
\[ \text{Relative roughness} = \frac{\varepsilon}{d} = \frac{0.05}{304.8mm} = 1.64 \cdot 10^{-4} \]

Moody diagram \( \Rightarrow f_3 = 0.0198 \)
The equivalent length of the tee is found in Crane Co, 1979, and is given as:

\[ l_3 \Rightarrow 12'' \text{ gives a length of: } 11.2m \]

The equivalent length of the bend is found in Crane Co, 1979, and is given as:

\[ l_4 \Rightarrow 12'' \text{ gives a length of: } 5.1m \]

\[
\Delta p_3 = f_3 \cdot \frac{(l_3 + l_4)}{d_3} \cdot \frac{v_3^2 \cdot \rho}{2} = 0.0198 \cdot \frac{(11.2 + 5.1)m}{0.3048m} \cdot (3.81m/s)^2 \cdot 1027kg/m^3 = 7893Pa
\]

\[
H_3 = \Delta p_{tot} = 1740Pa + 177Pa + 7893Pa = 9810Pa
\]

The inlet pressure of the flow valve (pressure upstream) will therefore be:

\[
p_i = H_1 - H_2 - H_3 = 1057861Pa - 360680Pa - 9810Pa = 687371Pa
\]

The outlet pressure of the valve (pressure downstream) will be affected by a 9 m water column, as will function as a backpressure. The seawater is later being dumped into an atmospherically seawater caisson.

The outlet pressure of the valve is assumed to be:

\[
p_o = \rho \cdot g \cdot h = 1027kg/m^3 \cdot 9.81m/s^2 \cdot 9m = 90673Pa
\]

We can now calculate the maximum flow through the flow valve:

\[
Q = C_v \cdot A \cdot \sqrt{\frac{\Delta p \cdot 2}{\rho}} \quad \text{(Fisher, 2005)}
\]

\[
Q = 924 \cdot 0.03243m^2 \cdot \sqrt{\frac{(687371 - 90673)Pa \cdot 2}{1027kg/m^3}} = 1022m^3/h
\]

The result we get is a slight lower than expected, but still means that we can use the minimum flow-valve to verify the first points of the left hand side of the characteristics of the pump.
### VRD Plant Performance Testing Project

#### Table 8 — Vibration limits for vertically-suspended pumps

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Location of vibration measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pump thrust bearing housing or Motor mounting flange (see Figure 2B)</td>
</tr>
</tbody>
</table>

**Pump bearing type**

<table>
<thead>
<tr>
<th></th>
<th>Hydrodynamic guide bearing adjacent to accessible region of shaft</th>
</tr>
</thead>
<tbody>
<tr>
<td>All</td>
<td></td>
</tr>
</tbody>
</table>

**Vibration at any flow within the pump’s preferred operating region**

<table>
<thead>
<tr>
<th>Overall</th>
<th>$v_u &lt; 5.0 \text{ mm/s RMS}$</th>
<th>$A_u &lt; (6.2 \times 10^6 \text{ } \mu \text{m peak-to-peak})$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$(0.20 \text{ in/s RMS})$</td>
<td>$[(10 \text{ 000}/n)^{0.5} \text{ mils peak-to-peak}]$</td>
</tr>
</tbody>
</table>

Not to exceed:

- $A_u < 100 \mu \text{m peak-to-peak}$
- $(4.0 \text{ mils peak-to-peak})$

**Discrete frequencies**

$\gamma_f < 0.67 \gamma_u$

$A_f < 0.75 A_u$

**Allowable increase in vibration at flows outside the preferred operating region but within the allowable operating region**

<table>
<thead>
<tr>
<th>Overall</th>
<th>$30%$</th>
</tr>
</thead>
</table>

Vibration velocity and amplitude values calculated from the basic limits shall be rounded off to two significant figures.

where

- $v_u$ is the unfiltered velocity, as measured;
- $\gamma_f$ is the filtered velocity;
- $A_u$ is the amplitude of unfiltered displacement, as measured;
- $A_f$ is the amplitude of filtered displacement;
- $n$ is the rotational speed, expressed in revolutions per minute.

### Appendix D. Vibration limits, vertically-suspended pumps

#### Table 14 — Performance tolerances

<table>
<thead>
<tr>
<th>Condition</th>
<th>Rated point (%)</th>
<th>Shutoff (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated differential head:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>— 0 m to 150 m (0 ft to 500 ft)</td>
<td>$-2$</td>
<td>$+10$</td>
</tr>
<tr>
<td></td>
<td>$+5$</td>
<td>$-10$</td>
</tr>
<tr>
<td>— 151 m to 300 m (501 ft to 1 000 ft)</td>
<td>$-2$</td>
<td>$+8$</td>
</tr>
<tr>
<td></td>
<td>$+3$</td>
<td>$-8$</td>
</tr>
<tr>
<td>— &gt; 300 m (1 000 ft)</td>
<td>$-2$</td>
<td>$+5$</td>
</tr>
<tr>
<td></td>
<td>$+2$</td>
<td>$-5$</td>
</tr>
<tr>
<td>Rated power</td>
<td>$+4$</td>
<td>—</td>
</tr>
<tr>
<td>Rated NPSH</td>
<td>0</td>
<td>—</td>
</tr>
</tbody>
</table>

**NOTE** Efficiency is not a rating value.

a. If a rising head flow curve is specified (see 6.1.13), the negative tolerance specified here shall be allowed only if the test curve still shows a rising characteristic.

b. Under any combination of the above (cumulative tolerances are not acceptable).

### Appendix E. Performance tolerances, centrifugal pumps
Appendix F. Compressibility factors, natural gases (17.40 kg/kmol)

Appendix G. Compressibility factors, natural gases (18.85 kg/kmol)
Appendix H. Compressibility factors, natural gases (20.30 kg/kmol)

Appendix I. Compressibility factors, natural gases (23.20 kg/kmol)
Appendix J. Compressibility factors, natural gases (26.10 kg/kmol)

Appendix K. Cooling Medium Pumps:

**Efficiency based on API Clearances at Wear Rings**
**Standard Clearances at Bushes**

---

**Sulzer Pumps**

**Model:** A52-692

**Bore:** 692 mm

**14 X 20 X 27 CD 1 stage**

**Designer:** G. O. 02197

**Engineer:** D. R. 02197

**J. J. 02185**

---

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Appendix M, Oil Booster Pumps:

Appendix N, Oil Export Pumps:
VRD Plant Performance Testing Project

Appendix O, 1st Stage Gas Compressor:

BP Valhall VRD RB71–5

<table>
<thead>
<tr>
<th>REFERENCE CURVE No</th>
<th>1</th>
<th>CURVE p1 (bar)</th>
<th>T1 (°C)</th>
<th>R.H.</th>
<th>MW</th>
<th>TW1</th>
<th>N/No</th>
<th>ANGLE (°)</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>6273</td>
<td>4.570</td>
<td>40.0</td>
<td>22.572</td>
<td>1.00</td>
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</table>

The graph shows the power at the compressor coupling against volume flow rate. The surge line is indicated on the graph with an 'X'.

MAN TURBO

Classification: RB71–5 Stage 1

Title: Predicted Performance Curves

Document No: 4-837048811

Rev: 2
Appendix P, 2nd Stage Gas Compressor:

![Chart showing performance curves for BP Valhall VRD RB45-5 stage gas compressor.](chart.png)

- **BP Valhall VRD RB45-5**
- **Reference Curve No**: 1
- **Curve**: 1
- **p1 (bar)**: 11.06
- **T1 (°C)**: 24.0
- **R.H.**
- **M.W.**
- **TW1**: 22.639
- **N/No**: 1.00
- **Angle (°)**

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**MAN TURBO**

- **Dept.**: SC-6
- **Name**: A. Louie
- **Date**: 16-OCT-07

**Classification**

- [ ] MAN only
- [ ] Project
- [X] Client
- [ ] Contract
- [ ] free Distribution

**Title**: Predicted Performance Curves

**MAN No**: H7800005.78

**Client No**

**Document No**: 4-B37048811

**Rev**: 2

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Appendix Q, 3rd Stage Gas Compressor:

<table>
<thead>
<tr>
<th>BP Valhall VRD RB45-3</th>
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<tbody>
<tr>
<td>REFERENCE CURVE</td>
</tr>
<tr>
<td>No</td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>CURVE</td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>p1 (baro)</td>
</tr>
<tr>
<td>34.29</td>
</tr>
<tr>
<td>T1 (%)</td>
</tr>
<tr>
<td>10.1</td>
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<tr>
<td>R.H.</td>
</tr>
<tr>
<td>23.857</td>
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<tr>
<td>MW</td>
</tr>
<tr>
<td>1.00</td>
</tr>
<tr>
<td>TW1</td>
</tr>
<tr>
<td>ANGLE (°)</td>
</tr>
</tbody>
</table>

POWER AT COMPRESSOR COUPLING

VOLUME FLOW (m³/h)

POLYTROPIC – 450 f(PSU/kg)

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Appendix R, 4th Stage Gas Compressor:

<table>
<thead>
<tr>
<th>BP Valhall VRD RB35—5</th>
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</thead>
<tbody>
<tr>
<td>REFERENCE CURVE No.</td>
</tr>
<tr>
<td>CURVE 1</td>
</tr>
<tr>
<td>(baro)</td>
</tr>
<tr>
<td>1</td>
</tr>
</tbody>
</table>

![Graph showing predicted performance curves for the 4th Stage Gas Compressor. The graph includes axes for power, polytropic head, and volume flow rate.]