NTNU
Norwegian University of Science and Technology
Department of Marine Technology

M.Sc.THESIS

Title: # Subsea Hydraulic Leakage Detection and Diagnosis	**Delivered:** 14.06.2010 **Availability:** UNCLASSIFIED
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Abstract:

The motivation for this thesis is reduction of hydraulic emissions, minimizing of process emergency shutdowns, exploitation of intervention capacity, and reduction of costs. Today, monitoring of hydraulic leakages is scarce and the main way to detect leakage is the constant need for filling of hydraulic fluid to the Hydraulic Power Unit (HPU). Leakage detection and diagnosis has potential, which would be adressed in this thesis.

A strategy towards leakage detection and diagnosis is given. The strategy defines three approaches, define an approach, explore the approach and propose a solution. Relevant instrumentation, both existing and additional instrumentation is discussed. Relevant methods towards leakage detection and diagnosis are presented. An overview of a bewidering amount of methods is given, and basics towards application. An example from pipelines of state-of-the –art leakage detection and diagnosis is also given.

A solution proposal for a simple and available leakage method with fair detectability and limited diagnostics is proposed. There tends to be a connection between performance of application and complexity. For today’s solution it would be preferable to scarify some overall performance for simplicity, considering the alternative.

Keyword:

Leakage
Hydraulic
Subsea

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MASTER THESIS
for
M.Sc. student Thomas Stavenes
Department of Marine Technology
Spring 2010

Subsea hydraulic leakage detection and diagnosis

The MSc. thesis will be concerned with methods for condition monitoring of subsea hydraulic systems. The focus will be on detecting and diagnosing hydraulic leakages.

The main tasks in this thesis should be to:

1. Describe state-of-the-art of leakage detection and its application to subsea installations.

2. Based on one of Statoil's installations describe and discuss equipment and instrumentation relevant for leakage detection.

3. Develop a strategy for detection and diagnosis and use suitable methods and tools (such as EFDD) on case data from Statoil.

During the period for this master thesis work the candidate need to have close cooperation with Statoil.

The thesis must be written like a research report, with an abstract, conclusions, contents list, reference list, etc.

During preparation of the thesis it is important that the candidate emphasizes easily understood and well written text. For ease of reading, the thesis should contain adequate references at appropriate places to related text, tables and figures. On evaluation, a lot of weight is put on thorough preparation of results, their clear presentation in the form of tables and/or graphs, and on comprehensive discussion.

Three copies of the thesis are required. One of these should the candidate deliver to Statoil.

Starting date: 18th January 2010
Completion date: 14th June 2010

Handed in

Tom Anders Thorstensen

Trondheim 18th February 2010.

Tom Anders Thorstensen
Associated Professor II

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Preface

This thesis represents the work towards a Master of Science in Marine Technology at the Norwegian University of Science and Technology, NTNU, with profile Operational Technology. The thesis is written after discoveries of potential improvements in a project assignment on general subsea condition monitoring during the autumn of 2009 written by, Thomas Stavenes.

The thesis has been in close cooperation with the oil company Statoil ASA R&D. The thesis makes up a workload of 21 weeks.

The gathering of data took longer time than anticipated, and caused limited time available for EFDD. In addition the program has a rather high entry level, and this way EFDD did not give the anticipated output.

I am grateful for all the guidance and support given to me at Statoil. I would like to thank my supervisor Prof. II Tom Anders Thorstensen, and Erling Lunde PhD for motivation, positive attitude and help throughout the thesis. I would like to thank Raymond Nilsen and others at Statoil's department Harstad for answering all my questions and providing the excel sheet for leakage detection.

I would also like to thank Anders Valland at MARINTEK for valuable inspiration and Rune Lien at Agito AS for the Simulation X software and guidance. Finally, I would like to thank Erlend Meland and my fellow students Magnus Vaarli and Jørgen Sæter for the times at Statoil.

14.06.2010

X Thomas Stavenes

Thomas Stavenes

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Terminology

Definition given according to IFAC SAFEPROCESS Technical Committee:

Failure:	A permanent interruption of a system's ability to perform a required function under specified operating conditions.
Fault detection:	Determination of the faults present in a system and the time of detection.
Fault diagnosis:	Determination of the kind, size, location and time of detection of a fault. Follows fault detection. Includes fault isolation and identification.
Fault:	An unpermitted deviation of at least one characteristic property or parameter of the system from the acceptable / usual / standard condition.
Monitoring:	A continuous real-time task of determining the conditions of a physical system, by recording information, recognizing and indicating anomalies in the behaviour.

Other report specific terminology

Black box model:	A model with no need for knowledge about the system.
Condition monitoring:	The process of monitoring one or more parameters of condition for an item or system to detect deviations that might be the result of an initiating failure.
Grey box model:	A combination of white box and back box models.
Leakage detection:	Determination of the leakage present in a system and the time of detection
Leakage diagnosis:	Determination primarily of the leakage location and size.
Leakage	A leakage in this context is all fluid loss, either internally or to surrounding environment, which is not used for normal operation.
Leakage system	An organized product for leakage detection and diagnosis.
Method:	Referred to as a way to perform monitoring to achieve detection, diagnosis or both.
Steady state:	The partial derivative is zero with respect to time.
White box model:	A model in need of detail knowledge about the system.

Abbreviations

BOP	Blowout Preventer
CBM	Condition Based Maintenance
CFD	Computational Fluid Dynamics
CM	Condition monitoring
CPM	Condition and Performance Maintenance
DCV	Directional Control Valve
DHSV	Down Hole Safety Valve
EFD	Early Fault Detection
EFDD	Early Fault Detection and Diagnosis
ETA	Event Tree Analysis
FMECA	Failure Mode, Effect and Criticality Analysis
FPSO	Floating Production Storage and Offloading Vessel
FTA	Fault Tree Analysis
HP	High Pressure
LP	Low Pressure
MBPCA	Model based Principal Component Analysis
MIV	Master Injection Valve
P&ID	Piping and Instrumentation Diagram
PCA	Principal Component analysis
PDA	Plant wide Disturbance Analysis
PMV	Primary Master Valve
RCM	Reliability-Centred Maintenance
SCM	Subsea Control Module
SCMMB	Subsea Control Module Mounting Base
SCS	Subsea Control System
SCSSV	Sub Surface Safety Valve
TM	Tag Monitoring

Nomenclature

Units are not given, because no calculation has been executed.

P	Pressure (Given bar gage unless other stated)
Q	Flow
T	Torque
ω	Angular velocity
n_p	Pump Overall Efficiency
V	Flow velocity, D is the diameter of the pipe, and v is the viscosity of the fluid.
T	Temperature
V	Volume
k	Constant
F	Force
A	Area
Δt	Time Difference

Appendices

Summary

This thesis deals with subsea hydraulic leakage detection and diagnosis. Hydraulic fluid is used in most of the subsea control systems today. Electric actuated systems are emerging, but hydraulic systems will be important in years to come. The main function of the system is to control the oil producing wells. Normally, one single system provides all wells on a field with control fluid; this is also the case at Norne.

Project limitations, basic condition monitoring and motivation are presented. The project is limited to Norne and its subsea production control system. Condition monitoring theory is said to apply also for monitoring leakages, though the basic definition may be somewhat different. The motivation for this thesis is reduction of hydraulic emissions, minimizing of process emergency shutdowns, exploitation of intervention capacity, and reduction of costs.

A basic of theory is presented, both for a general hydraulic system and Norne specific equipment. Flow through the system is given with a process flow diagram. Common failures with the subsea control system were faults with Directional Control Valves, which accounted for 98% of the leakages. Possible causes were reviled to be corrosion due to seawater ingress during installation and biodegradation.

An example of leakage detection and diagnosis from pipelines is given. It is state-of-the-art within leakage detection and diagnosis. Although there distinct differences, the methods used for pipelines can be applied for the subsea control system as well. Performance criteria, determining the quality of the detection and diagnosis are given. There tends to be a connection between complexity and performance. It may therefore be preferable to scarify some overall performance for simplicity. This is because monitoring today is very scarce.

There exist measurements which can be monitored today, and an additional amount of sensors which have the potential for further improvement. Additional sensors are not proposed subsea, due to high cost of sensor, installation and replacement. However, design improvements of subsea control module flow meters could be interesting.

Bewildering types of methods are organized with respect to description. Qualitative and quantitative methods have to distinct differences, which are used in this thesis. It is given an illustration of the connection between information amount and value, concerns and application. It illustrates the way towards automatization, and concerns when choosing methods and application to subsea installations.

Finally, a strategy towards leakage detection and diagnosis is given. The strategy defines three approaches: define an approach, explore the approach and propose a solution. It reviled that valuable information is available by looking at process data; however it would be preferable to automate. A solution for a simple, available detection method with fair detectability and diagnostics is proposed. The solution is to monitor steady state pressure drop using instrumentation and operational data. By monitoring the accumulator skid pressure and operations simultaneous, the transients could be ignored. When the transient period was over, monitoring and comparison would be executed until a new operation took place. Operations is therefore important to integrate. The excel sheet demonstrates that this is possible.

1 Introduction

This thesis is divided into five main chapters. The first chapter gives an introduction to the project limitations, general introduction to condition monitoring, and the motivation. The project is limited to the subsea control system. The main feature of this system is to control oil producing wells. Condition monitoring is a branch within maintenance, and is used to determine condition by monitoring of equipment. This theory is also applicable for leakages. The motivation is reduction of hydraulic emissions, minimizing of process emergency shutdowns, exploitation of intervention capacity, and reduction of costs.

In the second chapter a basic description of a hydraulic system is given, with respect to subsea components. Basics of fluids and phenomena like volumetric expansion, compressibility, resistance and contamination is briefly presented. An understanding of how components may interact when put together is also given.

Norne is presented with main focus towards Norne subsea control system. It describes some Norne specific details of equipment. The information flow and fluid flow through the subsea control system, and a process flow diagram are presented. In the latter part of the chapter, failure and causes of the control system are discussed.

The fourth chapter discusses basics of leakage detection and diagnosis. First a description is given. Then an example is gathered from pipelines, which would turn out to be very valuable. In general it is state-of-the-art within leakage detection and diagnosis. It is positive that it can directly benefit subsea hydraulic leakage detection and diagnosis. Dedicated state-of-the-art within subsea leakage detection and diagnosis is also presented, although this is scarce. It is mainly related to valves and actuators. General Electric and FMC Technologies are the only one discovered to have dedicated systems, but the detailed and interesting part of leakage detection and diagnosis is not available.

Relevant instrumentation, existing and additional is discussed. It should be possible to detect leakages in the system by monitoring of existing instrumentation. One of the biggest disappointments were the sensitivity of flow meters in the SCM, this is also confirmed in the fifth chapter. It is also found that some additional topside measurements would be of current interest.

Relevant methods towards leakage detection and diagnosis are also presented. Definitions are many, and congruent. Therefore an overview is given with respect to different methods, and then presented. Qualitative and quantitative methods are general terms used to distinguish between two distinct differences in methodology. The basics towards application are also given. This is done to clarify the need for both data and knowledge before applying methods. Important considerations when choosing methods and applicability towards subsea leakage detection and diagnosis are given.

The final chapter puts forward a strategy towards detection and diagnosis. It has three steps: Define an approach, explore and learn, and finally seek a solution. It is chosen to look at process data, and use of qualitative and quantitative approaches. In addition, an excel sheet provided by Norne organization is presented.

Looking at process data, combined with knowledge and expectations of behaviour from earlier explained theory turns out to be very valuable. In the other approaches problems are encountered. The excel sheet does not have the input needed, the qualitative approach needs too comprehensive amount of input, and data was too independent and sporadic to exploit EFDD potential.

Valuable experience is gained, and the excel sheet demonstrates that data of operations executed can be added; information which should turn out to be essential for subsea leakage detection and diagnosis. This would at least be the case if qualitative approaches as simulation models would be avoided due to complexity.

A proposal for solution is given with respect of today. Some point of views worth considering for tomorrow and the future is also given. The proposal for solution seems promising. This is because it is simple, available, and has a fair performance.

1.1 Project Limitations

As for all projects, also this one has boundaries. First off all this project is limited to Norne field. This is one of Statoil's installation located in the Norwegian Sea, Vest of Helgeland. Data used is mainly collected from Alve, which is one subsea template tied back to Norne. Even though this demarcation is taken, it does not mean that discoveries in this report are irrelevant for other similar installations.

Figure 1 illustrates the project boundaries. It covers the subsea control system, which has one part subsea and another topside.

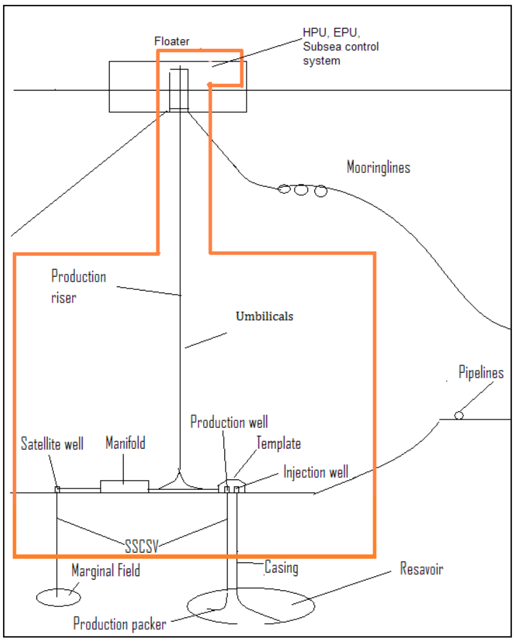

Figure 1 A sketch showing the project boundaries

The Low pressure (LP) side of the subsea control module (SCM) has been in focus. This is a logical isolation because the LP side has the most valves used in daily operation. The high pressure (HP) on the other hand acts as one out of two safety barriers, and controls the surface controlled sub surface safety valve (SCSSV) or down hole safety valve (DHSV).

The report is also limited to subsea operational phase. This implies that intervention and drilling modes are not considered. This does not mean that it is not of interest; on the contrary, it might be highly relevant for both intervention and drilling. As an example one of the faults on the Blowout Preventer (BOP) from the disaster taking place in the Gulf of Mexico was said to be hydraulic leakage[1]. Deepwater Horizon exploded 20th of April 2010. 11 workers lost their lives, and the rig sank. The following oil spill is not completely stopped as of 14th June 2010.

1.2 Condition Monitoring

Condition monitoring (CM) is the process of monitoring one or more parameters of condition for an item or system to detect deviations that might be the result of an initiating failure. By detecting a failure at an early stage, maintenance can be planned and scheduled and CM is hence an important part of preventive maintenance and predictive maintenance as shown in figure 2. And is basis for Condition Based Maintenance (CBM)

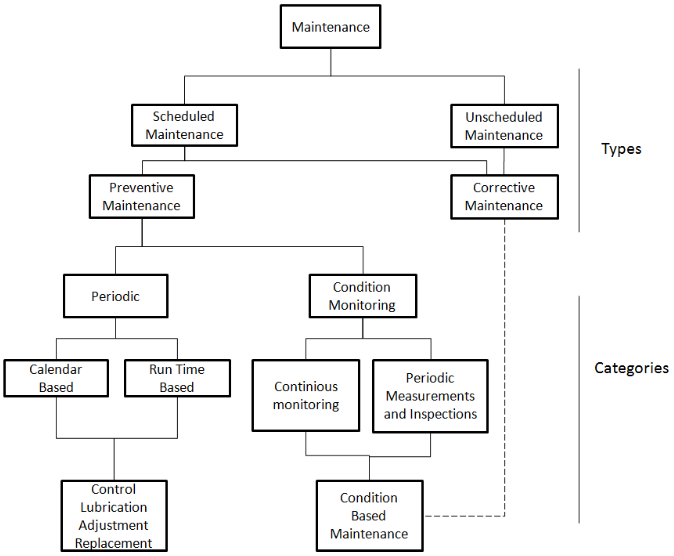

Figure 2 Different types of maintenance and their strategic operational categories[8]

CM does not predict failure; it only helps predicting the time to failure. Nevertheless, a deviation from a reference value (e.g. temperature or vibration behaviour) must occur to identify impeding failures. These limits will either come from quantitative or qualitative methods, or experience alone. This will be further discussed later on.

Normally CM is preferable for components which have an unclear failure distribution, hence, an optimal interval for maintenance is difficult to achieve. The CM process consists of three core processes, observation, analyzing, and decision-making as shown in Figure 3.

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[1] 7. Sæbø, S.H., *Bildet oljegiganten ikke ville at noen skulle se*, in *Dagbladet.no*. 2010 OSLO.

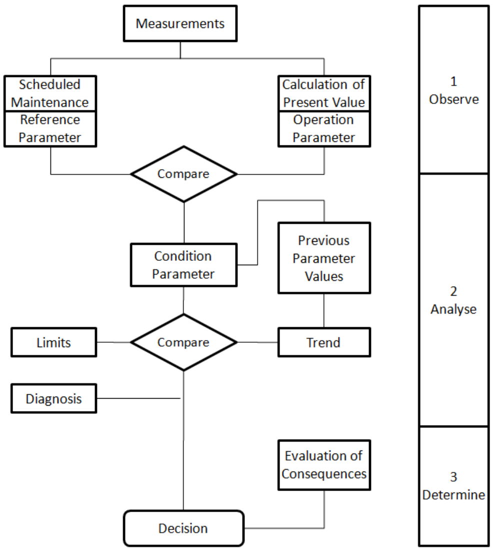

Figure 3 The different condition monitoring process [3]

Observation can be performed in several ways, both manually and automatically, online and offline. Every method gives some kind of indication of condition. However, there are considerable differences between the methods. The main difference is the time from detection to failure. There tends to be a connection between complexity of the observation and analysis and warning time as indicated in figure 5.

In process industries in general, processes are widely monitored, but gives a small or no particular warning of an initiating fault. This may be due to the complexity of the data monitored. A systematic use of these data could give us the desired warning. As stated in [8] (5.8) there is a blurred transition between monitoring itself and condition monitoring.

It is important to have in mind that not every component is ageing. A component may be as good as new even after several years. Replacing such a component could actually degrade our system. This is so because different components have different failure modes. These modes are important to have in mind when choosing maintenance strategy, such as CM. If a component suddenly fails, CM would not serve any predictive function.

Main parameters which need to be covered in order to make use of CM[8].

- The failure evolves slow enough to be able to do a maintenance action/intervention[2] before breakdown.
- An adequate control method exist.

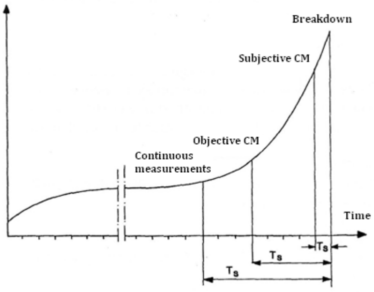

Figure 4 The impact of effort on warning capability[8]

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[2] Intervention includes system going in"safe-mode"/"shut down".

When it comes to how often measures of condition should be done, and choosing type of method it depends on:

- Criticality (health/safety, environment, economy)
- Common damages and consequences
- That a suitable method for the given failure exists
- Condition progressiveness and control frequency

1.2.1 KPI and TCI

KPI (Key Performance Indicator) and TCI (Technical condition Index) are measurements of the components actual state as an easy understandable unit. It is a specific number between 0-100%, where zero equals a failed component, and hundred percent is a perfect component. It is often used in the industry, because of its simplicity. However, it is not easy to estimate this parameter[3] which may take use of several of the measurements. The KPI and TCI function will literally tell you when to do a maintenance action.

1.2.2 Condition Monitoring and Leakage

The word leakage often implies that a failure already has occurred. Why should something be condition monitored if it already has failed? It was just stated that if CM suddenly failed it would not serve any predictive function.

A leakage in the SCS can normally have three impacts on production:

- Normal production may be continued
- Reduced production
- Stopped production

Depending on cause, leakages may happen suddenly or evolve over time. When a leakage is present, it is important to detect it as soon as possible, and diagnose the problem. It is also possible to trend leakage rates, to detect whether it is escalating. Generally, the longer time from a leakage to a repair, the bigger is the consequences, as illustrated in Figure 5. As mentioned earlier there is a blurred transition between monitoring itself and condition monitoring. The same advantages can be said to yield for leakage detection as for condition monitoring, even though the basic definition may be somewhat different.

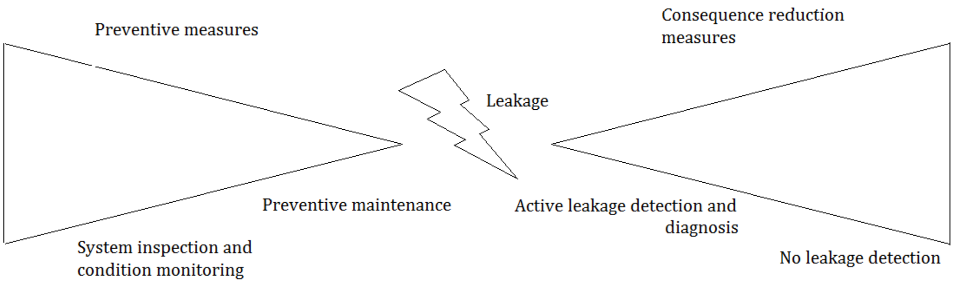

Figure 5 A bow-tie model with leakage as event.

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[3] It may be a combination of several methods, algorithms, measurements etc. The value of the parameter is highly dependent on the underlying work.

1.3 Motivation

What is the motivation for detecting and diagnosing subsea hydraulic leakages?

The answer is reduction of consequences from a leakage, and added confidence to the process. The consequence of leakage can be divided into four main groups

- Reduce hydraulic emissions
- Minimize impact of process emergency shutdown
- Use available intervention capacity
- Reduced costs

Reduction of hydraulic fluid pollution of the environment is important. Even if hydraulic fluid is allowed to be discharged to sea, it is unfortunate. It may also have has spill over effects. As an example it would be bad for the company's reputation to pollute. Conservationists and organizations as Bellona would surely not appreciate it. Also, Statoil needs to report to the Climate and Pollution Agency and Petroleum Safety Authority of Norway if the discharge is higher than the set limits. If crossing these limits frequently, it may be a paradox when bargaining for petroleum activity in delicate areas in Norway as Lofoten and Vesterålen, where oil production is prohibited today. Especially since regulatory authorities have a vision of zero emission.

As more direct consequence of control system leakage is production halt. If a leakage is big enough, the process will shut down due to fail-safe mechanisms. In worst case scenario it would shut the entire field, or several templates. An extensive troubleshooting and testing of hydraulic lines is then initiated to isolate the cause. With leakage monitoring, troubleshooting and isolating times could be reduced, and the healthy wells could be back on stream faster.

As stated by Anders Valland it is important to exploit available intervention capacity when an intervention is executed. A developing hydraulic leakage in a SCM is important to detect, since it then would be intervened at the first scheduled intervention action, even if it might be small for now. The alternative could be a rush action. Modules with minor defects can be replaced when other intervention actions take place.

By a systematic approach towards leakage detection and diagnose, manual troubleshooting may be considerably reduced. Use of specialists may also be reduced, which implies cost savings. The cost of extra hydraulic fluid needed to maintain operability may also be an issue.

Today, monitoring of hydraulic leakage in Statoil is scarce; the main way to detect leakage is the constant need for filling of hydraulic fluid to the hydraulic power unit (HPU). Leakage detection and diagnosis has potential. A look at Figure 6 also agrees. It is gathered from a workshop at MARINTEK [9], showing the value of work on the vertical axis and ease of implementation on the horizontal. Hydraulic leakage is placed marked with red, which is the motivation for the work presented in this report.

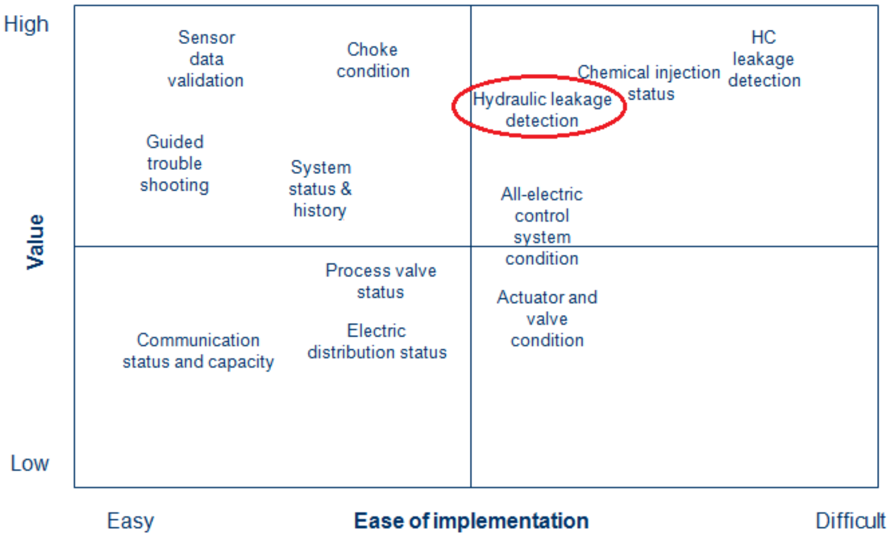

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Figure 6 Hydraulic leakage detection and some other challenges [9]

2 A Basic Description of a Subsea Hydraulic System

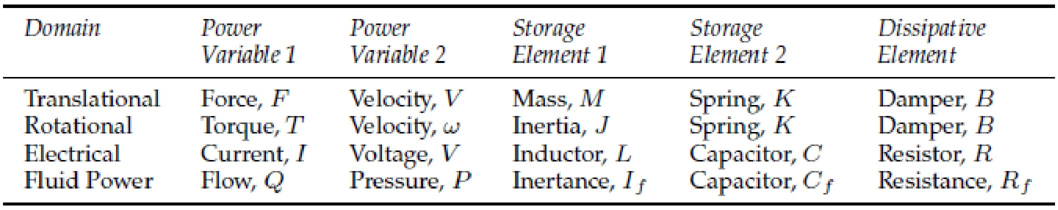
Almost every subsea control system is a hydraulic system. Field proven electrical actuators exist today[10], and one may argue that the future control system will be electrical, due to lower umbilical costs, no hydraulic fluid emission and other. Anyhow, the operation and maintenance of hydraulic control systems will be important in the future, simply because hydraulic systems are installed onsite today, and will endure for years to come.

2.1 A Hydraulic Power System

A hydraulic power system is one type of power system used to transmit and control power. A hydraulic power system has the same basic function as electric or mechanical system. In appendix II, Rabie [2] has classified the different power transmission systems. Rabie has compared the different power transmissions of the different power systems. It is not difficult to acknowledge the similarities between the different systems.

This is something to remember for those who know a lot more of one power system than others. Of course there are differences as well, and this thesis will only look into the details of hydraulic systems. A comparison of analogy is given in Table 1. Rabie has also a table of comparison of the different power systems, which can be found in appendix III.

In a hydraulic power system, the power is normally transmitted by controlling the pressure of the liquid. When a flow is initiated, power is dissipated. Hydraulic power in addition to pneumatic power systems is referred to as fluid power systems in engineering where the main difference is the fluid properties.



Domain	*Power Variable 1*	*Power Variable 2*	*Storage Element 1*	*Storage Element 2*	*Dissipative Element*
Translational	Force, F	Velocity, V	Mass, M	Spring, K	Damper, B
Rotational	Torque, T	Velocity, ω	Inertia, J	Spring, K	Damper, B
Electrical	Current, I	Voltage, V	Inductor, L	Capacitor, C	Resistor, R
Fluid Power	Flow, Q	Pressure, P	Inertance, I_f	Capacitor, C_f	Resistance, R_f

Table 1 Element analogies in several domains[11]

In order to be able to interpret data from our system it is important to know something of how the system behaves. To understand the basics of a system is emphasized. Increased complexity in combination with increased automation often put basic understanding in the shade.

Often when systems become more complex, it is preferable to use simplifications rather than the application of detailed system physics and dynamics. These are in most cases good estimates, but may give wrong results.

As an example Curtiss [12] stated a concern of BOP accumulator reliance using conventional sizing calculation in water depths above 2000 meters, due to assumptions of adiabatic processes. This is a relative basic understanding of physics, but where the general assumptions for calculation were forgotten.

The first step towards understanding the system is to understand how the components work individually, and then apply methods for how the different components interact. A typical hydraulic system consists of the components given in Figure 7. A motor drives a hydraulic pump. Hydraulic fluid is then transmitted from a tank via pipes to a directional control valve which decides whether to open or close the actuator. Fluid is then transmitted to a hydraulic cylinder which drives a load, for example a valve. The safety valve prevents to high pressure in the case of pressure build up in the circuit. The throttle check valve controls the flow. The filter ensures a fluid with minimal of derbies.

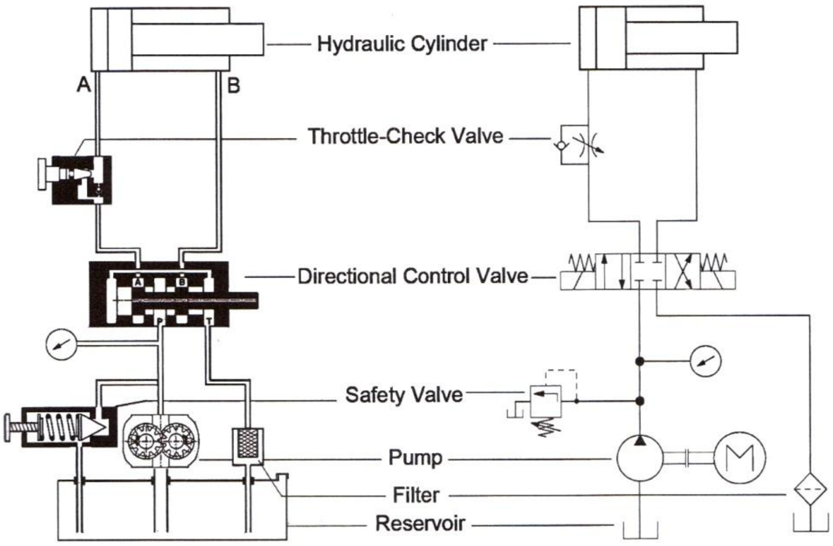


Figure 7 A hydraulic system and schematics

There are three types of hydraulic energy [13]:

1. Potential or pressure energy
2. Kinetic energy, the energy of moving liquids
3. Heat energy, the energy of resistance to flow.

2.2 Hydraulic Components

2.2.1 Hydraulic Pumps

The pump is the heart of the subsea control system. It provides power to the system in terms of flow and pressure. It is said that the pump creates flow, and the pressure is caused by resistance to flow.

The general expression of fluid power is mass.

$$P \cdot Q = Power \qquad (2\text{-}1)$$

The power generated by the pump would be the differential pressure across the pump times the flow. This would require some torque and velocity from a motor. The power output from the pump could then be written:

$$\Delta PQ = T\omega n_p \qquad (2\text{-}2)$$

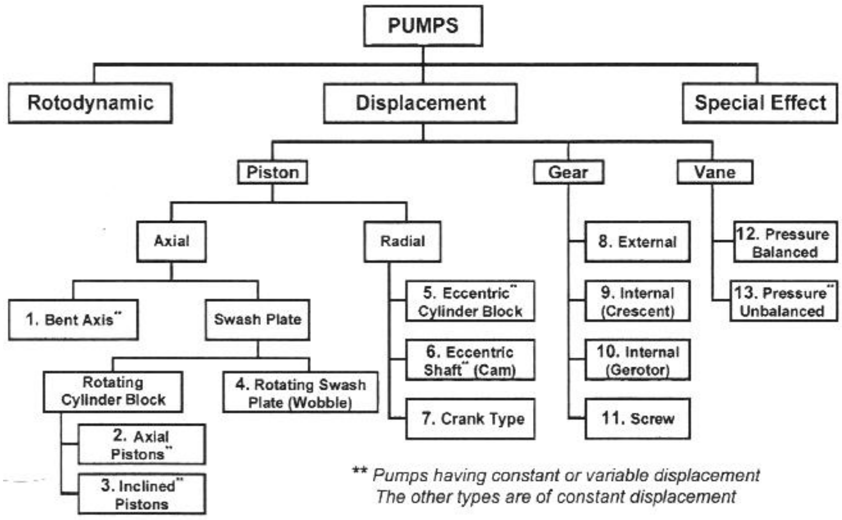
Where T equals torque, ω equals angular velocity, and n_p equals pump overall efficiency. The efficiency of our component would be output power divided by input power.

The efficiency is always lower than 1, which is due to volumetric, mechanical and hydraulic losses. The overall efficiency is often divided into these three products. This means that the actual flow rate is less than the theoretical flow rate. The main reasons are[14]:

- Internal leakage
- Pump cavitation and aeration
- Fluid compressibility
- Partial filling of the pump due to fluid inertia

Pressure is always measured according to a reference. This could either be a pressure drop across an element, or, if measuring at a point, it would in most cases be according to gage pressure. This means the pressure relative to the atmospheric pressure of 101.32 kPa. Pressure given in this report is always gage pressures unless other stated.

There are many types of hydraulic pumps. The most common are displacement pumps. An overview different types can be found in Figure 8. An example of a P&ID symbol of a pump is given in Figure 9. The arrow shows direction of flow.



*** Pumps having constant or variable displacement*
The other types are of constant displacement

Figure 8 Classification of different hydraulic pumps [2]

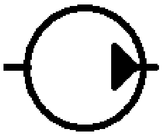


Figure 9 P&ID symbol of a pump

2.2.2 Hydraulic Fluid

The fluid is the transporter of energy in the system. Different types of hydraulic fluid exist, which are mineral oils, synthetic oils, oil/water emulsion or water-glycol fluids. All fluids have different properties. Subsea control system usually uses water-glycol fluids. This is mainly due to dumping of the fluid at sea. Subsea control systems using hydraulic oils exist as well, an example is Ormen Lange, but the oils are routed back onshore.

Pros and cons exist to both solutions. As an example, oils are better lubricators, but the closed loop tends to be negative impact on the return pressure, causing valves to float in intermediate position. In water-glycol fluids the same problem is addressed by the DCVs getting stuck, where lack of lubrication may be a problem.

From an environmental point of view there are also pros and cons. While a closed loop system provides no emissions to the environment, the consequences if leakage should occur would be much greater. This is due to the harmful effect of oils, compared to water-glycol fluids.

Additives are an important part of the fluids. They are added to gain certain effects. They might also address environmental concerns. Some types of additives might be[14]:

- Oxidation inhibitors
- Corrosion inhibitors
- Antifoaming agents
- Anti-wear
- Viscosity index improvers
- Pour point depressants
- Friction modifiers

- Detergents

Fluid engineering is not straight forward, but a basic concept of classical fluid mechanics is the continuum assumption. This means that each fluid has a definite value in every point of space, besides properties such as density, temperature, etc. It is not the aim of this report to quote fluid mechanics and dynamics. A lot of literature are available if one wants to go into details.

Fluid dynamics is one of the most advanced challenges of modern technology. As an example modern Computational Fluid Dynamics (CFD) is based upon Navier-Stokes equations which yet have minimal understanding. As a digression, a reward is given to the person reviles the secrets behind the Navier-Stokes equations[4].

Some of the fundamental concepts of fluid mechanics[4]:

- How to describe flows (timelines, path lines, streamlines, streak lines)
- Forces (surface, body) and stresses (shear, normal)
- Type of fluid (Newtonian, non newtoninan-dilatant, pseudoplastic, thixotrophic, rheopectic, Bingham plastic) and viscosity (Kinematic, dynamic, apparent)
- Type of flow (Turbulent/laminar, Viscous/inviscid, compressible/incompressible, internal/external)

2.2.2.1 *Viscosity*

Fluid characteristics are given mainly by fluid viscosity. The viscosity describe resistant to laminar movement between two parallel plates, see Figure 10. The viscosity for oils is highly dependent on temperature, but water-based fluids are not as dependent as oils.

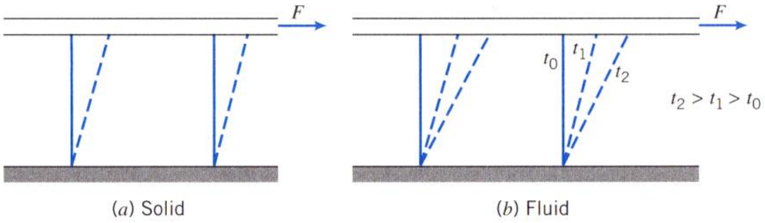


Figure 10 Difference between a solid and a fluid

2.2.2.2 *Head Loss*

Head loss is the sum of the major losses, and a major head loss contributor is resistance to flow or friction. Friction is dependent on wall roughness, pipe size and others. One of the most important friction factors is related to the type of flow. There are mainly two types of flow, Laminar and turbulent. Whether a flow is laminar or turbulent can be determined by calculation of Reynolds Number:

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[4] Millennium Prize Problems, Available: http://www.claymath.org/millennium/Navier-Stokes_Equations/

$$R_n = \frac{V \; D}{v} \tag{2-3}$$

V is given as flow velocity, D is the diameter of the pipe, and *v* is the viscosity of the fluid. To determine whether a flow is turbulent or not may be done by looking at a Moody chart. This is shown in appendix V.

Obviously, Reynolds Number is not constant trough the process. Dynamic variations cause movement in the fluid which may be laminar or turbulent; the velocity of fluid is dependent on pressure and pressure frequency pulsations. A typical variation of Reynolds Number in a subsea control cable is in the range 100 to 10000 [15]. The friction causes energy loss. In many ways these dynamics can be compared with reactive power in electronics.

2.2.2.3 Volumetric Expansion

The hydraulic fluids are subjected to volumetric expansion when exposed to temperature change. An example of this might be a boiler, where transition of the fluid to vapour may start. This is especially important for water-based fluids. If a process of volumetric expansion or compression occurs slowly enough, an isothermal process can be assumed, due to the heat transfer to the environment. If it happens rapidly, it cannot. The basic ideal processes are:

- Isochor process (V = constant)
- Isobar process (P = constant)
- Isothermal process (T = constant)
- Isentropic process (ΔQ = 0)
- Polytrophic process

2.2.2.4 Compressibility

It is also important to know that even if fluids most often is referred to as incompressible, they are in fact not. This is not that important for systems where the distance between source and consumer are short. For systems with long distances such as subsea control system it makes a difference. When the fluid is compressed, the pressure increases. If a valve suddenly closes, it will cause a rapid pressure build up and pulsation. For fluid dynamics, fluid capacitance and inertance are important terms.

The bulk modulus is an expression for compressibility in the fluid, and this parameter may not be constant.

Accumulators and line expansion are the main contributors to compressibility; these can also absorb pulsations mentioned above. Though it is not the fluid that is compressed, rather gas and elastic modulus of pipes, the hydraulic system "feel" the compression.

2.2.2.5 Contamination

Air contamination will influence the fluid with drastically changes in fluid properties. It will reduce the bulk modulus of the fluid, and reduce density and increase viscosity. It is possible that air will cause unreliable operation, noise and possible damage. If air is trapped in the system, large temperature variations can be generated by the pressure increase. This is especially undesirable in water-based fluids. Air contamination can be caused by[14]:

- Liberation of dissolved air due to local pressure drop
- Air leakages in suction lines, pipe connections, glands and others
- Returning fluid or tank filling which may contain free air, splashing freely down into fluid reservoir.
- Low fluid level in tank, insufficient residence time
- Bad design of tank
- Incorrect maintenance activity

The fluid may also carry debris. Debris contamination may damage components in the system, causing sticking and others.

2.2.3 Transmission Line/Piping

The main concern with transmission lines are resistance and volumetric expansion.

The tie-back distances may be very long, which implies major energy losses through the line. Long transmission lines generally imply slower dynamic response due to resistance.

The volumetric expansion caused by elastic volume expansion of for example steel pipes, makes pipes act as accumulators. The expansion of the lines diameter helps to store energy, which is released when pressure drops.

2.2.4 Accumulators

The main function of an accumulator is energy storage. It is used topside and at the sea bottom to provide consumers with the amount of energy needed, when it is needed. After a system operation is executed the system charges. After some time it is ready for new operations at full capacity.

If accumulators were not used topside, bigger pumps may be needed and these pumps would also have undesirable working conditions. Subsea, operation of multiple valves would be considerably slower.

Accumulators also have the characteristic of damping dynamic pressure variations often referred to as fluid/water hammering.

Different types of accumulators exist, but the once used in the subsea control system are normally nitrogen filled. Generally an accumulator uses the principle of Boyle’s law. When oil is entering an accumulator from a hydraulic line, it will displace an equal amount of nitrogen. When the pressure in the line drops, the fluid is forced back into the line. This process can be calculated using Boyle’s law, given that the process is slow, and thereby can be considered isothermal. In addition, the nitrogen gas is here considered to be ideal.

Boyle’s law:

$$PV = k \qquad (2\text{-}4)$$

$$PV = P_0V_0 \qquad (2\text{-}5)$$

Where, V = Volume P = Pressure k = Constant

An accumulator is however not perfect and there exists a pressure drop from a filled to an empty accumulator. If the pressure drops below a certain value, the pumps will start and try to compensate. When a certain pressure is reached the pump will stop. A typical efficiency is 0.9[5]. This can be estimated by calculating a compressibility factor for the real gasses. For nitrogen there exist tables which can be used.

Symbol of an accumulator is shown in Figure 11

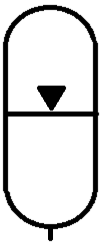

Figure 11 P&ID symbol of an accumulator

2.2.5 Directional Control Valves

Control valves are an important part of the subsea control system. Several types of control valves exist, but there are basically three elements: poppet valves, sliding spool and rotary spool valves. They may function as relief valves, pressure reduction valves, sequence valves etc. Control valve are often also used for valves which control a process loop. This could be a choke valve, because it controls the process flow. That is not the definition used here.

The main interest is directional control valves (DCVs). These valves are also often referred to as solenoid valves, if the direction is electrically controlled. DCV will be the reference throughout the report.

The DCV is used to supply pressure to either side of an actuator[6]. This is done by a basic control device, which may be manual by a hand leveller, hydraulic or electric. Subsea uses electric control to operate the control valves. The operation is done by creating a magnetic field, by energizing a coil with a certain amount of windings.

The DCV may be pilot operated, where the electrics control the pilot flow. An amount of hydraulic fluid is used to switch the DCV. This is done to reduce the size of the solenoids and simultaneously increase the response time. A self explaining function of a DCV is given in appendix VIII provided from [5]. The pressure supplied to the DCV is called pilot, while the flow going through the DCV when opened is called supply. Both are supplied from the umbilical.

The solenoids may be redundant. An example of real life DCV is given in Figure 12. Redundancy in solenoids and symbol is shown in Figure 13.

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[5] Source Hydac.com downloaded 04.04.2010 Available p 10: http://www.hydac.com/fileadmin/pdb/pdf/PRO00000000000000000003000000011.pdf

[6] There exist DCVs with a greater number of functions

Figure 12 A Directional Control Valve DCV[16]

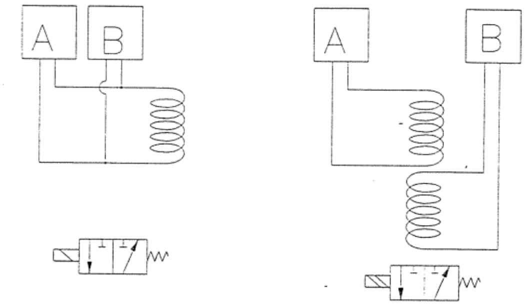

Figure 13 Redundancy in solenoids, and following P&ID symbol[5]

2.2.6 Actuators

A Typical subsea actuator consumes from 0.3 to 7 litres. The actuator is the component driving the gate valves on a Xmas tree, also referred to as cylinder. It converts the hydraulic power to mechanical power. When an actuator is operated, fluid is injected at one side of a piston forcing the piston in opposite direction. An actuator can create linear or rotary motion. An actuator may be single or double acting, meaning that pressure can be applied only at one side or both. In case of a push only, a spring may cause the actuator to retract by pressure bleed down.

The SCSSCV supplied by HP lines are typical single acting, where constant pressurizing is needed in order to keep the valve open. A choke valve may be an example of double acting, where pressure can be applied on both sides for open/close functions.

There are two main differences in an actuator, that is the rod end and the cap end. The rod end has less surface area than the cap end, meaning that higher force can be applied at the cap end with the same pressure. This also means that an actuator will use more fluid opening than closing if it is double acting, or vice versa. The general expressing for an ideal, friction-free, leak less cylinder is:

$$F = PA \qquad (2\text{-}6)$$

When doing dynamic simulations, friction and leakage will be accounted for. The efficiency may vary with pressure and operating conditions. As stated by Rabie[14]:

> *Leakage is inversely proportional to viscosity and directly proportional to the cube of radial clearance.*

As an example if the clearance should be doubled, the leakage rate would increase by a factor of 8. There will always be some internal leakage in a hydraulic system. Figure 14 shows normal internal leakage due to clearance between piston and housing. Figure 16 show a symbol of a gate valve and actuator.

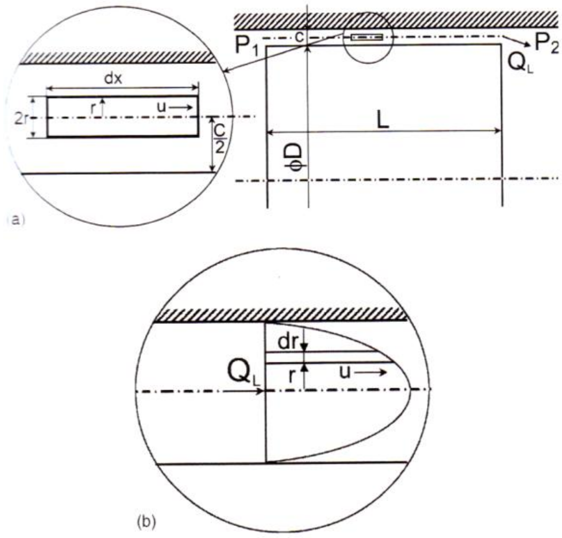

Figure 14 Internal leakage a) a leakage flow b) laminar fluid velocity profile [2]

2.2.7 Gate Valves

When talking about valves, the first thought is the mechanical barrier from a source of flow. It is where the mechanical power generated by the actuator is used. The valves perform the operation wanted, either it is to close a production line, open it, or manage it.

This is referred to in this report as gate valves, which is common for Xmas tree valves. The gate valve itself is actually not a part of the hydraulic components, because in the actuator the hydraulically power is converted to mechanical.

However, the main valves function normally influences the hydraulic system. A sticky valve may cause additional friction and cause pressure pulsations in the system. Changed well properties may cause the gate valves to actuate faster, due to reduced counter force. This depends on whether the gate valve has a balanced or unbalanced design. The main valves influence the hydraulic system, and process data may be one way to determine if the main valves operation commands have been executed.

Figure 15 shows a balanced gate valve with actuator. The actuator is shown to the left. It is easy to see that with some pressure measures, spring properties and seal frictions a representation of stem force could be estimated.

Figure 16 shows the symbol of a gate valve with actuator. It also contains a bit more information. A black gate valve for example implies a normally closed gate valve. The spring in the actuator indicates the spring retractable function.

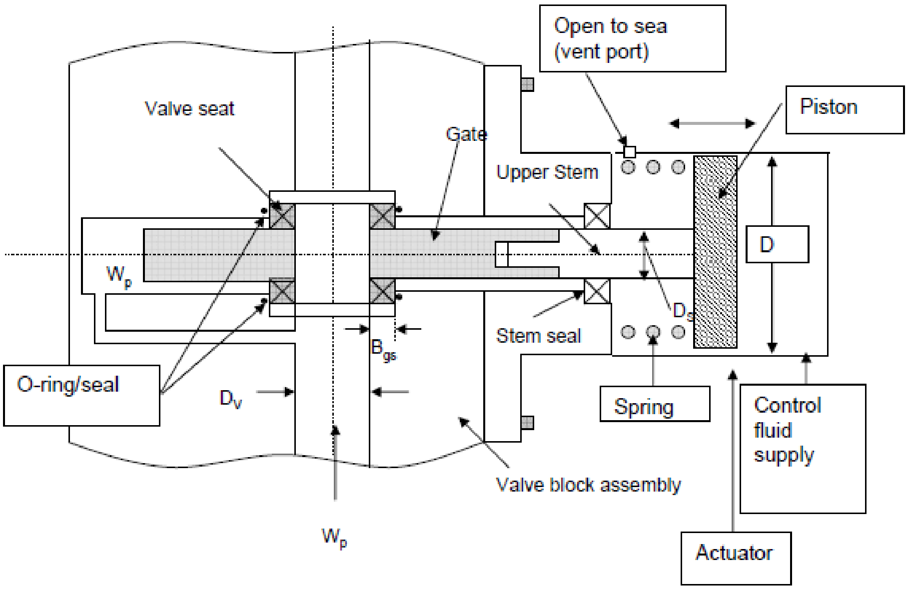

Figure 15 A Balanced Gate Valve with Actuator[5]

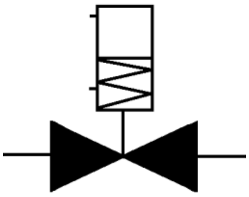

Figure 16 P&ID symbol of a gate valve with actuator

Some important influences of valves to be aware of:

- Dead band, mainly due to friction and backlash
- Valve type and sizing and performance
- Hysteresis
- Spring range
- Pressure
- Leakage
- Flow

2.2.8 Filters

Filters are important to ensure a clean fluid and smooth operations. Filters topside are often placed in parallel, while subsea, filters may have a bypass. Filter bypass is secondary path past the filter. The bypass has higher cracking pressure than the filter side, often made possible by check valves. This way flow is directed through the filter. If the filter gets jammed, a pressure is build up, and flow passes through the bypass.

Figure 17 P&ID symbol of a filter

2.2.9 Check Valves

Check valves typically has a certain cracking pressure to open. This is done by controlling stiffness of a spring, which keeps the valve closed. At a certain "crack pressure" fluid is allowed to flow. In addition allows flow in just one direction. Symbol of a ball type check valve is shown in Figure 18.

Figure 18 P&ID symbol of a ball type check valve

2.3 Understanding The System as a Whole

Now, a brief description of important components in the system is given. So how do the components interact? First of all that depends on how the pieces are put together, but generally there are three approaches for understanding the system.

- Make static calculations with reasonable assumptions.
- Model the process with reasonable assumptions.
- Look at the process, and try to understand why.

Static calculations are fast and easy, and may give interesting results. Static calculations are often used when dimensioning the system. However, static calculations do not tell anything about the dynamics. While algebraic equations are used for static system, differential equations are used for dynamic systems. When generating dynamic equations, fluid capacitance and inertance are inherent. Different methods and approaches on generating the equations exist. One method, which is used in this thesis, is simulation using dedicated software, presented in 5.6. The reason why this was used is that even simple systems can become very complex when doing time domain calculations.

When new subsea system is being designed, one of the design criteria is that hydraulic response analysis is executed. When the system is installed, it is possible to learn the system, by looking at process data.

Dynamic modelling provides a physical presentation, which can help us understand how more complex systems work together. This especially yields for looking at start up, shut down, and emergency conditions.

Subsea systems are relative simple systems. However, the combination of dynamic dependence, and number of operation possibilities of a complete system makes it advanced. Some of the influences are provided in Figure 19.

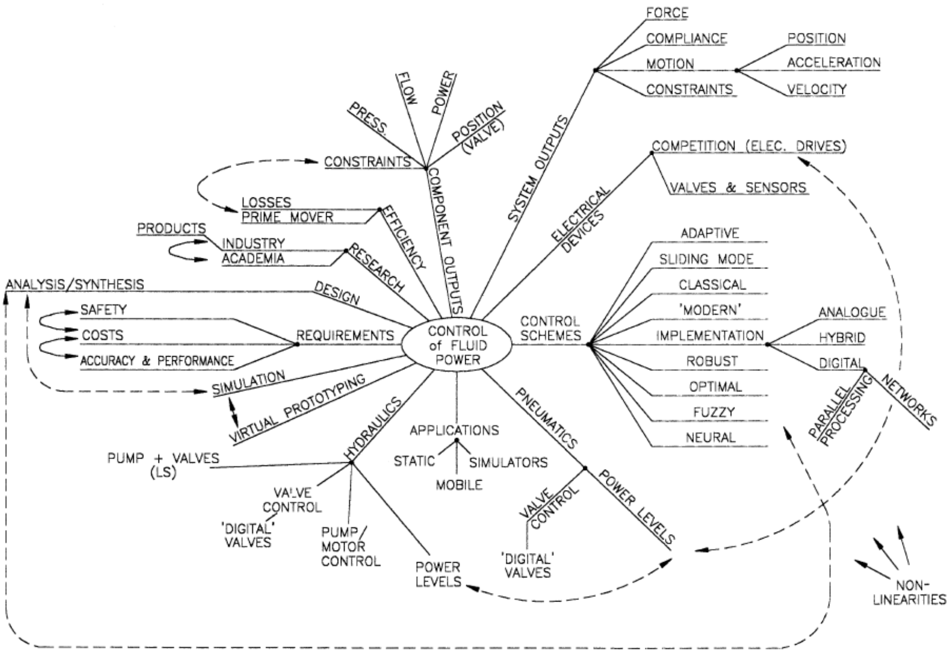

Figure 19 The domain of Fluid Power Control [17]

3 Norne

3.1 Norne General Information

The Norne field is located in the Norwegian Sea, in block 6608/10 and 6608/11, seen in appendix I. The license was awarded in 1986 and Norne came on stream in November 1997. Norne has in the later years expanded with step-out to Urd-field with Stær and Svale which came on stream in 2005, and Alve in 2009. This has extended lifetime. In addition, planned developments such as Marulk and Fossekall will increase lifetime even more.

The subsea layout can be seen in Figure 20. Marulk is located about 30 km south west of Norne FPSO. Fossekall is located 15 km south east of Norne FPSO.

The water depth is the area is approximately 350-380 meters.

Norne is an FPSO, which means Floating Production Storage and Offloading Vessel. A turret in the ships allows it to rotate, and production lines, umbilicals mooring lines etc. are connected to the turret. The ship can be disconnected in case of bad weather. Oil is stored in the ship for offloading, but gas from Norne is exported via Norne gas export pipeline to Åsgard transport and from there to Kårstø in Rogaland.

It should also be mentioned that Norne has 12 electrical actuated chokes.

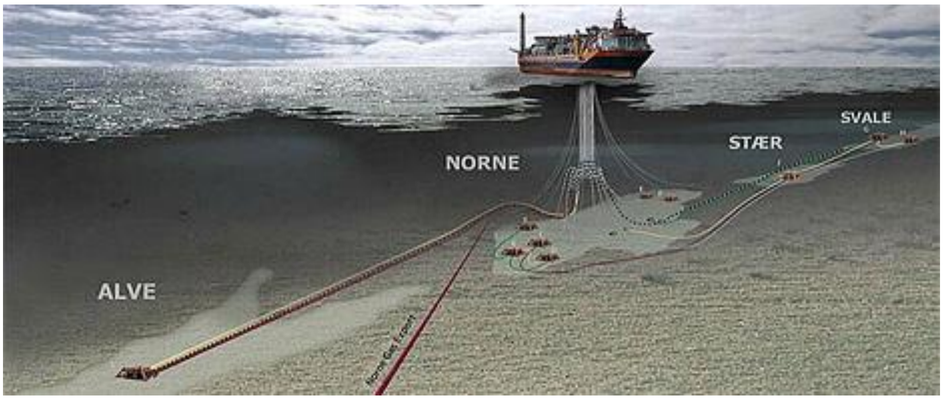

Figure 20 Layout of Norne FPSO and appurtenant templates

3.2 Alve

The reason for describing Alve is because easier to get hold of production data to analyze. The reason why it is easier to get a hold of data is that Alve is a new development. In addition, Alve is producing from only one well on the template. This is advantageous, because it limits the amount of data.

Alve is located 16 km south west of Norne. Alve is expected to extend the lifetime of Norne from 2016 to 2021 and produces gas and condensate. The Xmas tree is horizontal type, which is mainly used on this field. Even if Alve is a new development, Alve use the same subsea control modules as on the other templates on the field[7].

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[7] MKII E150

3.3 Norne Subsea Control System

When talking about Norne control system it implies the control of not only the Norne satellites[8], but also Norne M and K, Urd and Alve. The reason is that these other fields are tied back to Norne FPSO. All wells have the same HPU unit located onboard Norne FPSO. Different umbilicals transport hydraulic fluid, power and communication to the subsea wells.

The most common used subsea control system is multiplexed electro-hydraulic systems. The main components in multiplexed systems are hydraulic, electrical, and control features. The equipment on Alve is provided from FMC Technologies, and a general FMC Technologies SCS can be found in appendix IV.

3.3.1 Xmas Tree

In Figure 21 a typical horizontal subsea Xmas tree is shown. The tree function acts as one of two independent well barriers needed to maintain production. In addition the choke valve located in the tree regulates the flow from the well into the subsea manifold.

There are different types of subsea threes, and particularly two main differences. That is horizontal and vertical trees. The main advantage of a horizontal tree is that it is possible to do intervention without pulling the tree. The main advantage with a vertical tree is that you can pull the tubing without pulling the tree. Design and type varies somewhat from field to field.

The Xmas tree consists of a lot of valves, thereby its name. Some of the most important can be features can be seen in Figure 21. The valves are run mainly by the SCS, or they can be manually overridden by an ROV. On the Xmas tree the SCM is located.

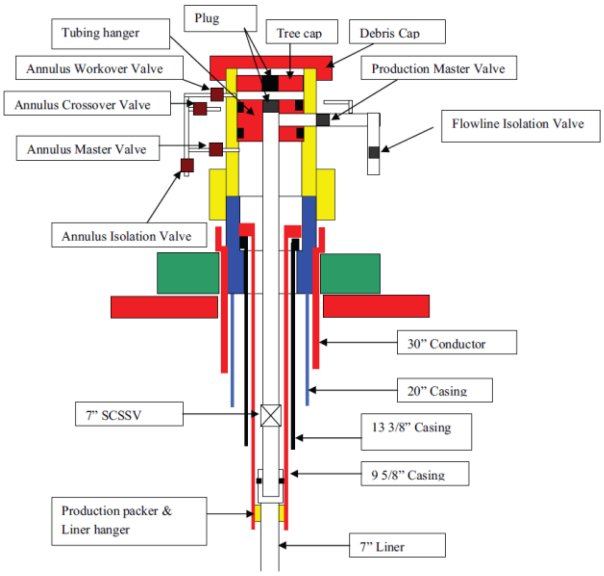

Figure 21 Main features of a horizontal Xmas tree[5]

3.3.2 Subsea Manifold

The manifold also contains a lot of valves. The manifolds task is to receive and manage production fluid from several satellite wells or template wells[9], in order to deliver a controlled flow to the flow lines, often with lower pressure rating. It also normally consists of a test line and water injection line. Since the pressure rating of flow lines may be lower, HIPPS valves may be

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[8] The first development at Norne is often referred to as Norne satellites, even though it really is templates.

[9] Some installations may have the manifold on the template

installed to cope for this by rapidly shutting down and protect the flow line, as seen in figure 13 to the right.

The manifold valves are normally operated manually, but Norne K has hydraulically and D has electrical operated valves. The valves shown in Figure 22 are in other words not part of the subsea control system given.

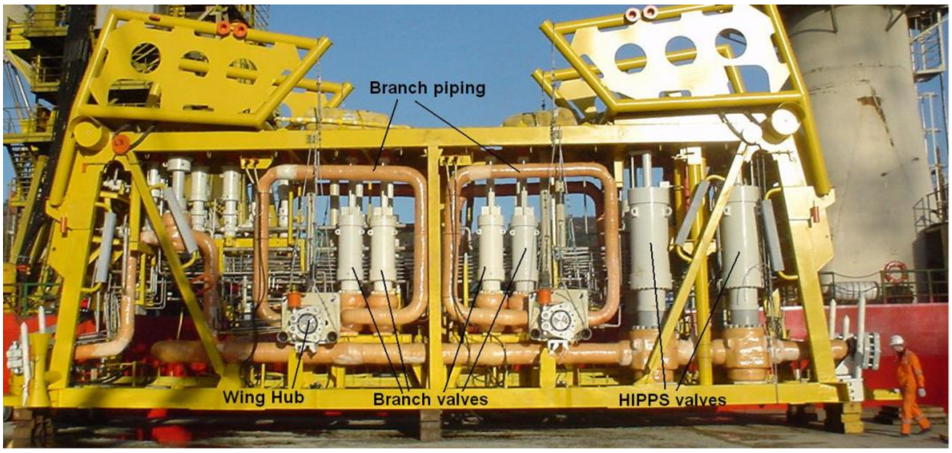

Figure 22 A subsea manifold[5]

3.3.3 Subsea Information Flow

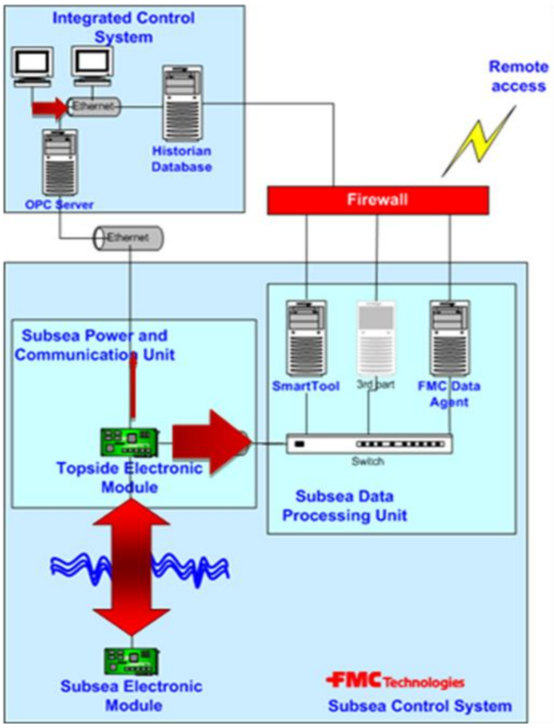

Figure 23 FMC Subsea control system information flow [3]

Figure 23 shows an example of the data flow from a subsea electronic module (SEM) located within the subsea control module (SCM) by FMC Technologies.

There is a big arrow between the subsea and topside electronic module. From there are two arrows, one as big as the first, and another considerably smaller. The idea behind this picture is to show the importance of extracting the raw data from the SCM.

These data are then stored, which may be used later for monitoring purposes, and thereby stored in a historical database. Data interesting for the operator are shown in the little arrow. He only needs to know some certain parameters of the wellbore and the annulus, making it easier to get the overview when reducing the data to the information needed.

The same flow also implies when connecting additional applications.

Today, a sampling rate from subsea installations is normally given by 1 minute middle values.

3.3.4 Hydraulic Fluid Used

Hydraulic fluid is needed to operate subsea valves. Emission of chemicals from offshore installations needs to be approved by The Climate and Pollution Agency of Norway. The agency has classified different chemicals used offshore in four different categories, green, yellow, red and black. Green chemicals are considered natural to saltwater environment, or do not have any environmental impact. Yellow chemicals are considered acceptable, while red and black chemicals are considered hazardous towards environment, and allowed only under special considerations. From 1997 to 2008, red and black emissions have been reduced with more than 99.5 %[10].

The hydraulic fluid used at Norne is a water-glycol based fluid that contains chemicals considered yellow by SFT. It is referred to as HW443. Fluid properties can be found in [18]. The HW443 at Norne earlier had a fluorescent added, which base function was to detect subsea leakages with ease by ROV. Due to hazardous impact on the environment stated by The Climate and Pollution Agency Norway, this is no longer used.

3.3.5 Fluid Flow Through the SCS

In Figure 24 a description of the fluid travel through the system is given. The different main parts of the system is shown. The information is gathered from P&ID drawings and Raymond Nilsen has provided supplementary information where needed.

We begin filling the system with hydraulic fluid, as shown by a big arrow in the HPU in the upper right part of Figure 24. The fluid then enters the return tank. Filling the supply tank is done by pumps from the return tank (not shown). These pumps also act as circulation for fluid filtering.

When the fluid is in the supply tank, it has four different paths further, two LP pumps and two HP pumps. Further guide trough the system is done on the LP side of the system.

When fluid leaves the pump it enters the accumulator skid for storage, assuring that pressure is kept within certain limits, and preventing pumps from constant start/stop. The fluid is then directed to different umbilicals. When the fluid has arrived subsea, it is directed to a given template, and to a given Xmas tree. When arriving at the three, it enters the SCM, as shown in the lower right in Figure 24.

In the SCM fluid is diverted into a supply and pilot stage. The pilot stage supply the directional control valves with a small amount of actuating fluid, which opens and closes the valves. When opened, fluid from the supply stage routes fluid to the valve actuator located on the Xmas tree, as shown on the bottom left on Figure 24. This makes the tree valve to open or close. Return fluid from the Xmas tree valve actuator, and the directional control valve, are directed to the return line. From the common return line fluid leaves the control module and enters the sea.

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[10] Available: http://www.klif.no/publikasjoner/2637/ta2637.pdf, page 5 Downloaded 02.04.2010

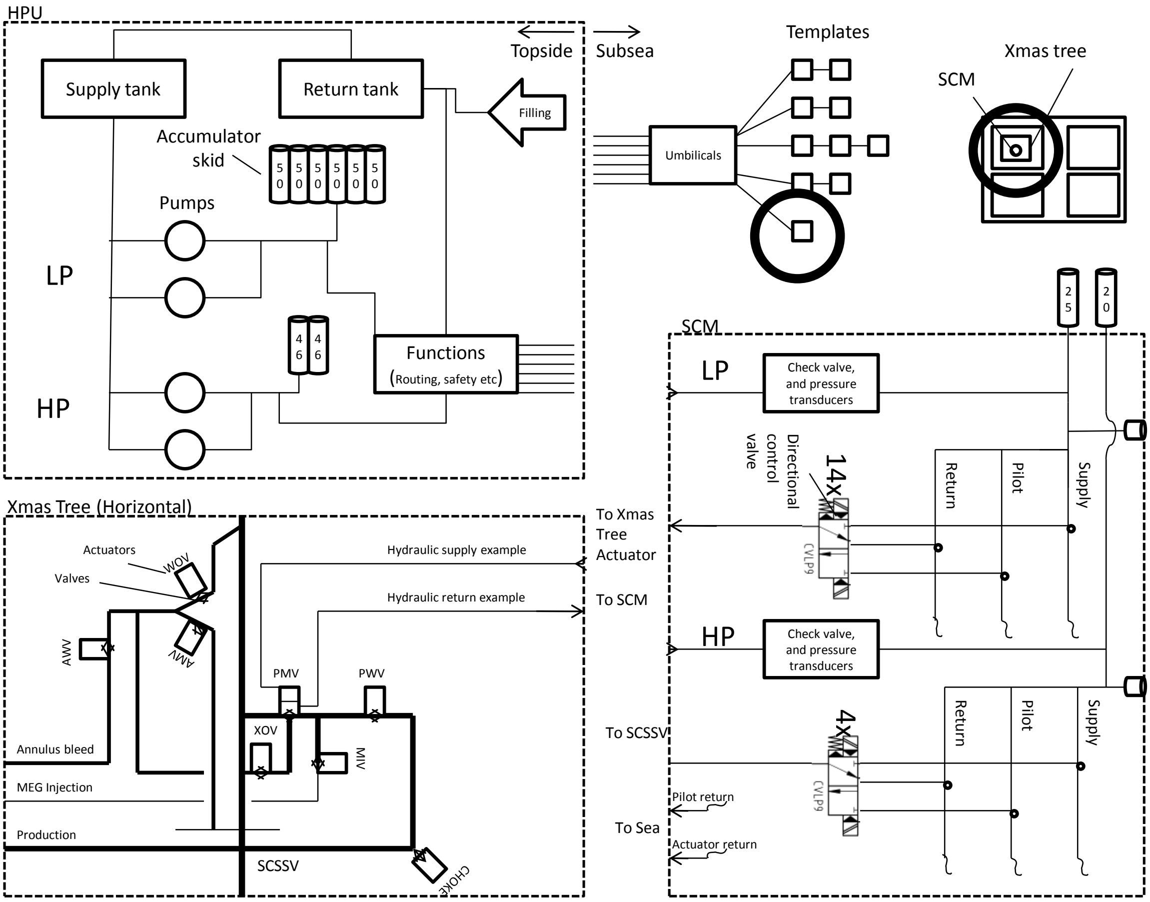

Figure 24 Norne SCS hydraulic system schematic

3.3.6 Hydraulic Pump Unit (HPU)

There is one Hydraulic Power Unit (HPU) delivering hydraulic control fluid to all the subsea wells. The HPU is located in a container in the turret aboard Norne. The data and information here is mainly gathered from technical documents, such as HPU technical document and Hydraulic response calculation reports available at Statoil.

The hydraulic pump unit is the heart of the system, securing hydraulic fluid to the consumers. The HPU has two supplies, low pressure (LP) and high pressure (HP). The HPU is redundant, that means that there are two pumps for both LP and HP supply. There are two low pressure (LP) circuits at 250 and 345 bar, and two high pressure (HP) circuits at 540 and 690 bar. The low pressure circuit act as secondary by adjusting a regulator. If pressure drops below the lower pressure, the second pump start, which insures a redundant circuit. If the pressure drops below 210 and 480 bar all the pumps shut down.

The LP hydraulic pump delivers 6,7l/min at 345 bar and 3.5l/min for HP pump at 690 bar. The electro motors are 5.5kW for LP and 7.5 kW for HP. Both are 690V, 50Hz and have three phases. By looking at process data an average filling time is about seven minutes, which implies that the capacity of the accumulators is not fully utilized.

The accumulator skids are 300 litres for LP, and 92 litres for HP. In case of emergency quick dump valves ensure that the umbilical and accumulator skid has no influence in the bleed down. It is a requirement that there should be room for a total stop of the pumps in 12 hours. This is done with a compensated leakage of 36.5 litre on the LP system over 12 hours.

Response of the HPU and operation is important. What is for example the response time for filing an LP system from a ventilated umbilical? From looking at hydraulic response calculations, it may take half an hour to gain 95% of steady state pressure at SCM, and an additional half an hour before steady state. This requires that pressure is kept within limits in the topside accumulator skid. These delays are important to be aware of, especially since it take an additional 30 minutes from 95%-100% of steady state. The last 5% only implies a total fluid consumption of 3 litres. During the first 30 minutes 54 litres is consumed. The curvature of the pressure over time may be seen as a horizontal asymptotic curve tending towards the charge pressure.

3.3.7 Umbilical

There are mainly two types of umbilicals used, dynamical and static. Dynamic umbilicals are used from topside to subsea. Subsea, static umbilicals are used via a connection on the sea bottom. If looking at the cross section of the static umbilical it can be seen that it consists of a Methanol injection, inhibitor injection LP and HP supply lines, power and communication. The structure of umbilicals varies. An example of a static umbilical is shown in Figure 25.

There are five umbilical leaving the Norne FPSO, one to template B, C and M, one to Alve, one to E and F, one to D and K, and finally one to Svale and Stær. Notice how the templates are connected in series. The umbilicals to Alve have two redundant pipes for both LP and HP.

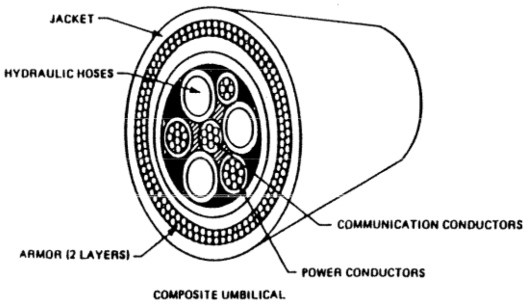

Figure 25 Example of a static umbilical

3.3.8 Subsea Control Module (SCM)

The SCM is in many ways the brain of the Xmas tree. It interprets signals, and distributes electrical and hydraulic power. In Figure 26 there are some pictures of a subsea control module (SCM). The construction is shown in a sketch to the left. In the lower right shows the Subsea Electronic Modules (SEM). The SCM consists of two identical separate electronic parts, making the module redundant with respect to failure, SEM A and B. The SCM are mounted to the subsea control module mounting base (SCMMB), and are retrievable.

The SEM interprets topside commands, and distributes electric power to the DCV solenoids. In addition it can manage permanent and additional sensors.

The DCVs used at Alve are 3 way 2 positions DCVs. This means that it has three ports, two positions (on/off). They are normally closed and spring retractable and have redundant solenoids. DCVs are shown in a rack in the middle of the SCM in left Figure 26.

For fluid power storage near the SCM, accumulators may be placed on the outer can. Normally this may be 25 litres, but this varies. Some may even not have a subsea accumulator.

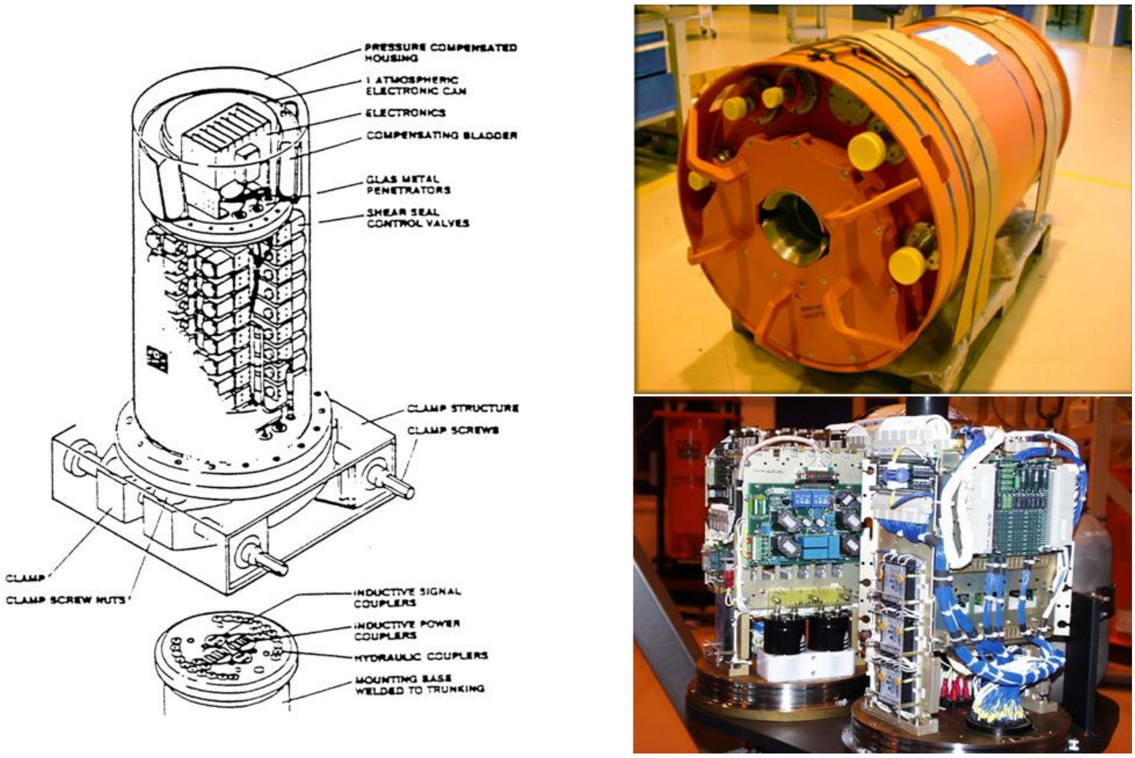

Figure 26 Subsea control module (SCM)[5]

3.4 Failures

When doing feasibility study for this master thesis, one of the statements made was SCMs failing a lot. Since it consists of signals, electronics and hydraulics the failure modes could be many. In order to reveal the vital few causes for leakage subsea, a Pareto analysis was on the agenda. Raymond Nilsen however stated that 98% of all leakages in the hydraulic system were caused by DCV problems. 98% could surely be characterized as vital few in a Pareto. Because of Nilsen's statement, DCV have been focused upon in this report, more than other failure modes causing leakages.

Why so high failure rate?

Zeng [19] states some interesting remarks from a case study in 1999 at Schiehallion Fields west of Shetland. After subsequent investigation, component damage was found on DCVs. This was a consequence of long term seawater presence due to seawater ingress during installation. In addition, the hydraulic fluid caused biodegradation, which resulted in DCV leakage. An individual leakage of 35 litres/hour and combined maximum leakage rate of 70 litres/hour were observed.

Zeng also states that a closed circuit system has proven more reliable than open circuit systems. One of the reasons is seawater ingress; another may be that closed system uses hydraulic oils, instead of water based fluids. As mentioned earlier, increased cost, and potentially increased environmental risks in case of leakage may be drawbacks of closed systems.

It should however not be forgotten that there are a lot of other failure modes. This might be electrical power problems, signal/data electronics, as well as hydraulic. They may be external as well as internal problems, due to degradation or due to external influence. It might be desirable to get an overview.

This is possible by using Failure Mode, Effect and Criticality Analysis, or FMECA. The FMECA is broken down in system functions, so it is clear which function that is lost in case of faults. Other tools are Fault Tree Analysis (FTA) and Event Tree analysis (ETA), determining causes and risk for a top event in addition to consequences of that event. This is part of the Reliability-Centred Maintenance[11] (RCM) e strategy. It is a time consuming process to make these overviews, and this is not part of this report.

Example of other possible leakages not considered, although a leakage detection system may detect these as well:

- Valve leakage, seat, rod, piston
- Couplings and connectors
- Static and dynamic umbilicals
- Topside, HPU
- And more

A collection of failure and causes in hydraulic systems is summarized by [20]. It is also possible to get more detailed information about statistic of faults in Sintef Industrial Management's *OREDA.*

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[11] As stated in [2]the RCM (Reliability based maintenance) is a method to enable maintenance strategies for all the components in a process based on internal and external criteria related to safety, environment, operation and economy. RCM sees the components in a system perspective based upon the demands of a specific function, functionality problems, and prevention of functionality problems

4 Basis of Detection and Diagnosis

4.1 What is a Leakage?

A leakage in this context is all fluid loss, either internally or to surrounding environment, which is not used for normal operation.

What is normal operation? It is dependent on a number of factors. First of all there is always some leakage from the hydraulic actuators. An estimated 5-6litres[12] for LP and HP per hour is considered normal, without any operation taking place.

A leakage has a leakage rate, which defines quantity. As an example, leakage rates have reached over 30 litres an hour before being detected. While leakage rates in the order 3-4 litres an hour would most probably not be detected at all[13]. As a comment 3-4 litre is equivalent to an increase of 50% of the normal leakage rate without operation.

4.1.1 Leakage Detection:

Question:	*Is the system leaking?*
Answer:	*Yes / No.*

The answer maybe not as easy as one should think. The most important feature when monitoring any system is to know whether the system is OK or not. This may be done visually, but that is not easy subsea. On-line flow sensors or/and pressure sensors, may indicate flow losses via systems analysis. Automatic detection would be a great advantage, rather than manual observation of data. This is why we apply methods.

A detection method for leakages should at least consider actual and allowable leakage rate, compensated for deviation uncertainties. In addition it should robust. Frequent false alarms would undermine the system, and should be avoided, or at least fixed when encountered. Performance criteria for leakage detection can be found in Table 3.

When the system is not OK, the diagnose starts.

4.1.2 Leakage Diagnosis

Question:	*Where is it leaking, how big is it, what is leaking, when did it start?*
Answer:	*It might be complicated.*

Diagnosis is all about information. It is desirable to know in details what caused the system to leak. In this case, it is known that a leakage is taking place. How much the system is leaking, where, what, and when is unknown.

It is important to determine to what degree diagnosis is preferable. The diagnosis may very well be automated, but often it requires some kind of service when considering details.

4.1.3 SCS Leakage Detection and Diagnosis.

There may be similarities between detection and diagnosis. Leakage detection in a SCM based on SCM instrumentation, would provide diagnostics as well. This is in spite of the fact that a

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[12] Assuming an average leakage rate of 0.3ml/min for HP and 0.25ml/min for LP, which according to the HPU technical document is a fair suggestion. 32 HP valves and 320 LP valves is assumed.

[13] As stated by Raymond Nilsen

detection method was used rather than a diagnostic method. The reason for this is the hierarchical structure of the SCS. By knowing which tree that causes leakage, diagnosis is provided to some extent. Figure 27 describes the structure. To the left, a possible number of branches are shown. If the model for detection detects leakages far down in the system hierarchy, an automated diagnose would also be given.

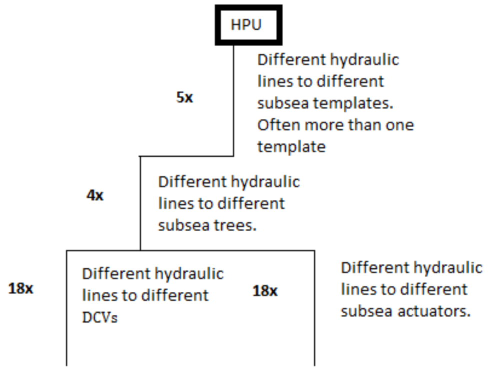

Figure 27 The hierarchical structure of the SCS

First of all, to provide good leakage systems for detection are normally first priority. This is because systems normally are operational, and since diagnosing a healthy system would have no value.

Diagnosis of systems is important as well, and the fact that detection may provide diagnostics, is interesting. Some methods may even provide both detection and diagnosis features. Diagnostic systems are scarce.

The following statement by Michelsen [21] may explain why the status is as it is:

> *In general, the literature references on industrial applications of diagnostic systems are not many. There are no case studies that analyze the specific benefits that can be attained trough the implementation of diagnostic systems. This could be due to the proprietary nature of the development of in-house systems. Also, there seems to be a general lack of overall penetration of diagnostic systems in process industries. This might be due to the gap between academic research and industrial practice.*

It would be more relevant to manually look at process data for diagnosis purposes, than detection. This might be a reason why system diagnosis is done in diagnostic centres, like the GE subsea centre. This also seems to be the trend within other diagnostic areas like subsea pumps

An impression from the operation departments is that the normal workload does not allow them to be dedicated towards detecting and diagnostic methods. It might be necessary implement it to a long time strategy, and provide dedicated work towards detection and diagnosis.

4.2 An Example from Pipelines

4.2.1 Instrumentation relevant for leakage detection of pipelines

An American Petroleum Institute (API) report[22], chapter 5.4 present nine steps for establishing leak detection potential. The first of these steps are the collection of data. Four main data areas are given.

1. Pipeline data (subsea control system data)
2. Fluid Data
3. Operational data
4. Uncertainties of process variable measurements

Pipeline data is property data of the pipeline, which can be viewed as system data for subsea hydraulic systems. Operational data is important, especially for subsea hydraulic systems, due to vast number of operation combinations, and the appurtenant response. Uncertainties of process variable measurements are sensors like pressure, temperature etc. Which are current, not a stet value. Certain methods may need additional certainty and sampling rate than others.

4.2.2 Methods for Pipeline Leakage Detection and Diagnosis

API has recommended practice for state-of-the-art leakage detection and diagnosis for pipelines. In Computational Pipeline Monitoring for liquids, the following methods are described [23]:

1. Line balance calculation

The conservation of mass ideology is used, which means that the sum of the fluid entering the system is the same which exit the system. These calculations are done over some time for pipelines, typically more than 15 minutes periods.

2. Real time transient model

This method uses a simulation model for the given pipeline, is a more sophisticated method of mass balance, capable of comparing transients in the pipeline against measured data by applying equations of motion. Normally, pressure and flow are the most interesting variables. This is mainly referred to as a qualitative method.

3. Statistical analysis

This method may be able to tell us something about the probability that a leakage occurs. By using defined pressure and flow of historical data, a constant comparison for deviations is executed. A leakage can then be defined with a given certainty, if pattern deviation increases. In addition to conservation of mass, signature recognition techniques may be used. This is mainly referred to as a qualitative approach.

4. Pressure/flow monitoring

This method looks at the relationship between different sensor output and an applied algorithm to determine abnormalities.

5. Acoustic/Negative Pressure Wave

When a leakage suddenly appears in a pipeline, an appurtenant pressure drop is created. By measuring time between a sensor feels the drop, an estimation of leakage can be extracted. This is a type of method in need for a very high sapling rate of data, where leakage size and location is provided.

Table 2 shows a comparison between method and data. The comparison yields for SCS as well. The “x” equals not needed, “v” equals needed, and “?” equals case dependent. As we can see, a real time transient method needs all the data, while a statistical approach may not need any data at all.

DATA Method	Pipeline data	Fluid Data	Operational data	Uncertainties of process variable measurements
Line balance calculation	x	x	v	v
Real time transient model	v	v	v	v
Statistical analysis	x	x	?	x
Pressure/flow monitoring	?	x	x	v
Acoustic/Negative Pressure Wave	x	x	x	v

Table 2 Comparison of data, method.

4.2.3 Performance Criteria for Leakage Detection and Diagnosis.

There are four main performance criteria for leakage detection and diagnosis:

1. Reliability
2. Sensitivity
3. Accuracy
4. Robustness

These criteria are important to have in mind. The criteria influence the quality of leakage detection and diagnosis. If certain sensitivity is required, it may not be satisfactory if a leakage is below the minimum detectable leak rate. This is obvious. The table is inspired from[22]:

Performance Metric	**Qualitative Performance Criteria Specification**
Sensitivity	Minimum detectable leak rate
	Minimum detectable leak volume
	Maximum volume loss prior to alarm
	Response time for large leak
	Response time for small leak
Reliability	Incorrect leak alarm declaration rate (overall)
	Incorrect leak alarm declaration rate (steady state flow)
	Incorrect leak alarm declaration rate (transient conditions)
	Incorrect leak alarm declaration rate (static Conditions)
Robustness	Loss of function due to pressure outage(s)

	Loss of function due to temperature outage(s)
	Loss of function due to flow measurement outage(s)
	Loss of function due to pump state changes
	Loss of function due to valve state changes
	Loss of sensitivity due to pump changes
	Loss of sensitivity due to valve state changes
	Start up stabilization period
Accuracy	Leak location error
	Leak flow rate error
	Leak volume error

Table 3 Performance criteria specifications of leakage detection and diagnosis

4.2.4 Pipeline Monitoring Systems Today

Monitoring of tools exist within pipeline and water plant systems for leakage detection and localization. These are systems utilizing both static and dynamic behaviour to detect leakages, which is done with the aid of computers, online data and in real time.

Example of such a system is GALILEO from Krohne. The system (model based pipeline leak detection and localization) has proven itself suitable for the industry[24]. The systems have shown great potential in detecting leaks during run-up and run-down. Another advantage with the model based approach is that it is possible to detect where the leak is located. This is for example done by using gradient intersection of pressure sensors along the pipeline, as point 5 in 4.2.2

A model of the GALILEO system is shown in Figure 28.

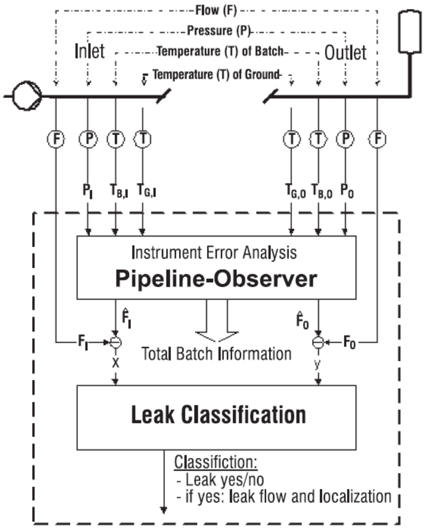

Figure 28 Model-based Pipeline Leak Detection and Localization by GALILEO, Krohne[24]

Also other types of system exist, which has shown great potential within leakage detection. ATMOS Pipe by ATMOSI has under a implementation on the Wilhelmshaven to Köln (the NWO Pipeline) and Hamburg (the NDO pipeline)[25] shown that leakages were detected even under severe transient conditions without generation of false alarms.

Mass conservation and hypothesis leak against leak free are used. Key feature of this system is comprehensive validation of data, and the combination of:

- Modified volume balance (1)
- Pressure and flow monitoring (4)
- Statistical analysis (3)

It has shown potential applying all three methods simultaneous. Notice that the Real time transient model is not a part of this system. It is also worth noticing the estimation of certainty, based on statics. Bottlenecks mentioned were mainly bandwidth and the importance of instrument reliability.

4.3 State-of-the-art, What is Available Subsea Today?

To begin with, very little exist when it comes to monitoring of hydraulic control systems subsea. The systems are monitored to some degree, but the data are not used actively. Today, leakages are detected by a constant need for hydraulic filling on the HPU. Leakages are diagnosed by closing of parts of the systems, and monitor the pressure head.

Topside more has been done and some systems provide leakage detection and diagnosis tools. These systems require more sensors than available subsea today. An example of hardware used by ValveWatch is given [26]:

- Dynamic Pressure Transducers
- Strain Gage
- Static Pressure Sensor
- Ultrasonic Leak Sensor

Most of the systems seem to use qualitative approaches, where comparisons of valve signatures are done manually. In addition the tools which will be presented here are mainly concerned with valves and actuators. Seen from a SCS leakage point of view, the actuator leakage would only be of interest, since production flow is outside the SCS boundaries. The SCS may function perfectly even if a gate valve has an internal leakage.

ValveWatch

ValveWatch by Crane inc. is an on-line condition monitoring and leak detection program for critical valves and actuators. ValveWatch collects data, and uses patented algorithms which run automatically for leakage calculation. Valve signatures are identified and analyzed, and a simple web interface ensures access to system status.

Some conditions may be analysed by partial stroke testing or even with open valves. A common strategy used is comparison of valve characteristics of a valve in good condition with valves with faults.

Fisher ValveLink

Fisher ValveLink by Emerson Process Management is another example. The program performs valve and actuator diagnosis. This is done mainly in three steps[27]:

- Performance diagnostics

- Dabbling diagnostics
- Diagnostics interpretation services

Performance diagnostics provides diagnostics while valves are in service. In addition to showing valve performance, it makes advices. However it requires that someone watches the data. Dabbling diagnostics is a diagnostic data interpretation feature. Actuator leak inspections are one among other signatures investigated.[14] The diagnostics interpretation services allow Emerson engineers to interpret valve data.

A promising solution which is being used within actuator and valve monitoring is acoustics. Even though it is influenced by noise, placement, process conditions, turbulent flow etc. [28]. Such sensors may be mounted on an ROV for inspection or permanently installed. An example of a permanent sensor may be the leakage detector by Clampon [29]. Another example may be an acoustic system as the NCM 4 system by Bjørge Naxys[30].

If this is relevant for the SCS might be discussed. It is not probable that acoustics are available for SCS hydraulic leakages at least not internal leakages. The ability to distinguish abnormal leakages from normal and the limited possibilities for changes inside SCM may be some reasons. For gate valves and actuator relevance may also be discussed. They may very well fail due to a bunch of factors, but it is not the dominating cause of leakage in the SCS.

Another approach is to use leak tracing fluorescent dye for external leakages, but since the use of dye is prohibited at Norne (3.3.4) it is not considered.

4.3.1 GE SmartCentre

The Smart Centre is part of General Electric (GE) overall remote monitoring and diagnostics tactics, and is located at Nailsea in UK. The centre officially opened in October 2009, with Ove Magne Kallestad (Vice President of Subsea Technology and Operations at Statoil) present. It all started with time consuming commission of subsea completions. The main task of the centre is to monitor and gather data from subsea fields from around the world, and then interpret the data in order to extract knowledge for decision purposes. It is not only the subsea control system which is monitored. The motivation is increased efficiency, uptime, production rates and maximizing lifetime.

Rod Tester said in an article in the OTC 3-6 May2010[31]:

> *We can look at all the data such as tracking insulation resistance, hydraulic leaks and valve signatures to provide useful information to customers that can greatly improve the effectiveness of all maintenance activities.*

Historical data may also be gathered and run trough simulators in order to study past events and gain insight. Tester also explained that the centre solved a problem at Snøhvit gas field in two hours, which normally could take a week.

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[14] Available: http://www2.emersonprocess.com/en-US/brands/fisher/DigitalValveControllers/FIELDVUESolutions/ValveDiagnostics/Pages/ActuatorLeakInspection.aspx Downloaded:20.05.2010

It would have been interesting to know more about this centre. A lot of questions about methods, implementation etc. remains unanswered.

4.3.2 FMC Technologies CPM

In an FMC Technologies brochure on Condition and Performance Maintenance (CPM) [32] one of the monitored systems are the SCS. The system collects raw data from the SCM and sensors, giving an indication of condition using Technical Condition Index (TCI)[15]. The idea is to gather key information, validate it, and then process it, leaving decision makers with the data they need, when they need it. Its core function is to get as much knowledge as possible with the data at hand, in addition to build up a system of expert network and historical data.

The details of what methods are used are not available. According to Guttorm Røed at FMC Technologies Ågotnes, this information is kept internally because patenting is ongoing.

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[15] TCI is similar to KPI

4.4 Instrumentation Relevant for Leakage Detection and Diagnosis

4.4.1 Example of a SCS Sensor Setup

By studying the P&ID's of Norne, these are the measures chosen of interest. In Figure 29 sensors have been added to Figure 24. The different sensors are numbered and explained in 4.4.2. Electrical instrumentation, signal and consumption have not been addressed. Although electrical energy balance of solenoids may be very interesting area to pursue.

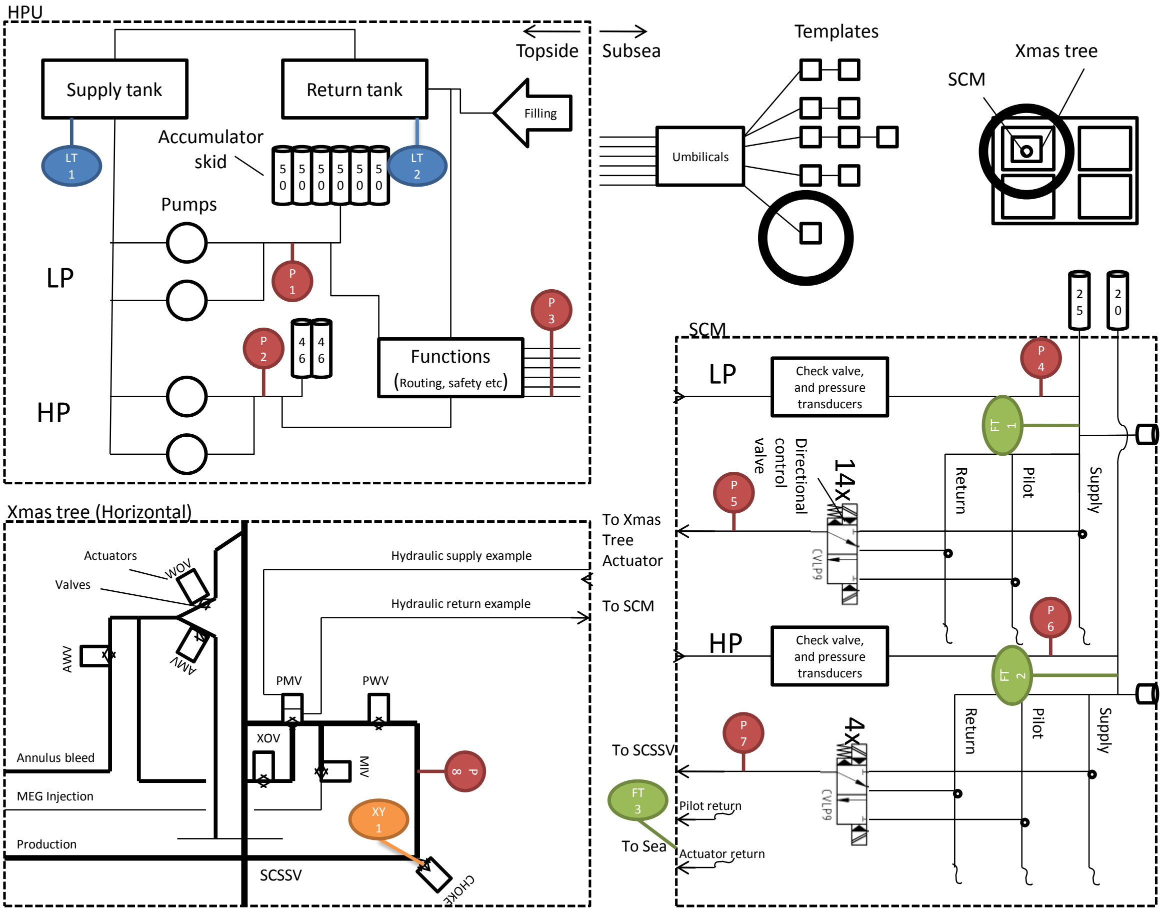

Figure 29 SCS sensors setup

Sensor	Description
LT 1, LT2	Tank level measurement supply and return
P 1, P 2	Accumulator skid pressure for LP and HP
FT 1, FT 3	SCM inlet and outlet flow
P4, P5, P6, P7	SCM inlet pressure and pressure after DCVs for LP and HP
XY 1	Choke valve actuation
P 8	Well pressure
P 3	Umbilical inlet pressure

Table 4 Sensor description for Figure 29

4.4.2 Comments to Instrumentation (Table 4):

The tank level measurements (LT1, LT2) are done by pressure differential measures. The measure tends to be very rough. This may be due to relative large tank compared with accumulator skid loading capacity, only being 4%[16] of total tank volume. Wave motion on the vessel may also be a contributor, making it difficult to use this measure to accurately calculate the amount of fluid entering the system. Trending over some time would however give accurate results. So fluid content changes in the tank must be seen over time.

When it comes to motor or pump data, the pumps are either off or on. The pumps run at constant speeds. Pump data was not available, but could be interesting to look at. It is however possible to register pump start/stop by looking at the charging of the system. The pumps start when the accumulator skid pressure (P1, P2) drops to a certain level, and stop when a certain pressure level is reached. This way if assuming no variation in nitrogen charge pressure from accumulators each time, a certain amount of fluid will enter each time the pumps run. Some variations may however be present, if the system is delivering fluid to its consumers while filling the accumulators.

In Figure 30 pump operating region is shown, with respect to accumulator pressure. The green line represents the accumulator skid pressure topside. When accumulators are completely empty, pressure drops rapidly, or when the accumulators reach max volume, the pressure rises rapidly. The relation is here given as linear for illustration purposes. In reality it is close to linear, but not linear.

The relation between start and stop are normally only affected by operation and normal leakage. A pump fill up without operations may take six and a half minute. With operation the time might be seven minutes. Of course, this is dependent upon number and type of operations. The relation between stop and start is highly dependent on operation. A period without operation could easily exceed 12 hours due to normal leakage rate.

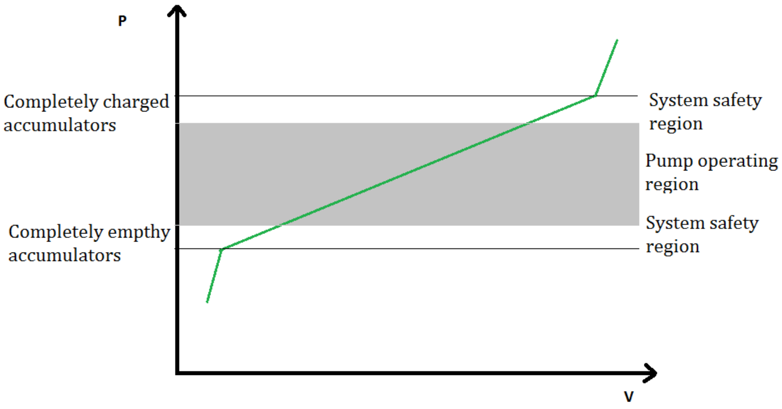

Figure 30 Pump operating region seen from P1 and P2

By watching the accumulator skid pressure (P1, P2), it is possible to know the amount of times the pump has run, and time used for filling. It is logical that if the pump should run constantly, or with greater frequency than normal, an abnormal situation would be present, that is leakage somewhere in the system, or constant dumping back to return tank from the HPU. The accumulator skid pressure is very interesting, because it will shape after different operations. In addition this pressure is measured by two identical transmitters, which increases the reliability of the measurement itself.

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[16] Assuming a tank size of equals 1500l, and accumulator skid charge equals 75l

If looking at the flow meters (FT1, FT2, FT3), it should be a great measure for suggesting leakages. If a flow from the SCM is greater than anticipated it could indicate leakage. Also, the tree causing the trouble would be revealed. Another consideration is that a leakage is normally internal, which means it will not be detected by the meters. This is because the internal leakage will be part of the flow meter measure both in and out. If considering operation it could be detected.

Not every SCM has flow meters. In addition, Anders Valland stated a concern regarding the measurement sensitivity. The flow meters may not register leakages. This should prove to be a valid concern. The flow meter used is turbine flow meter[17]. The value of the meters is in other words reduced.

The SCM pressure measurements (P4, P6) are also of interest. In the same manner as the accumulator skid pressure, the pressure at the SCM will vary within some range before the accumulator is empty. If valves should be operated a lot over a short period of time, the accumulator would empty, and a significant pressure drop would occur. Also the nature of check valves and or filter bypasses is interesting, requiring a certain crack pressure to open.

The pressure is measured over all DCVs (P5, P7). This is interesting, because the pressure drop over the DCV would be more or less zero. An increase in this pressure drop could indicate an actuator leakage.

The main interest of the choke valve actuation (XY1) and well pressure (P8) was to represent the operation. The umbilical inlet pressure (P3) was of interest because of the ability to diagnose a leaking umbilical. P3 is also used when umbilicals are tested for leakages today. Unfortunately, it was not able to extract the data from this sensor.

4.4.3 Additional Measurements

If looking towards monitored valves by software as ValveLink or ValveWatch, a considerable additional amount of sensors is available, compared to what existing subsea. As mentioned this could be dynamic pressure transducers, strain gages, ultrasonic leak sensors, piston travel etc. As stated at the ValveWatch homepage[33]:

> *Strain sensors and actuator pressure sensors monitor valve & actuator performance during operation, while dynamic pressure sensors and acoustic sensors monitor the valve for internal seat leaks. Together, these sensors provide operators an automated checkup on the condition of the valve and actuator package.*

And as stated in[34]*:*

> *… a large part of critical control valve conditions will most certainly be significantly reduced alone through self-adjusting, integrated, digital positioners without the utilization of additional diagnostic options*.

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[17] Vortex meters and positive-displacement have shown great accuracy13. Hehn, A.H., *Fluid power troubleshooting*. 2nd ed. 1995, New York: M. Dekker. xiii, 647 p.. However, it is not easy to make changes to the SCM from a Statoil point of view. Changes may also address new problems. Possible design improvements of the SCS would not be addressed here.

When looking at subsea leakage and additional measurements, it would first of all be sensible to use information available. The SCS is not made specifically for monitoring purposes, therefore limitations apply. When information already at hand has been exploited, additional data may be added to increase accuracy and robustness of the monitoring scheme.

It is not always easy to extract additional information. Topside, the implementation of sensors has been expensive. This is due to cabling costs, ex-requirements, calibration[18] etc. This has however improved with wireless sensors[35]. Topside wireless monitoring has made a huge impact, drastically reducing the overall cost of sensor implementation.

Subsea it has been even more difficult due to high installation costs, high sensor costs, limited bandwidth[19], and limited interfaces made possible.

This might be a fact to consider for increasing robustness and accuracy in the monitoring system. Generally it would be much easier to defend additional instrumentation topside, compared with subsea. An example of such a sensor could be a topside flow meter and pressure sensor placed before the pump. The flow meter could verify tank level measurements, and a pressure sensor could provide accurate pressure difference across the pump, which could be compared with pump data from manufacturer or new condition. The pump efficiency could then also be calculated. This would also better the performance criteria in a leakage detection and diagnosis system.

This idea was also addressed in [36]:

> *A few additional, basic subsea measurements would enable more precise fault detection and source identification than is possible with most systems today. For example, more accurate hydraulic flow rate measurement from the hydraulic power unit would improve the fluid consumption algorithms used to detect leakage. Additional pressure sensors combined with strategic isolation valves within the subsea hydraulic distribution termination assemblies would permit isolation of hydraulic anomalies associated with blockage or fluid leaks in complex subsea system architecture.*

A lot of measurements are relevant for leakage detection and especially diagnosis. And there are other measurements available not considered here, like electric consumption of subsea DCVs, which may be very interesting in terms of DCVs performance.

To get information of events and operations parallel to data information is probably the most important single additional information to current measurements, and the information is available. As an example it is extracted into the excel sheet in 5.4, which we will take a look at soon. It is just a question of information handling. A collaboration of information given in the time domain could provide a good diagnostic tool in itself for operators. Generally it is all about knowing what to expect from the process.

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[18] Calibration will normally not influence the condition monitoring. However, it might be important when modelling.

[19] The SCM is normally the limitation. (Newer SEMs may however have these possibilities like “semstar5” by GE and Aker)

4.5 Methods for Fault Detection and Diagnosis

A method is referred to as a way to perform monitoring to achieve detection, diagnosis or both. Myriad definitions exist, and it is easy to lose control. The methods does not have distinct differences, rather they describe the same with respect to different areas. There are four types of methods presented in this thesis:

1. Method with respect to solution (4.2.2.)
2. Method with respect to ways of implementation (4.5.2)
3. Method with respect to information (4.5.3)
4. Method with respect to model (4.5.4)

An example of methods with respect solution may be a "line balance calculation method". This simply tells us that the detection task is solved by line balance calculations. These are presented in the pipeline example in 4.2.2.

An example of methods with respect to ways of implementation may be a qualitative method. This method describe that a qualitative approach is used for implementation. It does not tell what solution it is based upon, information or model. Even though it indirectly might be a transient method for solution, change detection method regarding information or white box model method applied.

A method with respect to model tells us something about the system analysed and its input. For example a black box model method tell us that a black box model is used, which does not need system detailed input. The solution may be statistical, implementation quantitative, and change detection used.

The many methods available may have different identities, but they may very well have the same basis. It is not easy to get an overview in the vast amount of different terms used. However, it is important to be aware since literature may refer to many different methods. It is then vital to get to the core of the methods, and try to relate it to known relations. Otherwise good methods could be abandoned and poor methods pursued.

4.5.1 Basics Towards Application of Methods

The use of any method in a system mainly has the same motivation:

- Information amount decrease
- Information value increase

Figure 31 is illustrating the connection between information amount and value, concerns and application. This is a representation of an experience gained while working with this thesis. Notice how the information value increases with knowledge and systemization. Notice also how information decreases, meaning reduced amount of data and increased amount of value of information. The goal is to get to the top of this pyramid.

First of all we need to require data, and to store these data. Important considerations here are where to locate sensors, availability, quality of data needed. This is not possible without understanding the system.

Secondly, sound knowledge of the system is required. It is not possible to apply methods and tools without considering components in the system, system interaction, properties, and other information. This implies application of purely quantitative methods as well as qualitative methods. Indeed detail information about process physical properties may be left out, but if sound knowledge is lacking, it would become a problem when tuning the leakage detection tool.

In order to know what methods and tools to use, a systemization of information output and input is needed. What do we want to know, and how can we get it? All methods imply ways of "automating" detection and diagnosis, compared to logic reasoning by an expert looking at data. Sound knowledge may be valuable input to or basis for a application of a particular method or tool.

Thirdly, the application of methods and tools are executed. This is made possible by data acquisition and storage, understanding, sound knowledge and systemization of information. Also, concerns like performance criteria and interface arise, concerns which may require starting over at the bottom of the pyramid for improvements. An example may be that the needed quality was not satisfactory for method application.

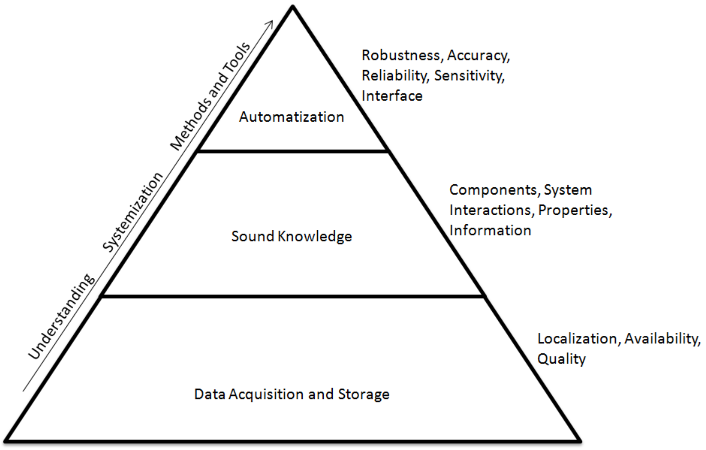


Figure 31 Information amount and value, concerns and application

4.5.2 Methods with Respect to Implementation:

The methods with respect to implementation can be divided into three main categories:

- Quantitative model methods
    - Use of history data to make models; rely on redundancy to make residuals.
- Qualitative model based methods
    - A process requiring fundamental knowledge of a system.
- Process history based methods
    - Only a large quantity of statistical data needed.

These methods are reviewed in three articles [37-39], and broken down in the following classification of diagnostic algorithms shown in Figure 32. These articles provided a very good overview in a wilderness of methods. Notice how process history based methods also has qualitative and quantitative approaches. The top event is given as diagnostic methods, and it was chosen to illustrate the broad spectre of alternatives within diagnostics. Surely the methods given could be used for fault detection as well as diagnosis.

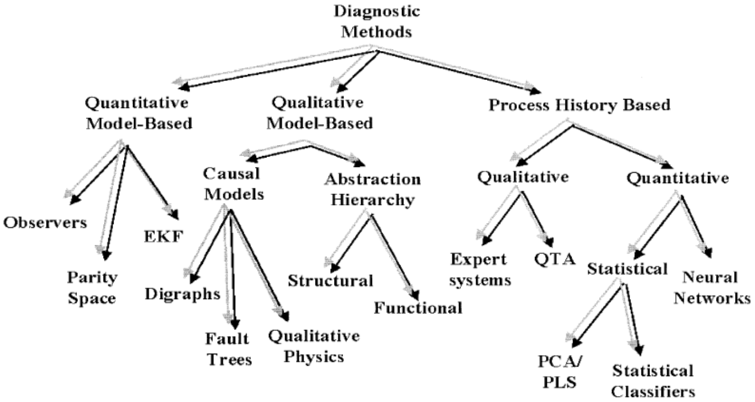
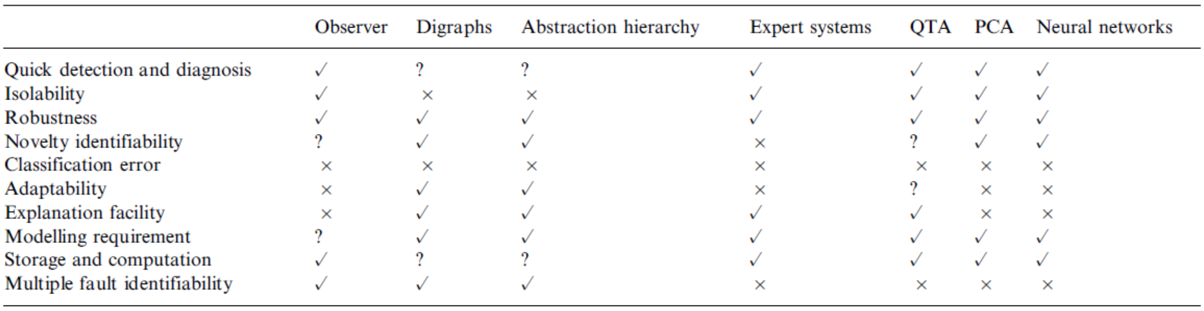


Figure 32 Classification of diagnostic algorithms [37]

The different methods will have strengths and weaknesses. One method does not have all the features. While a detailed qualitative approach may give great knowledge about the system, it is very system specific. It might need to be done from scratch when implementing it to a similar system. A comparison of various diagnostic methods is given in Table 5.



	Observer	Digraphs	Abstraction hierarchy	Expert systems	QTA	PCA	Neural networks
Quick detection and diagnosis	✓	?	?	✓	✓	✓	✓
Isolability	✓	×	×	✓	✓	✓	✓
Robustness	✓	✓	✓	✓	✓	✓	✓
Novelty identifiability	?	✓	✓	×	?	✓	✓
Classification error	×	×	×	×	×	×	×
Adaptability	×	✓	✓	×	?	×	×
Explanation facility	×	✓	✓	✓	✓	×	×
Modelling requirement	?	✓	✓	✓	✓	✓	✓
Storage and computation	✓	?	?	✓	✓	✓	✓
Multiple fault identifiability	✓	✓	✓	×	×	×	×

Table 5 Comparison of various diagnostic methods [39]

The table only show a few representative methods covered by the classification given. The check mark indicates satisfactory. The cross indicates unsatisfactory, and the question mark indicates that the method is case dependent. Consider for example the observer and PCA. While the observer method is qualitative, and provides an explanation of occurred fault, PCA does not. This is due to the fact that PCA only look at relation between variables.

4.5.3 Methods with Respect to Information

A report on state-of-the-art fault detection – with emphasis on topside experiences by Michelsen[21], has defined methods for fault detection and diagnosis. The methods are based upon information to the operator.

Michelsen define of early fault detection (EFD):

By early fault detection we mean ways of performing systematic and, preferably continuous, monitoring of the condition of a process with the objective of determination of the faults present in the process and the time of detection. By determination of faults we mean detection of whether a fault has occurred.

Michelsen [21] summer ices the methods available for fault detection and diagnosis. In addition, explanations and references to industry applications are given. The methods here are defined by information to the operator, inspired by [40]. The methods are also classified into detection and diagnostic methods.

Process model based	
	Parameter estimation
	State and output observers
	Parity equations
Signal model based	
	Frequency analysis (FFT and band filters)
	Parametric signal models
	Data reconciliation
	Data redundancy
Change detection methods	
	Statistical process control
	Control performance Monitoring

Table 6 Three main methods of fault detection

Classification method	
	Statistical classifiers (geometrical distance and probabilistic methods
	Artificial neural networks
Other reasoning methods	
	Forward and backward chaining, with Boolean algebra for binary facts
	Possibility reasoning with fuzzy logic (approximate reasoning)
	Diagraphs
	Fault trees
	Qualitative physics
	Abstraction hierarchies
	Qualitative trend analysis
	Expert systems

Table 7 Two main methods of diagnosis.

It was chosen not to describe every method presented here in detail. A quick search in the library or on the internet would give lots of hits, but the idea is to provide an overview. Short descriptions are given in [21].

4.5.4 Methods with Respect to Model

The type of method used is dependent upon system; methods are therefore often described by system identification. Generally all systems can be treated as black boxes. Input and output is known, but what happens inside is unknown. There are three main types of model methods which will be briefly presented. In literature, commonly used system identification models are:

- Black box models
- White box models
- Grey box models

Black box models use quantitative approaches. Details of systems are not important in order to extract information. Black box model are very popular in process industries because it is simple and robust. Simple because tools are available and robust because it is based on real process behaviour.

White box models use qualitative approaches, where the models are based on theory, and may be represented by models which try to adapt to the real process behaviour using first principles. Advantages are within diagnosis, system training, and as an active comparison with real process. Drawbacks are quite logical; time used to acquire detailed process data, modelling, and adjustment and adaptability of model.

Grey box models are a combination of both white and black box models. Not all system properties are known in the process, but some are. Often the models are based on experiments, or history data. The model may describe process behaviour within appurtenant boundary conditions.

4.6 When Selecting a Method

There are many considerations to take when choosing a detection and/or diagnosing method. The most important considerations:

- Understanding the methods. Determine importance of adaptability to system changes, cost of modelling and implementation. Importance of detection or diagnosis etc.
- Data and data related issues as reliability, sampling rate[20] etc.
- System knowledge.
- Available tools.

4.7 Application towards Subsea Installations

It is not easy to determine which methods to use for a given problem. If one method is understood, it might cast doubt upon methods that are not understood. As stated in [37]

> *Such a collection of bewildering array of methodologies and alternatives often pose a difficult challenge to any aspirant who is not a specialist in these techniques. Some of these ideas seem so far apart from one another that a non-expert researcher or practitioner is often left wondering about the suitability of a method for his or her diagnostic situation. While there have been some excellent reviews in this filed in the past, they often focused on a particular branch, such as analytical models, of this broad discipline.*

This statement is very important, since the author of this thesis is an aspirant within the field. To insist that some method is the best suited for subsea leakage detection and diagnosis, would be a paradox.

Rather, mainly two methods were chosen for further investigation. By choosing two completely different approaches, the author was able to experience the theory's advantages and

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[20] As an example a one minute middle value will not be sufficient to actively diagnose valve status which has an average open/close time of about 30 seconds.

disadvantages from different points of view. A completely quantitative approach by EFDD (5.5), and a completely qualitative approach by Simulation X (5.6). In addition the Excel sheet (5.4) using a simple hypothesis and test method was presented.

EFDD possibilities, and thereby PCA quantitative approach was weighted. This was mainly because it is the most used, simple, and robust method. It was also proposed by Statoil in the thesis description. The highly qualitative simulation approach was too comprehensive to use in comparison with process data, but on the other hand gave invaluable experience.

In the methods given for pipelines, are interesting for SCS as well. There are however some main differences:

- Pipelines do only consider flow in a pipe, not trough a system with lots of branches, and additional equipment. An example may be that accumulators and volume expansions tend to smoothen out sensor signatures.
- Detailed measures of what enters and exits the line are not available, and application of additional instrumentation subsea is not straight forward.
- More operations and thereby transients which can be compared to pipeline start up/run down.

If looking at the methods with respect to solutions presented in Table 2, generally all methods could be applicable subsea. However, some are more suited than others, mainly due to availability and applicability. The line balance calculation method utilizes the principal of mass conservation, and the pressure/flow monitoring use available instrumentation and information.

A real time transient model would require a quite complex, which may not be practically possible yet. However, it is interesting for subsea as well, because this would provide a very high performance of a leakage system.

5 Strategy for Leakage Detection and Diagnosis

Today, no monitoring is done of the SCS. Leakage of the SCS is as mentioned mainly detected by a constant need for filling on the HPU, and small leakages are often overlooked (4.1). When a leakage is detected, a testing of different supply lines is executed to isolating the faulty branches.

The excel sheet (5.4) provided from Norne organization is a simple but smart tool for leakage detection. It can be seen as state-of-the-art within this particular field at Statoil today. The sheet is also an indication of a need proposed by those who work close to the process. It is a highly relevant topic, and a good solution could benefit the whole organization.

5.1 Strategy

I. Define an approach.
II. Explore different approaches.
III. Propose a solution for leakage detection and diagnosis for the SCS.

5.2 I. Approach towards Problem.

The approach to the problem was to look at the methods for pipeline leakage detection in 4.2.2. By looking at the mass conservation, we are able to extract the important influences on out system.

Figure 33 show the mass conservation principle. It is simply a measurement of what goes into our system and a measurement of what comes out. If a leakage should occur, the measured output would be less than the input, and the leakage flow would be the difference between input and output.

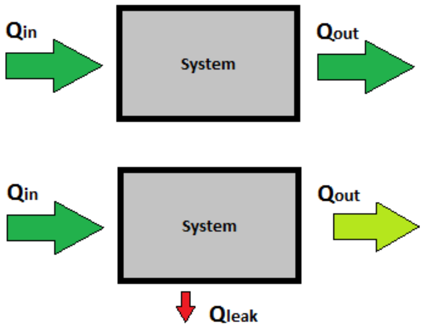


Figure 33 The Mass Conservation Principle

The system boundary is shown in Figure 24.

The mass balance can be written as:

$$Input - (Norm + Op + Return + Acc + Leak) \approx 0 \qquad (5\text{-}1)$$

This formula is meant only as a summary of important contributing elements within leakage detection of SCS, which is explained below. Since the HP system is seldom operated, the focus here is given on LP.

$\boldsymbol{Input}$ is the flow pumped into our system. It may be given by supply tank volume change, compensated for filling and returning fluid. This might be LP as well as HP pump. Each time a pump is run, also gives an estimation of either HP or LP consumption, since they are approximately the same amount as delivered each run. In addition, the time used filling up the accumulators can be an indication of each pump's condition.

Let us say operating conditions are the same (power, RPM, inlet pressure, pre charge pressure of accumulators etc.), and fluid leaving the accumulator skid equals zero. If a pump uses longer time to fill up the accumulators than before, a head loss of the pump can be a fair conclusion, i.e. the pump is degraded. The pump degradation may be a parameter relevant for KPI monitoring as well as leakage.

$\boldsymbol{Norm}$ is normal leakage. This is a leakage which cannot be avoided in a hydraulic system. It is difficult to accurately achieve this parameter. However, estimations are available on the basis of new condition. The parameter can also act as tolerated boundaries in a leakage plot.

$\boldsymbol{Op}$ is normal consumption due to operation of valves on the Xmas tree. There are 32 trees at Norne, which is controlled by the SCS. This is in the excel sheet (5.4) referred to as operation times valve consumption.

$\boldsymbol{Return}$ is the return fluid from the SCS. This might be due to subsea bleed off, or guided to return topside. It is important that this is not considered a leak. However, slow increases can be a sign of topside leakage to return, which is not desirable.

$\boldsymbol{Acc}$ is a compensating term for the fact that the system stores fluid. It is a highly dynamic parameter. It accounts for accumulator storing and dissipation, compressibility of the fluid, and pipe expansion etc. This parameter is mainly pressure dependent. It causes time delays in the system and smoothen the system response. When doing pipeline mass conservation calculations, one of the main uncertainties is fluid stored in the system.

This parameter is probably the most difficult to accurately account for. It may be used as a motivation towards steady state analysis instead of dynamic models. As an example of some of the facts a dynamic model has to account for:

- Friction causes pressure loss along the pipe, so that pipe expansion is not straight forward. It is also influenced by the hydrostatic column and temperature.
- Even though accumulators and pipe expansion provide damping to pressure pulsations, does not mean that they are not present.
- The lower pressure differential the lower flow rate, this time delay is also a problem when doing static calculations.

- Simultaneous operations of consumers tied up to the same umbilical. Geographical position between consumers, consumption size of consumers etc.

> ***Leak*** is the parameter which we want to extract from all the measurements and estimations.
>
> $\approx \mathbf{0}$ is given because of uncertainties and limitations, which will affect performance.

A mass calculation principle can be modelled for the SCS as described for pipelines in point 1 in 4.2.2 . Accurate estimations of all the variables are however a challenge. An exploration of the approach is given in 5.4, but also 5.3.

Adding the equations of motion to equation 4-2 would provide real-time transient leakage detection model as described point 2 in chapter 4.2.2. Transients describe the dynamical nature of a system. This is essential if detecting leakage when running valves[21], start-up and other changes in the time domain. This could be provided by an accurate simulation model, which will be discussed later in 5.6

Point 3 in 4.2.2 proposes to use statistical response data for different operating states and ranges, and compare those to the present situation. This will be discussed later in 5.5. Point 4 in 4.2.2 proposes to use pressure and flow meter relations, is part of 5.5, but also 5.3

5.3 II. Process History

The SCS process is somewhat slow, making it possible to see changes directly by looking at data. Some overall understanding of the system components is however needed in order to be able to explain why the process is behaving as it does. This is described in the previous chapters.

A selection of system tags (4.4.1) has been plotted and presented on graphs in appendix VI. The data presented are from real processes at Norne. The time interval chosen has been dependent on operation. Operation information has been gathered by conversation with Raymond Nilsen, and information from SAP[22].

Alve was originally chosen because of its easily available data, being a new development. This should however prove to be a disadvantage as well. Unfortunately, Alve has had no leakages. This is “unfortunate” because then it is not possible to gather data from a healthy state for comparison with a faulty state.

Information of operations is a key to success when determining process behaviour. With operations, we mean all the input commands to the system. If we know that two or more similar operations were taken on the same basis, it would actually be possible to study the operation in greater detail.

---

[21] I.e. under operation of the system

[22] A decision-support tool

5.3.1 System Response

An executed operation is initiated and consumes fluid. Pressure drops slightly due to accumulator supply. A pressure difference is created, and fluid starts to move in the umbilical, and then causes topside pressure to drop. If the pressure drops below a limit, the pump starts to maintain pressure. The pressure gradually reaches steady state again. Note that Figure 34 is only meant for illustrative purposes. Graphs and scales will differ from reality.

If looking at the top of Figure 34, actuator and DCV consumption is shown after an operation of a tree valve. The Δt for the execution is short, for example thirty seconds. Due to system dynamics, resistance accumulation etc as explained in 5.2, the corresponding flow topside has a time lag and is smoothened. It therefore has an increased Δt, which for example may be an hour.

The topside accumulators are filled with a certain time interval. When the pressure reaches a certain value, the pumps start to fill the accumulators. An operation may not trigger a pump start instantly, as illustrated. It will however, reduce the time between two pump runs. Therefore, a Δt may be even longer. The time without an operation may be twelve hours. When operated, time is reduced. Reduction depends on valve operation. The pump start is more “random”, and may as well be before or in between a valve operation, depending on accumulator pressure.

If looking at the lower graph, the pressure has a linear slope, until the flow due to the valve operation. This is due to steady state, with normal leakage rate. When the system re-enters the steady state, the same linear slope is back.

What is a steady state? A steady state is a state where the change of fluid flow in time is constant. The partial derivative is said to be zero with respect to time. It is the opposite of a transient or dynamic state.

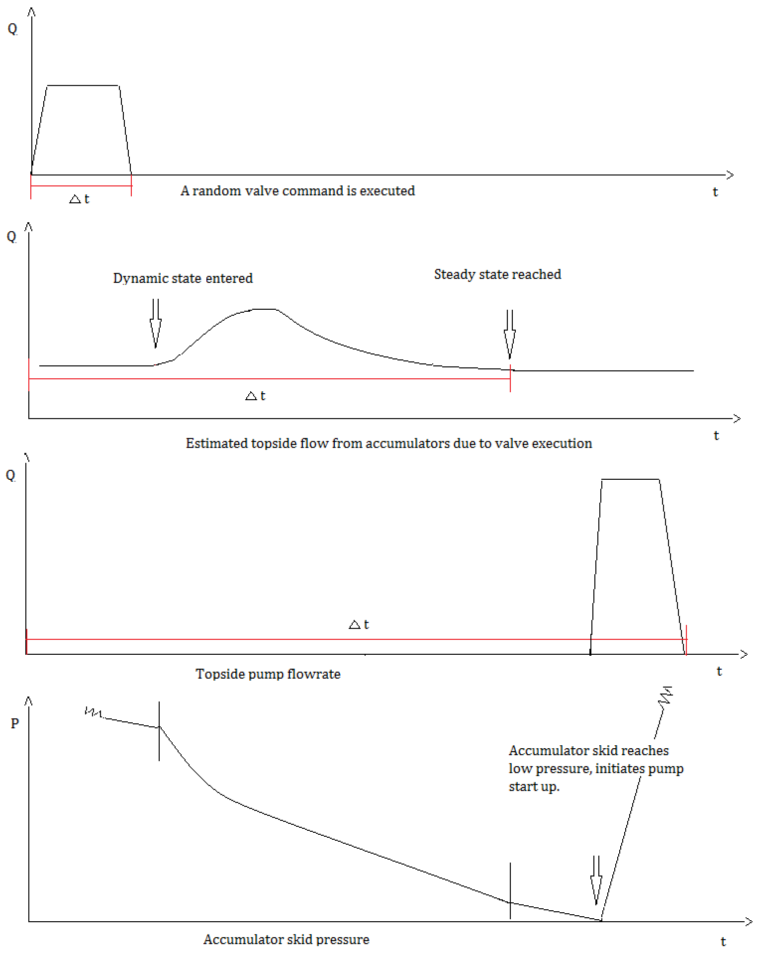


Figure 34 Illustration of system influence from operation of a tree vale.

5.3.2 Comments to Process Cases

Now, let us take a look at the data in appendix VI.

A. This picture shows the coherence between accumulator skid pressure (green) and supply tank level (red). Notice that return tank (blue) is stable, meaning that the supply tank is not receiving any fluid during this period. The green graph has to top points. At each of these the pump is started to supply the accumulator skid. This is done when the pressure reaches a certain value, explained in 4.4.2

   The accumulator skid pressure tells us quite a lot about the process. Assume that the charge pressure of accumulators is constant, and has a constant temperature. Frequent running of the pump without operations of valves, would imply leakage somewhere in the system. Longer time used filling up, i.e. time from bottom to top, could indicate a degrading pump, since these pumps are on/off with and with one speed setting. Curvature between top-top would be dependent on subsea operations.

   Monitoring only this pressure with operations, would surely be beneficial in terms of both leakage detection and diagnosis. Detection of leakage would of course mean that the top-bottom slope would elapse more rapid. A rough diagnosis could also be made, since most leakages are connected with operation[23]. A leakage occurring after an operation would make it the most probable cause. Details concerning the leakage would not be as intuitively, and other faults such as umbilical leakage location would not be that easy.

This picture also shows us that the level indicators of the tanks are a bit noisy. This is due to sea motion among others for the higher frequencies. The average value is not bad, but for more instant monitoring this might be an issue, like more detailed pump efficiency estimation.

B. This picture shows us a pump operating three times, due to different operating conditions. To illustrate that filling of accumulators take place, the supply tank level is also included. The return tank level is not shown, but is stable, and not supplying the supply tank. Clearly there are operations taking place here, but exactly which operations is not known. This behaviour is quite normal for the accumulator skid pressure. The variation of possible combinations of the accumulator pressure is almost limitless[24]. This makes the information almost useless, when not considering operation. The pressure is falling because of normal leakage and operation; an additional leakage would make the pressure drop faster. Notice how the same slope is repeated after transition.

C. In this picture a subsea steady state process can be seen. The top graph in purple shows the flow entering the SCM, as we can see it is steady. The two graphs at the bottom, in blue and green, are the well flow and the choke opening. Here we know that the other valves on the Xmas tree are not operated. The red graph in the middle shows the inlet pressure to the SCM. As can be seen, the pressure gradually decreases, before "jumping" up again, the sequence is repeated.

Why this happens might have several explanations, but let us make a hypothesis. Before the pressure sensor, poppet valves are installed. If these require a certain differential pressure to pop open and allow flow to pass, this might explain the behaviour. The subsea accumulator provides flow, up to a certain point. Then the accumulator is filled by fluid from the umbilical.

It was stated that a normal average leakage rate for a LP system would be 0.25ml/hour (4.1). If assuming 10 LP valves, and a period of 60 hours, we get an estimated 9 litres fluid, this could very well be within working range of a 25 litre accumulator. The slope between the jumps on the red graph could be an indication of internal leakage rate. This may be caused by check valves crack pressure as stated in 2.2.9.

Why is not this showing on the flow meter? The fact is, as stated earlier, that the flow meter requires a certain speed of the fluid passing, meaning that it might just not detect it.

D. This picture is a complementary to C. Legends are the same. Here the plot is from a different time span, and the choke is operated. Notice the flow registered by the flow

---

[23] DCV in intermediate position, gate/seat leakages in actuators etc.

[24] If the different valves are considered unique, and the valves being dependent on each other, it would imply 320^{320} possibilities. This can of course be reduced by practical assumptions, but hopefully point is made.

meter, when an operation is executed. The operation does not require a lot of fluid, only a couple of litres. Still it is registered by the flow meter, which is due to a higher fluid velocity over the meter.

If you look closely, it is possible to see the correlation between well pressure, choke, inlet pressure and inlet flow correlation. By drawing vertical lines it is easier to see the correlation. Notice how the slope of the red graph slowly decreases after reaching equilibrium after operation, which is the same slope as defined and seen in C.

E. Like the picture above we have now zoomed into more details concerning operation of the choke. The graphs acting almost as one line at the top are the SCM inlet pressure and respective pressure after DCVs for PMV and MIV. They are of course dependent on the inlet pressure. The purple line crossing the picture is the fluid flow; this is not merged with the other axis. The axes are however not that important, the physical nature is what we want to get a closer look at. The two counteracting graphs are choke position and well pressure. The graphs at the bottom of the picture are showing the pressure after DCVs for the closed valves, which sense the sea pressure.

It is quite interesting to see the distinct properties between flow and pressure, even though this is not a surprise. If you take a closer look at the largest closure it is possible to register pulsations or vibrations on the pressure curve. By studying such phenomena more closely one could use the data to for example determine choke friction. The time span in this case is however large, and the data is averaged.

The time it takes from the last amount of flow is registered to pressure reaches equilibrium is 6 hours. That is quite some time, and not expected, since a complete filling was stated to be an hour in the response analysis (3.3.6). This time is very important when looking at accumulator skid pressure topside. The system needs to reach its equilibrium before assuming leakages based on steady state. The flow rate will decline when approaching equilibrium, but is important to be aware of. A model would have the ability to determine a deviation before an equilibrium is reached, because topside response to subsea operation could then be foreseen.

F. This picture is included to highlight difficulties when looking at SCM inlet pressure. Alve is more or less an isolated case. The same principals may not yield for multiple well templates, or templates connected with the same umbilical in parallel or series. Therefore an example was gathered from Urd. At Urd the Svale template is connected in series with the Stær template. The figure shows inlet pressure of four SCMs, both at Stær, and Svale. Earlier when looking at Alve, it was easy to keep track. In this figure it might be more difficult to determine what happens.

As can be seen on the figure, the correlation between the pressures is self-evident. One should however not deter this challenge. There is just dependence between the variables. If accounted for operation, more information could probably be extracted. A registration of the inherent behaviour of multiple wells connected together in series and parallel is acknowledged.

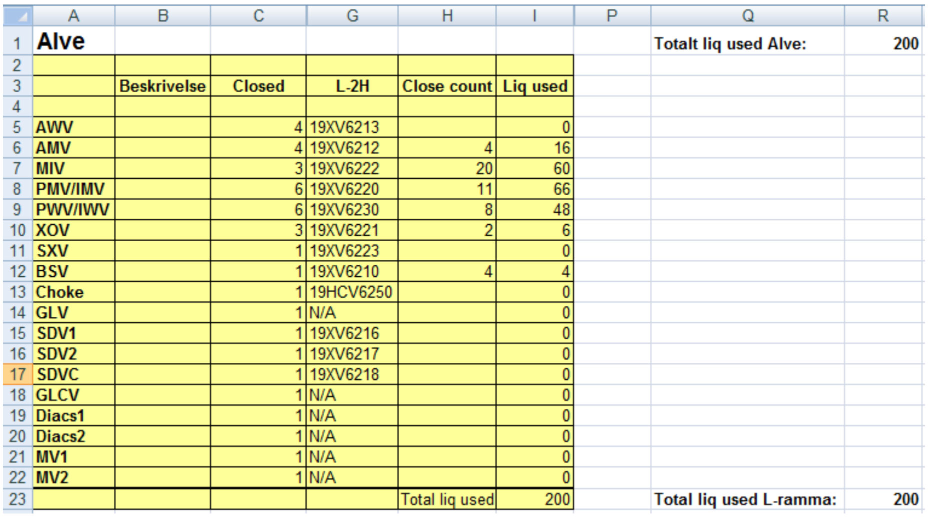
5.4 II. Excel Sheet

The excel sheet is a qualitative method approach, which uses the mass conservation principle. The excel sheet poses a hypothesis of consumption, and the value is compared with real process consumption. The hypothesis method for implementation is generally described in [38]. The excel sheet can been run once a day or once a week to detect abnormalities, but the comparison is done manually. The excel sheet has been made because of a present need, which is to know whether the system is leaking or not. The excel sheet is though not yet complete, which means that it has not been used in active comparison with topside tank level data.

Smart ideas evolve from the people working with problems on an everyday basis. The excel sheet is made by the Norne organization is an example. But the idea was actually proposed back in 1982 [41].

> *Leak rates, when understood and monitored on a periodic basis can be used to give an indication of the system condition. In addition to particle and biological analysis, seal performance can be determined by actual leak rates and the monitoring of reservoir levels can indicate whether or not an external leak exists.*
>
> *A point to bear in mind in systems where these leak rates may be experienced is the problem likely to be incurred if a water based fluid vented to sea is used as it will necessitate regular topping up of the fluid reservoirs.*

An example from the sheet:



	A	B	C	G	H	I	P	Q	R
1	Alve							Totalt liq used Alve:	200
2									
3		Beskrivelse	Closed	L-2H	Close count	Liq used			
4									
5	AWV		4	19XV6213		0			
6	AMV		4	19XV6212	4	16			
7	MIV		3	19XV6222	20	60			
8	PMV/IMV		6	19XV6220	11	66			
9	PWV/IWV		6	19XV6230	8	48			
10	XOV		3	19XV6221	2	6			
11	SXV		1	19XV6223		0			
12	BSV		1	19XV6210	4	4			
13	Choke		1	19HCV6250		0			
14	GLV		1	N/A		0			
15	SDV1		1	19XV6216		0			
16	SDV2		1	19XV6217		0			
17	SDVC		1	19XV6218		0			
18	GLCV		1	N/A		0			
19	Diacs1		1	N/A		0			
20	Diacs2		1	N/A		0			
21	MV1		1	N/A		0			
22	MV2		1	N/A		0			
23					Total liq used	200		Total liq used L-ramma:	200

Figure 35 Example from one well Alve in the excel sheet.

As we can see in Figure 35 the different consumers are shown to the left. The number of operations of these consumers is multiplied with the consumption of each, and a time range is chosen. Then, consumption from all templates is added into one total estimate of consumption within the time span. This is shown in the bottom right. The consumption entered in Figure 35 is not real, just illustrative. One of the remaining tasks is to get the right valve consumptions into the sheet.

The main interesting feature with the excel sheet is the use of operation data. The sheet uses SQL code to gather valve operations data, adding it to the sheet.

The excel sheet does not have diagnose features, because it compares the sum of all the consumers. However, it could show which operations that had been operated since leakage was registered. This could be a great start for further diagnosis.

The excel sheet does not consider normal leakage rates, HP operation or dynamic variations. Some of the influences are discussed in 5.2. It should be possible to add this and more to the model, and make it more complete. Somewhere there has to be an estimate of aspects not considered. Surely the hypothesis would deviate. However, the time from a leakage occur, to the time of detection might become longer. It is in other words a question of performance (4.2.3).

Another issue is that the models needs input for every valve. The characteristics may not be the same on the next one, which means about 6900 input parameters, if considering 460 Statoil subsea wells, and an average of 15 valves per tree. These are issues which quantitative, statistical methods try to avoid.

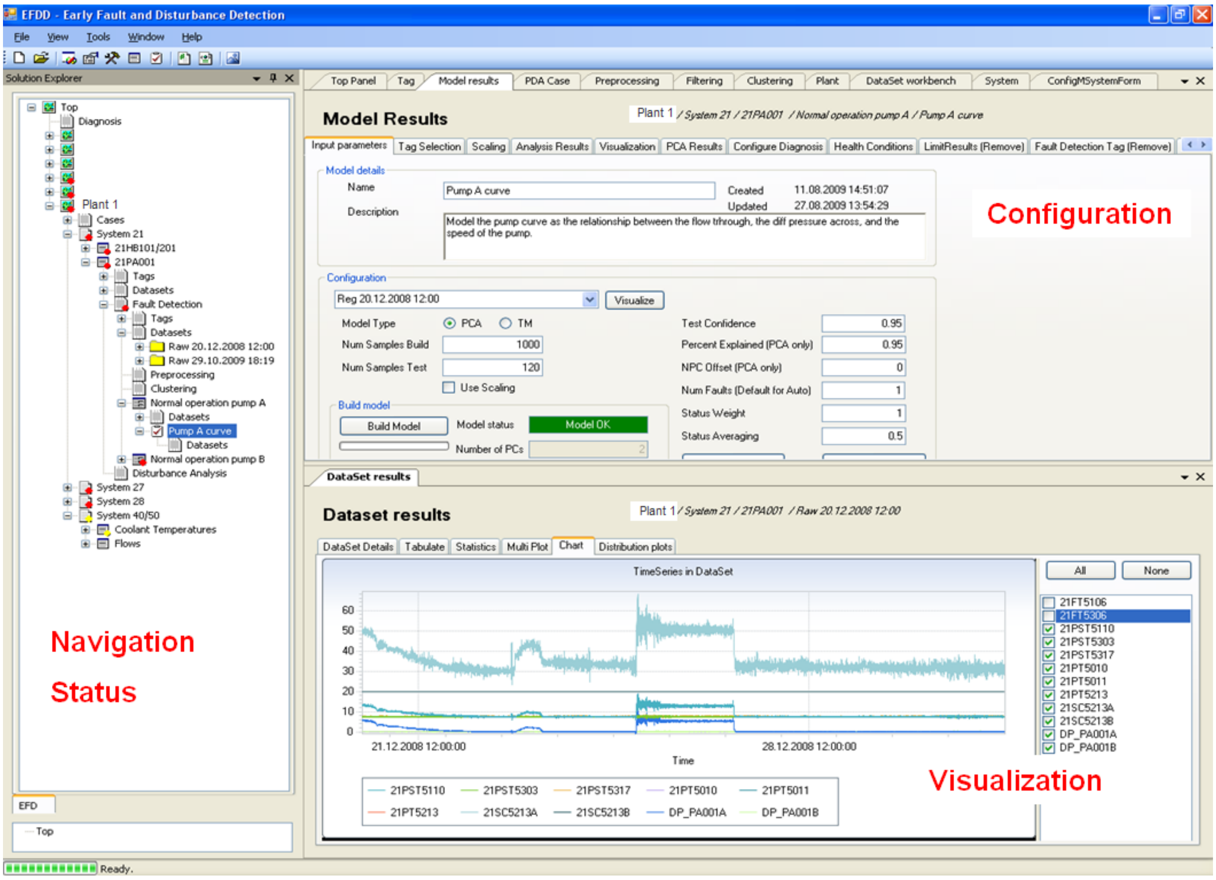
5.5 II. Early Fault and Disturbance Detection (EFDD)

Early fault and disturbance detection (EFDD) is a quantitative process history based tool. It is computer aided and is used to process data from plant components. The tool is under development, and it is part of TAIL IO, which is collaboration between Statoil R&D and the industry companies ABB, IBM, SKF, and Aker Kværner.

Statoil has a lot of data, and tools as EFDD may help to provide valuable information from the data. Processing gives a better understanding and overview of system condition. The amount of data to analyze can become vast, and it is not easy to control. One of the key motivations for EFDD has been to reduce information, as illustrated in 4.5.1, without need for system detailed input. In addition we have inaccessible systems and obscure data.

EFDD utilize the correlation between measures, meaning that processes with physical relationships monitored by sensors may be of interest. A pump may be an example, where it is an obvious relation between pressure, flow, RPM and power. EFDD has the ability to detect deviations from a defined normal operation and real time process using Principal Component Analysis (PCA). In addition, EFDD can look at different sensors trough a process and determine where a fault is accruing using Plant wide Disturbance Analysis (PDA).

Lunde [42] has published a general overview of EFDD, and an example of a screenshot from the program is given:



Plant 1 / System 21 / 21PA001 / Normal operation pump A / Pump A curve

Name: Pump A curve
Created: 11.08.2009 14:51:07
Updated: 27.08.2009 13:54:29
Description: Model the pump curve as the relationship between the flow trhrough, the diff pressure across, and the speed of the pump.

Reg 20.12.2008 12:00
Model Type: ● PCA ○ TM
Num Samples Build: 1000
Num Samples Test: 120
☐ Use Scaling
Model status: Model OK
Number of PCs: 2
Test Confidence: 0.95
Percent Explained (PCA only): 0.95
NPC Offset (PCA only): 0
Num Faults (Default for Auto): 1
Status Weight: 1
Status Averaging: 0.5

Plant 1 / System 21 / 21PA001 / Raw 20.12.2008 12:00

☐ 21FT5106
☐ 21FT5306
☑ 21PST5110
☑ 21PST5303
☑ 21PST5317
☑ 21PT5010
☑ 21PT5011
☑ 21PT5213
☑ 21SC5213A
☑ 21SC5213B
☑ DP_PA001A
☑ DP_PA001B

Figure 36 Screenshot of EFDD tool[42]

EFDD has a hierarchical functional structure, which means that a plant is broken down to systems functions and sub systems functions. This provides a great overview of the plant. Fault indications are shown all the way to the top level with a red dot. This can be seen in the navigation status in Figure 36.

Models are made in the configuration menu. EFDD consists of two different modules. Fault Detection and Plant Wide Disturbance Analysis. The fault detection module uses either PCA model or a Tag Monitoring (TM) model. Regimes are made to represent a normal case, and process data may be compared. It is also possible to visualize the different tags data sets. A view of the correlation between the different tags can also be visualized (not shown).

Meland [6]describes an intuitive waterfall model of EFDD shown in appendix IX. He also describes the different modules in the program and a case example. References are given to underlying theory of program functions, like PCA and Plant wide Disturbance Analysis (PDA).

5.5.1.1 Principal Component Analysis (PCA)

PCA can be seen as a black-box model, which means that it is possible to extract useful information from a process, without knowing all the details. It describes the real process, which is great for comparison.

Michelsen describes PCA:

> *Principal Component Analysis (PCA) and Projection to Latent Structures (PLS) are two common multivariate SPC methods. The main objective with these techniques is to transform (by projection) correlated data into a fewer number of relevant uncorrelated variables to monitor. By projecting new observations onto the plane defined by the PCA variables (called loading vectors), multivariate control charts based on Hotellings T2 statistic can in turn be plotted, and a decision can be made whether the observation is normal or not.*

First off all, the algebraic mathematics governing PCA will not be explained here. This can be found in a numerous of articles. For example [43]. The main interest is to get an understanding of what PCA is, and use of PCA trough EFDD.

PCA require a linear relation between the measurements, or at least approximately linear. Nonlinearity can be compensated by the use of regimes. Kernel PCA has also the ability to compensate for nonlinearity, but is not part of the program at the time being.

5.5.1.2 Tag Monitoring (TM)

The tag monitoring models are used to monitor a simple tag. It looks at mean value and deviations. Basically the tag needs to operate within preset limits. It is related to statistical process control given in the pipeline example 4.2.4. It is used for tags within small operating ranges.

Virtual tag is a feature in EFDD, which makes it possible to make tags which consists of four tags[25] and operators like +,-,*,/.

5.5.1.3 Plant wide Disturbance Analysis(PDA)

PDA is the diagnosis part of EFDD, and is often used in control loops, and detects oscillations and localization of contributors. A control loop ensures that a certain variable is kept within limits, for example motor speed by a governor. Different loads, inputs etc. may cause different oscillations.

It investigates upsets and disturbances in processes. Lunde summarize PDA significance for the following reasons:

- *It supports the control engineer in making a rapid and semi-automated assessment of operation of the process and control systems*
- *It provides a means of diagnosing the root causes of poor performance during normal operation without taking control loops offline for special tests.*
- *It distinguishes between primary sources of disturbance and secondary propagated disturbances.*

Root cause analysis compares time delays between, or smoothening of, oscillations. Smoothening uses the phenomena that a process disturbance will smoothen out when further from the source. This may help to track down the most likely source of a fault plant wide.

5.5.2 The EFDD Process:

The condition monitoring data is acquired from a dedicated database at Statoil. By looking at P&ID's desirable tags[26] can be found and added to the EFDD database. This is shown in Figure 37. After a search in the database for the exact tag string, all the desirable tags are written down in a file. When the database is updated, the tags are available in the program, and can be added as datasets[27].

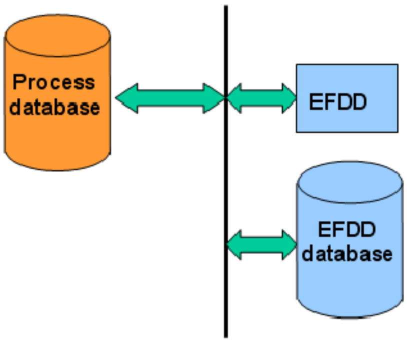


Figure 37 The system's three main components

When the data is in the program, fault detection or plant wide disturbance is chosen. In the fault detection module, pre processing and clustering are available before making a regime. Pre

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[25] It is however possible to add virtual tags into a virtual tag, meaning that there is no theoretical limit, rather a practical.

[26] Unique identification labels for components, instruments etc.

[27] A dataset is raw data from the chosen tags

processing can manipulate data or apply different filters. It is also possible to create virtual tags. This is a tag that can be dependent on other tags.

A fault detection model is then made by defining a regime. A regime is a representation of a PCA model within a certain range, and restriction of certain variations in data. A regime uses selected data in order to generate a model. The data is gathered from process history, and a fault detecting model needs fault free input data.

If the physics of the actual process is non-linear, it is possible to add several simple regimes within certain boundaries to counteract. This is required because validity and applicability is limited to linear processes. This is illustrated in Figure 38. Two different regime models are applied in two different operating domains. It is easy to see that a single domain covering the whole process would be a bad representation of physical coherence.

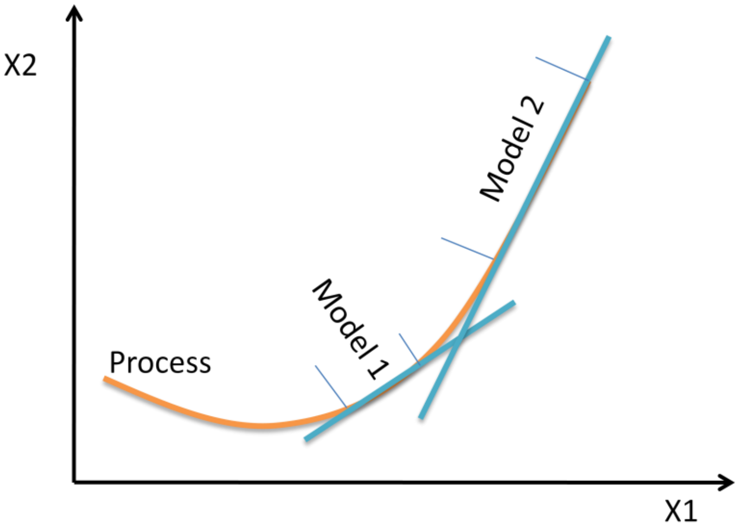

Figure 38 Compensation for PCA linearity using regimes

A regime may allow all data from the dataset to pass, define a boundary where a certain percentage of the data is within, or it may be defined by standard deviations. An example of the relation between two different measurements is given in Figure 39. As shown, the boundaries are defined by standard deviations. If data from the process exceeds the given limits, a deviation or fault contribution may be indicated. Weighting and sensitivity can be adjusted, which is a very important part of the modelling. Skill is needed to be able to get sensitive detection of faults and to avoid false alarms.

Figure 39 represents the mean value of the dataset in the middle, the regime axes are Y1 and Y2. Y1 represent deviation and Y2 the principal component coherence. The standard deviations represent the allowed data within the regime it may be given by a percentage. When comparing with process data, correlations outside the defined regime will give a system alarm. It is possible to add features like delay to require that the process is outside the defined regime for a certain time.

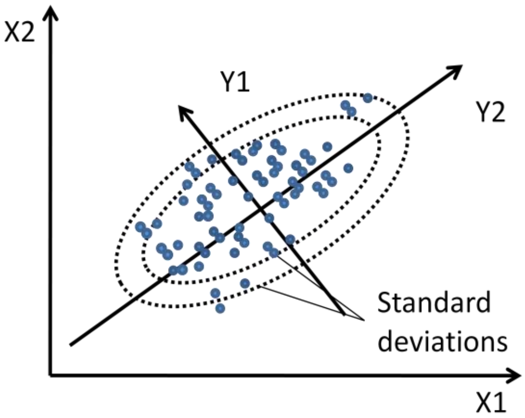

Figure 39 Defining standard deviation limits between two parameters

For representation purposes relations are given between two parameters. It is of course possible to add multiple correlations. Example of a three dimension correlation is given in Figure 40.

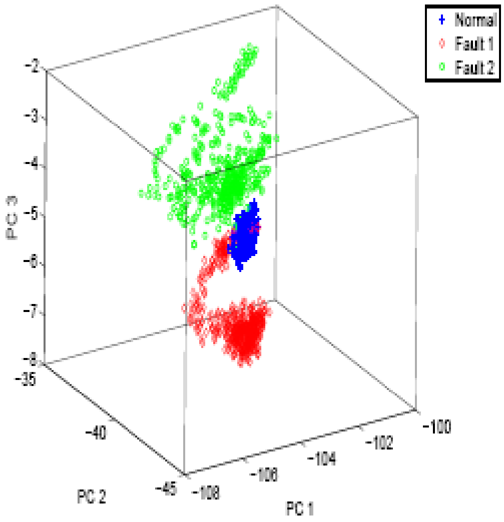

Figure 40 Three dimensional correlation between process parameters [21]

EFDD also had a diagnose feature using PDA. When utilizing PDA, there are four main steps needed for the analysis:

- Data Pre-processing
- Filtering
- Clustering
- Root cause analysis

As explained by Meland [6], data pre processing is similar to the fault detection module. After choosing tags and intervals, data is compressed, and frequency spectra are calculated. In the filtering part, disturbances can be removed to isolate certain frequencies. Clustering of groups of data is based on oscillation periods in the frequency spectra, or identification of groups with similar power spectra. And the Root Cause Analysis finds the most probable source of disturbance in each of the clusters discovered, by oscillations, time delay or transfer entropy.

The PDA part of EFDD was not used for subsea leakage detection diagnosis. The subsea control system is an open loop system. This could however be interesting for a pipeline, with the method defined as acoustic/negative pressure wave in 4.2.2.

5.5.3 Subsea Control System and EFDD using The Fault Detection Module.

When using PCA trough EFDD, it was not as easy to apply it to the chosen process data. Even though a fair understanding of EFDD was obtained, the fact that the author is an aspirant within the field may be a cause in itself, which should be accounted for.

The problems encountered made it difficult to exploit EFDD potential, and utilize it towards subsea control system. Main problems:

- There are relative few tags available with strong correlations between each other. This makes it difficult to analyse correlations between parameters. System components like pipes and accumulators smoothens signals, affecting relation, and repeatability dependent on operation.
- It is highly nonlinear processes. It is a challenge choosing reasonable models, data and ranges. This is why sound knowledge of process is the basis for application of models and tools, as illustrated in Figure 31.
- Processes may have large time delays between dependencies of variables.
- Lack of operational data available made it difficult to find relations, and utilization of the steady state relations found.

<u>KPI/TCI using Tag Monitoring (TM):</u>

Another idea was to use tag monitoring in the fault detection module. A comparison of the amount of fluid entering the system and leaving the system could be established. This could be done by summarizing all the flow meter tags in the SCM and compare it to tank level changes. This would be compensated by an estimate for normal leakage rate. The idea was to calculate consumption and look at drift over time. If the parameter exceeded certain limits, an alarm would be generated. Not every exit point had flow meters as stated in 5.3.2. In addition the sensitivity of the meters was poor, so it was rejected.

Additional ideas were generated, and example of ideas can be found in 5.3. Because limited possibilities to manipulate the virtual tags, they were not possible to execute. The possibility to do some more advanced calculations here concerning the virtual tag would be desirable. The tag monitoring function has a great potential towards monitoring of KPIs/TCIs. TM would also visualize trends in the virtual tag. An idea could be to add this possibility.

As mentioned in 4.5 no method has all the desirable features. Since the intention with EFDD is to act a single tool for the operator towards monitoring, it would be an advantage to add simple qualitative possibilities. It would however conflict the interest of a purely quantitative approach.

5.6 II. Simulation X -An approach towards Qualitative Method

Venkatasubramanian et al [38] describes simulation as the inverse of diagnosis. While the main function of simulation is to represent the true nature of a process, diagnosis is concerned with the deducting structure from the behaviour. It is also the opposite of the quantitative EFDD approach.

Evaluation of programs criteria for transient behaviour, such as changing Reynolds numbers has not been done, but would be an important part of a program evaluation.

Even though, a simulation model can help us provide a basis for cause and effect relationships changes. Especially when process history is dependent of a variation of process input, so that cause and effects are not consistent each time, which was a problem encountered in 5.5

The reason for looking at simulation has three main reasons:

- Learning effect
- Sensitive
- Available

First of all, simulation of systems gives insight to the underlying physic relationship. Sometimes when looking at real process history data, the process has too many dependencies, so that it is difficult to extract clear physical relations. The system provides learning capabilities. “How does it work?”, “What happens if...?”. This provided knowledge of system behaviour.

In addition, a good simulation model could be very sensitive to leakages in the system, providing faster and better quality of detection, especially during operation. In addition no prior knowledge about the faulty behaviour of the system is needed. At last, simulation programs and computers are available, and system models may already been made in the design stage of development. A problem which seemed impossible decades ago, or at least extremely time consuming, is now done in seconds. The making of the model would however be time-consuming.

Sometimes when simulating, is preferable to describe the system from basic relations. The bond graph method is one method to extract physical connections by differential equations of motion from a system. One of the main advantages with this method is the close connection between a system and its creator. In a systematic manner, effort or flow out of “junctions” is defined building up a model. Lots of literature related to bond graph modelling is available. Simulation tools are available having bond graph input possibilities. 20sim by Controllab Products is an example. It is, however, a time consuming process to define physical relations from scratch.

Today, dedicated user friendly tools may be available. This makes system modelling much easier than before. This is the main reason for choosing Simulation X by ITI Germany. The product has a dedicated subsea control system library made by Agito AS. Here it is possible to “drag and drop” desired components into the model and then define their properties, for example a HPU.

It is important to remember that the model is not better than the ones who made it. By handing over basic modelling to software providers, control of basics is somewhat lost. On the other hand, simulation software suppliers may add confidence, having verified their basic models, and being able to determine accuracy of the model. In this thesis the emphasis has not been laid on program documentation, but rather possibilities and limitations of use. It is however important to be aware. Limitations will always apply. A model is not the reality, and comparison with logical reasoning is important. One should always be critical. As it was said in [44]

> *Inaccurate simulation of the equations of a useful model is better than an accurate simulation of a poor model.*

Data was not available before later in this project and Simulation X provided understanding of system behaviour before looking at process data. A model was provided by Rune Lien at Agito AS. The model is given in appendix VII-CD. A similar model was also made from scratch. It was relative easy to build the model, but to get all the data input right was not. Even though this program makes it simpler to model the subsea system, still a lot of input is needed. This confirms the statements given in literature on the use of qualitative approaches, and discussed in 4.5.

Main drawbacks:

- Making a good model
- Limited adaptability

Generally a considerable effort is needed to make a good model. A large amount of input is needed, and all the influences are normally impossible to account for. In addition, the complexity of the system may become a limitation. This means looking at simplified subsystems, instead of complete systems. This might impose difficulties when actively comparison towards a real process is initiated.

Simulation models also have very limited adaptability. A perfect model on one system will be useless on another, even though some parts may be re-used and knowledge may be transferred.

5.6.1 Subsea Control System and Simulation X

The library explorer in the program contains all the defined physical components. As seen in appendix VII-A the subsea library is opened, showing the defined subsea components. To add the components they are simply dragged and dropped into the model window. When added to the model window, the components are easily connected by the click and drag.

The next step, and challenging step, is to add the data input. As an example HPU input are shown in appendix VII-B. To the left the HPU is marked, meaning that it is the one being displayed. The other components shown below will also need to be defined. The upper right window show some of the input needed for the HPU. The right lower window shows some possible output parameters from the HPU.

When all input is defined, it is possible to confirm an analysis. The details of the different analysis approaches and configurations are not given here. The analysis executed was done on default program settings provided by Agito, and manipulation of these. As mentioned the analyses was primarily used for learning purpose, and not for used comparison with a case data.

Rune Lien wrote an article [45] which goes through the different elements in the simulation model.

5.6.2 Use a Combination of Methods?

A requirement when designing subsea systems is that a response analysis has been carried out. The supplier, for example FMC Technologies, provides this information to Statoil. FMC Technologies uses a program called HYSDSIM by AVL. The fact that models are made when system is designed is important. An idea is that these models could be integrated and used for learning and understanding for the operator as well. In addition, this could be the basis for a condition monitoring model based approach[28]. This way one could kill two birds with one stone.

In addition to the physical understanding of the system, the comparison between a real process and a physical model could be interesting. By providing real process input to a model parallel to the real process, it would be possible to compare expected output with actual output. These data streams could then be input to EFDD for comparison (PCA), and deviation (TM).

This is not a new concept; there have been several studies for utilizing white box models, in addition to PCA. This may be referred to as model-based PCA, or MBPCA. In [46]the ability of MBPCA was confirmed using a simple model on an ethylene compressor. The following Is also concluded[46]:

> *MBPCA can deal with batch[29] processes, since the method is robust to a different batch length, and nonlinear processes, since it can handle the nonlinearity in the process, and it's relatively insensitive to changes in the operation point.*

A model parallel to the process could be used to describe the normal behaviour. If a leakage happens, it is detected by mismatch between the two. An example is shown Figure 41. The simulator models could also provide estimated tags. This could provide interesting information based on process input. If a sensitive and accurate model was available, the general sampling interval of 1 minute middle as stated in Subsea Information Flow (3.3.3) is clearly insufficient. This of course represents an ideal case.

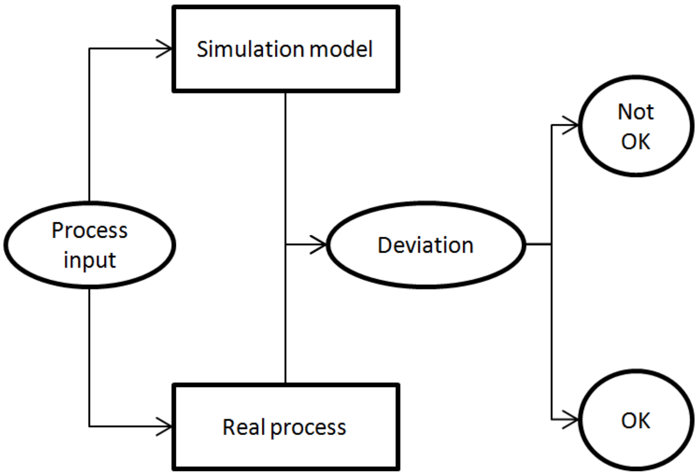

Figure 41 A simulation model in parallel with the real process

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[28] When both the real process and the model are available, one of the main advantages seen by Rune Lien was the ability to tune the model by real process data. This could provide very accurate models.

[29] Batch means a group of data that are dealt with at the same time. These batches are the root for comparison in PCA. Batch length was also considered a problem for purely PCA analysis (5.5.3)

5.7 III. Solution Proposal

This proposal for solution for subsea leakage detection and diagnosis is a result of the strategy given in 5.1. The reason for seeking a solution to the problem is that it triggers solution-oriented thinking, which may be valuable for Statoil. In addition it communicates the author's opinion. Of course some may disagree, which is preferable. A discussion will normally intercept weaknesses, and amplify the advantages. This is why this chapter is a solution proposal and not a solution. The proposal is based on the information and experience gained through this thesis.

The proposal is divided into three parts. First of all it considers what should be done today, which is considered bottom line. Here all the information is available. The proposal only requires a verification and implementation.

Interesting points of view for tomorrow and the future is given.

5.7.1 Today

Today, almost no dedicated monitoring of subsea control system leakage exists. The constant need for filling of topside tank has been mentioned. As stated in 1.2, there tends to be a connection between warning time and complexity. The same can be said to yield within leakage, with a twist. There tends to be a connection between performance and complexity. For today's solution it would be preferable to scarify some overall performance for simplicity, considering the alternative.

The proposal is highly connected with comments in 4.4.2 and observations in 5.3.

Is it possible to detect leakages in the SCS?

It is possible to tell which tree is leaking?

Leakage detection has been the main focus for the solution proposal, as detection is done prior diagnosis. It should be mentioned that looking at process data should not be underestimated; findings by looking at process data are very useful. It may also be a great advantage when considering quantitative statistical methods in EFDD. It is an advantage to know what we want to extract.

When talking about SCM pressures and flow, the main motivation is isolation of leakages, or leakage diagnosis.

In 4.1 it was stated that a leakage may be in the order of 30 litres an hour before being detected, and leakages of 3-4 litres would most likely not be detected at all, which is equivalent to 50% increase of the normal leakage rate.

Monitoring using subsea flow meters was turned down due to sensitivity and uncertainty issues as stated in 4.4.2.

In 5.3.1 Figure 34 show an illustration of system influence when operating a valve. It shows where the system enters a dynamic state and where it leaves. For the SCS operations are rather seldom. Therefore the system will enter a steady state most often after operation. As stated in 3.3.6 it might take at least an hour before the system has reached steady state after operation.

There is an endless amount of operating combinations which would generate different shapes on the in the accumulator skid pressure. Monitoring frequency of pump runs without regarding operation would cause many false alarms, and thereby destroy reliability of the method.

Operation is the largest contributor to system variations and should of course be considered when looking at process data. This information is also available. In the excel sheet presented in 5.4 the operation data was gathered. This implies that there is a solution for this problem.

Information needed:

1. Accumulator skid pressure.
2. Operations.

How can we use this information to detect leakage?

1. By monitoring the slope of the accumulator skid pressure.
2. Compensate for the operations when entering transient state.
3. Measure changes in accumulator skid pressure slope during steady state.

This is illustrated in Appendix VI B, and commented in 5.3.2 B. To refresh the memory, the pressure would not keep falling if there had not been any leakage in the system. An additional leakage would make the pressure drop faster. But every now and then the process is operated, and the pressure rapidly decreases. When an operation was executed the leakage detection was ignored for an hour or so. This way the steady state was the only one being considered for leakage.

If looking at Appendix VI B clearly linear slopes appear between dynamic variations. This is the steady state. A method for implementation of this proposal is not evaluated, since difficulties were encountered when using the methods. However, it should be possible to use statistical methods when compensated for operation.

Both the accumulator and the operational data could be input to a statistical tool as EFDD. This could be done by looking at relations of operation and accumulator pressure, and adding a certain delay. This would require Norne SCS operation as one tag, or it could be provided in terms of a TCI/KPI. EFDD could be used if the tag monitoring feature was expanded.

If this information was available, it would look like Figure 42. Notice that it would also give a diagnostic indication of probable cause.

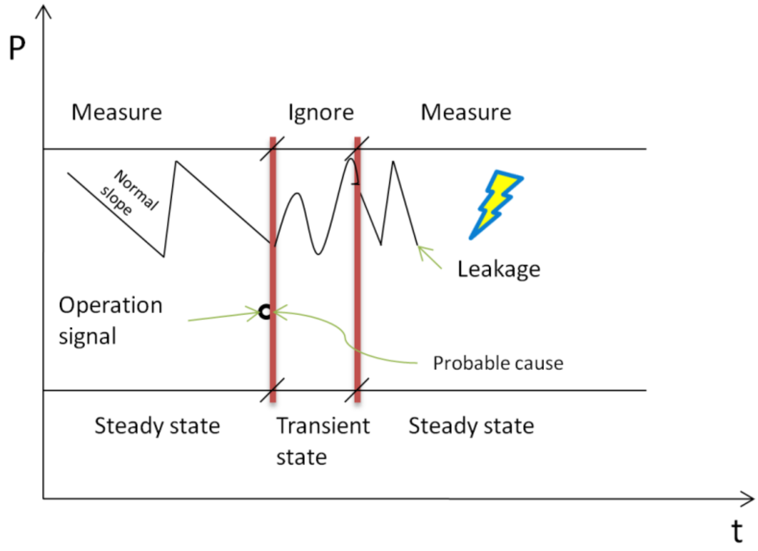

Figure 42 The solution proposal for a SCS leakage system.

Why to use this proposal:

- Simple.
- Data is available.
- Detect leakages which today are not detectable[30].
- Diagnose a probable cause.

And some detailed benefits:

- The method could also identify pump condition based on time used filling the accumulator skid.
- To parallel tags are available for sensing accumulator skid pressure, this could be used to increase measurement reliability.
- Only a few tags needed topside in addition to operational data. Input of valve consumptions could be left out.
- Completely adaptable.
- In addition, the time used filling up the accumulators can be an indication of pump condition.

Why not to use this proposal:

- Need for systemization of operational data.
- Reduced performance of leakage detection compared to other methods.
- Poor diagnosing feature compared with other methods.

An important concern is that 5.3.2 E states that a time of six hours is passed before the process enters steady state, compared to the anticipated time of one hour stated in 3.3.6. This would surely affect performance of this proposal. Further investigation is needed to reveal cause.

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[30] A leakage rate of 3-4 litres, or referred to as a change of 50%.

In addition, the behaviour of multiple wells connected together in series and parallel was not so clear as the Alve isolated case, discussed in 5.3.2 F.

5.7.2 Tomorrow

If proposal today was a verified success, it should be implement for all SCS. One of the advantages with this method is that it requires no adaptation, even if using KPI/TCI.

Tomorrow it would be interesting to look at possibilities to add topside wireless sensors discussed in 4.4.3 for additional performance of proposal for today, including pump degradation.

Further investigation of SCM inlet pressure as discussed in 5.3.2C, for possible isolation of leaking Xmas tree, providing better diagnosis.

5.7.3 Future

In the future it might be interesting to utilize simulation models made when designing the SCS. These models could be used for condition monitoring purposes, in parallel to the process as discussed in 5.6.2. This would enable detection and diagnosis during transient, and generally improve performance. Sampling rate of today's instrumentation will need to be increased.

6 Conclusion

Monitoring of subsea control systems is very scarce and has a great potential for improvement. State-of-the-art within leakage detection and diagnosis is monitoring of pipelines, and the methodology is directly applicable to subsea installations, though they have distinct differences.

Monitoring and storing of operations is a key issue towards monitoring of a subsea control systems. Any approach for a leakage system requires data, knowledge and an applicable method. Knowledge can be acquired by learning system basics, simulation and to look at history process data. No method has all the benefits, and a combination of methods has shown great potential from pipelines.

A solution proposal given has potential to discover leakages which today would be overlooked, and indicate a probable cause. All the data for detection is available. Operational data is however not integrated, but the excel sheet from Norne demonstrates that this is possible. A deviation between response analysis and discovery is however a concern, and application towards multiple well umbilical supplies.

Possible improvements exist by adding other parts of the system and additional instrumentation topside. A notable future proposal is to utilize design models for operational purposes. It tends to be a close relation between simplicity and performance. A simple approach would therefore be first priority, laying the basis for further development. The solution proposed for today is therefore recommended.

7 Further Work

- Organize information. Make operation data available parallel to process data, as demonstrated in the excel sheet from Norne, and illustrated in Figure 42. This would be beneficial both for operators looking at process data, and in a leakage system.
- Evaluate whether to expand the virtual tag in EFDD, for monitoring of KPI/TCI.
- Explain why there is a five hour time difference between response analysis and discoveries.
- Establish a case to verify benefit of solution proposal. Evaluate what methods to use for implementation, effect of implementation and possible improvements. Consider implementation.

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Svein Åge Holen	Statoil ASA Stjørdal
Guttorm Røed	FMC Technologies Ågotnes

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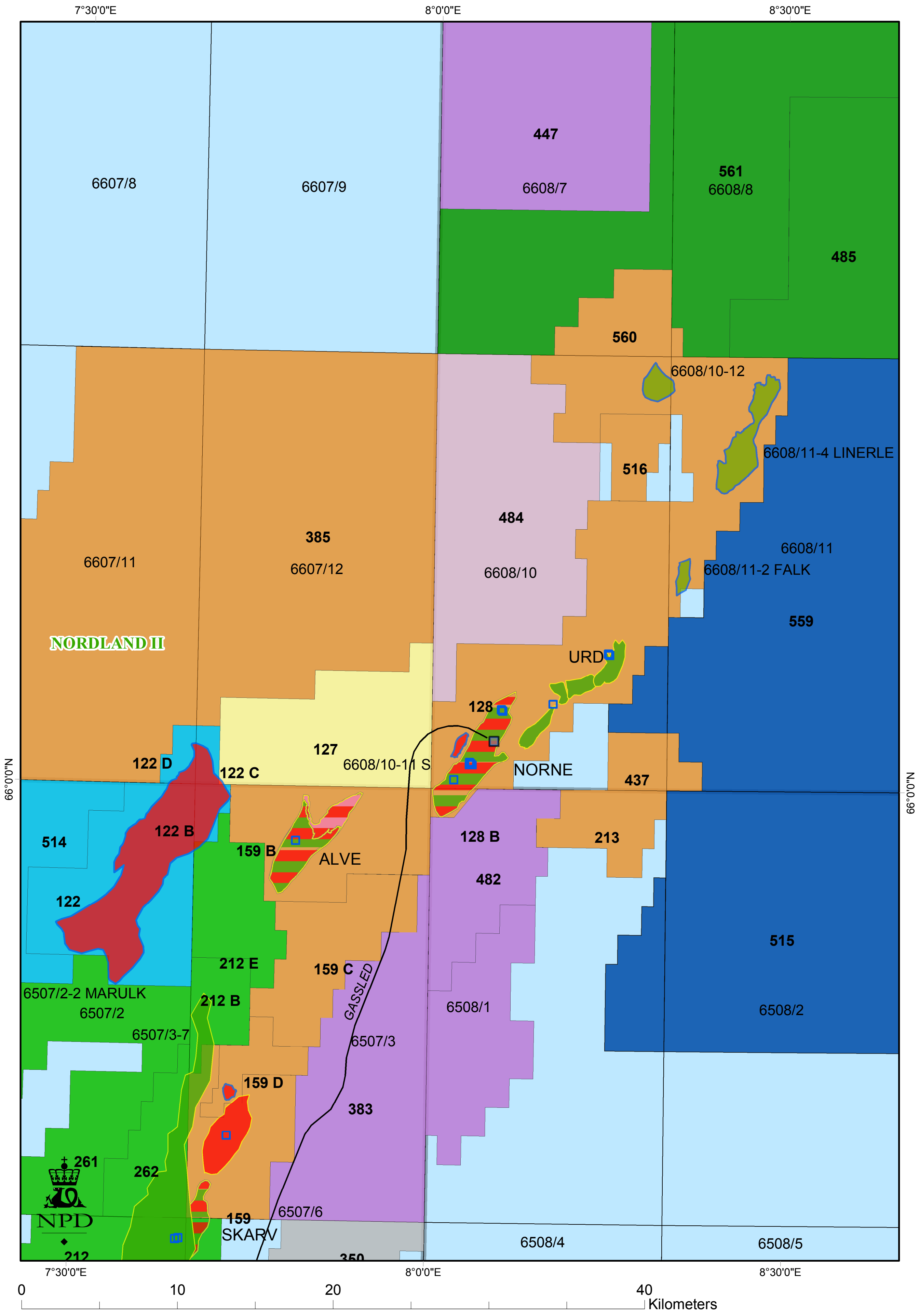
http://www.npd.no/factmaps

For map as WMS check http://npdwms.npd.no



Legend of the http://www.npd.no/factmaps

Development

Wellbore

- ● Production-oil
- ☼ Production-gas
- ✪ Production-gas/condensate
- ☼ Production-water
- ○ Production-not available
- ○ Production-not applicable
- ⊗ Observation
- ☼ Injection-gas
- ☼ Injection-cuttings
- ☼ Injection-water
- ● Injection-CO2
- ○ Injection - not available
- ○ Injection-not applicable

Exploration

Wellbore

- ● 0
- ⌖ Dry
- ● Oil
- ☼ Gas
- ☼ Shows
- ✹ Oil/Gas
- ✪ Gas/Condensate
- ○ Not available
- ◉ WILDCAT
- ◉ APPRAISAL
- ■ *Facility -* Surface
- □ *Facility -* SubSurface
- — *Facility -* Pipelines

Fields

- 🟩 Oil
- 🟥 Gas
- ▨ Oil w/Gas
- ▨ Gas/Condensate

Discoveries

- 🟩 Oil
- 🟥 Gas
- ▨ Oil w/Gas
- ▨ Gas/Condensate

- ▨ Area with stratigraphic licencing

Production licences

- ■ BG Group
- 🟩 bp
- 🟫 Bridge
- ■ Centrica
- ■ Chevron
- ■ ConocoPhillips
- ■ Dana
- 🟪 Det norske oljeselskap
- 🟨 Discover
- ■ DONG
- ■ E.ON Ruhrgas
- 🟦 ENI
- 🟩 Enterprise
- 🟥 ExxonMobil
- ■ GDF SUEZ
- ■ Hess
- ■ Idemitsu
- ■ Lotos
- ■ Lundin
- ■ Marathon
- 🟨 Mærsk
- 🟧 Nexen
- 🟫 Noil Energy
- ■ Noreco
- ■ North Energy
- ■ OMV Norge
- 🟥 Petro-Canada
- 🟫 Premier
- ■ Repsol
- 🟦 Rocksource
- ■ RWE DEA
- 🟩 Shell
- 🟧 Statoil
- ▨ StatoilMærsk
- ■ Talisman
- 🟨 Total
- 🟫 VNG Norge
- 🟩 Wintershall
- □ No operator
- ▨ Seismic areas

Faults and boundaries

- — Oceanic magnetic anomaly
- — other
- - - International Borders
- — Boundary of Tertiary lavas ("Inner flows")
- — Faults
- — Other Geological Boundaries
- — Subcrop of base Cretaceous below Quaternary
- — Subcrop of top Basement below Quaternary

Structural elements

- ■ Cretaceous High
- ■ Deep Cretaceous Basin
- ■ Marginal Volcanic High
- ■ Palaeozoic High in Platform
- ■ Platform
- ■ Pre-Jurassic Basin in Platform
- ■ Shallow Cretaceous Basin in Platform
- ■ Terraces and Intra-Basinal Elevations
- ■ Volcanics
- □ Blocks
- □ Quadrants
- □ Sub areas
- □ APA open
- □ Business areas
- □ *Seismic acquisition, gross area -* Planned
- □ *Seismic acquisition, gross area -* Ongoing
- □ *Seismic acquisition, gross area -* Paused
- □ *Seismic acquisition, gross area -* Finished
- — *Seismic acquisition -* Lines
- — *Seismic acquisition -* Lines
- — *Seismic acquisition -* Lines
- — *Seismic acquisition -* Lines
- □ *Seismic acquisition, net area -* Polygons
- □ *Seismic acquisition, net area -* Polygons
- □ *Seismic acquisition, net area -* Polygons
- □ *Seismic acquisition, net area -* Polygons

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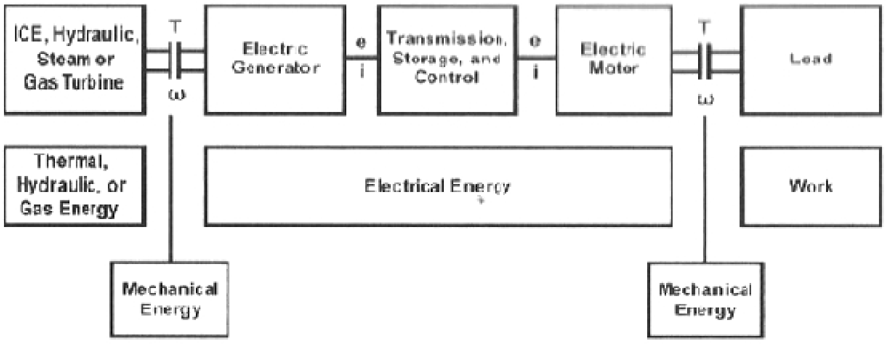
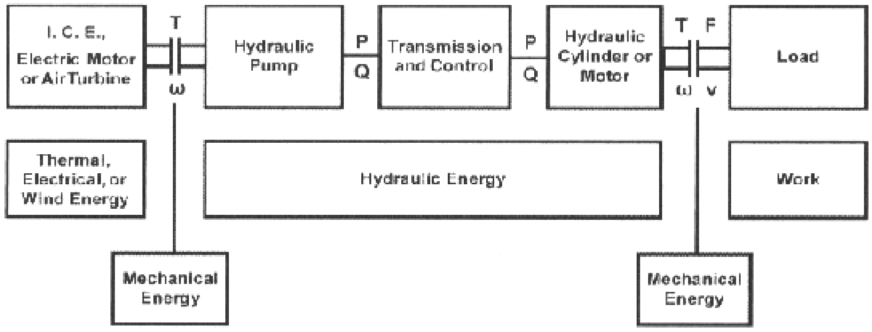
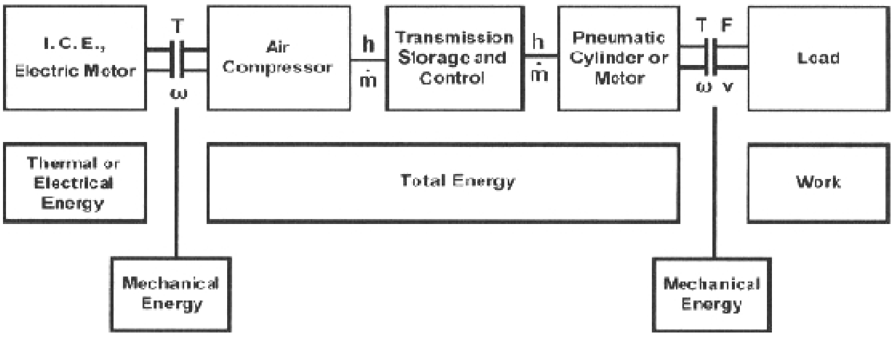

ICE, Hydraulic, Steam or Gas Turbine
T
ω
Electric Generator
e
i
Transmission, Storage, and Control
e
i
Electric Motor
T
ω
Load
Thermal, Hydraulic, or Gas Energy
Electrical Energy
Work
Mechanical Energy
Mechanical Energy


I. C. E., Electric Motor or Air Turbine
T
ω
Hydraulic Pump
P
Q
Transmission and Control
P
Q
Hydraulic Cylinder or Motor
T F
ω v
Load
Thermal, Electrical, or Wind Energy
Hydraulic Energy
Work
Mechanical Energy
Mechanical Energy


I. C. E., Electric Motor
T
ω
Air Compressor
h
ṁ
Transmission Storage and Control
h
ṁ
Pneumatic Cylinder or Motor
T F
ω v
Load
Thermal or Electrical Energy
Total Energy
Work
Mechanical Energy
Mechanical Energy

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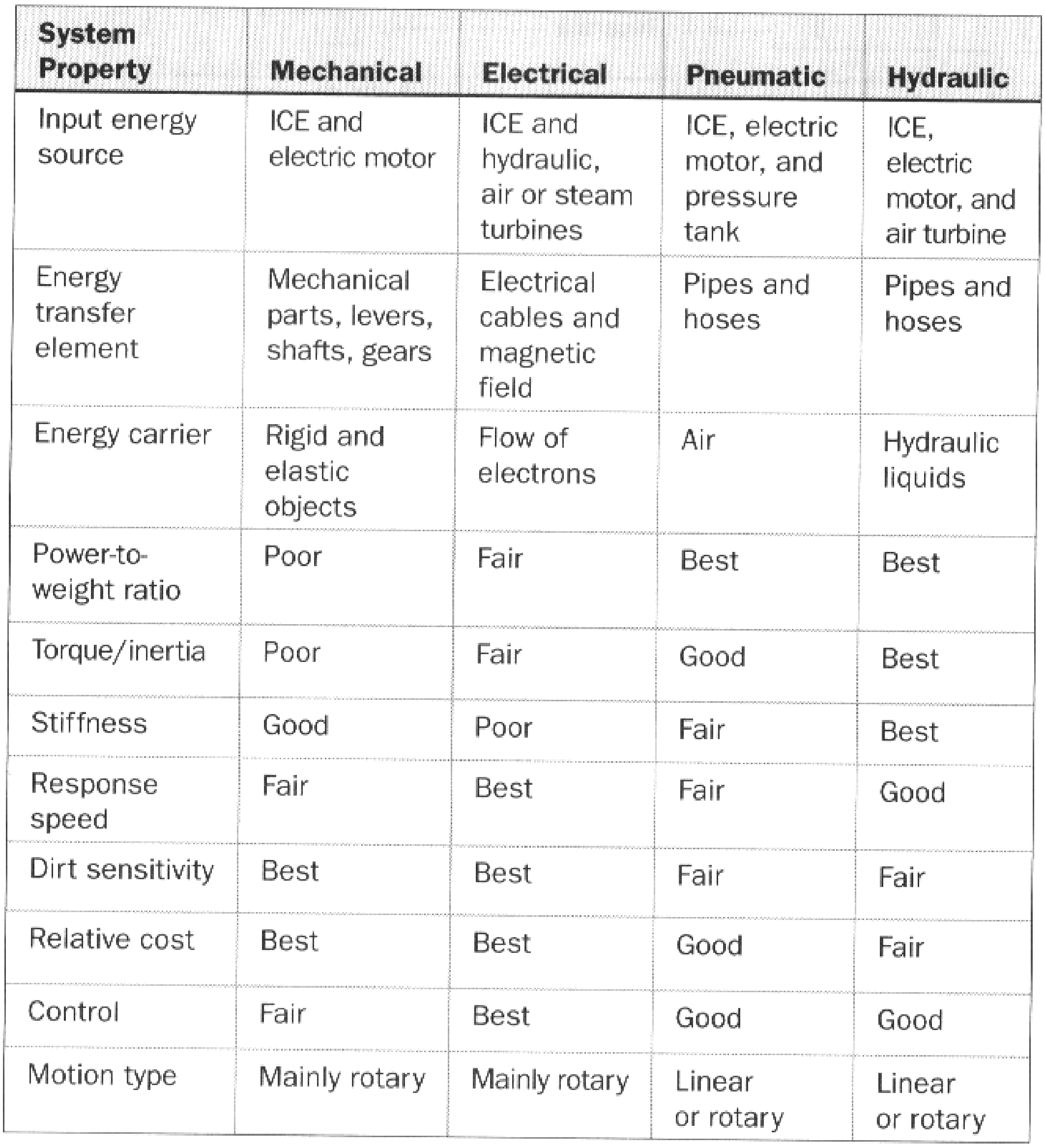

System Property	Mechanical	Electrical	Pneumatic	Hydraulic
Input energy source	ICE and electric motor	ICE and hydraulic, air or steam turbines	ICE, electric motor, and pressure tank	ICE, electric motor, and air turbine
Energy transfer element	Mechanical parts, levers, shafts, gears	Electrical cables and magnetic field	Pipes and hoses	Pipes and hoses
Energy carrier	Rigid and elastic objects	Flow of electrons	Air	Hydraulic liquids
Power-to-weight ratio	Poor	Fair	Best	Best
Torque/inertia	Poor	Fair	Good	Best
Stiffness	Good	Poor	Fair	Best
Response speed	Fair	Best	Fair	Good
Dirt sensitivity	Best	Best	Fair	Fair
Relative cost	Best	Best	Good	Fair
Control	Fair	Best	Good	Good
Motion type	Mainly rotary	Mainly rotary	Linear or rotary	Linear or rotary

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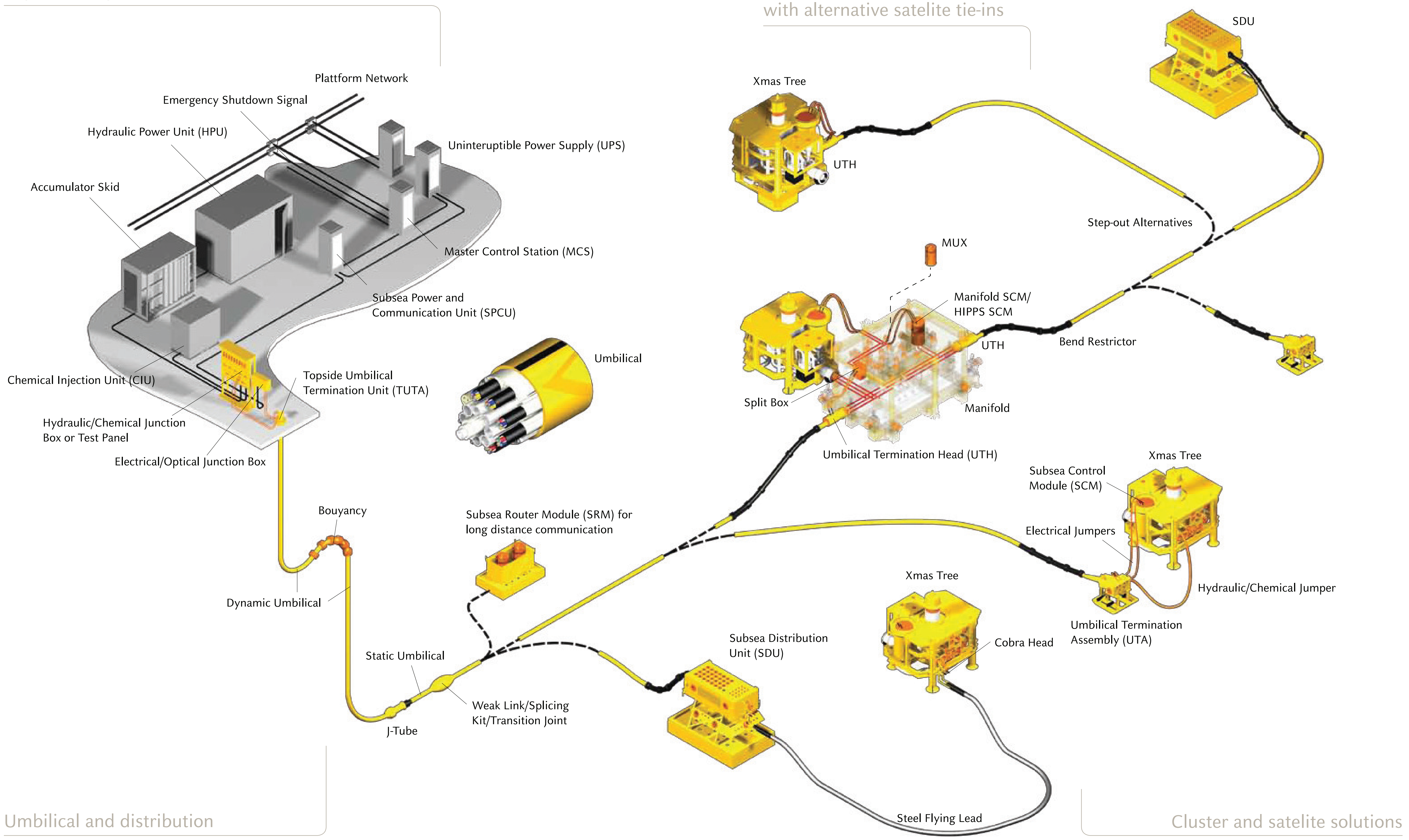

Topside components

Plattform Network

Emergency Shutdown Signal

Hydraulic Power Unit (HPU)

Uninteruptible Power Supply (UPS)

Accumulator Skid

Master Control Station (MCS)

Subsea Power and
Communication Unit (SPCU)

Chemical Injection Unit (CIU)

Topside Umbilical
Termination Unit (TUTA)

Hydraulic/Chemical Junction
Box or Test Panel

Electrical/Optical Junction Box

Umbilical

Template solutions with alternative satelite tie-ins

Xmas Tree

UTH

SDU

Step-out Alternatives

MUX

Manifold SCM/
HIPPS SCM

UTH

Bend Restrictor

Split Box

Manifold

Umbilical Termination Head (UTH)

Umbilical and distribution

Bouyancy

Subsea Router Module (SRM) for
long distance communication

Dynamic Umbilical

Static Umbilical

J-Tube

Weak Link/Splicing
Kit/Transition Joint

Subsea Distribution
Unit (SDU)

Steel Flying Lead

Cluster and satelite solutions

Subsea Control
Module (SCM)

Xmas Tree

Electrical Jumpers

Hydraulic/Chemical Jumper

Xmas Tree

Cobra Head

Umbilical Termination
Assembly (UTA)

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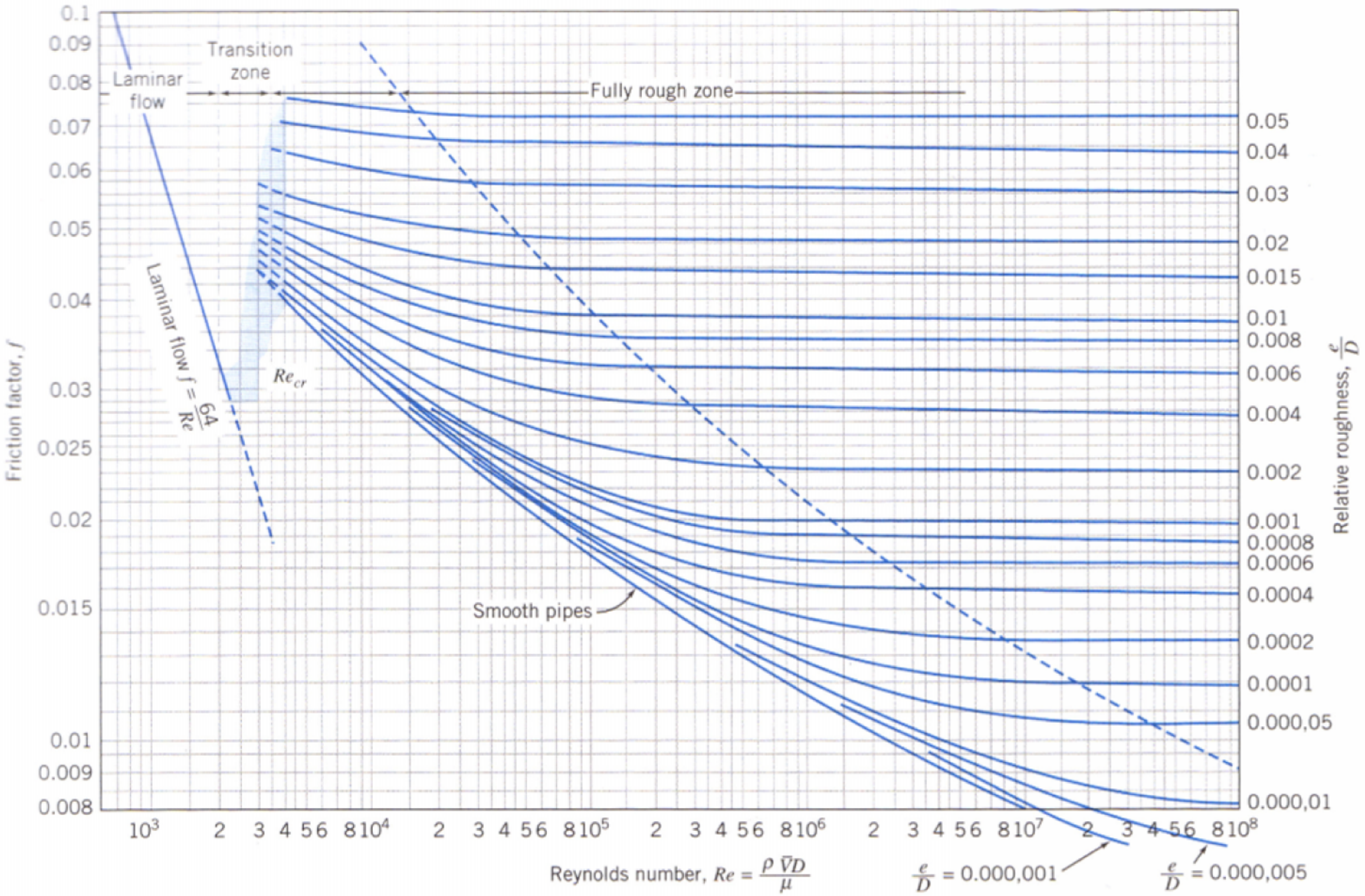


Friction factor for fully developed flow in circular pipes.

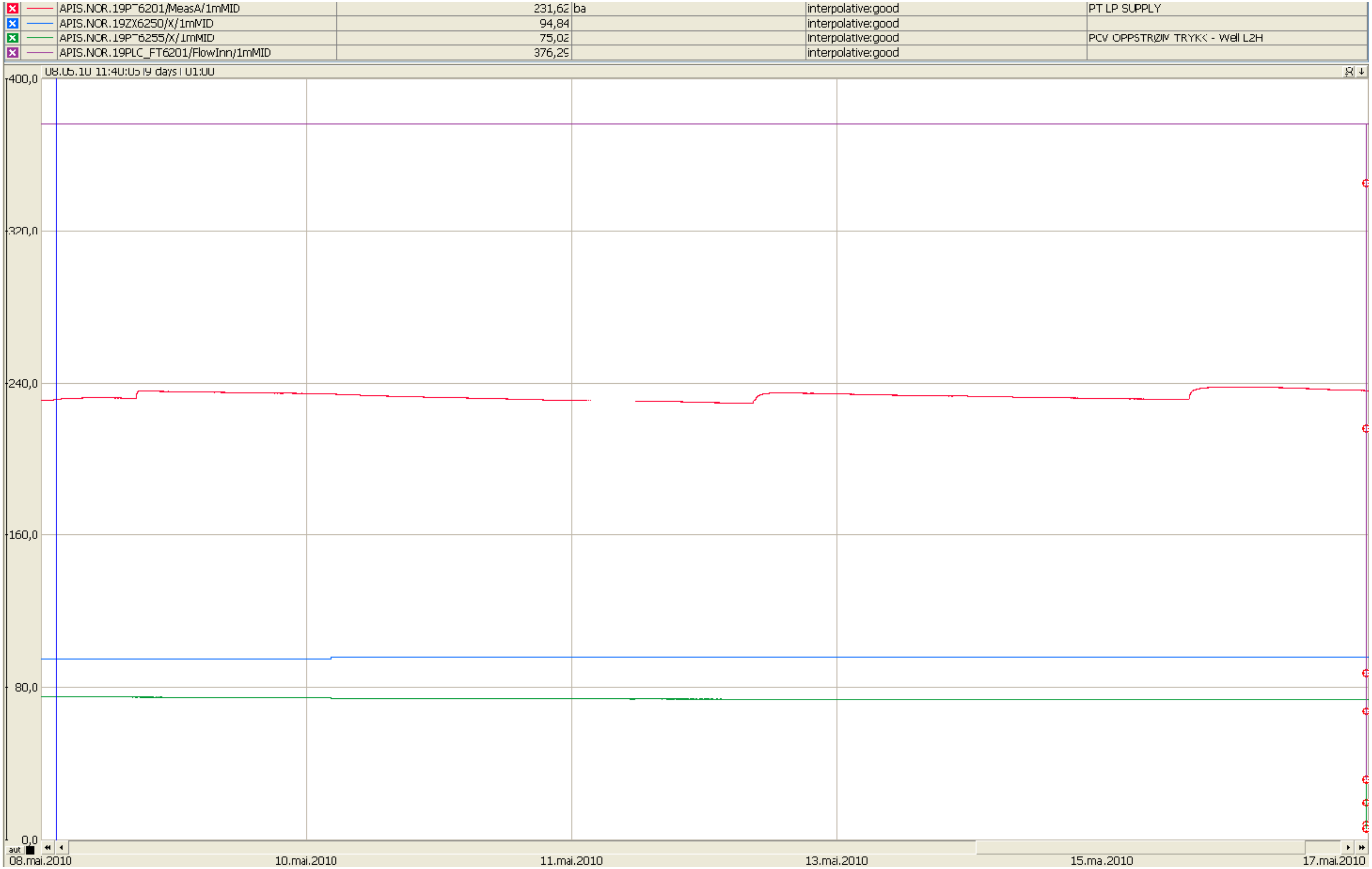
Appendix VI-A

☒	🟥	APIS.NOR.18LT4301/Meas1/1mMID	91,34		interpolative:good	Forsyningstank nivå
☒	🟦	APIS.NOR.18LT4302/Meas1/1mMID	75,8		interpolative:good	Returtank nivå
☒	🟩	APIS.NOR.18PT4201A/Meas1/1mMID	320,42		interpolative:good	Uregulert lavtrykk A

Appendix VI-B

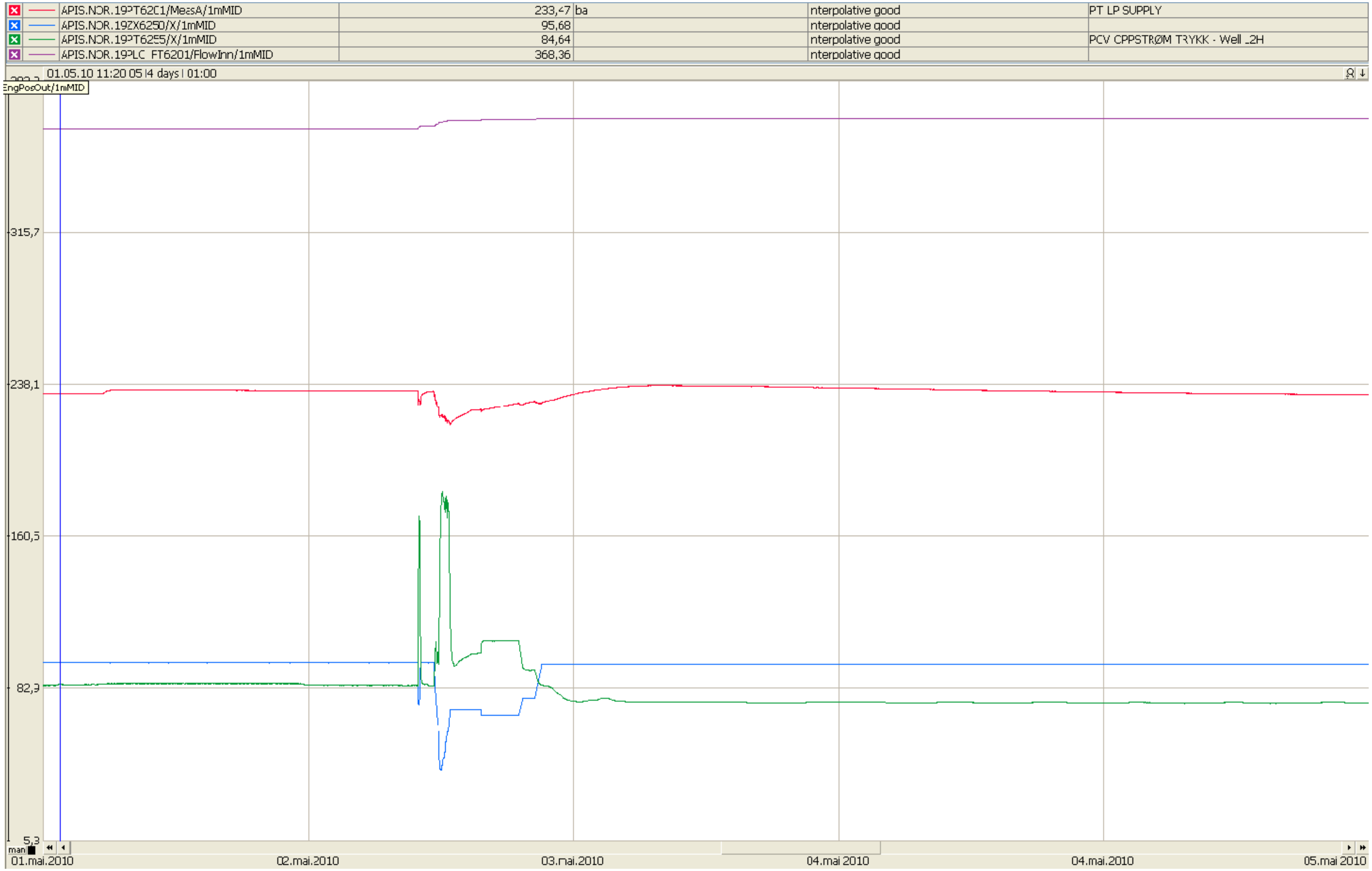
☒	APIS.NOR.18PT4201B/Meas1/1mMID	295,1	interpolative:good	Uregulert lavtrykk B
☒	APIS.NOR.18LT4301/Meas1/1mMID	71,54	interpolative:good	Forsyningstank nivå

Appendix VI-C



☒	🟥	APIS.NOR.19PT6201/MeasA/1mMID	231,62	ba	interpolative:good	PT LP SUPPLY
☒	🟦	APIS.NOR.19ZX6250/X/1mMID	94,84		interpolative:good	
☒	🟩	APIS.NOR.19PT6255/X/1mMID	75,02		interpolative:good	PCV OPPSTRØM TRYKK - Well L2H
☒	🟪	APIS.NOR.19PLC_FT6201/FlowInn/1mMID	376,29		interpolative:good	

Appendix VI-D



☒	APIS.NOR.19PT6201/MeasA/1mMID	233,47	ba	nterpolative good	PT LP SUPPLY
☒	APIS.NOR.19ZX6250/X/1mMID	95,68		nterpolative good	
☒	APIS.NOR.19PT6255/X/1mMID	84,64		nterpolative good	PCV CPPSTRØM TRYKK - Well _2H
☒	APIS.NOR.19PLC FT6201/FlowInn/1mMID	368,36		nterpolative good	

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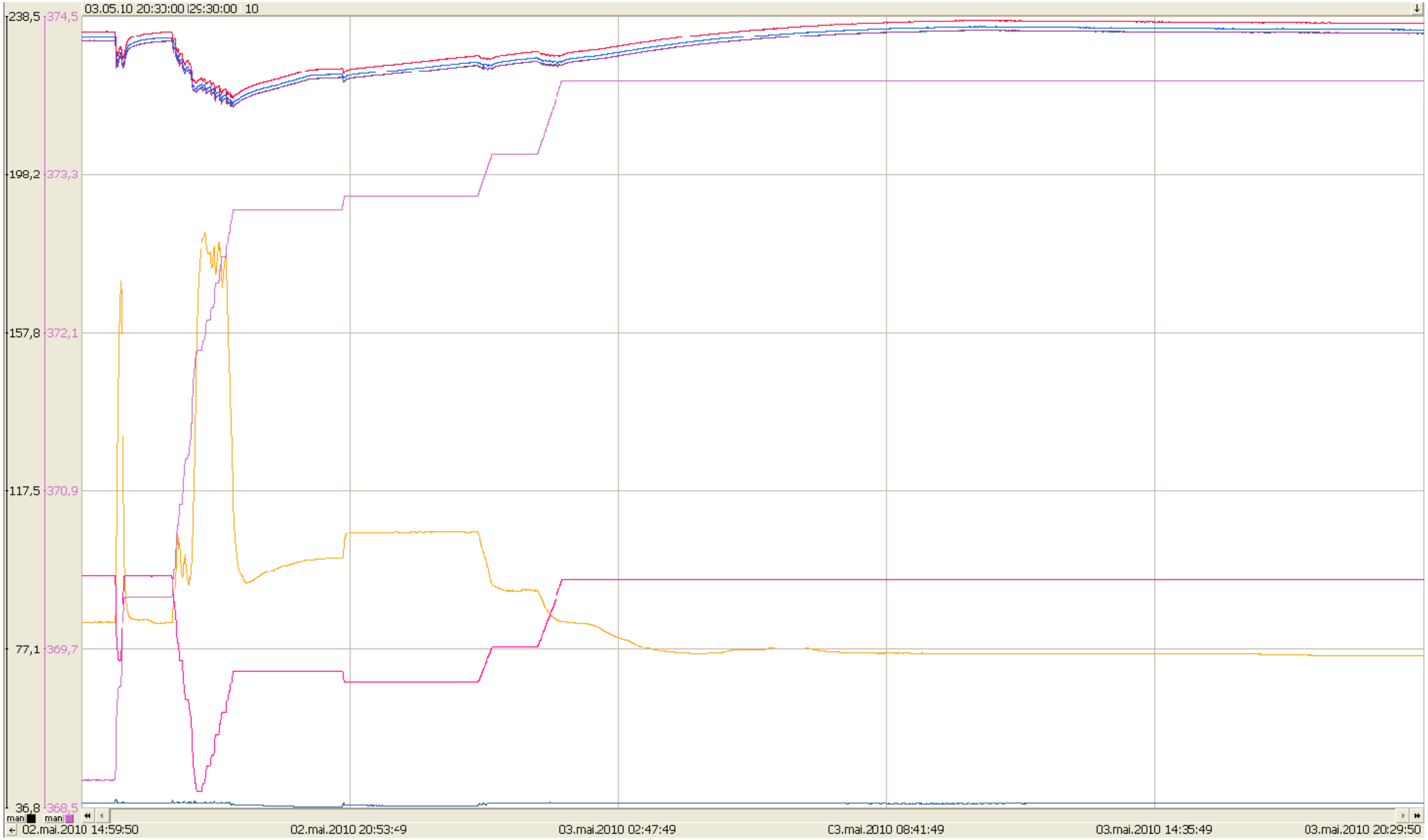
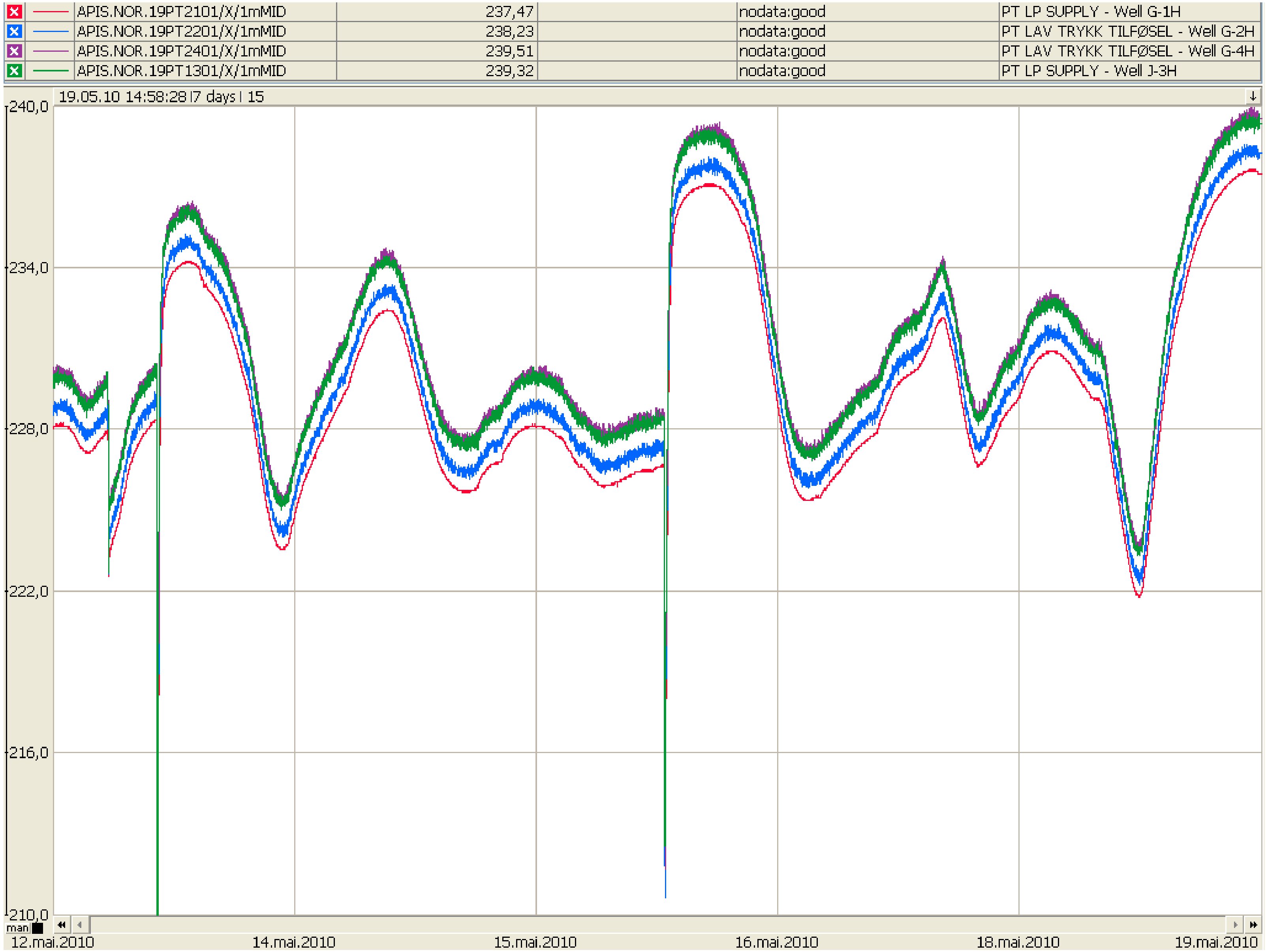
Appendix VI-E

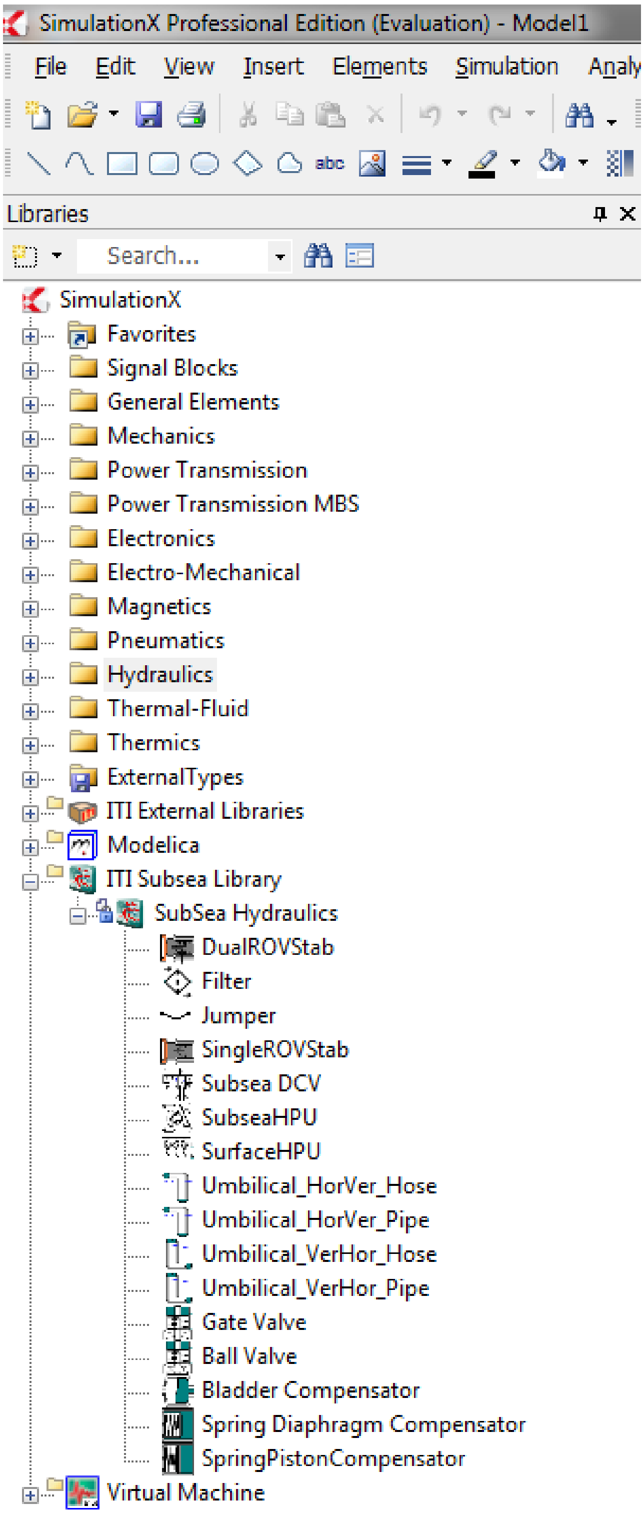


Appendix VI-F

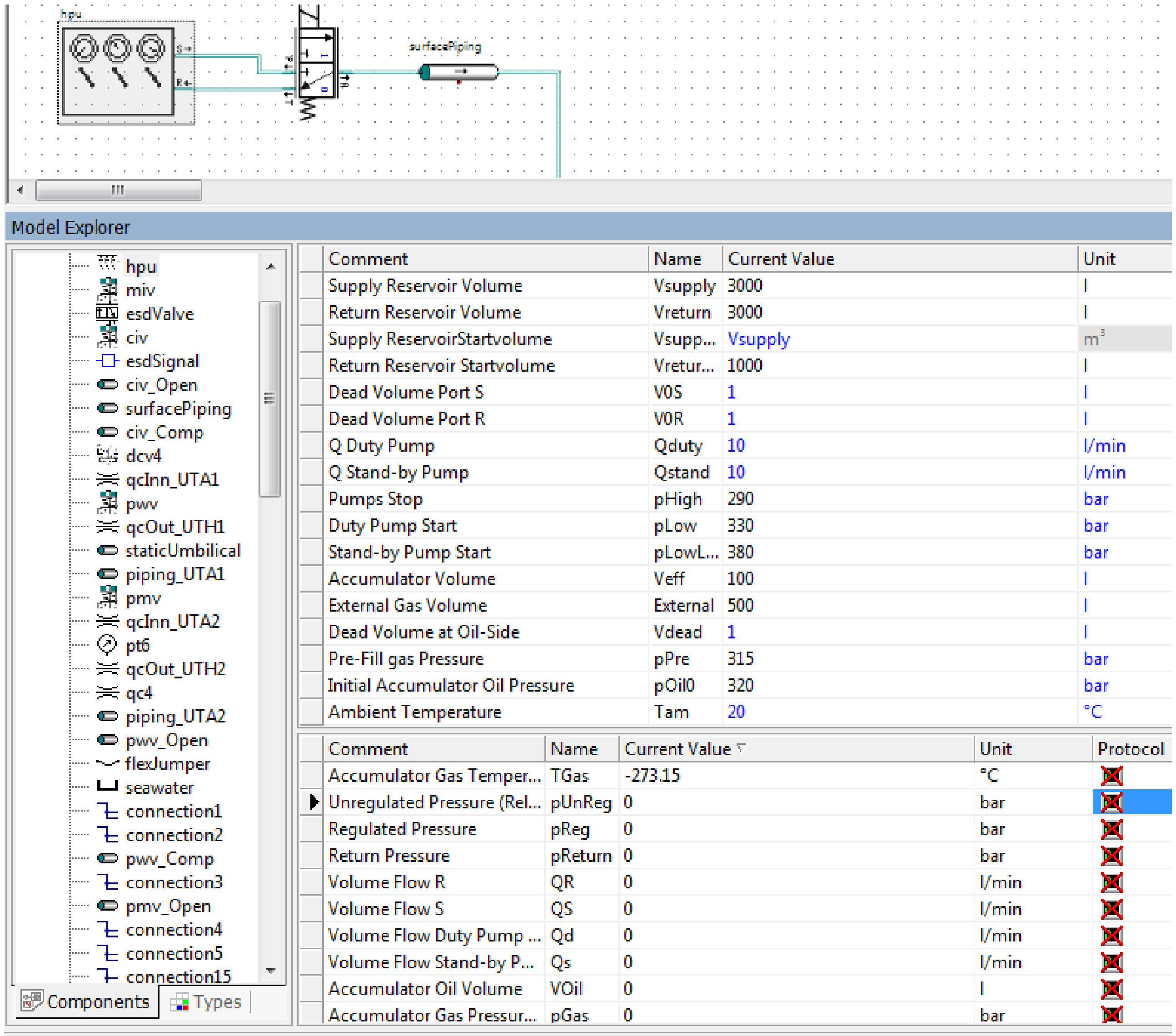


☒	—	APIS.NOR.19PT2101/X/1mMID	237,47	nodata:good	PT LP SUPPLY - Well G-1H
☒	—	APIS.NOR.19PT2201/X/1mMID	238,23	nodata:good	PT LAV TRYKK TILFØSEL - Well G-2H
☒	—	APIS.NOR.19PT2401/X/1mMID	239,51	nodata:good	PT LAV TRYKK TILFØSEL - Well G-4H
☒	—	APIS.NOR.19PT1301/X/1mMID	239,32	nodata:good	PT LP SUPPLY - Well J-3H

Appendix VII-A



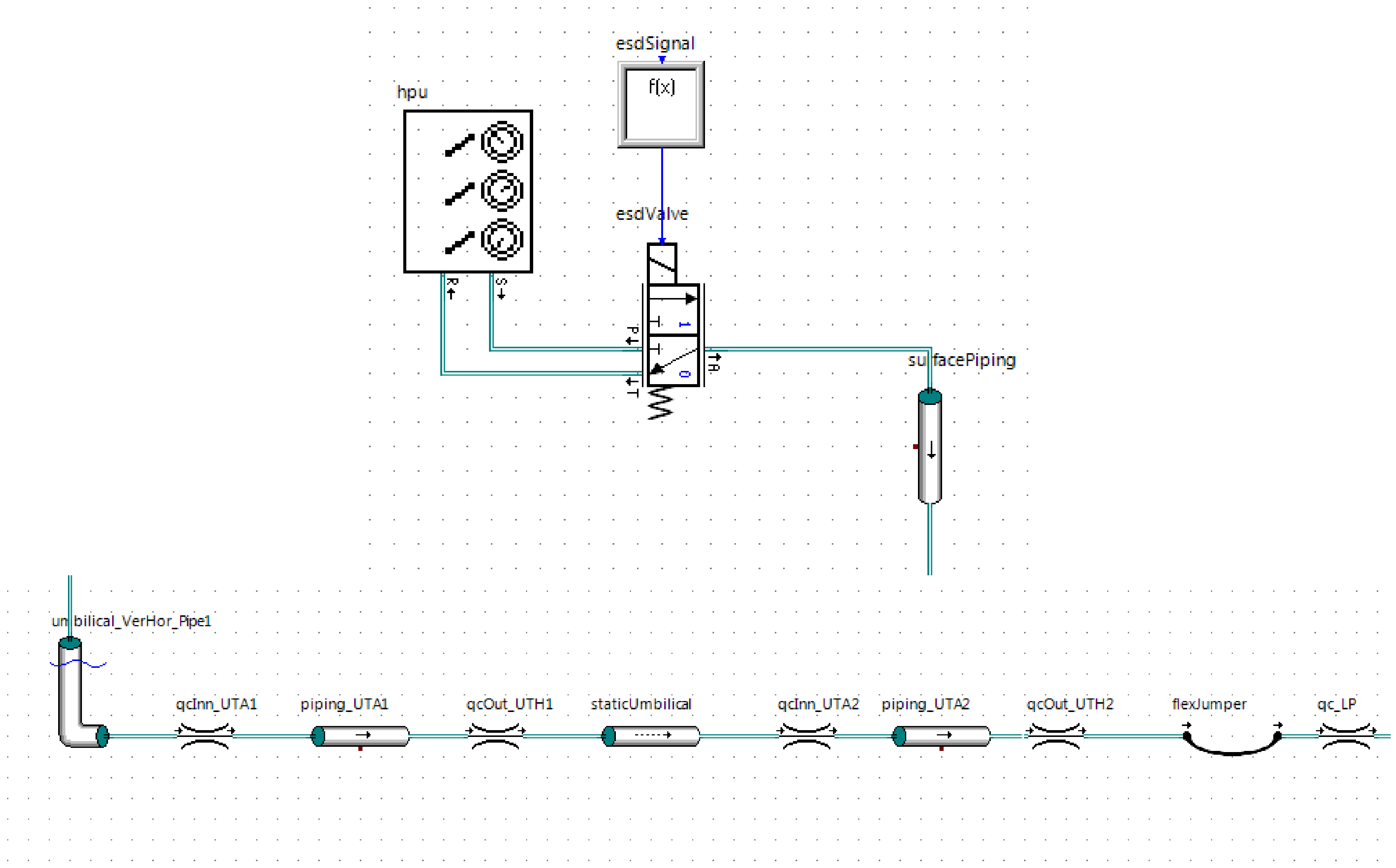
Appendix VII-B



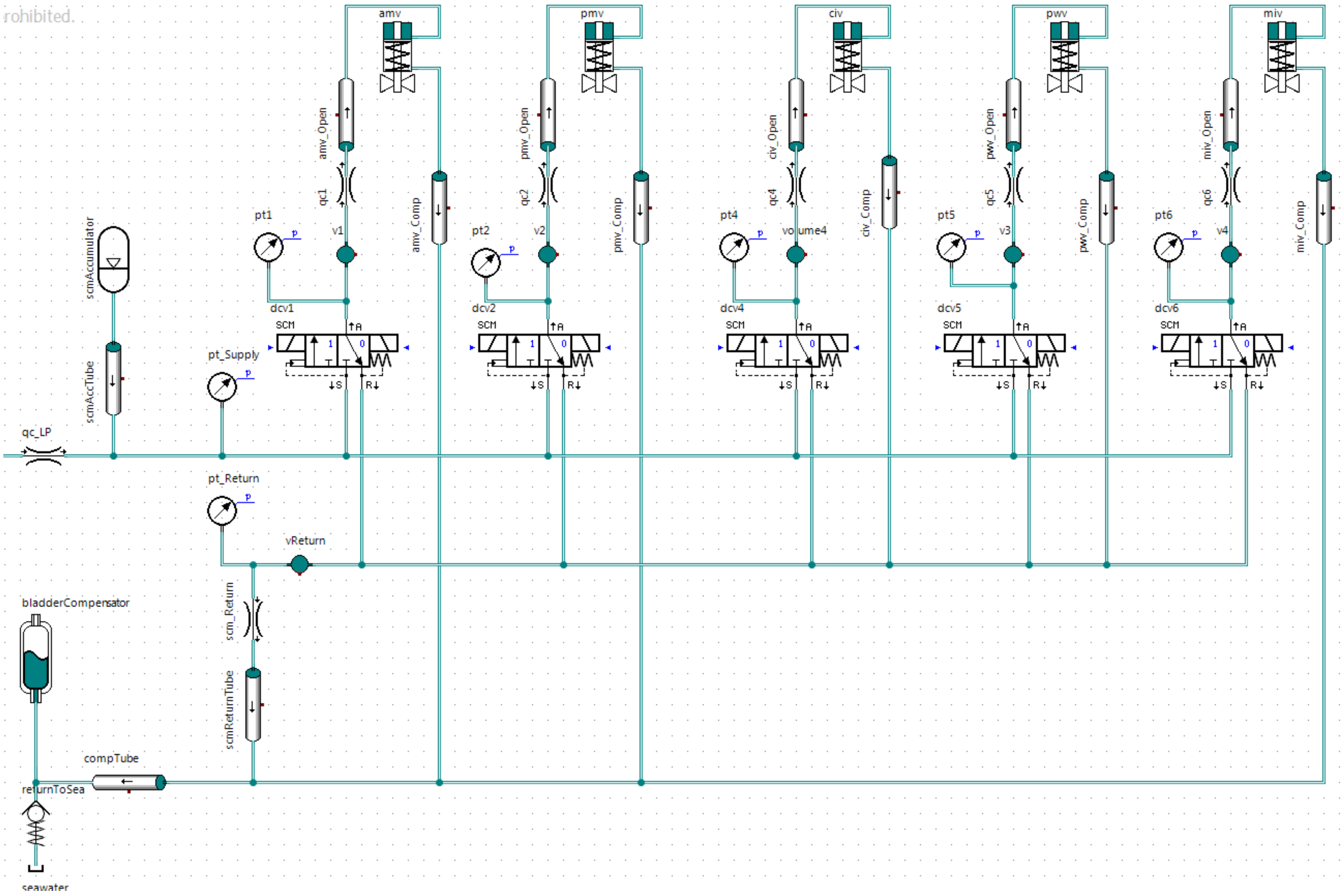
Comment	Name	Current Value	Unit
Supply Reservoir Volume	Vsupply	3000	l
Return Reservoir Volume	Vreturn	3000	l
Supply ReservoirStartvolume	Vsupp...	Vsupply	m^3
Return Reservoir Startvolume	Vretur...	1000	l
Dead Volume Port S	V0S	1	l
Dead Volume Port R	V0R	1	l
Q Duty Pump	Qduty	10	l/min
Q Stand-by Pump	Qstand	10	l/min
Pumps Stop	pHigh	290	bar
Duty Pump Start	pLow	330	bar
Stand-by Pump Start	pLowL...	380	bar
Accumulator Volume	Veff	100	l
External Gas Volume	External	500	l
Dead Volume at Oil-Side	Vdead	1	l
Pre-Fill gas Pressure	pPre	315	bar
Initial Accumulator Oil Pressure	pOil0	320	bar
Ambient Temperature	Tam	20	°C

Comment	Name	Current Value ▽	Unit	Protocol
Accumulator Gas Temper...	TGas	-273.15	°C	☒
Unregulated Pressure (Rel...	pUnReg	0	bar	☒
Regulated Pressure	pReg	0	bar	☒
Return Pressure	pReturn	0	bar	☒
Volume Flow R	QR	0	l/min	☒
Volume Flow S	QS	0	l/min	☒
Volume Flow Duty Pump ...	Qd	0	l/min	☒
Volume Flow Stand-by P...	Qs	0	l/min	☒
Accumulator Oil Volume	VOil	0	l	☒
Accumulator Gas Pressur...	pGas	0	bar	☒

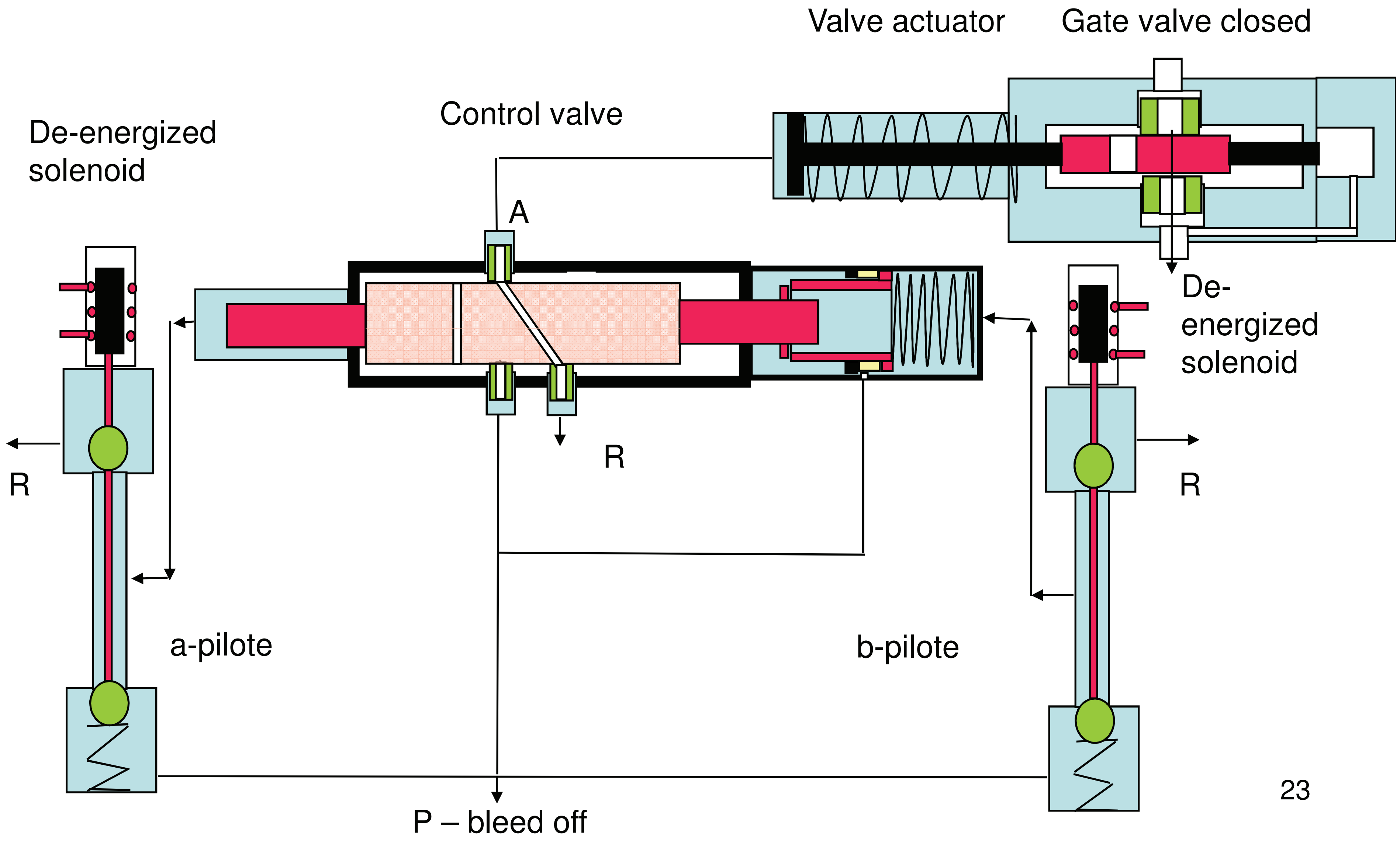
Appendix VII-C



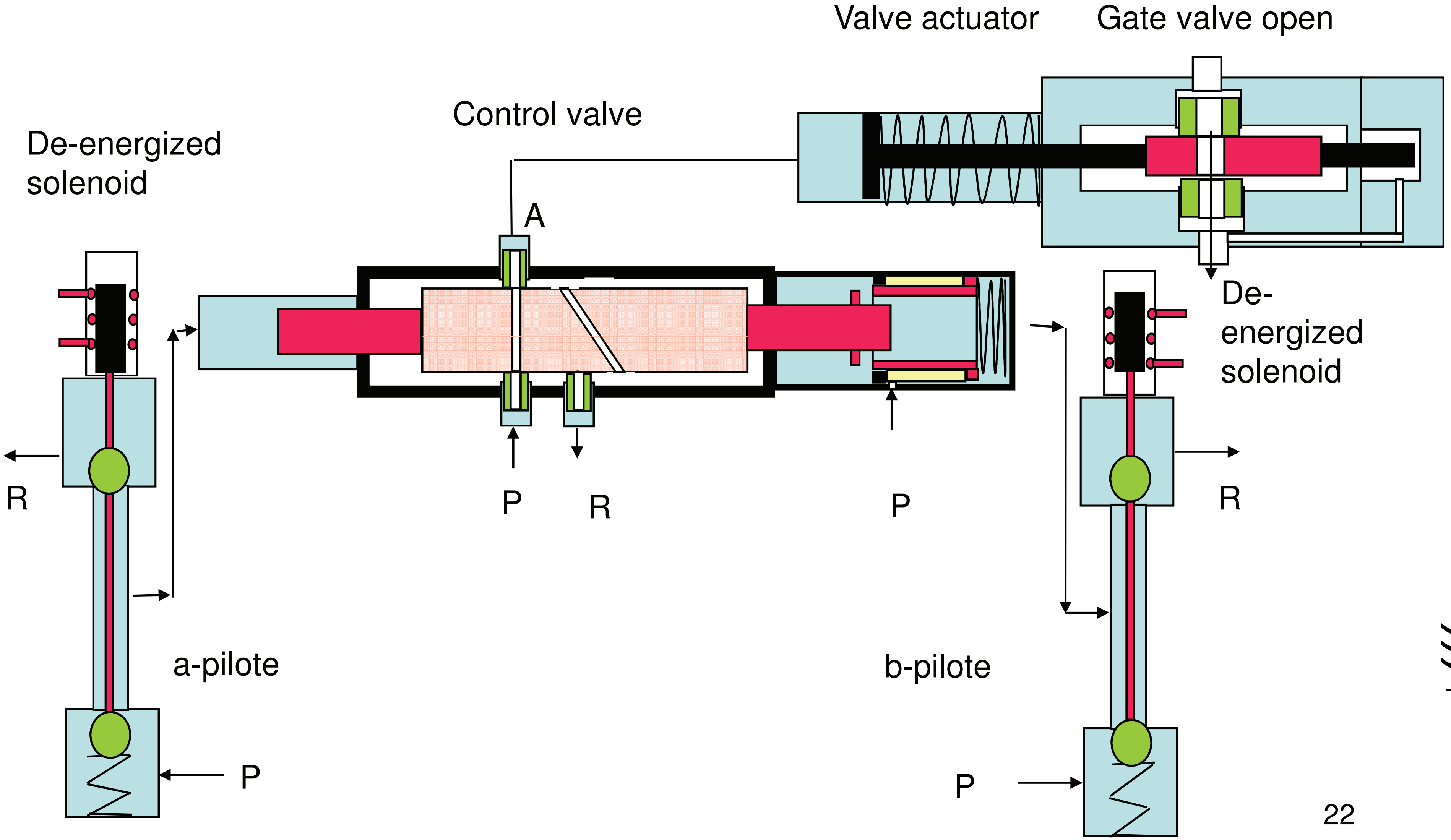
Appendix VII-D



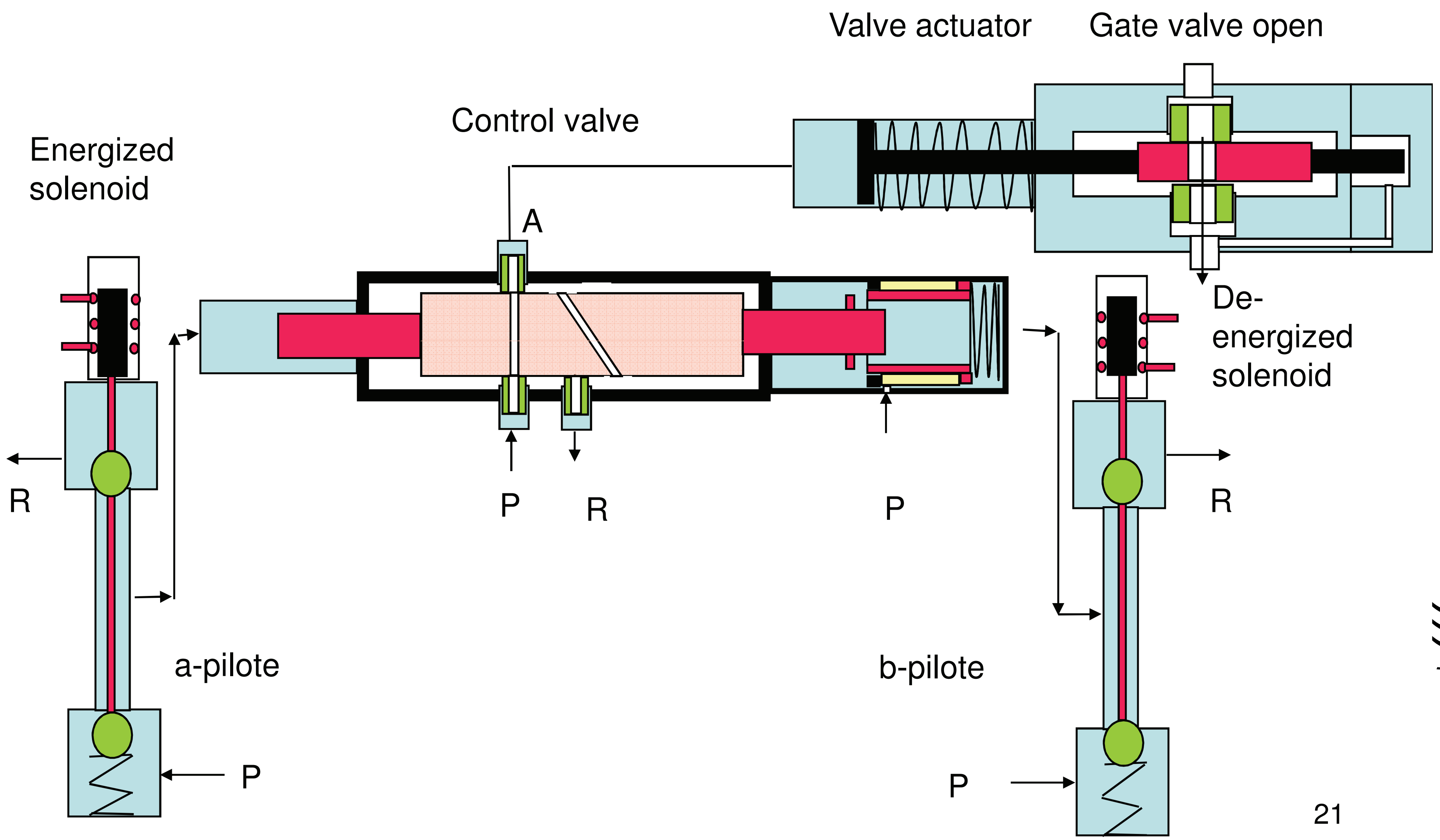
De-energizes solenoids for pilote stages (a) and (b) – Supply pressure (P) bleed off – Gate valve closed (Fail-safe-close)



De-energizes solenoids for pilote stages (a) and (b) – Control valve remains in last position (Gate valve closed or open)

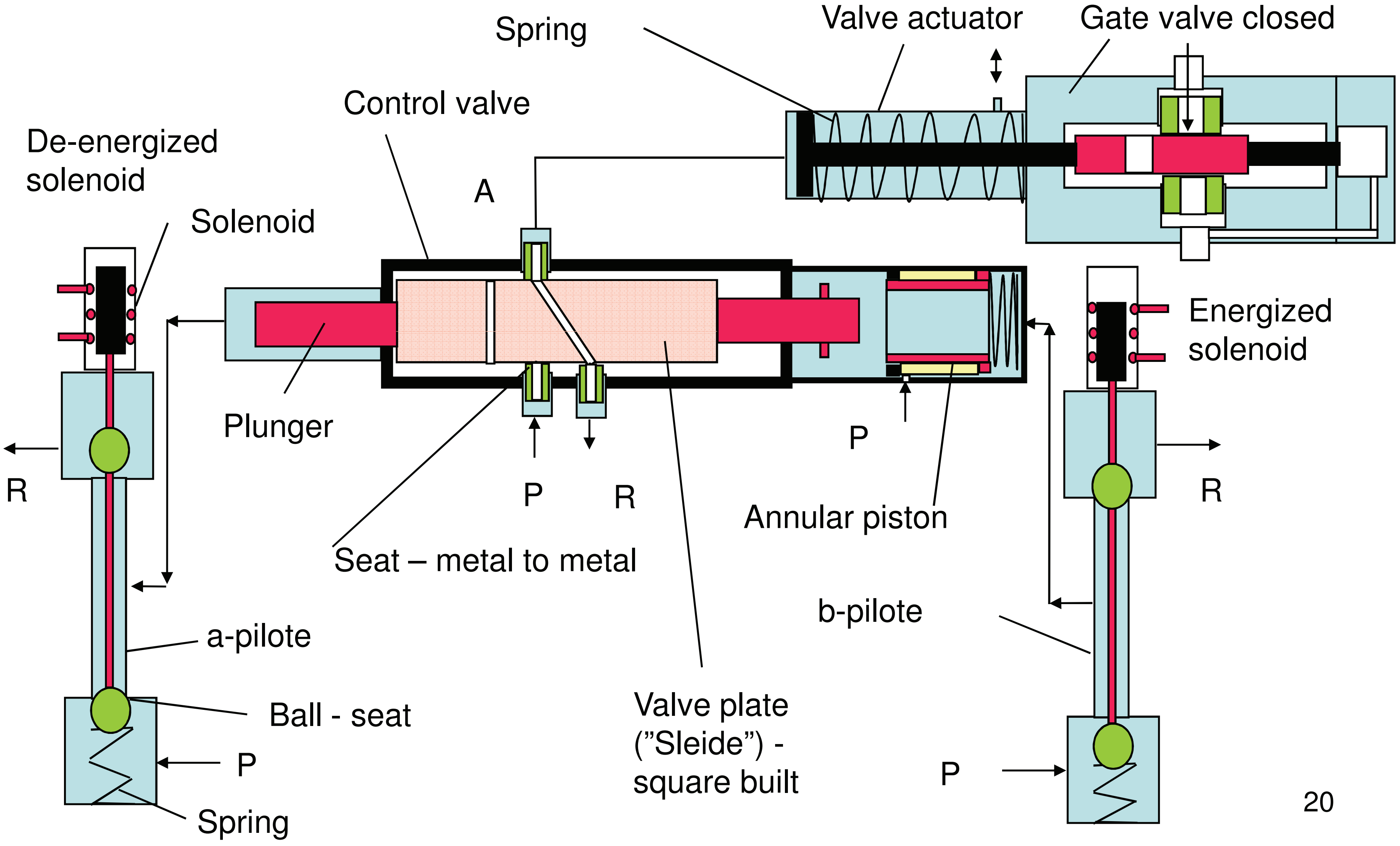


Energizes solenoid for pilote stage (a) – Gate valve open



3 ports, 2 position (3/2) control valve

Energizes solenoid for pilote stage (b) – Gate valve closed



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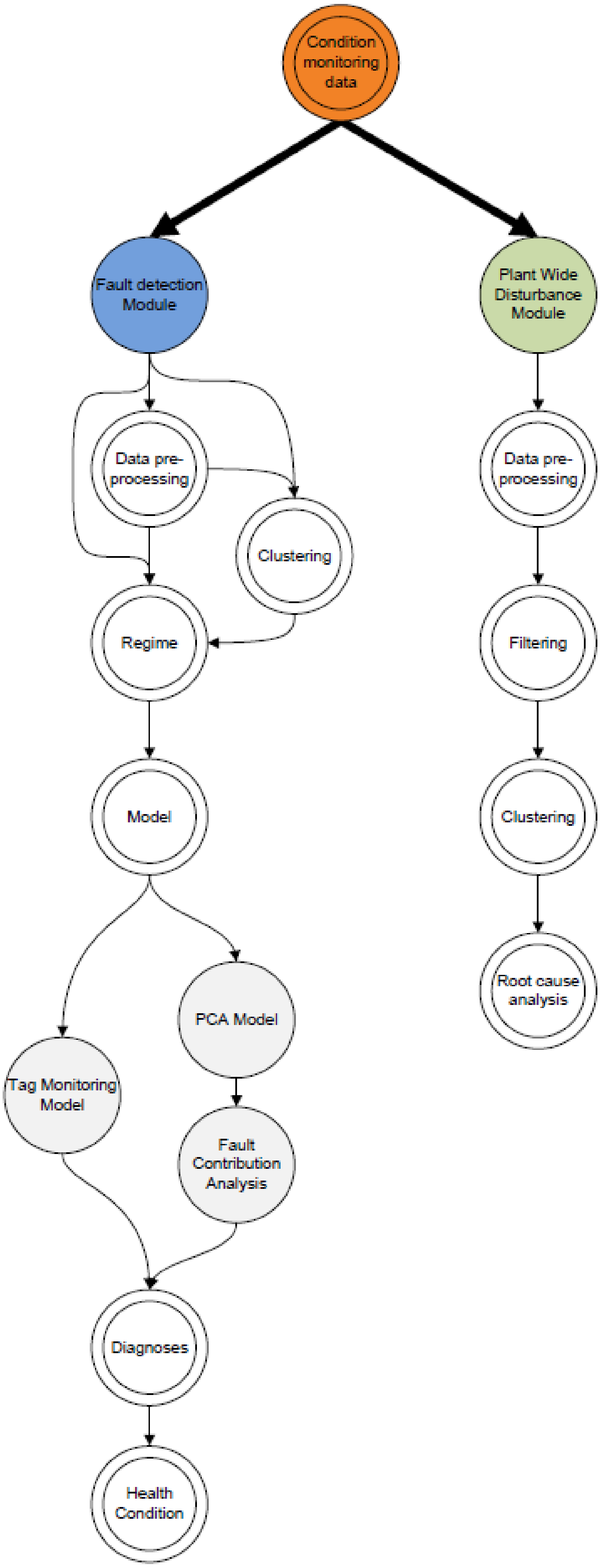
Condition monitoring data
Fault detection Module
Plant Wide Disturbance Module
Data pre-processing
Clustering
Regime
Model
PCA Model
Tag Monitoring Model
Fault Contribution Analysis
Diagnoses
Health Condition
Data pre-processing
Filtering
Clustering
Root cause analysis

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