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Abstract

This master thesis is looking into the feasibility of implementing Condition Monitoring (CM), Condition Based Maintenance (CBM) and principles from Integrated Operations (IO) on static equipment at the Kårstø Processing Plant (KPP). It consists of a literature study seeking for the state of the art; and then a study of the KPP, searching for the most relevant system or equipment that could benefit from such a combination of activities. The chosen unit for further studies was a Brazed Aluminium Plate-Fin Multiple Heat Exchanger (BAMHE), and a system for CM is described. The BAMHE was chosen due to its complex nature and the uncertainty related to how different working conditions affect its remaining life time. The system suggested for CM is not complete, but gives a conceptual idea and some concrete examples.

Preface

Already before starting on this master thesis the author has had a growing interest for the principles behind the development of IO on the Norwegian Continental Shelf (NCS). His knowledge of this is mostly based on different courses in the master program at the University of Stavanger (UoS), but also based on his own experience from his work at Gassco. What had been noticed from this experience was that almost all focus on this issue was related to heavy rotating equipment in combination with offshore installations. Over time, a curiosity has grown to find out if these principles and technologies also could be applied to onshore static equipment.

Gassco was asked if they wanted to support a master thesis based on a feasibility study of applying principles from CM, CBM and IO to onshore assets focused on static equipment. This was not directly within any of the predefined areas selected by Gassco as possible topics for master thesis, but after some discussions it was agreed that CM, CBM and IO in general were an interesting topic for Gassco and the suggested master thesis was approved. Gassco is the operator of several onshore gas related assets placed in Norway, UK, France, Belgium and Germany; but it was decided that the KPP would be the most relevant plant for detailed studies.

There was a literature search planned for relevant and comparable experiences, but due to limited results it was decided to widen the scope of the search to include general literature that was found relevant. Historical experience from Operation & Maintenance (O&M) was to be collected both through reports and interviewing experienced KPP maintenance personnel. Based on the results from the initial work, it was planned to search for systems or equipment that could benefit from the implementation of CM, CBM and IO.

Acknowledgment

I would like to thank my employer, Gassco, for the opportunity to study at the University of Stavanger while working in the company, and especially for their support during the work on my master thesis. Without this goodwill from my employer, this study would not have been possible.

I would like to thank my advisor at UoF, Jayantha Prasanna Liyanage, giving me valuable and constructive feedback on my work.

I would thank my advisors at Gassco, Per Aanestad and Karsten Leland, for their contribution to my master thesis. I have also received advice and guidance from other colleges at Gassco, and they have my gratitude.

Most of all I would like to thank my wife, Anne Beth N. Økland for her patience and understanding during the three years of combining regular work with part time studies at the University of Stavanger.

John Kristian Økland

Acronyms and Application definitions

AFS -	Atomic Fluorescence Spectrometry
ALPEMA -	The Brazed Aluminium Plate-Fin Heat Exchanger Manufacturers’ Association
ART -	Acoustic Resonance Technology
BAMHE -	Brazed Aluminium Plate-Fin Multiple Heat Exchanger
CBM -	Condition Based Maintenance
CCR -	Central Control Room
CM -	Condition Monitoring
CRAIER -	CO_2 Removal And Increased Ethane Recovery
D2B -	Device to Business
DNV -	Det Norske Veritas
FC -	Financial Crisis
GCICPMS -	Gas Chromatograph Inductively Coupled Plasma Mass Spectrometry
HAZ -	Heat Affected Zone
Hg -	Mercury
ICT -	Information and Communication Technology
IMS -	Intelligent Maintenance System
IO -	Integrated Operations
KEP2005 -	Kårstø Expansion Project 2005
KEP2010 -	Kårstø Expansion Project 2010
KMP -	Kårstø Master Plan
KPP -	Kårstø Processing Plant
MBM -	Monitoring Based Maintenance
MRU -	Mercury Removal Unit
MTBF -	Mean Time Between Failure
NCS -	Norwegian Continental Shelf
NDT -	None Destructive Testing
NPD -	Norwegian Petroleum Directorate
NTNU -	Norwegian University of Science and Technology
OCS -	Onshore Support Centre
OLF -	Oljeindustriens landsforening / Norwegian Oil Industry Association
O&G -	Oil & Gas
O&M -	Operation & Maintenance
PBM -	Program Based Maintenance
PDA -	Personal Digital Assistance
PdM -	Predictive Maintenance
PM -	Preventive Maintenance
RM -	Reactive Maintenance
PSA -	Petroleum Safety Authorities (Norway)
RBI -	Risk Based Inspection
RBM -	Risk Based Maintenance
RCM -	Reliability Centred Maintenance
SHC -	Safety/Health Clearance
TEG -	Tri Ethylene Glycol
UoS -	University of Stavanger

USNRC -	United States Nuclear Regulatory Commission
WO -	Work Order
WPAN -	Wireless Personal Area Network

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1 Introduction and background

The KPP is a large and complicated production terminal that processes two different kinds of hydrocarbon mixtures. These are rich gas and un-stabilized condensate. The rich gas enters the KPP via two separate gas pipelines, originating from the Statfjord/Gullfaks area and the Åsgard area (Åsgard Transport). The un-stabilized condensate enters the KPP via a condensate pipeline (Sleipner Condensate Pipeline).

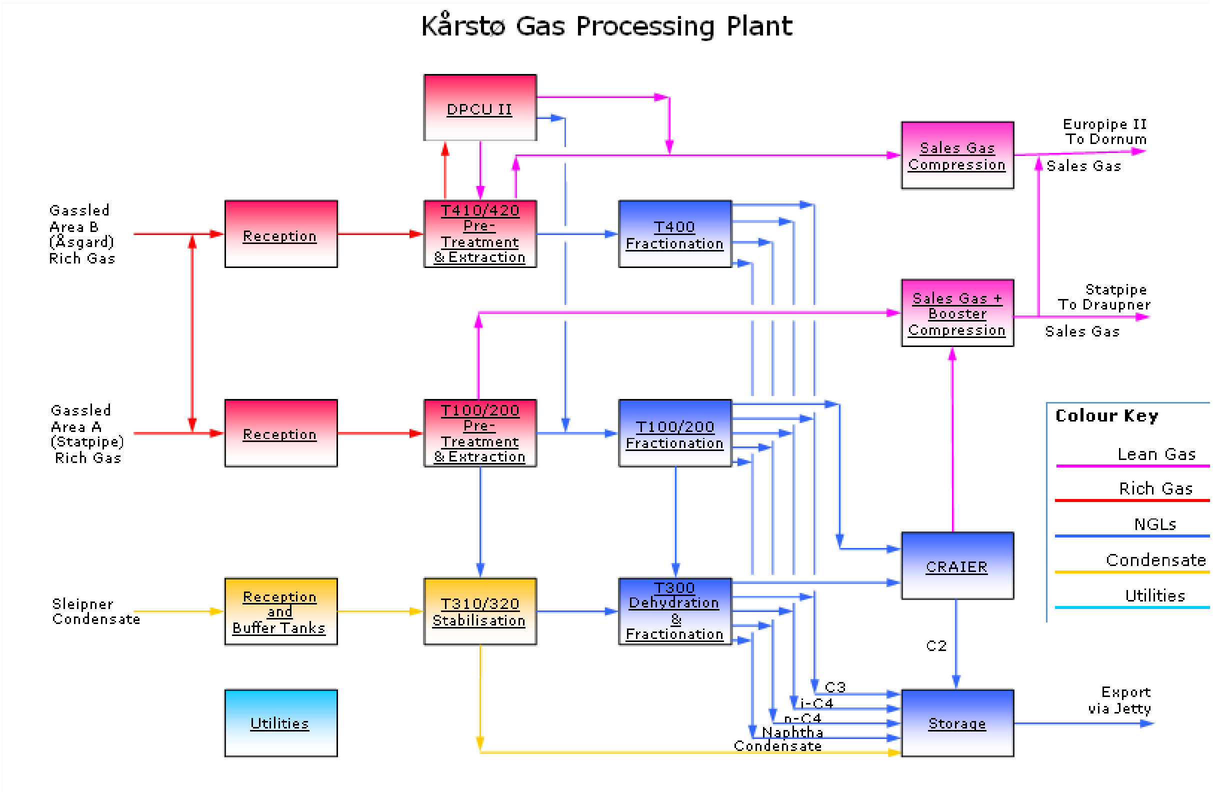

Figure 1.1.1: Schematics of the Kårstø Processing Plant

There has been a more or less continuous upgrade and expansion during the last 20 years, and this project activity is planned to continue for the coming years as sanctioned for the KEP2010 and the KMP projects.

To maintain a huge and complicated plant like the KPP a maintenance strategy needs to be established accompanied with necessary resources and managerial focus. The KPP have implemented a maintenance strategy today that is mostly based on preventive actions and additional manual inspection by qualified personnel. This means that most of the critical equipment has a maintenance interval that determines when to perform maintenance or inspection.

These intervals are normally rather conservative to make sure that the equipment does not fail when in operation, and are based on a combination of regulatory demands, manufacturer recommendations and operational experience. A well functioning system based on CM and CBM would reduce the total performed maintenance and limit it to the actual need. This has an increasing focus on the NCS where IO is pointed out to be a radical efficiency leap to the

O&M practice. The technology used at the NCS can also be beneficial for onshore assets like the KPP.

1.1 Thesis description

This master thesis is divided into two separate but connected parts. The first part has focus on literature dealing with issues that are relevant for maintenance of static systems or static equipments in the Norwegian O&G business, and this information provides suggestions to improve the effect and efficiency of the maintenance of static systems or equipment at the KPP.

The second part is to seek for systems or equipment at the KPP that could benefit from useful and well functioning CM; and that the maintenance of this system or equipment could be performed as CBM instead of pre-defined time intervals.
In addition, it is a goal to relate this CM and the performance of CBM to the ongoing development and implementation of IO on the NCS.

1.2 Problems and challenges

The author’s experience related to the process of implementing CM and CBM on industrial assets, mostly O&G industry on the NCS, is that the main focus has been on heavy rotation equipment like compressors, pumps and big engines. This technology has already been utilized for some time, and is accepted as an efficiency driver to the asset operator. The process of implementing IO at the NCS is recommended by OLF, PSA and NPD as a way of organizing O&M that will bring the Norwegian O&G industry to a higher level of performance.

The focus was to search for any studies or reports related to CM and CBM of static assets that could provide principles and ideas that in general were applicable for the study focusing on the KPP.

The first thought was to search for information within the space industry, US military industry, nuclear industry and air plane industry. All of these industries are historically known as important contributors to and developers of new technology and organizational improvements.

Recommended research personnel were contacted to ask for relevant reports and experiences.

There was a search for relevant literature, mostly by the use of the Internet and literature extracted from earlier courses at the University of Stavanger, but there was not much to find that could be directly linked to the thesis. Therefore the focus was changed to study general literature and technology developed for heavy rotating equipment and the development of IO on the NCS. These studies are focused on the principles of Information and Communication technology (ICT) and strategy, rather than detailed technology linked to heavy rotating equipment. These literature studies were much more fruitful, and provided a rather good understanding of the principles behind ongoing changes and future intentions.

When discussing these ideas and principles with experienced maintenance personnel at Gassco, with long experience from maintenance of static equipment at the KPP, the first feedback was that this was something new and exotic but also that they had difficulties to see how this could provide improvements to the existing maintenance system. The argument being mentioned several times was that the change of condition for static equipment is normally very slow, and that they had problems to see how this could be properly monitored by other means than visual inspection or other NDT-techniques during preventive maintenance.

Another topic mentioned was that comparing static equipment with rotating equipment could perhaps in some cases be feasible, but the fundamental difference linked to the extent and implementation of the two different kinds of equipment needed to be considered. There is by far more static equipment than rotating equipment at the plant, and the physical placement of static equipment is throughout the plant, compared to specific locations containing several components of rotating equipment. This would make it much more complicated to collect the monitoring data if the sensors had to be placed throughout the plant. There were also discussions about the kind of sensors or operational metering that could provide useful information about the condition of different equipment.

When trying to get more hands-on experience with regard to plant construction, operation and maintenance; this turned out to be more difficult than expected. The spring time is a very busy period at the KPP with preparation for extensive maintenance, in addition to activities related to the ongoing KEP 2010 and KMP projects. Most of the detailed studies are therefore based on data available from outside the actual factory.

1.3 Scope and objectives

The scope of this master thesis was to search for relevant literature giving a status of CM and CBM of static equipment, and have this as a basis when searching for systems or equipment at the KPP that potentially could benefit from such an implementation. The objective would then be to describe the principles of how a system for CM and CBM could be set up and organised using the principles described for IO.

1.4 Methodology

The work started as a literature study with the intention of gaining enough knowledge about the rather open scope of the thesis to be able to ask relevant questions to the maintenance experts and by that trigger their interest to contribute to the thesis.
After some reading, the experts were involved, and asked for advice to point out possible equipment that could be of interest for further investigation. These discussions were also used to gain general knowledge through their commentaries related to historical maintenance events during 25 years of operation at the KPP.

The next step was to start a philosophical conversation to challenge their extensive experience and see if this could bring up some open minded ideas that could be used further in the thesis .
After choosing one piece of equipment that was evaluated to have a significant CM, CBM and IO potential; documentation and historical data was collected and analyzed with the aim of producing concrete CM examples for future implementation.

2 State of the art

2.1 Maintenance of industrial asset

The attitude and the applied strategies related to maintenance of industrial assets have been changing during the last 60-70 years and several definitions of what maintenance is have been proposed. One of these is (Piltelton et al, 1997):

> “*the set of activities required to keep these means of production in the desired operating condition, or to restore them to this condition*”.

The development can very roughly be illustrated with the following figure.

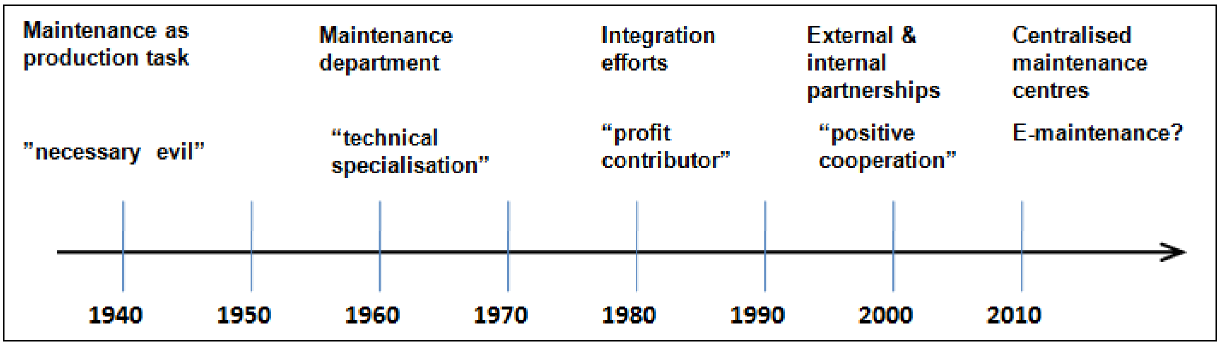

Figure 2.1.1: Maintenance Management in a time perspective

This figure is based on (Piltelton et al, 1997) but is extended to give an indication of trends and expectations for the near future (Baldwin 2001, Tsang 2002, Moore et al 2006, Liyanage 2007, Muller et al 2007).

The cost related to maintenance is varying between different assets depending on i.e. the kind of industry, expectations of regularity and the actual design basis for the asset. It will normally represent a significant part of the total budget for O&M. Studies over the last 20 years have indicated that around Europe, the indirect and direct cost of maintenance are split equally between the two, and each is between 4% and 8% of total sales turnover (Iung et al 2006).

In the beginning of the illustrated period, maintenance was based very much on “repair when broken” and “run until break down” (Piltelton et al, 1997, Moubrey, 1997). This approach to O&M was linked to the attitude that maintenance was a “necessary evil” and difficult to manage.

Gradually this changed towards an understanding that there was a need for a separate service called maintenance, organised through a maintenance department. This maintenance department could then train their staff to become specialised technicians that could perform efficient repairs when necessary.

Later, there appeared the philosophy that operation and maintenance were closely related and that the best way to achieve an efficient and effective maintenance was to include maintenance in the total business concept.

To continue the process of reducing the cost related to maintenance; out sourcing was introduced as a possible solution. This developed gradually and was normally based on the principle that maintenance tasks regarded as “none core” maintenance was subject to out sourcing. The definition of “none core” have shown a tendency to include more and more of the total maintenance of the assets. This has gradually created a market for maintenance service providers that specialise on performing different kind of maintenance and offer this service to similar assets regardless of any organisational relationships between them.

This growing industry for maintenance service providers has pushed the development of more sophisticated and specialised products that is offered as supplements to the total maintenance management of assets. This is part of the most recent development and what is expected to continue evolving in the time to come. Some flavours of the future are already in operation, materialised in O&M support centres remotely supporting assets globally.

2.2 Condition Monitoring

The expression Condition Monitoring (CM) is commonly used in connection with maintenance of industrial assets. The condition monitoring itself can be performed using a lot of different techniques and equipment, but the aim of the CM will always be to obtain an accurate and detailed description of the technical condition of the asset involved.

The development of technology needed to perform automated condition monitoring has evolved for more than 50 years and has been strongly dependent on improvements related to sensor technology, ICT and both computer software and hardware.
There are also a lot of manual techniques used for condition monitoring, and this often involves None Destructive Testing (NDT) of materials and human senses such as vision, hearing, smelling and feeling.

The development of automated CM has experienced significant steps forward the last 5-10 years, following the development of broad band data communication over long distances. This has made it possible to transfer large amounts of data from numerous sensors to any location locally, nationally or internationally. This has further contributed to the development of centralised units specialising on condition monitoring and support for different locations with similar needs.

The driving force in this development has been the need for condition monitoring of heavy rotating equipment such as compressors, pumps and other machinery. An example of this is SKF (SKF, 200?) that i.e. can provide CM services related to bearings in machinery.
The CM centres can perform continuous condition analysis of the relevant assets and together with local operators and maintenance personnel plan for corrective actions when determined necessary due to registered degradation and anticipated evolution.

CM is an important activity for establishing a maintenance concept based on prediction. This concept is called Predictive Maintenance (PdM) and is based on the principle of performing physical maintenance when the relevant asset has a real need for it. Other alternatives to PdM are Reactive Maintenance (RM) and Preventive Maintenance (PM).

RM means that you operate your asset without stopping it for maintenance. The asset will remain in operation until it breaks down and the broken equipment will then be repaired or replaced.

PM means that you establish time driven maintenance strategies that define a time of operation that will trigger maintenance of the asset. The time between each instance of planned maintenance and the extent of the work could be based on Mean Time Between Failure (MTBF) for the different parts of the asset. Expected time between failures will normally be based on historical data for this specific component in combination with recommendations from the manufacturer.

The normal reason for performing preventive maintenance on any systems or components is that these systems or components represent a critical function for the overall value creation of the production. Un-planned shut-downs of these systems or components are undesirable and the time between planned maintenance is conservative to avoid unexpected break-downs. Preventive maintenance strategies based on the conservative frequency of maintenance, result in more maintenance of the asset than actually needed. The system itself is less complicated and cheaper to manage though compared to a system based on CM. The CM can in some instances require a lot of data collected from different sensors and metres, and all of this data have to be organised and analysed before it can provide any useful information. This means that a broad evaluation should be performed of criticality and consequences of break down before any system or component is included in a CM program.

2.3 Condition Based Maintenance

Condition Based Maintenance (CBM) is a maintenance strategy based on the principle that maintenance should be performed when there has occurred an actual need for it, but before the degraded system or component is provoking a loss of production quality and/or quantity. The timing of the maintenance should be performed whenever it is most beneficial for the overall value creation of the asset. This means that condition monitoring is used to monitor the relevant system- or component condition, and this information is then combined with other considerations like the criticality of failure, consequences of failure and remaining time until next planned shut-down of the system or component.

The normal assumption is that if the system or component is evaluated to be of such importance for the asset that it qualifies for inclusion in the CM program, any critical degradation will be dealt with as soon as possible.
The most important way of implementing CM data into the maintenance management though is to analyse trends of degradation and estimate the remaining time before failure. Based on this plan for correction, actions can be performed at the overall best time. Depending on what system or equipment that is included in the CM program; supervision of vibration, temperature, oil debris, acoustic emission, ultrasonic, lubricant condition, chip detectors and time/stress detectors has shown good results in describing the actual condition. Even more important is that it can register changes over time that could indicate degradation.
To perform this kind of analysis Intelligent Maintenance Systems (IMS) need to be developed.
IMS serves the purpose to systematise and analyse relevant CM data to predict and forecast the future equipment performance to achieve as close to zero breakdowns as possible. The goal of the IMS is to present a graphical presentation of the equipment condition, both historical and for the future. These are some highly advanced systems that need especially skilled personnel to verify the accuracy of the results, but normal operation is more or less standard operation.

For some years now companies have been moving production facilities to China to reduce their production costs. Some of these companies have experienced that implementing remote supported CBM on their production facilities is the best way to secure the quality of the production. As long as the state of the production equipment is good, then the quality of the products also is expected to be acceptable. As soon as degradation is monitored, necessary maintenance can be activated and long distant transport of bad quality products is avoided. In this way the companies reduce their production downtime and secure the quality of their products. Valuable time and resources can then be spent on product development instead of guarantee repairing of bad quality products.

2.4 Static equipment

There is not much literature available dealing with the combination of CM, CBM and static equipment, and this seems to reflect the current status of academia and industrial involvement in this specific combination of topics. The most concrete examples related to these issues were studies related to, and implementations of, Monitoring Based Maintenance (MBM) of long span bridges, and a brief report on the condition monitoring of passive systems and components.

Based on this the KPP has been studied to seek out possible static systems or equipment that could make us of CM and CBM as an enhanced substitute to existing maintenance procedure.

2.4.1 Condition monitoring of long span bridges

The Akashi-Kaikyo Bridge in Japan is an enormous suspension bridge across the Akashi Strait linking Maiko in Kobe and Matsuho, on Awaji Island as part of the Honshu-Shikoku Highway. It has the longest central section of any suspension bridge in the world.
The bridge has three spans. The central span is 1991 meters, with the two other sections each 960 meters and the bridge is 3911 meters overall. The central span was originally only 1990 meters but was stretched further by a meter following the Kobe earthquake on January 17, 1995.

Figure 2.4.1: Picture of the Akashi-Kaikyo Bridge

As part of the construction of the Akashi-Kaikyo Bridge a monitoring system had to be implemented with the main objectives (Sumitro, 2001):

- Verification of design
    - Provide data on structural dynamic response to verify design assumptions used for a strong wind or earthquake.
    - Provide data for developing a better future design in a more rational manner.
    - Developing a reliable CM system that has a self check function to monitor malfunction of the system itself.

- Structural maintenance
    - Providing data for analyzing and evaluating the condition of the bridge structure.

- Providing data for assessing structural deterioration and performance degradation.

- Traffic management
  - Providing data to adjust safety levels for traffic control due to earthquake or strong wind.
  - Providing data for assessing post-earthquake or post-typhoon structural reliability to manage traffic control.

There are two major parameters that form the basic scope of the monitoring system described. These are load effects and responses. The load effects refer to those due to wind, earthquakes, temperature and live loads (movements and traffic). The responses refer to displacements, accelerations, stresses, strains and forces on the different bridge structures, and the displacements and stresses on the main cables.

Item	Main focus	Measured Parameter
Earthquake characteristics	Seismic motion and magnitude Earthquake frequency characteristics Ground characteristics Phase difference	Acceleration
Earthquake dynamic response	Acting seismic force Displacement Natural frequency Superstructure seismic motion	Response acceleration (velocity) Displacement Response acceleration (velocity)
Wind characteristics	Basic wind speed Design wind speed Variable wind speed characteristics - *Intensity of turbulence* - *Spatial correlation* - *Power spectrum*	Wind direction and wind speed
Wind dynamic response	Superstructure natural frequncy Vibration mode configuration Structural damping Gust response Action of main tower (TMD)	Response acceleration (velocity) Displacement Predominant frequency Wind speed and response acceleration Response displacement

Tabell 2.4.1: Design verification monitoring items

Device	Measuring
Seismometer	Seismic activity
Anemometer	Longitudinal and transversal wind speed
Accelerometer	Dynamic structural behaviour
Velocity gauge	Vibration response
GPS	Measure point displacement
Girder edge displacement gauge	Girder displacement
Tuned mass damper (TDM) displacement gauge	TDM displacement
Thermometer	Steel and air temperature

Tabell 2.4.2: Sensors used for CM of the Akashi-Kaikyo Bridge

Monitoring sensors are connected to different terminals, based on their location of installation. Each terminal is connected to a common work station via fibre optic cables. The data collected is processed to check if any predefined alarms are activated, graphically displayed and stored. A central control room get access to the stored data and performs any necessary analysis of data, time history data graphing, plus statistical and analytical processing.

2.4.2 Condition Monitoring of passive and long-lived systems and components

Historically the development of industrial safety regulations and systems for CM has been lead by interests within the United States nuclear power industry, the US Army and the space technology industry.
The nuclear power industry and the US Nuclear Regulatory Commission (USNRC) have developed two important sets of requirements for this industry. These are:

- Licence Renewal Rule
- Maintenance Rule

The licence renewal rule is focusing on the management of the aging degradation of “passive” and long-lived systems or components; and the maintenance rule is dealing with requirements for “active” systems.
The general definition of a passive system in this relation are systems or components that do not move to function, such as structures, heat exchangers, cables, valve and pump bodies and piping. Long-lived items are those that are not subject to replacement based on a qualified life of specified time period, and their age related degradation can only be monitored and trended by performing periodic condition assessments by inspection, testing and measurements.

The Petroleum Safety Authorities (PSA) in Norway had the Chockie Group International to develop a briefing report (Chockie et al, 2006) based on the work performed by the US nuclear industry to search for relevance to their own study titled *Design Life Extension Regulations*. This report was handed over to the PSA in October 2006.
The original licence period for nuclear power plants was set by the US Congress in 1954 at 40 years of operation, but this was mostly based on economical considerations rather than safety

or technical limitations. It was also decided that it should be possible to apply for an operation licence after 20 years of operation. The evaluation of the application is based on the assumption that it should be granted as long as the operator could document the ability to meet the valid USNRC regulations for the whole time of future operation. The new licence will then be valid for the remaining period of the last approved licence, and continue for up to 20 more years afterwards. There are no limits to the number of renewals.

Based on this system the USNRC started to experience applications to renew licences late in the 1970s, and concluded that they had to address the life extension issue.
In 1982 the USNRC arranged a large regulatory/industry work shop related to aging management and life extension. This work-shop was then part of the basic input in the extensive Nuclear Aging Research (NPAR) Program, spending 10 years and millions of dollars to conclude that extended operation was technically feasible.

The NPAR program identified aging as the cumulative, time-dependent degradation of a system or component that, if unmitigated, could compromise continuing safe operation of the plant. It was also stated that mitigated measures were needed to ensure that aging did not reduced either the operational readiness of a plant’s safety systems or the defence-in-depth through common-mode failures of redundant, safety related equipment.
The main technical objectives of the NPAR Program were to:

- Identify and characterise aging effects which, if unmitigated, could cause degradation of systems or components and impact plant safety.
- Develop supporting data to facilitate management of age-related degradation
- Identify methods of inspection, surveillance and monitoring, or of evaluating residual-life of systems or components, which will ensure timely detection of significant aging effects before loss of safety function.
- Evaluate the effectiveness of storage, maintenance, repair and replacement practices in mitigating the effects of aging and diminishing the rate and extent of degradation caused by aging.
- Provide technical bases and support for the licence renewal rule and the licence renewal process.

In addition to the NPAR program USNRC launched a study related to aging of nuclear plant vessels, piping, steam generators and non-destructive testing techniques, and another focused on age-related degradation of plant civil structures.
Numerous technical reports, papers and proceedings were produced mainly related to the aging of the subjects listed in Tabell 2.4.3.

Air operated valves	Compressors	Pipeing
Auxillary feed water pumps	Connectors, terminal blocks	Power operated relife valves
Batteries	Diesel generators	Small electric motors
Bistables/switches	Electrical penetrations	Snubbers
Cables	Chillers	Solenid valves
Charges/inverters	Heat exchangers	Steam generators
Check valves	Large electric motors	Transformers
Civil structures	Main stem isolation valves	Vessels
Circuit breakers/relays	Motor operated valves	

Tabell 2.4.3: Subjects examined by the NPAR and other related aging research programs

One of the conclusions from the report (Chockie et al, 2006) is that the rules and processes developed by the USNRC for licence renewal of US nuclear power plants and the NPAR studies are also relevant for similar issues related to Norwegian petroleum industry. It will therefore be of interest to examine results from this extensive collection of documented experience and recommended practice when inspection, monitoring and maintenance of static systems and equipment at the KPP are evaluated.

2.4.3 SmartPipe

The SINTEF Research Institute, in close cooperation with the Norwegian University of Science and Technology (NTNU) started a project in 2006 called SmartPipe (SmartPipe, 2006?).
The principal objective in the project is to develop the SmartPipe concept for online monitoring of the technical condition of pipelines.
A vital part in this is to couple materials degradation models and analysis tools with sensor input data, for immediate conversion to consequences with regards to safety level and remaining lifetime estimations. Key elements in the project are:

- Development of distributed sensor network
- Development of a communication infrastructure
- Finding solutions for power supply to sensors and communication
- Packaging solutions for integration in pipeline manufacturing
- Improvements of material degradation models
- Development of efficient numerical tool for “real-time” integrity assessment

No concrete developments from the SmartPipe project have been available for this thesis, but it indicates a growing interest in CM of static equipment using the IO principles.

2.5 Development towards Integrated Operations

It is hard to state when the principles for IO were used for the first time in relation to the O&G activity on the NCS, but the Tommeliten field was in 1988 the first field developed as a remote controlled satellite field connected to the Edda field (Norsk Oljemuseum et al, 2005). This was the start of an impressive development of technology for remote controlled facilities. Recently these innovations have been materialised in project developments like Snøhvit and Ormen Lange. IO is also applied successfully on mature field installation like the Conocophillips operated Ekofisk asset, the BP operated Valhall field and the StatoilHydro operated Tampen area. They are all examples of initiatives where operational and maintenance related duties have been moved to Onshore Support Centres (OSC).

A large portion of the fields at the NCS are now close to, or already into, tail of production; and most of the new discoveries are small and need to be connected to existing infrastructure to be commercialised.
Driven by the OLF initiative and also admitting that something radical had to be done to lower production cost, the O&G industry has since 2004-2005 accelerated their efforts to seek the opportunities related to IO. This is a controversial change from the conventional way of producing O&G, and as the development goes on new challenges are discovered that requires development of safe, effective and efficient solutions.

The economical potential in implementing IO at the NCS was first estimated to 250 billion NOK and later increased to 300 billion NOK (OLF, 2007a), but the process of implementing IO seems to take more time than expected and can reduce the economical benefits significantly (OLF, 2008, 2007b). The calculations are based on the assumption that IO is implemented on the relevant installations within 2015, but this seems difficult to fulfil.

2.5.1 Norwegian Oil Industry Association

In 2003 OLF issued their first report related to eOperation (OLF, 2003). The purpose of this report was to give a status of eOperation initiatives at the NCS and to chart the course for a radical change of reservoir optimization, well operation and O&M practice on offshore facilities.
The conclusion from the document is that the principles from eOperation should be sought out and implemented in a large scale, and is suggesting responsible parties for issues that need to be worked out.
The Norwegian Oil and Energy Department acknowledge and support the OLF initiative (Olje- og Energidepatrementet, 2004) and OLF is now functioning as a driving force for coordination of Norwegian efforts to improve and implement eOperation at the NCS. From 2004 the term Integrated Operation is used on the new development scenario of the offshore industry.

2.5.2 The IO catalysts

The main catalysts to the development of IO is the widespread implementation of broad band communication, development of cheaper and better sensor technology and the general development of Information and Communication Technology (ICT). Fibre optic cables, capable of transferring large quantities of data with close to on-line status, has been laid from most of the offshore facilities on the NCS to the main land; and made it possible to locate more support personnel at OSCs. The personnel working at an OSC are specialised in this kind of remote-but-live supervision and are delegated different responsibilities for one or more offshore assets by supporting it with:

- Optimization of production performance
- CM of systems or components
- Planning of maintenance
- Logistics
- Managerial issues

So far reservoir optimization and well operation have drawn most of the attention, but O&M has also seen some development and this is expected to pick up speed and give more concrete results in the years to come.
The intention is to develop the necessary technology and managerial solutions to be able to implement eOperation and eMaintenance on offshore assets. Much of the same improvements will be possible to implement also on onshore facilities, and the range of equipment that can be supported will increase.

2.5.3 Secure Oil Information Link

In Norway, a dedicated ICT network designated Secure Oil Information Link (SOIL) was established in 1998 by a handful of oil companies to replace complex dedicated communication lines between them. This SOIL system was introduced to facilitate the growing need for integrated data management and B2B communication.
SOIL is developed to serve as a common data link between most of the business sectors active in O&G on the NCS, the Danish and the UK sector of the North Sea. An independent company called OilCamp has since 2001 operated the SOIL network from offices in Stavanger and Aberdeen. SOIL is built on the idea of connecting the different stakeholders in this business closer together by using fibre optic cables, wire-less communication and a common ICT system to transfer data, voice and video. By providing this it is expected, and experienced, that:

- It has become possible to create highly reliable information and knowledge-sharing networks that don’t require common geographical location to serve the need for remote support of O&M on the NCS
- Authorised stakeholders will create spheres of cooperation where they simultaneously can share core information instead of serial processing.
- The different stakeholders only get access to data and information they are authorised to receive through a sophisticated log in system.
- The network is in principle accessible from anywhere with an internet connection.

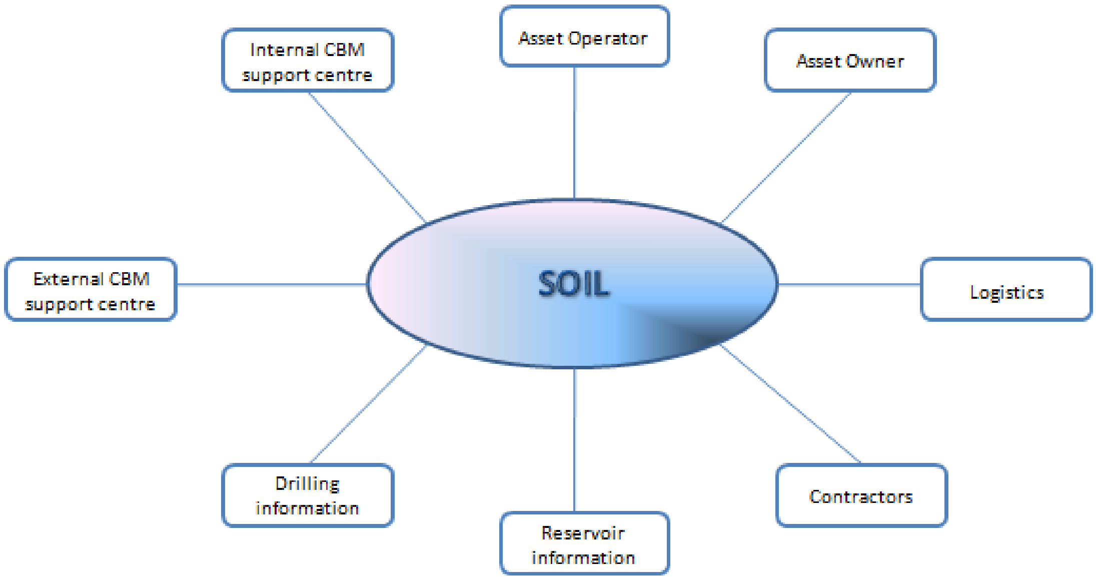

Figure 2.5.1: The basic idea of SOIL

SOIL is available also for onshore assets and provides the same services to plants like the KPP as the offshore facilities. The KPP could use the SOIL network both for connecting external expertise to their O&M databases, but also to create an onshore environment together with other O&G plants with similar needs.

2.5.4 Principles of eOperation and eMaintenance

eOperation and eMaintenance are concretisations of the intentions in IO. There is no common definition of what the e stands for but the general understanding seems to be Excellent. The main idea is that all data necessary to operate and maintain an asset should be available for all relevant parties simultaneously making the different stakeholders able to do their analysis on-line without any limitation related to geographical or organisational considerations. This is a radical change to the first developments of CM and CBM performed as vibration monitoring of heavy rotating equipment, thermography of electrical equipment and oil analysis. The data collection was often performed manually and the data processing was based on sequential work through several levels of responsibility and expertise. The **Feil! Fant ikke referansekilden.** shows an example of how conventional O&M was organised on the NCS before the introduction of IO.

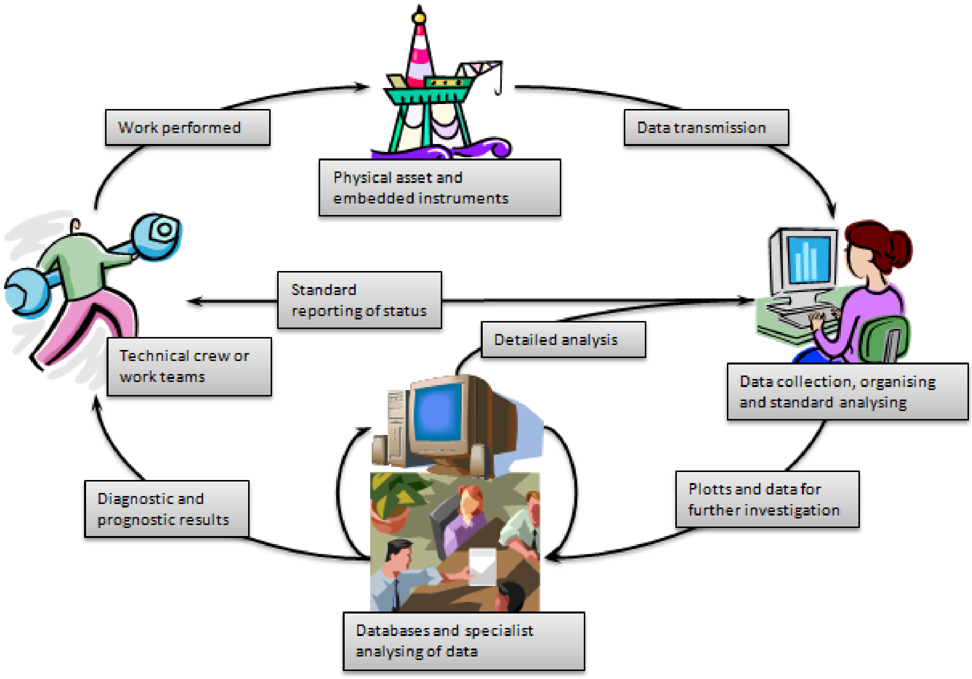

Figure 2.5.2: Conventional O&M intervention process

The **Feil! Fant ikke referansekilden.** is showing the principles of how eMaintenance could be set up with regards to communication and data access.

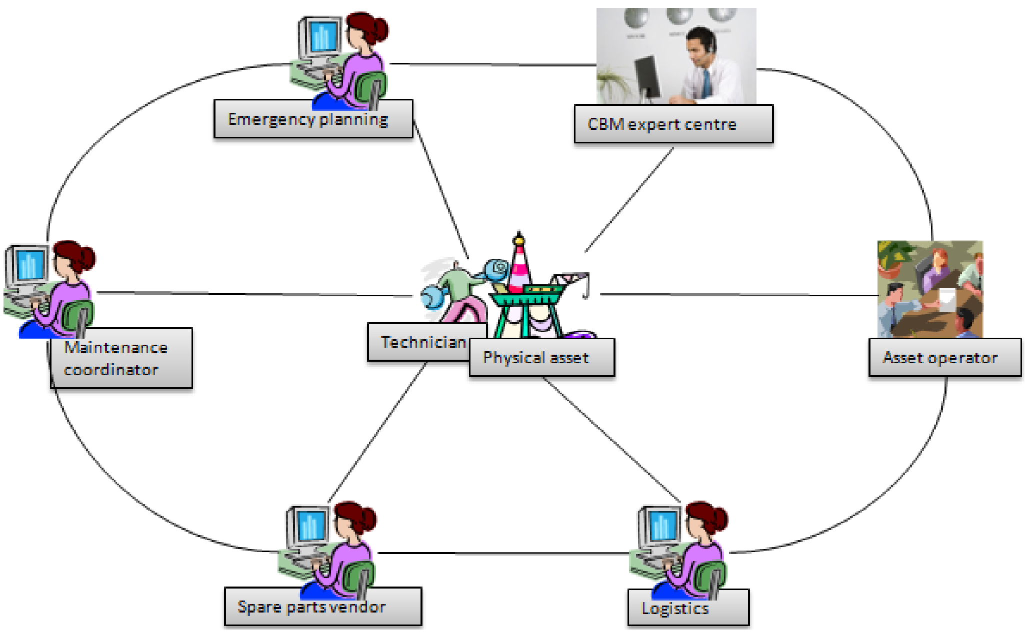

Figure 2.5.3: eMaintenance communication set up with many-to-many connectivity.

This way of coordination and cooperation between the different parties can be much more effective and efficient than the sequential way. To actually make it work, a lot of technical and non-technical issues need to be developed and sorted out. This process needs to be well planned and performed with a continuous focus on safety for the personnel involved, the surrounding environment, and the economical investments.

2.5.4.1 Thoughts about eMaintenance

There are many ways of defining eMaintenance. Some examples are as follows (Muller et al, 2007):

eMaintenance as a maintenance strategy
“*eMaintenance is an asset information network that integrates and synchronises the various maintenance and reliability applications to gather and deliver asset information where it is needed*”

eMaintenance as a maintenance type
“*eMaintenance is the symbol of the gradual replacement of traditional maintenance types by more predictive/proactive types*”

eMaintenance as s maintenance support
“*Distributed artificial intelligence environment, which includes information processing capabilities, decision support and communication tools, as well as the collaboration between maintenance processes and experts*”

Finally the elaboration around eMaintenance can be summed up as follows:

“*Maintenance support which includes the resources, services and management necessary to enable proactive decision process execution. This support includes e-technologies (i.e. ICT, Web-based, wireless, infotronics technologies) but also, eMaintenance activities (operations or process) such as e-monitoring, e-diagnosis, e-prognosis, etc.*”

2.5.4.2 Development of new technology to support eMaintenance

There are still several technical issues that need to be further developed to be able to effectuate the full potential of eMaintenance. These issues are:

- platforms for common data management
- smart decision support tools
- self testing logics and reporting capabilities for sensors and transducers
- intelligent watchdog agents
- portable video-communication technologies
- PDAs supplied with advanced functionalities and broad band communication

All of these technical improvements will then be used to predict the equipment condition and present it as a trend rather as a status as of today. The historical development of degradation and predictions of future development will allow means of maintenance to be performed with the optimum timing.

2.5.4.3 eMaintenance and non-technical challenges

On the NCS there is a common understanding in the O&G business that eOperation and eMaintenance are the solutions to today’s demand for a safer and more cost efficient way of producing oil and gas (Liyanage, 2007). It seems though, that the technical initiatives for implementing this new philosophy for O&G production have evolved quicker and have had more focus than the socio-political consequences.
In addition to the technical issues mentioned in 2.5.4.2 there are also numerous organisational and managerial issues that are just as important, to fulfil the goals described in the OLF initiative.
The experience of implementing eOperation and eMaintenance is that moving functions and responsibilities from the physical asset to different offsite locations have created a significant uncertainty amongst the remaining people working at the asset. They don’t feel comfortable about having to rely on people not being physically around, to take care of their safety.
Other issues that have been experienced are:

- People remaining at the asset feel degraded due to loss of responsibility.
- Especially older people are unsatisfied with having to “learn their work over again”.
- People being moved to an OSC might have to live in the same area. When working offshore this is no problem.
- Uncertainties related to the new way of communicating, both with regards to semantics and ontology.
- Uncertainties related to the security of the vital data communication.

2.6 Kårstø Processing Plant

The KPP is a plant of great complexity, a huge variety of equipment and consists of a lot of interdependencies. Some interactions are obvious and others are more difficult to observe. The original plant was sanctioned in 1980 and the first commercial gas deliveries commenced during 1985.
The KPP consists today of 6 separate processing trains that are connected with several cross-over connections to optimize the regularity and the production of the plant. Specifically these are:

- T100 and T200. These are the original processing trains that were installed to process rich gas from the Statpipe pipeline. These trains were designed to process 11 MSm^3/d of rich gas each.
- T300 is a condensate stabilizing train built to process un-stabilized condensate from the Sleipner field and further fractionate the lighter components into the same type of NGLs as T100/T200. This train was put in operation in 1993.
- T410 and T420 were built to process rich gas from the Åsgard transport pipeline and these were placed in operation during 2000. This increased the rich gas processing capacity at the KPP from 22 MSm^3/d to 61 MSm^3/d.
- T500 was developed as a two stage project. In 2003 the first stage added an additional extraction unit (NET-1) that was connected to the Åsgard Transport inlet facilities. The next step was completed 2005, increasing the capacity with the Dew Point Control Unit (DPCU). This increased the total rich gas processing capacity at the KPP to 88 MSm^3/d.

The numerous connections between the different processing trains and their auxiliary systems provide some operational flexibility both during normal operation and during planned maintenance, but it can also result in extenuating consequences.

The KPP plant is divided into an Eastern and a Western area, which are operated independently of each other. Notification is given only if an operation or system within one area affects the other area. The plant operators are dedicated to only one of the two areas.
Each area has a shift supervisor that report to a common production supervisor who has overall responsibility for the entire factory.
The main control room is used to control all of the process, most of the utility systems, the offsite and product loading; but a separate control room is responsible for the sales gas compressors, steam boilers and the power plant.
There are nine field operator areas, five in the West and four in the East. Each operator area has 3-4 field operators responsible for logging, operating manual valves, gas testing, visual inspection and so on during 24/7 operation. In addition the operators look after permitting work as well as isolating areas for maintenance, controlling that equipment is gas free and are involved both before and after any maintenance activity.
The KPP is also divided into system areas representing the different services provided. The criterion of segmentation is following the standards established at the NCS and each system

area is dedicated one person responsible for the system. The different systems areas are briefly described in Appendix A.

	Planned Maintenance %	Total Reduction %
2004	11,2	16,93
2005	2,0	14,51
2006	6,4	23,5
2007	3,4	13,8
2008	6,2	13,3
2009	2,4	
2010	7,0	
2011	2,7	
2012	6,3	
2013	3,1	

Tabell 2.6.1: Interruptions of yearly technical capacity at the KPP (Gassco).

The Tabell 2.6.1 is showing how much of the yearly capacity at the KPP that is left un-utilized, first due to planned maintenance and then the aggregated un-utilized capacity regardless of reason. This illustrates the significance of planned maintenance on the yearly available capacity. If the down time due to planned maintenance could be reduced, then this has the potential to make significant improvements to the available yearly capacity. The target turnaround (plant-wide shut down) frequency is once every six years.

As describe in the text above, there has been continuous upgrade and expansion during the last 20 years, and this is planned to continue in the years ahead from the KEP2010 and KMP project sanction. A very interesting thing about these two projects is that none of them are introduced to increase the maximum throughput of the plant, but rather to secure the robustness and availability of existing capacity. This has become challenged as the age of the plant has increased and the difficulty of providing spare parts is appearing.

The difference in applied technology at the plant is a big challenge when you are responsible for creating a reliable and efficient strategy for maintenance. New and sophisticated condition monitoring equipment and analyzing tools could be used in some cases, but is not necessarily the best and most cost efficient solution in all cases. So far it is only the expanders, sales gas compressors and cooling compressors that are included in a functional CBM program using a Bently-Nevada system called “Machinery Management System”.

2.6.1 Kårstø maintenance philosophy

History

During the first years of operation at the KPP, the performance of corrective maintenance was much more frequent than today. The main reasons for this were a high focus on keeping all equipment up and running, regardless of the consequences. Maintenance people were called in for overtime work without much focus on the actual urge. This has changed after the implementation of the PM program, reducing the number of break-downs; and the performance of risk critical analyses of the different equipment at the plant, allowing some equipment to wait for a suitable time for repair.

The planning of maintenance is now performed for 3 weeks at the time, making it predictable and possible to plan for all personnel.

The maintenance and inspection intervals were more frequent in the beginning of the operation period, and as experience was gained the intervals were extended if found reasonable and, if necessary, approved by the regulatory authority.

Up to 1993 remote controlled valves were the only valves given their own identity (tag number). This made it difficult to prepare any overview of experience and maintenance history on other valves. Also, a lot of other static equipment was without any specific identity up to 1993. The registry of “old” equipment took several years to fulfil.

As the KPP grew and became more complex, the maintenance personnel experienced problems with having the complete overview of the entire plant. The maintenance personnel were then divided into two completely separate organisations serving the eastern area and western area respectively.
The same argument has also been a driver to the increased documentation demand for procedures and detailed work packages.

The recorded equipment history is in some cases difficult to utilise due to changes in computer system. If historical records are left within the old systems, the experience is that it will remain there and never be used.

<u>Today</u>
The implemented maintenance philosophy at the KPP is based on a mix of Program Based Maintenance (PBM, both campaign and preventive) and Condition Based Maintenance, and the maintenance philosophy is founded in the Statoil document WR0154 that is valid for all StatoilHydro operated assets. This means that there are a lot of different strategies and approaches to maintenance on the same industrial asset. Based on the historical development of this plant, the combination of technology from 3 different decades and an enormous collection of different equipment this is probably a normal situation in this business.
There is a priority list established stating the key objectives as “established goals” of operation, maintenance and modification activities at the KPP. These are:

1. HSE integrity
2. Regularity of production
3. Optimisation of O&M cost/unit cost
4. Maintenance performance (i.e. an indication of how successful planned and executed maintenance activities are)

There is a target of a plant turnaround once every sixth year. This means that the entire processing plant is shut down for a period of 2-3 weeks. This is a costly exercise both with respect to the maintenance cost itself but also due to loss of production. A stop like this not only affects the KPP, but all the O&G producers reliant on the KPP to process their gas. These field can to some extend re-inject their gas into their reservoirs, but many of them have to cut back or completely stop both oil and gas production when the gas pipeline has reached the maximum operational pressure.

If the frequency of plant turnaround could be decreased and/or the duration shortened, this could increase the value creation at the NCS significantly.

2.6.1.1 Overall Execution Process

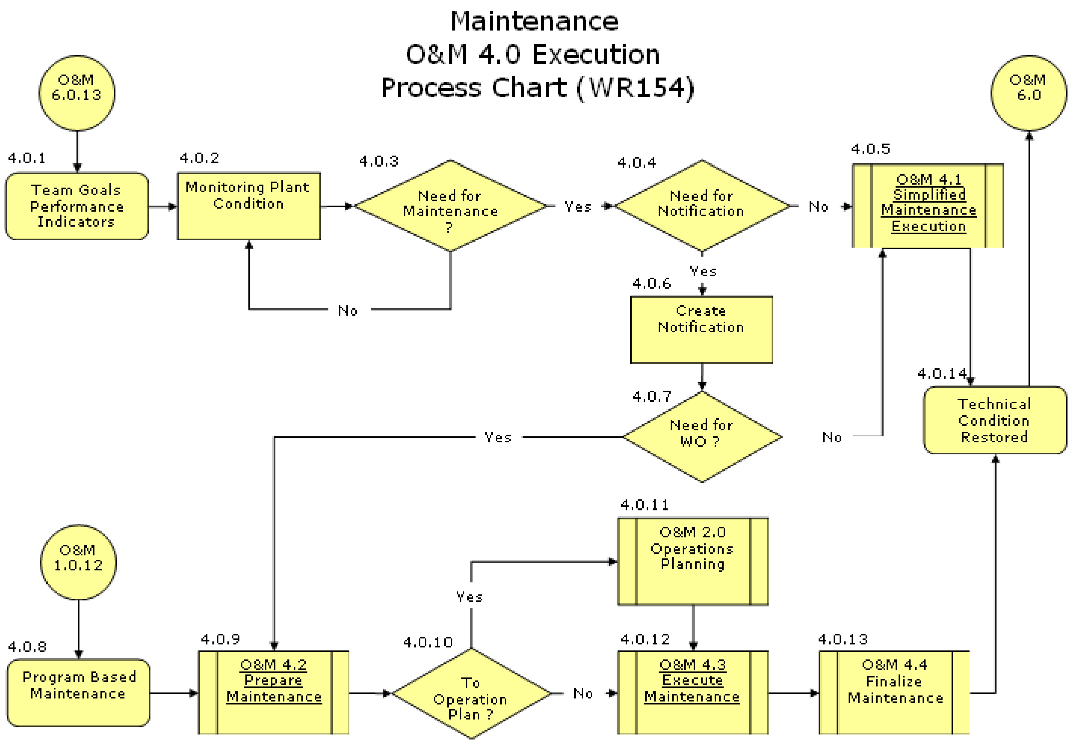

Figure 2.6.1: Maintenance Execution Process Chart

The WR0154 has two different alternatives for initiating maintenance on the plant. This is either based on monitored degradation of plant condition or on generic PBM. To be able to determine when an un-acceptable level of plant performance is reached, there needs to be a stated reference condition and a condition that will trigger a maintenance action. This is one of the inputs to the CM and is called "Team Goals Performance Indicators". As long as no limits for CBM are triggered the CM will not activate any maintenance activities, but the PBM will be activated as defined in the PBM program regardless of plant condition. Maintenance triggered by CM can be handled in two different ways. This is maintenance with or without notification. To sort out if a notification is needed, the following questions are raised:

- Is there a need for economical follow-up or history?
- Is this a frequent/repetitive fault?
- What is the expected work load and follow-up in remedial work?
- Is there a need for change in the PBM program?
- Is there a need for change of technical information related to execution of activities or findings during execution?
- Is there any need for awaiting the execution?
- Is there any requirement for safety clearance and/or Safe Job Analysis?

- Is there any need for coordination, planning and/or cost control?
- Any need for materials/services that have to be required or reserved?
- Does it require more time than one shift/one day?
- Is there any competence shortfall/need for special certificate?

Based on regulatory requirements all of these questions need to be answered and documented in case of any regulatory system revision.
If the conclusion is that all the questions are answered with "no", a "Simplified Maintenance Execution" (2.6.1.2) is performed. Otherwise a Notification has to be created. A Notification is a short description of the failure identified and a reference to the lowest TAG level available. A longer description of the failure can be attached to this notification.
The next step is to determine if there is a need for work order. This is determined by answering the following questions:

- Is there a Safety/Health Clearance (SHC) required?
- Are there any demands for coordination, planning and cost control?
- Is there any requisition/reservation of materials or services required?
- Does the activity require more time than one shift/one day?

If the conclusion is that all the questions are answered with "no", a "Simplified Maintenance Execution" (2.6.1.2) is performed. Otherwise a Work Order (WO) has to be created and a preparation of maintenance is initiated based on this WO.
Preparation of maintenance can in addition be initiated by:

- Predefined WOs triggered the PBM
- Manually entered inspection WOs, based on annual inspection program
- Manually entered WOs for surface maintenance based on the annual program

When the preparation for maintenance is done, the next step is to evaluate if the planned activities need to go through the planning process called "O&M Operations Planning" to coordinate with ongoing operation of the plant, or if the planned maintenance can be taken directly to the next step called "Execute Maintenance" (2.6.1.4).
When the maintenance has been executed the next step is to close the job. This means that the site should be cleared, documentation updated, history registered and WO/Notification closed. This process is called "Finalize Maintenance".
As a result of both administrative and executive maintenance efforts, the capacity and regularity of the system or component should now be sustained or restored, partly or entirely. In the "Technical Condition Restored" test, this will be measured and compared to the performance parameters that are established for efficiency, safety and availability for the actual system or component, and any non-conformance must be dealt with.

The results from this maintenance process will appear in MiS (StatioHydro's Balanced Score Card) for each team involved.

2.6.1.2 Simplified Maintenance Execution

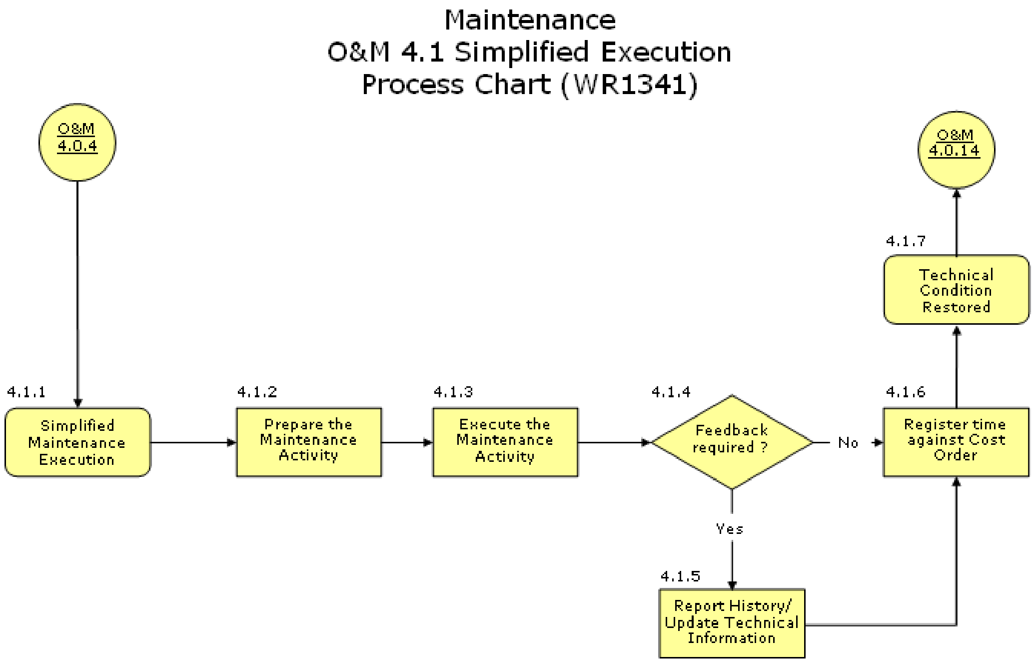

Figure 2.6.2: Simplified Execution Process Chart

The "Simplified Maintenance Execution" process is used for minor maintenance activities initiated through the CM system.
The maintenance activity is prepared and executed, and based on the experience from this operation the need is evaluated to report or update any technical documentation. The time used on the operation is registered on a Cost Order, and the technical condition is verified to meet the expected goal of the system or component.

2.6.1.3 Prepare Maintenance

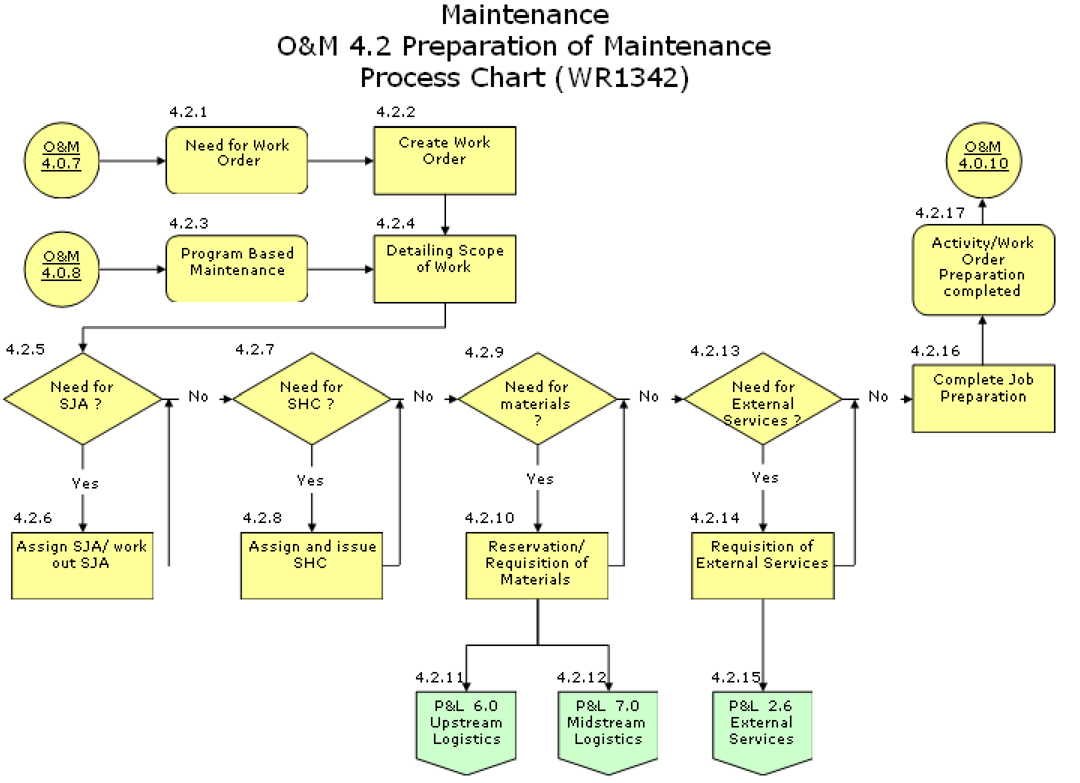

Figure 2.6.3: Preparation of Maintenance Process Chart

Input can be received from two different sources within the process for preparation of maintenance. These are maintenance initiatives either from the CM system, or from the PBM system. If the CM system is the source of a registered need for maintenance, then the “Preparation of Maintenance” process has to prepare a WO before starting to detail the scope of work. Maintenance initiatives generated from the PBM system are equipped with predefined WOs. When the detailed scope of work is ready, the following steps will be performed:

- Perform Safe Job Analysis if necessary
- Acquire Safety/Health Clearance if necessary
- Reserve or requisite materials if necessary
- Requisite external service if necessary

2.6.1.4 Execute Maintenance

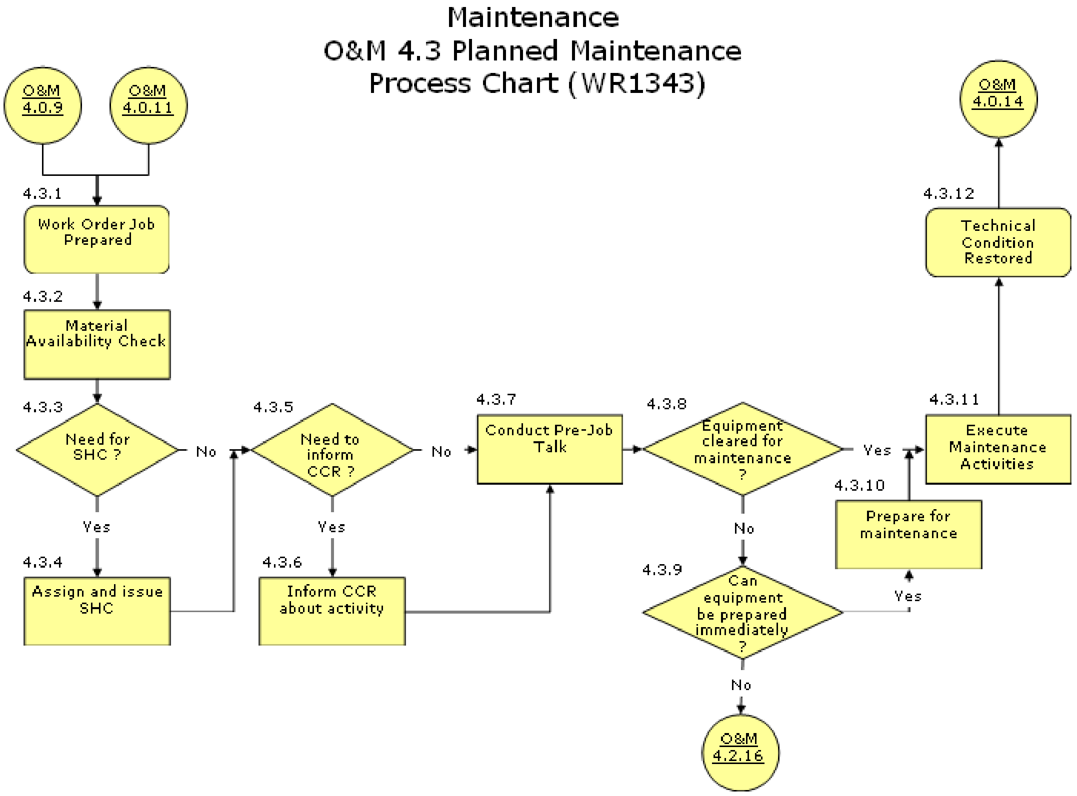

Figure 2.6.4: Planned Maintenance Process Chart

Based on the “Preparation of Maintenance” process (2.6.1.3), and input from “Operations Planning” the execution of the planned maintenance is performed. The execution process will then go on with:

- Checking the availability of any necessary materials
- Checking the need for Safety/Health Clearance, and acquire these if applicable
- Checking the need for informing the Central Control Room (CCR) , and acquire authorisation if applicable
- Conduct Pre-Job Talk
- Acquire necessary equipment to perform the planned maintenance activity

The maintenance personnel are now ready to execute the planned maintenance activities to restore the technical condition of the system or component.

2.6.2 Experience from O&M of static equipment at the KPP

The KPP is an extraordinary large and complex asset to operate, maintain and further develop for future needs and regulatory demands.
When interviewing personnel with long and relevant experience from inspection and maintenance of the plant they have mentioned several episodes and issues related to dangerous situations and unexpected behaviour related to static equipment. When asked if they ever used CM as a mean to detect and avoid similar repeating episodes, they concluded that this had never happened as far as they could recall. The general solution to this kind of issues was either to re-design the actual equipment or other related equipment to remove the potential of reappearance, or change the procedure of operation to avoid unhealthy conditions for the relevant equipment.
As some of the following examples in this chapter will highlight, there have been several episodes of corrosion on insulated pipes and vessels at the KPP. Normally the insulation should not create a corrosion problem in these cases, but a combination of damages, bad design and wrong installation of the insulation made it possible for water to accumulate inside the insulation. In combination with the right temperature, this creates an environment that is conducive to corrosion. Since the pipe or vessel is totally insulated it is not possible with normal visual inspection to detect any growing corrosion before the insulation is removed or even worse, when gas starts to leak.

During the interviews it was also stated that maintenance and construction activities in combination with parts or the entire plant being in operation has resulted in some critical situations and damage to static equipment.
This chapter gives some examples of historical events at the KPP that will support the general assumptions discussed and also relate earlier topics related to maintenance of static equipment. Most of the documentation is collected from safety investigation reports created after the relevant incidents.

2.6.2.1 Gas leakage from thermowells

One issue that was brought up during interviewing the maintenance experts was historical problems with thermowells. This is a rather simple tool used for temperature measurement inside pipelines and vessels. The construction can vary a bit, but in general it is a tapered device installed from the outside of the pipe pointing in to the centre of the pipe. Inside the thermowell there are one or more sensors that measure the temperature at the inside of the thermowell.

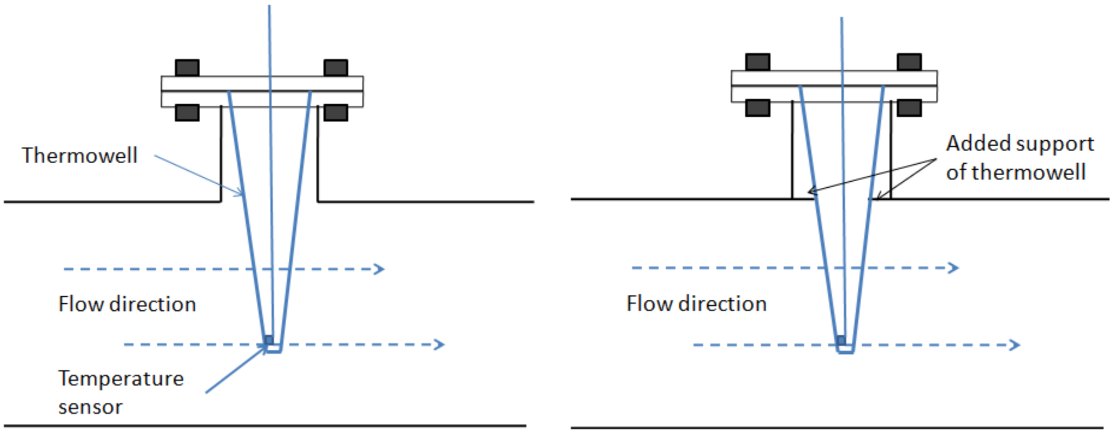

Figure 2.6.5: The principle thermowells and the solution to vibration problems

Originally a thermowell was manufactured to meet a design criterion and there were not many problems experienced. As extensions and modifications were introduced to increase the throughput, this created changes to the operation of the plant. The thermowells suddenly experienced problems as the sensors were damaged and the entire thermowell in some cases was destroyed, leading to gas leakages. It was then discovered that the change of operational environment caused the thermowells to start vibrating due to turbulence from the gas flowing past. This was solved by changing the thermowell with new ones that were designed to handle higher flow rates. This evaluation and possible implications should have been recognised before the change of operation, but this has been a lesson learned and included in later projects.

2.6.2.2 Corrosion on the Butane tower in T100

The 17th May 1989 there was a severe incidence of corrosion discovered on the T100 Butane tower. This tower was originally made out of 13 mm steel plates, but at the location of the corrosion there was only 3 mm left. The location of the corrosion was normally covered by insulation, and was discovered during regular inspection work.
The reason for this heavy corrosion on a rather concentrated spot was later concluded to be a transportation support that was not removed during installation of the tower at the plant. The tower was transported to the location horizontally and insulated before being raised up in a vertical position and installed.
The problem was that the transportation supports were not removed before insulation, and the insulation was just put around it. When the tower was put in a vertical position the transportation supports became similar to a small balcony that collected rain water and lead it under the insulation to the steel underneath. The combination of water contact and the temperature at that area of the tower created excellent conditions for corrosion.

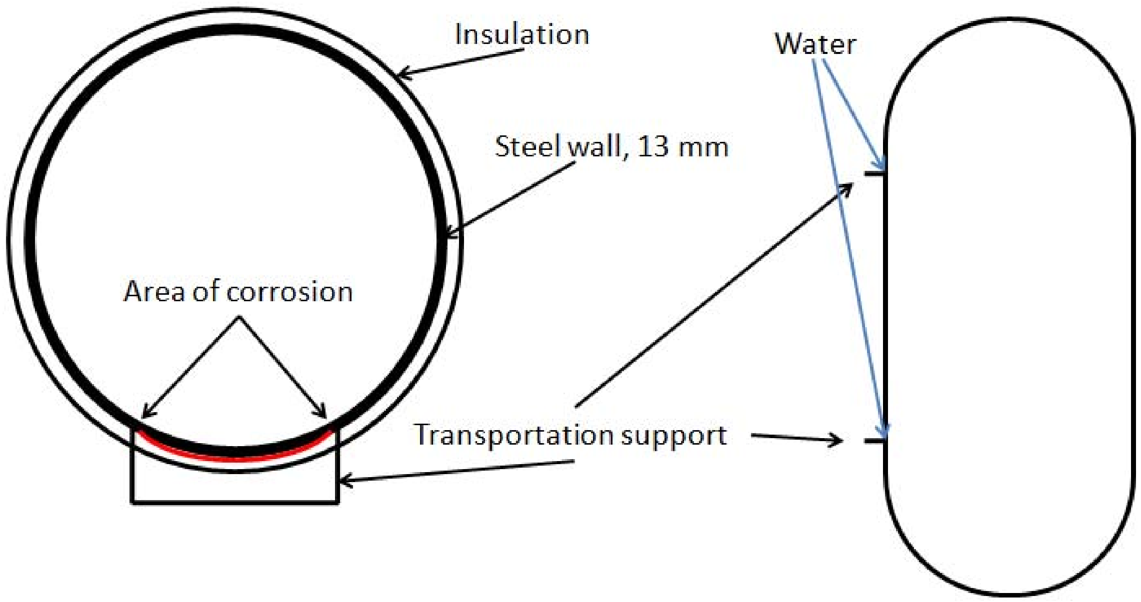

Figure 2.6.6: Illustration of the corrosion case on the T100 Butane tower. The first figure showing the tower from above and the second figure showing it from the side

To repair the damage caused by corrosion Statoil had to remove a section of the tower and weld in a new section to replace it. This was the kind of operation that was never performed in Norway previously, and no welding procedures existed stating how this should be done. The entire plant was out of operation for a long time to restore this vessel, and also to control other similar vessels that could have the same kind of problems.

During this control there were found several incidents of corrosion, but none of them were as bad as the T100 butane tower. All the remaining transportation supports were removed and new insulation had to be installed to avoid water penetration into the insulation. No automated means of CM was established.

2.6.2.3 Corrosion on T300 Stabilisation units, 2003

On June 4th 2003 (Osvåg et al, 2003) there was a gas leak discovered from a 3mm hole in a 2`` sample point on the 10`` pipe between the last condenser and the reflux container connected to Stabilisation unit 2 in T300. Stabilisation unit 2 was immediately shut down, de-pressurised and purged with N_2 to prepare for the repair of the damaged pipe. Stabilisation unit 1 was inspected in the same area and the same kind of corrosion was found with a wall thickness down to 0,4mm. It was then decided to start a controlled shut down of Stabilisation unit 1.

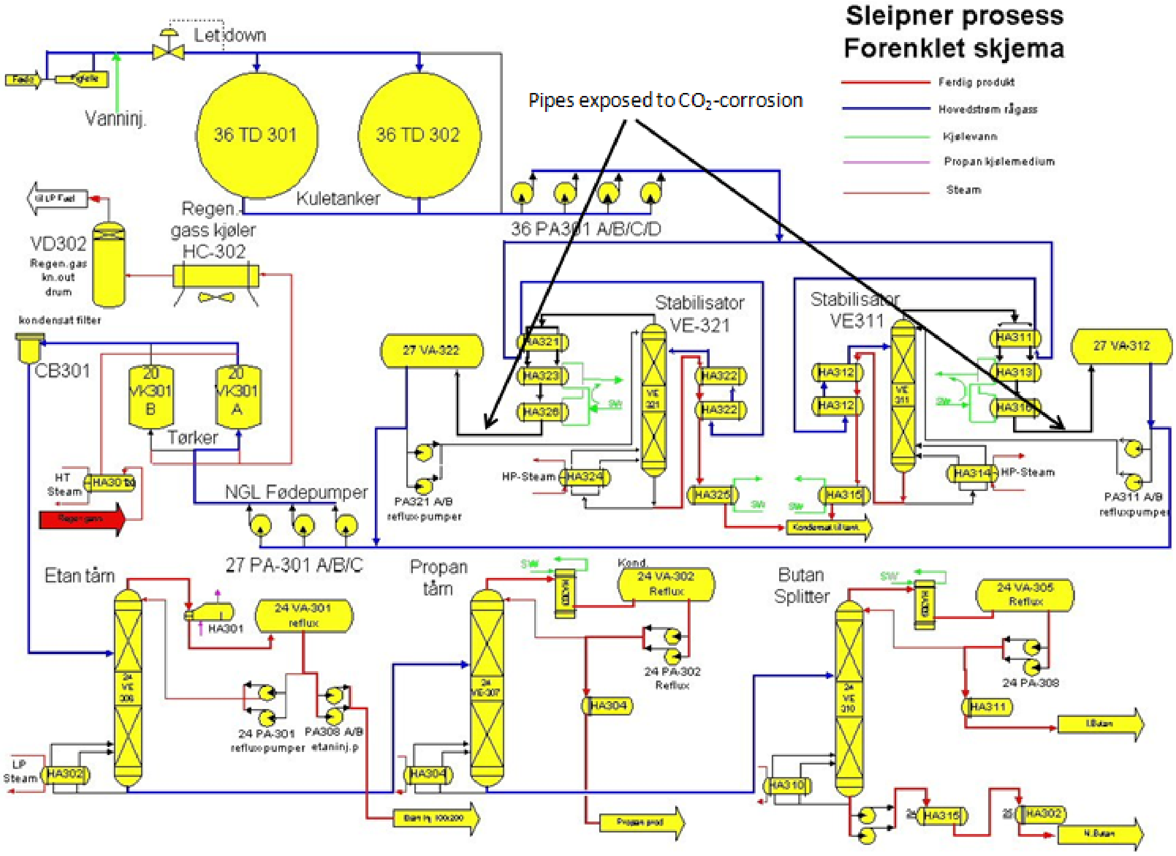

Figure 2.6.7: PDF showing the CO_2 -corrosion affected pipes in T300.

With both the stabilizers out of operation, inspection personnel started to control the 10`` main pipe between the condenser and the reflux container. Heavy corrosion was found mainly in the welding connections.
This incident resulted not only in a total shut down of T300 at KPP, but also required a full shut down of the Sleipner platforms for 8 days causing a loss greater than 50 MNOK.
During the following investigation it was concluded that there were four causes to how this could happened. These were:

- The choice of material in pipes and weldings.
- The introduction of condensate from Sleipner West, having a high CO_2 content.
- Incomplete inspection programs and routines.
- Lack of process monitoring and evaluation of change in condensate composition.

The corrosion discovered in this case was CO_2-corrosion growing from inside of the pipes in welding areas. CO_2 and free water had formed carbon acid that is highly corrosive to carbon steel and this has a tendency to be concentrated in welding areas.

Figure 2.6.8: Corroded hole in the 2`` sample point and in welding of 10`` pipe (Gassco)

The most interesting result from this incident, when relating it to the thesis, are the action points coming out from the investigation. It was stated that the choice of materials and the routines for inspection were not revised prior to the introduction of Sleipner West condensate at the KPP. A proper analysis of corrosion consequences would have discovered the potential of CO_2 corrosion when introducing Sleipner West into T300. This was not done, and the necessary changes in design and materials were not performed.
There were also organizational issues related to this episode. An incident of heavy corrosion was discovered one year before, and an inspection program for this area of T300 was initiated but never completed. If this had been completed the corrosion would have been discovered at an earlier stage and could have been dealt with in a more controlled and optimised process.

There is not much in the report discussing the possibility of introducing any kind of automated CM to avoid incidents like this in the future. The only issue mentioned in this relation is the recommendation to include condensate composition as one parameter to monitor for any changes in plant corrosion exposure.

The main conclusion though is that the materials should have been CO_2-corrosion resistant. This was the first time heavy corrosion was discovered on the inside of a pipe flowing hydrocarbons at the KPP, and could be one of the reasons why this risk was not properly investigated before introducing Sleipner West condensate in T300.

2.6.2.4 Corrosion on piping on T300 propane boiler, 2005

On 10th March and 21st Mach 2005 there were two incidents (Klyve et al, 2005) of diffuse gas leakage related to pipes entering and leaving the propane boiler in T300. In both cases the entire T300 and the Sleipner platforms had to shut down for approximately 2 days causing a loss of production of app. 37 000 tonnes and 30 000 tonnes un-stabilised condensate.

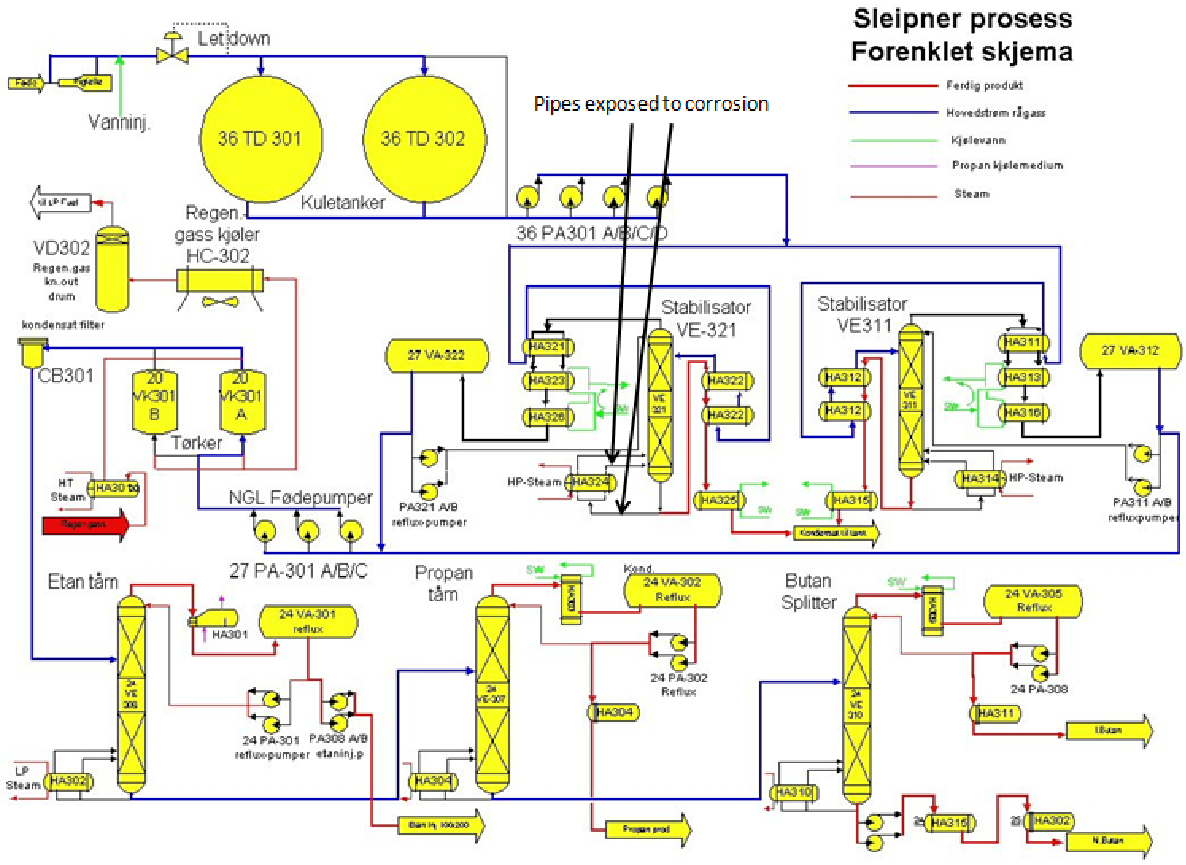

Figure 2.6.9: PFD showing the CO_2 -corrosion affected pipes in T300.

In April 2003 there was detected some local corrosion on the actual piping, and inspection personnel registered a work order to perform further investigations, and requested scaffolding to perform the work. This work was not performed for some unknown reason, and the registered work order was put aside.

When introducing a new system for organizing maintenance and inspection the old work order re-appeared but had its priority changed from “Moderate” to “Un-prioritised” without any evaluation from the inspection department.

According to the revised plan the inspection department was to start inspection the 10th March 2005, and insulation personnel were requested to remove the insulation around the actual piping. The insulation personnel claimed to smell gas during de-insulation, and this was said to increase when prickling in the corroded area. The areas were app. 70X15 cm and 20X10 cm with a corrosion depth of 8-9mm out of at total wall thickness of 10.1mm. The pressure in the pipe was 11.9 barg and the temperature app. 82°C.

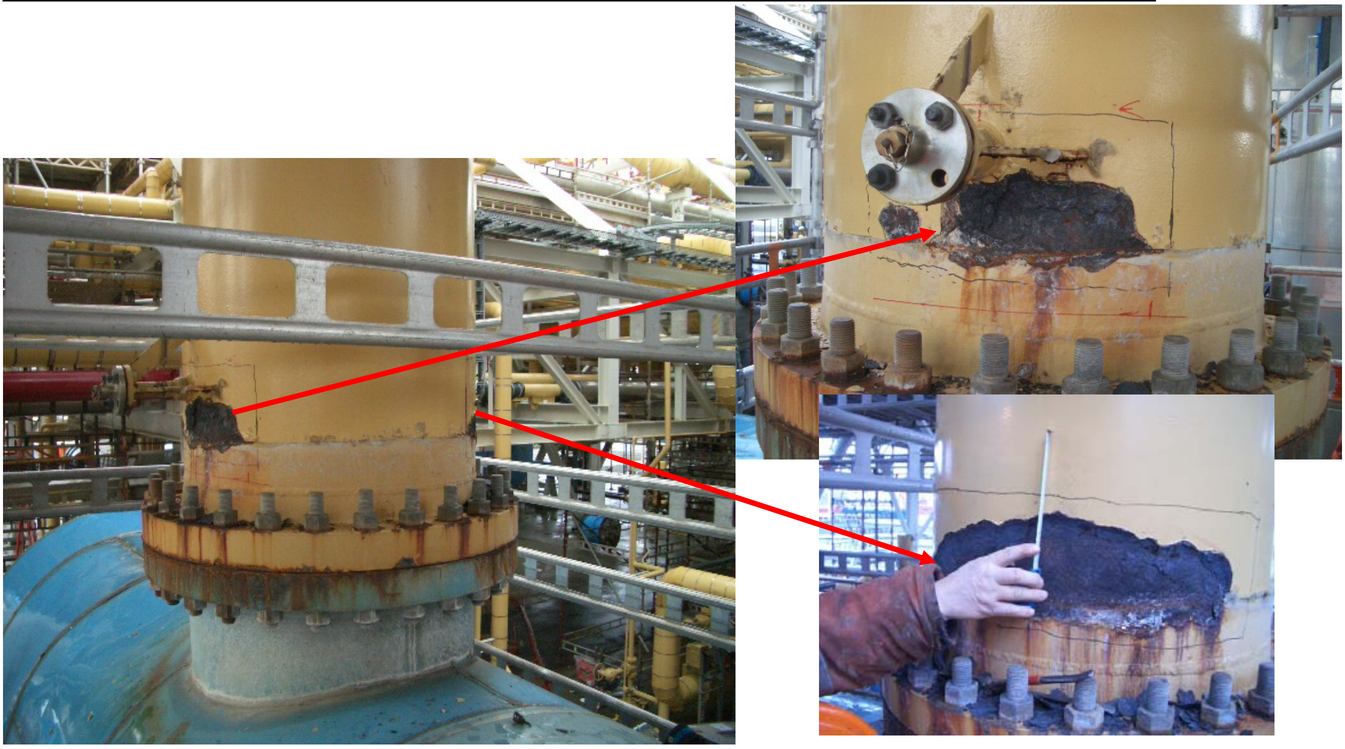

Figure 2.6.10: Corrosion on 30-PV-24-3037 (Gassco)

This detection of heavy corrosion triggered a comprehensive inspection of other insulated pipes that were operating under similar conditions and a similar case of corrosion with a diffuse gas leakage was discovered March 21st. Other incidents of concentrated corrosion were discovered during this period but none of them representing the same criticality.
The report created, based these incidents, concluded that the insulation deign was not optimal since water that managed to get into the insulation had no possibility to be drained out again. In combination with high temperature, this created a very corrosive environment that attacked weldings and HAZ-areas.
The report also concluded several recommendations of both technical and organisational nature, but none of them indicated any need for automated condition monitoring on this kind of equipment. The recommendation is rather in the direction of implementing Risk Based Inspection (RBI) and Risk Based Maintenance (RBM). Risk is defined to be Probability times Consequence. The probability is mostly related to the skin temperature and age of the equipment and the consequence mostly relate to product code and pressure.

2.6.2.5 The Removal of concrete from the Statpipe rich gas pipeline

The onshore portions of the Sleipner condensate pipeline, the Statpipe rich gas pipeline and the Statpipe sales gas pipeline are laid in three tunnels between the western coast of Karmøy and the KPP. The pipes are equipped with a corrosion protection system based on impressed current in these tunnels. During the past years high currents were recorded in the system. This was expected to be caused by stray current through the concrete anchors used to support the pipes.

The anchor bloc in the bottom of the Førlandsfjord tunnel was being removed by using a high pressure water blast device operating with a water pressure of app. 1000 bar. The three pipelines are in normal operation during the concrete removal.
The 6th October 2008 the water blast device got stuck in one position and was allowed to continue in operation for app. 30 minutes before any personnel were aware of the problem. By that time the water blast made a 460 mm long and 1.2 mm deep vertical gauge in the pipeline, but at one point the damage went 8 mm deep out of a total wall thickness of 25.4 mm of X65 steel.
This damage to the pipeline was evaluated by DNV and it was concluded that the pipeline integrity was maintained. The problem with the water blaster was discovered by a coincidence and could have made more damage to the pipe if it was allowed to continue for a longer time (Carlsen, Eide, et al 2008).
This is one of several episodes that exemplify the increased danger when performing maintenance on a system in operation.

3 Status for maintenance of static equipment at Kårstø, and possible improvements

During the search for static equipment that could be a potential for extended CM, CBM and other eOperation and/or eMaintenance related possibilities, several issues was evaluated. The thermowell problem described in 2.6.2.1 was one potential case. The initial theory was that vibration measurement inside the thermowells should give a good indication of potential future degradation and predict any need for correction. But after consulting one of my Gassco advisors (Leland) it was agreed to stop this project. The main argument was that since the problem first occurred the entire plant was checked for potential problems like this. All thermowells found to be in danger for vibration were re-designed and there have been no similar experiences since. All new changes of design or operation are also validated with regards to the potential thermowell problem.
Having in mind the definition of risk being Probability X Consequences the probability is now reduced to a level that could not justify investments in advanced eMaintenance technology.

Another potential issue was the many examples of heavy corrosion on insulated pipes. Some of these examples are described in Chapter 4, and I performed a literature search looking for alternatives to manual de-insulation followed by conventional NDT inspection. The most promising I could find was an ongoing R&D program performed in cooperation between Gassco and DNV (Gassco R&D, 2008). This R&D project has the aim to develop a hand-held probe that will use Acoustic Resonance Technology (ART) to detect water ingress into the insulation on pipes. This project has built a test facility at Kårstø, and initial tests were performed during 2008. These tests uncovered a need for modifications related to its capability to handle variations in materials and insulation thickness. Continuing testing is planned during 2009, but no breakthrough is achieved as of June 2009.

Then the suggestion of looking into the BAMHE issue appeared. It was stated from one of the Gassco processing engineers that there was un-certainties related to the operation, and a need for maintenance on these multiple heat exchangers.

3.1 Brazed aluminium plate-fin heat exchanger

At the inlet of both T410 and T420 (system area 21) there is one multiple heat exchanger installed. This is a sophisticated BAMHE having six individual product streams exchanging heat with each other. The heat exchangers are brazed and welded pressure vessel with no mechanical joints. BAMHEs are highly efficient heat transfer devices that represent a significant advance in technology, design and performance. They are used in a wide range of applications including industrial gas production, natural gas processing, refinery and petrochemical processing, and hydrogen and helium liquefaction.
This kind of heat exchanger has a very compact design and is typically representing only 20% the size of a conventional shell and tube exchanger providing the same purpose. The reason for this extraordinary performance compared to other conventional heat exchangers is the inherently high surface area, and compactness, that makes it possible to achieve close

proximity of temperature between the different streams. The heat transfer surface density can get up to 2000 m^2/m^3.
It consists of a block core of alternating layers (passages of corrugated fins). The layers are separated from each other by parting sheets and sealed along the edges by means of side bars, and are provided with inlet and outlet ports for the streams. The block is bounded by cap sheets at the top and bottom. The stacked assembly is brazed in a vacuum furnace to become a rigid core.
In general, the fluids introduced into the exchangers should be clean, dry and non-corrosive to aluminium. Trace impurities like H_2S, NH_3, CO_2, SO_2, CO, CI and other acid-forming gases do not create corrosion problems in streams with water dew point temperatures lower than the cold-end temperature of the exchanger. This is ensured by the rich gas dehydration vessels containing molecular sieve adsorbent beds and dried gas filters.
The most critical trace impurity at the KPP though is the presence of Hg in the feed gas from Åsgard transport. Hg can corrode aluminium, and therefore has to be removed to an acceptable level of concentration. In the KPP case, the design acceptances for Hg in the BAMHEs are 10 ng/Sm^3 and this is achieved by installing a Mercury Removal Unit (MRU) in the common T400 inlet facilities. The MRU is adsorbing Hg from the feed gas and is designed to last for 4 years before saturation.
The maximum working pressure for these kinds of exchangers varies from 0 to more than 100 barg, and the design temperature is normally between 65^{o}C and -269^{o}C. It is possible to have more than ten processing streams, at various pressures, in one single unit.
The KPP exchangers have a design pressure of 80 barg, design temperature between 50^{o}C and -90^{o}C and the heat exchanged with each other originates from the six processing streams.

The BAMHEs are often referred to as "cold box" due to their low operation temperatures and the fact that they actually are installed inside a box filled with insulating perlite. The units present at the KPP have a size of 4.5m(w) X 9.5m(h) X 10.4m(l) and are installed approximately 5 metres above the ground.
The manufacturing of these vessels is highly specialised and is supplied by only 5 manufacturers worldwide. The manufacturers of these exchangers have established their own standard through their common organisation called The Brazed Aluminium Plate-Fin Heat Exchanger Manufacturers' Association (ALPEMA). The objective of the association is to promote the safe use and ensure the quality for this type of heat exchanger. The standards contain relevant information for the specification, procurement and use of brazed aluminium plate-fin heat exchangers.

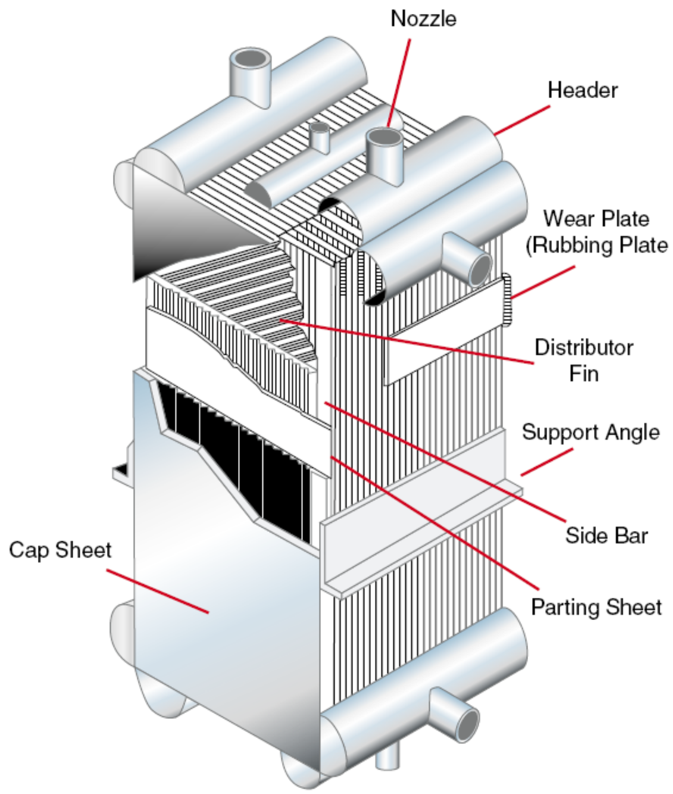

Figure 3.1.1: Example of a typical brazed aluminium heat exchanger.

3.2 Drivers to install CM on the BAMHE

The main drivers for implementing a well functioning CM system on the BAMHE are:

- T410 will be totally out of production as long as the BAMHE is unavailable. This means that an unplanned breakdown will reduce the total processing capacity at the KPP by approximately 19.5 MSm³/d. If the BAMHE in T420 is affected at the same time the loss of capacity will be doubled.

- The Ethylene plant in Stenungsund, Sweden, has experienced a BAMHE failure due to thermal stress. The Stenungsund BAMHE was not identical to the one at the KPP but similar.

- Due to the compact and sophisticated design the BAMHE; it is very difficult to repair.

- There are a limited number of manufacturers and the design is specialised. A need for replacement of a BAMHE has to be planned well in advance to minimise the down time. An unplanned replacement of the BAMHE by a StatoilHydro Engineer is estimated to take at least one year.

- The cost related to procurement, installation and commissioning of the BAMHE will be considerable.

- The value of lost production at the KPP would be significant as indicated in the following table:

	*Max daily production (MSm3/d - Tonn/day)	Unit value before the FC (NOK/m3 - NOK/tonn)	Tota value before the FC (Mill. NOK)	Unit value after the FC (NOK/m3 - NOK/tonn)	Tota value after the FC (Mill. NOK/day)	Yearly value before the FC (Mill. NOK)	Yearly value after the FC (Mill. NOK)
Dry gas	17,9	3,00	53,8	1,50	26,9	19 642,0	9 821,0
Propane	3174	5 000	15,9	2 500	7,9	5 792,6	2 896,3
I-butane	598	5 000	3,0	2 500	1,5	1 091,4	545,7
N-butane	1061	5 000	5,3	2 500	2,7	1 936,3	968,2
Nafta	910	5 000	4,6	2 500	2,3	1 660,8	830,4
Sum			82,5		41,3	**30 123,0**	**15 061,5**

*Based on max production = 19,5 MSm3/d

Figure 3.2.1: Estimated value of lost production during one year

The price of dry gas and the different liquid products from T410 have been varying considerably when comparing before and after the Financial Crisis (FC). The overview presented in Figure 3.2.1: Estimated value of lost production during one year is based on an average gas composition, average liquid recovery and prices both before and after the FC. This indicates that one year out of production will result in a loss representing a value of 15-30 Billion NOK.

- Restrictions on gas export from connected fields can lead to a cut in oil production

3.3 O&M of multiple heat exchangers

The nature of brazed BAMHEs makes it necessary to apply rather strict limitations to some areas within O&M at the KPP. The main issues of concern are:

- Control of Hg content in the different product streams
- Fouling and plugging caused by
  - Solid particles
  - Hydrates
  - CO_2
- Thermal stress
  - Start-up
  - Shut down
  - Frequent fluctuations in the product streams

3.3.1 Hg at the Kårstø Processing Plant

The Hg issue is highly relevant at the KPP since some of the reservoirs at the Åsgard field contain the cinnabar mineral, which is an Hg sulphide compound. This can lead to corrosion on non Hg tolerant equipment.

Since the presence of Hg was known before the start up of Åsgard, a MRU was installed during the Åsgard expansion project. This is adsorbing close to all Hg in the gas stream. The reduction of Hg is also desirable with respect to health and environmental considerations. During the main plant shut-down in 2004 the original MRU was replaced after 4 years of operation. After having analyzed the replaced MRU, it was discovered that it contained less Hg than expected, and that it was covered by Tri Ethylene Glycol (TEG). The TEG is reducing the adsorption efficiency, but the low Hg content in the MRU still indicated that the Hg content up-stream of the MRU probably has been less than previously expected (Staveland et al, 2005). The actual metering of Hg content up-stream and down-stream of the MRU has been performed since start-up, but this has been un-stable and impossible to reproduce for validation. After the stop in 2004 it was decided to re-design and improve the sampling system and also change analyzing methods for Hg measurement. The technology for measurement of small quantities of Hg in dense phase rich gas is not well developed. The new method implemented at the KPP is called Atomic Fluorescence Spectrometry (AFS), and the KPP laboratory is working on even further improvements of this measurement.

In parallel to this, alternative sampling methods for trace components like Hg are evaluated. The Gas Chromatograph Inductively Coupled Plasma Mass Spectrometry (GCICPMS) is expected to provide improved accuracy to the Hg measurement and is recommended as the best alternative for improved Hg control at the KPP (Kjøglum, 2007).

3.3.2 Fouling and clogging

The product streams going through the BAMHE at the KPP is normally clean and de-hydrated to a level that prevents any liquid water. The manufacturer’s requirement for the water dew point is – 70^{o}C. This is met by drying the incoming rich gas through the molecular sieve adsorbent beds, followed by particle filters.

The requirement related to CO_2 is set to maximum of 5 mol%. This should not be a problem, since the highest CO_2 concentration on any connected field is 4.2 mol%.
There have never been any problems reported with fouling or clogging in the BAMHE at the KPP.

3.3.3 Thermal stress in the heat exchangers

Thermal stress will occur in the heat exchangers due to the construction with close rigid connections in all directions. It is vulnerable to large local temperature differences, in and between the components of its structure.
Local metal temperature differences result from the components warming or cooling at different rates in response to thermal change. These differences produce a transient differential expansion or contraction within or between the components. Mechanical restraint to these thermally induced structural movements result in thermal stress in the component. If the local metal temperature differences are large, the combined thermally-induced stress and other stresses from imposed loads can exceed the yield stress and possibly, the ultimate stress of the material.
Temperature differences between adjacent parts of the heat exchanger, having the potential to produce significant thermal stresses, can arise from:

- Continuously unsteady operating conditions such as large flow fluctuations, unstable flow in boiling channels and inadequate plant control systems.
- Transient operating conditions during start-up, shut-down, plant upsets, de-riming, cool-down and warm-up.

The rate of warm-up and cool-down should be less than 1^{o}C per minute and less than 50^{o}C per hour, and a record of all relevant data should be kept for each individual start-up and shut-down. This is required if problems are discovered later in the lifetime (ALPEMA).

3.3.4 Evaluation of CM relevance to the KPP BAMHE

Based on the Kårstø Mercury Report it was chosen to assume that all product streams entering the relevant heat exchangers contain less than the recommended (ALPEMA) 10 ng/Sm^3 of Hg. The correctness of this has been discussed in 3.3.1 and it is difficult to conclude one or the other. It is important though that the Hg issue will also have focus in the future.

Based on the process setup and the use of filtering up-stream of the heat exchangers it is assumed that the probability for fouling or clogging is low. This can be monitored if sufficient pressure measurement, flow measurements and analysing tools are available.

When it comes to unsteady operation conditions and transient conditions this is very likely to occur. During shut-down and start-up the different stream flows and temperatures will be a product of what is going on in other parts of the process. The KPP central control room have included some temperature alarms in their monitoring systems, but this seems to be incomplete. Corrective measures are slow and difficult due to the lack of flow control valves on the relevant streams.

It is also of interest that the Kårstø Mercury Report included a recommendation of improving the monitoring of the BAMHEs, and that this is not finalized.

3.4 Measurement of product streams

To be able to set up a CM system for the heat exchanger it is necessary to get access to enough relevant data on the product streams going through the heat exchanger, ensure the quality of the data and understand the connection between the different streams. The Figure 3.4.1, Figure 3.4.2 and Figure 3.4.3 gives an overview of the different streams and how they are connected.

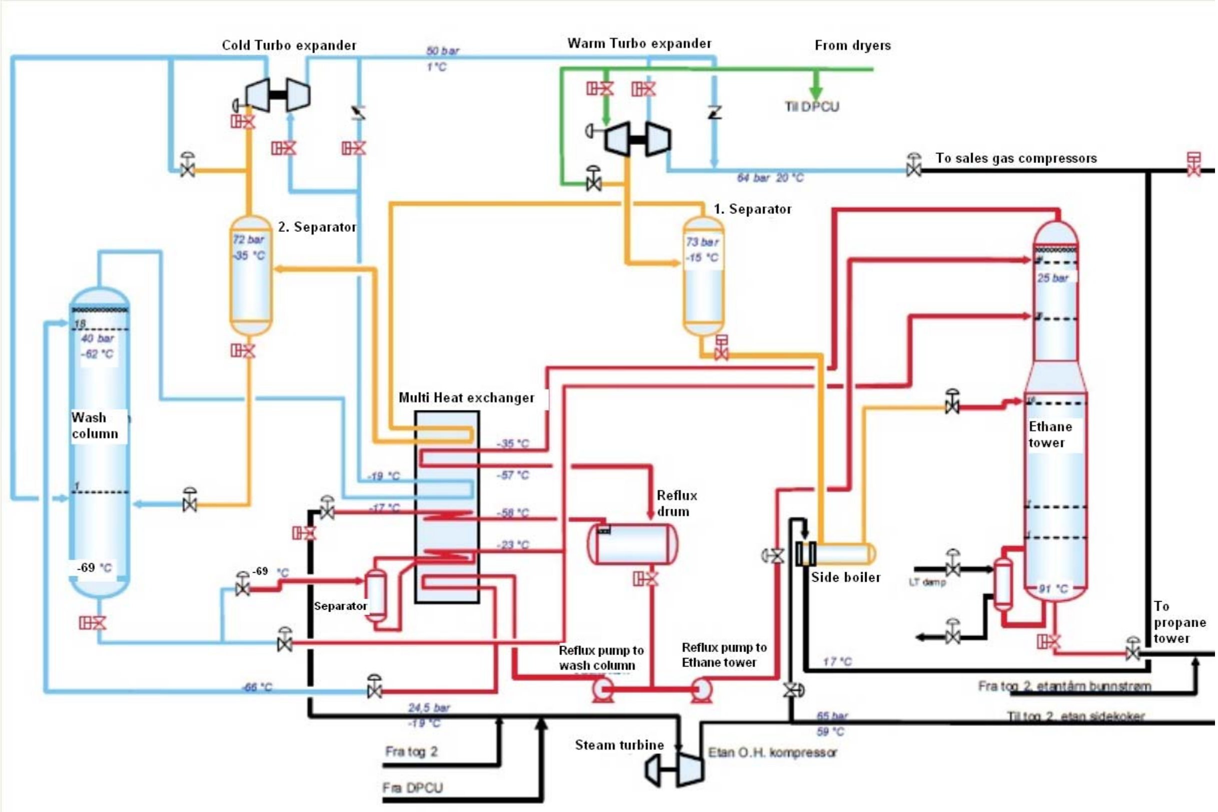

Figure 3.4.1: Process flow diagram for the product stream using the BAMHE

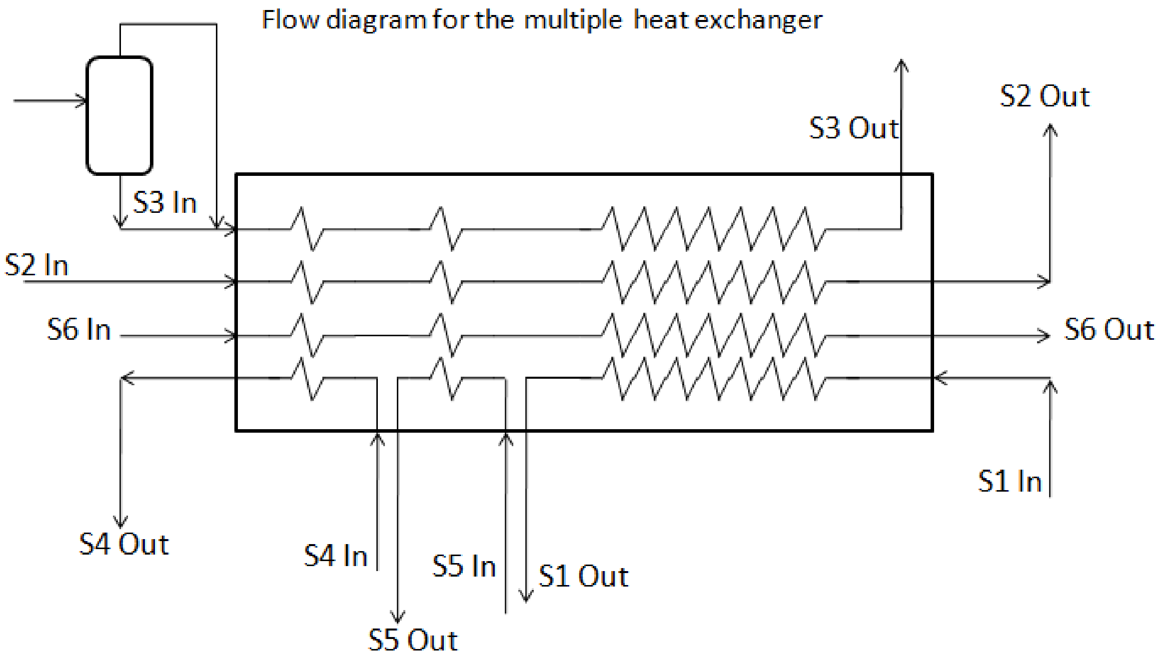

Figure 3.4.2: Flow diagram of the BAMHE.

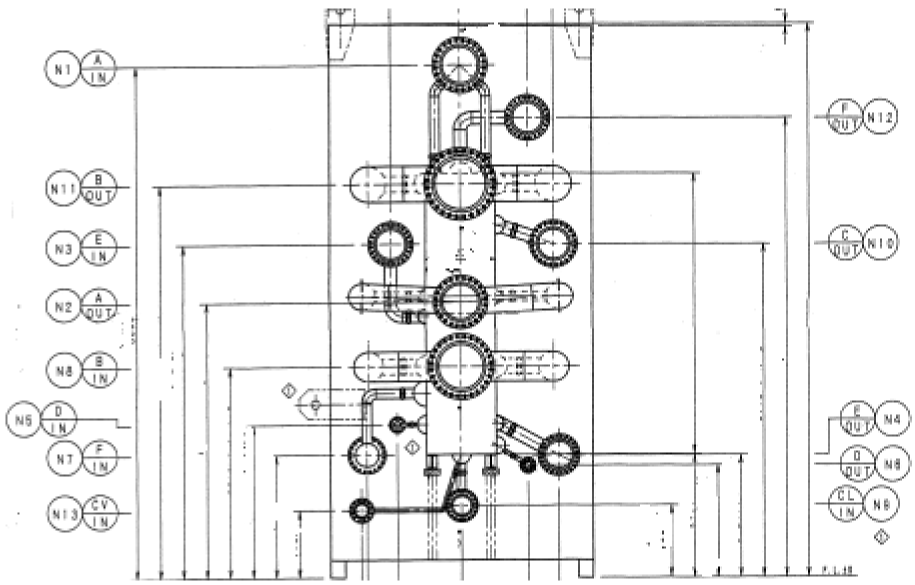

Figure 3.4.3: The placing of product stream nozzles in relation to each other.

To help understand and visualise the relation between the different streams Tabell 3.4.1 gives some data from the BAMHE Data specification Sheet.

	S1 In	S1 Out	S2 In	S2 Out	S3 In	S3 Out	S4 In	S4 Out	S5 In	S5 Out	S6 In	S6 Out
Vapour/Liquid	V/(L)	V/L	V	V	L/(V)	L/V	L	L	V	V/L	V	V
Temp [deg. C]	-15,88	-35,4	-60,9	-18,88	-69,25	-23,03	-53,6	-66,2	-35,29	-57,63	-57,63	-18,88
Pressure [Bara]	73,6	73,2	42,4	41,8	28,7	27,7	65,8	65,4	27	26,8	26,8	26,4
Flow [kg/hr]	633967		469102		228405		63540		281690		128030	
Heat exchanged [kW]	17385,4		16276,8		16122		649,5		17541,7		3177,9	

Tabell 3.4.1: Data Sheet for the BAMHE (incomplete).

3.4.1 Existing processing data

To limit the amount of work, it was decided to limit the scope and only focus on the heat exchanger in T410. T410 and T420 are identical processing trains having their feed gas from the same source, and by that it should be possible to copy the T410 CM system to T420.
The result from the search for existing processing data is displayed in Tabell 3.4.2. This shows that all the stream temperatures are available; six stream pressures, and only one of the stream flows.

Processing data - T410

	S1/A	S2/B	S3/C	S4/D	S5/E	S6/F
Inlet temp	21-TI-4166	21-TI-4323	21-TI-4194	21-TI-4191	21-TI-4335	21-TI-4192
Outlet temp	21-TI-4301	21-TI-4302	21-TI-4195	21-TI-4306	21-TI-4187	21-TI-4190
Inlet pressue	21-PI-4163	21-PI-4324	21-PI-4328			
Outlet pressure		21-PI-4158	21-PI-4345	21-PI-4327		
Flow		21-FI-4153				

Tabell 3.4.2: Available processing data for the T410 BAMHE.

3.4.2 Evaluation of existing processing data

The different processing measurements are not necessarily placed at the inlet or outlet of the heat exchanger and by that there is a possibility for the measurement to deviate from the actual conditions inside the heat exchanger. To evaluate the quality of the measurements Tabell 3.4.3 is prepared to present a comparison between average metre readings and the data sheet for the heat exchanger. The average metre readings are prepared and based on raw data from five months in the year 2007 interpolated into one sampling per 5 minutes. Each metre reading are also calculated a difference value from the equivalent stream value from the heat exchanger Data Sheet.

	21TI4166 S1 In	21TI4301 S1 Out	21TI4323 S2 In	21TI4302 S2 Out	21TI4194 S3 In	21TI4195 S3 Out	21TI4191 S4 In	21TI4306 S4 Out	21TI4335 S5 In	21TI4187 S5 Out	21TI4192 S6 In	21TI4190 S6 Out
January 2007	-17,700	-33,041	-60,794	-18,329	-67,798	-20,185	-56,927	-68,131	-35,478	-59,669	-59,820	-18,225
Diff	-1,820	2,359	0,106	0,551	1,452	2,845	-3,327	-1,931	-0,188	-2,039	-2,190	0,655
May 2007	-16,564	-32,282	-59,197	-17,177	-67,343	-19,154	-55,944	-64,045	-34,670	-59,120	-59,230	-17,080
Diff	-0,684	3,118	1,703	1,703	1,907	3,876	-2,344	2,155	0,620	-1,490	-1,600	1,800
July 2007	-16,518	-32,296	-60,152	-17,183	-67,414	-19,000	-56,244	-67,638	-34,863	-59,186	-59,274	-17,078
Diff	-0,638	3,104	0,748	1,697	1,836	4,030	-2,644	-1,438	0,427	-1,556	-1,644	1,802
August 2007	-16,655	-31,894	-60,221	-17,195	-67,271	-19,080	-56,160	-67,523	-33,986	-59,331	-59,407	-17,134
Diff	-0,775	3,506	0,679	1,685	1,979	3,950	-2,560	-1,323	1,304	-1,701	-1,777	1,746
Decembre 2007	-16,447	-31,449	-58,062	-16,978	-65,726	-18,670	-53,933	-63,866	-33,127	-57,125	-57,215	-16,839
Diff	-0,567	3,951	2,838	1,902	3,524	4,360	-0,333	2,334	2,163	0,505	0,415	2,041
Data sheet	-15,880	-35,400	-60,900	-18,880	-69,250	-23,030	-53,600	-66,200	-35,290	-57,630	-57,630	-18,880

	21PI4163 S1 In	21PI4324 S2 In	21PI4158 S2 Out	21PI4328 S3 In	21PI4345 S3 Out	21PI4327 S4 Out	21FI4153 S2 Out
January 2007	71,473	39,714	38,098	39,587	24,800	39,672	486,280
Diff	-2,127	-2,686	-3,702	10,887	-2,900	-25,728	17,178
May 2007	71,780	40,727	39,513	40,595	24,544	40,659	419,837
Diff	-1,820	-1,673	-2,287	11,895	-3,156	-24,741	-49,265
July 2007	71,822	39,892	38,585	39,738	24,727	39,800	435,364
Diff	-1,778	-2,508	-3,215	11,038	-2,973	-25,600	-33,738
August 2007	71,471	39,466	38,575	39,293	24,472	39,365	364,390
Diff	-2,129	-2,934	-3,225	10,593	-3,228	-26,035	-104,712
Decembre 2007	71,432	40,782	39,548	40,618	24,721	40,723	412,221
Diff	-2,168	-1,618	-2,252	11,918	-2,979	-24,677	-56,881
Data sheet	73,600	42,400	41,800	28,700	27,700	65,400	469,102

Tabell 3.4.3: Comparison between metering and Data Sheet.

The result from the data comparison indicates that some of the metered parameters are deviating significantly from the expected values. This indicates either that the processing data is not representative of the condition inside the heat exchanger or that the process is running at different conditions than expected from the Data Sheet. If a more thorough investigation was performed to establish the actual condition, it is expected that the differences documented in Tabell 3.4.3 will be explained as a combination of the two.

3.4.3 Need for more data and increased accuracy

As seen from Tabell 3.4.2 and Tabell 3.4.3 there are temperature readings connected to all streams to and from the heat exchanger, but there might be a potential for improvement on some of them.
There are only pressure readings on 6 out of 12 streams, and some of them are not giving any useful information. This makes it difficult to search for any tendencies with regards to fouling or clogging and un-stabile flow conditions.
There is only one stream having flow measurement and this makes it difficult to follow the actual heat value transferred to or from the different streams. Flow measurement would help detect un-stabile flow conditions and the establishment of an energy exchange calculation.
It has been established that any plastic deformation of a material is accompanied by an acoustic energy emission. By recording any acoustic emission signals emitted by the BAMHE during its rise in pressure, the elastic integrity of the stressed structure can be ascertained by the absence of a signal. Installation of one or more acoustic sensors would increase the possibility for early detection of any plastic deformation.

To complete the picture of the heat exchanger’s condition it could be a benefit to install vibration sensors at the different inlets and outlets. This could detect vibration either from its own support, the connected pipes, or any vibration from loose parts inside the heat exchanger.

3.5 Description of a CM system for the multiple heat exchanger

The scope for a potential CM system of the heat exchangers could be:

- Visualisation of current working condition in the heat exchanger
- Indication of fouling or clogging
- Trending of historical working conditions
- Analysing tools to predict behaviour based on historical data
- Logging of measured Hg content both up-stream and down-stream the MRU
- Prediction of remaining life time
- On-line analysing of data both for internal and external expertise

3.5.1 Visualisation of working conditions

Today there is no specialised monitoring picture focusing on the BAMHE, but the operators in the KPP central control room can see some relevant data on monitoring overview pictures. This gives them an idea of what is going on, but not enough details to reflect on optimising the BAMHE conditions.
If they had one or more monitoring pictures available on their screens to visualise the operational conditions in the BAMHE this could help the situation. The monitoring picture should be focused on the BAMHE showing the streams and the relevant data for these streams. It should also calculate:

- Differential pressure between entry and exit per stream
- Heat transfer per stream
- Overall heat transfer imbalance

The differential pressure calculations should have individual alarm limits to notify the operator when the pressure difference exceeds pre-defined limits. The overall heat transfer imbalance is calculated by adding up all the calculated heat transfer figures. This imbalance will give an indication of the quality of the visualised data. If the imbalance is large or is showing an increasing tendency, this indicates that something is wrong either with the BAMHE or the visualised data, and specialists should be involved to sort this out.
The Figure 3.5.1 is an example of how the data, relevant for the operators, can be displayed and organized. This should make it easy for the operator to get a good overview of the working conditions, at the same time as it can provide useful indications of things that could be further optimised. This CM picture will also be a good starting point for process engineers performing more thorough investigations related to the operation of the BAMHE.

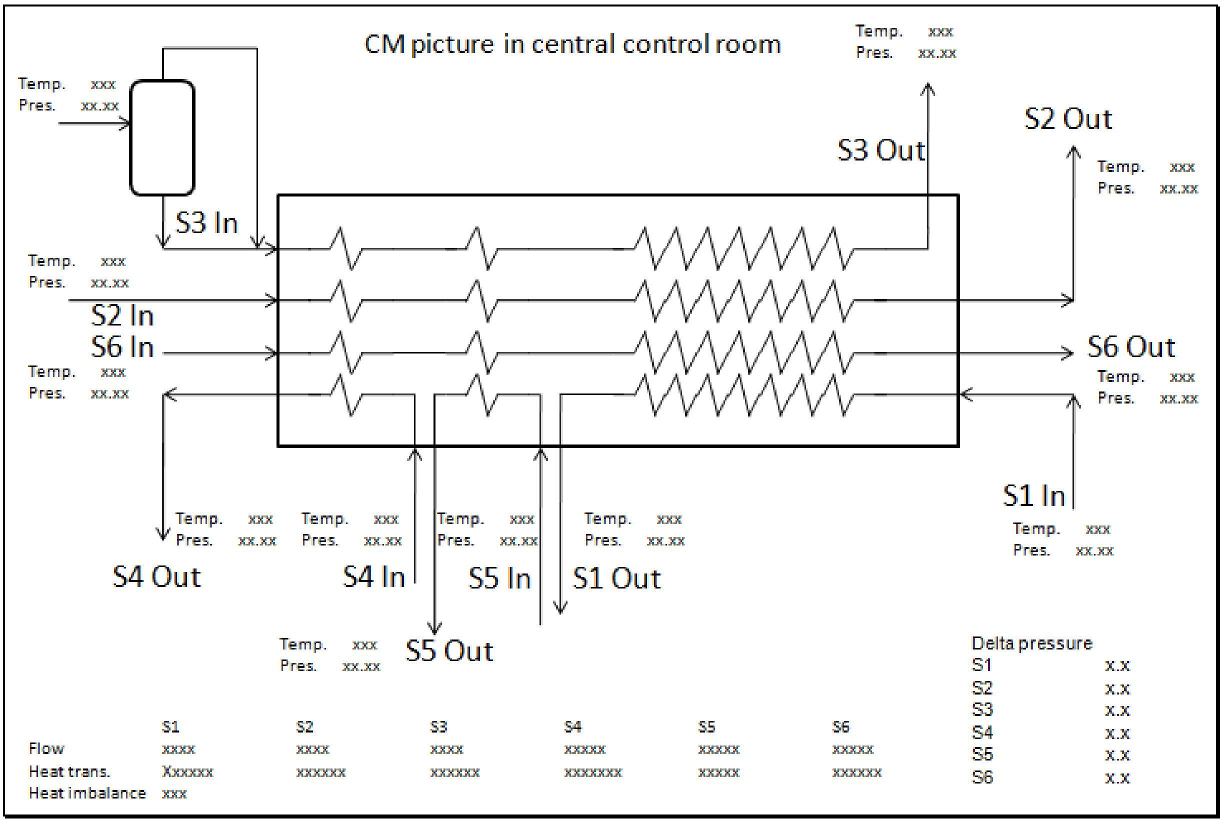

Figure 3.5.1: Proposed CM picture for use by control room operators.

3.5.2 Data storage of CM data

All sampled data related to the BAMHE should be stored in a central data server that provides possibilities for external access through a secure data network (SOIL). The data server should be able to serve several users at the same time and at a close proximity to real time access speed.

3.5.3 Access to data for internal and external experts

Selected personnel or organisations should be granted access to the data base and the BAMHE data. This makes it possible for them to set up their own CM system specialised for their specific purpose.

3.5.3.1 Process engineers

Process engineers responsible for follow-up of the BAMHE need access both to the operator CM picture, but also the historical data and analysing tools able to collect data from processing equipment. The processing engineer can then perform simulations to seek the optimal way of running the plant during different situations and upsets.

3.5.3.2 Remote support centre

One or more remote support centres could be hooked up to the database, monitoring the operation of the BAMHE to perform evaluations of performance, prediction of necessary maintenance, and predictions of remaining life time.

3.6 Predicting remaining lifetime

The prediction of remaining life time of the BAMHE is a complicated and highly specialised task. The manufacturers seem to limit the documentation of design and consequences of rough operation as limited as possible to their customers and other interested parties. The documentation of the BAMHE only states the operational limits to stay within the guarantee requirements, but does not relay specific details about the technical consequences of breaking down.
StatoilHydro as Technical Service Provider (TSP) at the KPP is running a project with the aim of establishing the remaining lifetime of the BAMHE. They have concluded that the manufacturer is the best suited party to perform such an evaluation. The TSP will try to collect relevant historical data to meet the manufacturer’s need as much as possible.
The most challenging issue related to these calculations are the effect of thermal stress in combination with the presence of Hg.

3.6.1 Technical support centre

The manufacturer seems to be the best suited party to set up a future support centre for continuous or frequent diagnosis of the BAMHE’s condition, but alternatives should be sought out. If possible, an independent support centre would be the preference, to avoid any conflicting business interest when evaluating the need for service or replacement.

To assist with this aspect, ALPEMA should include detailed information of necessary measurements required to set up support centres. This would provide the customers with the required measurements during technical specification of their asset.

NORDON CRYOGENIE is already using a self developed modelling system (Nordon Cryogénie, 200?) to:

- Calculate the outlet temperatures of each stream as in Figure 3.6.1
- Calculate the temperatures of each stream in all areas of the exchanger
- Calculate the parting sheet temperatures at all points.

These calculations can be made in steady-state conditions, as well as transient conditions during start-up, shut-down, change of operating cases, plant upsets etc.

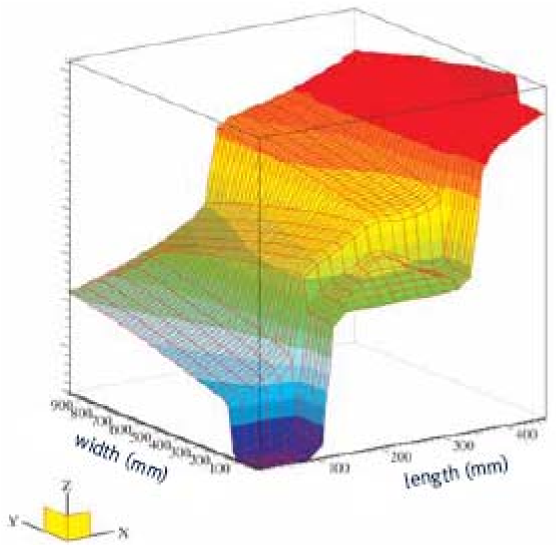

Figure 3.6.1: 3D representation of parting sheet temperatures of a Multi-pass cross flow heat exchanger (Nordon Cryogénie, 200?)

The next step will be to perform continuous stress and contaminant calculations based on online data, and report to the customer:

- How the different operational situations has affected the BAMHE.
- Areas of the BAMHE that have been most exposed to thermal stress.
- The most likely areas for Hg deposits.
- Updated calculations of expected remaining lifetime.

4 Installation of additional instrumentation

The need for both more measurements and more accurate measurements will always be linked to the question of cost, technical feasibility and the value of information gained It is expected that a functioning system for CM of the BAMHE would require improvements to the existing measurement.

4.1 Measurements

4.1.1 Temperature measurement

Temperature sensors are the main source of information to determine thermal stress. These sensors should be placed as close as possible to the entry and exit of all streams. The temperature sensors should be of a type, and installed in a way that facilitate quick response to changing operational conditions.

4.1.2 Pressure measurement

Pressure sensors are the main source of information to reveal fouling and clogging. These sensors should be placed as close as possible to the entry and exit of all streams. Accurate and efficient detection of pressure drops will be of great importance to initiate proper action.

4.1.3 Flow measurement

Flow measurement is essential to complete the CM system related to thermal stress. Each product stream should be equipped with flow measurement that is accurate enough to perform thermal stress calculation. The flow measurement would also help the detection of slugging.

4.1.4 Mercury measurement

The Hg control should be prioritised to improve the safety of the BAMHE, the quality of the processed products, and the environment in general. This will include the installation of a GCICPMS. In addition, further measures will be required to restrict the pollution by TEG on the MRU and on the GCICPMS sensor.

4.2 Wireless data transmission

The conventional solution for data transmission between a sensor and the monitoring system is the use of cabled connections. The development of wireless communication have recently experienced significant progress, and is increasingly considered as a secure and cost efficient solution for communication between sensors and the CM system (Liyanage, 2008). Different protocols for wireless communication are developed, such as WPAN, WiFi, WiMax, MobileFi, and post-3G. Out of the protocols mentioned, different subcategories of WPAN are developed. Two of the most relevant alternatives will be briefly presented.

4.2.1 WPAN, IEEE 802.15.1

The WPAN IEEE 802.15.1 is also known as Bluetooth. This can provide “secure” communication between devices such as PDAs, mobile phones, laptops and PCs. This is a widely implemented and well documented protocol, but due to its popularity amongst PC and mobile phone manufacturers there is experienced hacking on devices using this communication protocol. This could jeopardize the safe operation of the asset and needs to be evaluated before implementation.

4.2.2 WPAN, IEEE 802.15.4 WSN

The WPAN IEEE 802.15.4 WSN is also known as ZigBee. This is developed to provide low cost with low data transmission rate. This enables it to operate with a low power consumption and error resilience features. The ZigBee protocol is mostly used by wireless keyboard/mouse, remote controls, light-switches and temperature monitoring for automatic heating control.
Due to the use of static channels, it is susceptible to background noise and radio interference. This makes it less robust in industrial applications.
A further development called ZigBee Pro is available including the option to change channels when experiencing noise/interference. This version is developed for industrial use.

4.2.3 WirelessHart

WirelessHart is part of HART Field communication Specification, Revision 7.0.
It allows for wireless transmission of HART messages and is based on IEEE 802.15.4 PHY with a modified MAC Layer.
It utilises full mesh network topology and adaptive frequency hopping.
StatoilHydro have implemented this solution to perform temperature measurements on 13 wellheads at Gullfaks A. The 13 temperature transmitters are set up in a network; coordinated and controlled by a gateway, updating every 30 seconds. The range of the wireless communication is approximately 30m (Carlsen, Petersen, 2008).

4.3 Power supply

The conventional solution for power supply to sensors and transmitters has been cables. The development of battery technology and sensor self testing sequences makes battery power a satisfactorily alternative. If battery supply is preferred, a system to predict battery replacement has to be established. The BAMHE is placed 5 metres above the ground level and will require scaffoldings to be accessed. The preferred strategy for this kind of replacement would be campaign replacement.

In the StatoilHydro example at Gullfaks, battery power supply has been implemented. The specified lifetime of the batteries is five years.

5 Discussion

The intention of this thesis was to seek the possibility to include CM, CBM and IO principles on any static equipment present at the KPP. The literature search for CM, CBM, IO, eOperation and eMaintenance in relation to static equipment gave a limited result. After having discussed this with a representative from Center for Intelligent Maintenance Systems (US) it was recommended to either focus on specific equipment and search for manufacturer recommendations with regards to CM and IO principles, or use general literature covering the principles from eMaintenance and relate this to equipment at the KPP.
Studies of general literature were initiated with focus on searching for principles that could fit for static equipment. Other sources of information at this time were investigation reports from the KPP and discussions with the Gassco advisors. The most relevant findings were documented but mostly the cases were related to corrosion of insulated pipes or vessels. There was not any proven technology discovered to solve this and the search for other equipment continued.

Finally it was suggested by one of the Gassco processing engineers that the “cold boxes” (BAMHE) at the KPP could be a relevant case. This was rather late in the thesis process but it sounded interesting and also promising for the thesis.
A search for design data of the BAMHE gave some results, and a picture of how this unit is functioning was established. The general remark when contacting StatoilHydro representatives for more detailed design data was that this was not available for them and that the manufacturer was rather reluctant to provide this information. This was the general attitude amongst the different manufacturers and was regarded as part of the industry secrets.
P&IDs for the BAMHE and the relevant product streams was studied to detect all relevant existing measurements, and historical data was downloaded.

StatoilHydro representatives were also questioned to explain how the BAMHE was included in their monitoring systems and what procedures were applied during the different phases of operation and the response provided a fairly good overview.

The uncertainties in this thesis are mostly connected to providing sufficient and accurate measurement data relayed to a support centre with their needs for establishing an online CM model.

The mercury report conclude that the Hg content in the feed streams of the BAMHE have been within the ALPEMA limits, but this will never be known for sure. Also the existing Hg measurement system is a rather special type, but there are no indications that too high concentrations of Hg are getting into the BAMHE. Further improvements in Hg measurement should be found.

The BAMHE manufacturer might continue their reserved attitude with regards to sharing information, and this can make it difficult to establish the necessary trust between the support centre and the O&M personnel.

It was planned to perform a historical evaluation of the BAMHE operation, but this was not possible based on the available details and data. StatoilHydro is working on a project to retrieve enough information for an evaluation of remaining lifetime.

The thesis has only been looking at the BAMHE and not included studies of the surrounding equipment. If included, this would provide a broader understanding of why the BAMHE is operated the way it is.

During shut down and start up of the plant there is no direct flow control on the different streams. This can result in large temperature differences inside the BAMHE. A further study of the BAMHE should include pro and cons for installing measures of flow control on some or all of the streams.

6 Conclusions

The master thesis has documented that the combination of CM, CBM and IO related to static equipment is not focused on in the literature yet, but when studying general literature the subject seems to be mentioned more frequently as time goes by.

It is of great importance to be in control of the condition of static equipment. Several of the incident reports studied related to this kind of equipment have documented large economical losses.

Serious damage has been experienced at the KPP due to lack of organisational excellence. There are several incident reports explaining the reason for failure linked to prior detected fault conditions that were ignored.

In some cases it can be enough to do a proper evaluation of equipment design compared to physical working conditions, and by that conclude that the evaluated equipment should be out of danger for known failure mechanisms. At the KPP this is a part of the evaluation done in the Risk Centred Maintenance (RMC) program.

The optimal function of the BAMHE is essential for the performance of the entire T410. If the BAMHE is out of service the T410 gas processing will stop.

If the BAMHE experiences an unexpected critical failure, it will probably take more than a year to replace it. This is due to the limited number of manufacturers and the highly specialised characteristics of the construction.

A year of full stop in T410 can in the worst case result in lost production representing values of 15-30 billion NOK.

There has never been reported any problems with fouling or clogging in the BAMHEs at the KPP.

ALPEMA should include detailed information of required measurements necessary to set up support centres. This would provide the customers with the required measurements during technical specification of their asset.

It should be installed new instrumentation on all streams having a significant difference between current readings and expected conditions at the entry and exit of the BAMHE.

There is no documentation indentified related to any comparable BAMHE in the USNRC.

Based on the previous conclusions it is found reasonable to conclude that a system for CM of the BAMHE, based on the IO principles, is possible to achieve and would provide a valuable contribution to the safe and sound operation of the KPP.

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Appendix A – Kårstø system description

Process system setup

The KPP including necessary support, utilities and ancillary systems has been developed through several steps of expanding capacity and adjustments to fulfil the at any time relevant needs for processing and treatment services from the connected fields.
The processing plant is divided into separate sub systems to sort out functions or services of similar kind. This also helps the understanding of the plant and how it is set up to provide fulfil the customers need. The dividing into sub systems has been done with the aim to meet the standards for this kind of O&G assets connected to the NCS, even though there might be some variance to this in some cases.
The following sub-chapters will give an overview of the setup and the different equipment involved in the process system and the process support, utilities and ancillary systems.

System 31, Pig Receiving Facilities

System 31 Pig Receiving Facilities T100/200 is the reception facilities associated with the T100/200 processing trains. The system consists of the Statpipe Rich Gas Pig Trap and the Kårstø Slug Catcher.

System 31 Pig Receiving Facilities T400 is the reception facilities associated with the T400 processing trains. The system consists of the pig trap.

System 36 Condensate Pipeline, Pig Receiver and Buffer Tanks

System 36 Condensate Pipeline, Pig Receiver and Buffer Tanks T300 are the arrival facilities for the Sleipner condensate into the Kårstø Gas Processing Plant.
The system consists of a Pig Receiver, two Buffer Tanks and 4 x 33% Feed Booster Pumps.
The Sleipner condensate is piped underground from the Kalstø landfall valve station to the Kårstø Gas Processing Plant. A pig receiver is provided for pigging operations, during normal operation the condensate is diverted around the receiver straight via an orifice type metering device to the buffer tanks. These tanks provide buffer storage to allow for variations in the Sleipner condensate production rate and also for variations in the T300 Facilities processing rate. The condensate is pumped from the buffer tanks to the Feed Stabilisation System (System 27).

System 15, Feed gas letdown

System 15 Feed Gas Letdown T100/200 is the pipeline inlet system associated with the T100/200 Processing trains. The system consists of a Natural Gas Heater and associated pressure let down valves.

System 15 Feed Gas Letdown T400 is the pipeline inlet system associated with the T400 processing trains. The system consists of feed gas separation and filtration, heaters and associated pressure let down valves. Crossover metering control and H_2S removal are included within this system.

The objective of the system 15 is to let the pipeline pressure down to the correct pressure for processing. Preheating is necessary to avoid hydrocarbon liquids to condense from the gas before entering the extraction system. In addition any liquids and particulate matter are removed, and H2S removal is provided on the crossover line from T400 to T100/200 to ensure that the Statpipe H2S specification is not exceeded.

System 20, Gas Pre-treatment and Liquid Dehydration

System 20, Train 100/200 Gas Pre-treatment is the gas dehydration system associated with the T100/200 processing trains. There are two trains for gas treatment and each train consists of a knockout drum, two dehydration vessels containing molecular sieve adsorbent beds and a bed regeneration system. During normal operation, one dehydration vessel is on line and one is being regenerated or on standby following regeneration. Regeneration is achieved using preheated dry gas. The wet regeneration gas is cooled and passed through a KO drum to remove any liquids before being compressed and routed to the drier feed.
A single train of liquid dehydration is also installed; this takes liquid from the slug catcher in the event of pipeline depressurisation. The liquid dehydration system is not normally in operation and will need some modifications to be brought back into use.

System 20 (Series 400) Gas Pre-treatment T400 is the Hg removal system and H2S removal system associated with the T400 processing trains.
The system consists of two Hg removal vessels feed gas filter coalescers and H2S Removal facilities. Hg removal is required to protect the aluminium multi-stream feed gas exchanger located in System 21 NGL Extraction. The H2S removal facilities ensure that the level of H2S remaining in the gas is within the sales gas specification.

System 20, Train 410/420 Gas Pre-treatment T400 is the gas dehydration system associated with the T400 processing trains. The system consists of two trains of gas dehydration. Each train consists of four dehydration vessels containing molecular sieve adsorbent beds, dried gas filters and a drier regeneration system.
During normal operation, three dehydration vessel are on-line and one is being regenerated or on standby following regeneration. Regeneration is achieved by passing dry preheated gas through the drier bed. The wet regeneration gas from the bed is then cooled and passed through a KO drum to remove any liquids before routing to sales gas compression.

System 20 Liquid Dehydration T300 is the NGL liquids dehydration system associated with the T300 processing trains. The system consists of two dehydration vessels containing molecular sieve adsorbent beds. During normal operation, one vessel is on line and one is being regenerated or on standby following regeneration. Regeneration is with HP fuel gas which is preheated. The wet regeneration gas is cooled and passed through a KO drum to remove any liquids before returning to the LP fuel gas system.

System 21, NGL Extraction

System 21 NGL Extraction T100/200 is the NGL Extraction system associated with the T100/200 processing trains. There are two trains for NGL Extraction and each train consists of a knockout drum, a turbo expander / re-compressor, a fractionation column with a number of side-stream re-boilers which rely on heat from cross exchange with the incoming gas feed stream to the unit.

System 21 NGL Extraction T400 is the NGL Extraction system associated with the T400 processing trains. Two identical trains of NGL Extraction are provided consisting of knockout drums, turbo-expander / re-compressors, a wash column and a de-ethaniser fractionation column.

System 21 (Series 500) NGL Extraction DPCU II is the additional NGL Extraction system associated with the T400 processing trains. This additional train of NGL Extraction was installed as part of the KEP 2005 project and consists of a knockout drum, Gas/Gas Exchangers, turbo-expander/re-compressor and a de-methaniser fractionation column.

The 21 systems is designed to remove NGL’s from the incoming feed gas stream to produce a gas stream with the required sales gas quality and a natural gas liquid stream.

System 27 Condensate Stabilisation T300

System 27 Condensate Stabilisation T300 is the condensate stabilisation system associated with the Sleipner processing facilities. The system consists of two identical parallel trains, Train 310 and Train 320. This description is based on the Train 310 equipment.
The stabilisation system consists of feed pre-heaters, stabiliser column, overhead condensers, reflux drum, product and reflux pumps, a re-boiler and condensate cooler.
The un-stabilised condensate from the buffer tanks is heated and fed to the stabiliser column. The column operates as a component splitter by separating the light and heavier components based on their relative volatility. The product from the bottom of the column comprises the heavier stabilised condensate and this is routed to storage. The NGL overhead product is pumped to liquid dehydration (system 20) prior to being fractionated (system 24).

System 22, Sales Gas Compression

System 22 Sales Gas Compression T100/200 is the export compression system associated with the T100/200 processing trains. The sales gas compressor system receives gas from the de-methanisers and de-ethanisers. The system comprises three Sales Gas Compressors and three Booster Compressors with associated suction drums and after-coolers. The system is designed to compress sales gas from the T100/200 processing trains, to pressures suitable for export via the Europipe II and Statpipe dry gas pipelines.

System 22 Sales Gas Compression T400 is the export compression system associated with the T400 processing trains. The sales gas compressor system receives gas from the NGL Extraction System 21. The system comprises three Sales Gas Compressors with associated suction drums and coolers. The third Sales Gas Compressor was installed as part of the KEP 2005 project. The system is designed to compress sales gas from the T400 processing trains, to pressures suitable for export via the Europipe II dry gas pipeline.
In addition the de-ethaniser Overhead Compressors are included in this system. They compress gas from the de-ethanisers so that it can be commingled with the sales gas compressor suction gas.
A rich gas bypass stream from the Gas pre-treatment is routed into the second stage of the Sales Gas Compressors via the Rich Gas Bypass Drum.

System 23, Sales Gas Metering

System 23 Sales Gas Metering T100/200 is the export gas metering system associated with the Statpipe export pipeline. The sales gas metering system receives gas from the Booster Compressors; the gas is fiscally metered by a metering skid which is dedicated to the Statpipe export pipeline.

System 23 Sales Gas Metering T400 is the export gas metering system associated with the Europipe II export pipeline. This sales gas metering system receives gas from the T100/200 Booster Compressors and the T400 Sales Gas Compressors; the gas is fiscally metered by two different metering systems, the metering skids are dedicated to T400 and T100/200.

System 24, NGL Fractionation

System 24 NGL Fractionation T100/200 is the fractionation system associated with the T100/200 Statpipe processing trains. It consists of two identical trains of equipment designated as trains 100 and 200. Each train consists of a de-ethaniser, de-propaniser, debutaniser and a butane splitter. Each of these fractionation columns has a bottoms re-boiler, overheads condenser, reflux drum and reflux pumps. The de-ethaniser also has ethane injection pumps for the ethane product.

System 24 NGL Fractionation T400 is the fractionation system associated with the T400 processing trains. It consists of a single train of equipment designated as train 400. The train consists of a de-propaniser, debutaniser and a butane splitter. Each of these fractionation columns has a bottoms re-boiler, overheads condenser, reflux drum and reflux pumps.

The fractionation process separates the NGL stream from the NGL Extraction Units (System 21) into its component products of ethane, propane, iso- and normal butane and natural gasoline.

System 24 NGL Fractionation T300 is the fractionation system associated with the Sleipner processing trains. It consists of a single train of equipment designated as train 300.
The system consists of a de-ethaniser, de-propaniser, debutaniser and a butane splitter. Each of these fractionation columns has a bottoms re-boiler, overheads condenser, reflux drum and reflux pumps. The de-ethaniser also has ethane injection pumps for the ethane product.
The fractionation process separates the NGL stream from the Condensate Stabiliser into its component products of ethane, propane, iso- and normal butane and natural gasoline. Cross connections from the T100/200 processing trains permit the full capacity of the T300 Fractionation train to be utilised.

System 29, Ethane Treatment

System 29 Ethane Treatment is the main processing system of the CRAIER plant. Its purpose is to remove CO_2 and trace lighter components from ethane such that a purer liquid ethane product is obtained. The raw ethane and CO_2 from the de-ethanisers in the T100/200 (Statpipe), and T300 fractionation trains is fed to two CO_2 Stripper columns. The columns remove methane and CO_2 from the raw ethane, the ethane product (950 kTA) is then chilled and rundown to storage. The overhead CO_2 off gas is compressed and burnt as fuel or injected into the T100/200 sales gas.

System 25, Process Refrigeration

System 25 Process Refrigeration T100/200 is the refrigeration system associated with the T100/200 Processing trains. The system is a closed cycle propane refrigeration system utilising propane product to chill the propane, and n-butane products and to condense the de-ethaniser overheads. The system consists of product chillers, condensers, high and medium pressure refrigerant drums, a propane receiver, 1 x 100% 2 stage steam turbine driven propane compressor and a product refrigerant transfer pump.
The total chilling load of 14.4 MW is achieved by letting down the pressure of the propane so that it enters the chiller at a temperature lower than the required product temperature. The liquid vaporises and is then compressed to a pressure such that when condensed using seawater it is slightly sub-cooled. The cycle or loop of pressure let down, vaporisation, and compression is continually repeated.

System 25 Process Refrigeration T300 is the refrigeration system associated with the T300 Fractionation train. The system is a closed cycle propane refrigeration system utilising propane product to chill the propane, i-butane and n-butane products, and to condense the de-ethaniser overheads. The system consists of product chillers, condensers, high and low pressure refrigerant drums, a propane receiver, 1 x 100% two stage steam turbine driven propane compressor and a product refrigerant transfer pump. The total chilling load of 14.2 MW is achieved by letting down the pressure of the propane so that it enters the chiller at a temperature lower than the required product temperature. The liquid vaporises and is then compressed to a pressure such that when condensed using seawater it is slightly sub-cooled. The cycle or loop of pressure let down, vaporisation, and compression is continually repeated.

System 25 Process Refrigeration (CRAIER) Ethane Treatment is the refrigeration system associated with the CRAIER Plant. The system is a closed cycle propane refrigeration system utilising propane to chill the ethane product, condense and reboil ethane in the overhead and base of the CO_2 strippers. The system consists of product chillers, condensers, high/low pressure refrigerant drums, a propane receiver and a 1 x 100%, 2 stage steam turbine driven propane compressor. The total chilling load of 15.2 MW is achieved by letting down the pressure of liquid propane to a level so that it enters the chiller at a temperature lower than the required product temperature. The liquid vaporised in the chiller is then compressed to a pressure such that when condensed using seawater it is slightly sub-cooled. The cycle or loop of pressure let down, vaporisation, and compression is continually repeated.

System 34, Pig Launching Facilities

System 34 Pig Launching Facilities are the pigging facilities associated with the Statpipe gas export pipeline and the Europipe II gas export pipeline. The system consists of the Statpipe dry gas pig launcher and the Europipe II pig launcher.

Process support, utilities and ancillary systems setup

System 38, TEG Collection System

System 38 TEG Collection System is the TEG collection system associated with the Kårstø facilities. The system comprises a collection header, a collection drum and a tanker loading connection.

System 42, liquid product storage system

System 42 is the liquid product storage system. The system consists of storage tanks and in the case of propane storage caverns for the following liquid products:

- Ethane
- n-butane
- i-Butane
- Propane
- Natural Gasoline
- Condensate

The table below details the number of tanks and capacity available for each product

Storage	No Off	Capacity m^3 (each)
Ethane	1	25000
Propane (caverns)	2	116070 / 133930
i- Butane	2	8000
	1	35000
n- Butane	2	20000
	1	35000
Natural Gasoline	2	17000
Condensate	2	60000

System 46, Product Chilling

System 46 (Series 100) Product Chilling is the liquid product chilling and vapour recovery system associated with the T100/200 and T300 Processing trains. The system ensures that the optimum temperatures for product storage are maintained and that vapour recovery from storage and loading can be achieved.
The system is a closed cycle propane refrigeration system utilising propane product to chill the propane, and i/n-butane products. The system consists of product chillers, condensers, first and second level refrigerant drums, a propane receiver, 2 x 50% Propane Compressors and a product liquid return pump. The total chilling load of 5.6 MW is achieved by letting down the pressure of the propane so that it enters the chiller or condenser at a temperature lower than the temperature to which the product is to be cooled. The propane liquid vaporises and is then compressed to a pressure such that when condensed, using seawater, it is slightly sub-cooled. The cycle or loop of pressure let down, vaporisation, and compression is continually repeated. In addition to chilling the product rundown, propane vapour can be recovered from the Propane Loading system. In this scenario the system operates on a partly open cycle basis.

System 46 (Series 200) Product Chilling / Vapour Recovery is the liquid product chilling and vapour recovery system associated with the CRAIER (Ethane Treatment) plant. The system is an open cycle ethane refrigerant system utilising the ethane product and consists of an ethane rundown cooler, primary and secondary flash drums and a 2 stage ethane compressor. The chilling is achieved by letting down the pressure of the ethane so that it enters the chiller at a temperature lower than the temperature to which the product is to be cooled. The ethane liquid vaporises and is then compressed to a pressure so that when condensed, using propane, it is slightly sub-cooled. In addition to cooling the ethane product rundown, ethane vapour is recovered from the Ethane Storage Tank and loading system.

System 46 (Series 400) Product Chilling / Vapour Recovery is the liquid product chilling and vapour recovery system associated with the Åsgard processing trains. The system is an open loop propane refrigeration system utilising propane product to chill the ethane, propane and i/n butane products. The system consists of product chillers, condensers, HP and LP propane drums, a receiver drum, 2 x 50% propane compressors, propane condensers and a propane rundown pump. The system was upgraded as part of KEP2005 when new HP/LP propane drums and a condenser were installed to provide additional capacity to chill the new ethane rundown chiller. The total chilling load of 12.2 MW is achieved by letting down the pressure of the propane so that it enters the chiller or condenser at a temperature lower than the temperature to which the product is to be cooled. The propane liquid vaporises and is then compressed to a pressure such that when condensed, using seawater, it is slightly sub-cooled. In addition to chilling the product rundown, propane vapour is recovered from the Propane Storage Caverns.

System 52, Steam and Condensate

System 52 (Series 100) Steam and Condensate is the steam and condensate system associated with the T100/200 and T300 Processing trains. The system is the primary heating source and supplies steam to column re-boilers, feed pre-heaters and turbines. The system consists of waste heat recovery boilers with supplementary fuel gas firing and diesel burners as backup, fired boilers, HP, MP and LP steam headers, condensate return header and condensate water treatment system for purifying the returned condensate prior to recycling as boiler feed water. The total HP steam raising capacity of the T100/200 system incorporating T300 is 475 tonnes/hr at 60 barg and 430°C. This is achieved using a combination of waste heat recovery and fired boilers. Total steam demand for the T100/200 / T300 processing trains is approximately 350 tonnes/hr. There are crossover lines between the T100/200 and T400 steam systems, the HP crossover has a design capacity of 100 tonnes/hr. In addition the KEP 2005 boiler feeds directly into this system providing a further 120 tonnes/hr of steam capacity. The design allows for a number of boiler combinations to achieve the required system production.

System 52 (Series 500) Steam and Condensate is the steam and condensate system associated with the T400 Processing trains. The system is the primary heating source and supplies steam to column re-boilers, feed pre-heaters and turbines. The system consists of waste heat recovery boilers with supplementary fuel gas burners, HP, MP and LP steam headers, condensate return header and condensate water treatment system for purifying the returned condensate prior to recycling as boiler feed water. The total HP steam raising capacity of the T400 system is 200 tonnes/hr at 60 barg and 430°C. There are crossover lines between the T400 and T100/200 steam systems, the HP crossover has a design capacity of 100 tonnes/hr. The design allows for a number of boiler combinations to achieve the required system production.

System 52 (Series 600) Steam and Condensate is the steam and condensate system upgrade installed as part of the KEP 2005 project. The system is designed to provide additional HP steam to the T100/200 / T300 system. The KEP 2005 Boiler 52-XT-601 is designed to be fueld on a combination of CRAIER offgas and fuel gas. The total HP steam raising capacity of the KEP2005 system is 120 tonnes/hr at 60 barg and 430 °C. The HP steam produced is routed directly to the T100/200 / T300 system. Boiler feed water is taken from the T100/200 condensate system.

System 53, Chemical Injection

System 53 Chemical Injection is the chemical injection system for the Kårstø facilities. The chemical injection systems at Kårstø comprise the following:

- Methanol
- Caustic Soda
- Hydrochloric Acid
- Ammonia and Oxygen Scavenger
- Glycol

System 54, Flare System

System 54 Flare System comprises the relief, blowdown and drain systems associated with the Kårstø Gas Processing Plant. The system consists of five flare disposal systems:

- Existing Cold Flare (HP)
- New Cold Flare (HP)
- Warm Flare (HP)
- Low Pressure (LP) Flare
- Offsites (system 46) Flare

Each disposal system comprises collection headers, liquid knock out drum/pumps and an elevated flare stack. The relieved gases are burnt in the flare stacks and any separated liquid returned to the process facilities. Separate flare headers are used to segregate warm and wet relief's from cold to minimize the use of low temperature materials and the potential for hydrate formation. The system has developed as the facilities have expanded with the use of HIPPS, additional knock out drums and the provision of the New Cold Flare as part of the KEP2005 project in order to maximize the available capacity.

System 55, Sea Cooling Water

System 55 (Series 100) Sea Cooling Water is the seawater cooling water system associated with the T100/200 and T300 processing trains and their utilities. The system consists of intake tunnel, intake screens, trash collector, seawater cooling pumps, distribution and return system, weir box and outfall tunnel. The system is a direct seawater cooling system whereby seawater is contacted directly with the process fluid in a heat exchanger.

System 55 (Series 400) Sea Cooling Water is the seawater cooling water system associated with the T400 Processing trains and their utilities. The system consists of intake tunnel, intake screens, trash collector, seawater cooling pumps, distribution and return system, weir box and outfall tunnel. The system is a direct seawater cooling system whereby seawater is contacted directly with the process fluid in a heat exchanger.

System 56, Tempered Cooling Water

System 56 (Series 100) Tempered Cooling Water is the tempered water cooling system associated with the T100/200 Processing trains and their utilities. There is no interconnection to the T400 tempered water cooling system. The tempered water cooling system provides cooling water to machinery users. Machinery users generally are not cooled directly by seawater as salt water contamination due to leakage is to be avoided. The system is a closed loop cooling system whereby a mixture of fresh water and glycol (to prevent freezing) is circulated to the users and then cooled against seawater in an exchanger. Two separate systems are provided, one for T100/200 and T300 process and utilities cooling and one for the T100/200 sales gas booster compressor system cooling (which was installed at a later date). Each cooling system consists of seawater / tempered water plate heat exchangers, tempered water supply and return headers, a surge drum / storage tank and circulation pumps.

System 56 (Series 400) Tempered Cooling Water is the tempered water cooling system associated with the T400 Processing trains and their utilities. There is no interconnection to the T100/200 tempered water cooling system. The tempered water cooling system provides cooling water to machinery users. Machinery users generally are not cooled directly by seawater as salt water contamination due to leakage is to be avoided. The system is a closed loop cooling system whereby a mixture of fresh water and glycol (to prevent freezing) is circulated to the users and then cooled against seawater in an exchanger. Two separate systems are provided, one for the T400 process trains, sales gas compression, ethane treatment and utility plant, and one system for the offsite facilities. Each cooling system consists of seawater / tempered water plate heat exchangers, tempered water supply and return headers, a surge drum / storage tank and circulation pumps.

System 57, Fuel Gas / Diesel Oil Systems

System 57 (Series 100) Fuel Gas / Diesel Oil Systems is the fuel gas and diesel oil system associated with the T100/200 and T300 Processing trains. Crossover lines between the T100/200 and T400 systems for LP fuel gas are provided. The fuel gas system is the primary source of power for fired heaters and gas turbines. It is also used for continuous flare system purging. Fuel gas demand for the T100/200 / T300 facilities is around 41 tonnes/hr. The diesel system is used as backup to the fuel gas system for fired steam boilers, by the emergency power generators and the firewater pumps. The users are not normally continuous and the system is designed to provide up to 25 m^3/hr of diesel. The system has been extended to include the emergency power generators installed as part of the KUP 2000 project.

System 57 (Series 400) Fuel Gas / Diesel Oil Systems is the fuel gas and diesel oil system associated with the T400 Processing trains. Crossover lines between the T400 and T100/200 systems for LP fuel gas are provided. The fuel gas system is the primary source of power for fired heaters and gas turbines in the T400 process area. It is also used for continuous flare system purging. Fuel gas demand for the T400 facilities is around 28 tonnes/hr. The diesel system is used by the emergency power generators. The system is an extension of the T100/200 system.

System 60, Instrument & Plant Air

System 60 (Series 100) Instrument & Plant Air is the instrument and plant air system associated with the T100/200 and T300 facilities. Crossover lines between the T100/200 and

T400 systems are provided. The system provides air to the consumers at 8 barg, the design capacity of the air compression system is 3369 Nm³/hr with two compressors operating, the normal air consumption for T100/200 and T300 facilities is 2492 Sm³/hr.

System 60 (Series 400) Instrument & Plant Air is the instrument and plant air system associated with the T400 facilities. Crossover lines between the T400 and T100/200 systems are provided. The system provides air to the consumers at 9 barg, the design capacity of the air compression system prior to the KEP 2005 upgrade was 3900 Sm³/hr. The system has been upgraded to a capacity of 9600 Sm³/hr as a result of the KEP 2005 project.

System 61, Nitrogen

System 61 (Series 100) Nitrogen is the inert gas system associated with the T100/200 and T300 facilities. A crossover line between the T100/200 and T400 systems is provided. The nitrogen is used intermittently for purging and blanketing purposes and continuously as buffer gas in compressor seals. Two nitrogen generation systems are provided. The main nitrogen system is an air separation plant which produces nitrogen by cryogenic distillation of air. It provides nitrogen to the consumers at 13 barg. The air separation system can be operated to produce nitrogen liquid or gas. Liquid storage is useful as it provides a supplementary supply during periods of high demand, such as start up or shut down or if the separation plant is shutdown. The second system is a membrane separation package which uses racks of membranes to separate nitrogen from air. This system is dedicated to the T100/200 booster compressor nitrogen requirements and produces nitrogen at 6 bara. This system can be supplemented with nitrogen from the main nitrogen system by a cross connection.

System 61 (Series 400) Nitrogen is the inert gas system associated with the T400 facilities. A crossover line between the T400 and T100/200 systems is provided. The nitrogen is used intermittently for purging and blanketing purposes and continuously as buffer gas in compressor seals. The system provides nitrogen to the consumers at 13 barg. Two Inert Gas Generator Packages are installed, each of 300 Sm³/hr capacity. The second package was installed as part of the KEP 2005 upgrade.

System 62, Fresh Water and Demineralised Water

System 62 Fresh Water and Demineralised Water is the water system associated with the Kårstø facilities. The water is used for general utility uses, fire main pressurisation and as a feed to the steam system demineralised water plant. The fresh water system is normally fed from Lake Storavatn which is located in the region of Kårstø. Raw water from the lake is routed to the fresh water distribution header and the Water Demineralisation Plant. Additional equipment has been installed as the Kårstø facilities have expanded to include T300 and T400 process trains.

System 63, Potable Water

System 63 Potable Water is the potable water system associated with the Kårstø facilities. The system is fed from one of two lakes in the region of Kårstø. A network of distribution headers supplies water to the consumers which include control buildings, analyser houses and substations. The network has been extended to cover the T400 process area and is extended further to cover the new KEP 2005 facilities.

System 64, Effluent Treatment

System 64 Effluent Treatment is the oily water treatment and disposal system associated with the Kårstø facilities. The system is designed to gather all effluent water. Oily water from the process areas and rainwater from potentially oil contaminated areas is treated to remove oil and clean water is returned to the sea.

The system consists of:

- A network of oily water collection headers.
- Sumps and Tanks with Pumps.
- Equalisation and Overflow Basin.
- Chemical Flocculation Unit.
- Oil/Water Separation Unit.
- Demulsifier Unit.
- Sludge Thickener (routed to disposal by Road Tanker).
- Slop Oil Storage Tank (routed to disposal by Road Tanker).

Clean water from the effluent treatment system is discharged to the sea via the seawater cooling system outfall.

System 65, Sewage

System 65 Sewage is the sewage system associated with the Kårstø Gas Processing Plant. There are three separate existing sewage systems located at Kårstø. These are connected to the Main Control Building, the Harbour Control Building and the Utility Substation.

Systems 70, 71, 72 & 73, Firewater and Firefighting

Systems 70, 71, 72 & 73 Firewater and Firefighting are the fire protection systems associated with the Kårstø facilities. The system consists of firewater pumps, a firewater ringmain, hydrants, monitors, foam monitors, deluge facilities and a fire station.

System 83 is the Emergency/Essential Power system

System 83 is the Emergency/Essential Power system associated with the Kårstø Gas Processing Plant. The system consists of four diesel driven emergency power generators. Two generators were installed as part of the Statpipe project with additional generators installed as part of the Sleipner and KUP2000 projects.