University of
Stavanger

Faculty of Science and Technology

MASTER’S THESIS

Study program/ Specialization: Offshore Technology – Industrial Technology and Asset Management	Spring semester, 2010 Open / Restricted access
Writer: Eirik Homlong	………………………………………… (Writer’s signature)

Faculty supervisor: Tore Markeset

External supervisor(s): Sukhvir Singh Panesar

Title of thesis:

“Reliability, Availability, Maintainability and Supportability factors in an Arctic offshore operating environment: Issues and challenges”

Credits (ECTS): 30

Key words: Reliability, Availability, Maintainability and Supportability factors, preventive Maintenance, Arctic conditions, Offshore Maintenance, Risk and Regularity.	Pages: ………………… + enclosure: ………… Stavanger, ……………….. Date/year

Abstract

With oil and gas production reaching its tail end on many fields on the Norwegian Continental Shelf, the industry is looking towards the Arctic to start exploration and production. It is estimated that 14% of the worlds remaining oil and natural gas reserves are found in Arctic areas, most of these offshore. The harsh Arctic conditions concerning climate, lack of infrastructure and long distances generate challenges in respect to keeping risk low and regularity high on oil and gas producing installations in this area.

The research presented in this thesis highlights the challenges concerning operation and maintenance of offshore production installations in Arctic areas. Challenges to Reliability, Availability, Maintainability and Supportability (RAMS) in Arctic areas are identified.

The case study conducted as a part of this study indicates that maintenance will be essential in keeping regularity high on an offshore oil and gas production facility in the Arctic. Harsh operating conditions can cause increases in failure frequencies, failure modes and failure mechanisms resulting in a need for different and more frequent preventive maintenance. Many maintenance tasks and corrective repairs can be expected to be more time consuming in the Arctic than in temperate areas. Furthermore, the economic model gives an overview of the increase in man-hours and costs when the activities are planned to be conducted in arctic areas.

Acknowledgement

The thesis is submitted to fulfill the degree Master of Science at the faculty of Science and Technology at the University of Stavanger, Norway. The research and writing was carried out from January to June 2010.

I would like to express my special gratitude to my supervisor Professor Tore Markeset for helping me in getting in contact with my present employer ApplySørco AS and for giving me advice and help through my two years as a student at the University in Stavanger.

I would also like to express my gratitude to my industrial supervisor, Doctor Sukhvir Singh Panesar for advice and help, my colleagues Doctor Jawad Raza, Electrical Engineer Einar Edvardsen and Joachim Juverud and Mechanical Engineer Rolf Anton Skare for help, advice and technical input.

I would also like to express my gratitude to PhD. Student Dina Kayrbekova for giving me important input on the thesis and providing help and advice in developing the model described in the thesis.

Stavanger June 15th, 2010

Eirik Homlong

Content

1. Introduction

The aim of this chapter is to introduce the background and the aim of this thesis, the scope and limitations are also explained.

1.1 Maintenance in oil & gas industry: opportunities, issues and challenges

Maintenance plays an important role in business success (Deming 2000, Löfsten 1999, Piltelton et. al., 1997). For the offshore oil and gas business maintenance expenses can be as high as 60% of the operating costs (OPL., 1991). The maintenance function has gone through big changes. From being a necessary evil where the maintenance personnel had a run-to-failure philosophy to the maintenance being a part of the integrated business concept. Piltelton et. al. (1997) states that the reason for this change is that there is more competition in the market, this makes cost control very important. The machinery and equipment is becoming more complex and the market demands a degree of flexibility, quality and reliability of supply that can only be secured by reliable and well maintained equipment. Surveys carried out in the United States indicate that one third of all costs related to maintenance are wasted as a result of bad or unnecessary maintenance (Mobley, 1990). The most important factor for an oil and gas production installation is that it is profitable. Effective operations and maintenance together with new technologies can help in reducing costs and defend production on fields with lower production levels (NPD, 2009). An effective maintenance system can significantly contribute to competitiveness in a global market, because of lower production costs, less down time and a smaller loss of production.

A definition of maintenance given by the British standard BS EN 13306 (2008) on maintenance is: "*All technical, administrative and managerial actions during the life cycle of an item, intended to retain it in, or restore it to a state in which it can perform the required function. This includes dependability, cost reduction, product quality, environment protection and safety preservation of the facilities*". Bad maintenance or failures in maintaining equipment can lead to maintenance related problems. An example is the accident on the offshore oil platform Piper Alpha in the North Sea. On July 7, 1988 where 169 persons lost their lives in a fire that started because of a routine maintenance job. A test procedure of a backup propane condensate valve led to the removal of the valve, the maintenance crew couldn't finish the job before evening and sealed the hole to continue the consecutive day. Later that evening a propane condensate pump stopped working and the backup pump with the missing valve was started. This led to a large fire. A series of unfortunate events then led to the catastrophic accident (Lord Cullen, 1990). This accident illustrates the importance of having a good maintenance and reporting system.

The Norwegian continental shelf is entering its tail end phase, even though there are resources left for many years of production there are reason to believe that the largest fields are already found and put into production. As the production goes down in temperate areas off the coast of Norway the industry looks northward to start exploration and production in the Arctic areas north of Norway. This trend can be seen in all countries bordering to offshore areas in the Arctic. As traditional sources of energy are being depleted, there is an increasing interest in exploiting oil from technically challenging areas. Challenging areas means large depth fields, smaller fields and fields in geographically remote areas such as the Arctic.

The true extent of resources in the Arctic area is unknown, the US Geological Survey (USGS) have estimated that areas north of the Arctic circle have up to 14% of the world's oil and natural gas reserves, and this is a conservative estimate because of the vast areas ignored in the study due to lack of data (Coomber, 2008). Despite of a gradual increase in temperatures and a decrease in the Arctic ice covers there are large challenges for equipment, designers and operators of these Arctic installations. To maintain production regularity on an Arctic installation similar to an installation in temperate areas there will be different changes in design, engineering and in operation and maintenance.

1.2 Problem description

Arctic conditions in the form of climate, darkness, ice, remoteness to infrastructure, etc. will cause different and bigger strains on personnel and machinery than temperate conditions do, this together with a lack of historical and factual data on offshore activities in Arctic areas makes maintenance a challenging field. To keep risks and the regularity of an offshore installation in Arctic areas similar to what we find at an installation on the Norwegian Continental Shelf (NCS) one has to be prepared to face these challenges. The focus area for this assignment will be to identify challenges for Arctic offshore maintenance, and look at how the Arctic conditions will change reliability, availability, maintainability and supportability, and how changes in preventive maintenance can help keep regularity as high in the Arctic as on the NCS. The problem description is split into three main questions listed here:

- How will Arctic conditions affect Reliability, Availability, Maintainability and Supportability (RAMS)?
- How will Arctic conditions affect preventive maintenance on an oil and gas production installation contrary to an installation on the NCS having similar demands for regularity?
- How can the regularity be kept as high in the Arctic as on the NCS?

1.3 Thesis scope and objectives

The main objective of the thesis is to establish how Arctic conditions will affect reliability, availability, maintainability and supportability on an oil and gas production installation in the Arctic. This will be reached through the following four points:

- Define how RAMS will be influenced by Arctic conditions
- Identify and suggest important design- and operational implications helping in keeping risk and regularity in the Arctic similar to the NCS
- Study statistical and experience data to establish failure frequencies, failure modes, failure mechanisms and preventive maintenance on the NCS, and use these data together with the information from sub objective one and two to make a FMECA analysis and identify differences in these factors in the Arctic compared to the NCS
- Study statistical and experience data to develop a model to estimate increases in man-hours and costs Arctic conditions cause on maintenance and corrective repairs

1.4 Limitations

- Statistical data are available for the NCS through the OREDA-2009 database. There are very little data present for machinery in Arctic areas, this means the case studies for Arctic areas haven’t got any quantitative values on failure frequencies. In the thesis the failure modes and failure mechanisms expected to have an increased frequency are identified but not quantified

- Large plant specific variables are expected for Arctic areas, this has further limited the possibility to quantify data
- The two systems covered in the case study are large systems with large amounts of components. A limitation on the equipment covered in the case study is set, meaning that some parts of the systems and bordering systems are neglected, examples are the electro chlorination packages, the foam and the water misting systems, etc.
- The systems considered in the case study have an identical setup in the Arctic and on the NCS. For much of the equipment considered increase in redundancy levels and alternative setup of the equipment could increase reliability and maintainability

1.5 Methodology

- Most of the research is done based on literature studies of reports, documents, books and databases and through informal interviews with experts. This method is qualitative meaning it is based on non-numerical data collection
- Some statistical data are obtained from statistic databases, reports and books. The research made based on these data is quantitative, meaning that numerical observation values are analyzed and interpreted to get results

Based on the data collected in the literature study and in the interviews with experts a case study is conducted. In this case study necessary changes in preventive maintenance between the Arctic and the NCS to obtain similar production regularity is defined, and differences in failure frequencies, failure modes and failure mechanisms are identified. In the case study a model is developed for predicting the increase in man-hours and costs for a preventive maintenance procedure or corrective repair in Arctic conditions compared to Norwegian Continental Shelf conditions. To develop this Model Monte Carlo simulation is used. Monte Carlo simulation is a tool that is good to model phenomena with large uncertainties in the input. In the Monte Carlo simulation probability distributions are assigned to the quantitative data obtained in the research. Repeated computation of these inputs gives an estimate of the increase in man-hours.

1.6 Thesis outline

As described in Figure 1.1 the thesis has eight chapters, where the first chapter is an introduction to the subject and the thesis. The second gives a theoretical background on the Arctic, maintenance, the factors Reliability, Availability, Maintainability and Availability (RAMS), Arctic conditions, preventive maintenance scheduling and statistical theory. The third chapter is a deeper study into Arctic conditions and the effects these have on design, operations, machinery and personnel on an oil and gas producing installation. The fourth and fifth chapter show how these conditions will affect RAMS and how regularity of the installation can be kept as high as on the Norwegian Continental Shelf despite of the harsh conditions. This research is the basis for the discussion and case study presented in chapter six. Concluding remarks and suggestions for future research can be found in chapter seven and eight.

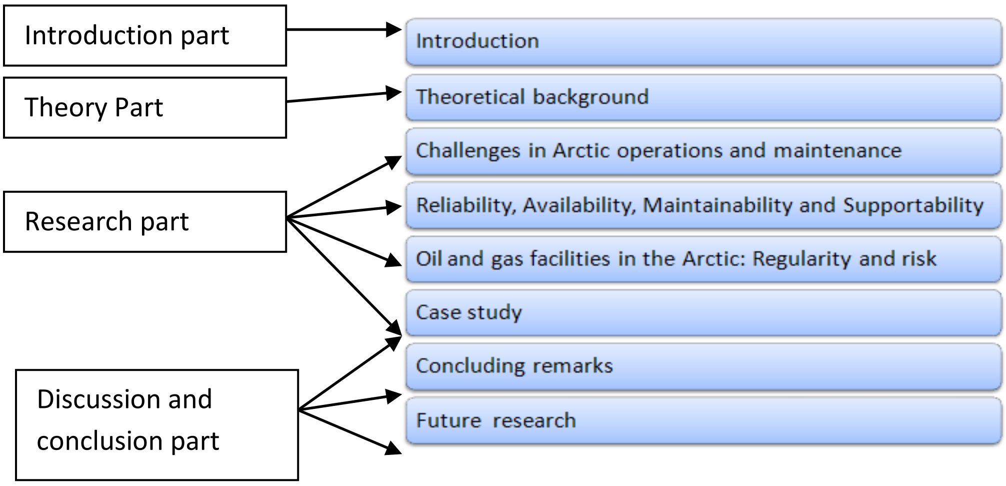


Figure 1.1 Outline of thesis

2 Theoretical background

In this chapter a theoretical background and introduction will be given on the the Arctic, the concept of maintenance, RAMS (Reliability, Availability, Maintainability and supportability) thinking and the state of the art and limitations on knowledge on Arctic offshore operations and maintenance.

2.1 The Arctic

Orheim (2003) defines the Arctic as the areas above 66`33``N (the Arctic Circle), it is covering 12 million km². This area is mostly covered with ice during parts of the year, but with climate change and melting ice caps larger and larger areas opens for geological surveys and oil and gas exploration. Together with a large demand for energy, problems with keeping up production in easier available areas and development of new technologies, exploration in these areas become more and more interesting. The common view that the Arctic is pristine and vulnerable makes the legislation considering pollution and outlets to sea and air very strict. The climate and dark season together with large distances and bad infrastructure makes logistics, spare parts and resupplying a large challenge in the Arctic.

Denmark (Greenland), Canada, USA, Russia and Norway are the countries bordering the Arctic which are actively working to find hydrocarbons on their continental shelves. The true extent of resources in the Arctic area is unknown, the US Geological Survey (USGS) have estimated that areas north of the Arctic Circle have 90 billion barrels ($1,4x10^9$ m^3) of undiscovered technically recoverable oil, and 44 billion barrels ($7x10^9$ m^3) of natural gas liquids. That means up to 14% of undiscovered oil and gas resources can be found in the Arctic regions, it is estimated that 84% of this is offshore resources. (U.S. Geological Survey, 2008) this is a conservative estimate because of the vast areas was ignored in the study due to lack of data (Coomber, 2008). Figure 2.1 and table 2.1 show undiscovered oil in the Arctic and the results of the 2008 U.S. Geological Survey appraisal.

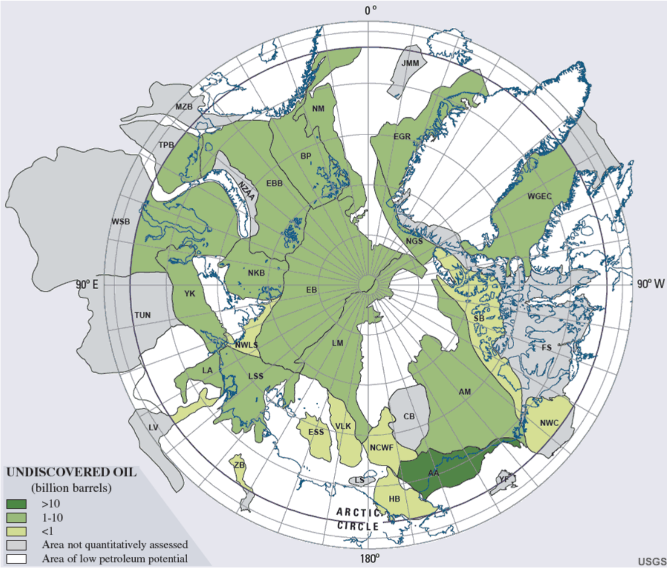
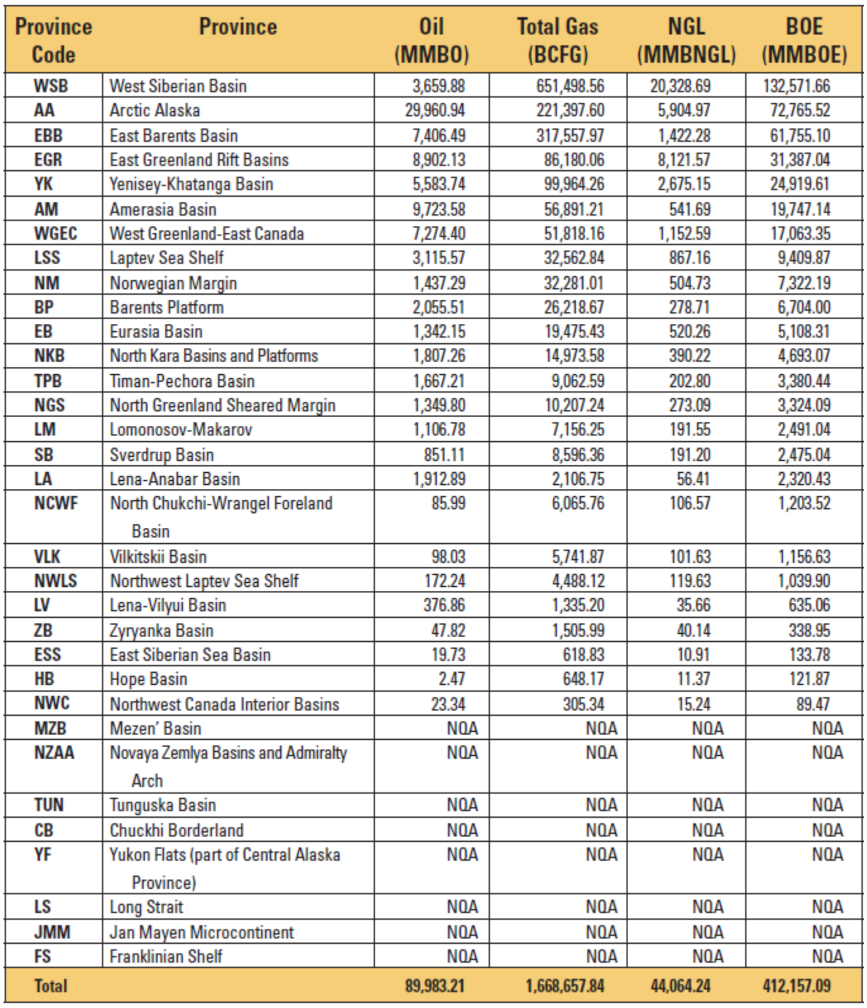


Figure 2.1 Assessment of Arctic resources color coded by assessed probability of the prescience of undiscovered oil and gas fields with recoverable resources greater than 50 million barrels of oil equivalent (MMBOE) (USGS, 2008).

Table 2.1 Arctic prospective resource (U.S. Geological Survey, 2008)



Province Code	Province	Oil (MMBO)	Total Gas (BCFG)	NGL (MMBNGL)	BOE (MMBOE)
WSB	West Siberian Basin	3,659.88	651,498.56	20,328.69	132,571.66
AA	Arctic Alaska	29,960.94	221,397.60	5,904.97	72,765.52
EBB	East Barents Basin	7,406.49	317,557.97	1,422.28	61,755.10
EGR	East Greenland Rift Basins	8,902.13	86,180.06	8,121.57	31,387.04
YK	Yenisey-Khatanga Basin	5,583.74	99,964.26	2,675.15	24,919.61
AM	Amerasia Basin	9,723.58	56,891.21	541.69	19,747.14
WGEC	West Greenland-East Canada	7,274.40	51,818.16	1,152.59	17,063.35
LSS	Laptev Sea Shelf	3,115.57	32,562.84	867.16	9,409.87
NM	Norwegian Margin	1,437.29	32,281.01	504.73	7,322.19
BP	Barents Platform	2,055.51	26,218.67	278.71	6,704.00
EB	Eurasia Basin	1,342.15	19,475.43	520.26	5,108.31
NKB	North Kara Basins and Platforms	1,807.26	14,973.58	390.22	4,693.07
TPB	Timan-Pechora Basin	1,667.21	9,062.59	202.80	3,380.44
NGS	North Greenland Sheared Margin	1,349.80	10,207.24	273.09	3,324.09
LM	Lomonosov-Makarov	1,106.78	7,156.25	191.55	2,491.04
SB	Sverdrup Basin	851.11	8,596.36	191.20	2,475.04
LA	Lena-Anabar Basin	1,912.89	2,106.75	56.41	2,320.43
NCWF	North Chukchi-Wrangel Foreland Basin	85.99	6,065.76	106.57	1,203.52
VLK	Vilkitskii Basin	98.03	5,741.87	101.63	1,156.63
NWLS	Northwest Laptev Sea Shelf	172.24	4,488.12	119.63	1,039.90
LV	Lena-Vilyui Basin	376.86	1,335.20	35.66	635.06
ZB	Zyryanka Basin	47.82	1,505.99	40.14	338.95
ESS	East Siberian Sea Basin	19.73	618.83	10.91	133.78
HB	Hope Basin	2.47	648.17	11.37	121.87
NWC	Northwest Canada Interior Basins	23.34	305.34	15.24	89.47
MZB	Mezen' Basin	NQA	NQA	NQA	NQA
NZAA	Novaya Zemlya Basins and Admiralty Arch	NQA	NQA	NQA	NQA
TUN	Tunguska Basin	NQA	NQA	NQA	NQA
CB	Chuckhi Borderland	NQA	NQA	NQA	NQA
YF	Yukon Flats (part of Central Alaska Province)	NQA	NQA	NQA	NQA
LS	Long Strait	NQA	NQA	NQA	NQA
JMM	Jan Mayen Microcontinent	NQA	NQA	NQA	NQA
FS	Franklinian Shelf	NQA	NQA	NQA	NQA
Total		**89,983.21**	**1,668,657.84**	**44,064.24**	**412,157.09**

2.2 Maintenance philosophy

The focus on maintenance and maintenance management has increased during the last 20-30 years, before this maintenance was regarded as a “necessary evil” (Ref chapter 1). Further to this, the earlier run-to-failure philosophy means that the plant spends little money on maintenance other than on basic preventive machine adjustments and lubrication work before a machine breaks down. When the machine breaks down, the necessary repairs are done. This philosophy can lead to large expenses in spare parts inventory costs, high overtime labour costs, high machine downtime and lower production availability (Mobley, 1990). A more modern maintenance philosophy is preventive maintenance. In preventive maintenance the maintenance tasks and machine repairs are scheduled in intervals based on the expected life of a component, ideally the component is replaced or repaired just before it breaks. This is in most cases better than the reactive “run-to-failure” philosophy because it is possible to plan the repair work and schedule it in a way it has the smallest possible effect on the production and give the lowest possible costs. There are some potential weaknesses to this method as well as the “run-to-failure” philosophy. Because of plant specific variables mean-time-between failures (MTBF) are often hard to establish, resulting in maintenance work being scheduled too often leading to repairs of well working machines, or to seldom leading to downtime and shutdowns (Mobley,1990). In figure 2.2 figure this is illustrated, where maintenance is scheduled to seldom for failure A, just in the right time for failure B and too early for failure C.

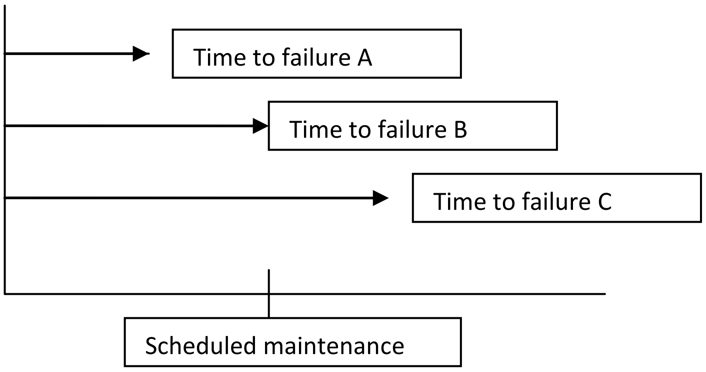


Figure 2.2 Modified figure of timing of scheduled maintenance with respect to failures (Markeset, 2008)

Development of condition monitoring technologies, micro processors and computer-based instrumentation used to monitor the condition of plant equipment together with a more competitive global market has made predictive maintenance more and more common and important. In the predictive maintenance way of thinking condition monitoring of components are used to detect, identify and prevent machine failures. Different methods and indicators such as vibration monitoring, thermography, tribology and visual inspections are used to provide data to ensure maximum possible intervals between the repairs, and to help make the maintenance work go as fast as possible (Mobley, 1990). Further to this Mobley points out that this method can give benefits in form of large reduction in maintenance costs, machine breakdowns, necessary spare parts inventory, machine downtime, overtime salaries and an increase in machine lifetime, productivity and profit for the company.

As mentioned in the last paragraph a predictive maintenance strategy is based on condition monitoring. Condition monitoring has gone from its simplest form which is machine operators looking and listening for unusual sounds, to systematic measurements of different parameters, purpose built sensors, measuring equipment and tailor-made measuring techniques. With a constant increase in the capacities of electronic equipment allowing more and more data to be processed and stored together with easier communication by means of internet, satellite and other means of communication and a equipment price going down makes predictive maintenance more and more common. This leads to condition monitoring software systems are becoming increasingly sophisticated and has self diagnosis systems with easier result collection, analysis and storage. This development has led to a new way of working and thinking, where the condition monitoring process is not just used to predict the time between failures but also to improve the equipment reliability and increase the equipment performance (Dunn, 2007)

In the oil and gas industry the term integrated operations is becoming increasingly important. Integrated operations means that fast communication links gives the possibility to transfer video-surveillance, data and dialogue between field installations and onshore centrals. Concerning maintenance aspects this makes it possible to use human resources more effectively, meaning it is no longer necessary with an expert on each field or each plant, it is enough with one expert sitting in central receiving information from the field. The signals from the condition monitoring sensors on the offshore facilities are sent directly to onshore centrals where trained personnel monitor the different machines and components. Sundberg

(2003) points out that integrated operations gives possibility to direct questions from the field to centrals in time zones where it is day so that no land based workers need to work during the night. Another very important aspect for integrated operations in the oil and gas business is the possibilities concerning the use of unmanned sub sea facilities. The condition monitoring of fields such as these must be based on sending, receiving and interpreting digital data.

When moving into Arctic areas there will be changes in the maintenance compared to similar installations in more temperate areas. Advanced condition monitoring, computerized maintenance programmes and integrated operations will be imperal to cope with the Arctic climate, lower supportability, reliability and maintainability. The possibilities of unmanned subsea facilities can also eliminate many problems with climate, ice features, human factors etc. All of this will be addressed further in the coming chapters.

2.3 State of the art for the Arctic offshore industry

The system design and maintenance strategies are under constant development, experience and statistical data from over thirty years of oil production on the Norwegian Continental Shelf exists. These data are gathered in for example the oil companies generic strategies, in government regulations and standards and in databases such as the OREDA database for the Norwegian Continental Shelf. The OREDA project was started in 1981 as collaboration between The Norwegian Petroleum Directorate and eight companies on the NCS which have gathered and analyzed data on equipment and systems on installations (OREDA, 2009). There is much literature on industry in Arctic areas but very little quantitative data.

Industry in Arctic areas is not new, industries such as mining, shipyards and onshore oil and gas production are and have traditionally been important industries in the region. Even though offshore exploration started in the Beaufort Sea already several decades ago only a few production facilities are built and put into production. Already producing fields are Prudhoe Bay in Alaska, Offshore Newfoundland in Canada, the Petsjenga-Pechora peninsula in Russia and the Norwegian gas field Snohvit. Goliat is an oilfield in the Norwegian part of the Barents Sea scheduled for production start in 2013. In the north Caspian Sea, offshore Sakhalin and in Bohai Bay offshore China the offshore installations are facing problems with ice, temperatures and conditions similar to the ones we find in the Arctic and valuable lessons can be drawn from these fields (Offshore-technology.com, 2010). Several concepts have been used to cope with the harsh conditions offshore. Large gravity based structures, gravel islands and floating units (See figure 2.3). But these fields have all been situated close to the shore in shallow waters. A way to cope with deep water fields is to use floating production units and bottom subsea installations (Gudmestad, 2005). The most similar fields to the concept looked at in the assignment is the Terra Nova FPSO located on Grand Banks 350 km northeast of Newfoundland in 94 m water depth and the Sea Rose FPSO situated in the same area. These are floating turret moored production vessels equipped with release systems that make them capable of disconnecting from the risers in case of heavy ice features threatening the installation. To cope with the low temperatures affecting the machinery and systems extensive heat tracing combined with heavy insulation is used (Gudmestad, 2005). The Terra Nova FPSO is built on a design based on the Brown & Root PV150 which was originally designed for the Haltenbanken area in the North Sea, which have similar wave conditions as the Grand Banks. To cope with Arctic conditions it is dimensioned to take 2000 tonnes of superstructure icing, and it is strengthened with 3000 tonnes of steel to be able to withstand impacts with icebergs sized up to up to 100000 tonnes and sea ice up to 0,3 m thick. This steel reinforcement of 3000 tonnes along with the weight margin of 2000 tonnes of superstructure icing increase the dead weight of the ship and thus decreases weight margins that can be used for topside processing and storage. The ship is also equipped with an ice radar which can detect ice features, and send out a dedicated towing vessel to try to tow the iceberg out of collision course, historical data show that this is successful in 48% of the time, when this does not work the vessel disconnects from the risers and sails to safety (Offshore Shipping Online, 2000).

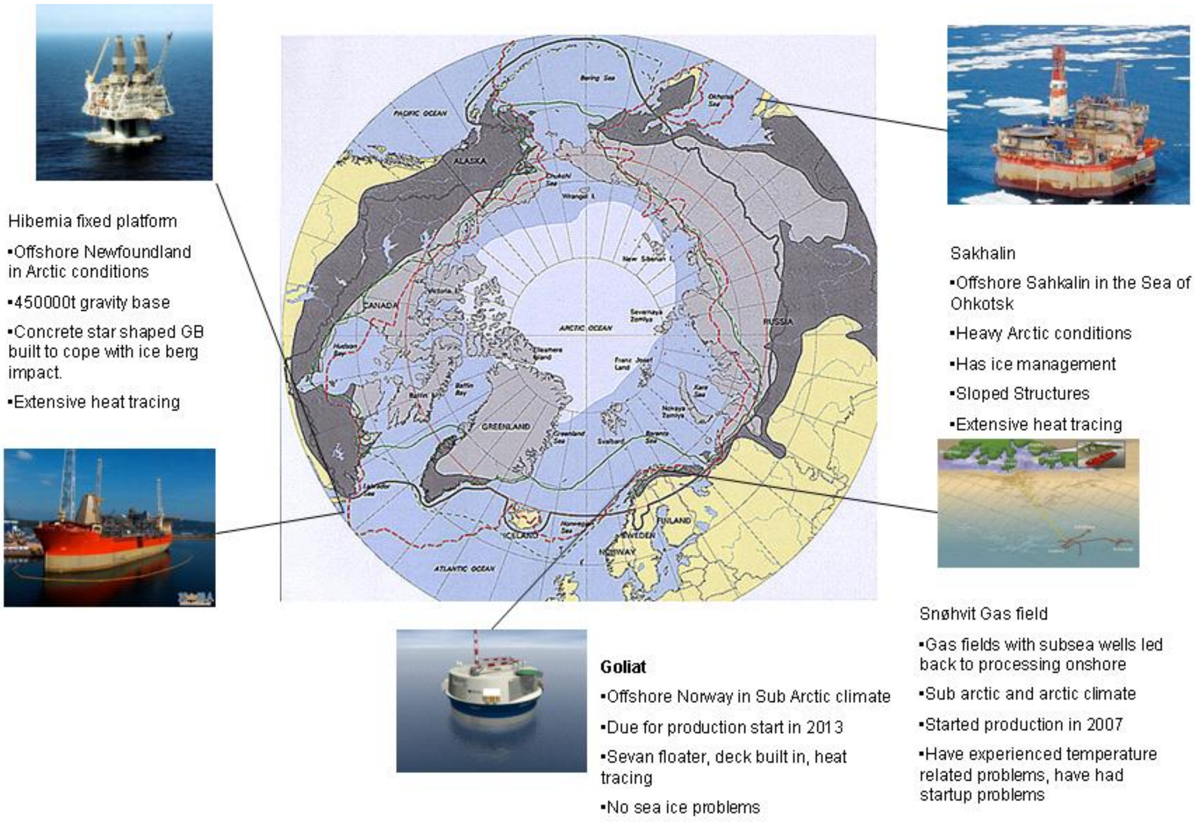
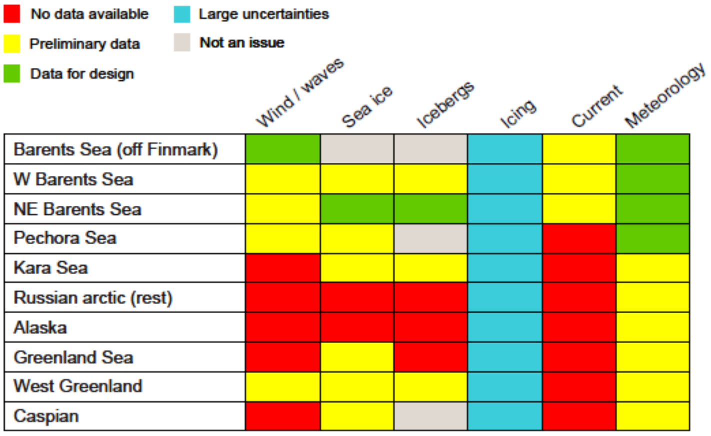


Figure 2.3 Arctic offshore oil and gas production facilities.

2.4 Gap in existing knowledge

As the industry moves northward new challenges occurs, the statistical and experience data from the NCS cannot be directly used when designing offshore installation and maintenance of these. The large uncertainties in design factors in cold and Arctic regions are described in this table, shown at the Arctic challenge Barents Sea youth conference held by StatoilHydros Sverre Kojedal on the 18.04.2009 in Hammerfest.

Table 2.2 Uncertainties in design factors in Arctic areas.



🟥 No data available
🟨 Preliminary data
🟩 Data for design
🟦 Large uncertainties
⬜ Not an issue

	Wind / waves	Sea ice	Icebergs	Icing	Current	Meteorology
Barents Sea (off Finmark)	🟩	⬜	⬜	🟦	🟨	🟩
W Barents Sea	🟨	🟨	🟨	🟦	🟨	🟩
NE Barents Sea	🟨	🟩	🟩	🟦	🟨	🟩
Pechora Sea	🟨	🟨	⬜	🟦	🟥	🟩
Kara Sea	🟥	🟨	🟨	🟦	🟥	🟨
Russian arctic (rest)	🟥	🟥	🟥	🟦	🟥	🟨
Alaska	🟥	🟥	🟥	🟦	🟥	🟨
Greenland Sea	🟥	🟨	🟥	🟦	🟥	🟨
West Greenland	🟨	🟨	🟨	🟦	🟥	🟨
Caspian	🟥	🟨	⬜	🟦	🟥	🟨

The matrix shows the scarcity of environmental data from Arctic areas. Statistic data on equipment and machinery are also scarce. Even though the systems looked into in the thesis are well known from NCS and from offshore production facilities in temperate areas and similar systems are already in use on floating production units in the Arctic, there is a gap in the knowledge on both design of systems, machinery and maintenance plans for the Arctic. Experience from the NCS together with the OREDA data can give us a good pin point for much of the equipment performance and failure data, but the information is not good enough to use directly under Arctic conditions because it does not take into account the difference in operating conditions. In general, quantitative data from Arctic areas is hard to obtain, probably due to the small amount of industry and experience in the area.

2.5 Reliability, Availability, Maintainability and Supportability (RAMS)

RAMS is an abbreviation for Reliability, Availability, Maintainability and supportability. These are keywords that are important to focus on in design and engineering of an oil and gas installation to help ensure a highest possible regularity, low repair times and a reliable installation. In the next paragraph this will be further explained. Arctic conditions will have a large impact on RAMS, these effects will be thoroughly explained in chapter 4.

2.5.1 Reliability:

The reliability of a system or a component is often defined as: "*The ability of a system to perform its required functions under stated conditions at a given instant of time or over a given time interval, assuming that the external resources are provided*" (ISO, 2006).

Reliability is a design engineering principle which makes use of scientific and statistical knowledge to assure that a system will perform its intended function for the required duration in its operating environment. This mean there has to be designed in an ability to maintain, test and support a system through its lifetime. The reliability of a system is its performance over time (IEEE Reliability Society - Reliability Engineering, 2010). Reliability is quantified as MTTF (Mean Time To failure) for non-repairable components and MTBF (Mean Time Between Failure) for repairable components, this is the expected time to failure for a component (Speaks, 2001). It is important in the design phase and in the selection of equipment phase to gather information on MTTF and MTBF of the different components and to use engineering methods such as block diagrams and fault trees which is graphical means used to evaluate the relationships between different parts of system. The reliability of a system is increased through using more reliable parts or through redundancies.

The lower the reliability is on a system or component, the larger is the probability of a break down, which can lead to downtime, loss of lives and environmental pollution. To increase the reliability we have to make more robust components and design in redundancies. This is costly, so it has to be balanced against the cost factor to get the optimal result (ref. figure 2.4). Larsen (2007) has stated that the design should be optimized in regards to:

- Requirements to the safety of the equipment obtained from risk analysis and overall acceptance criteria in regards to HSE
- Requirements from standards
- Requirements to design or operations given by authority regulations
- Project constraints like budget, realization times and national and international agreements
- Requirements to market performance

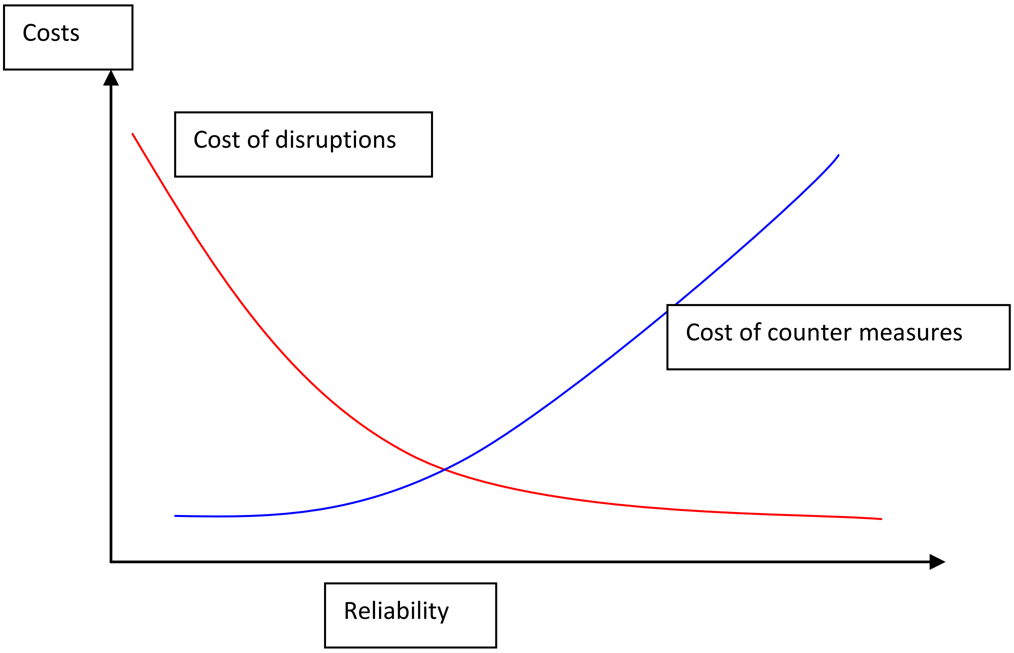


Figure 2.4 Reliability vs. cost

2.5.2 Availability:

The definition of availability is given as: “*The ability of an item (under combined aspects of its reliability, maintainability and maintenance support) to perform its required function at a stated instant of time or over a stated period of time*” (Rausand and Høyland, 2004).

The formula for average availability is given as:

$$A = \frac{MTBF}{MTBF + MTTR} \quad [1]$$

This formula gives the availability where MTBF is the parameter mean time between failures, which means the expected time to failure and MTTR is the mean time to repair showing how much time it takes to repair the component after it has failed.

The higher the number A is, the higher the availability of the component. Another more intuitive way of understanding it is if the availability of a system is 90% the downtime is 10%, which adds up to 365x0,1 = 36,5 days per year. In principle an oil and gas producing installations are designed for continuous operation, but shutdowns and maintenance leads to downtime. The goal for availability is assigned a percentage value less than 100%, because the downtime will cost less than 100% reliable equipment and operations.

2.5.3 Maintainability:

Birolini (2007) defines maintainability as *"the ability of an item under given conditions for use, to be retained in, or restored to, a state in which it can perform a required function, when maintenance is performed under given conditions and using stated procedures and resources."* Further to this he states that the objective of maintainability in a system is to minimize maintenance time and labor hours considering design characteristics such as accessibility, standardization, interchangeability, standardization of tools, etc. Measures of maintainability are generally related to distribution of time needed for the performance of specified maintenance actions such as mean-time-to-repair (MTTR).

The theory behind maintainability is to ensure component design that provides the equipment the attributes needed for it to be serviced and repaired efficiently and effectively. The general objective is thus to maximize the availability and uptime of the component through making it easy maintainable. Niebel (1994) states that there are some fundamental principles for designing for maintainability, it is important to implement these in the design and planning phase since it is hard to change after the construction phase, these principles are listed here:

- Strive to minimize the need for maintenance, eliminate it if it economically feasible. Have focus on which parts, materials or design changes can be implemented to do this
- Minimize the frequency and complexity of the maintenance tasks. This can be done by the use of standardized parts, quick disconnect and connect parts for quick operations, and a conscious use of standardized tools and easy access
- Strive to make the maintenance easy, so the personnel won't need extensive training and the work can be done by different workers
- Make good and clear routines to ensure that the mechanic, electrician or automatician is not forced to use a lot of initiative and judgment. Establish how much training and education the maintenance personnel need to do to have a balanced and good ability to do both preventive and possible unique maintenance
- Have good preventive maintenance plans, planned maintenance is most often much easier to do and to acquire personnel and resources to do than run to failure maintenance
- Provide accessibility to all equipment and components requiring maintenance, removal, inspection or adjustments. This can be very hard to ensure for all components in because of space problems
- Provide possibilities of easy fault identification through censoring, inspection windows and trouble shooting charts and fault tree diagrams

- Make it easy to use performance measures to predict the need for maintenance. This can be done by using speed, vibration, noise measurements, use instrumentation and test points wherever it is feasible
- Use posters, signs, part numbering and color codes to make it easy to identify components, component rating, type of lubricants, fuels, etc.
- Use standard tools wherever it is possible for easy work
- Have a good spare parts philosophy and plans, to have parts present to prevent downtime
- Have a plan on the use of cranes, hoists and lifting equipment. With for example dedicated rail hoists for heavy equipment that have to be maintained or replaced
- Provide parts with long lives, strive to put the parts in assemblies so they can be changed in one operation and provide self adjusting components where it is possible
- Use vibration isolators where it is needed and use materials that do not corrode in its operating environment

2.5.4 Supportability:

The term supportability refers to the characteristics of the system design and installation that enable effective and efficient maintenance and support through the life cycle of the product.
This means that in the design of the system we do not only have to think of the reliability and maintainability characteristics, but also the support infrastructure we have available to use to fulfill the demands of the maintenance process (San Jose University, 2010).
In the design and operation phase of an installation it is important to have a support infrastructure to support and ensure high reliability, availability and maintainability. Table 2.3 illustrates different elements of support that will affect the supportability

Table 2.3 Factors influencing supportability modified from Gross (2002)

Supportability issues:	Description:
Maintenance personnel	Sustaining support and maintenance crew installation
Training and training support	Ensures competence and skills to do necessary maintenance and repairs
Maintenance facilities	Facilities to support scheduled and unscheduled maintenance
Support equipment	Tools, conditioning monitoring, calibration equipment, etc.
Storage and transportation	Transportation and infrastructure
Computer rescources	Software necessary to support maintenance, databases, operation and maintenance instructions etc.
Supply support	Spares, consumables, special supplies, etc.
Integrated operations	Support from shore based centrals through transfer of real-time data.

Spare parts:
Gross (2002) asserts that “ *The best maintenance system only work as well as the parts, inventory and supply system that supports it*”.

An important factor when looking at supportability is the spare parts. Spare part selection and storage of these are critical for ensuring the installations regularity and uptime. The risk of down-time is reduced the bigger the spare part storage is, but it is important to find a balance (Niebel,1994). Too large spare parts storage can lead to degradation, disappearing, space consuming store rooms, much weight, reducing asset ownership, etc.

When making spare part plans it is important to be aware and have thought through:

- Uptime requirements (can downtime when parts are obtained be afforded)
- Costs (what is the inventory holding costs)
- Parts accessibility (How fast can the parts be obtained)
- Purchase price: Price of part or component
- Loss consequence: What is the consequence of not having the spare part. This varies with oil price and economic climate
- Holding cost: The lost opportunity of investing the money in other projects or financial institutions, and the cost of warehousing, which is the cost of storage, scavenging and administration. An oil company on the Norwegian Continental Shelf works with a holding cost of 20% of the equipment price annually.
- Redundancy: The redundancy of the system or component
- Demand rate: Reliability data, failure data
- Parts changed in preventive maintenance

2.5.5 Relation between Reliability, Availability, Maintainability and Supportability:

Figure 2.5 show how reliability, maintainability, availability and supportability relates to each other and to facility output. Reliability, Maintainability and Supportability are all factors that help ensure a high availability on the equipment, which again leads to a better facility output which means a higher uptime for an oil and gas installation.

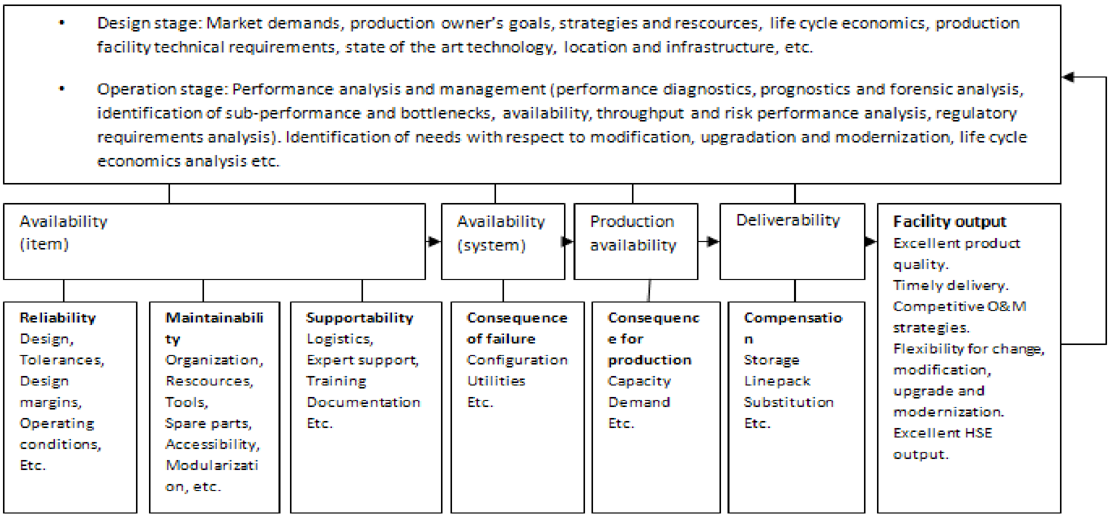


Figure 2.5 The relationship between some production assurance terms (Gao and Markeset 2007).

2.6 Statistical theory

Risk is defined as probability of failure times the consequence of failure. Formula [2] show the equation for risk where the probability of accidents are multiplied with a numerical value for each accident and summed for each possible accident sequence (DNV, 2009). Aven (1992) points out that: "*Risk is used to express the danger that undesirable events represents to human beings, the environment and to economic value*".

[2] $$R = \sum(P \times C)$$

This formula shows how the risk R is a function of probability of accidents (P) and consequence of accidents (C).

Frequency: Frequency expresses average number of events per unit of time per operation. In this assignment I have choosen to use to the frequency value described with the function described in formula [3].

[3] $$ET = \int_0^\infty t f(t) = \int_0^\infty R(t)dt$$

Formula [3] show the expected lifetime, ET is expected lifetime (MTTF), t is time and f(t) is the probability density function of the lifetime T

For most mechanical components the bath tub curve is a good way to describe the shape of the frequency of failures.

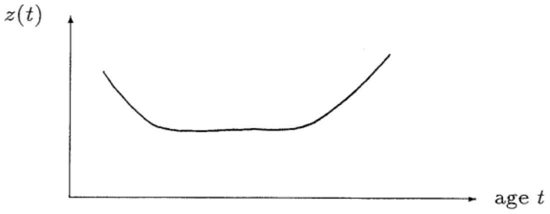


Figure 2.6 Bath-tub shape of the failure rate

In figure 2.6 we see that in the first period a component or equipment is in operation there is a decreasing intensity of failure. This is due to problems from manufacturing, run in failures etc. Next follows a period where the failure intensity is approximately constant, the failures here are mainly "random" failures. The intensity then increases due to wear and fatigue. The most ideal way to make a maintenance strategy is to buy material that is factory tested to eliminate most of the initial weaknesses, then schedule preventive maintenance just before the random failures happen and change or overhaul the unit before the wear and fatigue period starts.

For some components the failure rate is described as exponential, meaning that the lifetime of the component is exponentially distributed (see formula [4]).

[4] $F(t) = 1 - e^{-\lambda t}, t \geq 0$

Where F(T) is probability of failing at time T, λ is the mean number of failures per unit of time and t is time

This gives a constant failure rate which means that the probability of failure is independent of how long the component has been working. The exponential distribution is often used to describe the lifetime of electrical components and for old mechanical units which have been in operation for a relatively long period of time and maintenance has led to different ages of the components in the unit (Aven, 2008).

In the OREDA database it is assumed that all data is taken from the useful life phase, between the burn in and wear out phase in the bathtub curve. This means that the failure rate is assumed constant and exponentially distributed. Meaning that the component is considered as good as new as long as it is functioning and the failures are chance failures independent of age and use of the equipment. Based on this assumption the MTTF = 1/ λ (OREDA-2009)

The failure rates used in the assignment is the mean value in a 90% confidence interval, I will use this and neglect the upper 95% and lower 5% percentiles in this assignment.

Criticality: Aven (2008) points out that the criticality value is based upon the consequences of the component not working. The consequences are divided into:

- The life and health of operating personnel
- Environmental consequences of failure
- Economic impact

The economic impact factor is divided into loss in production and maintenance related costs due to failure. Based on the seriousness of the consequences of a failure regarding these three factors the components get their criticality value (Aven, 2008). A utility pump will be assigned a much lower criticality value than a fire water pump. This implies that it might be more cost effective to let the utility pump run to failure or assign it with preventive maintenance frequencies much lower than for a fire water pump because a failure in this pump can lead to much larger consequences.

The failure mode: The failure mode is the manner in which the component failure has occurred, examples of failure modes can be low output, fail to start, breakdown, etc. The failure modes are divided into critical-, degraded-, incipient- and unknown failures (OREDA, 2009) where:

- Critical failure: Complete loss of system capability
- Degraded failure: Not critical, but is a partial or gradual failure which can develop into a critical failure
- Incipient failures: failure that can lead to critical or degraded failure in near future
- Unknown failure: Failure severity is not recorded or could not be deducted

A critical failure results in 100% production loss, a degraded failure results in partial production loss and 100% loss during repair. Incipient failure does not cause production loss and the failure is found during other repairs or scheduled maintenance (DNV Consulting, 2006).

The failure mechanism: The failure mechanism is the cause for the failure mode, examples of this can be corrosion, vibration, etc.).

Redundancy: In an item, the existense of more than one means at a given instant of time for performing a required function (NORSOK Z-0016,1998).

A component capable of delivering the whole capacity is assigned a redundancy value 100%. Two components in parallell each capable of delivering 100% capacity is thus assigned with a redundancy value of 2x100%. This means that if there are two pumps with the capacity to deliver the designated amount of flow for a system, one pump can fail without the system failing. The redundancy is given as 2x100%.

2.7 Preventive maintenance scheduling

In the NORSOK standard Z-008 “Criticality analysis for maintenance purposes”, two different ways preventive maintenance can be established are described, either by use of detailed maintenance analysis or by the use of generic strategies, the points describing what a detailed maintenance analysis comprises of are quoted from the NORSOK STANDARD Z-008.

2.7.1 Detailed maintenance analysis:

The NORSOK standard Z-008 states that a maintenance analysis comprises of the following elements:

- Specific company authority requirements for maintenance and assumptions/requirements for/from risk analysis
- Dominating failure modes with approximate probability
- Failure mechanisms with approximate probability

- Repair time (approximate)
- Selected maintenance activities to reduce the probability of failure
- Detectability of failure
- Experience from using a known maintenance strategy along with periodic monitoring of the result. If this is used on equipment which performs safety critical functions where a fault is not evident to the operator, the availability requirement shall be defined and the compliance verified by documented tests. The percentage of periodic testing resulting in “Fail to operate on demand” may be used as a performance indicator
- Required competence of maintenance personnel
- Estimated man-hours for maintenance activities
- Repair time
- Essential spare parts and lead time

2.7.2 Generic maintenance concept:

A generic maintenance concept is maintenance actions defined for a group of similar equipment working under similar frame contditions. These concepts are based on similar equipment, experience and statistical data. (NORSOK Z-008, 2001). The oil companies operating oil and gas installations make generic maintenance concepts for their equipment based on their experience and on rules and regulations.

2.7.3 Procedure for preventive maintenance scheduling:

Gross (2002) proposes a procedure to establish maintenance procedures which include the following steps:

1. Establish scheduling: This means that the scheduling process must be established to make sure that the work orders are scheduled effectively.
2. Break the facilities into logical parts: Break the facility or plant into logical parts based on physical structure, production processes etc.
3. Develop an equipment list and assign equipment numbers: Identify and number all the pieces of equipment. The list of equipment will serve as the structure for tracking the maintenance activities.
4. Develop and issue preventive maintenance instructions: In this step PM work order instructions for all of the equipment identified in the previous step . Use equipment manuals and prior experience to write work orders and schedule them.
5. Locate and/ or develop equipment manuals: Obtain good manuals, continuously update these with own experience to make them better.
6. Develop a managed inventory: Create a managed inventory system that tracks use and stock of spare parts, repair history, costs etc. Also make plans on how and where to store the parts and how to maintain the inventory.
7. Monitor the programs effectiveness and make improvements.

3 Typical challenges in Arctic operations and maintenance

When oil and gas exploration are moved into Arctic areas, there are several challenges which have to be addressed. These will be described in this paragraph.

3.1 The Arctic climate

The climate in the Arctic is harsh with strong, fast changing winds and low temperatures. The phenomenon polar low pressure can cause a year around sudden change of wind direction and increases in wind speed of 2-4 beaufort within a few hours (Gudmestad, 2005). There are also less metocean data collected here than for many other offshore areas. The low temperatures and strong winds together with the dark season significantly shorten the time spans for marine operations such as interventions, trenching pipe laying, maintenance, resupplying etc. Another feature of Arctic offshore areas is fog, these areas are very susceptible for heavy fog which can stay for long periods, Grand Banks offshore Newfoundland are considered to be the foggiest area in the world with over 200 foggy days annually (Burt, 2007) . Another important aspect of the low temperatures is the problems, especially in the high Arctic with icing of platform superstructures and sea ice problems. Icing is a problem when the temperature is low combined with high air humidity or when low temperatures ($T<-10^{\circ}C$) combined with high wind speeds results in a spray blowing of the sea and freezing on the platform or ship superstructure causing loss of stability and ice layers covering the hull and the equipment.

There are three fundamental ways that can be used to mitigate icing on the installation superstructure, this is thermal, mechanic and chemical removal.

Thermal: Thermal removal of ice and snow can either be done preventive or reactive, preventive means using constant heat in cold temperatures to keep ice from accumulating, reactive is to remove ice after it have adhered. This can be done either by electrical heating, flushing with warm water, high temperature and pressure steam or by hot air. The melted ice and snow drains overboard or into designated tanks if it is polluted (Braset, 2007).

Chemical: Chemical removal of ice can be done either by lowering the freezing point of fluids by applying frost liquids. These chemicals have to be environmental friendly. The other method is to use paint that stops the ice and snow from adhering to surfaces. This paint is often very slippery when it is wet, and can only be used in certain areas like walls, below deck to stop sea spray from adhering to the superstructures and on pillars (Braset; 2007).

Mechanical: Mechanical ways to reduce icing is to induce shear stress to the ice to break it, or crush it mechanically and shovel it overboard. This can be done manually by the platform personnel, with pneumatic panels, with high pressure water, through vibrations or with ultrasound (Braset; 2007).

Other design implications of the cold and harsh weather is that the drilling deck must be enclosed to keep personnel and equipment sheltered from cold temperatures and weather, and the span between the sea surface and the drilling deck must be higher due to wave action. The platforms need heating systems to handle the icing problems. The installation must have the ability to shut down and restart without freezing and the firefighting system must work in cold weather. This implies that all fluid systems susceptible for freezing need flow assurance in the form insulation, anti freeze liquids, fluid circulation systems and fluid heating systems. The platform needs systems to stop formation of wax and hydrates in hydrocarbon systems such as pipes, risers and processing equipment. The evacuation systems must be designed for cold climate and lubrication and sealing systems for cold conditions and the construction materials have to be suitable for operation in a very large temperature span. The cold temperatures may demand shelters on workstations and drilling decks, it is important that these are designed regarding to area classification, ventilation of gas, escape routes and explosion hazards. Snow and ice may also cover openings and hatches and make gangways freeze and become slippery (Sæbø, 2007).

In the high Arctic cold weather makes sea ice in different forms an important aspect. Sea ice is a problem where low temperatures causes the sea surface to freeze into level ice which can cause large loads on the structure if it adfreezes to it, or drifts past it and complicates loading and offloading, resupplying and evacuation. Ice ridges and/or ice bergs from calving glaciers also cause problems because of large impact loads on the installation due to collision or scourging of pipelines and structures at the sea bottom in shallow areas. Ways to mitigate this is to have effective ice management with ice breakers that can crush the ice or tow away ice bergs, good systems to detect ice features which can come in contact with the platform, to have ice breaking capabilities on tankers and supply vessels and to have plans on how to do loading and offloading operations in ice free periods or on a sheltered and ice free side of the installations (Gudmestad 2005).

For gravity based structures problems with ridges and level ice can be lessened by using sloped structures which break the ice instead of crushing it, the tensile strength of ice is in the size 10 times lower than the compressive strength , example of this kind of structure is the Molikpaq platform offshore Sakhalin. Another option is using large heavy concrete structures to protect the platform, this is used on the Hibernia platform on the Grand Banks. For FPSO`s the problem can be mitigated using quick disconnect risers with sub sea structures dug down in glory holes in shallow areas. This means that the FPSO can disconnect and sail away from the ice, and pipelines and subsea structures are put into pre-dug holes to be sheltered from ice scouring, this method is used on the Terra Nova and Sea Rose FPSO`s on the Grand Banks.

The effect of the Arctic climate on production facility operations and maintenance can be summarized as:

- Planning and timespans for resupplying, maintenance, interventions etc. is harder due to bad weather
- Evacuation is harder due to bad weather and possibilities of sea ice
- Icing
- Possible problems with sea ice features like level ice, ice ridges, icebergs etc.
- Strains on machinery and personnel due to cold climate and large temperature variations
- Smaller weight and processing capabilities due to ice strengthening and topside weight safety margin because of icing
- Poor visibility due to foggy conditions

3.2 Darkness:

Whole or large parts of the day and night will be dark in late autumn, winter and early spring in the Arctic. In this period visual observation will naturally be harder, this season also coincides with the worst weather and temperature periods making resupplying, maintenance and potential ice management more complex.

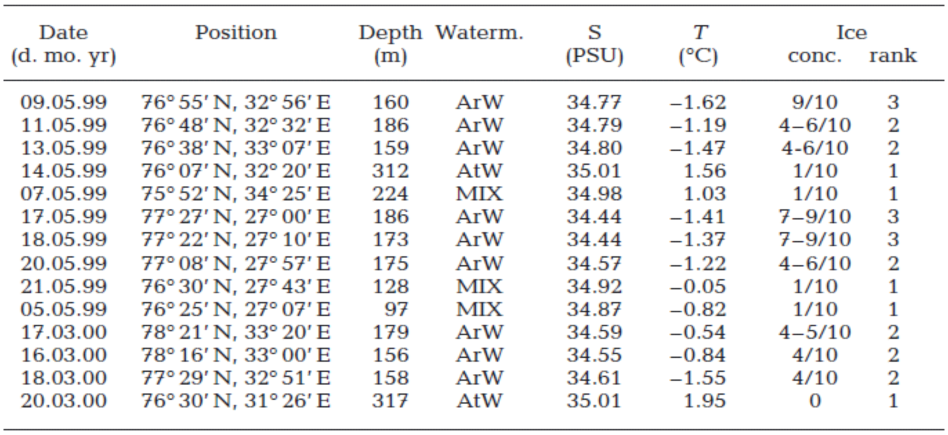
The effect of darkness on production facility operations and maintenance can be summarized as:

- General operations and resupplying can be harder due to darkness
- Strain on personnel can increase due to darkness

3.3 Ocean factors:

Large areas in the Arctic offshore are in large depths up to 1000 meters. This implies that the drill ships and rigs must be able to drill in deep waters and deep reservoirs and in some areas have means to break and cope with sea ice. The export tankers need to be designed with concern to the high environmental demands with clean classes, high security and ice breaking capabilities. Arctic pipelines need to be dimensioned to cope with cold temperature environment with hydrate inhibitors and insulation. The bad weather in the winter season cause large waves which means the span from the sea surface to the platform decks have to be larger. The waves caused by winds, especially in the autumn and winter season significantly shortens time spans for well interventions, work and resupplying operations (Gudmestad, 2005). Table 3.1 describes the sea water temperatures and ice conditions measured by the Norwegian Polar Institute for some Arctic areas (Søreide et. al.,2003).

Table 3.1 The Norwegian Polar Institutes temperature measures in Arctic waters, mean temperature (T), salinity (S) and ice concentration give, Ice ranking (1: open water, 2: open drift-ice, 3: close pack-ice). ArW, AtW, MIX: Arctic watermasses, Atlantic watermasses and a mixture of these.



Date (d. mo. yr)	Position	Depth (m)	Waterm.	S (PSU)	*T* (°C)	Ice conc.	rank
09.05.99	76° 55′ N, 32° 56′ E	160	ArW	34.77	–1.62	9/10	3
11.05.99	76° 48′ N, 32° 32′ E	186	ArW	34.79	–1.19	4–6/10	2
13.05.99	76° 38′ N, 33° 07′ E	159	ArW	34.80	–1.47	4-6/10	2
14.05.99	76° 07′ N, 32° 20′ E	312	AtW	35.01	1.56	1/10	1
07.05.99	75° 52′ N, 34° 25′ E	224	MIX	34.98	1.03	1/10	1
17.05.99	77° 27′ N, 27° 00′ E	186	ArW	34.44	–1.41	7–9/10	3
18.05.99	77° 22′ N, 27° 10′ E	173	ArW	34.44	–1.37	7–9/10	3
20.05.99	77° 08′ N, 27° 57′ E	175	ArW	34.57	–1.22	4–6/10	2
21.05.99	76° 30′ N, 27° 43′ E	128	MIX	34.92	–0.05	1/10	1
05.05.99	76° 25′ N, 27° 07′ E	97	MIX	34.87	–0.82	1/10	1
17.03.00	78° 21′ N, 33° 20′ E	179	ArW	34.59	–0.54	4–5/10	2
16.03.00	78° 16′ N, 33° 00′ E	156	ArW	34.55	–0.84	4/10	2
18.03.00	77° 29′ N, 32° 51′ E	158	ArW	34.61	–1.55	4/10	2
20.03.00	76° 30′ N, 31° 26′ E	317	AtW	35.01	1.95	0	1

The effect of Arctic ocean factors on production facility operations and maintenance can be summarized as:

- Limitations on operations due to large waves
- Strain on machinery due to ocean temperatures sinking as low as -1,9C during winter season
- Strain on machinery due to large temperature variations

3.4 Material and lubricant characteristics in the Arctic

When materials are affected by cold temperatures their thermo-mechanical properties change. These changes occur at a molecular level. Contractions cause stresses in the metals which strain the molecular bonds. This makes the metal more exposed to quick brittle breaks. There are different treatments that can be applied to metals to minimize this effect. Especially for iron alloys which is widely used in machinery and structures have a narrow transition zone from ductile to brittle properties (Freitag, 1997).

Cold weather welding is also an important aspect of metals in cold weather. A welding process melts a small part of a metal to adhere it to another, this creates a heat affected zone (HAZ) which has had a large temperature raise. If this area is cooled very quickly you get a zone with very brittle material. This can be mitigated by using post- and preheating.

We can see the same effects in polymers. When the temperature drops these materials change properties and become stiff and brittle, this can be problematic in gaskets, sealings and hoses. This makes it important to use polymers which are made for the temperatures they are to work in, or change from polymer to elastomeric components, these parts are often more expensive.

Fluids in cold temperatures change properties. Oil viscosity increase which changes its lubricating properties and make it harder to apply. At very low temperatures the oil reaches its pour point and stops flowing. If this happens both the risk of machine break downs and the wear between parts gets much higher. Especially for hydraulic systems a slight increase in viscosity of the oil can cause large strain on the system, hoses and filters. A way to hinder these problems according to Freitag (1997) is to use Arctic graded oils which are more expensive, but have pour points below -59°C. It is also important to keep the engine warm at all times, a way to do this can be to keep it running constantly and use time to heat the engine before it starts running in cold weather.

On an Arctic installation there will also be systems containing other fluids than oil, such as fresh water systems. When liquids freeze they increase in volume and can destroy systems and rupture pipes if they are not designed to operate in Arctic conditions. A way to mitigate this according to Braset (2007) is equip these systems with insulation, antifreeze liquids to decrease the freezing point, heating and/or systems circulating the fluids to keep them moving constantly. (Braset, 2007)

The effect of Arctic climate on materials and lubricants can be summarized as:

- Change in material properties due to cold temperatures
- Change in properties in lubricants and hydraulic oils due to low temperatures
- Fluids freeze

3.5 Political issues:

The Arctic areas have a large environmental focus because of its vulnerability and pristine nature resulting in government legislations demanding zero discharges from the searching, installing and production phase of the installation. This means that all water draining from the platform has to be collected and cleaned or transported away, all chemicals and hydraulic fluids have to be environmental friendly and all drill cuttings have to be cleaned out deposited in a waste well or transported to shore. Wildlife protection and social cooperation with various groups of indigenous people are also important. Failure in doing this or any polluting of the environment will have a large impact on company reputation. An example of this can be found in the ENI practice on native inhabitants (ENI Norway, 2007) where the company has stated that it is obliged to let the natives actively participate in counseling based on their social and cultural values. And actively evaluate how the operations can affect the native people.

Effects of political issues on Arctic operations and maintenance can be summarized as:

- High environmental demands make CAPEX and OPEX higher

- Drain, storage and cleaning or transport of water from the installation to minimize outlets, increases demand for storage space and logistics
- Transport of all cuttings to shore, increases demand for storage space and logistics

3.6 Remote location and infrastructure:

In the Arctic areas there is a shortage of infrastructure, qualified workforce, marine vessels, airports, roads, supply bases and deep water ports. This complicates the resupply situation and makes the installation vulnerable concerning spare parts, spare personnel and supplies. This makes it important for the platform to have a large deck space dimensioned for heavy loads not only to cope with snow- and ice loads, but also to be self sufficient with spare parts for an extended period without resupplies.

If an installation is situated far from land, it will need to be self-sufficient in emergency situations. This applies for emergency systems, evacuation systems and oil spill response systems. Jensen (2010) states that the oil spill response systems are very insufficient in the Arctic at the present time.

Another supportability problem in the Arctic is the quality of the weather reports. Especially for the Barents sea the there are few weather stations and weather sensors. Regular weather observations are done from stations at Svalbard, Bjørnøya, Hopen, Novalja Zemlja and from areas onshore in the Russian Arctic. But for the large offshore areas there are big gaps. Over the sea ice almost no weather observations are made. The current models are weak in these areas because they have problems in predicting and estimating polar lows and Arctic fronts and the rapid changes in weather these cause. Statistic data from wind and wave measurements from the area also have their limitations because of the rapid climate changes in the Arctic (Braset, 2007). Arctic weather reporting are getting better and is a focus area, use of satellite observations and computer analysis will increase the quality of these reports together with increased cooperation between countries bordering the Arctic in sharing data and experience. Tuesday 27.04.2010 an agreement was made between the Norwegian minister of Science and the Russian minister of natural resources and environment on meteorological cooperation and sharing of meteorological data to increase quality (yr.no, 27.04.2010).

The effects of remoteness of infrastructure on Arctic operations and maintenance can be summarized as:

- Resupplying of spare parts and supplies can be complicated
- Scarcity of qualified personnel willing to stay in the Arctic
- Lack of emergency infrastructure and oil spill contingency measures
- Lack of infrastructure for robust weather predictions

3.7 Human factors in the Arctic:

Human factors and ergonomics are considered to be a major contributor to operational safety, loss prevention and for optimization of system performance in the oil and gas business. Vinnem (2007) states that often that as much as 80% of accidents offshore are caused by personnel. This is a high number and there is reason to believe that it can increase in Arctic conditions. One reason for this is that manual performance is a combination of many abilities such as tactile sensitivity, hand dexterity and motor coordination, and cooling of body parts has direct effect on all of these aspects(Holmér et al.).

The physiological and mental effects cold exposure has on the human body and behavior are many. When the body is exposed to cold the metabolic rate is not sufficient to uphold a normal heat balance in the body which leads to a reduced blood supply. Blood is drawn from the extremities to prevent heat loss and to keep the internal organs warm leading to extremity cooling and a loss of sensitivity and grip strength. The cold exposure lead to a viscosity increase in synovial fluids in the body, which is a non- Newtonian fluid found in joint cavities to reduce joint friction, supply oxygen and nutrients and remove carbon-dioxide and metabolic waste (Johansen et. al. 1993). This viscosity increase causes slower movement, loss of strength and joint stiffness. Effects from scientific studies show that the cold exposure leads to a decreased level of vigilance, short term memory and general intelligence. Simple tasks remain unaffected whilst for complex cognitive tasks a clear effect is shown. Under more severe conditions long-term memory and consciousness are affected. These effects cause an increase in the risk for accidents and accidental injuries on the installation (Mäkinen et. al., 2006). Cold induced decrease in manual, muscular and aerobic performance, simple and choice reaction time, vigilance, ability to perform cognitive tasks, etc. (Holmér et al.). This means that all force, power, endurance, velocity, coordination and cognitive abilities are affected negatively.

Another important aspect of working in the Arctic offshore is the winter season. Together with lack of infrastructure, the harsh weather, self sufficiency in emergency situations and the dark season this can cause a feeling of isolation which can cause depressions that can have a negative effect on the cognitive abilities of the personnel. Effects found in studies of personnel on Antarctic research stations have shown that 51,5% of the personnel showed signs of depression, 47,6% had increased levels of irritability and anger, 62,1% had periods with impaired concentration or memory (Palinkas et al. 1995).

Effects of cold and dark environment on operating personnel include:

- Challenges in human-machine interface due to reduced sensitivity, dexterity, coordination and strength
- Increased risk of damages to muscles and joints due to reduced blood flow and joint stiffness
- Lowered sensitivity causes an impaired ability to feel burning, freezing, cuts and blows, increasing the risk for injuries
- Discomfort from freezing, runny nose, shivering, stiff joints increase risk of hurrying and doing bad work and decreases concentration
- Reduced alertness, short time memory, decision making ability and ability to do complex work leads to a higher risk of accidents
- Prolonged exposure to dark and isolation can cause reduced cognitive abilities in personnel
- All of these conditions will make it harder to get qualified personnel

4 Reliability, Availability, Maintainability and Supportability (RAMS) factors in the Arctic

Reliability, Availability, Maintainability and Supportability are keywords that are important to design for when moving oil and gas production into the Arctic. The earlier in the design and planning phase these factors are considered the easier the RAMS measures are to implement. In the early phases it is easier to make design changes, choose better materials, change parts, concepts, etc. It is important to map factors such as degradation mechanisms that work on the machines in Arctic conditions, the working environment, common operational failures, human errors, historical data etc. Because of the challenges already listed in chapter 3 the systems and components should be designed with good RAMS characteristics. Markeset and Kumar (2001) states that: Where it is economically feasible and technically possible maintenance should be designed out, where this is impossible the systems should be designed for maintenance.

4.1 Reliability

In the Arctic there are several factors influencing the reliability of a system. The environmental factors will obviously influence the reliability through low temperatures, large temperature variations, strong winds, icing and snowdrift. These factors can decrease the lifetime (MTTF and MTBF) of a system which is not properly sheltered. The low temperatures will also brittle materials and increase the viscosity of many lubricating fluids. Another important factor is the skill level of the operating personnel. In the remote Arctic it might be harder to acquire competency and experts, this can lead to a faster degradation of the machines (Gao, 2009). This can be mitigated by having a strong focus on designing for Arctic conditions with trace heating, Arctic graded materials and oils, sheltered areas and through condition monitoring and tailored preventive maintenance. The lack of skilled personnel can partially be mitigated by having a strong focus on the development of internal competence for better control and coordination of the maintenance activities and to train the installation personnel to perform first line maintenance. But even though the installation is designed for Arctic conditions and the mechanical failure rate is expected to be the same as on the NCS, an oil company operating an installation in Arctic conditions has experienced system and alarm trips due to bad weather and instrumentation, valves and supply lines freezing up. Some of these trips cause the systems to shutdown and results in lower reliability.

4.2 Availability

A system in the Arctic will potentially have a lower reliability and maintainability and most definitively have a lower supportability than the same system on an installation on the NCS. For many cases this will lead to longer repair- and downtimes, and a higher frequency of failure, which means a lower availability (Ref formula [1]). A large potential problem for availability in the Arctic is the supportability, if a part needs to be supplied from shore, the distances are long from manufacturers, and the harsh weather can cause long delays.

4.3 Maintainability

Component/system maintainability will be influenced by metocean factors such as wind, waves, snow and icing. Location factors such as darkness, distance to market and suppliers and support factors like transportation, spare parts and the human factors in the form of lack of skilled personnel and maintenance crews. The harsh conditions can also affect the operation effectivity negatively, darkness and hard weather will make everything go slower and can make demands for more frequent maintenance intervals.

As mentioned the Arctic climate and conditions have design impacts on the technical part of the platform, and on the physical and psychological performance of the operators. This makes it important to be very conscious of ergonomics when designing for maintainability. The International Ergonomics Association (2008) defines ergonomics as: "*Ergonomics (or human factors) is the scientific discipline concerned with the understanding of interactions among humans and other elements of a system, and the profession that applies theory, principles, data and methods to design in order to optimize human well-being and overall system performance".* As mentioned in paragraph 3.7 (Human factors) climate is a potential stress factor on operating personnel making them wear cold protective clothing.(Duggan 1988) the consequence for ergonomics is that the body dimensions increase and the machines should be designed in such a way that it is possible to reach them with cold protective clothing and to use gloves when maintaining them. Lights should be places in such a way that the machines are properly illuminated.

The use of remote monitoring through censoring and instrumentation to get a good basis to do predictive maintenance is a good solution to increase maintainability in the Arctic. In this way the results obtained from different sensor types (temperature, pressure, vibration, etc.) can be sent back to sheltered and heated rooms where the operators can read and react to the data without getting exposed to the cold temperatures and harsh conditions.

Here follows an example of a maintainability issue from an installation on the NCS experienced by an experienced electrical engineer. On the platform it was demanded to wear working gloves whenever moving outside the living quarters. This rule made it very hard for electricians and electric engineers to do maintenance work on small electric components. On an Arctic installation one can expect lower temperatures resulting in a demand for thicker gloves further complicating maintenance tasks. To help keep maintainability high this must be mitigated either by designing out maintenance, making the maintenance easier through design changes, heating the workspace with permanent or mobile heaters and through sheltering of the workspace either permanently or temporarily during the work.

4.4 Supportability

In the Arctic there will be some challenges regarding especially transportation. The infrastructure is worse than on the Norwegian Continental shelf, both the suppliers of spare parts and special personnel are far away and these can be time consuming to acquire and muster. Together with this the metocean factors with bad weather, fog and darkness will limit the time windows for resupplying compared to facilities in more temperate areas. These factors will make parts accessibility lower combined with a higher demand rate because of bigger strains on the equipment and a higher price of parts due to long distances from the markets. All of these points make it important to have good systems on stock keeping, parts needed for preventive maintenance, and which spare parts to keep on the platform. One possibility is to increase the size of the storage space on the installation to be able to keep a bigger stock of spare parts than on an NCS installation where supportability is better. A challenge for an Arctic installation is that it needs safety weight margins for icing, meaning that the installation must be designed to cope with superstructure icing without capsizing, this will increase the deadweight and lessens weight margins for storage and process equipment.

In the Arctic integrated operations will be a very important mean to increase supportability. During the last decades the development in telecommunications and information transfer has made it possible to transfer large amounts of real time data from the installation to shore. This can solve parts of the competence and infrastructure problems, because it is possible for experts and competent personnel to sit onshore, for example in Stavanger, and look at real time video from the remotely located installation. This makes it possible for the offshore personnel on the platform to interactively diagnose and resolve problems together with the offshore experts (Panesar and Markeset, 2006). This can make the installation less reliant on vendor experts coming to the installation if something should fail.

There will also be a big challenge concerning the evacuation of the platform in case of accidents in the Arctic. Evacuation systems have to be designed for self sufficiency because bad weather, ice, darkness, fog, long distances etc. which can make rescue work from ships and helicopters harder than for the NCS.

5 Oil & gas production facilities in the Arctic: Regularity and risks

In this chapter the measures needed to take to reduce risk and increase regularity on an Arctic installation are listed.

What we can expect when we move production into Arctic areas is that the risk of failure for the equipment will increase because of larger environmental strain. We can also expect that the consequences increase because of the fragile environment, the long distances, weather prohibiting rescue operations etc.(formula [2]). This means we can expect a shift in system and component criticality to a higher level when we move into the Arctic. Regularity is a term used to describe how a system is capable of meeting its demand for performance.

When looking at how to decrease risk and increase regularity, the RAMS measures explained earlier in the thesis are important (ref. chapter 4). As mentioned the Arctic conditions have different impacts on all of the factors in RAMS, this will have to be considered in design of both technical- and maintenance design and in design of the support strategies of the installation. To get the same risk as on the NCS for an oil and gas production installation in harsh Arctic climate, new designs and other maintenance measures either to lessen the consequences or the probability of failure has to be used. These measures in designing for RAMS are also similar to the ones which must be taken to keep regularity as high as on the NCS. For Arctic areas it might be hard to obtain data on RAMS characteristics meaning information on repair times for exposed equipment, failure frequencies and logistic delay times might be hard to establish. In the report "design for high performance for offshore production facilities in remote harsh and sensitive areas" by Tore Markeset three key factors affecting production performance are identified, and must be checked for when designing the systems and the maintenance for these (Markeset, 2008):

- Will the equipment be placed in such a way that it will be exposed to harsh and cold environment.
- Will the delivery time for the spare parts be affected due to location, infrastructure or weather?
- Will the system need to be modified due to environmental requirements?

These three questions will also be essential to identify to keep the regularity high on systems in the Arctic. In the standard NORSOK Z-016 ways to keep regularity high is divided into technical and operational measures, it can be argued that many of the measures are of both technical and operational character, but a division is made. The technical measures being choice of technology, redundancy at a system level, redundancy at equipment or component level, functional dependencies, capacities, instrumentation/automation philosophy, reduced complexity, material selection, selection of make etc. And the more operational factors are ergonomic design, protection from the environment, reliability testing, self-diagnosis systems, buffer and standby storage, bypass, flaring, utilization of design margins, spare parts, maintenance strategy and maintenance support (NORSOK Z-016, 1998).

The American Bureau of shipping (ABS, 2008) which is a classification company have made a design guide for ships operating in cold environment, many of the recommendations in the design guide can be directly transferred to technical measures to keep regularity high on Offshore installations in the Arctic, these will be listed and explained here together with technical measures to keep regularity high and risks low in Arctic conditions based on NORSOK Z-016:

- Use analyses and pre-engineering: This will be very important because experience data is scarce for offshore installations in Arctic areas (ref table 1.1). Focus on this point can throw light on different challenges and give better RAMS characteristics and regularity
- Use materials and liquids that can cope with Arctic conditions: Essential for high regularity in Arctic conditions
- Use a design that makes maintenance as easy as possible: Based on the findings on maintainability in Arctic conditions (ref paragraph 4.3). A higher maintainability will give better availability and regularity
- Use components and systems with high reliabilities and redundancies where possible: Higher redundancies and component reliability will lead to fewer failures and a higher uptime. This will reduce the consequences of a component failure, and will lessen the problems caused by lower maintainability and supportability
- Use extensive heating and heat tracing: Essential to keep up reliability of machinery and process equipment affected by cold temperatures
- Valves and closures should be selected and located to avoid freezing on either side, and situated in such a way that they are not subjected to accumulation of ice and snow. Moving parts should be heated continuously or prior to operation
- Pipes must be designed with good drainage, heating systems and circulation systems where they are subjected to temperatures which can lead to fluid freezing
- Tank vents must be placed in such a way that they are not clogged by freezing, snow or ice accumulation
- Systems such as hose reels and fire hydrants must be placed in such a way that they are not subjected to accumulation of ice and snow. These should be heated to ensure operation even in cold areas
- Precautions must be made to prevent freezing up of nozzles on sprinkler and water systems
- All electrical cables exposed for low temperatures must be protected
- All control panels exposed to cold should be equipped with space heaters
- Heat tracing, de-icing systems and insulation should be used effectively
- Additional temperature and flow monitoring

Here operational measures to keep regularity high and risks low in Arctic conditions will be listed:

- Design for maintenance in Arctic conditions: This will directly increase maintainability and lower repair times, and it may indirectly increase reliability through better maintenance. And in that way increase the regularity
- Condition monitoring systems: Increases reliability and maintainability of the systems
- Keep a high degree of internal competence: A higher degree of internal competence will make the installation less dependent on external experts and increase regularity through less downtime due to low supportability
- Use integrated operations: Integrated operations will make the installation less dependent on external experts and lessen the effects of low supportability
- Good spare part plans, and large storage capacity: Will lessen downtime due to low supportability
- Good preventive maintenance plans: Good preventive maintenance plans will lessen downtime and thus increase regularity
- Databases for experience, and experience based upgrading on the maintenance of the installation: This point will lead to a documentation of experience which will make it

easier to identify failure mechanisms and modes, react to these and increase regularity of the installation

An illustration of a problem for regularity and risk in the Arctic is topside design. Platforms on the NCS are built with an open design to ensure ventilation to mitigate accumulations of gases from leaks and reduce pressure from possible explosions. In the Arctic the platform has to be more sheltered and built in to stop icing and to ensure the possibility to perform maintenance on systems and process equipment. A way to mitigate this is a design proposed at the 2008 meeting Society of Petroleum Engineers (SPE) conference on Health, Safety and Environment in Oil and Gas exploration and Production held in Nice, France at the 15-17 April 2008. The proposal is to use rotating wall elements together with gas detectors, which opens and ventilates the sheltered areas when a leak or accumulation of gas is detected (Høiset et al. 2008). The open design reduces risk through lessening the probability of explosions and lessening the consequences. For the Arctic an open design will possibly lower maintainability and reliability due to exposition to the harsh conditions, while a closed design will increase the risk of explosions and fires. The design proposed at the SPE conference is a measure that will both reduce the risk and keep the equipment and personnel sheltered, but it will be a cost factor in building and operating the installation (Ref figure 2.4 graph on reliability vs. cost).

6 Discussion of results

A case study is conducted to identify the differences in preventive maintenance needed because of differences in RAMS factors on an installation on the NCS and in the Arctic when the aim is to have a similar production regularity. The case study starts with the procedure used to establish preventive maintenance routines and schedules. The next paragraph describes the systems. Based on the research study conducted the effects Arctic conditions will have on the equipment and components are identified. This information is gathered in FMECA analyses of the components in the system (ref. appendix A and B) where the differences in failure modes, failure mechanisms, failure frequencies, and preventive maintenance needs are identified. This is followed by description of failure scenarios Arctic conditions can cause on the two systems.

Based on the results from the FMECA analysis and the research conducted on Arctic conditions in the thesis, a model is developed to estimate the increases in man-hours and costs that can be expected in Arctic areas due to differences in RAMS factors.

6.1 Preventive maintenance scheduling

The procedure explained in paragraph 2.8 on preventive maintenance scheduling is used to establish the PM-routines. It is focused on the points two, three, four and five. The systems are split into main parts based on the components function, and further into components which are required for the main part to perform its main function. Each of the sub units is given a criticality value and the redundancy is identified.

When the criticality value and the redundancy are identified, information regarding failure modes, failure mechanisms and frequency of failures are gathered from the OREDA database. Maintenance needs are gathered from generic maintenance plans from two oil companies working on the NCS, experience data gathered in talks with engineers at a company working with maintenance of offshore installations and vendor documents from the equipment described in the systems. Based on these data together with the level of importance and criticality of the equipment the Preventive maintenance schedules are made. The results obtained are shown both for NCS conditions and Arctic conditions and the differences are marked.

An important factor when establishing PM- intervals for the Arctic is that the work is done when it is possible due to weather, and to schedule it in such a way that the maintenance process is constant, with a stable amount of work for the maintenance personnel and to schedule it in such a way that production downtime is minimized.

The preventive maintenance described in the thesis and the intervals proposed will need to be revised based on plant specific variables, information from maintenance personnel, new technology, experience etc.

6.2 The seawater cooling system and firewater system

In this thesis two systems that are important on an oil installation are chosen, a sea water lift pump system and a fire water pump system on an FPSO. These systems have the approx. same capability characteristics, but very different characteristics when it comes to used hours, safety criticality, redundancies etc. In the following subchapters the two systems in the case study will be described.

6.2.1 Firewater Pump package:

The system focused on in the thesis is the system for firefighting on the installation. Its main function is to stop, limit, control and put out fires by using seawater, seawater/foam and water mist systems. The firewater system will be placed in the hull of the FPSO with piping leading to the different sections in the hull, process, accommodation, turret section and helideck. The system is self contained, meaning it is capable of performing its function independent of other systems on the installation. This system also covers the fire hydrants, fire hoses and sprinkler systems placed on the FPSO.

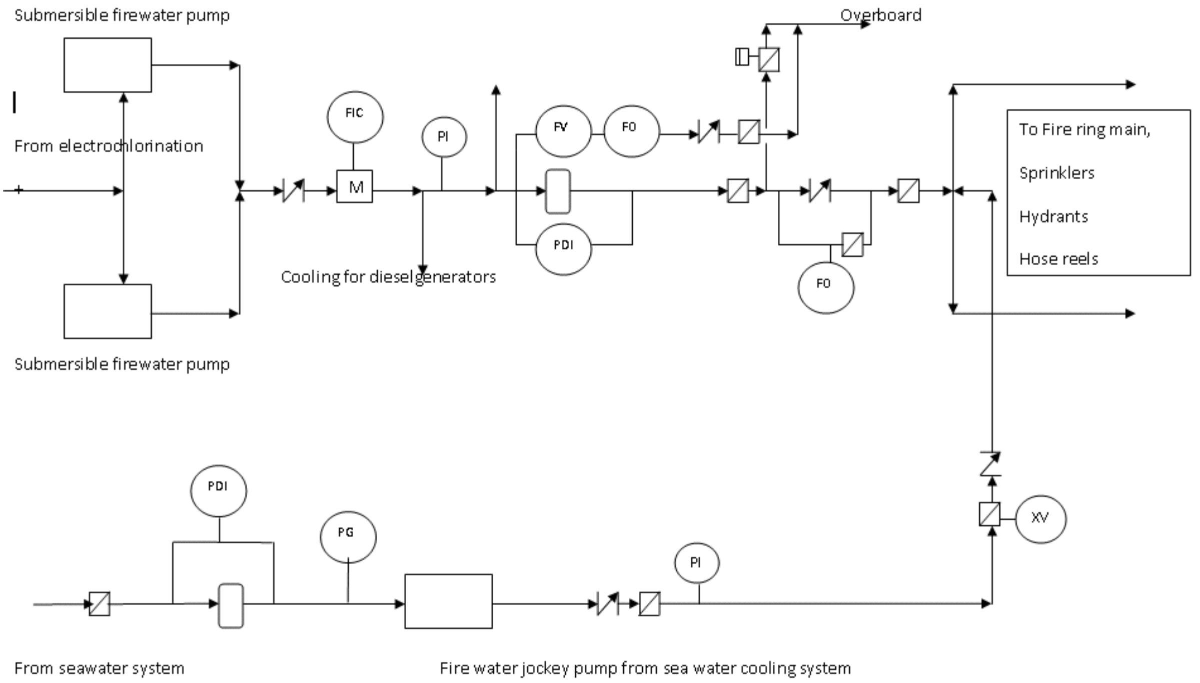


Figure 6.1 Process diagram, firewater system

The firewater system consists of four individual submerged pumps that is driven by four submerged electrical motors (6,6 kV, 60 Hz) cooled by a mixture of water and glycol. The cooling medium is stored in tanks censored with high level and low level alarms, and is measured with temperature sensors with high level alarm, this is because an increase in the temperature of the cooling fluid is a signal that something is wrong with the pump.

Each of the four pumps is identical and set up in a 4x50% configuration (redundancy 4x50%). The pumps can function at max capacity 3300 m^3/hr for eighteen hours. To protect the pumps they are monitored by magnetic minimum flow censors who control flow regulators that regulate the flow.

Downstream of the pump there are pressure indicators. Differential pressure indicators measure the pressure over the intake filters and indicate clogging or damage in these.

To mitigate the growth of algae and bacteria the water at the intake is constantly added copper and hypochlorite from another system.

The diesel generator units have an effect of 3125 kVA and are equipped with two independent 24DC starter engines. A dedicated pump in the generator circulates lubrication oil at given intervals. The cooling is supplied with seawater delivered from the firewater pump it is running. The generator exhaust is condition monitored with temperature censors. The generator control panels are separate units which control the whole power generating system, these panels show the alarms, process values, controls and survey the condition monitoring systems for lube oil system, circulation pumps, cooling system etc.

Two pumps called jockey pumps starts if the pressure in the firewater system sinks, these are electrical driven vertical centrifugal pumps designed to work at 100% 85 m^3/h. These pumps are rigged with differential pressure transmitters on the filters that give alarm if the filters need change.

The fire water is pumped up from the sea into a large fire water ring, this is a large diameter pipe with high pressure water that goes on the outside of the platform. The fire water ring goes on the outside of the installation because a rupture in this pipe would lead to the platform filling with water. This fire water ring has two closing valves to isolate it if there is a rupture. All the firefighting systems get their water from this fire water ring.

6.2.2 Seawater cooling system:

The seawater systems function is to deliver seawater to oil- and gas coolers, gas compressors, pumps and generators that use seawater as cooling medium. To mitigate algae- and bacterial growth copper and hypochlorite is added to the water from a separate system.

The system consists of three submersible centrifugal pumps (3x50% redundancy) with intake hoses which take in water from a water depth of 50m to ensure constant temperature and low growth of algae in the system. The pumps are designed to deliver 6600 m^3/hr. Each of these pumps has minimum flow valves and pressure sensors in the outlet. Downstream of the pumps it is placed filter designed to filter away all particles bigger than 80 microns.

In the system there are two circulation pumps (2x100) which pump hot seawater from a return manifold and mix it with seawater to get the wanted temperature. This mix is then delivered back to various cooling systems such as oil coolers, wet gas coolers, and inlet coolers.

A hydrocarbon analyzer is placed on the return manifold to discover leaks into the system.

The system also has a series of feed pumps going to other systems on the installation. This is to the forward fresh water cooler, to the fresh water generators, to the main generators and to the inert gas system.

The seawater system is normally configured to use two pumps 50% and have one in reserve, each of the pumps are run by a 11 kV electrical motor with its own cooling circuit using a mix of water and glycol as a cooling medium. The water is pumped to a manifold for distribution. The flow through the coolers are based and regulated by temperature measurements of the water stream through the cooler. From the return manifold the seawater is led back to sea through a sea water caisson. This caisson is kept full with fluid to ensure a constant backpressure to the system.

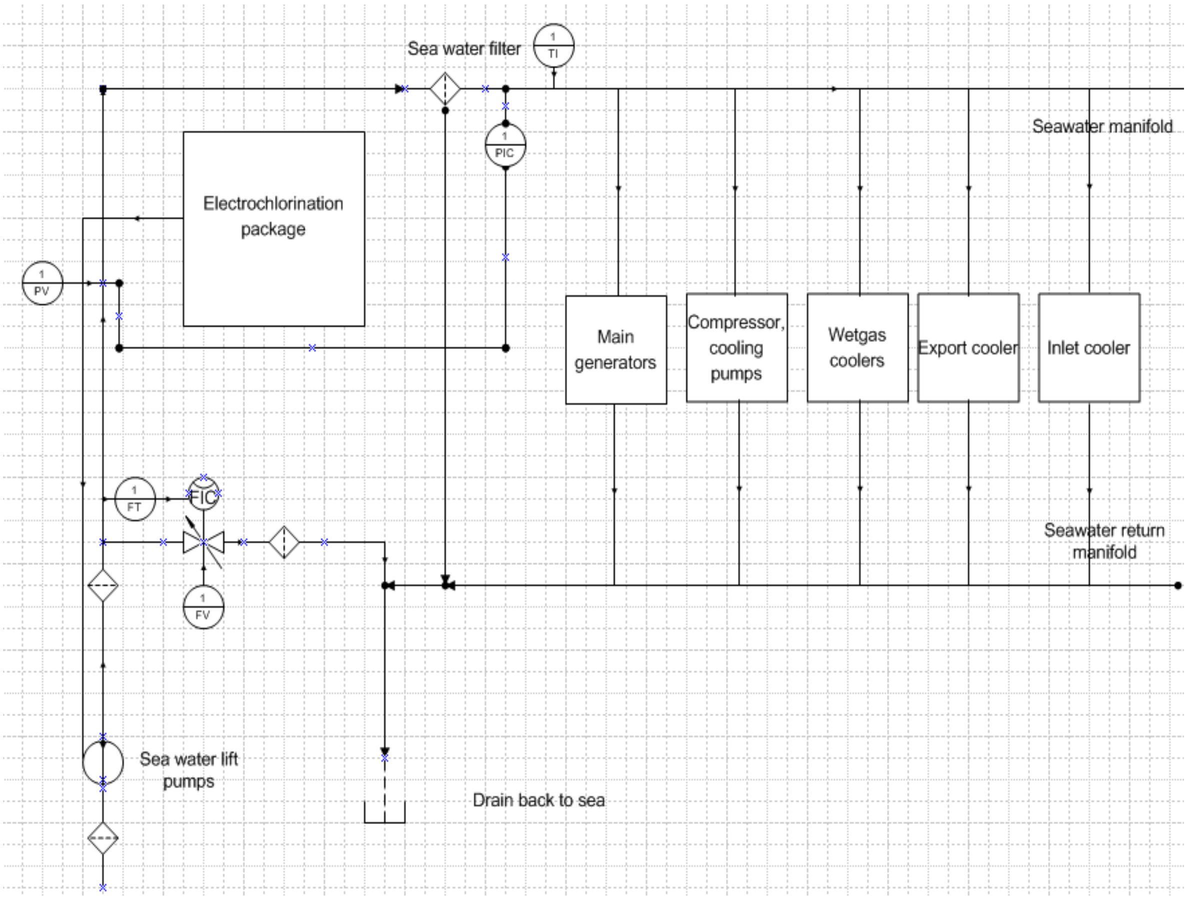


Figure 6.2 Process diagram, seawater cooling system

6.3 The systems in Arctic climate

The working temperatures for the sea and firewater system will be much lower than for systems similar on the NCS. Studies done by the Norwegian Polar Institute show that in temperate waters outside the Norwegian coast we find Atlantic water masses. It can be expected that the lowest sea temperatures at approx. 50 meters will be 1-2 degrees C. In sub Arctic areas we find modified Atlantic water masses, and the temperatures can go down as low as to -1 degree Celsius (Ref table 3.1, Arctic water masses). For high Arctic areas the lowest temperatures we find at this depth can go down to as low as -1,9 degrees Celsius depending on salinity. Temperatures going into the sub-zero range will cause different strains on the system than water with a higher temperature.

The failure rates used when describing the equipment in the next paragraph are gathered from the OREDA 2009 edition. The data on maintainable item for failure mode are used to get percentages of the total failure rate for a failure mechanism/failure mode combination. This gives a pin point on what parts of the equipment that fails most often, and where to focus the maintenance work. For the equipment where there is a lack of available statistical information, experience from oil companies and from electric- and mechanical engineers will be used to find possible failure modes.

6.3.1 Instrumentation

The basic functions of instrumentation is to measure a certain physical parameter such as vibration, temperature, level, gas content etc. and convert that parameter to an electrical signal and then perform actions such as displaying, controlling, trip alarms or do an executive action (shutdown system, start sprinkler etc.)

Much modern instrumentation tend to have an exponential failure rate (Wheeler and Ganji 2004), this means that in many cases preventive maintenance will have minimal benefit, and can actually increase the failure rate because of maintenance induced failures. The strategy behind instrumentation maintenance is to detect hidden failures and repair evident failures as they happen. Hidden random failures on safety critical instrumentation can be critical and these instruments should have periodic testing. It is also important to make sure that functional failure in one unit does not cause a dangerous situation through redundancies monitoring etc. Instrumentation subjected to time dependent failure modes such as catalytic gas detectors, detection windows, etc. must have periodic maintenance (ref. table A.5, appendix A).

For flow sensors the 25% of the failures originate in the sensing element due to mainly leaks. For level indicators this number is 66,7% due to mainly blockages. For temperature sensors 50% of the failures are due to electronics failures.

For the fire and gas system instrumentation the function is to detect explosive gases, fire, heat or smoke and generate alarm and/or executive action dependent on the degree of hazard detected. These are all safety critical. Different failure modes for these is spurious alarms, optical sensors can be fouled and obscured and catalytic gas detectors can get contaminated and loose its effect. Data from the OREDA 2009 database show that the biggest reason for failures on fire and gas detectors are the detector head, for fire and gas detectors as much as 83,77% of the failures origin from problems here. For smoke/combustion sensors the largest amount of failures can be found in the cabling (84,62%).

For Fire and gas detectors a periodic function testing will be done annually.

Heat detectors is tested periodically with a heat source radiating lower heat than the one needed to trip alarms and do executive action, such as a heat gun[1].

Smoke detectors are tested and changed with different intervals because of degradation of radioactive ionization source (ref table. A.21, appendix A)

Instrumentation in the Arctic:

Cold temperatures make instrumentation fail more often, an oil company operating an oil installation in Arctic areas have reckoned that there will be one or more trip of alarm systems on their installation pr. month during the winter periods due to the cold weather affecting valves, instrumentation or freezes up air supply lines. This implies, a large increase in failures in comparison with the OREDA 2009 database. Ways to mitigate this is to use instruments that have been through cold soak tests at -40°C, place transmitters within electric heated closures and fit instrument panels exposed to cold with space heaters and use cabling tested and proved for cold temperatures.

---

[1] Heat gun: Electric tool used to emit a stream of hot air, similar in shape and construction to a hairdryer.

Blizzards is also expected to be a problem for fire detection equipment on Arctic installations because wind and snowdrift leads to a setting off fire and gas alarms, in some cases it will be hard to investigate and repair for the installation personnel because of the bad weather. These blizzards come at different intervals depending on where in the Arctic the installation is situated.

For more specific info see table A.6 and table A.22, Appendix A.

6.3.2 Pumps:

Submerged centrifugal pump: The submerged pumps are designed to be more or less maintenance free, there are no need for grease and lubrication due to bearing lubrication from the water passing through. Apart from damage the only factors reducing the pump effectivity is wear and marine growth. The only maintenance for this in temperate waters is a performance test of the pump every five years, if it is reduced more than 10% it will be pulled up and overhauled. This is a large operation demanding divers, and pulling of the pump-riser.

Vertical centrifugal pump: This is a standing pump which uses a rotating impeller to increase fluid pressure. For these pumps the maintenance is split into daily checks for vibration, sounds and leaks during operation, and calendar based checks of flow rate every third month and change of oil, oil analysis, change of lubricants and mechanical inspection at set intervals.

Maintainable parts causing failure (OREDA, 2009):

- Instrumentation: 24,39% of total failures
- Seals: 22,52% of total failures
- Piping: 10,59% of total failures
- Control unit: 3,15% of total failures

These data show that instrumentation and seals cause the biggest percentage of failures. Instrumentation will be covered with own PM tasks (ref table B.13 and table B.14), the seals will covered by daily checks for leaks and mechanical inspections at set intervals (ref table B.1 in appendix B).

Pumps in the Arctic:

In correspondence with a Norwegian company with experience in offshore pumps, the technical manager (Eide, 2010) explains that the most critical aspect for pumps operating in polar areas are ice or slush clogging the sea caisson, suction filters or grating in front of the water intake. If this happens fast and the pump loses whole or parts of the suction string and the pump starts to cavitate, this can lead to vibrations destroying the shaft sealings and over time the pump bearings. These problems are well known from ship pumps operating in polar areas or for pumps sucking in water from areas close to the bottom where mud and vegetation can give the same effects.

There are several ways commonly used to mitigate this:

- Using alternative intakes if one is clogged
- Periodic stops of the pump and use of pressurized air to blow away ice at the intake
- Circulation of seawater through box coolers instead of taking new seawater into the ship or installation

For dry pumps on the installation the same failure modes and frequencies as on the NCS are expected. For pumps outside heat tracing and shelter may be necessary (ref. table B.2, appendix B).

6.3.3 Electric motor

Electric motors driving pumps: The electric motor produces mechanical energy by interactions between a magnetic field and an electric current and converts this into rotational power driving the pumps. The maintenance of these motors will be based on the standard worked out by The National Fire Protection Association (NFPA), (NFPA 70B-2006) which is the Recommended Practice for Electrical Equipment Maintenance, which is widely used in the North Sea. This standard recommends inspections every 1,5 months for vibrations and damages, lubrication analysis every fourth month, lubrication as proposed by manufacturer, annual electrical isolation tests, and a larger test every fourth year with thermo graphic check, change of worn parts and IR and continuity tests to find failings in cables and junction boxes. For safety critical high voltage motors (5 kV and above) will have monitoring of stator windings (NFPA, 2006).

Maintainable parts causing failure (OREDA, 2009):
- Subunit: 17,39% of total failures
- Control unit:10,14% of total failures
- Wiring:8,7% of total failures
- Thrust bearing: 7,25% of total failures
- Vibration instrumentation 5,8% of total failures

For electrical motors in the firewater systems which are safety critical will have be tested at weekly intervals and a full scale test annually to verify that the motors and pumps can deliver their required amount of firewater (ref. table A.9, appendix A).

Electric motors in the Arctic:

All electrical motors situated outdoors and in areas without heating must have anti-condensation heaters. And all cabling must be selected to be able to withstand bending and impact in low temperatures (ref. table A.10, appendix A)

6.3.4 Tools, electric equipment, screens etc.

As mentioned cold temperatures have various effects on tools and equipment. The biggest challenges in use of electric equipment in the Arctic are all kinds of electrical tools such as hand drills, saws etc. which have problems starting and breaks easily. Tools using engines also have the same problems with condensation, freezing of fuel etc. Other big problems are cables and cable terminations which break easily at sub-zero conditions and equipment with screens (especially touch screens) which stops working or get very long response times, keyboards and buttons stop working and equipment with batteries such as VHF (Very High Frequency) radios and telephones get a very limited battery capacity (Claes, 2010).

There are also problems with mechanical equipment being brought from inside to outside, if these have been exposed to moist or condensation this freezes instantly when coming outdoors.

6.3.5 Electric heaters and heat tracing

Electric heaters convert electric energy into heat which is transferred towards colder areas through conduction, convection and radiation. Heaters are divided into process heaters which heats electrical equipment and process and service fluids mainly through air convection, and domestic heaters which heats inhabited areas.

The heaters looked closer into in the assignment are all electrical equipment heaters. These heaters will be maintained at the same time as the equipment they are heating are checked, and will be electrical conductivity tests, and function testing of the heater control instrumentation (ref. table A.11 appendix A).

Electrical trace heating: are used to maintain a pre-determined surface temperature in a material or fluid. Electrical trace heating will be very important on a winterized platform and are divided into the following types:

- Constant wattage trace heating: Designed to give out a constant output, used on low to medium temperature duties
- Self- limiting trace heating: This is self regulating heating cables which are used on low to high duties
- Mineral insulated trace heating: Pure resistance heaters and used for high duties.
- Skin effect trace heaters: Use a ferromagnetic heat tube thermally coupled to the pipe that is heat traced and uses an automatic controller

Heat tracing in the Arctic:

The maintenance activities for the electric trace heating will be designed to maintain functionality and prevent catastrophic failures. The failure modes are considered random for this equipment, so the maintenance will be in the form of periodic function testing and condition monitoring. The PM task on the NCS is function testing of frost protection circuits, controllers and process related circuits once before every winter. For Arctic areas which have a longer freezing period it is suggested to have one test before winter and one in the middle of winter (ref. table B.16 appendix B).

Process fluid and water heaters are often more exposed and will have tests on continuity, insulation resistance and phase balance test together with visual inspections of heater elements and thermostats every fourth year (NFPA, 2006).

6.3.6 Gearboxes

Gearboxes are used in many of the motors on an oil and gas production facility. Gearbox maintenance programmes is typically divided into two main components:

1. Mechanical condition activities to establish the state of the gearbox, this includes data trending, vibration monitoring and lube oil sampling. Visual inspection will be done weekly to establish the state of the gearbox together with data uploading and trending from temperature sensors on the bearings and in the gearbox and oil level checks. Every fourth month there will be done an analysis of the lubricating oil. More extensive preventive maintenance like disassembling and changing of parts will follow the maintenance intervals of the driven units

2. Function testing of gearboxes used intermittently every six months

Gearboxes in safety critical systems such as the ones in the firewater system will be tested as a part of the fire water system every week and with a large annual test to ensure that it can operate on demand (ref. table A.11, appendix A).

Gearboxes in the Arctic:

Gearboxes in the Arctic will have the same failure modes and frequencies as gearboxes on the NCS when situated inside. If outside they need heat tracing and oil capable of function in low temperatures (ref. table A.12, appendix A).

6.3.7 Firewater diesel engine

The firewater diesel engine is a safety critical combustion engine. It will undergo function testing every week, and performance tests every 12 months. Together with this it will undergo a large annual service and inspection (ref. table A.13 and table A.14 appendix A).

Maintainable parts causing failure (OREDA, 2009):

- Piping: 7,14% of total failures
- Cylinders: 6,04% of total failures
- Starting unit: 6,04% of total failures
- Start energy: 5,49% of total failures
- Valves: 5,04% of total failures
- Exhaust: 4,4% of total failures
- Control unit: 3,85% of total failures
- Heat exchanger: 3,85% of total failures
- Pumps: 3,3% of total failures
- Temperature instrumentation: 3,3% of total failures

These data show that the biggest fraction of failures are mechanical, this makes it important to have good preventive maintenance routines on the mechanical state of the engine.

6.3.8 Firewater generator

A generator is used to transform rotational energy into electrical energy. The fire water Generator set is an emergency/standby generator, and will be function tested with the diesel engine every week, and has a large performance test every year. There will also be monthly vibration and oil samplings and detailed inspections and if necessary overhauls every fourth year (ref. table A.18 and table A.19, appendix A).

Maintainable parts causing failure (OREDA, 2009):

- Control unit: 26,67% of total failures
- Subunit: 16,67% of total failures
- Instrumentation: 10% of total failures
- Wiring: 6,67% of total failures

The biggest percentage of generator failures can be found in the instrumentation, control unit and junction boxes. Instrumentation will be covered under own PM-tasks, therefore it is important to focus on cabling and the control unit in the preventive maintenance.

6.3.9 Piping in the Arctic

All piping that is exposed to outside temperatures and contains liquids that can freeze must be protected. The fire ring main is probably the biggest and most exposed pipe on the installation. This ring on the outer deck on the platform will be subjected to freezing conditions and accumulation of ice and snow. A solution tried and tested on an onshore Arctic processing facility to use heat tracers along the pipe, under a thick layer of insulation, the pipes are instrumented with a temperature-sensing device that is activated when temperature drops below 5C. The insulation must be covered with metal to keep it from getting damaged. The valves on the pipe will be critical, in this area the heat tracing cables are laid down in loops around the valve to give more heat to this critical area, which has moving parts and more metal that needs heating. These loops must be big enough to give enough slack in a case where the valve has to be removed or maintained. All pipes going from the fire water ring to the systems inside of the platform should be insulated and heat traced in the same way through the outer walls. The insulation should go a distance into the heated area to prevent cold bridge effects from the pipe.

6.3.10 Hose reels, hydrants and sprinklers

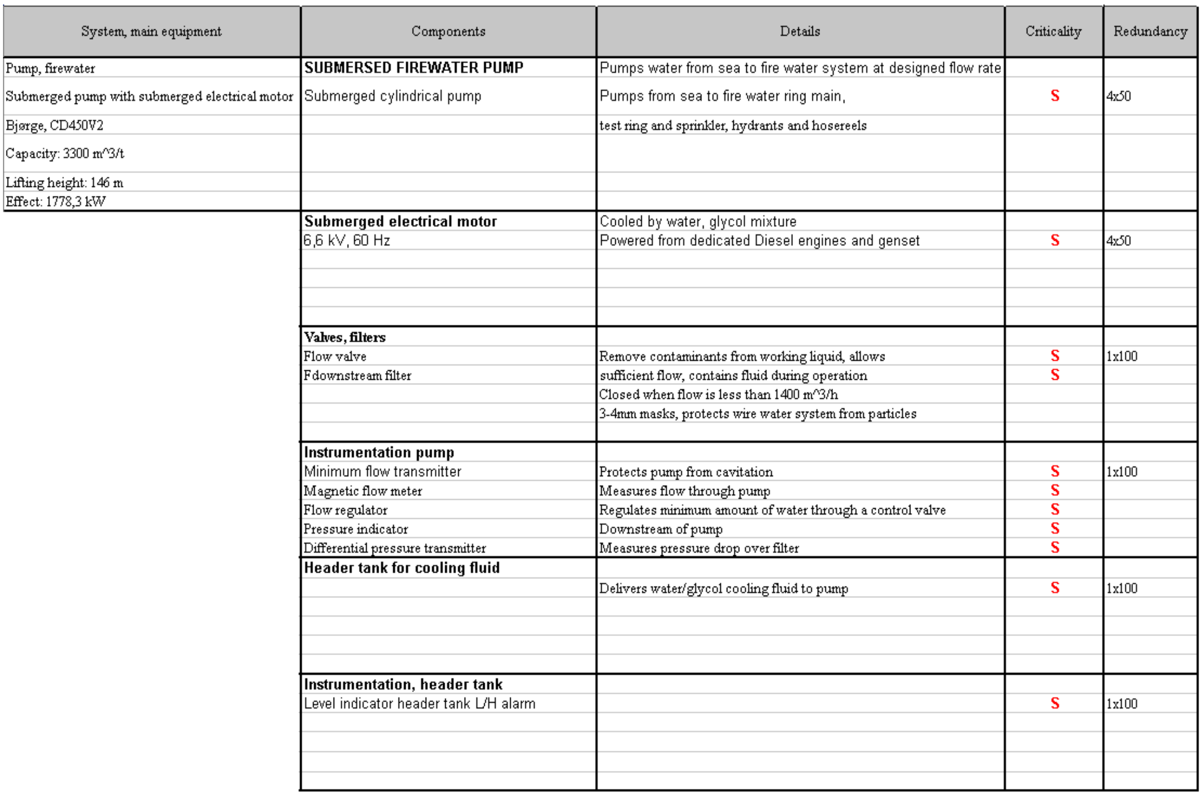
All hose reels subjected to freezing conditions shall be fitted in cabinets with heat tracing. All hydrants and sprinklers must be self draining to stop freezing and corrosion, for sprinkler pipes pressurized air in the piping can be used for complete draining (ref. table A.23 and table A.24, appendix A).

6.4 Failure mode, effects and criticality analysis (FMECA) of firewater pump

In this chapter the FMECA analysis in the excel sheets will be further explained. For further information on the systems see appendix A and B, where they are covered in whole.

The first column in the excel sheet shows the system discussed, and describes the main equipment. In the second column the main equipment are split down into component level. In Table 6.1 the FMECA of the firewater pump is shown. It is split into a pump component, an electrical motor, valves, filters, instrumentation and tanks. In the third column a short description of the components functions are given. The fourth and fifth column shows the components redundancy and criticality. All of these columns accept criticality will be the same for both Arctic and NCS areas, the criticality value are different for some components based on the possible consequences a failure can have, this is further explained in paragraph 2.6, statistical theory.

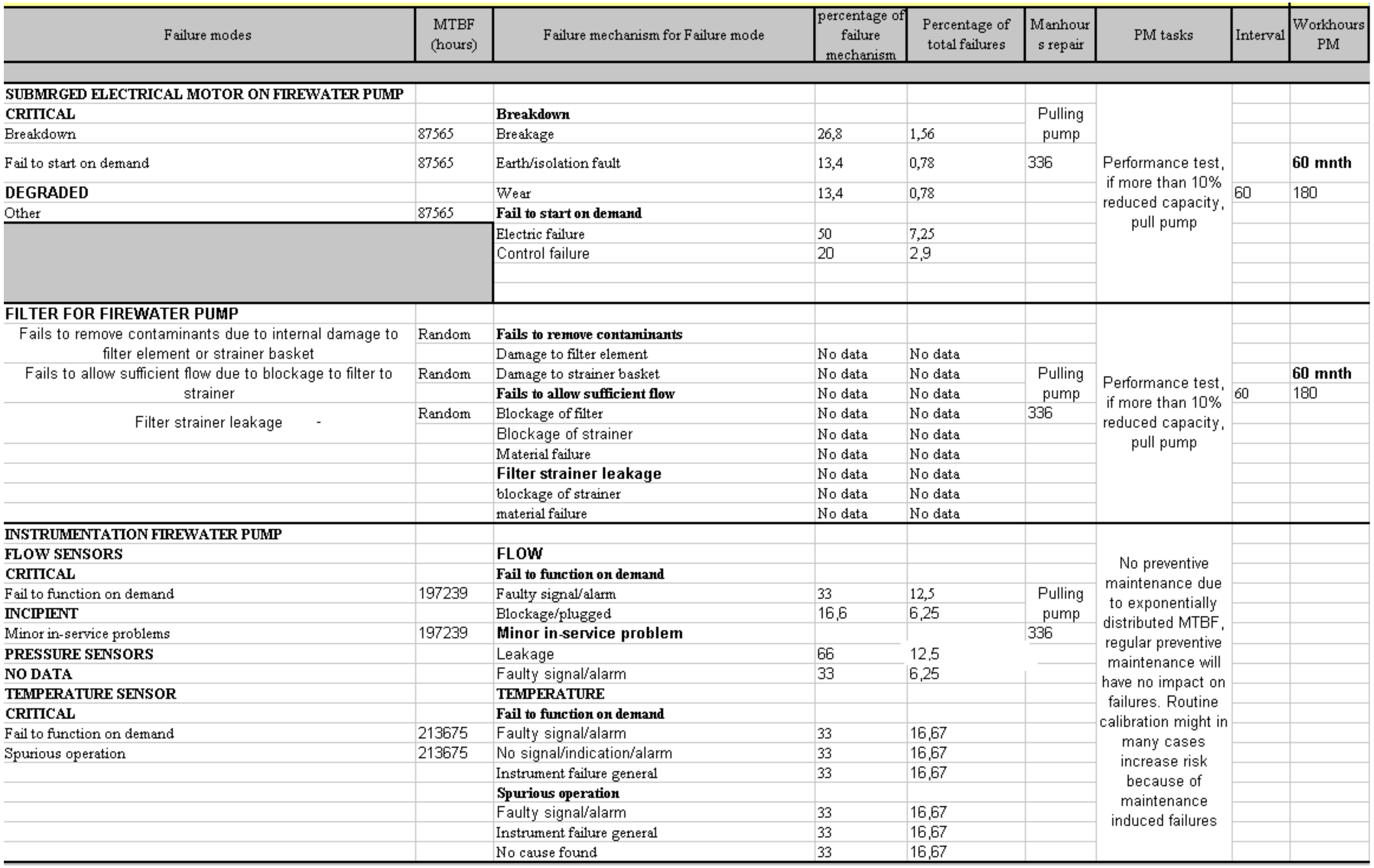
Table 6.1 FMECA analysis, submersed firewater pump



System, main equipment	Components	Details	Criticality	Redundancy
Pump, firewater	**SUBMERSED FIREWATER PUMP**	Pumps water from sea to fire water system at designed flow rate		
Submerged pump with submerged electrical motor	Submerged cylindrical pump	Pumps from sea to fire water ring main,	S	4x50
Bjørge, CD450V2		test ring and sprinkler, hydrants and hosereels		
Capacity: 3300 m^3/t				
Lifting height: 146 m				
Effect: 1778,3 kW				
	Submerged electrical motor	Cooled by water, glycol mixture		
	6,6 kV, 60 Hz	Powered from dedicated Diesel engines and genset	S	4x50
	Valves, filters			
	Flow valve	Remove contaminants from working liquid, allows	S	1x100
	Fdownstream filter	sufficient flow, contains fluid during operation	S	
		Closed when flow is less than 1400 m^3/h		
		3-4mm masks, protects wire water system from particles		
	Instrumentation pump			
	Minimum flow transmitter	Protects pump from cavitation	S	1x100
	Magnetic flow meter	Measures flow through pump	S	
	Flow regulator	Regulates minimum amount of water through a control valve	S	
	Pressure indicator	Downstream of pump	S	
	Differential pressure transmitter	Measures pressure drop over filter	S	
	Header tank for cooling fluid			
		Delivers water/glycol cooling fluid to pump	S	1x100
	Instrumentation, header tank			
	Level indicator header tank L/H alarm		S	1x100

The next column in the Excel sheet is failure modes. Here different failure modes and their frequencies are gathered from the OREDA 2009 database to show the most common critical, degraded and incipient failures (ref chapter 2.6, statistical theory). In the failure mechanism column the most common failure mechanisms for the particular failure modes are given. The next columns show the percentage of failure mechanisms for the particular failure mode and the percentage of total failures in the component described. The column "man-hours repair" presents the average value of the repair time for the particular failure modes. The two next columns give a short summary of the Preventive time-based maintenance tasks and the intervals recommended to keep the equipment running with a high regularity and to mitigate failures. The last column show how many man-hours it is expected to use on the particular preventive maintenance task. An example from table 6.2 for the submerged motor on the firewater pump on the NCS is; A critical breakdown in the circulation pump has a frequency of 342466 hours, which means the MTTF is 87565 hours (OREDA 2009). 26,8% of these breakdowns happen due to the failure mechanism, general mechanical failure, 13,4% due to earth/isolation faults in the motor and 13,4% due to wear. The next column "percentage of total failures" gives the value 1,56% which means that 1,56% of all failures observed in these pumps on the NCS are breakdowns due to general mechanical failures (OREDA 2009). The man-hours for repair for this failure mechanism are 336 hours. The PM tasks for this pump on the NCS will be a performance test every five years, if the capacity of the pump the motor is running is reduced by 10% or more it will be pulled up and overhauled. The time estimated for the PM-task is 180 hours. The same FMECA analysis is done for the same equipment in Arctic conditions. Changes in each of the categories are identified and changes in PM-tasks, intervals and used man-hours are proposed.

Table 6.2 FMECA analysis, submersed electrical motor, filter and instrumentation.



Failure modes	MTBF (hours)	Failure mechanism for Failure mode	percentage of failure mechanism	Percentage of total failures	Manhours repair	PM tasks	Interval	Workhours PM
SUBMRGED ELECTRICAL MOTOR ON FIREWATER PUMP						Performance test, if more than 10% reduced capacity, pull pump		
CRITICAL		**Breakdown**			Pulling pump			
Breakdown	87565	Breakage	26,8	1,56				
Fail to start on demand	87565	Earth/isolation fault	13,4	0,78	336			**60 mnth**
DEGRADED		Wear	13,4	0,78			60	180
Other	87565	**Fail to start on demand**						
		Electric failure	50	7,25				
		Control failure	20	2,9				
FILTER FOR FIREWATER PUMP						Performance test, if more than 10% reduced capacity, pull pump		
Fails to remove contaminants due to internal damage to filter element or strainer basket	Random	**Fails to remove contaminants**						
		Damage to filter element	No data	No data				
Fails to allow sufficient flow due to blockage to filter to strainer	Random	Damage to strainer basket	No data	No data	Pulling pump			**60 mnth**
		Fails to allow sufficient flow	No data	No data			60	180
Filter strainer leakage -	Random	Blockage of filter	No data	No data	336			
		Blockage of strainer	No data	No data				
		Material failure	No data	No data				
		Filter strainer leakage	No data	No data				
		blockage of strainer	No data	No data				
		material failure	No data	No data				
INSTRUMENTATION FIREWATER PUMP						No preventive maintenance due to exponentially distributed MTBF, regular preventive maintenance will have no impact on failures. Routine calibration might in many cases increase risk because of maintenance induced failures		
FLOW SENSORS		**FLOW**						
CRITICAL		**Fail to function on demand**						
Fail to function on demand	197239	Faulty signal/alarm	33	12,5	Pulling pump			
INCIPIENT		Blockage/plugged	16,6	6,25				
Minor in-service problems	197239	**Minor in-service problem**			336			
PRESSURE SENSORS		Leakage	66	12,5				
NO DATA		Faulty signal/alarm	33	6,25				
TEMPERATURE SENSOR		**TEMPERATURE**						
CRITICAL		**Fail to function on demand**						
Fail to function on demand	213675	Faulty signal/alarm	33	16,67				
Spurious operation	213675	No signal/indication/alarm	33	16,67				
		Instrument failure general	33	16,67				
		Spurious operation						
		Faulty signal/alarm	33	16,67				
		Instrument failure general	33	16,67				
		No cause found	33	16,67				

6.5 Sea water lift pump in Norwegian Continental Shelf and Arctic conditions

In this chapter some examples from the excel sheet are shown to explain how to interpret the results. Further results are in the excel sheet in the appendix B. The first equipment considered is the seawater lift pumps.

Table 6.3 Differences between NCS and Arctic offshore for sea water lift pumps

	Norwegian Continental Shelf	***Arctic offshore***
Criticality	The criticality of this system are defined as high and not safety critical on the NCS, this is because a failure in this system might lead to large costs, but small consequences for human life and the environment.	Safety critical. Because of a larger need for cooling water to keep the main generators and essential generators running and a lower supportability. Failure in system might cause environmental and safety consequences.
Redundancy	The system consists of two pumps with one in reserve each capable of delivering 50% of the needed water, which gives a redundancy value of 3x50%.	A identical setup of the system is considered, Redundancy increase is proposed.
Failure modes	The failure modes are taken from OREDA 2009 data on failures on sea water lift pumps on the NCS. The two most common critical failure modes are failure to start on demand and vibrations.	The same failure modes are considered. A general increase in failure modes is expected due to the cold water and possibilities of ice clogging the intake filter leading to cavitation.
Failure mechanisms	The most common failure mechanism for failure to start on demand is general instrument failure. For vibration failure mode it is clearance/alignment failures and general mechanical failures.	An increase in especially the failure mechanisms blockage and general mechanical failure can be expected due to ice problems.
Frequency	The frequency of failures is taken from the OREDA handbook for seawater lift pumps on the NCS. We can see that the most common critical failure is external leakage of process medium with a MTBF of 66622 hours which is every 7,6 years. The most common failure is abnormal instrument readings which has a MTBF of 38986 hours which is every 4,45 years.	Because of cold fluids in the pump there are possibilities of ice and slush related problems the frequency of problems can be expected to increase. Especially spurious stops, vibration and leaks can be expected to increase. The filter downstream of the pump will also be more subjected to damage because of ice and slush clogging or forming in the filter element. This can be monitored with differential pressure measurement over the filter element.

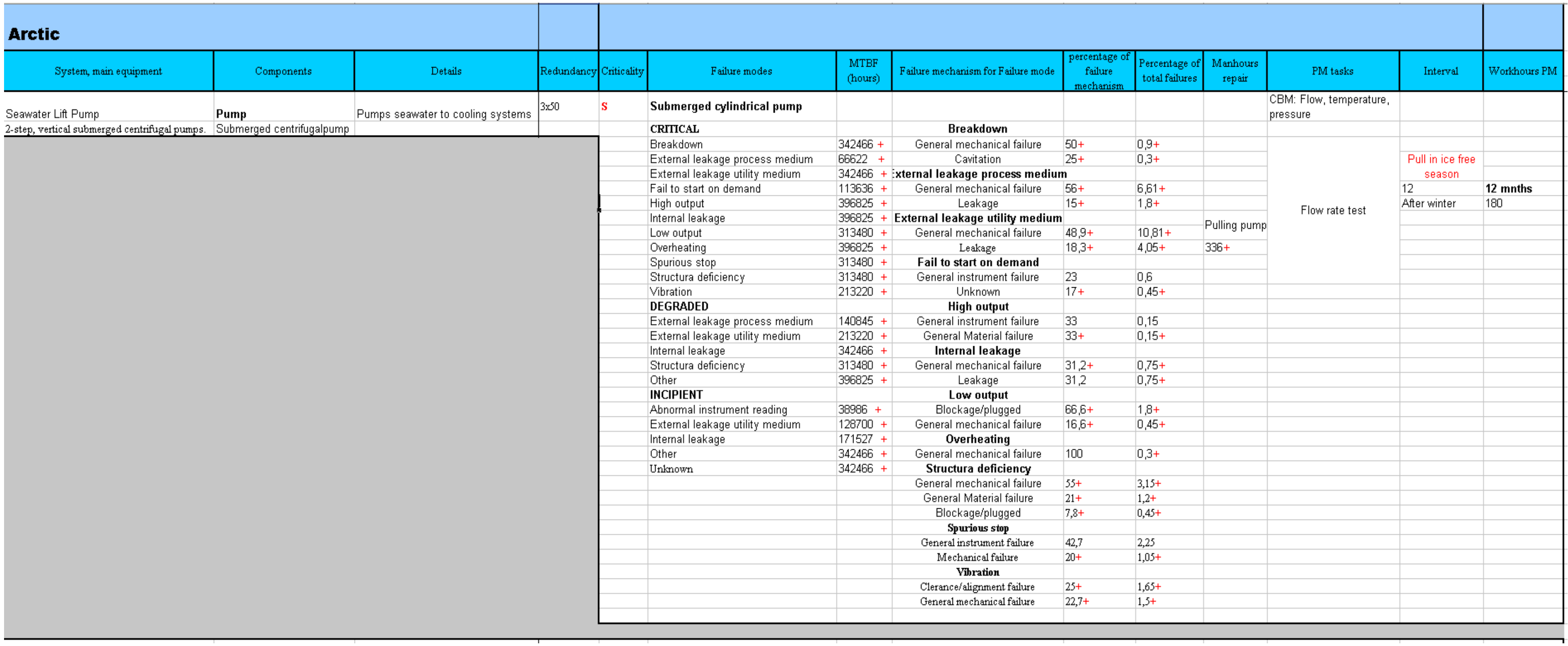
PM-tasks	The pulling of a seawater lift pump is an extensive operation where divers or ROV`s are needed. Because the pump is considered non-critical. It is chosen to schedule a performance test every five years of the pump. If the flow is reduced 10% or more it is pulled and overhauled.	The 60 flow test is increased to one after every winter season to find possible damages caused by ice.
Man-hours	If the pump has to be pulled this is a large operation demanding 336 man-hours (168 pulling and 168 placing spare pump).	If the pump is pulled during winter season a higher demand of work hours can be expected due to smaller weather windows for divers and ROV`s (Remote operated vehicles) and colder weather leading to slower work (ref. chapter 6.9).

Table 6.4 Case study, Seawater lift pump, NCS

NCS

System, main equipment	Components	Details	Criticality	Redundancy	Failure modes	MTBF (hours)	Failure mechanism for Failure mode	percentage of failure mechanism	Percentage of total failures	Manhours repair	PM tasks	Interval	Workhours PM
Seawater Lift Pump	**Pump**	Pumps seawater to cooling systems	Only cost, not safety critical	3x50	**SEAWATER LIFT PUMP**						CBM: Flow, temperature, pressure		
2-step, vertical submerged centrifugal pumps.	Submerged centrifugalpump				**SUBMERGED CYLINDRICAL PUMP**		**Breakdown**				Performance test, if more than 10% reduced capacity, pull pump		
					CRITICAL		General mechanical failure	50	0,9	Pulling pump			
					Breakdown	342466	Cavitation	25	0,3			60	**60 mnths**
					External leakage process medium	66622	**External leakage process medium**			336			180
					External leakage utility medium	342466	General mechanical failure	56	6,61				
					Fail to start on demand	113636	Leakage	15	1,8				
					High output	396825	**External leakage utility medium**						
					Internal leakage	396825	General mechanical failure	48,9	10,81				
					Low output	313480	Leakage	18,3	4,05				
					Overheating	396825	**Fail to start on demand**						
					Spurious stop	313480	General instrument failure	23	0,6				
					Structura deficiency	313480	Unknown	17	0,45				
					Vibration	213220	**High output**						
					DEGRADED		General instrument failure	33	0,15				
					External leakage process medium	140845	General Material failure	33	0,15				
					External leakage utility medium	213220	**Internal leakage**						
					Internal leakage	342466	General mechanical failure	31,2	0,75				
					Structura deficiency	313480	Leakage	31,2	0,75				
					Other	396825	**Low output**						
					INCIPIENT		Blockage/plugged	66,6	1,8				
					Abnormal instrument reading	38986	General mechanical failure	16,6	0,45				
					External leakage utility medium	128700	**Overheating**						
					Internal leakage	171527	General mechanical failure	100	0,3				
					Other	342466	**Structura deficiency**						
					Unknown	342466	General mechanical failure	55	3,15				
							General Material failure	21	1,2				
							Blockage/plugged	7,8	0,45				
							Spurious stop						
							General instrument failure	42,7	2,25				
							Mechanical failure	20	1,05				
							Vibration						
							Clerance/alignment failure	25	1,65				
							General mechanical failure	22,7	1,5				

Table 6.5 Case suty, Sea water lift pump, Arctic



Arctic

System, main equipment	Components	Details	Redundancy	Criticality	Failure modes	MTBF (hours)	Failure mechanism for Failure mode	percentage of failure mechanism	Percentage of total failures	Manhours repair	PM tasks	Interval	Workhours PM
Seawater Lift Pump	**Pump**	Pumps seawater to cooling systems	3x50	S	**Submerged cylindrical pump**						CBM: Flow, temperature, pressure		
2-step, vertical submerged centrifugal pumps.	Submerged centrifugalpump				**CRITICAL**		**Breakdown**						
					Breakdown	342466 +	General mechanical failure	50+	0,9+		Flow rate test		
					External leakage process medium	66622 +	Cavitation	25+	0,3+			Pull in ice free season	
					External leakage utility medium	342466 +	**:xternal leakage process medium**						
					Fail to start on demand	113636 +	General mechanical failure	56+	6,61+			12	**12 mnths**
					High output	396825 +	Leakage	15+	1,8+			After winter	180
					Internal leakage	396825 +	**External leakage utility medium**			Pulling pump			
					Low output	313480 +	General mechanical failure	48,9+	10,81+				
					Overheating	396825 +	Leakage	18,3+	4,05+	336+			
					Spurious stop	313480 +	**Fail to start on demand**						
					Structura deficiency	313480 +	General instrument failure	23	0,6				
					Vibration	213220 +	Unknown	17+	0,45+				
					DEGRADED		**High output**						
					External leakage process medium	140845 +	General instrument failure	33	0,15				
					External leakage utility medium	213220 +	General Material failure	33+	0,15+				
					Internal leakage	342466 +	**Internal leakage**						
					Structura deficiency	313480 +	General mechanical failure	31,2+	0,75+				
					Other	396825 +	Leakage	31,2	0,75+				
					INCIPIENT		**Low output**						
					Abnormal instrument reading	38986 +	Blockage/plugged	66,6+	1,8+				
					External leakage utility medium	128700 +	General mechanical failure	16,6+	0,45+				
					Internal leakage	171527 +	**Overheating**						
					Other	342466 +	General mechanical failure	100	0,3+				
					Unknown	342466 +	**Structura deficiency**						
							General mechanical failure	55+	3,15+				
							General Material failure	21+	1,2+				
							Blockage/plugged	7,8+	0,45+				
							Spurious stop						
							General instrument failure	42,7	2,25				
							Mechanical failure	20+	1,05+				
							Vibration						
							Clerance/alignment failure	25+	1,65+				
							General mechanical failure	22,7+	1,5+				

6.6 Fire detectors in Norwegian Continental Shelf and Arctic conditions

From the firewater system the example will be a infrared fire detector, this is a small piece of equipment but there will be many such detectors around the installation meaning that increases in scheduled maintenance and work hours will sum up to a large amount of hours. Most of the fire detectors have self diagnosting systems, in this case a infrared fire detector without a self diagnosting system will be considered. The infrared fire detector in the case study is situated outside. For FMECA analysis of the whole firewater system, see appendix A.

Table 6.6 Differences between NCS and Arctic offshore for infrared fire detectors situated outdoors

	Norwegian Continental Shelf	**Arctic offshore**
Failure modes	The failure modes for a fire detector are taken from the OREDA 2009 database	For the Arctic instrumentation is expected to have more spurious alarms due to frost affecting the instrumentation, we can also expect that blizzards and snowdrift can set off the fire detectors.
Failure mechanisms	General instrument failures, out of adjustment and contamination are the most important failure modes for these kind of sensors.	For these sensors we can expect a higher degree of contamination on the lens because of ice, and more frequent general instrument failures.
Frequency	Erratic output is the most frequent failure mode.	The failure mode erratic output is expected to increase due to increase in the failure mechanism contamination, this is because of ice and snowdrift problems on sensor head.
PM-tasks	The PM-tasks will consist of a Check of fastening, check for objects blocking sensor, visual inspection for damages and a cleaning of the sensor lens every 12 months. Every 84 months there is a scheduled change of batteries.	Interval on check of fastening, check for objects blocking sensor, visual inspection for damages and a cleaning of the sensor lens are increased to every 6 months. The scheduled change of batteries must be increased because of cold temperatures draining the power, 24 months is suggested in the case study.
Man-hours	For the NCS the needed amount of man-hours is set to one hour, the work is expected to go fast, but due to placing access can be hard.	For the Arctic the needed amount of man-hours are set to one hour during summer season, and two hours during winter season because of use of heavier clothes, cold fingers, bad weather etc.

Table 6.7 Case study, Infrared fire detector NCS

NCS													
System, main equipment	Components	Details	Criticality	Redundancy	Failure modes	MTBF (hours)	Failure mechanism for Failure mode	percentage of failure mechanism	Percentage of total failures	Manhours repair	PM tasks	Interval	Workhours PM
Fire detectors	Infrared		S	-	**FLAME DETECTOR, INFRARED**		**FLAME DETECTOR, INFRARED**				**FLAME DETECTOR, INFRARED**		
	Catalytic	Detects fire, sets of alarm	S	-	**CRITICAL**		**Spurios operation**				Most firedetectors are self verifying, meaning that if it is malfunctioning it gives warning to operators		
	gas detectors		S	-	Spurious operation	1694920	instrument failure- general	100	11,11	4	Check fastening and sensor pointing	12	**12 mnth**
	smoke detectors		S	-	**DEGRADED**		**Erratic output**				in right direction		1
	heat detectors		S	-	Erratic output	336700	Out of adjustment	60	33,33	1,6	Check for blockings in front of	12	
					Unknown	840336	Contamination	40	22,22	2	detector		**84 mnth**
					INCIPIENT		**Minor in service problem**				Visuell inspection for damage	12	1
					Minor in-service problem	1694920	Leakage	100	11,11	1	clean lens	12	
					FIRE & GAS DETECTOR, H2S GAS		**FIRE & GAS DETECTOR, H2S GAS**				Change battery	84	
					DEGRADED		**Erratic output**				**FIRE & GAS DETECTOR, H2S GAS**		**6 mnth**
					Erratic output	724638	Faulty signal/indication/alarm	100	9,82	1	Function test	6	1
					Fail to function on demand	3225810	**Fail to function on demand**			1	Check fastening and sensor pointing	12	
					Very low output	134409	External influence general	83	3,07	1	in right direction	12	**12 mnth**
					Other	568182	Out of adjustment	17	0,61	1	Check for blockings in front of detecto	12	1
					UNKNOWN		**Very low output**				Visuell inspection for damage and dirt	12	
					Very low output	2702700	Out of adjustment	100	72,39	1	clean lens	12	
					HEAT		**Other**				Check gaskets and seals	12	
					NO DATA		External influence general	78	11,04		Change battery	12	
					HYDROCARBON GAS DETECTOR		Out of adjustment	22	3,07				
					CRITICAL		**HYDROCARBON GAS DETECTOR**				**HYDROCARBON GAS DETECTOR**		
					Fail to function on demand	952381	**Erratic output**			4,3	Check fastening and sensor pointing	6	**6 mnth**
					Spurious alarm	649351	Out of adjustment	63	15,45	3	in right direction		1
					Spurious operation	625000	Vibration	20	4,88	5,6	Check for blockings in front of	6	
					DEGRADED		**Fail to function on demand**				detector		
					Erratic output	341297	instrument failure- general	33	3,25	3	Visuell inspection for damage and dirt	6	
					High output	534759	Contamination	16,7	1,63	2,3	clean lens	6	
					INCIPIENT		Vibration	16,7	1,63		Set alarm set point	6	
					Minor in-service problem	925926	**High output**			4,9	Check suction fan	6	
					SMOKE DETECTOR		Out of adjustment	83,4	4,07		Function test	6	
					INCIPIENT		Contamination	16,6	0,81		Change battery	6	
					Minor in-service problem	306748	**Spurious alarm**			6			
					INFRARED DETECTOR		instrument failure- general	40	4,88		**SMOKE DETECTOR**	12	**6 mnth**
					NO DATA		Out of adjustment	40	4,88		Check fastening and sensor pointing in right direction		1
							Minor in service problem					12	
							Out of adjustment	53	6,5		Visual inspection for damage and dirt	6	**12 mnth**
							clearance/alignment failure	26,5	3,25		Function test		1
							SMOKE DETECTOR				Change battery		
							Minor in service problem						
							Common mode failure	100	84,62				

Table 6.8 Case study, Infrarefired fire detector, Arctic

Arctic

System, main equipment	Components	Details	Criticality	Redundancy	Failure modes	MTBF (hours)	Failure mechanism for Failure mode	percentage of failure mechanism	Percentage of total failures	Manhours repair	PM tasks	Interval	Workhours PM
Fire detectors	Infrared		S	-	**FLAME DETECTOR, INFRARED**		**FLAME DETECTOR, INFRARED**				**FLAME DETECTOR, INFRARED**		
	Catalytic	Detects fire, sets of alarm	S	-	**CRITICAL**		**Spurios operation**				Most firedetectors are self verifying, meaning that if it is malfunctioning it gives warning to operators		
	gas detectors		S	-	Spurious operation	1694920+	instrument failure- general	100	11,11	4	Check fastening and sensor pointing in right direction	12	**12 mnth**
	smoke detectors		S	-	**DEGRADED**		**Erratic output**						1(2)
	heat detectors		S	-	Erratic output	336700+	Out of adjustment	60	33,33	1,6	Check for blockings in front of detector	12	
					Unknown	840336	Contamination	40+	22,22	2			**84 mnth**
					INCIPIENT		**Minor in service problem**				Visuell inspection for damage	12	1(2)
					Minor in-service problem	1694920+	Leakage	100	11,11	1	clean lens	12	
					FIRE & GAS DETECTOR, H2S GAS		**FIRE & GAS DETECTOR, H2S GAS**				Change battery	24+	
					DEGRADED		**Erratic output**				**FIRE & GAS DETECTOR, H2S GAS**		**6 mnth**
					Erratic output	724638+	Faulty signal/indication/alarm	100	9,82	1	Function test	6	1(2)
					Fail to function on demand	3225810	**Fail to function on demand**			1	Check fastening and sensor pointing in right direction	12	
					Very low output	134409+	External influence general	83+	3,07	1		12	**12 mnth**
					Other	568182	Out of adjustment	17	0,61	1	Check for blockings in front of detector	12	1(2)
					UNKNOWN		**Very low output**				Visuell inspection for damage and dirt	12	
					Very low output	2702700	Out of adjustment	100	72,39	1	clean lens	12	
					HEAT		**Other**				Check gaskets and seals	12	
					NO DATA		External influence general	78	11,04		Change battery	6+	
					HYDROCARBON GAS DETECTOR		Out of adjustment	22	3,07				
					CRITICAL		**HYDROCARBON GAS DETECTOR**				**HYDROCARBON GAS DETECTOR**		
					Fail to function on demand	952381+	**Erratic output**			4,3	Check fastening and sensor pointing in right direction	6	**6 mnth**
					Spurious alarm	649351+	Out of adjustment	63	15,45	3		6	1(2)
					Spurious operation	625000+	Vibration	20	4,88	5,6	Check for blockings in front of detector	6	
					DEGRADED		**Fail to function on demand**						
					Erratic output	341297+	instrument failure- general	33+	3,25	3	Visuell inspection for damage and dirt	6	
					High output	534759	Contamination	16,7+	1,63	2,3	clean lens	6	
					INCIPIENT		Vibration	16,7	1,63		Set alarm set point	6	
					Minor in-service problem	925926+	**High output**			4,9	Check suction fan	6	
					SMOKE DETECTOR		Out of adjustment	83,4	4,07		Function test	6	
					INCIPIENT		Contamination	16,6+	0,81		Change battery	6+	
					Minor in-service problem	306748+	**Spurious alarm**			6			
					INFRARED DETECTOR		instrument failure- general	40	4,88		**SMOKE DETECTOR**		**6 mnth**
					NO DATA		Out of adjustment	40	4,88		Check fastening and sensor pointing in right direction	12	1(2)
							Minor in service problem				Visuell inspection for damage and dirt	12	
							Out of adjustment	53	6,5		Function test	6	**12 mnth**
							clearance/alignment failure	26,5	3,25		Change battery	6+	1(2)
							SMOKE DETECTOR						
							Minor in service problem						
							Common mode failure	100	84,62				

6.7 Failure scenario in the Arctic for the seawater cooling system

Scenarios on systems failing which is undramatic on the NCS might prove dangerous in the Arctic due to the Metrologic, oceanographic and supportability differences. Here two scenarios are identified and described for the two systems discussed in the case study.

On a platform there are a large degree of redundancy in the power generating systems and these very seldom go down. On an Arctic installation the strains on the machinery can be bigger and the low supportability that can be experienced at times can lead to higher risks of such a scenario. In this scenario there is a breakdown in the seawater lift system. On a platform the main power is delivered by the main generators (typically 20-40 Mega Volt-amperes (MVA)). The setup of the generators is different from installation to installation depending on the effect needed to run all the systems. in this case it is assumed that the installation has three main generators, two essential generators and an emergency generator.

In this setup the three main generators have a 40 MVA effect and delivers power to the whole platform, the essential generators deliver an effect of 8 MVA and the emergency generators deliver 2,5 MVA. If the main generators go down the essential generators start and can deliver effect to the installation for a short time. If these generators go down the emergency generator which have a capacity of 2,5 MVA kicks in, this one only delivers power to emergency lights, evacuation systems, process shutdown systems, the fire systems, the communication, the alarm systems and restart systems for the main and essential generators. Other power generating possibilities on the platform is the UPS battery banks which for this example has effects of 4x300 kVA and the generators on the firefighting systems which are self sufficient diesel generators.

In the scenario described here the platform experiences a failure in the sea water cooling systems which delivers cooling water to the generators and the essential generators and most of the other systems on the installation. A failure on all three seawater pumps (3x50%) is very unlikely, but if pumps which are not designed for Arctic operations are used, the hard conditions can lead to problems. Such a failure leads to an overheating situation on the generators leading to a shutdown. The heating and heat tracing on an Arctic installation will need much power in cold periods. With a loss of heating and trace heating the liquid filled systems, pipes, valves, etc. will be exposed to freezing problems and domestic areas will become very cold. It is possible to design Arctic offshore installations with bigger emergency diesel generators, bigger UPS battery banks, or possibilities to draw power to heating from for example the firewater generators. Another possibility is to use power cables from standby supply vessels to draw power from these in an emergency. But with the regular setup for NCS systems the heating of all systems on the platform could not be upheld by the emergency systems. This scenario shows the importance of scenario identification from analyses (Fault tree analysis, Failure Modes, Effects, Criticality Analysis), correct design, PM-routines and competence from personnel to fix the problems in periods of isolation because of weather or ice.

6.8 Failure scenario in the Arctic for a fire detector

A scenario is that a false alarm, fire or a malfunction causes the sprinkler system to start in very cold weather, as stated in paragraph 6.3.1 instrumentation affected by cold temperatures fail more often, and an oil company working in Arctic conditions have assumed that there will be one or more trip of alarm systems on their installation pr. month due to the cold weather. Saltwater sprayed into areas or draining into areas with minus degrees can freeze, causing icing on the superstructure, in gangways, on machinery etc. This can cause machine and component failures, especially for electronics, evacuation problems, etc. The water will cause a rapid cool down that can be stronger than the heating effect delivered by the heat tracing. If the system is flushing for a prolonged period of time, this can have large synergistic effects on other systems and be expensive because of downtime and repairs on other systems.

6.9 Economic case

The cost perspective is very important for an oil and gas production facility. Based on information from the research, the FMECA analyses and the differences identified in preventive maintenance in the case study, an economic model is developed. The model estimates the economic impact Arctic conditions cause on maintenance and corrective repairs. This model can give a better basis for planning maintenance operations, and show the estimated delays in the maintenance work.

Because of the lack of statistical data on environment factors and data on maintenance and repair times in the Arctic the factors in the model will be based on assumptions. The factors in the model will be very different for different areas and plant specific variables. As more data becomes available on the climate the oil and gas installation is working in, experience data on maintenance times etc. the model can be updated and the results will get stronger. But the model is a good tool to play with different operational and maintenance scenarios. In order to develop the model Monte Carlo simulation method is used. Monte Carlo simulation is useful when modeling phenomena with significant uncertainties in the input. The method relies on random sampling to compute the results. Series of discrete random events is generated to establish a probability distribution (CSEP, 2010). The method is widely used and can be a more certain tool than other alternative methods or human intuition, because it gives a probability distribution instead of one discrete value.

The consequences for longer repair and maintenance times will be different from equipment to equipment, from process equipment where downtime can be very expensive to routine maintenance operations where the only cost is the man-hours for the personnel. The model gives the amount of hour’s delay that can be expected, this can be multiplied with the cost per hour to get the cost of the delay.

The factors influencing man-hours identified for the model is:

- Weather: Cold weather, strong winds, rain and snow make the work go slower.
- Darkness: Darkness makes work go slower
- Sea ice: Sea ice features can delay the operations, especially for operations where divers and ROV`s are needed.
- Equipment failure: Failures in tools, cranes etc. used for the task due to Arctic conditions makes work go slower. These failures can be due to increased strains on machinery, larger risk of human errors etc. (ref chapter 3).
- Delivery of parts, weather and infrastructure: Delivery of parts needed for the operation that is not stored on the platform and is delayed because of weather or bad infrastructure
- Delivery of parts, sea ice: Delivery of parts needed for the operation that is not stored on the platform and is delayed due to sea ice features

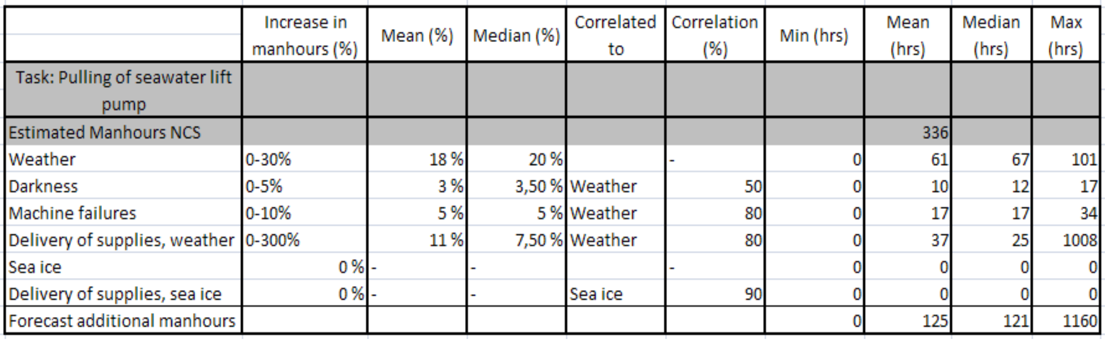
These factors will vary a lot depending on several different aspects. If the equipment is placed indoors or sheltered the weather will not have any effect on the task itself, and the same conditions as on the NCS is expected, but delivery of parts can still be a problem. Sea ice will only be a problem in certain geographical areas, climatic conditions will vary a lot based on season and geographic loction of the installation. These data have to be put into the model for the results to have any value. It is possible to divide the factors into supportability, maintainability and reliability and assign values to these based on the factors described in the model, but for this model the direct input is choosen.

Scenario: After the winter season on an FPSO in the Barents Sea the annual flow test of the seawater lift pumps show that one of the pumps have been damaged during the winter season and have lost much of its capacity. A replacement and corrective repair must be done. The seawater lift pump has a 3x50% redundancy, with one of the pumps shutdown for repair, the system is still fully operational, but the system redundancy is now 2x50%. The sea water cooling system is safety critical to keep the cooling of the generators running to ensure heat tracing and heating of the installation meaning that corrective repairs has to be done as fast as possible.

The pulling and replacing of the seawater lift pump is an extensive operation where external experts have to be present. An oil company operating on the NCS schedule 168 hours for pulling the pump and 168 hours for placing the spare (336 hours in total), external experts are needed for the operation, these are paid per hour on the platform, meaning that a one day delay increases the manhours spent on the operation by 24 hours. The Arctic conditions will as discussed in chapter 4 possibly influence the supportability and maintainability of the equipment and make the operation take longer time.

Based on the information on Arctic conditions and the task to be performed a set of assumptions are made. In the model it is assumed that the amount of man-hours used without delays will be the same as on the NCS (336 hours). Based on the research work done in the assignment different Arctic factors are assigned probability distributions on how they will affect the used man-hours for the operation.

Table 6.9 Assumptions in Monte Carlo simulation



	Increase in manhours (%)	Mean (%)	Median (%)	Correlated to	Correlation (%)	Min (hrs)	Mean (hrs)	Median (hrs)	Max (hrs)
Task: Pulling of seawater lift pump									
Estimated Manhours NCS							336		
Weather	0-30%	18 %	20 %		-	0	61	67	101
Darkness	0-5%	3 %	3,50 %	Weather	50	0	10	12	17
Machine failures	0-10%	5 %	5 %	Weather	80	0	17	17	34
Delivery of supplies, weather	0-300%	11 %	7,50 %	Weather	80	0	37	25	1008
Sea ice	0 %	-	-		-	0	0	0	0
Delivery of supplies, sea ice	0 %	-	-	Sea ice	90	0	0	0	0
Forecast additional manhours						0	125	121	1160

Table 6.9 show the minimum, the mean and the maximum addition to manhours for the task in Arctic conditions. The mean values are set in the input for all factors except for the “delivery of supplies, weather”, where the median value is set. The min values are calculated with formula [5], the max values are calculated by changing the min% with the max% percentage value for increase in manhours.

[5] $$\text{FCA min(hrs)} = \sum((W(\text{min}\%) \times ENCS) + (D(\text{min}\%) \times ENCS) + (MF(\text{min}\%) \times ENCS) + (DSW(\text{min}\%) \times ENCS) + (SI(\text{min}\%) \times ENCS) + (DSI(\text{min}\%) \times ENCS))$$

Where FCA min(%) is the smallest increase in forecast additional manhours (%) defined in the assumption and ENCS is estimated manhours for the NCS. The other abbreviations is: W is weather, D is darkness, MF is machine failures, DSW is delivery of supplies, weather, SI is sea ice and DSI is delivery of supplies, sea ice.

Input distributions:

Weather (Figure 6.3): The transition between winter and spring is a period where harsh weather can be experienced in the Barents sea with low temperatures, storms and blizzards. The operation pulling and installing a spare pump is weather sensitive. The weather is modelled as a triangular distribution assigned values from 0-101 hours (0-30%) increase in man-hours with a likeliest value of 84 hours (25%).

Figure 6.3 Triangular distribution of increase in manhours due to weather

Darkness (Figure 6.4): Early spring in the Barents Sea means that there are little daylight. This can be mitigated by the use of artificial light, but is still modelled as a triangular distribution assigned with the value 0-17 hours (0-5%) with a likeliest value of 10 hours (3%) increase in manhours because of strain on personnel, areas without lighting etc. This value is assigned a correlation of 50% to the weather. Figure 6.3 illustrates how the delays due to darkness is correlated to the delays due to bad weather, on the figure the grey line show the weather distribution and the green dots show the results for darkness.

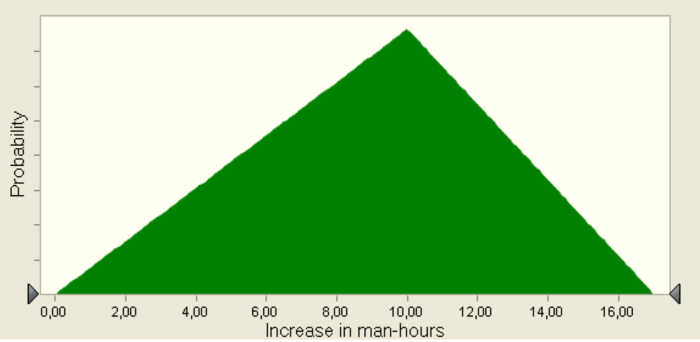


Figure 6.4 Triangular distribution of increase in manhours due to darkness

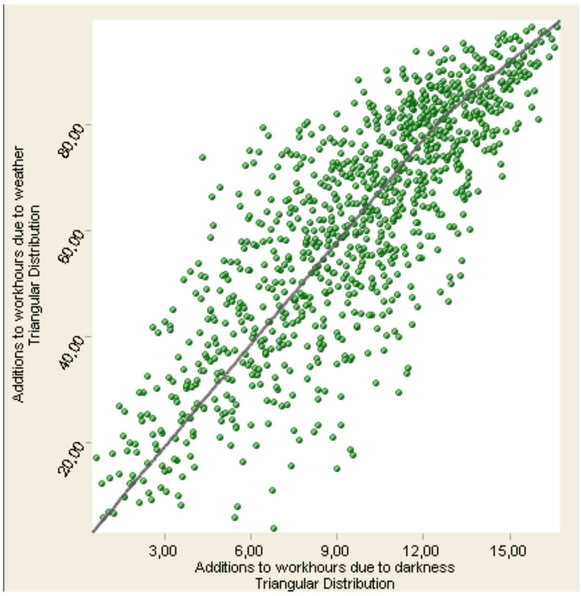


Figure 6.5 Correlation between darkness and weather

Sea ice: Sea ice will not be considered in this scenario.

Equipment failure (Figure 6.6): Failures in tools and equipment is modelled as a triangular distribution assigned with the values 0-34 hours (0-10%) increase in workhours with a likeliest value of 17 hours (5%). It is assumed that the main equipment and systems are designed to cope with Arctic conditions, but the strains will still be higher in cold weather, the risk of human errors is higher, etc. Failures of hand tools and tools used for the repair is covered in this factor. This factor is 80% correlated to the weather, because in good weather the same failure frequency is expected for the NCS as for the Arctic.

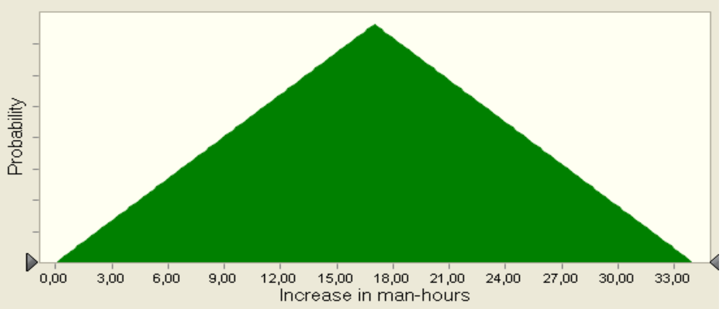


Figure 6.6 Triangular distribution of increase in manhours due to equipment failure

Delivery of parts and specialists due to weather and infrastructure (Figure 6.7): This factor is Gamma distributed and assigned the value 0-1008 hours (0-300%) increase in man-hours with a median value of 25 hours (7,5%). It is assumed that a spare pump is stored on the platform, but other parts, tools and experts needed might be delayed. This factor is considered weather sensitive and 80% correlated with the weather because bad weather is expected to give the largest delays for this case. The 300% delay will be very rare, and caused by for example long storm periods, equipment deliveries over long distances with truck, etc.

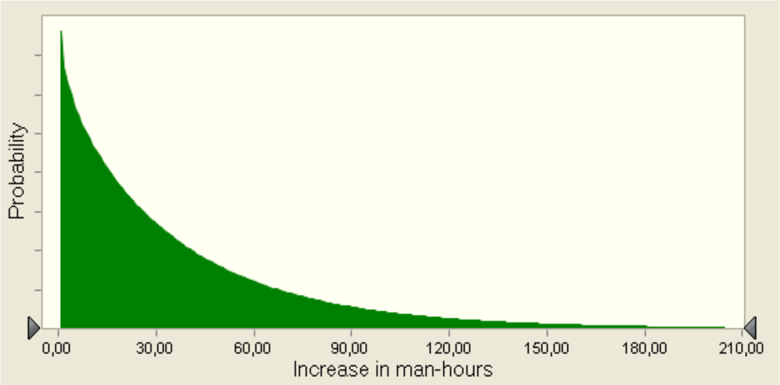


Figure 6.7 Gamma distribution of increase in manhours due to delays caused by weather and bad infrastructure

The largest uncertainty in the model is found in this distribution, it has a variance of 1488 hours due to the uncertainty in data. The Gamma distribution for the supply delays from weather gives very low chances for delays over 200 hours, this is due to difficulties in making distributions with a likeliest value much lower than the max value. If statistical data on weather can be obtained this can be solved by making discrete probability distributions based on the weather observations.

Delivery of parts and specialists due to sea ice: This factor is assigned the value 0% in this example because ice features is not expected in the part of the Barents Sea assessed for this season.

Of all of these factors the weather is expected to be the most important, and it is expected that there is a correlation between some of the other factors to bad weather. This assumption is based on the fact that the dark period coincides with the period with the worst weather, the reliability of the equipment is lower in bad weather, risk of human errors increase (ref. chapter 3) and the delivery of spare parts is weather sensitive.

Based on the probability distrubutions described, a Monte Carlo simulation with 100000 trials is run giving the gamma distribution shown in Figure 6.6. The distribution has a mean increase in manhours of 125 hours with a variance of 4005 hours. The large variance illustrates that there are large uncertainties in the estimate, this will get better when more data on the input distributions are gained from experience and analyses. In spite of the large uncertainties the model gives reason to believe that for this operation there will be an increase in man-hours due to Arctic conditions.

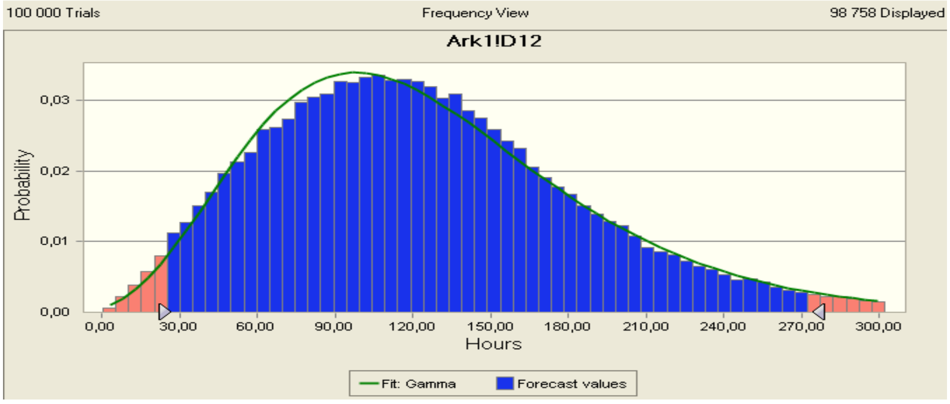


Figure 6.8 Estimated increase in manhours

By using Figure 6.6 a probability of 50% of delays between 75 and 155 hours is identified,
To find the economic consequence of this delay the price pr. manhour is analysed, for this case where there are no production downtime this will be solely the price pr. hour pr. worker. In this case it is assumed that the price pr. manhour pr. external specialist is 650 NOK. This assumption gives a 50% chance that the increase in costs for this task is between 48750 NOK and 102700 NOK (22-47% increase in costs). The mean cost increase identified in the model will be 81988 NOK (37%). If the worst case scenario defined in the assumption happen the delay will be 1160 hours meaning a cost increase of 754000 (345%), based on this model the chance for this is neglectible.

7. Concluding remarks

Arctic conditions will give challenges regarding RAMS factors on an offshore oil and gas production installation. The availability of the equipment can be kept high by identifying measures and designing for reliability, maintainability and supportability. As discussed in the results of this study, the reliability can be kept high through using reliable equipment designed for Arctic operating conditions, increase redundancies and by the use of shelters, heaters and heat tracing. The maintainability can be kept high by designing the equipment with ergonomics ensuring a good human-machine interface in Arctic conditions, sheltered workspaces, good illumination and by conscious maintenance planning and scheduling. The supportability challenges can be partially mitigated by having good spare part plans, large storage capacity offshore, ensurance of high internal competence through training and hiring of skilled personnel and by the use of integrated operations.

The results of the study also indicate that the preventive maintenance will assume greater importance in keeping the regularity high and lowering the risks through repairs, assessing the state of the equipment, mapping degradation factors, etc. Since the preventive maintenance will also be affected by the harsh environment, there will be a need to consider all the challenges presented in this study while planning and executing the preventive maintenance tasks. For the equipment situated indoors, the maintenance time and procedures will be similar to the equipment in the offshore in the temperate areas in North Sea. However, the equipment in the arctic will have higher criticality values due to possibilities of colder process fluids, changes in systems, as well as their influence on the utility systems that may directly or indirectly influence the safety of personnel on board. This equipment might need to have maintenance scheduled more often as compared to equipment in the temperate areas. The equipment situated in weather affected areas might have bigger strains and might need maintenance and checks more often than similar equipment on the NCS. Moreover, in the arctic areas, there will be additional auxiliary equipment such as heaters, heat tracing, etc. that needs to be maintained. In addition, the maintenance in arctic will be limited to summer seasons to lessen the strain on the personnel. The maintenance will take longer time both in preparation and in action due to cold weather, need for protective clothing, darkness and other arctic influencing factors identified in this study.

8. Future research

Based on the findings in the thesis some points for future research is suggested, these are listed here:

- Quantitative data on failure modes, failure mechanisms and failure frequencies would increase the accuracy of analyses on reliability, availability of equipment, and ease planning of both design, operations and maintenance. These data will also be useful in identifying risks and establish regularity goals for the installation.
- More data on Arctic physical conditions will give a better possibility to plan design of the installation, operations and maintenance. These data would strengthen models such as the Monte Carlo simulation used in this assignment, and give better a better base for engineering decisions.
- Data on Reliability, availability, maintainability and supportability in the Arctic should be gathered and analyzed to further increase the base for making engineering decisions and operation and maintenance decisions.

9 References

American Bureau of Shipping (ABS), (2008). ABS publication N-0151: *Guide for vessels operating in low temperature environments.*
Aven, T., (1992*). Reliability and Risk Analysis*, 1st ed., Springer: Berlin, Germany

Aven, T. (2008). Lecture notes from course Reliability and Risk Analysis: Common lifetime distributions. University of Stavanger

Birolini, A., (2007). *Reliability engineering: theory and practice*, 5th ed., Springer: Berlin, Germany

Braset, E., (2007). Masteroppgave University of Stavanger: *Evaluering av de fysiske forhold på boredekk og I boretårn ved operasjoner I arktiske Atlanterhavet med spesiell oppmerksomhet mot effektene vind og lave temperaturer skaper*.

British Standards (2008). BS EN 13306: *Maintenance terminology*

Burt, C., (2007). *Extreme Weather a guide & record book*, Norton: NY, USA

Claes S. (2010). Mail correspondence with senior electrical engineer Stefan Claes, University centre on Svalbard.

CSEP (Computational Science Education Project), (1995). *Introduction to Monte Carlo Methods*, available online: http://www.phy.ornl.gov/csep/CSEP/MC/MC.html. (Accessed at 27.05.2010)

Coomber, S (2008). *Race to the Arctic.* Published on Offshore-technology.com, available online: http://www.offshore-technology.com/features/feature1800/ (Accessed 13.01.2010)

Deming, W. E., (2000) *"Out of the crisis",* Cambridge, Mass., MIT Press

DNV Recommended Practice, (2009). DNV – RP – G101: *Risk Based Inspection of Offshore Topsides Static Mechanical Equipment*, Det Norske Veritas: Høvik, Norway

Duggan, A. (1988). *Energy cost of stepping in to protective clothing ensembles*. Ergonomics, 31,(1), 3-11.

Dunn, S, (2007). "*Condition monitoring in the 21 century*", Assetivity pty. LTD, Queensland, Australia.

Edvardsen, E. (2010). Conversation with electrical engineer Einar Edvardsen, ApplySørco As, Sandnes.

Eide A. (2010). Mail correspondence with technical manager Anders Eide, PG Marine AS.

ENI Norge, (2007). ENI Norway practice on native inhabitants, available online: http://www.eninorge.no/EniNo.nsf/files/Eni%20Norge%20-%20Praksis%20overfor%20urbefolkning/$file/Eni%20Norge%20-%20Praksis%20overfor%20urbefolkning.pdf, (accessed at 05.04.10)

Freitag, D. R. and McFadden, T. (1997). *Introduction to Cold Region Engineering*. ASCE Press: Reston, US

Gao, X., (2009). *Design for production performance, Reliability, Maintainability, and Arctic conditions*, PhD Thesis University of Stavanger no. 85 – Dec. 2009, Stavanger, Norway.

Gross, J. M., (2002). *Fundamentals of Preventive Maintenance*, Amacom: NY, USA

Gudmestad, O.T., (2005). Statoil presentation: *Water Waves And Floating Bodies in the perspective of Arctic Offshore Engineering*, Presented at "20th" International Workshop on Water Waves and Floating Bodies", Svalbard, 30.05.05. Available online: http://www.math.uio.no/iwwwfb/include/Gudmestad.pdf (accessed 29.12.2009).

Gudmestad, O. T. Løset, S. Alhimenko, A. L. Shkinek, K. N. Tørum, A. and Jensen, A., (2007) *Engineering aspects related to arctic offshore developments*, LAN Publishing House, ST. Petersburg, Russia

Holmer I., Granber P., Dahlstrom G.: *Cold environments and cold work*, available online: http://www.ilo.org/safework_bookshelf/english?content&nd=857170522 (accessed 20.01.2010)

Høiset S., Fossan I., Kaasa Ø., (2008): *Managing Explosion Risks in Arctic Areas*, Society of Petroleum Engineers, Nice, france) Available online: http://www.scandpower.com/upload/News/files/SPE-111583%20Managing%20Explosion%20Risk%20in%20Arctic%20Areas.pdf. (Accessed at 01.05.10).

IEEE Reliability Society – Reliability Engineering (2010). Definition of Reliability Engineering, available online: http://www.ieee.org/portal/site/relsoc/menuitem.e3d19081e6eb2578fb2275875bac26c8/index.jsp?&pName=relsoc_level1&path=relsoc/Reliability_Engineering&file=index.xml&xsl=generic.xsl (Accessed 23.04.2010)

International Ergonomics Association, (2008). Definition of Ergonomics, available online: http://www.iea.cc/browse.php?contID=what_is_ergonomics, (accessed 17.04.2010)

International Standardization organisation (ISO), (2006). ISO standard #14224: "*Petroleum, Petrochemical and Natural Gas Industries – Collection and exchange of reliability and maintenance data for equipment*"

Jensen, N., WWF (2010): Lecture *"Hva er det ved Norsk teknologi som gjør at vi ikke kan operere sikkert I Nordområdene"* at Center for Industrial Asset Managements Workshop "Oljevirksomhet i Nordområdene-muligheter og utfordringer" at University in Stavanger (11.02.2010)

Johansen, J. S., Jensen, H. S., Price, P. A, (1993). A new biochemical marker for joint injury. *"Analysis of YKL-40 in serum and synovial fluid"*Department of Biology at University of California, San Diego, USA.

Kojedal, S. (2009) StatoilHydro presentation on Arctic challenge Barents Sea youth conference, (18.04.2009) Hammerfest, Norway.

Larsen, A., C. (2007). *Production facility design for operation, maintenance and support in cold regions*, Published in Papers from the University of Stavanger N-19, Stavanger, Norway

Löfsten, H. (1999). *"Management of industrial maintenance ± economic evaluation of maintenance policies".* International Journal of Operations & Production Management, available online: http://www.emeraldinsight.com/Insight/viewPDF.jsp?contentType=Article&Filename=html/Output/Publishe EmeraldFullTextArticle/Pdf/0240190705.pdf , (accessed 05.05.2010)

Mäkinen T. M., Palinkas L. A., Reeves D. L., Pääkönen T., Rintarmäki H., Leppäluoto J., Hassi J., (2006): *Effect of repeated exposures to cold on cognitive performance in humans*, published in Physiology & Behaviour, Vol. 87, Issue 1, pages 166-176, 30.01.2006).

Markeset, T. (2008). *Design for Production Performance in Arctic Locations Considering Maintenance and Support Services*, In the Proceedings of the Mine Planning and Equipment Conference (MPE2008), October 20-22nd Beijing, China

Markeset T., Kumar U., (2001). *R&M and Risk-analysis tools in product design to reduce life cycle costs and improve attractiveness*

Mobley, R.K. (1990). *An introduction to predictive maintenance*, New York, Van Nostrand Reinhold, USA

National fire protection association (NFPA) (2010). NFPA 70B: *Recommended practice for electrical equipment maintenance*

Niebel, B. W. (1994). *Engineering Maintenance Management*, Marcel Dekker Inc, pp, New York, US

NORSOK, (2001). NORSOK STANDARD Z-008: *Criticality analysis for maintenance purposes*, Rev 2. Norwegian Technology Centre.

NORSOK, (1998). NORSOK STANDARD Z-016: *Regularity Management & Reliability Technology*, Rev 1. Norwegian Technology Centre.

NPD (Oljedirektoratet), (2009). *"Fakta- Norsk Petroleumsverksemd 2009"*

Offshore Shipping Online, (2000). *Terra Nova FPSO sets sail for Newfoundland*. Published in Offshore Shipping Online, available online: http://www.oilpubs.com/oso/article.asp?v1=4533 (Accessed 18.03.2010)

Offshore-technology.com (2010). Key data Prirazlomonoye Oilfield- Barents Sea, Russia, available online: http://www.offshore-technology.com/projects/Prirazlomnoye/ (Accessed 25.01.2010)

(OPL) Oil Publications Ltd (1991). "*Introduction to offshore maintenance"*, Ledbury, UK

OREDA (2009). Offshore Reliability Data (5th ed.*), Vol. 1 Topside Equipment*, SINTEF Technology and Society, Trondheim, Norway.

Orheim, O., (2003). "*Protecting the environment of the Arctic ecosystem*" Panel at the fourth meeting of the United Nations open-ended informal consultative process on ocean and the law of the sea, 2-6 jan 2003, Tromsø, Norway.

Palinkas L. A., Cravalho M. J., Browner D. (1995). *Seasonal variation of depressive symptoms in Antarctica*, published in Acta Psyychiatrica Scandinavia Volume 91, Issue 6 Pages 423-429.

Piltelton, L., Gelders, L. and Puyvelde, F. van (1997).*Maintenance management*, Leuven: Acco.

Rausand, M. and Høyland A. (2004). *System Reliability Theory – Models, Statistical Methods and Application*. John Wiley & Sons

San Jose University, Electrical Engineering department (2010). PPT from lecture on: Design for Supportability(serviceability), available online: http://www.google.no/url?sa=t&source=web&ct=res&cd=15&ved=0CBwQFjAEOAo&url=http%3A%2F%2Fwww.engr.sjsu.edu%2Fazargar%2FTech-101%2FTECH%2520101-Supportability.ppt&rct=j&q=supportability&ei=_MVeS87tMYWF-QaEgdGSBg&usg=AFQjCNGEUx4wBf0mPphakpLpj4QmGLAxLg (Accessed 06.02.2010)

Speaks, S. (2001): *Reliability and MTBF Overview,* Paper Prepared for Vicor Reliability Engineering, Andover, USA

Panesar, S., S., Markeset T., (2006). *Maintenance optimization process in the Norwegian Petroleum industry – key issues, challenges, and opportunities*

Sundberg, A. (2003). *"Management aspects on Condition Based Maintenance – the new opportunity for maritime industry",*paper presented at the 9th International Conference on Marine Engineering Systems at the Helsinki University of Technology (HUT) ship laboratory and on board MS Silja Serenade 19-21 May, 2003, Helsinki, Finland

Sæbø E. for DNV, (2007). PPT: *RP for Application of Offshore Technology in Arctic Conditions*. On the Arctic Oil and Gas Conference (17-18 January 2007) Available online: http://www.tekna.no/arkiv/Arrangementer/Arctic%20Oil%20and%20Gas%20Conference%202007/torsd%201000%20erling%20saebo.dnv.pdf (Accessed 21.01.2010).

Søreide E. J., Hop H., Falk-Petersen S., Gulliksen B., Hansen E. (2003). *Macrozooplankton communities and environmental variables in the Barents Sea marginal ice zone in late winter and spring*. Norwegian Polar Institute, Tromsø, Norway.

The Hon. Lord Cullen, (1990). *The Public Inquiry into the Piper Alpha Disaster, Vol. 1* (Report to Parliament by the Secretary of State for Energy by Command of Her Majesty.

U.S. Geological Survey, (2008). Fact sheet; "USGS Arctic Oil and Gas Report: Estimates of Undiscovered Oil and Gas North of the Arctic Circle", available online: http://geology.com/usgs/arctic-oil-and-gas-report.shtml, (accessed 07.01.2010)

U.S. Geological Survey, (2008). Press release: "*90 Billion Barrels of Oil and 1,670 Trillion Cubic Feet of Natural Gas Assessed in the Arctic*", released 23.07.2008, available online: http://www.usgs.gov/newsroom/article.asp?ID=1980 (accessed 07.01.2010)

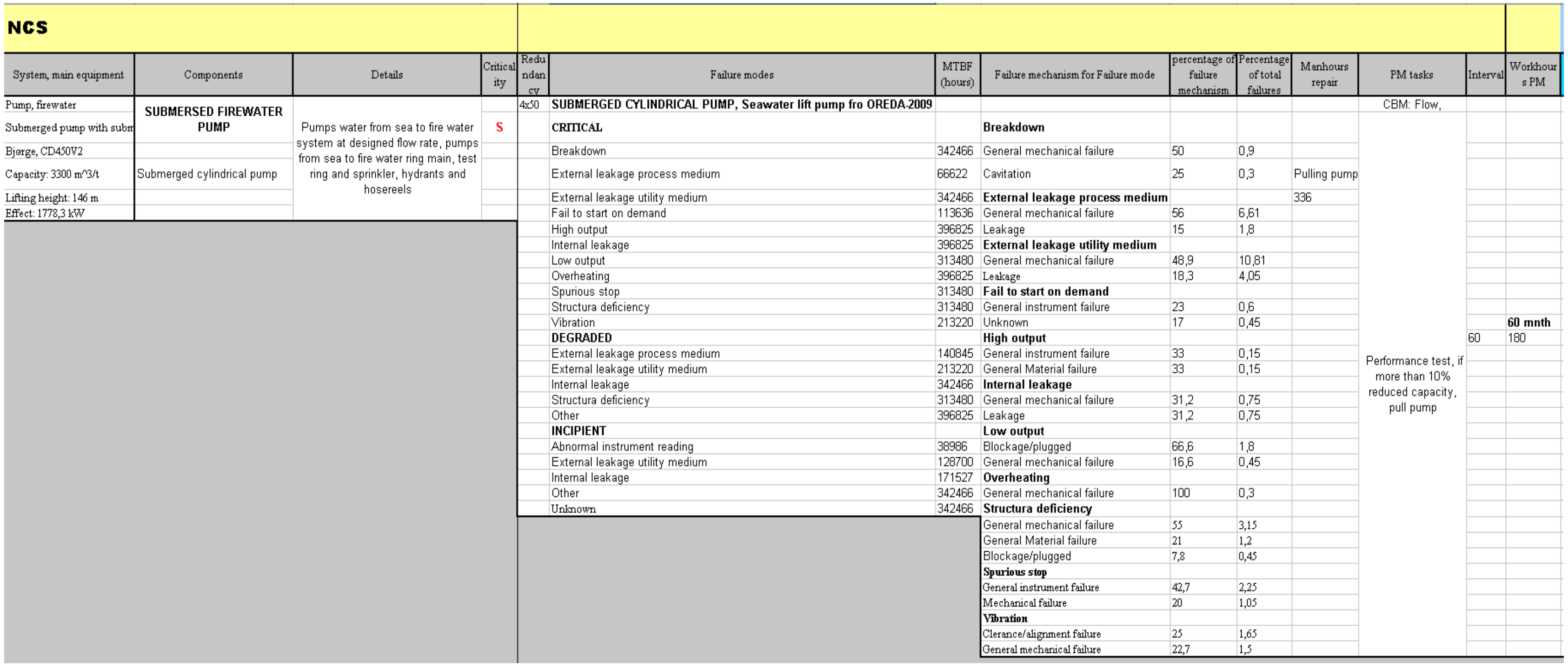
Vinnem, J. E., (2007). *Principles, Modeling and Applications of QRA Studies*, 2nd Ed., Springer: Berlin, Germany.

Wheeler A., Ganji A. R (2004). *Exponential failure in instrumentation*, 3rd ed., Prentice Hall: New Jersey, US

Yr.no (27.04.2010): News article: *Arktisk uvær kan bli fatalt*, published 27.04.2010, available online: http://www.yr.no/nyheter/1.7098552 (accessed 27.04.2010)

Appendix A FMECA Analysis, firewater System

Table A.1. FMECA, Firewater pump, NCS



NCS

System, main equipment	Components	Details	Criticality	Redundancy	Failure modes	MTBF (hours)	Failure mechanism for Failure mode	percentage of failure mechanism	Percentage of total failures	Manhours repair	PM tasks	Interval	Workhours PM
Pump, firewater	**SUBMERSED FIREWATER PUMP**			4x50	**SUBMERGED CYLINDRICAL PUMP, Seawater lift pump fro OREDA-2009**						CBM: Flow,		
Submerged pump with subm		Pumps water from sea to fire water system at designed flow rate, pumps from sea to fire water ring main, test ring and sprinkler, hydrants and hosereels	S		**CRITICAL**		**Breakdown**				Performance test, if more than 10% reduced capacity, pull pump		
Bjørge, CD450V2					Breakdown	342466	General mechanical failure	50	0,9				
Capacity: 3300 m^3/t	Submerged cylindrical pump				External leakage process medium	66622	Cavitation	25	0,3	Pulling pump			
Lifting height: 146 m					External leakage utility medium	342466	**External leakage process medium**			336			
Effect: 1778,3 kW					Fail to start on demand	113636	General mechanical failure	56	6,61				
					High output	396825	Leakage	15	1,8				
					Internal leakage	396825	**External leakage utility medium**						
					Low output	313480	General mechanical failure	48,9	10,81				
					Overheating	396825	Leakage	18,3	4,05				
					Spurious stop	313480	**Fail to start on demand**						
					Structura deficiency	313480	General instrument failure	23	0,6				
					Vibration	213220	Unknown	17	0,45				**60 mnth**
					DEGRADED		**High output**					60	180
					External leakage process medium	140845	General instrument failure	33	0,15				
					External leakage utility medium	213220	General Material failure	33	0,15				
					Internal leakage	342466	**Internal leakage**						
					Structura deficiency	313480	General mechanical failure	31,2	0,75				
					Other	396825	Leakage	31,2	0,75				
					INCIPIENT		**Low output**						
					Abnormal instrument reading	38986	Blockage/plugged	66,6	1,8				
					External leakage utility medium	128700	General mechanical failure	16,6	0,45				
					Internal leakage	171527	**Overheating**						
					Other	342466	General mechanical failure	100	0,3				
					Unknown	342466	**Structura deficiency**						
							General mechanical failure	55	3,15				
							General Material failure	21	1,2				
							Blockage/plugged	7,8	0,45				
							Spurious stop						
							General instrument failure	42,7	2,25				
							Mechanical failure	20	1,05				
							Vibration						
							Clerance/alignment failure	25	1,65				
							General mechanical failure	22,7	1,5				

Table A.2 FMECA, Firewater pump, Arctic

Arctic

System, main equipment	Components	Details	Criticality	Failure modes	MTBF (hours)	Failure mechanism for Failure mode	percentage of failure mechanism	Percentage of total failures	Man hours repair	PM tasks	Interval	Workhours PM
Pump, firewater	**SUBMERSED FIREWATER**			**Submerged cylindrical pump**						CBM: Flow, temperature, pressure		
Submerged pump with subm	Submerged cylindrical pump	Pumps water from sea to fire water system at designed flow rate, pumps, water to all firefighting systemspumps from sea to fire water ring main,	S	**CRITICAL**		**Breakdown**						
Bjørge, CD450V2				Breakdown	342466 +	General mechanical failure	50+	0,9+				
Capacity: 3300 m^3/t				External leakage process medium	66622 +	Cavitation	25+	0,3+			After winter	
Lifting height: 146 m				External leakage utility medium	342466 +	**External leakage process medium**						
Effect: 1778,3 kW				Fail to start on demand	113636 +	General mechanical failure	56+	6,61+				
				High output	396825 +	Leakage	15+	1,8+				
				Internal leakage	396825 +	**External leakage utility medium**						
				Low output	313480 +	General mechanical failure	48,9+	10,81+	Pulling			
				Overheating	396825 +	Leakage	18,3+	4,05+				
				Spurious stop	313480 +	**Fail to start on demand**			336+			
				Structura deficiency	313480 +	General instrument failure	23	0,6			Pull in ice free season	
				Vibration	213220 +	Unknown	17+	0,45+				**12 mnth**
				DEGRADED		**High output**					12	180
				External leakage process medium	140845 +	General instrument failure	33	0,15				
				External leakage utility medium	213220 +	General Material failure	33+	0,15+				
				Internal leakage	342466 +	**Internal leakage**				Performance test after every ice season		
				Structura deficiency	313480 +	General mechanical failure	31,2+	0,75+				
				Other	396825 +	Leakage	31,2	0,75+				
				INCIPIENT		**Low output**						
				Abnormal instrument reading	38986 +	Blockage/plugged	66,6+	1,8+				
				External leakage utility medium	128700 +	General mechanical failure	16,6+	0,45+				
				Internal leakage	171527 +	**Overheating**						
				Other	342466 +	General mechanical failure	100	0,3+				
				Unknown	342466 +	**Structura deficiency**						
						General mechanical failure	55+	3,15+				
						General Material failure	21+	1,2+				
						Blockage/plugged	7,8+	0,45+				
						Spurious stop						
						General instrument failure	42,7	2,25				
						Mechanical failure	20+	1,05+				
						Vibration						
						Clerance/alignment failure	25+	1,65+				
						General mechanical failure	22,7+	1,5+				

Table A.3. FMECA, Submerged electrical motor and filter for firewater pump, NCS

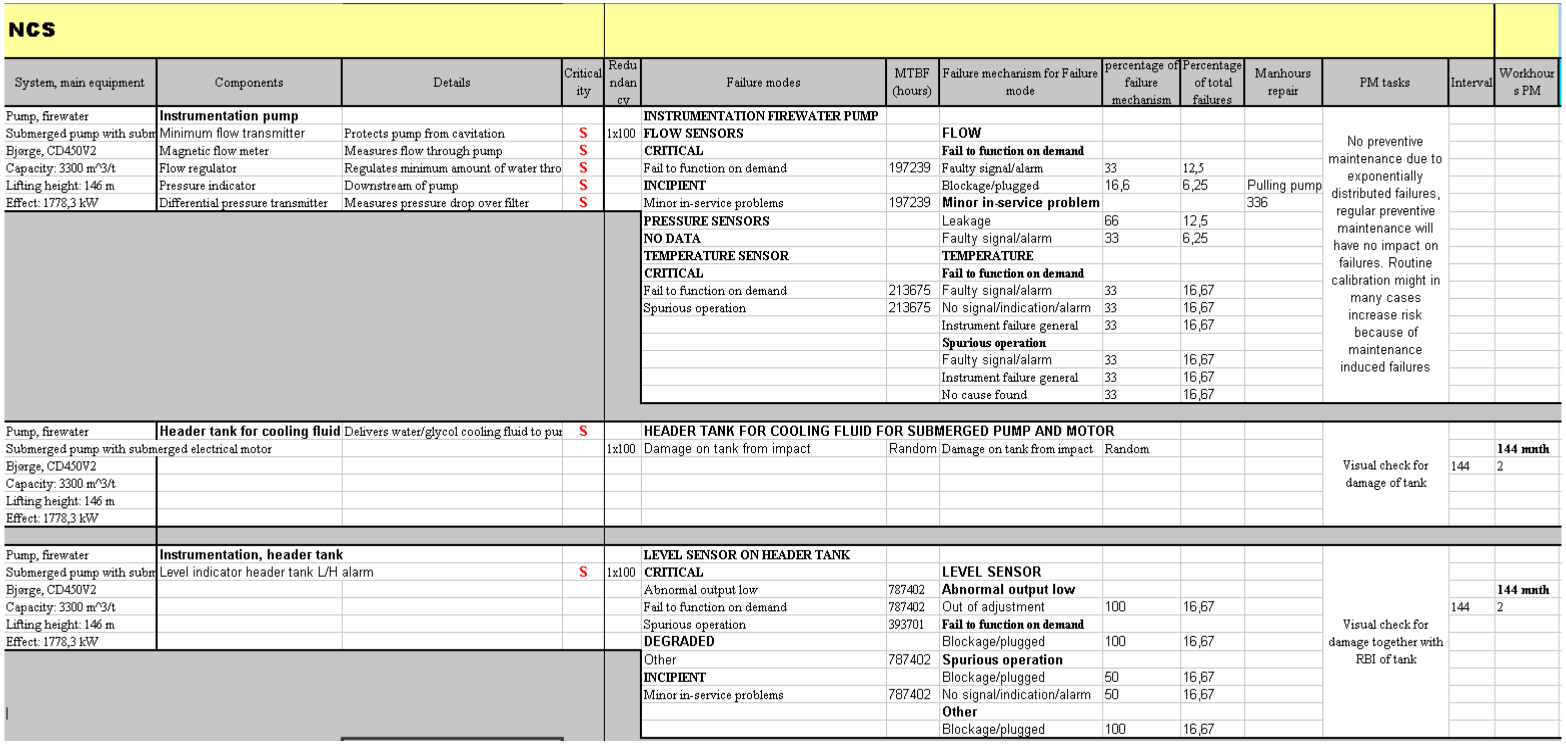
NCS														
System, main equipment	Components	Details	Criticality	Redundancy	Failure modes	MTBF (hours)	Failure mechanism for Failure mode	percentage of failure mechanism	Percentage of total failures	Manhours repair	PM tasks	Interval	Workhours PM
Pump, firewater	**Submerged electrical motor**	Cooled by water, glycol mixture		4x50	**SUBMRGED ELECTRICAL MOTOR ON FIREWATER PUMP**						Performance test, if more than 10% reduced capacity, pull pump		
Submerged pump with subm	6,6 kV, 60 Hz	Powered from dedicated Diesel engine	S		**CRITICAL**		**Breakdown**						
Bjørge, CD450V2					Breakdown	87565	Breakage	26,8	1,56	Pulling pump			
Capacity: 3300 m^3/t					Fail to start on demand	87565	Earth/isolation fault	13,4	0,78	336			**60 mnth**
Lifting height: 146 m					**DEGRADED**		Wear	13,4	0,78			60	180
Effect: 1778,3 kW					Other	87565	**Fail to start on demand**						
							Electric failure	50	7,25				
							Control failure	20	2,9				
Pump, firewater	**Valves, filters**				**FILTER FOR FIREWATER PUMP**						Performance test, if more than 10% reduced capacity, pull pump		
Submerged pump with subm	Flow valve	Remove contaminants from working liqui	S	1x100	Fails to remove contaminants due to internal damage to filter element or strainer basket	Random	**Fails to remove contaminants**						
Bjørge, CD450V2	Fdownstream filter	sufficient flow, contains fluid during ope:	S				Damage to filter element	No data	No data				
Capacity: 3300 m^3/t		Closed when flow is less than 1400 m^3/h			Fails to allow sufficient flow due to blockage to filter to strainer	Random	Damage to strainer basket	No data	No data				**60 mnth**
Lifting height: 146 m		3-4mm masks, protects wire water system from particles					**Fails to allow sufficient flow**	No data	No data	Pulling pump		60	180
Effect: 1778,3 kW					Filter strainer leakage	Random	Blockage of filter	No data	No data	336			
							Blockage of strainer	No data	No data				
							Material failure	No data	No data				
							Filter strainer leakage	No data	No data				
							blockage of strainer	No data	No data				
							material failure	No data	No data				

Table A.4 FMECA Submerged electrical motor and filter, Arctic

Arctic

System, main equipment	Components	Details	Criticality	Failure modes	MTBF (hours)	Failure mechanism for Failure mode	percentage of failure mechanism	Percentage of total failures	Man hours repair	PM tasks	Interval	Workhours PM
Pump, firewater	**Submerged electrical mot**	Cooled by water, glycol mixture		**SUBMRGED ELECTRICAL MOTOR ON FIREWATER PUMP**								
Submerged pump with subm	6,6 kV, 60 Hz		S	**CRITICAL**		**Breakdown**				Flow rate test		
Bjørge, CD450V2				Breakdown	87565 +	Breakage	26,8	1,56				
Capacity: 3300 m^3/t		Powered from dedicated Diesel engines and generator		Fail to start on demand	87565 +	Earth/isolation fault	13,4	0,78	Pullin		Pull in ice free	**12 mnth**
Lifting height: 146 m				**DEGRADED**		Wear	13,4	0,78	336+	Performance test after every ice season	12+	180
Effect: 1778,3 kW				Other	87565 +	**Fail to start on demand**						
						Electric failure	50	7,25				
						Control failure	20	2,9				
Pump, firewater	**Valves, filters**			**FILTER FOR FIREWATER PUMP**								
Submerged pump with subm	Flow valve	Remove contaminants from wc	S	Fails to remove contaminants due to internal damage to filter	Random +	**Fails to remove contaminants**						
Bjørge, CD450V2	Fdownstream filter	sufficient flow, contains fluid c	S			Damage to filter element	No data	No data		Performance test, if more than 10% reduced capacity, pull pump		
Capacity: 3300 m^3/t		Closed when flow is less than 1400 m^3/		Fails to allow sufficient flow due to blockage to filter to strainer	Random +	Damage to strainer basket	No data	No data			Pull in ice free	**12 mnth**
Lifting height: 146 m		3-4mm masks, protects wire water syster				**Fails to allow sufficient flow**	No data	No data	Pullin		12+	180
Effect: 1778,3 kW				Filter strainer leakage	Random +	Blockage of filter	No data	No data	336+			
						Blockage of strainer	No data	No data				
						Material failure	No data	No data				
						Filter strainer leakage	No data	No data				
						blockage of strainer	No data	No data				
						material failure	No data	No data				

Table A.5 FMECA, Instrumentation pump, header tank and instrumentation on header tank, NCS



NCS

System, main equipment	Components	Details	Criticality	Redundancy	Failure modes	MTBF (hours)	Failure mechanism for Failure mode	percentage of failure mechanism	Percentage of total failures	Manhours repair	PM tasks	Interval	Workhours PM
Pump, firewater	**Instrumentation pump**				**INSTRUMENTATION FIREWATER PUMP**						No preventive maintenance due to exponentially distributed failures, regular preventive maintenance will have no impact on failures. Routine calibration might in many cases increase risk because of maintenance induced failures		
Submerged pump with subm	Minimum flow transmitter	Protects pump from cavitation	S	1x100	**FLOW SENSORS**		**FLOW**						
Bjørge, CD450V2	Magnetic flow meter	Measures flow through pump	S		**CRITICAL**		**Fail to function on demand**						
Capacity: 3300 m^3/t	Flow regulator	Regulates minimum amount of water thro	S		Fail to function on demand	197239	Faulty signal/alarm	33	12,5				
Lifting height: 146 m	Pressure indicator	Downstream of pump	S		**INCIPIENT**		Blockage/plugged	16,6	6,25	Pulling pump			
Effect: 1778,3 kW	Differential pressure transmitter	Measures pressure drop over filter	S		Minor in-service problems	197239	**Minor in-service problem**			336			
					PRESSURE SENSORS		Leakage	66	12,5				
					NO DATA		Faulty signal/alarm	33	6,25				
					TEMPERATURE SENSOR		**TEMPERATURE**						
					CRITICAL		**Fail to function on demand**						
					Fail to function on demand	213675	Faulty signal/alarm	33	16,67				
					Spurious operation	213675	No signal/indication/alarm	33	16,67				
							Instrument failure general	33	16,67				
							Spurious operation						
							Faulty signal/alarm	33	16,67				
							Instrument failure general	33	16,67				
							No cause found	33	16,67				
Pump, firewater	**Header tank for cooling fluid**	Delivers water/glycol cooling fluid to pur	S		**HEADER TANK FOR COOLING FLUID FOR SUBMERGED PUMP AND MOTOR**						Visual check for damage of tank		
Submerged pump with submerged electrical motor				1x100	Damage on tank from impact	Random	Damage on tank from impact	Random					**144 mnth**
Bjørge, CD450V2												144	2
Capacity: 3300 m^3/t													
Lifting height: 146 m													
Effect: 1778,3 kW													
Pump, firewater	**Instrumentation, header tank**				**LEVEL SENSOR ON HEADER TANK**						Visual check for damage together with RBI of tank		
Submerged pump with subm	Level indicator header tank L/H alarm		S	1x100	**CRITICAL**		**LEVEL SENSOR**						
Bjørge, CD450V2					Abnormal output low	787402	**Abnormal output low**						**144 mnth**
Capacity: 3300 m^3/t					Fail to function on demand	787402	Out of adjustment	100	16,67			144	2
Lifting height: 146 m					Spurious operation	393701	**Fail to function on demand**						
Effect: 1778,3 kW					**DEGRADED**		Blockage/plugged	100	16,67				
					Other	787402	**Spurious operation**						
					INCIPIENT		Blockage/plugged	50	16,67				
					Minor in-service problems	787402	No signal/indication/alarm	50	16,67				
							Other						
							Blockage/plugged	100	16,67				

Table A.6 FMECA, Instrumentation on pump, header tank for cooling fluid and instrumentation on header tank, Arctic

Arctic

System, main equipment	Components	Details	Criticality	Failure modes	MTBF (hours)	Failure mechanism for Failure mode	percentage of failure mechanism	Percentage of total failures	Man hours repair	PM tasks	Interval	Workhours PM
Pump, firewater	**Instrumentation pump**			**FLOW SENSORS**						No preventive maintenance due to exponentialfordelt failures, regular preventive maintenance will have no impact on failures. Routine calibration might in many cases increase risk because of		
Submerged pump with subm	Minimum flow transmitter	Protects pump from cavitation	S	**CRITICAL**		**FLOW**						
Bjørge, CD450V2	Magnetic flow meter	Measures flow through pump	S	Fail to function on demand	197239	**Fail to function on demand**						
Capacity: 3300 m^3/t	Flow regulator	Regulates minimum amount of	S	**INCIPIENT**		Faulty signal/alarm	33	12,5				
Lifting height: 146 m	Pressure indicator	Downstream of pump	S	Minor in-service problems	197239	Blockage/plugged	16,6	6,25				
Effect: 1778,3 kW	Differential pressure transmitte	Measures pressure drop over f	S	**PRESSURE SENSORS**		**Minor in-service problem**						
				NO DATA		Leakage	66	12,5	Pullin			
						Faulty signal/alarm	33	6,25	336+			
				TEMPERATURE SENSOR		**TEMPERATURE**						
				CRITICAL		**Fail to function on demand**						
				Fail to function on demand	213675	Faulty signal/alarm	33	16,67				
				Spurious operation	213675	No signal/indication/alarm	33	16,67				
						Instrument failure general	33	16,67				
				No maintenance	MTBF 20 ye	**Spurious operation**						
				No maintenance on instrumentation		Faulty signal/alarm	33	16,67				
						Instrument failure general	33	16,67				
				N/A		No cause found	33	16,67				
Pump, firewater	**Header tank for cooling fl**	Delivers water/glycol cooling f	S									
Submerged pump with submerged electrical motor										Visual check for damage together with RBI of tank		**144 mnth**
Bjørge, CD450V2											144	2
Capacity: 3300 m^3/t												
Lifting height: 146 m												
Effect: 1778,3 kW												
Pump, firewater	**Instrumentation, header tank**									Visual check for damage together with RBI of tank		
Submerged pump with subm	Level indicator header tank L/H alarm		S	Spurious operation	393701	**LEVEL SENSOR**						
Bjørge, CD450V2				**DEGRADED**		**Abnormal output low**						**144 mnth**
Capacity: 3300 m^3/t				Other	787402	Out of adjustment	100	16,67			144	2
Lifting height: 146 m				**INCIPIENT**		**Fail to function on demand**						
Effect: 1778,3 kW				Minor in-service problems	787402	Blockage/plugged	100	16,67				
				TEMPERATURE SENSOR		**Spurious operation**						
				CRITICAL		Blockage/plugged	50	16,67				
				Fail to function on demand	213675	No signal/indication/alarm	50	16,67				
				Spurious operation	213675	**Other**						
						Blockage/plugged	100	16,67				

Table A.7 FMECA, Jockey pump and instrumentation pump, NCS

NCS

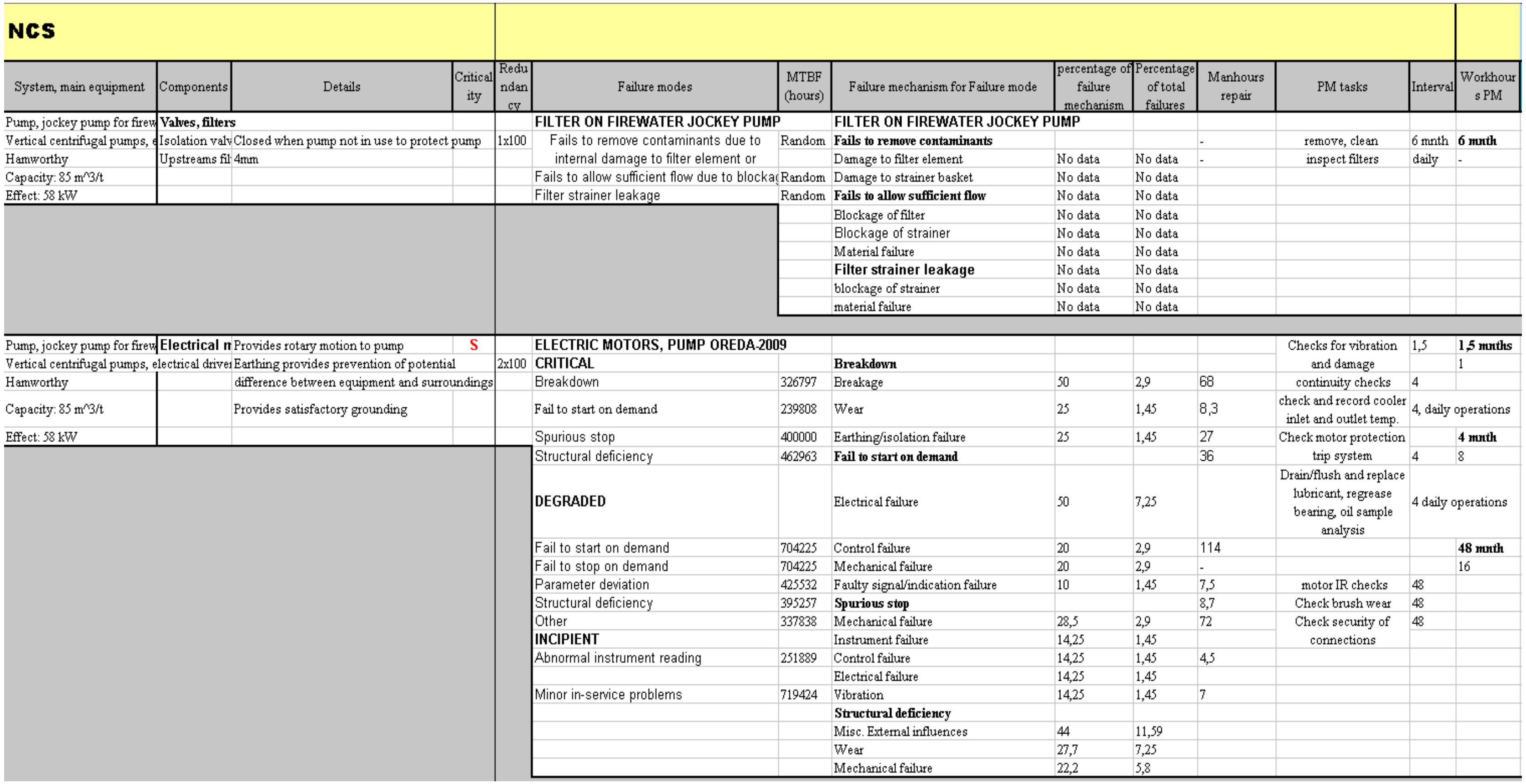
System, main equipment	Components	Details	Criticality	Redundancy	Failure modes	MTBF (hours)	Failure mechanism for Failure mode	percentage of failure mechanism	Percentage of total failures	Manhours repair	PM tasks	Interval	Workhours PM
Pump, jockey pump for firew	**JOCKEY PUMP FOR FIREWATER SYSTEM**				**FIREWATER JOCKEY PUMP, centrifugal fire fighting pump from OREDA-2009**								
Vertical centrifugal pumps, e	Centrifugal p	Pumps seawater from seawater syste	S	2x100	**CRITICAL**		**Breakdown**						
Hamworthy		pressure in fire water ring main.			Breakdown	694444	General mechanical failure	50	0,9	211	CBM:		
Capacity: 85 m^3/t					Erratic output	649351	Cavitation	25	0,3	378	Monitor drive coupling		
Effect: 58 kW					Low output	694444	**External leakage process medium**			52	Flow monitoring	daily	
					Parameter deviation	735294	General mechanical failure	56	6,61	3	Vibration monitoring on	daily	
					Spurious stop	694444	Leakage	15	1,8	5	bearing		
					Vibration	308642	**External leakage utility medium**			76	Inspections:		
					DEGRADED		General mechanical failure	48,9	10,81		Sounds, vibrations, leaks	daily	
					Erratic output	204499	Leakage	18,3	4,05	21			
					External leakage utility medium	72516	**Fail to start on demand**			40	Flow rate test, check oil	3	**3 mnth**
					Internal leakage	346021	General instrument failure	23	0,6	8	level		1
					Low output	588235	Unknown	17	0,45	92	Check drive belt for	3	
					Minor in-service problems	694444	**High output**			24	degradation		
					Parameter deviation	735294	General instrument failure	33	0,15	6			
					Other	175131	General Material failure	33	0,15	11			
					INCIPIENT		**Internal leakage**				Thorough inspection	24	**24 mnth**
					Abnormal instrument reading	78247	General mechanical failure	31,2	0,75	6,1	Oil sample analysis	24	6
					External leakage utility medium	161551	Leakage	31,2	0,75	11			
					Internal leakage	694444	**Low output**			9			
					Minor in-service problems	45065	Blockage/plugged	66,6	1,8	19			
					Other	325733	General mechanical failure	16,6	0,45	5			
							Overheating						
							General mechanical failure	100	0,3				
							Structura deficiency						
							General mechanical failure	55	3,15				
							General Material failure	21	1,2				
							Blockage/plugged	7,8	0,45				
							Spurious stop						
							General instrument failure	42,7	2,25				
							Mechanical failure	20	1,05				
							Vibration						
							Clerance/alignment failure	25	1,65				
							General mechanical failure	22,7	1,5				
Pump, jockey pump for firew	**Instrumentation pump**												
Vertical centrifugal pumps, e	Differential pressure transmitter, H alarm		S	1x100	**PRESSURE SENSORS**								
Hamworthy	Pressuretransmitter upstream		S		**NO DATA**								
Capacity: 85 m^3/t	Pressuretransmitter downstream L alarm		S										
Effect: 58 kW	Pressuretrans	Autostarts pump at low pressures	S										

Table A.8 FMECA, Jockey pump and instrumentation on pump, Arctic

Arctic

System, main equipment	Components	Details	Criticality	Failure modes	MTBF (hours)	Failure mechanism for Failure mode	percentage of failure mechanism	Percentage of total failures	Man hours repair	PM tasks	Interval	Workhours PM
Pump, jockey pump for firew	**JOCKEY PUMP FOR FIREWATER SYSTEM**			**FIREWATER JOCKEY PUMP, centrifugal fire fighting pump from OREDA-2009**								
Vertical centrifugal pumps, e	Centrifugal pump	Pumps seawater from seawater system to uphold pressure in fire water ring	S	**CRITICAL**		**Breakdown**						
Hamworthy				Breakdown	694444	General mechanical failure	50	0,9	211	CBM:		
Capacity: 85 m^3/t				Erratic output	649351	Cavitation	25	0,3	378	Monitor drive coupling		
Effect: 58 kW				Low output	694444	**External leakage process medium**			52	Flow monitoring	daily	
				Parameter deviation	735294	General mechanical failure	56	6,61	3	Vibration monitoring on bearing	daily	
				Spurious stop	694444	Leakage	15	1,8	5			
				Vibration	308642	**External leakage utility medium**			76	Inspections:		
				DEGRADED		General mechanical failure	48,9	10,81		Sounds, vibrations, leaks	daily	
				Erratic output	204499	Leakage	18,3	4,05	21			
				External leakage utility medium	72516	**Fail to start on demand**			40	Flow rate test, check oil level	3	**3 mnth**
				Internal leakage	346021	General instrument failure	23	0,6	8	Check drive belt for degradation	3	1
				Low output	588235	Unknown	17	0,45	92			
				Minor in-service problems	694444	**High output**			24	Thorough inspection	24	**24 mnth**
				Parameter deviation	735294	General instrument failure	33	0,15	6	Oil sample analysis	24	6
				Other	175131	General Material failure	33	0,15	11			
				INCIPIENT		**Internal leakage**						
				Abnormal instrument reading	78247	General mechanical failure	31,2	0,75	6,1			
				External leakage utility medium	161551	Leakage	31,2	0,75	11			
				Internal leakage	694444	**Low output**			9			
				Minor in-service problems	45065	Blockage/plugged	66,6	1,8	19			
				Other	325733	General mechanical failure	16,6	0,45	5			
						Overheating						
						General mechanical failure	100	0,3				
						Structura deficiency						
						General mechanical failure	55	3,15				
						General Material failure	21	1,2				
						Blockage/plugged	7,8	0,45				
						Spurious stop						
						General instrument failure	42,7	2,25				
						Mechanical failure	20	1,05				
						Vibration						
						Clerance/alignment failure	25	1,65				
						General mechanical failure	22,7	1,5				
Pump, jockey pump for firew	**Instrumentation pump**											
Vertical centrifugal pumps, e	Differential pressure transmitter, H alarm		S	**PRESSURE SENSORS**								
Hamworthy	Pressuretransmitter upstream		S	**NO DATA**								
Capacity: 85 m^3/t	Pressuretransmitter downstream L alarm		S									
Effect: 58 kW	Pressuretransmitter fire ring ma	Autostarts pump at low pressu	S									

Table A.9 FMECA, Filter on firewater jockey pump, electric motor, NCS



NCS

System, main equipment	Components	Details	Criticality	Redundancy	Failure modes	MTBF (hours)	Failure mechanism for Failure mode	percentage of failure mechanism	Percentage of total failures	Manhours repair	PM tasks	Interval	Workhours PM
Pump, jockey pump for firew	**Valves, filters**				**FILTER ON FIREWATER JOCKEY PUMP**		**FILTER ON FIREWATER JOCKEY PUMP**						
Vertical centrifugal pumps, e	Isolation valv	Closed when pump not in use to protect pump		1x100	Fails to remove contaminants due to	Random	**Fails to remove contaminants**			-	remove, clean	6 mnth	**6 mnth**
Hamworthy	Upstreams fil	4mm			internal damage to filter element or		Damage to filter element	No data	No data	-	inspect filters	daily	-
Capacity: 85 m^3/t					Fails to allow sufficient flow due to blockag	Random	Damage to strainer basket	No data	No data				
Effect: 58 kW					Filter strainer leakage	Random	**Fails to allow sufficient flow**	No data	No data				
							Blockage of filter	No data	No data				
							Blockage of strainer	No data	No data				
							Material failure	No data	No data				
							Filter strainer leakage	No data	No data				
							blockage of strainer	No data	No data				
							material failure	No data	No data				
Pump, jockey pump for firew	**Electrical m**	Provides rotary motion to pump	S		**ELECTRIC MOTORS, PUMP OREDA-2009**						Checks for vibration	1,5	**1,5 mnths**
Vertical centrifugal pumps, electrical drive		Earthing provides prevention of potential		2x100	**CRITICAL**		**Breakdown**				and damage		1
Hamworthy		difference between equipment and surroundings			Breakdown	326797	Breakage	50	2,9	68	continuity checks	4	
Capacity: 85 m^3/t		Provides satisfactory grounding			Fail to start on demand	239808	Wear	25	1,45	8,3	check and record cooler inlet and outlet temp.	4, daily operations	
Effect: 58 kW					Spurious stop	400000	Earthing/isolation failure	25	1,45	27	Check motor protection		**4 mnth**
					Structural deficiency	462963	**Fail to start on demand**			36	trip system	4	8
					DEGRADED		Electrical failure	50	7,25		Drain/flush and replace lubricant, regrease bearing, oil sample analysis	4 daily operations	
					Fail to start on demand	704225	Control failure	20	2,9	114			**48 mnth**
					Fail to stop on demand	704225	Mechanical failure	20	2,9	-			16
					Parameter deviation	425532	Faulty signal/indication failure	10	1,45	7,5	motor IR checks	48	
					Structural deficiency	395257	**Spurious stop**			8,7	Check brush wear	48	
					Other	337838	Mechanical failure	28,5	2,9	72	Check security of	48	
					INCIPIENT		Instrument failure	14,25	1,45		connections		
					Abnormal instrument reading	251889	Control failure	14,25	1,45	4,5			
							Electrical failure	14,25	1,45				
					Minor in-service problems	719424	Vibration	14,25	1,45	7			
							Structural deficiency						
							Misc. External influences	44	11,59				
							Wear	27,7	7,25				
							Mechanical failure	22,2	5,8				

Table A.10 FMECA, Filter on firewater jockey pump and el. Motor on pump, Arctic

Arctic												
System, main equipment	Components	Details	Criticality	Failure modes	MTBF (hours)	Failure mechanism for Failure mode	percentage of failure mechanism	Percentage of total failures	Man hours repair	PM tasks	Interval	Workhours PM
Pump, jockey pump for firew	**Valves, filters**			**FILTER ON FIREWATER JOCKEY PUMP**								
Vertical centrifugal pumps, e	Isolation valve			Fails to remove contaminants due t	Random +	**Fails to remove contaminants**				remove, clean	6 mnth+	**6 mnth**
Hamworthy	Upstreams filter			Evident		Damage to filter element	No data	No data		inspect filters	daily	-
Capacity: 85 m^3/t				Fails to allow sufficient flow due to	Random +	Damage to strainer basket	No data	No data				
Effect: 58 kW				evident, hidden		**Fails to allow sufficient flow**	No data	No data				
				Filter strainer leakage	Random +	Blockage of filter	No data	No data				
						Blockage of strainer	No data	No data				
						Material failure	No data	No data				
						Filter strainer leakage	No data	No data				
						blockage of strainer	No data	No data				
						material failure	No data	No data				
Pump, jockey pump for firew	**Electrical motor**	Provides rotary motion to pump	S	**ELECTRIC MOTORS, PUMP OREDA-2009**						Checks for vibration and damage	1,5	**1,5 mnths**
Vertical centrifugal pumps, electrical driven.				**CRITICAL**		**Breakdown**						1
Hamworthy				Breakdown	326797	Breakage	50	2,9	68	continuity checks	4	
Capacity: 85 m^3/t				Fail to start on demand	239808	Wear	25	1,45	8,3	check and record cooler inlet and outlet temp.	4, daily operations	
Effect: 58 kW				Spurious stop	400000	Earthing/isolation failure	25	1,45	27			**4 mnth**
				Structural deficiency	462963	**Fail to start on demand**			36	Check motor protection trip system	4	8
				DEGRADED		Electrical failure	50	7,25		Drain/flush and replace lubricant, regrease bearing, oil sample analysis	4 daily operations	
				Fail to start on demand	704225	Control failure	20	2,9	114			**48 mnth**
				Fail to stop on demand	704225	Mechanical failure	20	2,9	-			16
				Parameter deviation	425532	Faulty signal/indication failure	10	1,45	7,5	motor IR checks	48	
				Structural deficiency	395257	**Spurious stop**			8,7	Check brush wear	48	
				Other	337838	Mechanical failure	28,5	2,9	72	Check security of connections	48	
				INCIPIENT		Instrument failure	14,25	1,45				
				Abnormal instrument reading	251889	Control failure	14,25	1,45	4,5			
						Electrical failure	14,25	1,45				
				Minor in-service problems	719424	Vibration	14,25	1,45	7			
						Structural deficiency						
						Misc. External influences	44	11,59				
						Wear	27,7	7,25				
						Mechanical failure	22,2	5,8				

Table A.11 FMECA, Gearbox and electrical heater, NCS

NCS

System, main equipment	Components	Details	Criticality	Redundancy	Failure modes	MTBF (hours)	Failure mechanism for Failure mode	percentage of failure mechanism	Percentage of total failures	Manhours repair	PM tasks	Interval	Workhours PM
Pump, jockey pump for firew	**Gearbox**	Provides transmission of power from elec	S		**GEARBOX ON ELECTRICAL MOTORS INSIDE**						CBM, temperature,		
Vertical centrifugal pumps, electrical driven.				1x100	Drive coupling failure	No data	No data				vibration and level		
Hamworthy					Gearing damaged due to wear, corrosion and physical amage						Check and record	3, daily	**3 mnths**
Capacity: 85 m^3/t					Bearing damage due to lack of lubrication, increase in temperature and vibration						surface vibration and		-
Effect: 58 kW					Bearing damage due to contamination in lubrication or lack of lubrication						Check flow rate and	3, daily operations	
					Drive coupling failure						vibration, check oil		
					Heat exchangers and heaters separately						Drain/flush and replace	3, daily operations	
					Casing leakage from seals, gaskets connections etc.						lubricant, regrease		
					Gearbox fails whilst shutdown						Visual inspection for leaks	3, daily operations	
					Loss of lubricant function						Oil sample, check oil	3, daily operations	
					Pinion oil supply nozzle blocked						level, check lube pump		
Pump, jockey pump for firew	**Electrical he**	Provides heat to maintain temperature and stop conden			**ELECTRIC HEATER**		**Fail to function**				Checks for vibration	1,5	**1,5 mnths**
Vertical centrifugal pumps, electrical driven.				1x100	Fail to function		Heater fail to function heat				and damage		1
Hamworthy					Function at wrong temperature		Control circuit failure				continuity checks	4	
Capacity: 85 m^3/t							Heater element failure				check and record cooler inlet and outlet temp.	4, daily operations	
Effect: 58 kW							Loose connection				Check motor protection		**4 mnth**
						No data	Neutral ground resistor failure				trip system	4	8
							Earthing connection failure due to wear or damage				Drain/flush and replace lubricant, regrease bearing, oil sample analysis	4 daily operations	
							Over current protection failure						**48 mnth**
							Circuit break failure						16
							Electrical brush failure				motor IR checks	48	
							Bearing damage due to lack of lubrication, increase in temperature and vibra				Check brush wear	48	
							Bearing damage due to contamination in lubrication or lack of lubrication				Check security of	48	
							Heater, junction box/cable fault				connections		
							Earthing connection failure due to wear or damage						
							Neutral ground resistor failure						
							Loose connection						
							Function at wrong temperature						
							Thermostat controls at lower temp than set						
							Heater thermostat controls at a higher temperature than set						
							Build up of deposits on heater failure						

Table A.12 FMECA, Gearbox and electrical heater, Arctic

Arctic

System, main equipment	Components	Details	Criticality	Failure modes	MTBF (hours)	Failure mechanism for Failure mode	percentage of failure mechanism	Percentage of total failures	Man hours repair	PM tasks	Interval	Workhours PM
Pump, jockey pump for firew	**Gearbox**	Provides transmission of powe	S	**GEARBOX ON ELECTRICAL MOTORS INSIDE**						CBM, temperature, vibration and		
Vertical centrifugal pumps, electrical driven.				Drive coupling failure	NO DATA	NO DATA				level		
Hamworthy				Gearing damaged due to wear, corrosion and physical amage						Check and record surface	3, daily operations	**3 mnths**
Capacity: 85 m^3/t				Bearing damage due to lack of lubrication, increase in temperature and vibration						vibration and temperature,		-
Effect: 58 kW				Bearing damage due to contamination in lubrication or lack of lubrication						Check flow rate and vibration,	3, daily operations	
				Drive coupling failure						check oil level, vibration		
				Heat exchangers and heaters separately						Drain/flush and replace	3, daily operations	
				Casing leakage from seals, gaskets connections etc.						lubricant, regrease bearing, oil		
				Gearbox fails whilst shutdown						Visual inspection for leaks	3, daily operations	
				Loss of lubricant function						Oil sample, check oil level, check	3, daily operations	
				Pinion oil supply nozzle blocked						lube pump		
Pump, jockey pump for firew	**Electrical heaters on electrica**	Provides heat to maintain temperature and stop condensation		**ELECTRIC HEATER**		**Fail to function**						
Vertical centrifugal pumps, electrical driven.				Fail to function		Heater fail to function heat						
Hamworthy				Function at wrong temperature		Control circuit failure						
Capacity: 85 m^3/t						Heater element failure				continuity checks		
Effect: 58 kW						Loose connection				check and record cooler inlet and	4	**4 mnth**
						Neutral ground resistor failure				outlet temp.	4, daily operations	8
						Earthing connection failure due to wear or damage				Check motor protection trip systen	4	
						Over current protection failure				Drain/flush and replace	4 daily operations	**48 mnth**
						Circuit break failure				lubricant, regrease bearing, oil		16
						Electrical brush failure				motor IR checks	48	
						Bearing damage due to lack of lubrication, increase in temperature and v				Check brush wear	48	
						Bearing damage due to contamination in lubrication or lack of lubrication				Check security of connections	48	
						Heater, junction box/cable fault						
						Earthing connection failure due to wear or damage						
						Neutral ground resistor failure						
						Loose connection						
						Function at wrong temperature						
						Thermostat controls at lower temp than set						
						Heater thermostat controls at a higher temperature than set						
						Build up of deposits on heater failure						

Table A.13 FMECA, Diesel engine, NCS

NCS

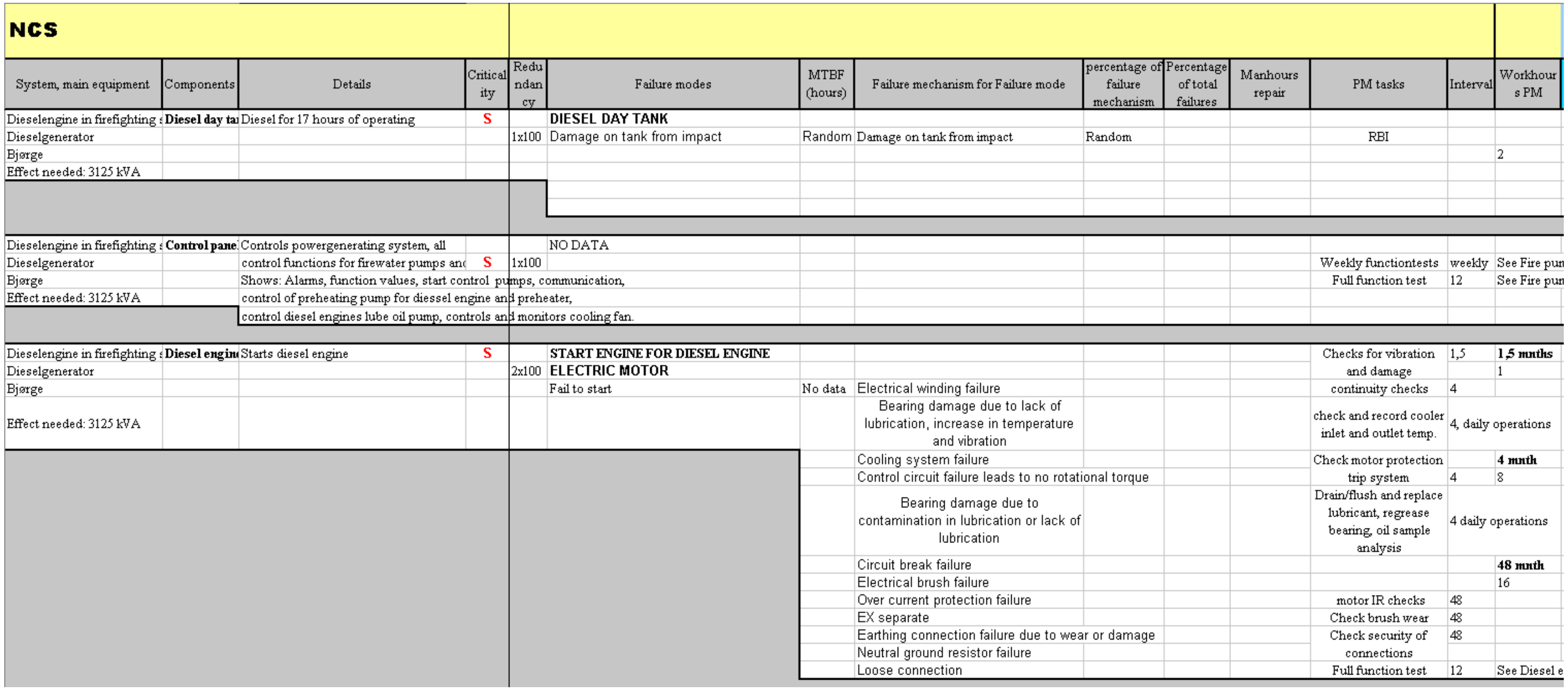
System, main equipment	Components	Details	Criticality	Redundancy	Failure modes	MTBF (hours)	Failure mechanism for Failure mode	percentage of failure mechanism	Percentage of total failures	Manhours repair	PM tasks	Interval	Workhours PM
Dieselengine in firefighting s	**DIESEL ENG**	Provides effect to generator	S		**DIESEL ENGINE**								
Dieselgenerator				4x50%	**Critical failures**		**Breakdown**				Weekly functiontests		
Bjørge					Breakdown	251889	Breakage	24,7	0,53	105			
Effect needed: 3125 kVA					External leakage of utility medium	406504	General mechanical failure	24,7	0,53	-	12		
					Fail to start on demand	55340	**External leakage of utility medium**			23	Check condition of hoses and gaskets		
					Noise	1063830	Leakage	23,7	3,74	5			
					Spurious stop	641026	Unknown	27,1	4,28	97	Check level of oil and cooling fluids		**12 mnth**
							Mechanical failure general	12,5	2,14				16
					Degraded		**Fail to start on demand**			7	Check exhaust manifold		
					Abnormal instrument reading	641026	Mechanical failure general	20,5	2,41	34	Full functiontest		**12 mnth Fu**
					Erratic output	406504	Electrical failure general	13,6	1,6	20			6
					External leak fuel	184843	**Spurious stop**			27	24		
					Fail to start on demand	235294	Mechanical failure general	28,5	1,6	8,8	Change oil and filters		
					High output	1136360	Other	9,4	0,53	4			**24 mnth**
					Internal leakage	101937	Control failure	9,4	0,53	22			36
					Low output	255102	**Abnormal instrument reading**			10	48		
					Noise	290698	Instrument failure general	33	1,6	12	Change air filters		**48 mnth**
					Overheating	543478	Control failure/faulty signal	33	1,6	36			36
					Parameter deviation	427350	**Erratic output**			8,7			
					Spurious stop	1234570	Mechanical failure general	22	0,53	12	3000		
					Structural deficiency	143885	Unknown	22	0,53	34	Overhaul		
					Vibration	452489	**External leakage of fuel**			64			
					Other	74515	Leakage	55	1,34	24			
							Vibration	21	0.53		6000		
					Incipient		**Internal leakage**				Overhaul		
					Abnormal instrument reading	96525	Unknown	26,6	1,07	13			
					Erratic output	214113	Material failure	20	0,8	16			
					External leakage of utility medium	141844	**Low output**			25			
					Fail to start on demand	203666	Out of adjustment	16,5	0,53	12			
					Internal leakage	1234570	Control failure	16,5	0,53	24			
					Minor in service problems	127877	Mechanical failure general	16,5	0,53	17			
					Noise	1234570	**Overheating**			6			
					Overheating	549451	Electrical failure general	12,3	0,53	9			
					Parameter deviation	1063830	Mechanical failure general	12,3	0,53	24			
					Structural deficiency	406504	Unknown	12,3	0,53	20			
					Other	163934	**Structural deviation**			34			
							Mechanical failure general	40	1,6				
					Unknown		Corrosion	20	0,53				
					Overheating	1234570	**Vibration**			35			
					Other	1234570	Mechanical failure general	50	0,53	170			
					Unknown	207900	Overheating	25	0,27	23			
							Erosion	25	0,27				

Table A.14 FMECA, Diesel engine, Arctic

Arctic

System, main equipment	Components	Details	Criticality	Failure modes	MTBF (hours)	Failure mechanism for Failure mode	percentage of failure mechanism	Percentage of total failures	Man hours repair	PM tasks	Interval	Workhours PM
Dieselengine in firefighting s	**DIESEL ENGINE**	Provides effect to generator	S	**DIESEL ENGINE**								
Dieselgenerator				**Critical failures**		**Breakdown**						
Bjørge				Breakdown	251889	Breakage	24,7	0,53	105	Weekly functiontests		
Effect needed: 3125 kVA				External leakage of utility medium	406504	General mechanical failure	24,7	0,53	-			
				Fail to start on demand	55340	**External leakage of utility medium**			23	12		
				Noise	1063830	Leakage	23,7	3,74	5	Check condition of hoses and gas	12	
				Spurious stop	641026	Unknown	27,1	4,28	97	Check level of oil and cooling flui	12	**12 mnth**
						Mechanical failure general	12,5	2,14		Check exhaust manifold	12	16
				Degraded		**Fail to start on demand**			7	Full functiontest	12	
				Abnormal instrument reading	641026	Mechanical failure general	20,5	2,41	34			**12 mnth Functiontest**
				Erratic output	406504	Electrical failure general	13,6	1,6	20			6
				External leak fuel	184843	**Spurious stop**			27	24		
				Fail to start on demand	235294	Mechanical failure general	28,5	1,6	8,8	Change oil and filters	24	
				High output	1136360	Other	9,4	0,53	4			**24 mnth**
				Internal leakage	101937	Control failure	9,4	0,53	22			36
				Low output	255102	**Abnormal instrument reading**			10	48		
				Noise	290698	Instrument failure general	33	1,6	12	Change air filters	48	**48 mnth**
				Overheating	543478	Control failure/faulty signal	33	1,6	36			36
				Parameter deviation	427350	**Erratic output**			8,7			
				Spurious stop	1234570	Mechanical failure general	22	0,53	12	3000	3000 hours	
				Structural deficiency	143885	Unknown	22	0,53	34	Overhaul		
				Vibration	452489	**External leakage of fuel**			64			
				Other	74515	Leakage	55	1,34	24			
						Vibration	21	0,53		6000	6000 hours	
				Incipient		**Internal leakage**				Overhaul		
				Abnormal instrument reading	96525	Unknown	26,6	1,07	13			
				Erratic output	214113	Material failure	20	0,8	16			
				External leakage of utility medium	141844	**Low output**			25			
				Fail to start on demand	203666	Out of adjustment	16,5	0,53	12			
				Internal leakage	1234570	Control failure	16,5	0,53	24			
				Minor in service problems	127877	Mechanical failure general	16,5	0,53	17			
				Noise	1234570	**Overheating**			6			
				Overheating	549451	Electrical failure general	12,3	0,53	9			
				Parameter deviation	1063830	Mechanical failure general	12,3	0,53	24			
				Structural deficiency	406504	Unknown	12,3	0,53	20			
				Other	163934	**Structural deviation**			34			
						Mechanical failure general	40	1,6				
				Unknown		Corrosion	20	0,53				
				Overheating	1234570	**Vibration**			35			
				Other	1234570	Mechanical failure general	50	0,53	170			
				Unknown	207900	Overheating	25	0,27	23			
						Erosion	25	0,27				

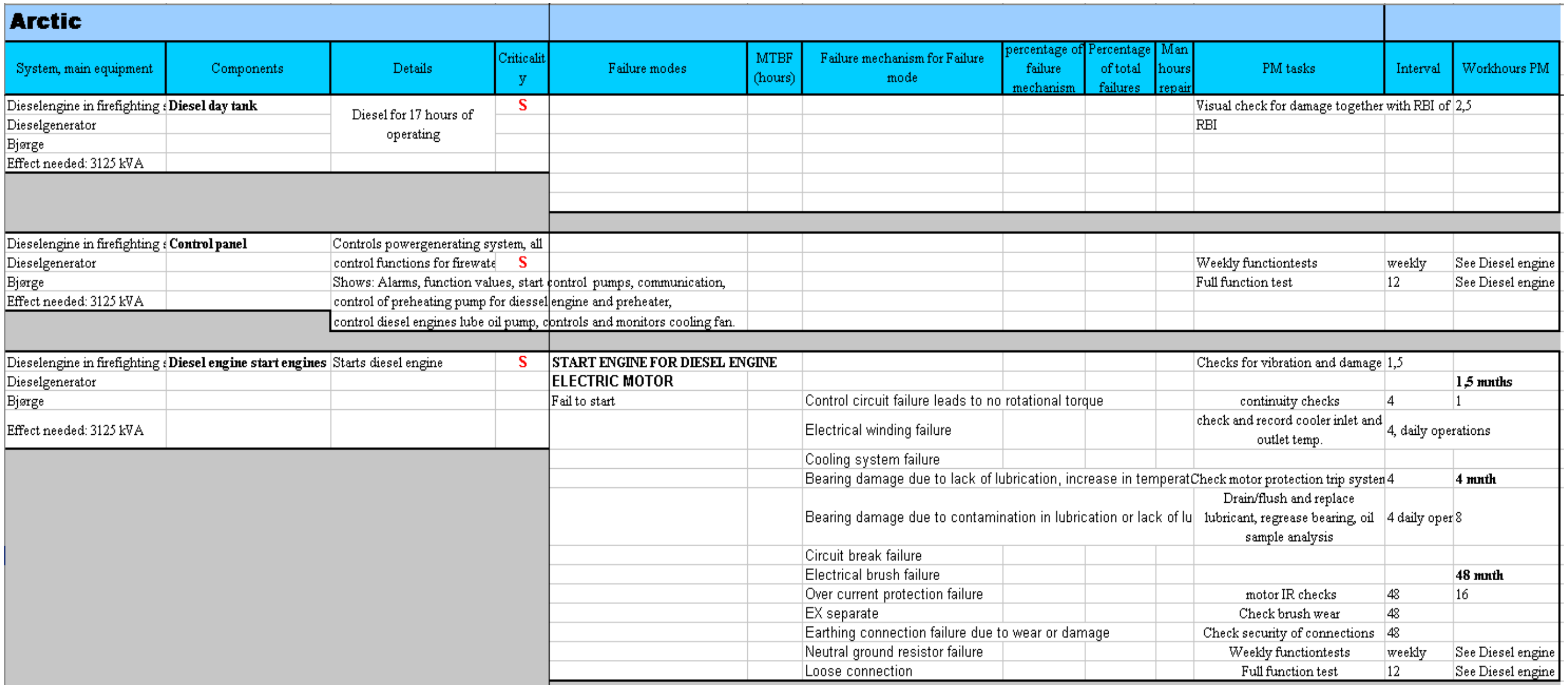
Table A.15 FMECA, Diesel day tank, control panel and electrical heater, NCS



NCS

System, main equipment	Components	Details	Criticality	Redundancy	Failure modes	MTBF (hours)	Failure mechanism for Failure mode	percentage of failure mechanism	Percentage of total failures	Manhours repair	PM tasks	Interval	Workhours PM
Dieselengine in firefighting s	**Diesel day ta**	Diesel for 17 hours of operating	S		**DIESEL DAY TANK**								
Dieselgenerator				1x100	Damage on tank from impact	Random	Damage on tank from impact	Random			RBI		
Bjørge													2
Effect needed: 3125 kVA													
Dieselengine in firefighting s	**Control pane**	Controls powergenerating system, all			NO DATA								
Dieselgenerator		control functions for firewater pumps and	S	1x100							Weekly functiontests	weekly	See Fire pun
Bjørge		Shows: Alarms, function values, start control pumps, communication,									Full function test	12	See Fire pun
Effect needed: 3125 kVA		control of preheating pump for diessel engine and preheater,											
		control diesel engines lube oil pump, controls and monitors cooling fan.											
Dieselengine in firefighting s	**Diesel engin**	Starts diesel engine	S		**START ENGINE FOR DIESEL ENGINE**						Checks for vibration	1,5	**1,5 mnths**
Dieselgenerator				2x100	**ELECTRIC MOTOR**						and damage		1
Bjørge					Fail to start	No data	Electrical winding failure				continuity checks	4	
Effect needed: 3125 kVA							Bearing damage due to lack of lubrication, increase in temperature and vibration				check and record cooler inlet and outlet temp.	4, daily operations	
							Cooling system failure				Check motor protection		**4 mnth**
							Control circuit failure leads to no rotational torque				trip system	4	8
							Bearing damage due to contamination in lubrication or lack of lubrication				Drain/flush and replace lubricant, regrease bearing, oil sample analysis	4 daily operations	
							Circuit break failure						**48 mnth**
							Electrical brush failure						16
							Over current protection failure				motor IR checks	48	
							EX separate				Check brush wear	48	
							Earthing connection failure due to wear or damage				Check security of	48	
							Neutral ground resistor failure				connections		
							Loose connection				Full function test	12	See Diesel e

Table A.16 FMECA, Diesel day tank, control panel and Diesel start engines, Arctic



Arctic												
System, main equipment	Components	Details	Criticality	Failure modes	MTBF (hours)	Failure mechanism for Failure mode	percentage of failure mechanism	Percentage of total failures	Man hours repair	PM tasks	Interval	Workhours PM
Dieselengine in firefighting s	**Diesel day tank**	Diesel for 17 hours of operating	S							Visual check for damage together with RBI of		2,5
Dieselgenerator										RBI		
Bjørge												
Effect needed: 3125 kVA												
Dieselengine in firefighting s	**Control panel**	Controls powergenerating system, all										
Dieselgenerator		control functions for firewate	S							Weekly functiontests	weekly	See Diesel engine
Bjørge		Shows: Alarms, function values, start control pumps, communication,								Full function test	12	See Diesel engine
Effect needed: 3125 kVA		control of preheating pump for diessel engine and preheater,										
		control diesel engines lube oil pump, controls and monitors cooling fan.										
Dieselengine in firefighting s	**Diesel engine start engines**	Starts diesel engine	S	**START ENGINE FOR DIESEL ENGINE**						Checks for vibration and damage	1,5	
Dieselgenerator				**ELECTRIC MOTOR**								**1,5 mnths**
Bjørge				Fail to start		Control circuit failure leads to no rotational torque				continuity checks	4	1
Effect needed: 3125 kVA						Electrical winding failure				check and record cooler inlet and outlet temp.	4, daily operations	
						Cooling system failure						
						Bearing damage due to lack of lubrication, increase in temperat				Check motor protection trip systen	4	**4 mnth**
						Bearing damage due to contamination in lubrication or lack of lu				Drain/flush and replace lubricant, regrease bearing, oil sample analysis	4 daily oper	8
						Circuit break failure						
						Electrical brush failure						**48 mnth**
						Over current protection failure				motor IR checks	48	16
						EX separate				Check brush wear	48	
						Earthing connection failure due to wear or damage				Check security of connections	48	
						Neutral ground resistor failure				Weekly functiontests	weekly	See Diesel engine
						Loose connection				Full function test	12	See Diesel engine

Table A.17 FMECA Electrical heater on start engine and generator, NCS

NCS													
System, main equipment	Components	Details	Criticality	Redundancy	Failure modes	MTBF (hours)	Failure mechanism for Failure mode	percentage of failure mechanism	Percentage of total failures	Manhours repair	PM tasks	Interval	Workhours PM
Dieselengine in firefighting	**Electrical heaters on start engine**	Provides heat to maintain temperature and stop condensation	S		**ELECTRIC HEATER**		**Fail to function**						
Dieselgenerator				1x100	Fail to function		Heater fail to function heat						
Bjørge					Function at wrong temperature		Control circuit failure						
Effect needed: 3125 kVA							Heater element failure				continuity checks	12	
						No data	Loose connection				check and record cooler	12, daily	operations
							Neutral ground resistor failure				inlet and outlet temp.		**12 mnth**
							Earthing connection failure due to wear or damage				Check motor protection	12	8
							Over current protection failure				trip system		
							Circuit break failure				Drain/flush and replace		**48 mnth**
							Electrical brush failure				lubricant, regrease	12 daily	16
							Bearing damage due to lack of lubrication, increase in temperature and vibra				motor IR checks	48	
							Bearing damage due to contamination in lubrication or lack of lubrication				Check brush wear	48	
							Heater, junction box/cable fault				Check security of connectic	48	
							Earthing connection failure due to wear or damage						
							Neutral ground resistor failure						
							Loose connection				Weekly functiontests	weekly	See Diesel e
							Function at wrong temperature				Full function test	12	See Diesel e
							Thermostat controls at lower temp than set						
							Heater thermostat controls at a higher temperature than set						
							Build up of deposits on heater failure						
Dieselengine in firefighting	**GENERATOR**	Creates power for submerged electrical motors powering firewaterpumps	S		**GENERATOR, Electric generators, motor driven (diesel) Water fire fighting OREDA-20009**						Bolts and fastening	12	
Dieselgenerator				4x50	**CRITICAL**		**Fail to start on demand**				Oil replacement	12	**12 mnth**
Bjørge					Fail to start on demand	105152	Unknown	75	10	6	Inspection of diodes	12	8
Effect needed: 3125 kVA					Fail to synchronize	105152	Faulty signal/indication/alarm	25	3,33	100	Visual inspection	12	
					DEGRADED		**Fail to synchronize**				IR- test and polarization te	48	**48 mnth**
					Abnormal instrument reading	105152	Electrical failure general	100	3,33	12	CBM, Drain/flush and		16
					Overheating	105152	**Abnormal instrument reading**			2	replace lubricant,	48	
							Electrical failure general	40	6,67		Vsual inspection,	48	
							Unknown	40	6,67		continuity checks		
							Control failure	20	3,33		Earthing tests	48	
							Overheating				Weekly functiontests	weekly	See Diesel e
							Electrical failure general	100	3,33		Full function test	12	See Diesel e

Table A.18 FMECA, Elecric heater on start engine and generator, Arctic

Arctic

System, main equipment	Components	Details	Criticality	Failure modes	MTBF (hours)	Failure mechanism for Failure mode	percenta	Percen	Manh	PM tasks	Interval	Workhours PM
Dieselengine in firefighting :	**Electrical heaters on start e**	Provides heat to maintain ten	S	**ELECTRIC HEATER**		**Fail to function**						
Dieselgenerator				Fail to function		Heater fail to function heat						
Bjørge				Function at wrong temperature		Control circuit failure						
Effect needed: 3125 kVA						Heater element failure				continuity checks	12	
						Loose connection				check and record cooler inlet and	12, daily operations	
						Neutral ground resistor failure				outlet temp.		**12 mnth**
						Earthing connection failure due to wear or damage				Check motor protection trip	12	8
						Over current protection failure				system		
						Circuit break failure				Drain/flush and replace		**48 mnth**
						Electrical brush failure				lubricant, regrease bearing, oil	12 daily ope	16
						Bearing damage due to lack of lubrication, increase in temperature and v				motor IR checks	48	
						Bearing damage due to contamination in lubrication or lack of lubrication				Check brush wear	48	
						Heater, junction box/cable fault				Check security of connections	48	
						Earthing connection failure due to wear or damage						
						Neutral ground resistor failure						
						Loose connection				Weekly functiontests	weekly	See Diesel engine
						Function at wrong temperature				Full function test	12	See Diesel engine
						Thermostat controls at lower temp than set						
						Heater thermostat controls at a higher temperature than set						
						Build up of deposits on heater failure						
Dieselengine in firefighting :	**GENERATOR**	Creates power for submergec	S	**GENERATOR, Electric generators, motor driven (diesel) Water fire fighting OREDA-20009**						Bolts and fastening	12	
Dieselgenerator				**CRITICAL**		**Fail to start on demand**				Oil replacement	12	**12 mnth**
Bjørge				Fail to start on demand	105152	Unknown	75	10	6	Inspection of diodes	12	8
Effect needed: 3125 kVA				Fail to synchronize	105152	Faulty signal/indication/alarm	25	3	#	Visual inspection	12	
				DEGRADED		**Fail to synchronize**				IR- test and polarization test	48	**48 mnth**
				Abnormal instrument reading	105152	Electrical failure general	##	3	12	CBM, Drain/flush and replace		16
				Overheating	105152	**Abnormal instrument reading**			2	lubricant, regrease bearing, oil	48	
						Electrical failure general	40	7		Vsual inspection, continuity	48	
						Unknown	40	7		checks		
						Control failure	20	3		Earthing tests	48	
						Overheating				Weekly functiontests	weekly	See Diesel engine
						Electrical failure general	##	3		Full function test	12	See Diesel engine

Table A.19 FMECA, Generator cooling pump and jacket water preheating pump, NCS

NCS

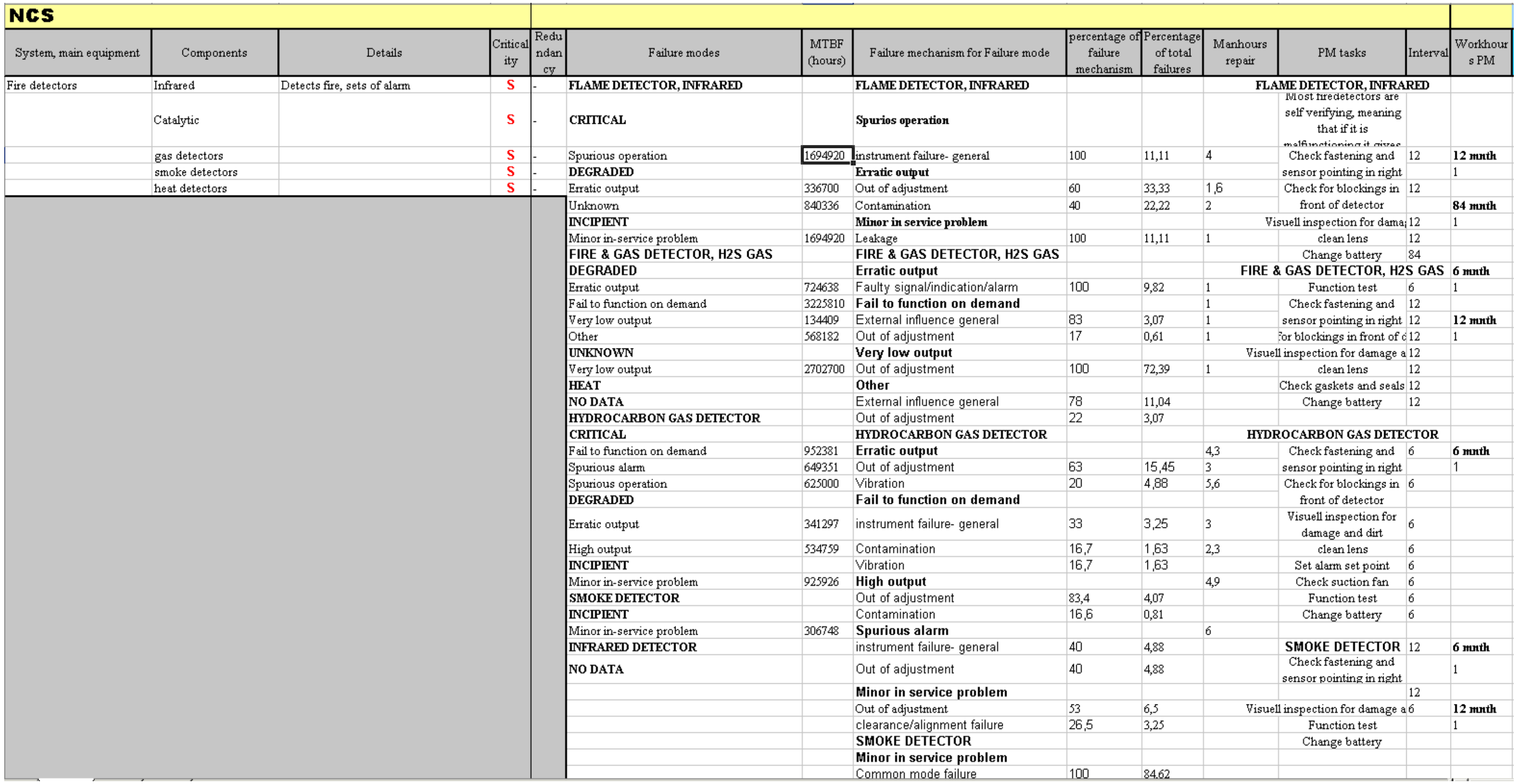
System, main equipment	Components	Details	Criticality	Redundancy	Failure modes	MTBF (hours)	Failure mechanism for Failure mode	percentage of failure mechanism	Percentage of total failures	Manhours repair	PM tasks	Interval	Workhours PM
Dieselengine in firefighting s	**Generator cooling pump**	Cools generator	S		**GENERATOR COOLING, JACKET WATER PREHEATING**						CBM: Vibration, flow rate		
Dieselgenerator		Centrifugal pump		1x100	**CRITICAL**		**Breakdown**						
Bjørge	**Jacket water preheating pump**				Breakdown	694444	General mechanical failure	50	0,9	211	Weekly function tests		
Effect needed: 3125 kVA		Preheats jacket water	S		Erratic output	649351	Cavitation	25	0,3	378			**6 mnth**
		Centrifugal pump		1x100	Low output	694444	**External leakage process medium**			52	Visual check for damages, vibration,	6	5
					Parameter deviation	735294	General mechanical failure	56	6,61	3			
					Spurious stop	694444	Leakage	15	1,8	5			
					Vibration	308642	**External leakage utility medium**			76			
					DEGRADED		General mechanical failure	48,9	10,81				
					Erratic output	204499	Leakage	18,3	4,05	21	Weekly functiontests	weekly	See Diesel e
					External leakage utility medium	72516	**Fail to start on demand**			40	Full function test	12	See Diesel e
					Internal leakage	346021	General instrument failure	23	0,6	8			
					Low output	588235	Unknown	17	0,45	92			
					Minor in-service problems	694444	**High output**			24			
					Parameter deviation	735294	General instrument failure	33	0,15	6			
					Other	175131	General Material failure	33	0,15	11			
					INCIPIENT		**Internal leakage**						
					Abnormal instrument reading	78247	General mechanical failure	31,2	0,75	6,1			
					External leakage utility medium	161551	Leakage	31,2	0,75	11			
					Internal leakage	694444	**Low output**			9			
					Minor in-service problems	45065	Blockage/plugged	66,6	1,8	19			
					Other	325733	General mechanical failure	16,6	0,45	5			
							Overheating						
							General mechanical failure	100	0,3				
							Structura deficiency						
							General mechanical failure	55	3,15				
							General Material failure	21	1,2				
							Blockage/plugged	7,8	0,45				
							Spurious stop						
							General instrument failure	42,7	2,25				
							Mechanical failure	20	1,05				
							Vibration						
							Clerance/alignment failure	25	1,65				
							General mechanical failure	22,7	1,5				

Table A.20 FMECA, Generator cooling pump and jacket water preheating pump, Arctic

Arctic

System, main equipment	Components	Details	Criticality	Failure modes	MTBF (hours)	Failure mechanism for Failure mode	percentage of failure mechanism	Percentage of total	Manhours repair	PM tasks	Interval	Workhours PM
Dieselengine in firefighting	**Generator cooling pump**	Cools generator	S	**GENERATOR COOLING, JACKET WATER PREHEATING**						CBM: Vibration, flow rate		
Dieselgenerator		Centrifugal pump		**CRITICAL**		**Breakdown**						
Bjørge				Breakdown	694444	General mechanical failure	50	0,9	211	Weekly function tests		
Effect needed: 3125 kVA	**Jacket water preheating pump**	Preheats jacket water	S	Erratic output	649351	Cavitation	25	0,3	378			**6 mnth**
		Centrifugal pump		Low output	694444	**External leakage process medium**			52	Visual check for damages, vibration, etc	6	5
				Parameter deviation	735294	General mechanical failure	56	6,61	3			
				Spurious stop	694444	Leakage	15	1,8	5			
				Vibration	308642	**External leakage utility medium**			76			
				DEGRADED		General mechanical failure	48,9	10,81		Weekly functiontests	weekly	See Diesel engine
				Erratic output	204499	Leakage	18,3	4,05	21	Full function test	12	See Diesel engine
				External leakage utility medium	72516	**Fail to start on demand**			40			
				Internal leakage	346021	General instrument failure	23	0,6	8			
				Low output	588235	Unknown	17	0,45	92			
				Minor in-service problems	694444	**High output**			24			
				Parameter deviation	735294	General instrument failure	33	0,15	6			
				Other	175131	General Material failure	33	0,15	11			
				INCIPIENT		**Internal leakage**						
				Abnormal instrument reading	78247	General mechanical failure	31,2	0,75	6,1			
				External leakage utility medium	161551	Leakage	31,2	0,75	11			
				Internal leakage	694444	**Low output**			9			
				Minor in-service problems	45065	Blockage/plugged	66,6	1,8	19			
				Other	325733	General mechanical failure	16,6	0,45	5			
						Overheating						
						General mechanical failure	100	0,3				
						Structura deficiency						
						General mechanical failure	55	3,15				
						General Material failure	21	1,2				
						Blockage/plugged	7,8	0,45				
						Spurious stop						
						General instrument failure	42,7	2,25				
						Mechanical failure	20	1,05				
						Vibration						
						Clerance/alignment failure	25	1,65				
						General mechanical failure	22,7	1,5				

Table A.21 FMECA, fire detectors, NCS



NCS													
System, main equipment	Components	Details	Criticality	Redundancy	Failure modes	MTBF (hours)	Failure mechanism for Failure mode	percentage of failure mechanism	Percentage of total failures	Manhours repair	PM tasks	Interval	Workhours PM
Fire detectors	Infrared	Detects fire, sets of alarm	S	-	**FLAME DETECTOR, INFRARED**		**FLAME DETECTOR, INFRARED**				**FLAME DETECTOR, INFRARED**		
	Catalytic		S	-	**CRITICAL**		**Spurios operation**				Most firedetectors are self verifying, meaning that if it is malfunctioning it gives		
	gas detectors		S	-	Spurious operation	1694920	instrument failure- general	100	11,11	4	Check fastening and	12	**12 mnth**
	smoke detectors		S	-	**DEGRADED**		**Erratic output**				sensor pointing in right		1
	heat detectors		S	-	Erratic output	336700	Out of adjustment	60	33,33	1,6	Check for blockings in	12	
					Unknown	840336	Contamination	40	22,22	2	front of detector		**84 mnth**
					INCIPIENT		**Minor in service problem**				Visuell inspection for dama	12	1
					Minor in-service problem	1694920	Leakage	100	11,11	1	clean lens	12	
					FIRE & GAS DETECTOR, H2S GAS		**FIRE & GAS DETECTOR, H2S GAS**				Change battery	84	
					DEGRADED		**Erratic output**				**FIRE & GAS DETECTOR, H2S GAS**		**6 mnth**
					Erratic output	724638	Faulty signal/indication/alarm	100	9,82	1	Function test	6	1
					Fail to function on demand	3225810	**Fail to function on demand**			1	Check fastening and	12	
					Very low output	134409	External influence general	83	3,07	1	sensor pointing in right	12	**12 mnth**
					Other	568182	Out of adjustment	17	0,61	1	for blockings in front of d	12	1
					UNKNOWN		**Very low output**				Visuell inspection for damage a	12	
					Very low output	2702700	Out of adjustment	100	72,39	1	clean lens	12	
					HEAT		**Other**				Check gaskets and seals	12	
					NO DATA		External influence general	78	11,04		Change battery	12	
					HYDROCARBON GAS DETECTOR		Out of adjustment	22	3,07				
					CRITICAL		**HYDROCARBON GAS DETECTOR**				**HYDROCARBON GAS DETECTOR**		
					Fail to function on demand	952381	**Erratic output**			4,3	Check fastening and	6	**6 mnth**
					Spurious alarm	649351	Out of adjustment	63	15,45	3	sensor pointing in right		1
					Spurious operation	625000	Vibration	20	4,88	5,6	Check for blockings in	6	
					DEGRADED		**Fail to function on demand**				front of detector		
					Erratic output	341297	instrument failure- general	33	3,25	3	Visuell inspection for damage and dirt	6	
					High output	534759	Contamination	16,7	1,63	2,3	clean lens	6	
					INCIPIENT		Vibration	16,7	1,63		Set alarm set point	6	
					Minor in-service problem	925926	**High output**			4,9	Check suction fan	6	
					SMOKE DETECTOR		Out of adjustment	83,4	4,07		Function test	6	
					INCIPIENT		Contamination	16,6	0,81		Change battery	6	
					Minor in-service problem	306748	**Spurious alarm**			6			
					INFRARED DETECTOR		instrument failure- general	40	4,88		**SMOKE DETECTOR**	12	**6 mnth**
					NO DATA		Out of adjustment	40	4,88		Check fastening and sensor pointing in right		1
							Minor in service problem					12	
							Out of adjustment	53	6,5		Visuell inspection for damage a	6	**12 mnth**
							clearance/alignment failure	26,5	3,25		Function test		1
							SMOKE DETECTOR				Change battery		
							Minor in service problem						
							Common mode failure	100	84,62				

Table A.22 FMECA, Detectors, Arctic

Arctic

System, main equipment	Components	Details	Criticality	Failure modes	MTBF (hours)	Failure mechanism for Failure mode	percentage of failure mechanism	Percentage of total	Manhours repair	PM tasks	Interval	Workhours PM
Fire detectors	Infrared	Detects fire, sets of alarm	S	**FLAME DETECTOR, INFRARED**		**FLAME DETECTOR, INFRARED**				**FLAME DETECTOR, INFRARED**		
	Catalytic		S	**CRITICAL**		**Spurios operation**				Most firedetectors are self verifying, meaning that if it is malfunctioning it gives warning to operators		
	gas detectors		S	Spurious operation	1694920+	instrument failure- general	100	11,11	4	Check fastening and sensor	12	**12 mnth**
	smoke detectors		S	**DEGRADED**		**Erratic output**				pointing in right direction		1(2)
	heat detectors		S	Erratic output	336700+	Out of adjustment	60	33,33	1,6	Check for blockings in front of	12	
				Unknown	840336	Contamination	40+	22,22	2	detector		**84 mnth**
				INCIPIENT		**Minor in service problem**				Visuell inspection for damage	12	1(2)
				Minor in-service problem	1694920+	Leakage	100	11,11	1	clean lens	12	
				FIRE & GAS DETECTOR, H2S GAS		**FIRE & GAS DETECTOR, H2S GAS**				Change battery	24+	
				DEGRADED		**Erratic output**				**FIRE & GAS DETECTOR, H2S GAS**		**6 mnth**
				Erratic output	724638+	Faulty signal/indication/alarm	100	9,82	1	Function test	6	1(2)
				Fail to function on demand	3225810	**Fail to function on demand**			1	Check fastening and sensor	12	
				Very low output	134409+	External influence general	83+	3,07	1	pointing in right direction	12	**12 mnth**
				Other	568182	Out of adjustment	17	0,61	1	Check for blockings in front of d	12	1(2)
				UNKNOWN		**Very low output**				Visuell inspection for damage an	12	
				Very low output	2702700	Out of adjustment	100	72,39	1	clean lens	12	
				HEAT		**Other**				Check gaskets and seals	12	
				NO DATA		External influence general	78	11,04		Change battery	6+	
				HYDROCARBON GAS DETECTOR		Out of adjustment	22	3,07				
				CRITICAL		**HYDROCARBON GAS DETECTOR**				**HYDROCARBON GAS DETECTOR**		
				Fail to function on demand	952381+	**Erratic output**			4,3	Check fastening and sensor	6	**6 mnth**
				Spurious alarm	649351+	Out of adjustment	63	15,45	3	pointing in right direction	6	1(2)
				Spurious operation	625000+	Vibration	20	4,88	5,6	Check for blockings in front of	6	
				DEGRADED		**Fail to function on demand**				detector		
				Erratic output	341297+	instrument failure- general	33+	3,25	3	Visuell inspection for damage and dirt	6	
				High output	534759	Contamination	16,7+	1,63	2,3	clean lens	6	
				INCIPIENT		Vibration	16,7	1,63		Set alarm set point	6	
				Minor in-service problem	925926+	**High output**			4,9	Check suction fan	6	
				SMOKE DETECTOR		Out of adjustment	83,4	4,07		Function test	6	
				INCIPIENT		Contamination	16,6+	0,81		Change battery	6+	
				Minor in-service problem	306748+	**Spurious alarm**			6			
				INFRARED DETECTOR		instrument failure- general	40	4,88		**SMOKE DETECTOR**		**6 mnth**
				NO DATA		Out of adjustment	40	4,88		Check fastening and sensor pointing in right direction	12	1(2)
						Minor in service problem				Visuell inspection for damage an	12	
						Out of adjustment	53	6,5		Function test	6	**12 mnth**
						clearance/alignment failure	26,5	3,25		Change battery	6+	1(2)
						SMOKE DETECTOR						
						Minor in service problem						
						Common mode failure	100	84,62				

Table A.23 FMECA, Sprinkler system, trace heating and hosereel with space heater, NCS

NCS

System, main equipment	Components	Details	Criticality	Redundancy	Failure modes	MTBF (hours)	Failure mechanism for Failure mode	percentage of failure mechanism	Percentage of total failures	Manhours repair	PM tasks	Interval	Workhours PM
Sprinkler nozzle and pipe weather affected:			S	-	**SPRINKLER SYSTEM**		**Fail to function**				Inspection of control valves and gaskets	1	**1 mnth**
					Fail to function		Freezing of nozzle						0,5
					Pipe rupture		Freezing of pipe				Inspection of swivels and alarm devices	1	
					Detector fails to initiate an ESD action	random	Impact damage						
					Detector initiates an ESD action spuriousl	random	**Pipe rupture**						
							Freezing of nozzle				carry out function tests,	6	**6 mnth**
							Freezing of pipe						
							Circulation pump failure				Check by sprinkler contractor	12	**12 mnth**
							Impact damage						
							Detector fails to initiate ESD action						
											thorough inspection, change of damaged	60	**60 mnth**
							Detector initiates ESD action spuriously						
Trace heating	Trace heating cables		S	-	**TRACE HEATING**						Function test trace heating	Before v	**12 mnth**
	Thermostat, Temperature controller				Fail to function	random	Short circuiting						
	Junction box				Spurious operation	random	Open circuit				Function test overtemperature	Before winter 12 mnt	
							Earth fault						
							Overtemp protection fails spuriously,trace heating will overheat causin fire ris				Function test temperature control	Before winter 12 mnt	
							Temperature controller fails spuriously, result is high or low temperatures.						
Hose reel with space heater	Hosereel heater	Hose reel for firefighting with space heat	S	-	**HOSEREEL WITH SPACE HEATER OUTSIDE**		**Fail to function**						
					Integrated heater with junction box		Heater fail to function heat				continuity checks	12	
					Fail to function		Control circuit failure				Check motor protection trip system	12	
					Function at wrong temperature	No data	Heater element failure						
							Loose connection				check and record cooler inlet and outlet temp.	12, daily operations	
							Neutral ground resistor failure						
							Earthing connection failure due to wear or damage						
							Over current protection failure				Drain/flush and replace lubricant, regrease	12 daily	**12 mnth**
							Circuit break failure						8
							Electrical brush failure				motor IR checks	48	
							Bearing damage due to lack of lubrication, increase in temperature and vibra				Check brush wear	48	**48 mnth**
							Bearing damage due to contamination in lubrication or lack of lubrication				Check security of connections	48	16
							Heater, junction box/cable fault						
							Earthing connection failure due to wear or damage						
							Neutral ground resistor failure						
							Loose connection						
							Function at wrong temperature						
							Thermostat controls at lower temp than set						
							Heater thermostat controls at a higher temperature than set						
							Build up of deposits on heater failure						

Table A.24 FMECA, Sprinkler system, trace heating, Hosereel with space heater, Arctic

Arctic

System, main equipment	Components	Details	Criticality	Failure modes	MTBF (hours)	Failure mechanism for Failure mode	percentage of failure	Percentage	Manhours repair	PM tasks	Interval	Workhours PM
Sprinkler nozzle and pipe weather affected:			S	**SPRINKLER SYSTEM**		**Fail to function**				Inspection of control valves and gaskets	1	**1 mnth**
				Fail to function		Freezing of nozzle				Inspection of swivels and alarm devices	1	0,5
				Pipe rupture		Freezing of pipe						
				Detector fails to initiate an ESD action	random	Impact damage				carry out function tests,	3	**3 mnth**
				Detector initiates an ESD action spuriously	random	**Pipe rupture**						
						Freezing of nozzle				Check by sprinkler contractor	12	**12 mnth**
						Freezing of pipe						
						Circulation pump failure						
						Impact damage				thorough inspection, change of damaged parts	36	**36 mnth**
						Detector fails to initiate ESD action						
						Detector initiates ESD action spuriously						
Trace heating	Trace heating cables		S	**TRACE HEATING**						Function test trace heating	6, Before winter, after winter	
	Thermostat, Temperature controller			Fail to function	random	Short circuiting						
	Junction box			Spurious operation	random	Open circuit				Function test overtemperature protection	6, Before winter, after winter	
						Earth fault						
						Overtemp protection fails spuriously,trace heating will ove				Function test temperature control device	6, Before winter, after winter	
						Temperature controller fails spuriously, result is high or low temperatures.						
Hose reel with space heater	Hosereel heater	Hose reel for firefighting wit	S	**HOSEREEL WITH SPACE HEATER OUTSIDE**		**Fail to function**						
				Integrated heater with junction box		Heater fail to function heat						
				Fail to function		Control circuit failure						
				Function at wrong temperature		Heater element failure				continuity checks	6	
					random	Loose connection				check and record cooler inlet and outlet temp.	6	
					random	Neutral ground resistor failure						**6 mnth**
					random	Earthing connection failure due to wear or damage				Check motor protection trip system	6	8
					MTBF 12	Over current protection failure				Drain/flush and replace lubricant, regrease bearing, oil sample analysis	6	
					MTBF 12	Circuit break failure						**48 mnth**
					MTBF 24	Electrical brush failure				motor IR checks		16
						Bearing damage due to lack of lubrication, increase in ter				Check brush wear	48	
						Bearing damage due to contamination in lubrication or lac				Check security of connections	48	
					random	Heater, junction box/cable fault				Check security of connections	48	
					random	Earthing connection failure due to wear or damage						
					random	Neutral ground resistor failure						
					random	Loose connection						
						Function at wrong temperature						
						Thermostat controls at lower temp than set						
						Heater thermostat controls at a higher temperature than set						
						Build up of deposits on heater failure						

Appendix B FMECA analysis, seawater cooling system

Table B.1 FMECA, Seawater lift pump, NCS

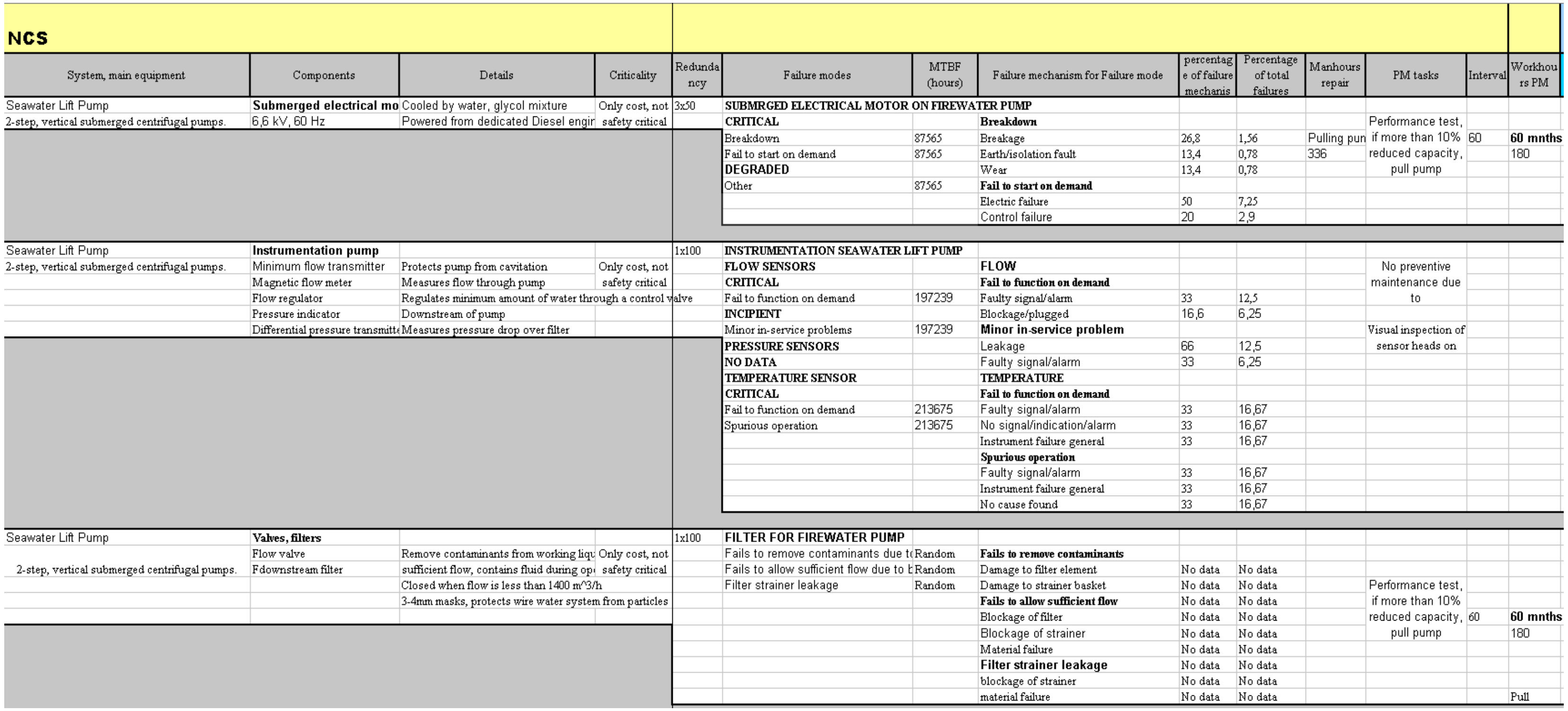
NCS													
System, main equipment	Components	Details	Criticality	Redundancy	Failure modes	MTBF (hours)	Failure mechanism for Failure mode	percentage of failure mechanis	Percentage of total failures	Manhours repair	PM tasks	Interval	Workhours PM
Seawater Lift Pump	**Pump**	Pumps seawater to cooling systems	Only cost, not safety critical	3x50	**SEAWATER LIFT PUMP**						CBM: Flow, temperature,		
2-step, vertical submerged centrifugal pumps.	Submerged centrifugalpump				**SUBMERGED CYLINDRICAL PUMP, Seawate**		**Breakdown**				Performance test, if more than 10% reduced capacity, pull pump		
					CRITICAL		General mechanical failure	50	0,9				
					Breakdown	342466	Cavitation	25	0,3	Pulling pun		60	**60 mnths**
					External leakage process medium	66622	**External leakage process medium**			336			180
					External leakage utility medium	342466	General mechanical failure	56	6,61				
					Fail to start on demand	113636	Leakage	15	1,8				
					High output	396825	**External leakage utility medium**						
					Internal leakage	396825	General mechanical failure	48,9	10,81				
					Low output	313480	Leakage	18,3	4,05				
					Overheating	396825	**Fail to start on demand**						
					Spurious stop	313480	General instrument failure	23	0,6				
					Structura deficiency	313480	Unknown	17	0,45				
					Vibration	213220	**High output**						
					DEGRADED		General instrument failure	33	0,15				
					External leakage process medium	140845	General Material failure	33	0,15				
					External leakage utility medium	213220	**Internal leakage**						
					Internal leakage	342466	General mechanical failure	31,2	0,75				
					Structura deficiency	313480	Leakage	31,2	0,75				
					Other	396825	**Low output**						
					INCIPIENT		Blockage/plugged	66,6	1,8				
					Abnormal instrument reading	38986	General mechanical failure	16,6	0,45				
					External leakage utility medium	128700	**Overheating**						
					Internal leakage	171527	General mechanical failure	100	0,3				
					Other	342466	**Structura deficiency**						
					Unknown	342466	General mechanical failure	55	3,15				
							General Material failure	21	1,2				
							Blockage/plugged	7,8	0,45				
							Spurious stop						
							General instrument failure	42,7	2,25				
							Mechanical failure	20	1,05				
							Vibration						
							Clerance/alignment failure	25	1,65				
							General mechanical failure	22,7	1,5				

Table B.2 FMECA, Seawater lift pump, Arctic

Arctic

System, main equipment	Components	Details	Criticality	Failure modes	MTBF (hours)	Failure mechanism for Failure mode	percentage of failure mechanism	Percentage of total failures	Manhours repair	PM tasks	Interval	Workhours PM
Seawater Lift Pump	**Pump**	Pumps seawater to cooling systems	S	**Submerged cylindrical pump**						CBM: Flow, temperature,		
2-step, vertical submerged centrifugal pumps.	Submerged centrifugalpump			**CRITICAL**		**Breakdown**						
				Breakdown	342466 +	General mechanical failure	50+	0,9+				
				External leakage process medium	66622 +	Cavitation	25+	0,3+				
				External leakage utility medium	342466 +	**xternal leakage process medium**					Pull in ice free season	
				Fail to start on demand	113636 +	General mechanical failure	56+	6,61+			12	**12 mnths**
				High output	396825 +	Leakage	15+	1,8+		Flow rate test	After winter	180
				Internal leakage	396825 +	**External leakage utility medium**						
				Low output	313480 +	General mechanical failure	48,9+	10,81+	Pulling pun			
				Overheating	396825 +	Leakage	18,3+	4,05+	336+			
				Spurious stop	313480 +	**Fail to start on demand**						
				Structura deficiency	313480 +	General instrument failure	23	0,6				
				Vibration	213220 +	Unknown	17+	0,45+				
				DEGRADED		**High output**						
				External leakage process medium	140845 +	General instrument failure	33	0,15				
				External leakage utility medium	213220 +	General Material failure	33+	0,15+				
				Internal leakage	342466 +	**Internal leakage**						
				Structura deficiency	313480 +	General mechanical failure	31,2+	0,75+				
				Other	396825 +	Leakage	31,2	0,75+				
				INCIPIENT		**Low output**						
				Abnormal instrument reading	38986 +	Blockage/plugged	66,6+	1,8+				
				External leakage utility medium	128700 +	General mechanical failure	16,6+	0,45+				
				Internal leakage	171527 +	**Overheating**						
				Other	342466 +	General mechanical failure	100	0,3+				
				Unknown	342466 +	**Structura deficiency**						
						General mechanical failure	55+	3,15+				
						General Material failure	21+	1,2+				
						Blockage/plugged	7,8+	0,45+				
						Spurious stop						
						General instrument failure	42,7	2,25				
						Mechanical failure	20+	1,05+				
						Vibration						
						Clerance/alignment failure	25+	1,65+				
						General mechanical failure	22,7+	1,5+				

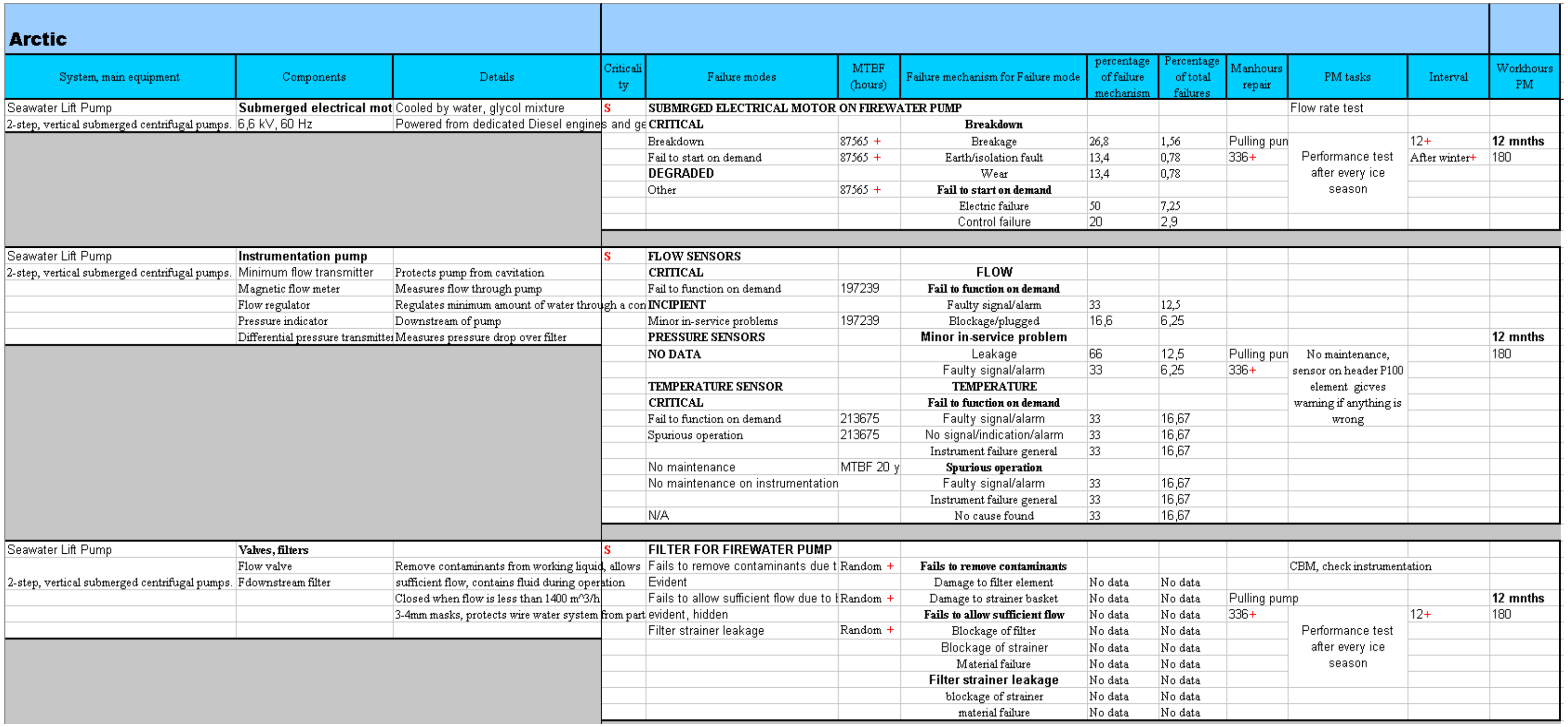
Table B.3 FMECA, Submerg. el. Motor, Instrumentation pump and filter in firewater pump, NCS



NCS

System, main equipment	Components	Details	Criticality	Redundancy	Failure modes	MTBF (hours)	Failure mechanism for Failure mode	percentage of failure mechanis	Percentage of total failures	Manhours repair	PM tasks	Interval	Workhours PM
Seawater Lift Pump	**Submerged electrical mo**	Cooled by water, glycol mixture	Only cost, not	3x50	**SUBMRGED ELECTRICAL MOTOR ON FIREWATER PUMP**								
2-step, vertical submerged centrifugal pumps.	6,6 kV, 60 Hz	Powered from dedicated Diesel engir	safety critical		**CRITICAL**		**Breakdown**				Performance test,		
					Breakdown	87565	Breakage	26,8	1,56	Pulling pun	if more than 10%	60	**60 mnths**
					Fail to start on demand	87565	Earth/isolation fault	13,4	0,78	336	reduced capacity,		180
					DEGRADED		Wear	13,4	0,78		pull pump		
					Other	87565	**Fail to start on demand**						
							Electric failure	50	7,25				
							Control failure	20	2,9				
Seawater Lift Pump	**Instrumentation pump**			1x100	**INSTRUMENTATION SEAWATER LIFT PUMP**								
2-step, vertical submerged centrifugal pumps.	Minimum flow transmitter	Protects pump from cavitation	Only cost, not		**FLOW SENSORS**		**FLOW**				No preventive		
	Magnetic flow meter	Measures flow through pump	safety critical		**CRITICAL**		**Fail to function on demand**				maintenance due		
	Flow regulator	Regulates minimum amount of water through a control valve			Fail to function on demand	197239	Faulty signal/alarm	33	12,5		to		
	Pressure indicator	Downstream of pump			**INCIPIENT**		Blockage/plugged	16,6	6,25				
	Differential pressure transmitte	Measures pressure drop over filter			Minor in-service problems	197239	**Minor in-service problem**				Visual inspection of		
					PRESSURE SENSORS		Leakage	66	12,5		sensor heads on		
					NO DATA		Faulty signal/alarm	33	6,25				
					TEMPERATURE SENSOR		**TEMPERATURE**						
					CRITICAL		**Fail to function on demand**						
					Fail to function on demand	213675	Faulty signal/alarm	33	16,67				
					Spurious operation	213675	No signal/indication/alarm	33	16,67				
							Instrument failure general	33	16,67				
							Spurious operation						
							Faulty signal/alarm	33	16,67				
							Instrument failure general	33	16,67				
							No cause found	33	16,67				
Seawater Lift Pump	**Valves, filters**			1x100	**FILTER FOR FIREWATER PUMP**								
	Flow valve	Remove contaminants from working liqu	Only cost, not		Fails to remove contaminants due t	Random	**Fails to remove contaminants**						
2-step, vertical submerged centrifugal pumps.	Fdownstream filter	sufficient flow, contains fluid during op	safety critical		Fails to allow sufficient flow due to b	Random	Damage to filter element	No data	No data				
		Closed when flow is less than 1400 m^3/h			Filter strainer leakage	Random	Damage to strainer basket	No data	No data		Performance test,		
		3-4mm masks, protects wire water system from particles					**Fails to allow sufficient flow**	No data	No data		if more than 10%		
							Blockage of filter	No data	No data		reduced capacity,	60	**60 mnths**
							Blockage of strainer	No data	No data		pull pump		180
							Material failure	No data	No data				
							Filter strainer leakage	No data	No data				
							blockage of strainer	No data	No data				
							material failure	No data	No data				Pull

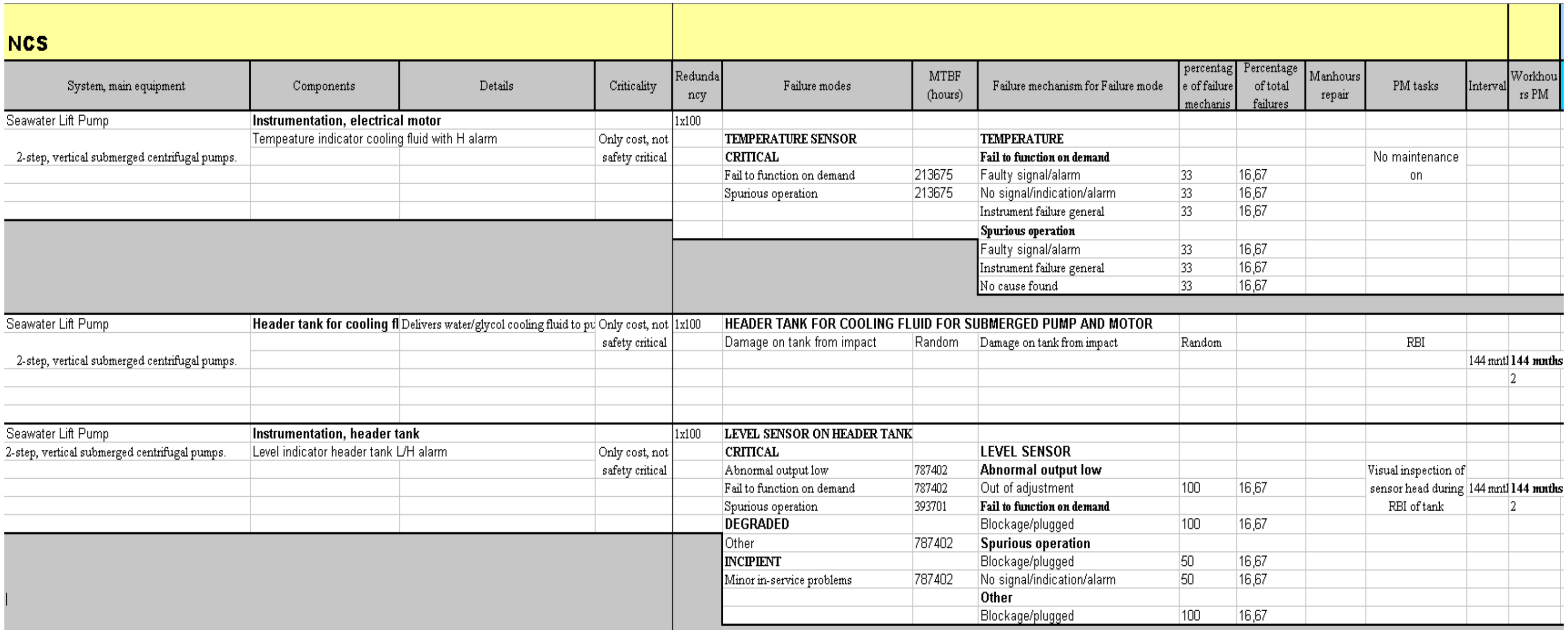
Table B.4 FMECA, Submerged el motor, instrumentation on pump, filter for seawater pump, Arctic



Arctic

System, main equipment	Components	Details	Criticality	Failure modes	MTBF (hours)	Failure mechanism for Failure mode	percentage of failure mechanism	Percentage of total failures	Manhours repair	PM tasks	Interval	Workhours PM
Seawater Lift Pump	**Submerged electrical mot**	Cooled by water, glycol mixture	S	**SUBMRGED ELECTRICAL MOTOR ON FIREWATER PUMP**						Flow rate test		
2-step, vertical submerged centrifugal pumps.	6,6 kV, 60 Hz	Powered from dedicated Diesel engines and ge		**CRITICAL**		**Breakdown**						
				Breakdown	87565 +	Breakage	26,8	1,56	Pulling pun		12+	**12 mnths**
				Fail to start on demand	87565 +	Earth/isolation fault	13,4	0,78	336+	Performance test after every ice season	After winter+	180
				DEGRADED		Wear	13,4	0,78				
				Other	87565 +	**Fail to start on demand**						
						Electric failure	50	7,25				
						Control failure	20	2,9				
Seawater Lift Pump	**Instrumentation pump**		S	**FLOW SENSORS**								
2-step, vertical submerged centrifugal pumps.	Minimum flow transmitter	Protects pump from cavitation		**CRITICAL**		**FLOW**						
	Magnetic flow meter	Measures flow through pump		Fail to function on demand	197239	**Fail to function on demand**						
	Flow regulator	Regulates minimum amount of water through a con		**INCIPIENT**		Faulty signal/alarm	33	12,5				
	Pressure indicator	Downstream of pump		Minor in-service problems	197239	Blockage/plugged	16,6	6,25				
	Differential pressure transmitte	Measures pressure drop over filter		**PRESSURE SENSORS**		**Minor in-service problem**						**12 mnths**
				NO DATA		Leakage	66	12,5	Pulling pun	No maintenance, sensor on header P100 element gicves warning if anything is wrong		180
						Faulty signal/alarm	33	6,25	336+			
				TEMPERATURE SENSOR		**TEMPERATURE**						
				CRITICAL		**Fail to function on demand**						
				Fail to function on demand	213675	Faulty signal/alarm	33	16,67				
				Spurious operation	213675	No signal/indication/alarm	33	16,67				
						Instrument failure general	33	16,67				
				No maintenance	MTBF 20 y	**Spurious operation**						
				No maintenance on instrumentation		Faulty signal/alarm	33	16,67				
						Instrument failure general	33	16,67				
				N/A		No cause found	33	16,67				
Seawater Lift Pump	**Valves, filters**		S	**FILTER FOR FIREWATER PUMP**								
	Flow valve	Remove contaminants from working liquid, allows		Fails to remove contaminants due t	Random +	**Fails to remove contaminants**				CBM, check instrumentation		
2-step, vertical submerged centrifugal pumps.	Fdownstream filter	sufficient flow, contains fluid during operation		Evident		Damage to filter element	No data	No data				
		Closed when flow is less than 1400 m^3/h		Fails to allow sufficient flow due to t	Random +	Damage to strainer basket	No data	No data	Pulling pump			**12 mnths**
		3-4mm masks, protects wire water system from part		evident, hidden		**Fails to allow sufficient flow**	No data	No data	336+		12+	180
				Filter strainer leakage	Random +	Blockage of filter	No data	No data		Performance test after every ice season		
						Blockage of strainer	No data	No data				
						Material failure	No data	No data				
						Filter strainer leakage	No data	No data				
						blockage of strainer	No data	No data				
						material failure	No data	No data				

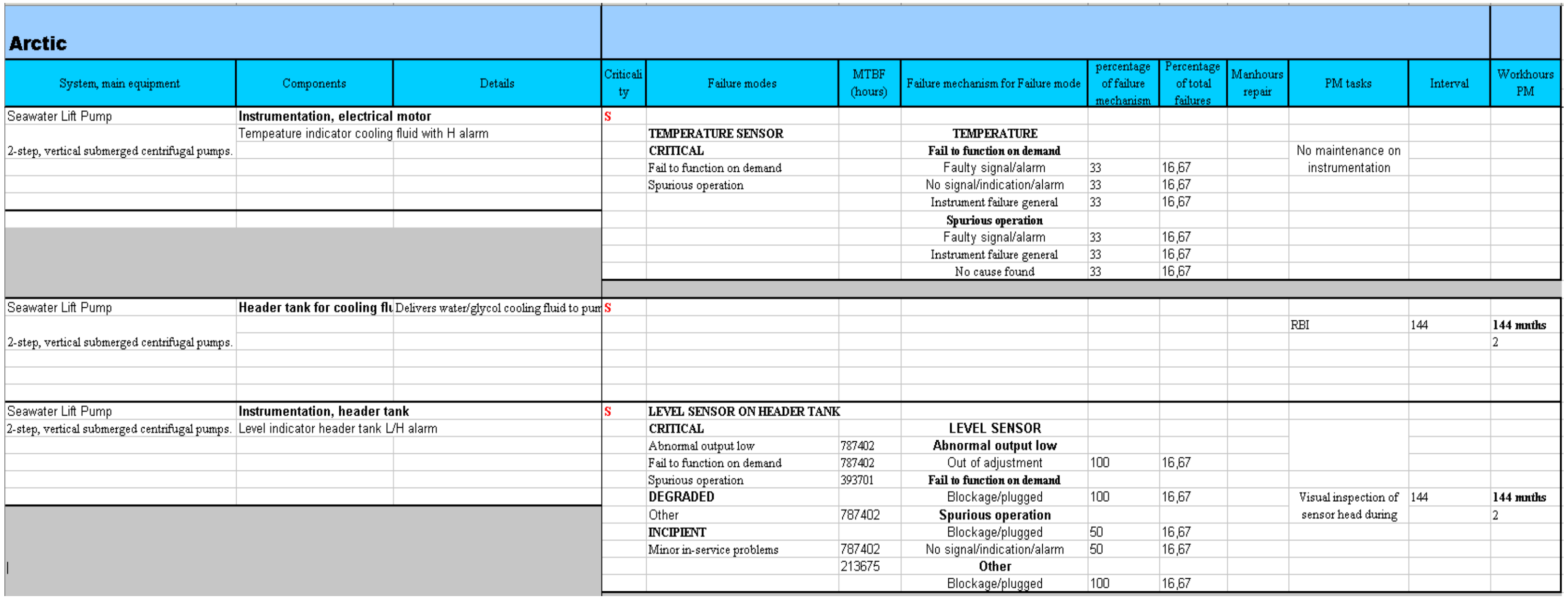
Table B.5 FMECA, Instrumentation electrical motor, Header tank for cooling fluid and Instrumentation on header tank, NCS



NCS

System, main equipment	Components	Details	Criticality	Redundancy	Failure modes	MTBF (hours)	Failure mechanism for Failure mode	percentage of failure mechanis	Percentage of total failures	Manhours repair	PM tasks	Interval	Workhours PM
Seawater Lift Pump	**Instrumentation, electrical motor**			1x100									
	Tempeature indicator cooling fluid with H alarm		Only cost, not		**TEMPERATURE SENSOR**		**TEMPERATURE**						
2-step, vertical submerged centrifugal pumps.			safety critical		**CRITICAL**		**Fail to function on demand**				No maintenance		
					Fail to function on demand	213675	Faulty signal/alarm	33	16,67		on		
					Spurious operation	213675	No signal/indication/alarm	33	16,67				
							Instrument failure general	33	16,67				
							Spurious operation						
							Faulty signal/alarm	33	16,67				
							Instrument failure general	33	16,67				
							No cause found	33	16,67				
Seawater Lift Pump	**Header tank for cooling fl**	Delivers water/glycol cooling fluid to pu	Only cost, not	1x100	**HEADER TANK FOR COOLING FLUID FOR SUBMERGED PUMP AND MOTOR**								
			safety critical		Damage on tank from impact	Random	Damage on tank from impact	Random			RBI		
2-step, vertical submerged centrifugal pumps.												144 mntl	**144 mnths**
													2
Seawater Lift Pump	**Instrumentation, header tank**			1x100	**LEVEL SENSOR ON HEADER TANK**								
2-step, vertical submerged centrifugal pumps.	Level indicator header tank L/H alarm		Only cost, not		**CRITICAL**		**LEVEL SENSOR**						
			safety critical		Abnormal output low	787402	**Abnormal output low**				Visual inspection of		
					Fail to function on demand	787402	Out of adjustment	100	16,67		sensor head during	144 mntl	**144 mnths**
					Spurious operation	393701	**Fail to function on demand**				RBI of tank		2
					DEGRADED		Blockage/plugged	100	16,67				
					Other	787402	**Spurious operation**						
					INCIPIENT		Blockage/plugged	50	16,67				
					Minor in-service problems	787402	No signal/indication/alarm	50	16,67				
							Other						
							Blockage/plugged	100	16,67				

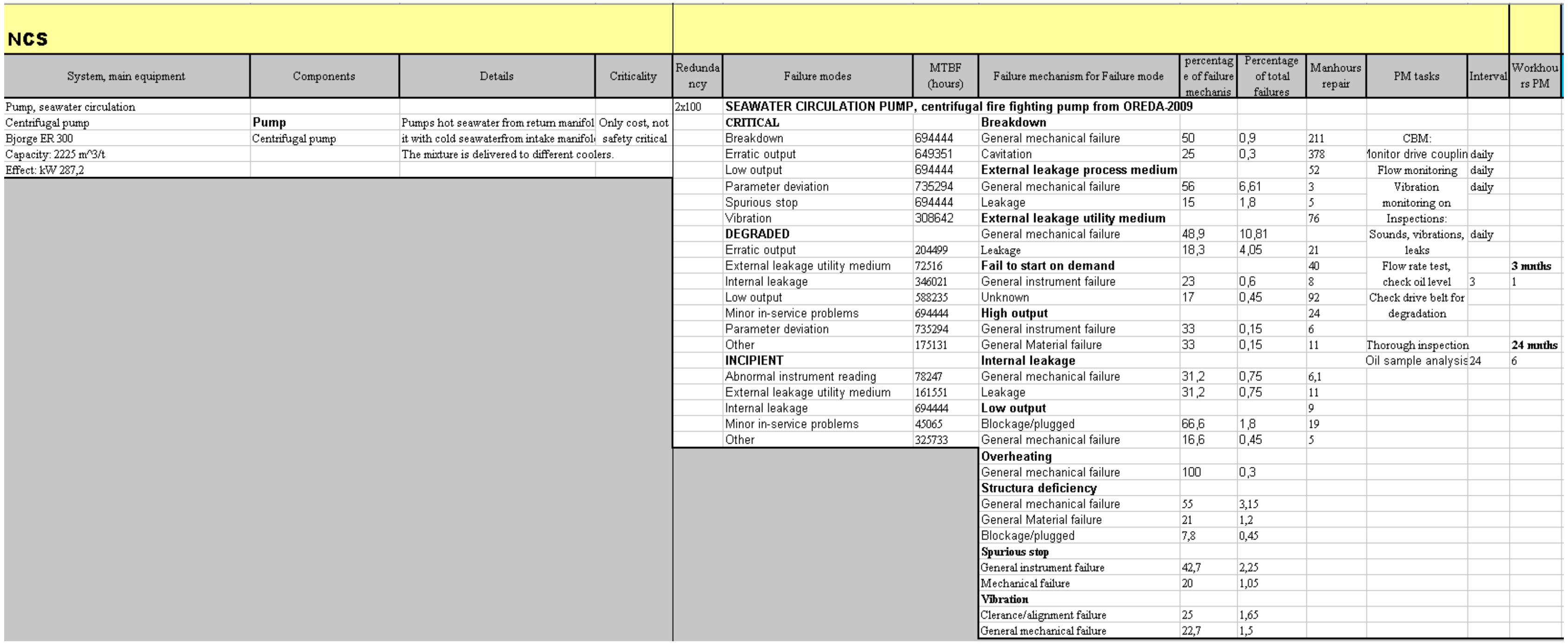
Table B.6 FMECA, Instrumentation on el. motor, header tank for cooling fluid and instrumentation on header tank, Arctic



Arctic

System, main equipment	Components	Details	Criticality	Failure modes	MTBF (hours)	Failure mechanism for Failure mode	percentage of failure mechanism	Percentage of total failures	Manhours repair	PM tasks	Interval	Workhours PM
Seawater Lift Pump	**Instrumentation, electrical motor**		S									
	Tempeature indicator cooling fluid with H alarm			**TEMPERATURE SENSOR**		**TEMPERATURE**						
2-step, vertical submerged centrifugal pumps.				**CRITICAL**		**Fail to function on demand**				No maintenance on instrumentation		
				Fail to function on demand		Faulty signal/alarm	33	16,67				
				Spurious operation		No signal/indication/alarm	33	16,67				
						Instrument failure general	33	16,67				
						Spurious operation						
						Faulty signal/alarm	33	16,67				
						Instrument failure general	33	16,67				
						No cause found	33	16,67				
Seawater Lift Pump	**Header tank for cooling flu**	Delivers water/glycol cooling fluid to pum	S									
										RBI	144	**144 mnths**
2-step, vertical submerged centrifugal pumps.												2
Seawater Lift Pump	**Instrumentation, header tank**		S	**LEVEL SENSOR ON HEADER TANK**								
2-step, vertical submerged centrifugal pumps.	Level indicator header tank L/H alarm			**CRITICAL**		LEVEL SENSOR						
				Abnormal output low	787402	**Abnormal output low**						
				Fail to function on demand	787402	Out of adjustment	100	16,67				
				Spurious operation	393701	**Fail to function on demand**						
				DEGRADED		Blockage/plugged	100	16,67		Visual inspection of sensor head during	144	**144 mnths**
				Other	787402	**Spurious operation**						2
				INCIPIENT		Blockage/plugged	50	16,67				
				Minor in-service problems	787402	No signal/indication/alarm	50	16,67				
					213675	**Other**						
						Blockage/plugged	100	16,67				

Table B.7 FMECA, Seawater circulation pump, NCS



NCS

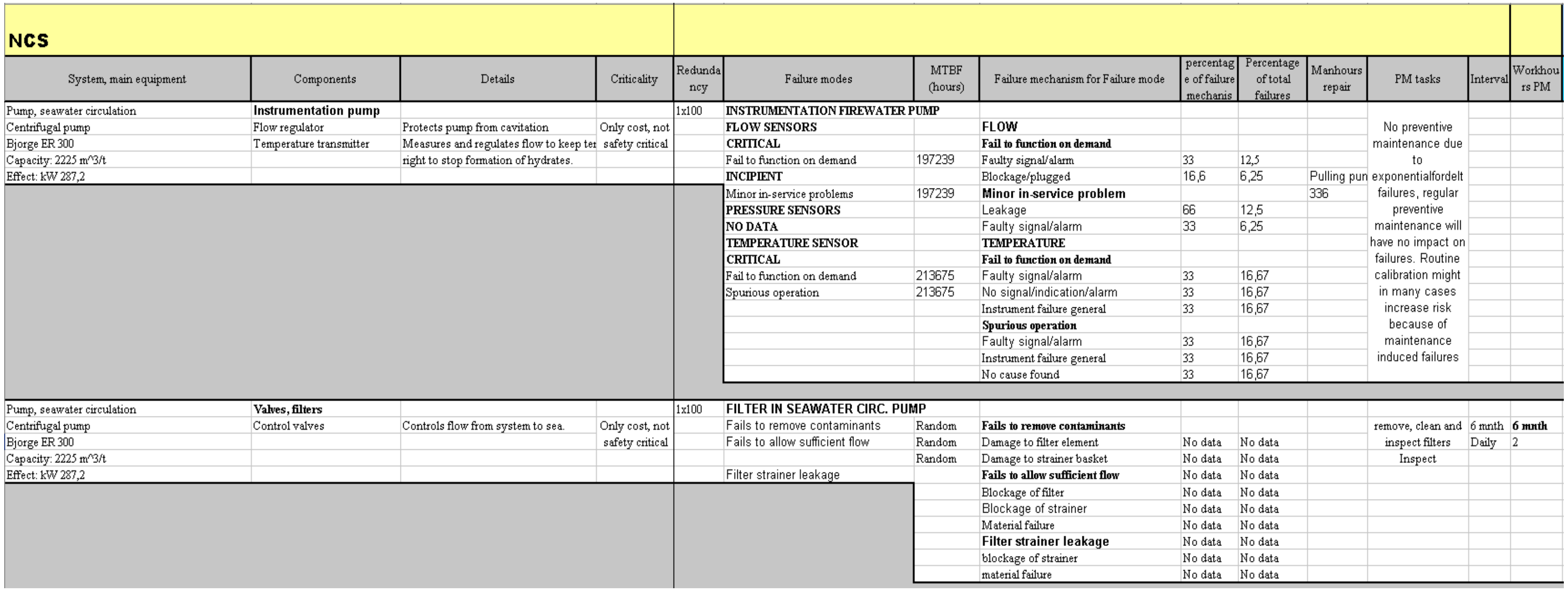
System, main equipment	Components	Details	Criticality	Redundancy	Failure modes	MTBF (hours)	Failure mechanism for Failure mode	percentage of failure mechanis	Percentage of total failures	Manhours repair	PM tasks	Interval	Workhours PM
Pump, seawater circulation				2x100	**SEAWATER CIRCULATION PUMP, centrifugal fire fighting pump from OREDA-2009**								
Centrifugal pump	**Pump**	Pumps hot seawater from return manifol	Only cost, not		**CRITICAL**		**Breakdown**						
Bjorge ER 300	Centrifugal pump	it with cold seawaterfrom intake manifol	safety critical		Breakdown	694444	General mechanical failure	50	0,9	211	CBM:		
Capacity: 2225 m^3/t		The mixture is delivered to different coolers.			Erratic output	649351	Cavitation	25	0,3	378	lonitor drive couplin	daily	
Effect: kW 287,2					Low output	694444	**External leakage process medium**			52	Flow monitoring	daily	
					Parameter deviation	735294	General mechanical failure	56	6,61	3	Vibration	daily	
					Spurious stop	694444	Leakage	15	1,8	5	monitoring on		
					Vibration	308642	**External leakage utility medium**			76	Inspections:		
					DEGRADED		General mechanical failure	48,9	10,81		Sounds, vibrations,	daily	
					Erratic output	204499	Leakage	18,3	4,05	21	leaks		
					External leakage utility medium	72516	**Fail to start on demand**			40	Flow rate test,		**3 mnths**
					Internal leakage	346021	General instrument failure	23	0,6	8	check oil level	3	1
					Low output	588235	Unknown	17	0,45	92	Check drive belt for		
					Minor in-service problems	694444	**High output**			24	degradation		
					Parameter deviation	735294	General instrument failure	33	0,15	6			
					Other	175131	General Material failure	33	0,15	11	Thorough inspection		**24 mnths**
					INCIPIENT		**Internal leakage**				Oil sample analysis	24	6
					Abnormal instrument reading	78247	General mechanical failure	31,2	0,75	6,1			
					External leakage utility medium	161551	Leakage	31,2	0,75	11			
					Internal leakage	694444	**Low output**			9			
					Minor in-service problems	45065	Blockage/plugged	66,6	1,8	19			
					Other	325733	General mechanical failure	16,6	0,45	5			
							Overheating						
							General mechanical failure	100	0,3				
							Structura deficiency						
							General mechanical failure	55	3,15				
							General Material failure	21	1,2				
							Blockage/plugged	7,8	0,45				
							Spurious stop						
							General instrument failure	42,7	2,25				
							Mechanical failure	20	1,05				
							Vibration						
							Clerance/alignment failure	25	1,65				
							General mechanical failure	22,7	1,5				

Table B.8 FMECA, Seawater circulation pump, Arctic

Arctic

System, main equipment	Components	Details	Criticality	Failure modes	MTBF (hours)	Failure mechanism for Failure mode	percentage of failure mechanism	Percentage of total failures	Manhours repair	PM tasks	Interval	Workhours PM
Pump, seawater circulation			S	**SEAWATER CIRCULATION PUMP, centrifugal fire fighting pump from OREDA-2009**								
Centrifugal pump	**Pump**	Pumps hot seawater from return manifold mixing		**CRITICAL**		**Breakdown**						
Bjorge ER 300	Centrifugal pump	it with cold seawaterfrom intake manifold.		Breakdown	694444	General mechanical failure	50	0,9	211	CBM:		
Capacity: 2225 m^3/t		The mixture is delivered to different coolers.		Erratic output	649351	Cavitation	25	0,3	378	Monitor drive coupling		
Effect: kW 287,2				Low output	694444	**xternal leakage process medium**			52	Flow monitoring	daily	
				Parameter deviation	735294	General mechanical failure	56	6,61	3	Vibration monitoring on	daily	
				Spurious stop	694444	Leakage	15	1,8	5			
				Vibration	308642	**External leakage utility medium**			76	Inspections:		
				DEGRADED		General mechanical failure	48,9	10,81		Sounds, vibrations, leak	daily	
				Erratic output	204499	Leakage	18,3	4,05	21			
				External leakage utility medium	72516	**Fail to start on demand**			40	Flow rate test, check oil	3	**3 mnths**
				Internal leakage	346021	General instrument failure	23	0,6	8	Check drive belt for deg	3	1
				Low output	588235	Unknown	17	0,45	92			
				Minor in-service problems	694444	**High output**			24	Thorough inspection	24	**24 mnths**
				Parameter deviation	735294	General instrument failure	33	0,15	6	Oil sample analysis	24	6
				Other	175131	General Material failure	33	0,15	11			
				INCIPIENT		**Internal leakage**						
				Abnormal instrument reading	78247	General mechanical failure	31,2	0,75	6,1			
				External leakage utility medium	161551	Leakage	31,2	0,75	11			
				Internal leakage	694444	**Low output**			9			
				Minor in-service problems	45065	Blockage/plugged	66,6	1,8	19			
				Other	325733	General mechanical failure	16,6	0,45	5			
						Overheating						
						General mechanical failure	100	0,3				
						Structura deficiency						
						General mechanical failure	55	3,15				
						General Material failure	21	1,2				
						Blockage/plugged	7,8	0,45				
						Spurious stop						
						General instrument failure	42,7	2,25				
						Mechanical failure	20	1,05				
						Vibration						
						Clerance/alignment failure	25	1,65				
						General mechanical failure	22,7	1,5				

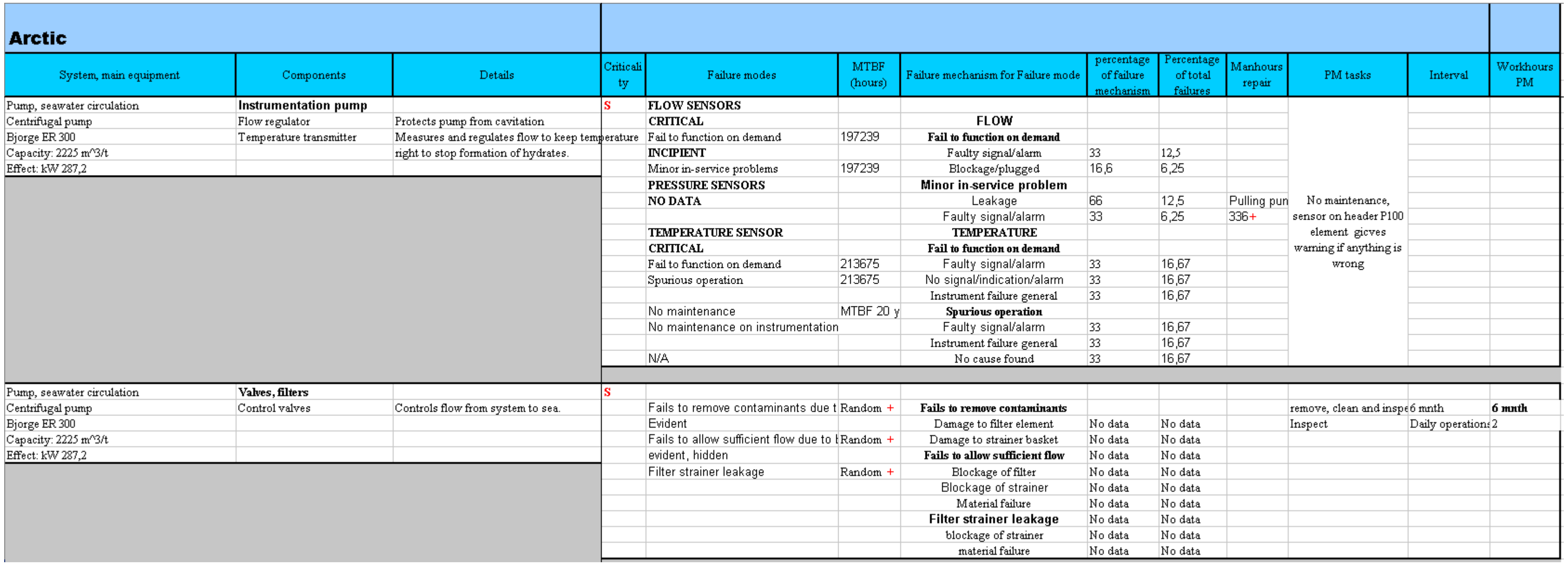
Table B.9 FMECA, Instrumentation pump and filter on seawater circulation pump, NCS



NCS

System, main equipment	Components	Details	Criticality	Redundancy	Failure modes	MTBF (hours)	Failure mechanism for Failure mode	percentage of failure mechanis	Percentage of total failures	Manhours repair	PM tasks	Interval	Workhours PM
Pump, seawater circulation	**Instrumentation pump**			1x100	**INSTRUMENTATION FIREWATER PUMP**								
Centrifugal pump	Flow regulator	Protects pump from cavitation	Only cost, not		**FLOW SENSORS**		**FLOW**				No preventive maintenance due to exponentialfordelt failures, regular preventive maintenance will have no impact on failures. Routine calibration might in many cases increase risk because of maintenance induced failures		
Bjorge ER 300	Temperature transmitter	Measures and regulates flow to keep ter	safety critical		**CRITICAL**		**Fail to function on demand**						
Capacity: 2225 m^3/t		right to stop formation of hydrates.			Fail to function on demand	197239	Faulty signal/alarm	33	12,5				
Effect: kW 287,2					**INCIPIENT**		Blockage/plugged	16,6	6,25	Pulling pun			
					Minor in-service problems	197239	**Minor in-service problem**			336			
					PRESSURE SENSORS		Leakage	66	12,5				
					NO DATA		Faulty signal/alarm	33	6,25				
					TEMPERATURE SENSOR		**TEMPERATURE**						
					CRITICAL		**Fail to function on demand**						
					Fail to function on demand	213675	Faulty signal/alarm	33	16,67				
					Spurious operation	213675	No signal/indication/alarm	33	16,67				
							Instrument failure general	33	16,67				
							Spurious operation						
							Faulty signal/alarm	33	16,67				
							Instrument failure general	33	16,67				
							No cause found	33	16,67				
Pump, seawater circulation	**Valves, filters**			1x100	**FILTER IN SEAWATER CIRC. PUMP**								
Centrifugal pump	Control valves	Controls flow from system to sea.	Only cost, not		Fails to remove contaminants	Random	**Fails to remove contaminants**				remove, clean and	6 mnth	**6 mnth**
Bjorge ER 300			safety critical		Fails to allow sufficient flow	Random	Damage to filter element	No data	No data		inspect filters	Daily	2
Capacity: 2225 m^3/t						Random	Damage to strainer basket	No data	No data		Inspect		
Effect: kW 287,2					Filter strainer leakage		**Fails to allow sufficient flow**	No data	No data				
							Blockage of filter	No data	No data				
							Blockage of strainer	No data	No data				
							Material failure	No data	No data				
							Filter strainer leakage	No data	No data				
							blockage of strainer	No data	No data				
							material failure	No data	No data				

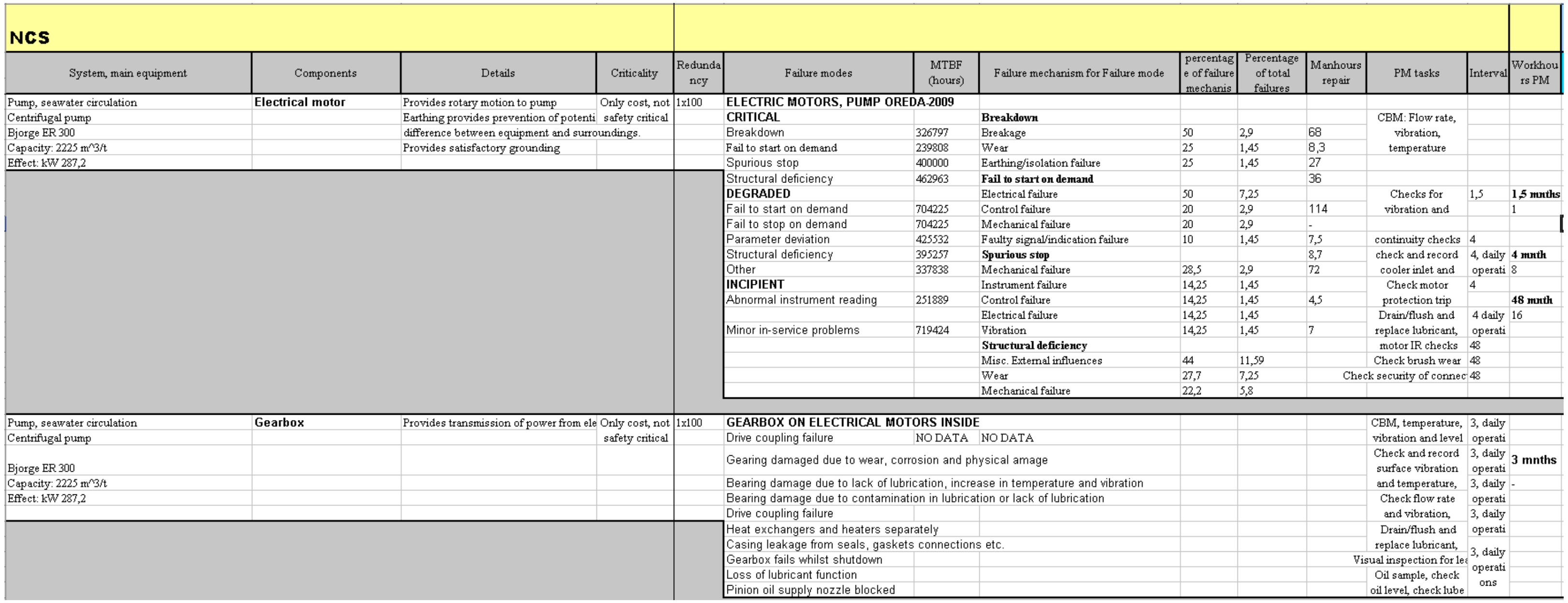
Table B.10 FMECA, Instrumentation on seawater circulation pump and filter, Arctic



Arctic

System, main equipment	Components	Details	Criticality	Failure modes	MTBF (hours)	Failure mechanism for Failure mode	percentage of failure mechanism	Percentage of total failures	Manhours repair	PM tasks	Interval	Workhours PM
Pump, seawater circulation	**Instrumentation pump**		S	**FLOW SENSORS**								
Centrifugal pump	Flow regulator	Protects pump from cavitation		**CRITICAL**		**FLOW**						
Bjorge ER 300	Temperature transmitter	Measures and regulates flow to keep temperature		Fail to function on demand	197239	**Fail to function on demand**						
Capacity: 2225 m^3/t		right to stop formation of hydrates.		**INCIPIENT**		Faulty signal/alarm	33	12,5				
Effect: kW 287,2				Minor in-service problems	197239	Blockage/plugged	16,6	6,25				
				PRESSURE SENSORS		**Minor in-service problem**						
				NO DATA		Leakage	66	12,5	Pulling pun	No maintenance, sensor on header P100 element gicves warning if anything is wrong		
						Faulty signal/alarm	33	6,25	336+			
				TEMPERATURE SENSOR		**TEMPERATURE**						
				CRITICAL		**Fail to function on demand**						
				Fail to function on demand	213675	Faulty signal/alarm	33	16,67				
				Spurious operation	213675	No signal/indication/alarm	33	16,67				
						Instrument failure general	33	16,67				
				No maintenance	MTBF 20 y	**Spurious operation**						
				No maintenance on instrumentation		Faulty signal/alarm	33	16,67				
						Instrument failure general	33	16,67				
				N/A		No cause found	33	16,67				
Pump, seawater circulation	**Valves, filters**		S									
Centrifugal pump	Control valves	Controls flow from system to sea.		Fails to remove contaminants due t	Random +	**Fails to remove contaminants**				remove, clean and inspe	6 mnth	**6 mnth**
Bjorge ER 300				Evident		Damage to filter element	No data	No data		Inspect	Daily operations	2
Capacity: 2225 m^3/t				Fails to allow sufficient flow due to t	Random +	Damage to strainer basket	No data	No data				
Effect: kW 287,2				evident, hidden		**Fails to allow sufficient flow**	No data	No data				
				Filter strainer leakage	Random +	Blockage of filter	No data	No data				
						Blockage of strainer	No data	No data				
						Material failure	No data	No data				
						Filter strainer leakage	No data	No data				
						blockage of strainer	No data	No data				
						material failure	No data	No data				

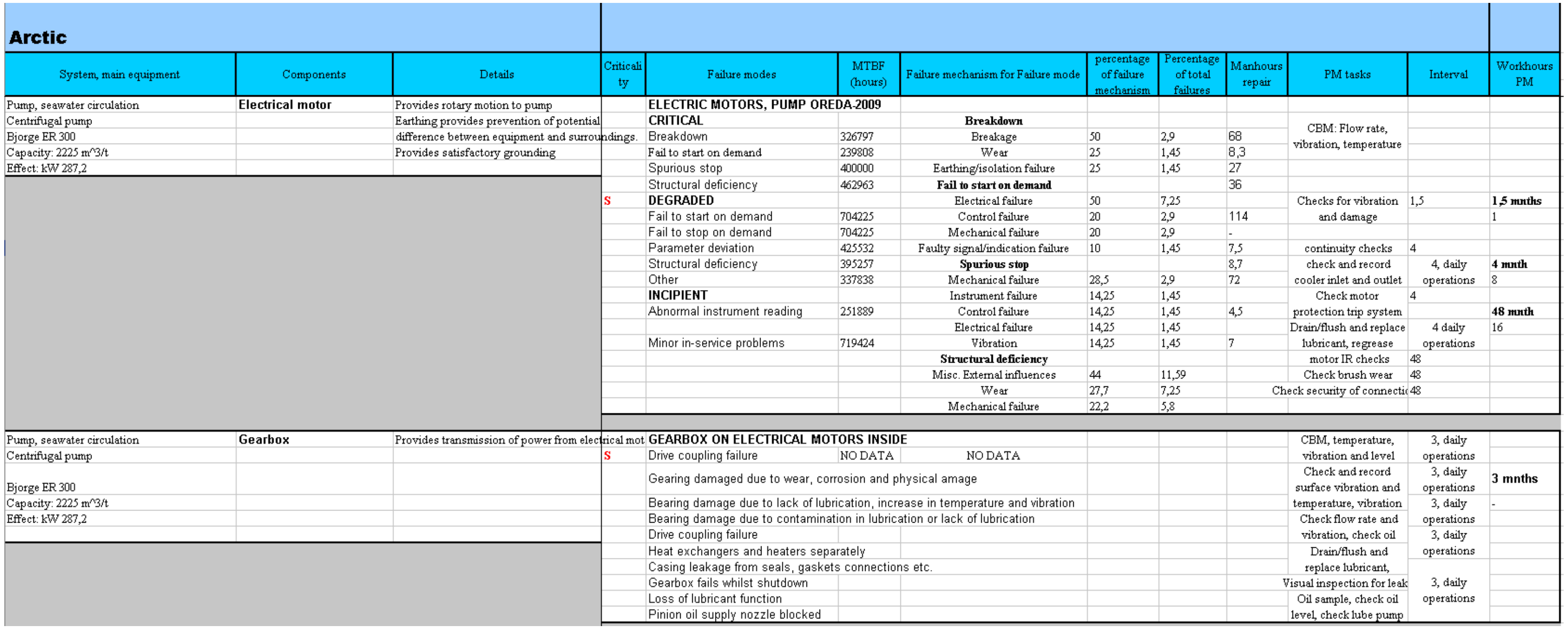
Table B.11 FMECA, Electrical motor and gearbox, NCS



NCS

System, main equipment	Components	Details	Criticality	Redundancy	Failure modes	MTBF (hours)	Failure mechanism for Failure mode	percentage of failure mechanis	Percentage of total failures	Manhours repair	PM tasks	Interval	Workhours PM
Pump, seawater circulation	**Electrical motor**	Provides rotary motion to pump	Only cost, not	1x100	**ELECTRIC MOTORS, PUMP OREDA-2009**								
Centrifugal pump		Earthing provides prevention of potenti	safety critical		**CRITICAL**		**Breakdown**				CBM: Flow rate,		
Bjorge ER 300		difference between equipment and surroundings.			Breakdown	326797	Breakage	50	2,9	68	vibration,		
Capacity: 2225 m^3/t		Provides satisfactory grounding			Fail to start on demand	239808	Wear	25	1,45	8,3	temperature		
Effect: kW 287,2					Spurious stop	400000	Earthing/isolation failure	25	1,45	27			
					Structural deficiency	462963	**Fail to start on demand**			36			
					DEGRADED		Electrical failure	50	7,25		Checks for	1,5	**1,5 mnths**
					Fail to start on demand	704225	Control failure	20	2,9	114	vibration and		1
					Fail to stop on demand	704225	Mechanical failure	20	2,9	-			
					Parameter deviation	425532	Faulty signal/indication failure	10	1,45	7,5	continuity checks	4	
					Structural deficiency	395257	**Spurious stop**			8,7	check and record	4, daily	**4 mnth**
					Other	337838	Mechanical failure	28,5	2,9	72	cooler inlet and	operati	8
					INCIPIENT		Instrument failure	14,25	1,45		Check motor	4	
					Abnormal instrument reading	251889	Control failure	14,25	1,45	4,5	protection trip		**48 mnth**
							Electrical failure	14,25	1,45		Drain/flush and	4 daily	16
					Minor in-service problems	719424	Vibration	14,25	1,45	7	replace lubricant,	operati	
							Structural deficiency				motor IR checks	48	
							Misc. External influences	44	11,59		Check brush wear	48	
							Wear	27,7	7,25		Check security of connec	48	
							Mechanical failure	22,2	5,8				
Pump, seawater circulation	**Gearbox**	Provides transmission of power from ele	Only cost, not	1x100	**GEARBOX ON ELECTRICAL MOTORS INSIDE**						CBM, temperature,	3, daily	
Centrifugal pump			safety critical		Drive coupling failure	NO DATA	NO DATA				vibration and level	operati	
Bjorge ER 300					Gearing damaged due to wear, corrosion and physical amage						Check and record surface vibration	3, daily operati	**3 mnths**
Capacity: 2225 m^3/t					Bearing damage due to lack of lubrication, increase in temperature and vibration						and temperature,	3, daily	-
Effect: kW 287,2					Bearing damage due to contamination in lubrication or lack of lubrication						Check flow rate	operati	
					Drive coupling failure						and vibration,	3, daily	
					Heat exchangers and heaters separately						Drain/flush and	operati	
					Casing leakage from seals, gaskets connections etc.						replace lubricant,	3, daily operati ons	
					Gearbox fails whilst shutdown						Visual inspection for le		
					Loss of lubricant function						Oil sample, check		
					Pinion oil supply nozzle blocked						oil level, check lube		

Table B.12 FMECA, Electrical motor and gearbox, Arctic



Arctic

System, main equipment	Components	Details	Criticality	Failure modes	MTBF (hours)	Failure mechanism for Failure mode	percentage of failure mechanism	Percentage of total failures	Manhours repair	PM tasks	Interval	Workhours PM
Pump, seawater circulation	**Electrical motor**	Provides rotary motion to pump		**ELECTRIC MOTORS, PUMP OREDA-2009**								
Centrifugal pump		Earthing provides prevention of potential		**CRITICAL**		**Breakdown**				CBM: Flow rate,		
Bjorge ER 300		difference between equipment and surroundings.		Breakdown	326797	Breakage	50	2,9	68	vibration, temperature		
Capacity: 2225 m^3/t		Provides satisfactory grounding		Fail to start on demand	239808	Wear	25	1,45	8,3			
Effect: kW 287,2				Spurious stop	400000	Earthing/isolation failure	25	1,45	27			
				Structural deficiency	462963	**Fail to start on demand**			36			
			S	**DEGRADED**		Electrical failure	50	7,25		Checks for vibration	1,5	**1,5 mnths**
				Fail to start on demand	704225	Control failure	20	2,9	114	and damage		1
				Fail to stop on demand	704225	Mechanical failure	20	2,9	-			
				Parameter deviation	425532	Faulty signal/indication failure	10	1,45	7,5	continuity checks	4	
				Structural deficiency	395257	**Spurious stop**			8,7	check and record	4, daily	**4 mnth**
				Other	337838	Mechanical failure	28,5	2,9	72	cooler inlet and outlet	operations	8
				INCIPIENT		Instrument failure	14,25	1,45		Check motor	4	
				Abnormal instrument reading	251889	Control failure	14,25	1,45	4,5	protection trip system		**48 mnth**
						Electrical failure	14,25	1,45		Drain/flush and replace	4 daily	16
				Minor in-service problems	719424	Vibration	14,25	1,45	7	lubricant, regrease	operations	
						Structural deficiency				motor IR checks	48	
						Misc. External influences	44	11,59		Check brush wear	48	
						Wear	27,7	7,25		Check security of connectic	48	
						Mechanical failure	22,2	5,8				
Pump, seawater circulation	**Gearbox**	Provides transmission of power from electrical mot		**GEARBOX ON ELECTRICAL MOTORS INSIDE**						CBM, temperature,	3, daily	
Centrifugal pump			S	Drive coupling failure	NO DATA	NO DATA				vibration and level	operations	
Bjorge ER 300				Gearing damaged due to wear, corrosion and physical amage						Check and record surface vibration and	3, daily operations	**3 mnths**
Capacity: 2225 m^3/t				Bearing damage due to lack of lubrication, increase in temperature and vibration						temperature, vibration	3, daily	-
Effect: kW 287,2				Bearing damage due to contamination in lubrication or lack of lubrication						Check flow rate and	operations	
				Drive coupling failure						vibration, check oil	3, daily	
				Heat exchangers and heaters separately						Drain/flush and	operations	
				Casing leakage from seals, gaskets connections etc.						replace lubricant,		
				Gearbox fails whilst shutdown						Visual inspection for leak	3, daily	
				Loss of lubricant function						Oil sample, check oil	operations	
				Pinion oil supply nozzle blocked						level, check lube pump		

Table B.13 FMECA, Heater and instrumentation on EL. Motor, feed pump to main generators and instrumentation on pump, NCS

NCS

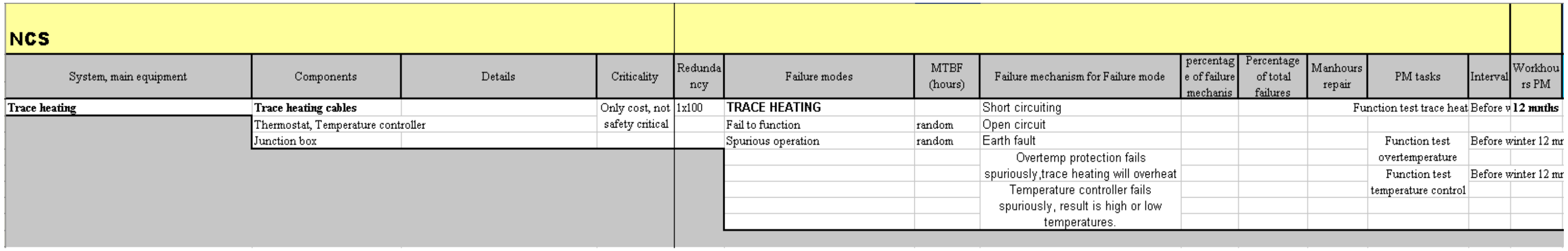
System, main equipment	Components	Details	Criticality	Redundancy	Failure modes	MTBF (hours)	Failure mechanism for Failure mode	percentage of failure mechanis	Percentage of total failures	Manhours repair	PM tasks	Interval	Workhours PM
Pump, seawater circulation	**Electrical heaters on electrica**	Provides heat to maintain temperature a	Only cost, not	1x100	**ELECTRIC HEATER**		**Fail to function**						
Centrifugal pump			safety critical		Fail to function		Heater fail to function heat						
Bjorge ER 300					Function at wrong temperature		Control circuit failure						
Capacity: 2225 m^3/t							Heater element failure				continuity checks	4	
Effect: kW 287,2							Loose connection				check and record	4, daily	**4 mnth**
							Neutral ground resistor failure				cooler inlet and	operati	8
							Earthing connection failure due to wear or damage				Check motor	4	
							Over current protection failure				protection trip		**48 mnth**
							Circuit break failure				Drain/flush and	4 daily	16
							Electrical brush failure				replace lubricant,	operati	
							Bearing damage due to lack of lubrication, increase in temperature and vi				motor IR checks	48	
							Bearing damage due to contamination in lubrication or lack of lubrication				Check brush wear	48	
							Heater, junction box/cable fault				Check security of connec	48	
							Earthing connection failure due to wear or damage						
							Neutral ground resistor failure						
							Loose connection						
							Function at wrong temperature						
							Thermostat controls at lower temp than set						
							Heater thermostat controls at a higher temperature than set						
							Build up of deposits on heater failure						
Pump, seawater circulation	**Instrumentation, electrical motor**		Only cost, not	1x100	**TEMPERATURE SENSOR**		**TEMPERATURE**				No preventive		
Centrifugal pump			safety critical		**CRITICAL**		**Fail to function on demand**				maintenance due		
Bjorge ER 300					Fail to function on demand	213675	Faulty signal/alarm	33	16,67		to		
Capacity: 2225 m^3/t					Spurious operation	213675	No signal/indication/alarm	33	16,67		exponentialfordelt		
Effect: kW 287,2							Instrument failure general	33	16,67		failures, regular		
							Spurious operation				preventive		
							Faulty signal/alarm	33	16,67		maintenance will		
							Instrument failure general	33	16,67		have no impact on		
							No cause found	33	16,67		failures. Routine		
Pump, Essential feed pump to main generators	**Pump**	Pumps	Only cost, not	1x100	SEE SEAWATER CIRCULATION PUMP								
Vertical centrifugal pump	Vertical centrifugal pump	Delivers seawater to the cooling of the	safety critical										
Hamworthy HU081		main generators when nessescary.											
150m^3/h													
	Instrumentation pump		Only cost, not	1x100	SEE SEAWATER CIRCULATION PUMP								
	Flow regulator	Protects pump from cavitation	safety critical										
	Temperature transmitter	Measures and regulates flow to keep											
		temperature right to stop formation of hydrates.											

Table B.14 FMECA, Heater and instrumentation on EL. Motor, feed pump to main generators and instrumentation on pump, Arctic

Arctic

System, main equipment	Components	Details	Criticality	Failure modes	MTBF (hours)	Failure mechanism for Failure mode	percentage of failure mechanism	Percentage of total failures	Manhours repair	PM tasks	Interval	Workhours PM
Pump, seawater circulation	**Electrical heaters on electrical**	Provides heat to maintain temperature and stop co		**ELECTRIC HEATER**		**Fail to function**						
Centrifugal pump				Fail to function		Heater fail to function heat						
Bjorge ER 300			S	Function at wrong temperature		Control circuit failure						
Capacity: 2225 m^3/t						Heater element failure				continuity checks	**4 mnth**	
Effect: kW 287,2						Loose connection				check and record cooler	4, daily	**4 mnth**
						Neutral ground resistor failure					operations	8
						Earthing connection failure due to wear or damage				Check motor	**4 mnth**	
						Over current protection failure				protection trip system		**48 mnth**
						Circuit break failure				Drain/flush and replace	4 daily	16
						Electrical brush failure				lubricant, regrease	operations	
						Bearing damage due to lack of lubrication, increase in temperature and vibration				motor IR checks	**48 mnth**	
						Bearing damage due to contamination in lubrication or lack of lubrication				Check brush wear	**48 mnth**	
						Heater, junction box/cable fault				Check security of conne	**48 mnth**	
						Earthing connection failure due to wear or damage						
						Neutral ground resistor failure						
						Loose connection						
						Function at wrong temperature						
						Thermostat controls at lower temp than set						
						Heater thermostat controls at a higher temperature than set						
						Build up of deposits on heater failure						
Pump, seawater circulation	**Instrumentation, electrical motor**			No maintenance on instrumentation		**TEMPERATURE**				No preventive		
Centrifugal pump						**Fail to function on demand**				maintenance due to		
Bjorge ER 300			S	N/A		Faulty signal/alarm	33	16,67		exponentialfordelt		
Capacity: 2225 m^3/t						No signal/indication/alarm	33	16,67		failures, regular		
Effect: kW 287,2						Instrument failure general	33	16,67		preventive		
						Spurious operation				maintenance will		
						Faulty signal/alarm	33	16,67		have no impact on		
						Instrument failure general	33	16,67		failures. Routine		
						No cause found	33	16,67		calibration might in		
Pump, Essential feed pump to main generators	**Pump**	Pumps										
Vertical centrifugal pump	Vertical centrifugal pump	Delivers seawater to the cooling of the	S									
Hamworthy HU081		main generators when nessescary.		**See seawater circulation pump, identical maintenance**								
150m^3/h												
	Instrumentation pump											
	Flow regulator	Protects pump from cavitation	S									
	Temperature transmitter	Measures and regulates flow to keep		**See seawater circulation pump, identical maintenance**								
		temperature right to stop formation of hydrates.										

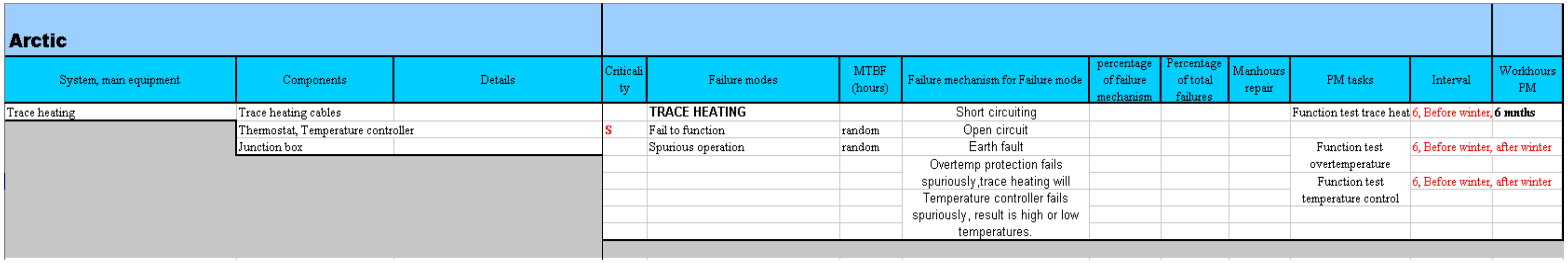
Table B.15 FMECA. Trace heating, NCS



NCS

System, main equipment	Components	Details	Criticality	Redundancy	Failure modes	MTBF (hours)	Failure mechanism for Failure mode	percentage of failure mechanis	Percentage of total failures	Manhours repair	PM tasks	Interval	Workhours PM
Trace heating	**Trace heating cables**		Only cost, not safety critical	1x100	TRACE HEATING		Short circuiting				Function test trace heat	Before v	**12 mnths**
	Thermostat, Temperature controller				Fail to function	random	Open circuit						
	Junction box				Spurious operation	random	Earth fault				Function test overtemperature	Before winter 12 mr	
							Overtemp protection fails spuriously,trace heating will overheat				Function test temperature control	Before winter 12 mr	
							Temperature controller fails spuriously, result is high or low temperatures.						

Table B.16 FMECA, trace heating, Arctic



Arctic

System, main equipment	Components	Details	Criticality	Failure modes	MTBF (hours)	Failure mechanism for Failure mode	percentage of failure mechanism	Percentage of total failures	Manhours repair	PM tasks	Interval	Workhours PM
Trace heating	Trace heating cables			**TRACE HEATING**		Short circuiting				Function test trace heat	6, Before winter,	**6 mnths**
	Thermostat, Temperature controller		S	Fail to function	random	Open circuit						
	Junction box			Spurious operation	random	Earth fault				Function test overtemperature	6, Before winter, after winter	
						Overtemp protection fails spuriously,trace heating will						
						Temperature controller fails spuriously, result is high or low temperatures.				Function test temperature control	6, Before winter, after winter	