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MASTER'S THESIS

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Abstract

Offshore installations are complex and need to be maintained properly to keep expected performance. Critical failures on these installations might induce great threats on productivity, personnel safety, and environment. A maintenance strategy that combines corrective, preventive and predictive maintenance practices will be suggested to achieve reliability as well as cost-efficiency. During the operation and maintenance (O&M) activities, much data is collected, and it has great potential values to help understanding the condition of offshore facilities, and to help making reliable decisions.

The thesis is designed to suggest maintenance decision-making practices that incorporate all data collected, analyzed and accumulated from O&M activities, failure histories and other data sources. The methodology used in the thesis is suggested by the author. Drawworks is selected as an example to explain the idea of achieving the target.

The research will start from identification of the most critical failure modes of drawworks. This will be done in several ways at the same time to ensure most failure modes are included in the discussion. Then qualitative (Fault tree analysis) and quantitative analysis (reliability analysis, assignment of Monitoring Priority Number) will be implemented. The results from these analyses will provide some reference of risk criticality of potential failures. With the risk analysis results and data integrity management, comprehensive and straightforward data architecture could be built in purpose of providing the right data to the right person at the right place. In technical integrity management context, competence management, decision support system and integrated work process will also be studied to help identifying necessary and critical elements in a reliable and efficient decision making practice on maintenance notificaitons.

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Abbreviations

AHP	Analytical Hierarchy Process
AT	Work Permit
BOP	Blowout Preventer
CBM	Condition-based Maintenance
CCR	Central Control Room
CM	Condition Monitoring
CMS	Competence Management System
DCS	Drawworks Control System
DNV	Det Norske Veritas
DOE	U.S. Department of Energy
DSS	Decision Support System
DW	Drawworks
EPCIC	Engineering, Procurement, Construction, Installation, and Commissioning
ES	Expert System
ESDV	Emergency Shutdown Valve
EX equipment	Equipment unit certified for use in hazardous area (explosion prone)
FMECA	Failure Modes, Effects and Criticality Analysis
FMSA	Failure Modes and Symptoms Analysis
FTA	Fault Tree Analysis

HMI	Human-machine Interface
HSE	Health, Safety, Environment
ICT	Information and Communication Technology
IEC	International Electrotechnical Commission
IO	Integrated Operation
IPC	Integrated Planning Center
IPL	Integrated Planning
ISO	International Standardization Organization
IWP	Integrated Work Process
LCC	Life Cycle Cost
MCC	Motor Control Center
MMS	Minerals Management Service (before 2011)
MPN	Monitoring Priority Number
MRU	Motion Reference Unit
MTP	Medium Term Plan
MTTF	Mean Time To Fail
MTTR	Mean Time To Repair
NCS	Norwegian Continental Shelf
NDT	Non-Destructive Test

O&G	Oil and Gas
OGP	Oil and Gas producer Database
OLF	Norwegian Oil Industry Association
O&M	Operation and Maintenance
PLC	Programmable Logic Controller
PdM	Predictive maintenance
PM	Preventive Maintenance
RBM	Reliability Based Maintenance
RCM	Reliability Centered Maintenance
RED	Required End Date
RM	Reliability and Maintenance
SAP	Systems, Applications & Products in Data Processing (enterprise software)
SJA	Safety Job Analysis
STP	Short Term Plan
TBA	Travelling Block Assembly
TIM	Technical Integrity Management
TSP	Technical Service Provider
UbiDSS	Ubiquitous Decision Support System
WOAD	World Offshore Accident Database

Part 1 Introduction of thesis

1 Introduction

1.1 Background

Offshore installations are complex and need to be maintained properly to keep expected performance. Critical failures on these installations might induce great threats on productivity, personnel safety, and environment (Norsok Z-008 2011). According to data from IHS energy (IHS 2015), average day rate in northwest Europe for jack-up is about 150,000 USD in February 2015. To keep operation efficiency and maintain reliability are to save cost. Currently, preventive and corrective maintenance on offshore installations are widely used in purpose of reducing downtime and increasing reliability, while predictive maintenance based on condition monitoring (hereafter CM) technologies is becoming more and more popular.

To ensure reliability of offshore installations, there is an increasing need of incorporating data from CM technologies as well as other data sources into decision-making procedure in maintenance scope. The case studied in this master thesis is a company operating on the southwest of Stavanger in North Sea.

1.2 Challenges

Which parameters should be monitored?

Condition monitoring demands investment on resources like money and personnel. It is costly and is thus recommended to be utilized with proof of profitability/efficiency. What's more, not every component needs to be monitored, and some of them can be difficult to monitor due to space limitation and so on. All of these require that a methodology of identifying critical monitoring parameters needs to be designed and should be reliable and convincible.

What data needs to be collected and how could it be used in decision-making process?

Plenty of data from various sources is saved during operation and maintenance activities. It becomes almost impossible for even specialists to decide where to start with and which to use. Under present decision-making structure, data needed for different disciplines is not clearly defined/classified or properly analyzed, and this normally ends up with some very sketchy analysis done by decision-makers. How to define the right data for the right person needs to be discussed in the thesis.

Normally, catastrophic systematic failures do not happen in one second, as there is always some time and several stages for them to propagate. How to identify the stage of propagation as well as its corresponding data sets, the competence of people in charge, and how to make decision based on relative data need to be discussed. Through the utilization of risk analysis tools and company practice, decision-making related data would be identified and structured. Decision-making process is suggested to be redesigned to combine data architecture and risk-based failure analysis (both qualitative and quantitative).

1.3 Scope definition of the thesis

The research objective in the thesis is set to suggest some ideas of data-driven decision-making practices on maintenance notifications. Data management, competence management and work process management will be discussed in purpose of providing more robust and reliable decision making practice. Drawworks will be used as the example to illustrate the research methodology.

The criticality of maintaining drawworks will be discussed both qualitatively (FMEA, FTA, company practice) and quantitatively (reliability analysis with Birnbaums's importance measure). In this thesis, both structures and control system will be discussed. Condition monitoring data will not be analyzed or diagnosed here in this project, but classification of data will be done to classify the most critical data that is needed for decision-making. A data management architecture will be developed with help of risk analysis, reliability analysis and data integrity principles. The data-driven decision making practice will be suggested.

To implement the research, failure modes identification will be studied firstly to have an overall risk picture of the equipment. Secondly, through failure cause analysis, the parameters that need to be monitored could be identified and relative CM techniques could be recommended. At last, present decision-making structures on maintenance notifications will be studied and then improved with utilization of relative data as well as competence management and decision support system. Besides, some figures derived from the FMEA could be used to indicate the maintenance priority of drawworks to help decision-making.

1.4 Main goals of the thesis

The thesis is aimed to suggest some ideas to decision-making practice with utilization of necessary data with response to maintenance notifications. Wider technical integration on data management, competence management and decision support system will be combined into maintenance decision-making process. With this work done, the company could hopefully achieve:

1) Better understanding of interrelationship between facility condition (every critical parameter) and failure mechanisms;
2) Increased reliability and reduced risk for offshore operation;
3) Continuous improvement of maintenance decision-making practice;
4) Data-driven decision making practice on maintenance notifications;

1.5 Main deliverables

The thesis is oriented with an intension from the company to classify and utilize CM data from drawwork system on maintenance decision-making. The scope is latterly widened to suggest a data-driven decision-making processes on maintenance notifications after discussion with company and faculty supervisor from the university. With the analysis made in the research, the author hopes the methodology used in this research could suggest some fresh ideas to the whole O&G industry to help make more robust decisions in response with notifications and maintenance refinements. The main deliverables include:

1) The most critical failure modes of drawworks;
2) Methods to identify which parameter/component should be monitored;
3) Methods to implement technical integrity management in a systematic and practical way;

4) Method of combining data management into decision making process in response with maintenance notifications;

Besides, the research is supposed to be a template for decision-making practice on maintenance notificaitons, which could be duplicated on other critical equipment/ system. The basics of the template include: FMEA report, FTA analysis, and data management system, decision support system, etc.

1.6 Methodology

The case study part in this research is based on real case. Technical drawings on drawworks are available and will be used as the basis for relative risk analysis. Referring to specific equipment, basic risk analysis reports are normally provided by vendors, for instance the FMEA report. In this research, FMEA report is developed by the author due to the absence of the original FMEA report.

Critical failure modes could be identified by three ways: company practice, literature review, and FMEA. Risk analysis approach like FMEA could provide a systematic view of potential failure modes and causes. Study on company's failure data and maintenance histories gives an insight from company's practices. And literature review on failure modes of drawworks helps to build a full risk picture of the equipment.

FTA will then be implemented based on all critical failure modes (as basic events of FTA). It helps to identify the most critical parameters that need to be monitored. The results from fault tree analysis are used to build up the data architecture and used as part of decision support system. With elaboration of competence management, a comprehensive data-driven decision-making practice on maintenance notifications is suggested. The research path could be seen in Figure 1.

During the research work of FMEA, FTA and decision-making practices, some interviews with experts from DNV-GL as well as the company are done. These give the author the insight from both operator and third party consultancy company, so that a full picture of problem could be generated.

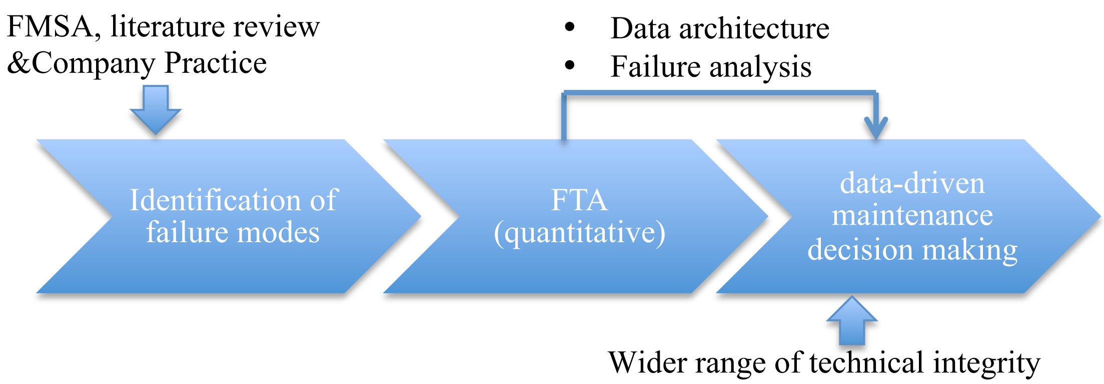

Figure 1 Methodology of research

Referring to the outline o›f the thesis, there are four major parts, which are introduction, theory descriptions, case study, and discussion & conclusion. The first part of the thesis is introduction of current challenge and requirements of maintaining critical systems like drawworks in offshore drilling rig. And the main goal, methodology of research and challenges are explained in this part. The second part will focus on the introduction and explanation of theories that will be mentioned in case study part of the thesis. As shown above in Figure 1, the case study will be elaborated in three chapters, chapter 3, 4 and 5.

Discussion about the methodology reliability and certification, research results and contributions, learning outcomes and future scope of work will be done in chapter 6. Finally, a conclusion of the work will be drawn in chapter 7.

1.7 Assumptions and limitations

The research is conducted with several restrictions. There are also some assumptions that are supposed to make the research reasonably easier, and some limitations due to capability and reach of resources. As stated by Simon, confusion is quite common when things come to what are the differences among assumptions, and limitations in conducting research. (Marilyn Simon, 2011)

Assumptions made in the thesis:

1) Assume condition monitoring techniques are cost-efficient to be used on the equipment the author picks during the research;
2) Information on failure records and other relative documents or information the company are assumed to be right within acceptable range of deviation, and the analysis developed from these information is therefore reasonable and acceptable;
3) Reliability data from OREDA is assumed to be reliable;

Limitations in the thesis:

1) Due to time limit and scope of master thesis, the discussion of decision-making process on maintenance notifications is implemented is implemented by using drawworks as the example. The decision-making process might be different for the overall system from drawworks;
2) Due to the author's competence from his master program, when topic goes to technical integrity concept, the thesis does not focus on design and operation part. Mainly technological aspects are discussed;
3) The availability and amount of literature is limited;
4) Not all reliability data could be found in OREDA or other literature. This means the quantitative reliability analysis could not be done on the overall system;
5) Data used in this thesis is limited inside Norwegian oil and gas industry;
6) The methodology adopted in the thesis is tailor-made for the company case, and thus is recommended to adapt the method accordingly to match different conditions for different equipment/companies;

Part 2 Theory descriptions

In this part, all the theories and principles that are relative to the research will be explained and disscussed. And they will be the basis for the case study which will be illustrated later in part 3.

2 Literature review

2.1 Hoisting system on drilling rig

Hoisting system is one of the key systems on drilling rig. As described by Baker (Baker 1998), hoisting system consists of drawworks, derrick, crown block, traveling block, and drilling line (Figure 2). The drilling line is spooled in the drum of the drawworks. The drilling line go through several pulleys in the crown block and then connected to the travelling block. As drilling line in this section runs fast and accordingly wears easily, the line is normally spooled for 4 to 6 times between the pulleys on crown block and travelling block. Drilling strings or casings are connected to the hook on the bottom of traveling block. The drilling line then runs to the dead end anchor with force sensor stretching on the line (Gusman & Porozhskogo 2002). Derrick provides the support to the drawworks, crown block and traveling block. Through the power from electrical motors, drawworks could achieve the hoisting functions by rolling in or out the drilling line.

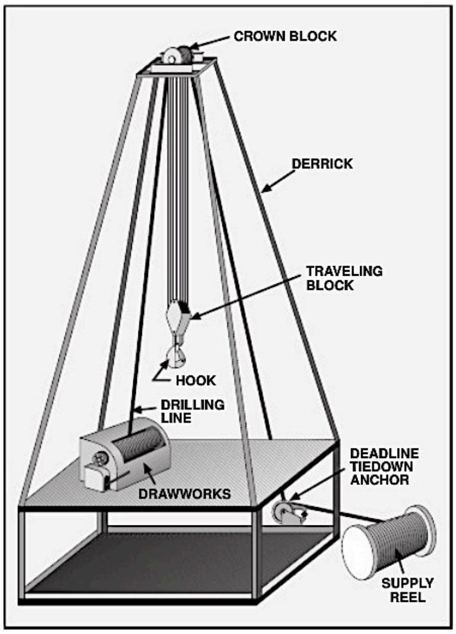

Figure 2 The hoisting system (Ron Baker 1996)

2.1.1 Drawworks system description

Drawworks is the key component in hoisting system. It is an essential part during the drilling operation. It is supposed to perform five essential functions, which are:

1) Exert a pull on the drilling line, and through the blocks and other suspension equipment drag the drill string or casing out of the hole;
2) Control of speed of lowering the drill string or casing down to the hole with braking system;
3) Through braking system, drawworks could limit and control the weight that is applied on the bit;
4) Provide a power takeoff for chain driven rotary table if no other hoist equipment is installed;

5) Catshaft is mounted on with catheads, which provide numerous rig floor lifting services (optional).

According to Baker (Baker 1998), a typical drawwork is consisted of seven major systems (Figure 3, cathead is excluded as the drawwork in this case does not have cathead). This breakdown is beneficial to the further analysis about condition monitoring execution on various components of drawworks.
The systems include:

1) Hoisting drum assembly, which is the key component of the drawworks;

2) Braking system, including mechanical brakes and emergency electromagnetic brakes, provides redundant braking insurance during hoisting and loading operation;

3) Electric motors and power transmission system, which produce, transmit and distribute power;

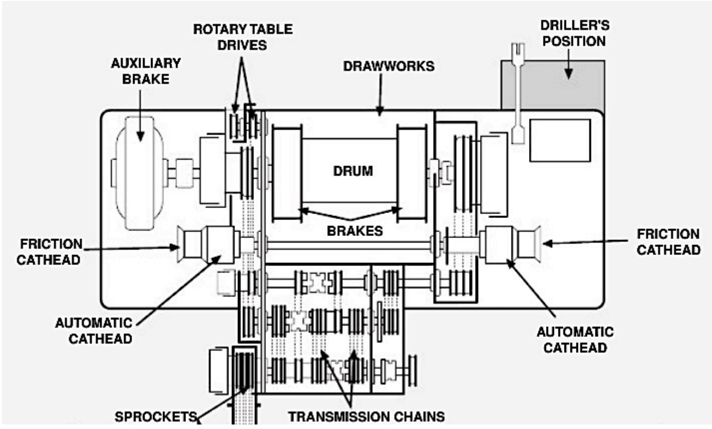

Figure 3 Typical arrangement of drawworks (Baker 1998)

4) Control system, including driller's control system (DCS) like motion reference unit (MRU) and human-machine interface, and drawworks's control system like alarms, transducers, valves and other control units;

5) Lubrication system, including grease, oil spray, sealed transmission, and compulsory lubrication;

6) Supporting system, including frames, case and seat.

In point of power driven methods, there are hydraulic motor driven, DC motor driven and AC motor driven drawworks. For electric system as DC motor or AC motor driven drawworks, the average efficiency is 15%-20% higher than hydraulic system (Rium Tapjan and Hege Kverneland 2010). DC motor driven drawworks is known for its high capacity and efficiency of hoisting, and also vast volume and heavy weight. And the structure is more complicated compared to AC motor driven. AC motor driven drawworks has become more and more popular due to its simpler structure, relatively smaller footprint and increasing hoisting capacity. However, to achieve the same hoisting capacity as DC motor does, higher power AC motor is normally needed.

Referring to transmission mechanism, there are chain driven and gear driven drawworks. Chain driven needs higher precision of installation during manufacturing and has relatively low transmission efficiency. It also needs to be clutch-shifted quite a lot during operation. Chain or gear is connected to the motor to transmit power to the drum shaft through opening/ closing the clutch. It needs to be adjusted properly and lubricated with right oil.

The control of hoisting/loading speed is achieved with assistance of motors and brakes. The drawworks is supposed to be able to hoist as much as 300 tons weight (Baker 1998), and should be able to stop and hold the load at any point during loading (Dreco drawworks manuel). The clutch is designed to be open when loading operation is in place and programmable (with PLC) braking system works to control the loading speed. The braking energy is transferred into heat and absorbed by resistor located with the AC drive panels. The brake discs are air-cooled which allows a high rate of energy absorption. There are usually two independent braking systems, mechanical and electromagnetic (Figure 4). The mechanical brake works as main brake. The emergency braking system is connected to PLC main brake with spring. Once power or pressure fails, the emergency brake will be triggered and the brake calipers are activated.

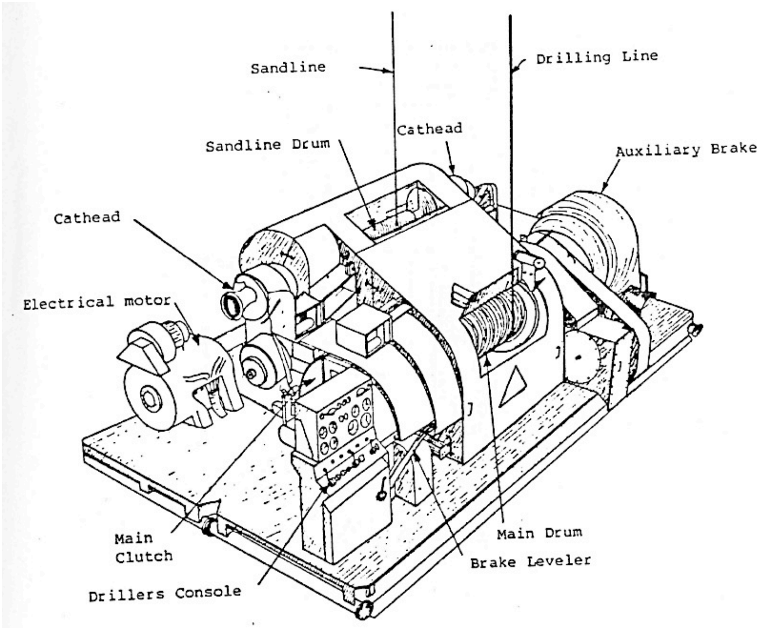

Figure 4 Layout of drawworks (Mortensen,1984)

2.1.2 Current maintenance practices for drawworks

Drawworks is one of the most critical machinery during drilling operation. The drawworks, as described in chapter 2.1.1, mainly include six systems. The current maintenance practices on drawworks will be discussed in the following. Generally, based on each company's risk matrix or risk analysis results, corrective maintenance is preferred to be implemented on component/sub-system that has slight influence on productivity or total cost. For critical component/sub-system, which failure might induce downtime or accident, is preferably monitored periodically or by condition.

1) Hoisting drum shaft assembly:

For rotary machine, the industry tends to adopt condition-monitoring techniques to monitor parameters like vibration, proximity, torque and temperature. Referring to the drawworks drum assembly, the external Groove (mounted on drum for better seating wire lines) is normally set to be examined regularly and replace periodically. It is in scope of *preventive maintenance*. The replacement is relatively flexible. The arrangement of this kind of preventive maintenance is recommended to merge with other major maintenance activities to reduce the interruption of production.

For the shaft assembly, predictive maintenance (*PdM)* is widely utilized. Maintenance targets normally include lubrication oil, bearing, shaft wearing and alignment, temperature, etc. The monitoring of these parameters has been proved with great benefits on reliability, safety and cost efficiency. The monitoring could be periodically or continuous. Condition monitoring techniques are normally conducted independently, and could diagnose about 30%-40% of all faults usually (Hunt 1996, Newell 1999, Anderson 1982). However, recent research indicates more accurate and reliable information could be gained with the combination of different condition monitoring techniques (Mathew, Stecki 1987, Maxwell, Johnson 1997, Troyer 1999). Oil debris analysis (periodically collected) could be an essential method to examine the condition of shaft assembly. The size and origin of debris from oil analysis could indicate the condition of bearing, shaft and lubrication oil. With the help of vibration, proximity and temperature transducers, the maintenance needs could be evaluated and identified.

2) Braking system

Braking system is always designed with redundancy (called as emergency braking system), while the engagement of emergency braking system also means unexpected downtime. Braking system is so critical for safe operation and thus is normally recommended to use *PdM and PM* to improve reliability. Pneumatic control system is relatively easy to incorporate parameter monitoring sensors, like pressure, temperature and flow rate detector. Visual inspections could be coped with these techniques to help eliminate undetected failure symptoms. Besides visual inspection, acoustic detector could also be used as predictive condition monitoring tools to indicate possible failure in a relatively general way. Actually, noise and vibration are the most recognizable and obvious indications of failure for pneumatic system.

Braking disc and band are not redundant as braking system is. The control of engaging or opening braking disc might function perfectly, while the failure of braking disc/bands will still end up with failure of braking. Preventive replacement of braking bands periodically is recommended for higher reliability of the whole system. Air-gap between braking disc and band need to be examined and adjusted as part of *preventive maintenance* program.

3) Electric motors and power transmission system

Due to the complexity and criticality of motors, maintenance programs on motors are often set with priority of preventive/predictive maintenance. Corrective maintenance is still acceptable due to redundancy design principle. However, the risk of total failure in case of losing one of the redundant motors will be high. As Benbouzid explains, motor-driven equipment often provides the key capabilities that are essential to business success and to safety of equipment and personnel (Benbouzid 2000). *Preventive and predictive maintenance programs* are seemingly more preferable from the industry on motors. Many commercially available techniques and tools to monitor motors to improve reliability could be utilized currently. Variety of sensors are now used on monitoring failure symptoms of motor, like air-gap, voltage and current of stator, output torque, vibration, internal and external temperature, and so on.

For chain driven transmission system, noise and lubrication oil (discussed later) is often set as the monitoring parameter in maintenance programs. Excessive noise during operation might indicate a too large chain pitch, sprockets misalignment, excessive chain slack, or loose shaft mounts. Ignorance of uncommon noise may gradually lead to failure of chain/ sprockets parts, which plays a critical role in transmission system. The loss of any of them will definitely cause failure of the whole system. *Preventive maintenance* is often chosen on transmission system. Wearing of thickness of link-plate, if beyond 5% (API 2003), or wearing of sprocket tooth thickness, if beyond 10%, will lead to misalignment of sprocket. The sprockets need to be replaced immediately to avoid its impact on the whole system.

Mid-span movement of chain should be within tabulated limit (for example Table 1). Adjustment needs to be made on center distance to obtain desired amount of slack. Normally 2 pitches are removed if elongation (Figure 5) exceed the adjustment limit and wear elongation length does not exceed 3% or the functional limit (API 2003). If necessary, 1 pitch replacement is allowed and offset link might be used instead.

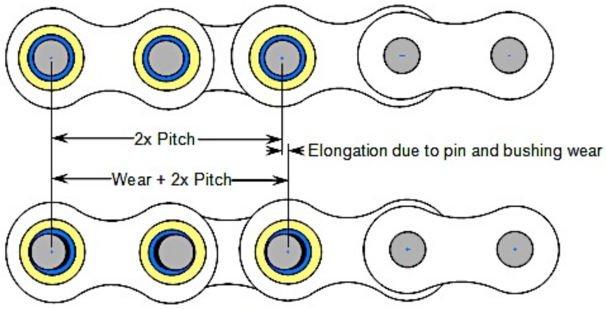

Figure 5 Wear diagram (Diamond chain)

Recommended Possible Mid-span Movement, AC, in. (mm)						
Drive Center-line	Tangent Length Between Sprockets, in. (cm)					
	10 (25)	20 (51)	30 (76)	50 (127)	70 (178)	100 (254)
Horizontal to 45°	0.4–0.5 (10–15)	0.8–1.2 (20–30)	1.2–1.8 (30–45)	2.0–3.0 (51–76)	2.8–4.2 (71–107)	4.0–6.0 (102–152)
45° to vertical	0.2–0.3 (5–8)	0.4–0.6 (10–15)	0.5–0.9 (15–23)	1.0–1.5 (25–38)	1.4–2.1 (36–53)	2.0–3.0 (51–76)

Table 1 Mid-span Movement (Diamond chain)

4) Control system

As described above, control system including driller's control system (DCS) as motion reference unit (MRU) and human-machine interface, and drawworks's control system as alarms, transducers, valves and other control system. Maintaining of these control system involves both software verification and updating, and physical control units maintenance. For management software and operating system HMI, software providers normally provide updating or patching service due to adding of function or modification of possible failure. The updating of software could be either corrective or preventive when tailor-designed function features need to be incorporated into present system. For transducers, fail-safe modes are required in most situations. The failure of sensors is detectable through HMI reading, and its failure will put no impact on other part of the system. Sometimes, self-testing is even incorporated in some sensors, while it is not widely utilized due to cost consideration. *Corrective maintenance* could thus be used on control units like transducers as well as alarms. For valves, calipers and other critical control units, the failure of them normally induces the failure of certain control system. Referring to specific control system, criticality of consequence varies. In general, failure of control system is less visible and more difficult to be identified when it comes to failure, which means longer time of downtime. Oil analysis, acoustic detection, or visual inspection could be used in a combined way to reveal failures as part of *PdM* program.

5) Lubrication system

Lubrication system itself is not the kind of system, which failure will bring in total systematic failure immediately. Anyway, it is one of the most important systems to drawworks. Rotary shafts, bearing, chains and sprockets all need adequate lubrication to keep operation efficiency. As mentioned above, oil debris analysis, as part of periodic *PdM* program, could be used to reveal the property of lube oil, size and origin of debris, or overheat condition. As stated by Ehlert, lube oil sampling (collected when in use) is never a one-time event (Ehlert 2013), and should be done in a certain period with consideration of failure rate bathtub curve especially when new component/equipment is brought into use. Besides the regular on-site inspection, purification and cleaning of lubrication oil should also be developed and implemented (Ehlert 2013). For physical part of lubrication system, visual inspection is normally done periodically to ensure the functionality of, for instance, oil spray holes, oil reservoir tank integrity, etc. Beside lube oil, lubrication pump (electric motor driven) is the essential component of the whole system. It is normally designed with no redundancy. Pressure and flow rate transducers could be used to monitor the working condition or the pump. According to Cummings bridgeway's presentation on pump maintenance (Trombly 2015), for instance, preventive maintenance program could be conducted on pumps weekly, monthly, semiannually, or annually.

Table 2 Preventive maintenance on pumps (Adapted from Trombly 2015)

Weekly	Monthly	Semiannually	Annually
• Record suction/discharge gauge readings • Record elapsed time meter readings • Record amp readings if possible	• Exercise valves	• Check impeller clearance if applicable • Check oil levels in seal and motor housing	• Change oil in seal and motor housing if applicable • Test alarms for proper operation • Perform basic electrical tests

6) Supporting system

Preventive maintenance program is normally conducted on supporting system. Annual/periodical verification from third party classification society usually covers NDT on major structure/case to ensure integrity and safety besides the visual inspection by operators. Fatigue cracks or corrosion could be identified and assessed for sake of safe operation. For drawworks, the NDT test could only be done onshore due to testing equipment limitation. During the time, it is recommended that other maintenance or upgrading work could be done simultaneously.

2.2 Overview of maintenance concepts

2.2.1 Common maintenance practices

In dictionary, maintenance is defined as "the work of keeping something in proper condition". In the modern world as today, the efficient running of the society depends on the smooth operation of many complex systems. All equipment is unreliable in a sense that it degrades with ageing, and fails when it no longer has capacity to deliver required services or products (Kobbacy and D.N.P. Murthy 2008). The consequences of failure of any critical system could be dramatic. This might immediately bring in great threat on human safety, environment damage, and economic efficiency. In this sense, maintenance is introduced to ensure equipment and systems running efficiently for their designed life at least. According to Markeset (Markeset 2012), there are different aspects of maintenance, including safety-enhancing aspects of maintenance, performance enhancing aspects, economical aspects, quality enhancing aspects, environmental aspects, life span increasing aspects, and aesthetic aspects. There are mainly four kinds of maintenance programs in use, which are corrective maintenance, preventive maintenance and predictive maintenance.

Failure develops as time increases, shown in Figure 6. Different maintenance approach starts from different stage of the curve. According to NASA's, corrective maintenance still accounts for more than 55% of maintenance resources. Preventive maintenance and predictive maintenance accounts for 31% and 12% separately. Other maintenance programs account for 2% (NASA 2000).

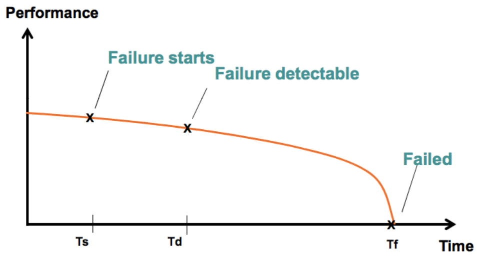

Figure 6 Failure development process (Markeset 2012)

2.2.1.1 Corrective maintenance

As years ago, corrective maintenance is adopted as the main solution to restore failed systems. The procedure is also called 'operate to failure'. Nothing is done until failure happens. This kind of failure tends to make maintenance a headache and emergency, which requires immediate investment of time, labor force and money. At that time, failure was supposed to be inevitable and was not treated as part of value creation procedure. By implementing corrective maintenance plan, no human labor or capital is invested into the project until it fails. This looks like money and labor force have been saved, while more money may be spent afterwards due to serial failure caused by the first one. Besides, unplanned downtime would be very costly. In addition of the emergency condition of such failure, more than needed labor may be involved in purpose of improving maintenance efficiency. Overtime working could barely be avoided, which in return induce more cost on labor force.

Table 3 Pros and cons of corrective maintenance (DOE 2010)

Pros	Cons
• Low cost • Less staff	• Increased cost due to unplanned downtime of equipment. • Increased labor cost, especially if overtime is needed. • Cost involved with repair or replacement of equipment. • Possible secondary equipment or process damage from • Equipment failure. • Inefficient use of staff resources.

2.2.1.2 Preventive maintenance

The program sometimes is called time-based preventive maintenance. The approach of doing maintenance has changed a lot over the past few years. In order to avoid costly corrective maintenance, some preventive maintenance approaches are developed gradually. By saying so, these maintenance activities occur before the total failure of equipment/system. With the increasing of complexity of equipment, failures may easily happen during early use due to inadequate coupling, wrong operation, insufficient lubrication and so on. As time moves on, failure rate decreases and keeps stable for a long period hopefully. As wearing becomes obvious, failure rate increases again. This could be seen in famous bathtub failure curve in

Figure 7. Preventive maintenance plan could be developed based on the indication from bathtub curve, and better safe operation of systems/ equipment could be achieved. According to NASA's report, in addition to an increased reliability as a result of using preventive maintenance program, 12% to 18% savings could be achieved compared to corrective maintenance plan (NASA 2000).

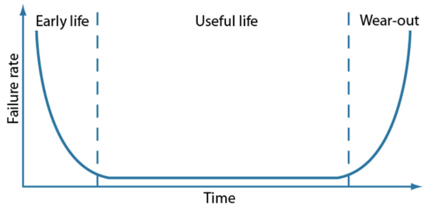

Figure 7 Bathtub failure curve

Table 4 Pros and cons of preventive maintenance (DOE 2010)

Pros	Cons
• Cost effective in many capital-intensive processes. • Flexibility allows for the adjustment of maintenance periodicity. • Increased component life cycle. • Energy savings. • Reduced equipment or process failure. • Estimated 12% to 18% cost savings over corrective maintenance program.	• Catastrophic failures still likely to occur. • Labor intensive. • Includes performance of unneeded maintenance. • Potential for incidental damage to components in conducting unneeded maintenance.

2.2.1.3 Predictive maintenance

Predictive maintenance is also called condition-based preventive maintenance. Condition monitoring, as an important part of it, is the process of monitoring the performance of a parameter (vibration, temperature, oil debris, etc.) of equipment, in order to identify a significant change, which is indicative of a developing fault. Condition could be monitored in subjective, objective or continuous way. Other than subjective observations, with the development of modern condition monitoring technique, performance could be monitored and measured in a systematical way to give indication of whole health condition of the equipment/system. With one or more indicators (according to operator's risk criteria acceptance) showing the trend of failure or deterioration of the component, maintenance need is suggested to be assessed and performed if necessary.

Some widely used condition monitoring techniques in industries include: vibration monitoring, process parameter monitoring, thermodynamic, thermography, tribology, lubrication oil analysis, and visual inspection. As development of sensor technology, conditions could be monitored through different kinds of pre-installed instrumentations or handed in places that are of interest. Real-time data will be recorded and sampled for further analysis. To design a monitoring system, the most critical aspect is to determine which parameter to monitor and how it is monitored. A typical condition-monitoring program could be implemented through following steps according to Markeset (Markeset 2012), shown in Figure 8.

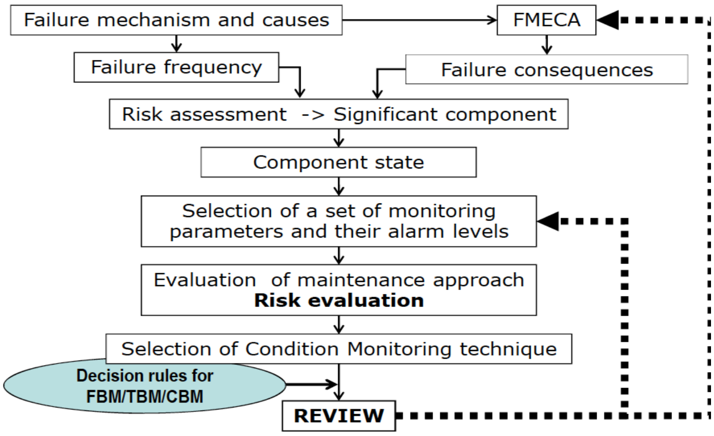

Figure 8 Condition Monitoring Methodology (Markeset 2012)

Table 5 Pros and cons of predictive maintenance (DOE 2010)

Pros	Cons
• Increased component operational life/availability. • Allows for preemptive corrective actions. • Decrease in equipment or process downtime. • Decrease in costs for parts • Improved worker and environmental safety. • Estimated 8% to 12% cost savings over preventive	• Increased investment in diagnostic equipment. • Increased investment in staff training. • Savings potential not readily seen by management.

The main objective of the predictive maintenance is to predict failures at an earlier stage so that maintenance activities could be planned to take place at a time convenient to management and to minimize unplanned interruption of the operation system. Real-time data is collected and analyzed to prioritize the maintenance resources. However, to finish such kind of work, highly skilled workers are needed in position to implement the work; more equipment is introduced into the system, which increases maintenance need of more equipment unexpectedly; and unplanned maintenance may be increased due to potential serious failure indications analyzed from condition monitoring data. This is not to say that without doing this corrective maintenance will be less costly. It is always advised to assess the value and cost efficiency before implementing predictive maintenance.

2.2.2 Reliability centered maintenance strategy

Every time a maintenance plan is put into practice, there is no differentiation of the criticality for various equipment/ components from preventive maintenance and predictive maintenance program. If preventive maintenance and predictive maintenance program should be done on every failure potential with the same weight of consequence, it will be very costly and brings unnecessary downtime of production due to maintenance activities. RCM is defined as ‘a process used to determine the maintenance requirements of any physical asset in its operating context’ (Moubray 1997). Unlike other maintenance programs, RCM does not consider different equipment to have equal importance on either the process or facility safety. By doing this, unlike preventive or predictive maintenance plan, RCM actually admits the limitation of personnel and financial resources, and the use of both needs to be prioritized and optimized. RCM relies on predictive maintenance and corrective maintenance due to need of monitoring condition and optimizing maintenance resources. Some inexpensive and unimportant equipment would be preferably left to corrective maintenance.

As stated in IEC, RCM is considered to be a method of creating an comprehensive overview of the equipment, and developing the most appropriate maintenance approach to achieve availability, reliability, safety, productivity and cost-efficiency (IEC 60300-3 2011). To gain cost-efficiency is the key challenge during execution of RCM strategy, cost and maintenance level need to be balanced properly, as shown in Figure 9 (Holme 2006).

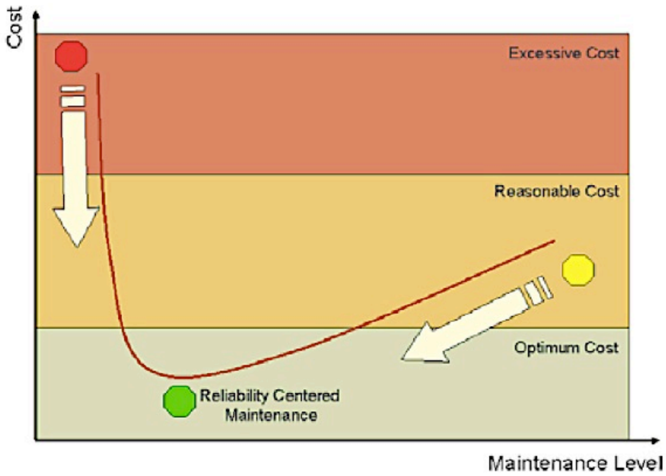

Figure 9 Operational cost on different maintenance level (Holme 2006)

The arrangement of different maintenance policies on different equipment/ components recommended by NASA is shown in Table 6 (NASA 2000):

Table 6 Reliability centered maintenance element applications (DOE 2010)

Reliability Centered Maintenance Hierarchy		
Reactive Element Applications	Preventive Element Applications	Predictive Element Applications
Small parts and equipment	Equipment subject to wear	Equipment with random failure patterns
Non-critical equipment	Consumable equipment	Critical equipment
Equipment unlikely to fail	Equipment with known failure patterns	Equipment not subject to wear
Redundant systems	Manufacturer recommendations	Systems which failure may be induced by incorrect preventive maintenance

RCM process could be arranged as shown in Figure 10. It typically follows a route of initiation and planning, functional failure analysis, and task selection according to IEC (IEC 60300-3 2011). Initiation and planning is to define the scope/ boundary of the analysis. In this phase, system function will be evaluated and criticality of consequence from single failure would be ranked. If the consequence seems to be critical, some functionality risk analysis like FMEA could be used to evaluate the severity consequence to the whole system out of single failure. With the result from the above analysis, actions could be made with consideration of both criticality and probability of occurrence. Different maintenance methods could be utilized for improving the reliability or correcting mistakes.

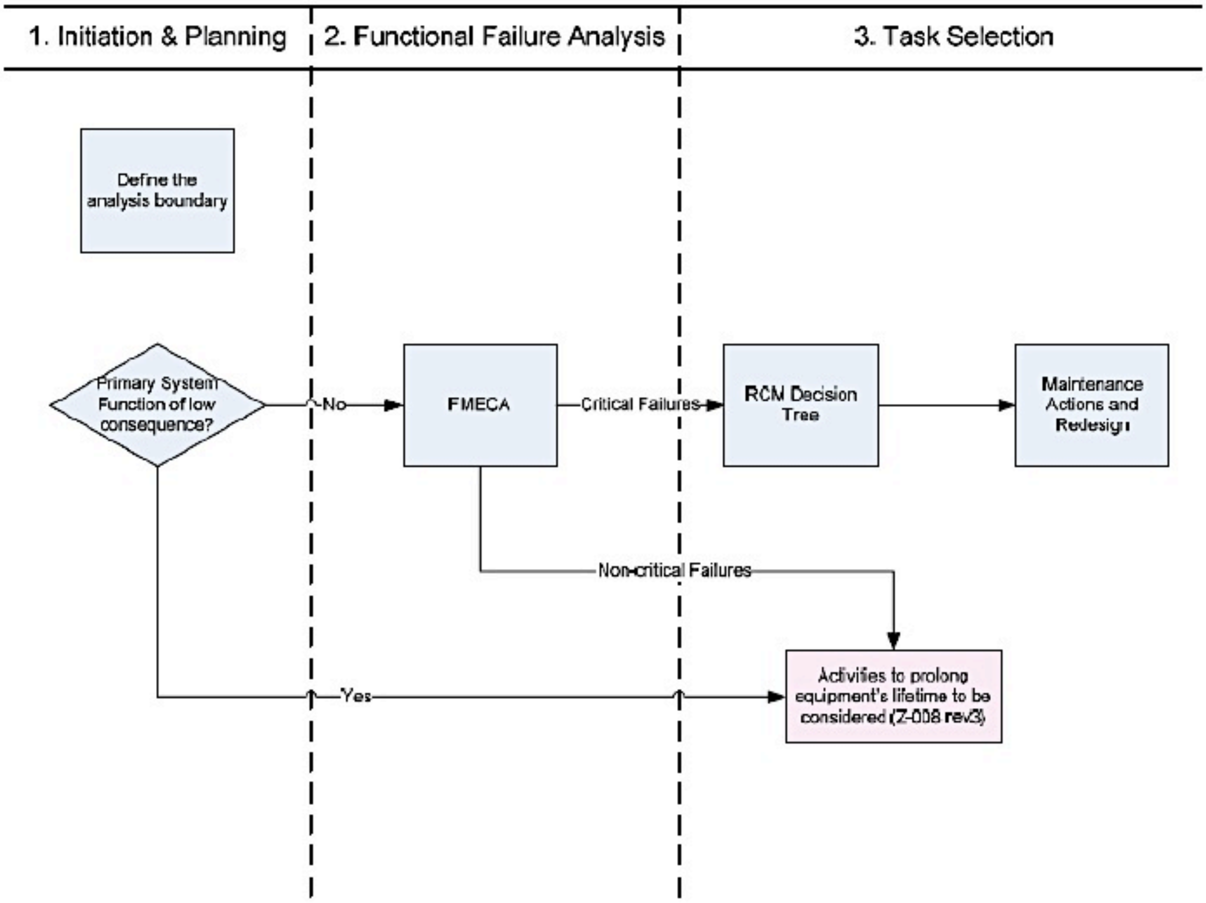

Figure 10 RCM process (IEC 60300-3 2011)

In Figure 10, the 'RCM decision tree' set the rule of selecting proper maintenance actions. By answering a serial of questions, the assessment of possible maintenance plans could be done, and proper maintenance practice could be chosen to implement. According to the definition from Alan (Alan 2010), the process is explained with more details in Figure 11.

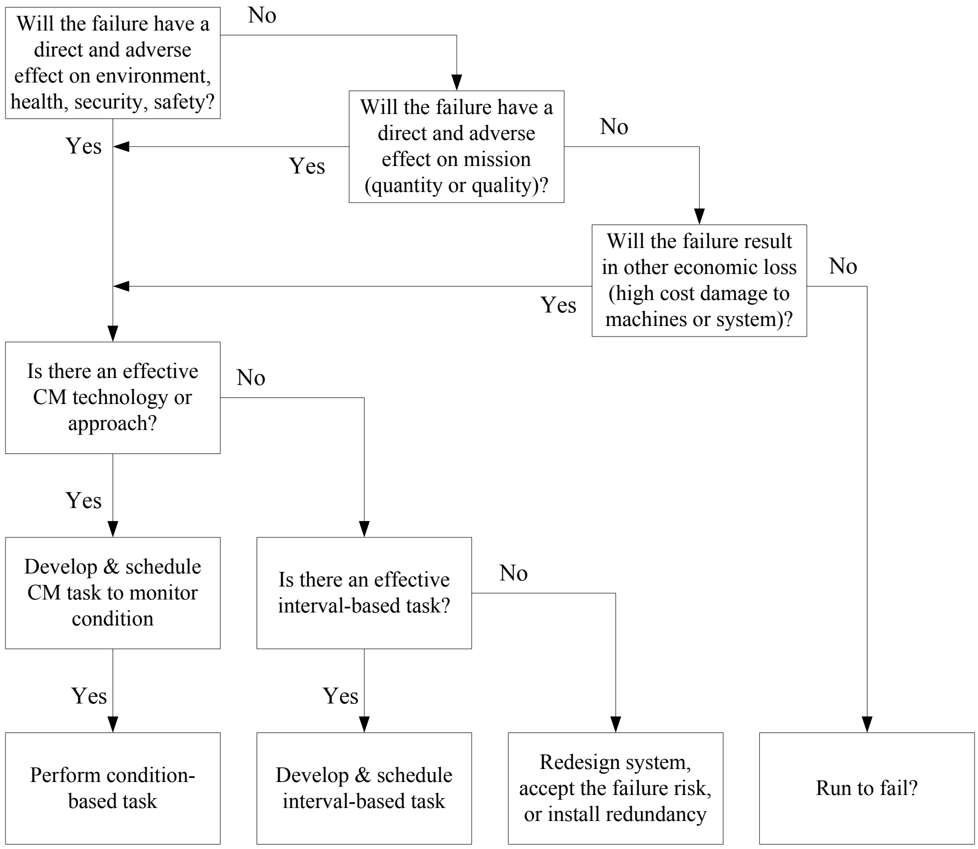

Figure 11 RCM decision tree (Alan 2010)

Reliability centered maintenance is introduced to make full use of the present resources and at the same time increase the system's reliability as well as cost efficiency. A comprehensive maintenance plan will be implemented during the production process, and it also means the competence of employees needs to be adapted accordingly to do a proper work. The pro and cons of RCM is listed in Table 7.

Table 7 Pros and cons of Reliability centered maintenance (DOE 2010)

Pros	Cons
• Increased component operational life/availability. • Allows for preemptive corrective actions. • Decrease in process downtime. • Decrease in costs for parts and labor. • Better product quality. • Improved worker/environment safety. • Improved worker morale. • Energy savings. • Estimated 8% to 12% cost savings over preventive maintenance program.	• Increased investment in diagnostic equipment. • Increased investment in staff training. • Savings potential not readily seen by management.

2.3 Hazard identification, FTA

2.3.1 Hazard identification

2.3.1.1 Main principles

Hazard is defined as the event that its occurrence could contribute or lead to unexpected event (incidents or accidents). The identification of hazards is the first step of further risk analysis, here in this thesis referring to FTA. Through systematic and unsystematic way of analyzing failure potentials, hopefully all critical hazardous conditions could be figured out and further risk analysis could be developed based on the results form hazard identification. There are many sources that contribute to hazard identification:

- Historical records;
- Regular and random safety reporting;
- Data analysis results from condition monitoring tools;
- Results from safety inspections, and operational safety audits;
- Contributes from risk analysis team;
- Information shared among all stakeholders, like operators, contractors, etc.

The sources should be as wide as possible. Any hazard that is not identified at the analysis stage will not be discussed in further assessment (NORSOK Z013). Thus different methods of identifying hazards are suggested to collaborate for full cover of possible failure modes. For O&G industry in Norway, hazards identification is normally done with cooperation of HSE staff and third party risk analysis experts with rich experience and expertise. As consultancy service is quite expensive, only the most critical systems should be selected for analysis, and they should be done with consideration of various real operation conditions. The scope of the work is important for companies to define. And hazard identification should always be done in a comprehensive and accurate way. One implementation process of hazard identification is described by Comcare, shown in Figure 12 (Comcare 1994).

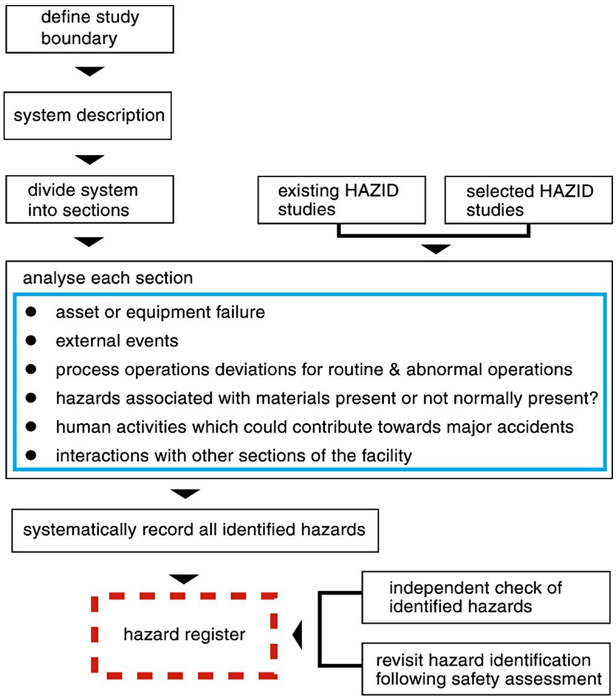

Figure 12 Hazard identification process (Comcare 1994)

In the process, despite of existing hazard identification report, history records from company and industry performance could also be valuable attributes to systematic analysis. The analysis is recommended to be done on component's level so that no major failure mode is going to be missed hopefully. There is a checklist recommended by British standards for analysts to go through (BS EN ISO17776:2002):

- Hydrocarbons
- Refined hydrocarbons
- Other flammable materials
- Explosives
- Pressure hazards
- Hazards associated with differences in height
- Objects under induced stress
- Dynamic situation hazards
- Environmental hazards
- Hot surfaces
- Hot liquid
- Cold surfaces
- Cold fluids
- Open flame
- Electricity
- Electromagnetic radiation
- Ionizing radiation — Open source
- Ionizing radiation — Closed source
- Asphyxiates
- Toxic gas
- Toxic fluid
- Toxic solid
- Corrosive substances
- Biological hazards
- Ergonomic hazards
- Psychological hazards
- Security-related hazards
- Use of natural resources
- Medical
- Noise
- Entrapment

Some requirement for hazard identification are explained by NORSOK (NORSOK Z-013 2010):

- Hazards should include all no matter they are under control of the company or not;
- Utilization of BS EN ISO 17776 (listed above) checklist, safety survey and audits, internal/ external report, and FMEA;
- The system basis for hazard identification analysis should be built up, and make sure that relevant personnel are aware of it;
- To ensure all relevant hazard be identified, disciplines scope should be carefully defined;
- The analysis should include:

a) Broad view of possible hazards and sources of accidents, and no relevant hazards should be overlooked;
b) Critical and non-critical hazards should at least be roughly classified;
c) Identification of measure to control hazard;
d) Classification of hazards relevant to emergency preparedness analysis if it is in it scope;

- The documentation of the hazard identification shall as a minimum include:
  a) Personnel attending,
  b) Method/guide words applied,
  c) Statement of the criteria used in the screening of the hazards,
  d) Documentation of the evaluations made for the classification of the non-critical hazards,
  e) Hazards that are excluded from further assessment, and the basis for this evaluation,
  f) Hazards identified with description of causes and consequences,
  g) Description of implemented safety barriers,
  h) Hazards that are to be subjected for further evaluation,
  i) Description of the system basis used in the hazard identification.

To cover as wider as possible range of possible hazards, the analysis is normally done in three dimensions of time: past, present and future (Comcare 1994, Figure 13). Past refers to historical records from both internal and external sources. This gave an extra input of what has gone wrong in the past practice inside the whole industry. WOAD, HSE database, OGP risk assessment database, etc. could be used to screen relevant hazards. Present dimension is the hazards indicated from current condition and data. The work is normally done with various risk analysis tools like HAZOP and FMEA. If changes occur in either management or technical aspects, potential hazards should be identified, which is in the scope of future dimension.

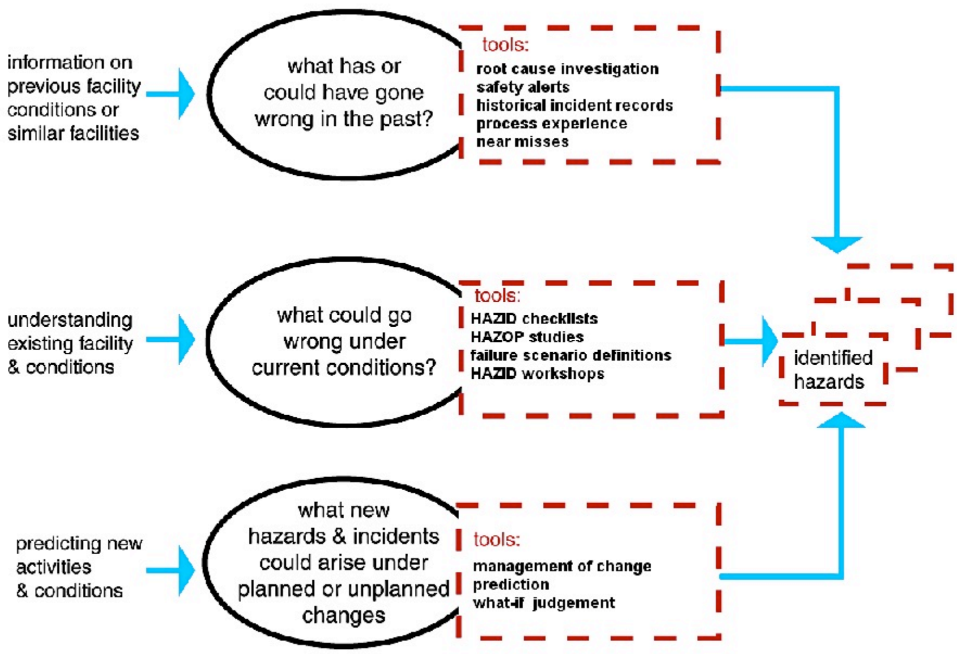

Figure 13 Past, present and future hazards (Comcare 1994)

2.3.1.2 *Failure modes, effects and criticality analysis*

Failure modes, effects and criticality analysis (FMECA) is an analysis that is designed to reveal the single failure effect and criticality to the system as a whole (Aven 2008). FMECA is a systematic functionality and reliability analysis tool, when implementing it the whole system is breakdown into components' level. The procedure of conducting FMECA were firstly defined by US Armed Forces Military in 1994 (US department of defense 1949), and then spread to other industry in 1970s. In nowadays, FMECA is widely accepted as an effective tool to identify failure modes, and it nearly a must-do for manufacturers as well as operators during design phase. Feedback from this analysis is aslo an important input for designers to make necessary modifications in the early phase of a project, in a cost-effective way.

According to IEC (IEC 60812 2006), the main objectives of FMEA include:

- Referring to each component/sub system, identification and evaluation of possible causes as well as local and general effects due to unexpected events;
- Classification of equipment with priority or criticality based on each failure mode;
- Based on predefined relevant charactistics, rank failure modes;
- Development/modification of design from the most critical failure modes;
- Mitigation measures implemented to improve maintenance strategy.

To ensure a systematic analysis of the whole system, a specific FMEA form need to be defined. There are many forms of displaying a FMECA analysis, like failure modes and effect analysis (FMEA), failure modes and maintenance analysis (FMMA), failure modes and symptoms analysis (FMSA), and etc. In the thesis, FMSA (ISO 13379 2002) is chosen as the form format due to the connection between its characteristic and CBM. Symptom is the core term in the analysis. It is defined, according to ISO (ISO 13379 2002), as a perception/measurement from visual observation or instrumentations. A FMSA table format is recommended by ISO 13379, shown in Table 8.

Table 8 FMSA table sample (ISO 13379 2002)

Failure Mode and Syptom Analysis of Drawworks																		
Item	Part No	Fuction or process	Failure mode	Effect of failure	Cause of failure	Failure syptoms	Primary technique	Frequency of monitoring	Primary MPN				Correlation Technoques	Frequency of monitoring	Correlation MPN			
									DET	SEV	DGN	PGN			DET	SEV	DGN	PGN

In this thesis, the utilization of data, and selection of data that is most critical to decision making in response with maintenance need are the main target. Due to the special needs of FMSA in this projects, some modifications to this FMSA format need to be done. And to make the conclusion clearer and easier to use, some formalized explanation/interpretation to certain columns in Table 8 will refer to items described in ISO 14224 (ISO 14224 2006). The modified table could be checked in Table 9.

Table 9 Modified FMSA table format (Adapted from ISO 13379 2002)

Failure Mode and Syptom Analysis of Drawworks													
System	Sub-system	Fuction or process	Failure syptoms	Failure mode (ISO 14224)	Failure mechanism (ISO 14224)	Cause of failure (ISO 14224)	Local failure effect	System failure effect	DET	SEV	DGN	PGN	MPN= DET* SEV* DGN* PGN

The columns in Table 9 are explained in the following:

System, subsystem: Specific component/system is identified here, and sometimes a system drawing or a functional diagram could be referred to as well;

Function or process: Brief description of the functionality of the component/system, when in normal operation state.

Failure symptoms: As described above, symptoms could be measurements from instrumentations, and perceptions during inspection/operation. It could be expressed in different forms:

- Time, e.g. delayed, slow movement, etc.
- Parameter measurements, e.g. pressure, temperature, etc.
- Type of development and degree of change, e.g. stability, 10% deviation, etc.
- Operation conditions, e.g. capacity utilization, noise, etc.

Failure modes: It displays all the possible ways that one component might fail to function as designed. This is also in scope of single failure, which means combination of failures is not included in the discussion. The failure modes are defined in this project according to the definition in ISO 14224. (Appendix E)

Failure mechanism: failure mechanism is a physical, chemical or other process, or a combination of any process that leads to the failure. Typically, according to ISO 14224, failure mechanism falls into following six failure types, and specific failure mechanism could be checked in appendix D.

- Mechanical failure;
- Material failure;
- Instrumentation failure;
- Electrical failure;
- External influence;
- Miscellaneous;

Cause of failure: identification of initial event that might lead to the unexpected consequence. There are five main categories from ISO 14224, which are: design-related causes; fabrication/installation-related causes; failures related to operation/maintenance; failures related to management; miscellaneous. Detailed causes could be checked in appendix C.

Local failure effect and system failure effect: single failure of component/system may induce a local impact on surrounding (logical and physical) component/system. Its dependency might fail as a result of its failure. Similarly, the system might be influenced in certain level of severity depending on the criticality and redundancy of the component/system. In this case, deficiencies of operation, safety threat to facility and human life, environmental pollution are the most critical consequence. And the failure modes that lead to any of these should be considered unacceptable. Detailed consequence could be checked in Table 10.

Table 10 Failure consequences classification (ISO 14224 2006)

Consequences	Category			
	Catastrophic Failure that results in death or system loss	**Severe** Severe injury, illness or major system damage (e.g. < USD 1 000 000)	**Moderate** Minor injury, illness or system damage (e.g. < USD 250 000)	**Minor** Less than minor injury, illness or system damage (e.g. < USD 50 000)
Safety	I — Loss of lives — Vital safety-critical systems inoperable	V — Serious personnel injury — Potential for loss of safety functions	IX — Injuries requiring medical treatment — Limited effect on safety functions	XIII — Injuries not requiring medical treatment — Minor effect on safety function
Environmental	II Major pollution	VI Significant pollution	X Some pollution	XIV No, or negligible, pollution
Production	III Extensive stop in production/operation	VII Production stop above acceptable limit [a]	XI Production stop below acceptable limit [a]	XV Production stop minor
Operational	IV Very high maintenance cost	VIII Maintenance cost above normal acceptable [a]	XII Maintenance cost at or below normal acceptable [a]	XVI Low maintenance cost

[a] It is necessary to define acceptable limits for each application.

Monitoring priority number (MPN): the concept is defined by ISO (ISO 13379 2002) as a value that helps to prioritize the monitoring possibility and criticality to the system. It is a balanced value with consideration of four parameters:

$$MPN=DET*SEV*DGN*PGN$$

Where,

DET: probability of detection, rating ranges from 1 (low) to 5 (high);

SEV: severity of failure, rating ranges from 1 (negligible) to 5 (severe);

DGN: diagnosis confidence, rating ranges from 1 (low) to 5 (high);

PGN: prognosis confidence, rating ranges from 1 (low) to 5 (high);

***Likert Scale:**

To determine the value of each parameter, Likert Scale (Likert 1932) model is introduced. A Likert scale is symmetric with, for example, the leftist item standing for entirely disagree, and the rightest item standing for entirely agree, and the middle point standing for neutral (Figure 14 as an example). The value a respondent gives could be either subjective or objective. Here in this case, the likert scale starts from neutral point without negative values. The values for DET, SEV, DGN, and PGN are given by the author from his own experience, literature review and the company's practice.

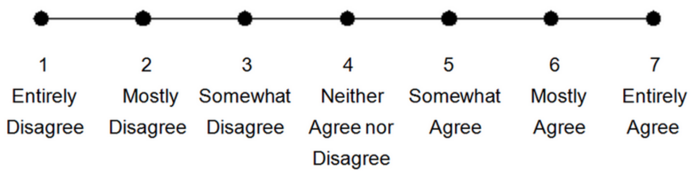

Figure 14 Likert scale as an example

2.3.2 Fault tree analysis

2.3.2.1 Description of FTA

Fault Tree Analysis (FTA) was firstly introduced in 1962 at Bell Laboratories by H.A. Watson to evaluate the one missile launch control system (Ericson 1999). FTA is a top-down deductive risk analysis tool, which is often used to find potential reasons that might lead to the 'top event'. Here the top event normally refers to an unexpected event/incident/accident. A typical FTA diagram includes a top event, logic gates (Figure 15), propagation/sub event and basic events. The logic and propagation of incident/accident occurrence is thus shown quite clearly in the FTA diagram.

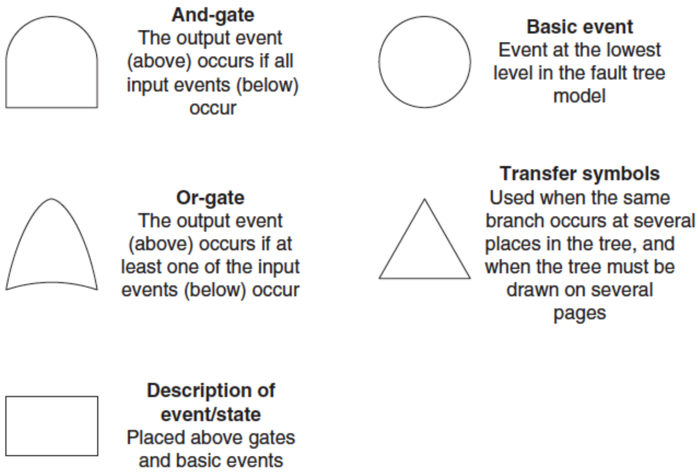

Figure 15 Logic gates symbol (Aven 2008)

Construction of a fault tree could follow below sequence (Pintelon, Frank 2006):

- System definition. For hoisting system and its subsystems, components, functions and interrelations should be identified.
- Top event selection, or failure mode definition.
- Fault tree construction starting from the top event.
- Probability assignment (will be discussed in future scope of work).

From the FMEA analysis, the most critical systems could be ranked according to MPN value. FTA will be done on these subsystems. And a FTA on overall drawworks system will then be done afterwards. FTA could be done in a qualitative and quantitative way. Probability could be assigned to each events (basic events and sub-events) according to data from OREDA. The probability of occurrence of top event could then be calculated. In this project, the work will not be done due to limited data availability and time.

2.3.2.2 Reliability analysis – Birnbaum's importance measure

According to Professor Aven (Aven 1992), quantitative analysis of FTA could be done in two aspects:

1) Occurrence probability of top event
2) Reliability importance (criticality) of the basic events of the tree.

In this thesis, a reliability analysis method will be discussed as the quantitative analysis or criticality of failure. The importance of each component (basic events, sub-events) will be calculated for indication of condition monitoring priority. The calculation will be done partly instead of overall system due to limited database in chapter 4.2 in the thesis (Birnbaum's measure). The section is made to explain the method to implement reliability analysis as an quantitative extension development from FTA analysis.

Reliability analysis provides a quantitative way to assess the criticality of single failure. Birnbaum's importance measure, as a well-known sensitivity analysis method, is chosen to calculate each component in FTA's reliability. It is quite appropriate in operation phase in oil production where each action is related to operation and maintenance parameters (Aven 1992). Due to limited reliability data, the calculation will only done in one system just to show how to make this kind of analysis.

For component i, the unreliability $q_i = \frac{MTTR}{MTTR+MTTF}$

In OREDA, all failure rates are assumed to be exponential distributed with parameter λ. MTTF is thus calculated as: $MTTF = \frac{1}{\lambda}$

For failure on the component level, the failure rate of each part of the system is not given directly by OREDA. However, percentage of total failure rate for actual maintainable items failure modes/failure mechanism could be read directly in OREDA, and total failure rate could be read form OREDA database (for electric motors, the total failure rate is 58.72 per 10^6 hours. MTTF on component/functionality level could thus be calculated. MTTR will be set equal to the average value from different failure modes.

The logic gates in FTA could be transferred into reliability diagram, referring to Figure 16. The system reliability could then be easily calculated from reliability diagram with each component's reliability available.

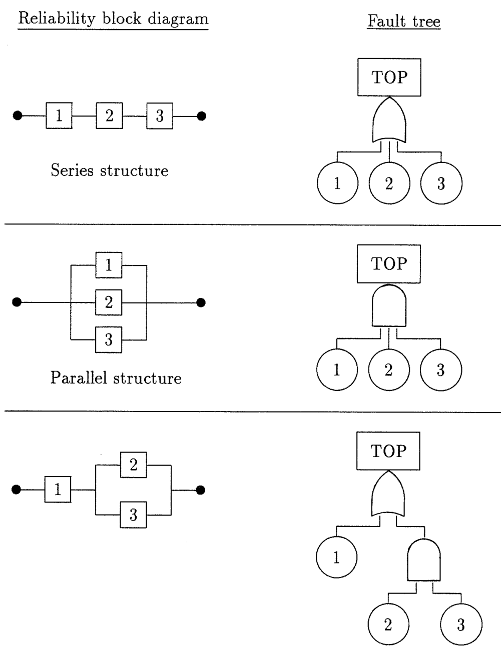

Figure 16 Connection between reliability block diagram and FT (Aven 1982)

The equation of Birnbaums's importance measure is:

$$I_i^B = h(1_i, p) - h(0_i, p) \quad (Aven\ 1992)$$

where, p is the system reliability at the time the analysis is implemented, q is the system unreliability, $h(1_i, p)$ is the reliability of the system when component number i is in its best condition, and $h(0_i, p)$ is the reliability of the system when component number is fails to function.

2.4 Technical integrity management

Technical integrity (TI) is defined as a facility's fitness-for service and compliance with regulations for HSE protection and at the same time assuring the optimum return on investment (Ratnayake 2012). The purpose of TIM is to 'reduce adverse affects caused by performance killers and cost drivers through a systematic analytical process' (Kumar, Panesar, Markeset 2009). Integrity could only be achieved with a system thinking on design, technology and operation concerning. DNV has released two standards on establishing and maintaining integrity (DNV-OS-F101 2013, DNV-RP-F116 2009). Concept, design, construction and operation are preceded in a system-thinking manner. Contributors for integration management are shown in Figure 17, according to DNV. Generally, data management, integrated work process, decision support system, and competence management together provide the basis to achieve technical integrity. The flow to achieve better return on HSE, cost efficiency and productivity is shown in Figure 18.

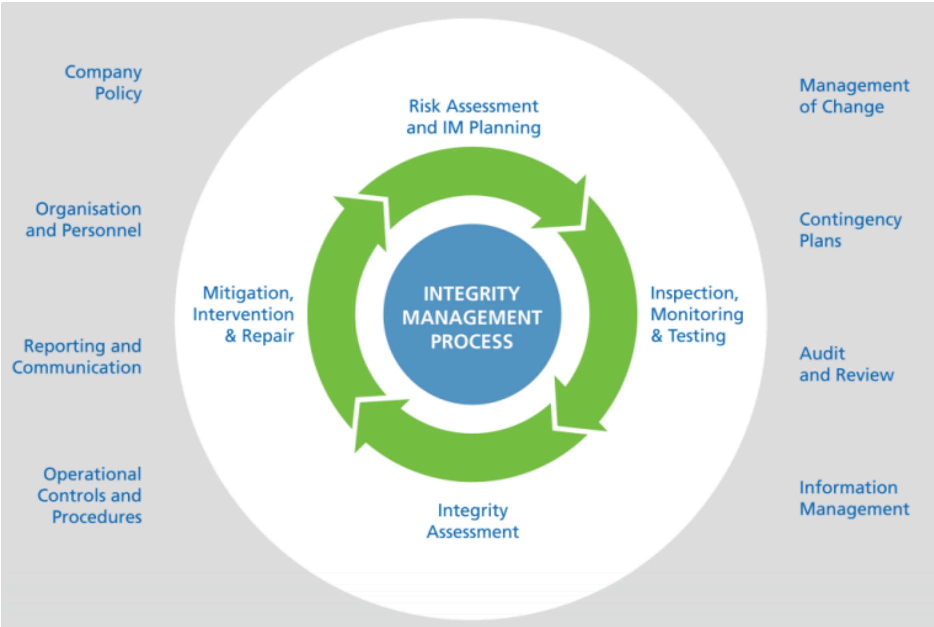

Figure 17 Integrity management (DNV-RP-F116 2009)

In today's context, O&G industry is widely experiencing a declining oil production, fiercer market competition, fluctuating prices (at present very low), aging facilities, and increased complexity of system. Like before, oil price stayed above US$100, which covered some of the problems mentioned above. Oil companies could invest more money on developing new oil fields to get more production, or increase maintenance frequency to maintain functionality. The management tended to pursue short-term profits. As the development of shale oil&gas, and over supply of O&G in the market, the present oil price could no longer support traditional way oil companies used to do. The reliability, safety and efficiency of operation and maintenance are facing great challenges. Long-term facility availability and efficiency, and reduced life-cycle-cost (LCC) are more attracting targets. Technical integrity management provides a solution to these emerging challenges. TI depends on available and qualitative data and information, managements' ability and capacity to define operational and maintenance strategies, and personnel of obtaining and applying technical, economic, social and legal knowledge to ensure that a product, process, or system meets designed/expected safety, legal, and business requirements. "Ideally, the technical integrity of a facility is achieved when, under specified operating conditions, there is no feasible risk of failure endangering safety of personnel, environment or asset value." (Officer W.S. 1991). Technical integrity management (TIM) is achieved through the implementation of the following managements.

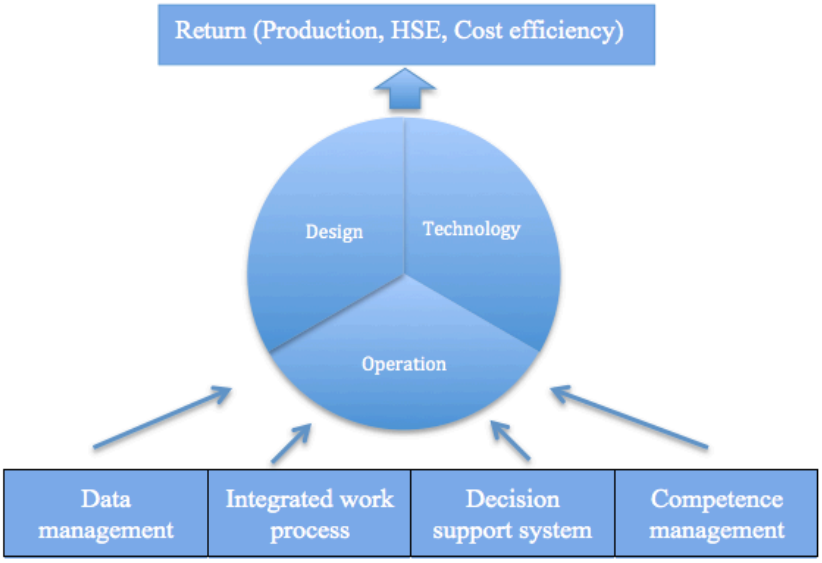

Figure 18 Integrity flow (Adapted from Liyanage 2003)

2.4.1 Data management

Data hides behind almost every operation and maintenance activities. The vibration spectrum is data. The wind speed and wave height is data. The frequency of preventive maintenance is data. Different kinds of data form a complex data structure for a facility. To collect correct data, and to assess data could add a great value on technical integrity management, which assist decision-making. Data is information, and should be flowing freely without limitation of business domains. Good management of data give the management acknowledges of what the situation they are standing in, and is the basis for making decisions and assuring technical integrity. However, data collection always needs trade-offs. The balance between cost and benefits of data is a continuously challenging task. Sometimes, accessibility of data is even impossible. For the common equipment, international standards organization give a list of what kinds of data is recommended to collect, and in what form should they be recorded and interpreted. As Soma (Soma et al. 2006) stated, a big challenge for manager is to ensure the accuracy of data, in what format should the data be recorded and transferred, and at what time the data is recorded and could be accessed.

2.4.1.1 Data categories

There are many kinds of data during the operation and maintenance activities. ISO identifies three kinds of data that needs to be collected.

a) Equipment data

To describe the equipment's function and condition, classification data, equipment attributes, and operation data could be used. Some data is required to be collected for common equipment, and for certain category of equipment specific data needs to be collected. As illustrated by ISO (ISO 14224 2006), data to all common equipment is listed in Table 11.

Table 11 Equipment data common to all equipment classes (ISO14224 2006)

Data category	Data	Taxonomic level [a]	Business category (examples)			
			Upstream (E & P)	Midstream	Downstream (refining)	Petro-chemical
Equipment attributes	Equipment class (see Annex A) (*)	6	Pump	Compressor	Heat exchanger	Heater
	Equipment Type (see Annex A) (*)	6	Centrifugal	Centrifugal	Shell and tube	Fired
	Equipment identification/ Location (e.g. tag number) (*) [b]	6	P101-A	C1001	C-21	H-1
	Equipment description (nomenclature)	6	Transfer	Main compressor	Reactor effluent	Charge heater
	Unique equipment identification number [b]	6	12345XL	10101	Cxy123	909090
	Manufacturer's name (*)	6	Johnson	Wiley	Smith	Anderson
	Manufacturer's model designation	6	Mark I	CO_2	GTI	SuperHeat A
	Design data relevant for each equipment class and subunit/component as applicable, e.g. capacity, power, speed, pressure, redundancy, relevant standard(s) (see also Annex A)	6	Equipment-specific	Equipment-specific	Equipment-specific	Equipment-specific
Operation (normal use)	Normal operating state/Mode (*)	6	Running	Active standby	Intermittent	Running
	Initial equipment commissioning date	6	2003.01.01	2003.01.01	2003.01.01	2003.01.01
	Start date of current service (*)	6	2003.02.01	2003.02.01	2003.02.01	2003.02.01
	Surveillance time, h (calculated) (*)	6	8 950	8 000	5 400	26 300
	Operational time, h (measured/calculated)	6	3 460	100	5 200	4 950
	Number of demands during the surveillance period as applicable (includes both operational and test activation) (*)	6	340	2	N.A.	N.A.
	Operating parameters as relevant for each equipment class; e.g. ambient conditions, operating power (see Annex A)	6	Equipment-specific	Equipment-specific	Equipment-specific	Equipment-specific
Additional information	Additional information in free text as applicable	6	Specify as needed	Specify as needed	Specify as needed	Specify as needed
	Source of data, e.g. P & ID, data sheet, maintenance system	6	Specify as needed	Specify as needed	Specify as needed	Specify as needed

[a] See definitions in Figure 3.

[b] The serial number is required for potential change-out at the equipment level. The tag number identifies only the physical location of equipment in the plant. If the equipment is replaced with, e.g. an overhauled unit, the tag number remains the same but the serial number changes.

(*) Indicates the minimum data that is required to be collected.

Data category	Data	Taxonomic level [a]	Business category (examples)			
			Upstream (E & P)	Midstream	Downstream (refining)	Petro-chemical
Use/ Location attributes	Industry	1	Petroleum	Natural gas	Petroleum	Petrochemical
	Business category (*)	2	E & P	Midstream	Refining	Petrochemical
	Installation category	3	Oil/gas production	Pipeline	Refinery	Petrochemical
	Installation code or name (*)	3	Delta	Beta gas line	Charlie refinery	Delta chemical
	Owner code or name	4	Smith Ltd.	Johnsen Inc.	JPL Corp.	ABC ASA
	Geographic location	3	UKCS	Europe	Mid-west USA	UK
	Plant/Unit category (*)	4	Oil/gas platform	Compressor station	Hydro-cracker	Ethylene cracker
	Plant/Unit code or name (*)	4	Alpha 1	CS 3	HH 2	EC 1
	Section/System (see Annex A) (*)	5	Oil processing	Compression	Reaction	Reaction system
	Operation category	5	Remote control	Remote control	Manned	Manned

b) Failure data

Failures that occur during operation, maintenance or other activities should be recorded in a detailed and formalized way. The description of which equipment, in what situation, the occurrence date, failure modes, failure impact, failure causes, failure detection method should be done when a failure happens. Data that needs to be recorded in common equipment is recommended by ISO in Table 12.

Table 12 Failure data (ISO 14224 2006)

Category	Data to be recorded	Description
Identification	Failure record (*)	Unique failure record identification
	Equipment identification/Location (*)	E.g. tag number (see Table 5)
Failure data	Failure date (*)	Date of failure detection (year/month/day)
	Failure mode (*)	Usually at equipment-unit level (level 6) (see B.2.6) [a]
	Failure impact on plant safety (e.g. personnel, environment, assets) [b]	Usually zero, partial or total
	Failure impact on plant operations (e.g. production, drilling, intervention) [b]	Usually zero, partial or total
	Failure impact on equipment function (*)	Effect on equipment-unit function (level 6): critical, degraded, or incipient failure [c]
	Failure mechanism	The physical, chemical or other processes which have led to a failure (see Table B.2)
	Failure cause [d]	The circumstances during design, manufacture or use which have led to a failure (see Table B.3)
	Subunit failed	Name of subunit that failed (see examples in Annex A)
	Component/Maintainable item(s) failed	Name of the failed maintainable item(s) (see Annex A)
	Detection method	How the failure was detected (see Table B.4)
	Operating condition at failure	Running, start-up, testing, idle, standby
Remarks	Additional information	Give more details, if available, on the circumstances leading to the failure: failure of redundant units, failure cause(s) etc.

[a] For some equipment categories such as subsea equipment, it is recommended to also record failure modes on taxonomic levels lower than the equipment-unit level.

[b] See example of failure consequence classification in Table B.2.

[c] For some equipment categories and applications it may be sufficient to record critical and non-critical (degraded + incipient) failures only.

[d] The failure cause and sometimes the failure mechanism are not known when the data are collected, as they commonly require a root cause analysis to be performed. Such analysis shall be performed for failures of high consequence, high repair/down time cost, or failures occurring significantly more frequent than what is considered "normal" for this equipment unit class ("worst actors").

(*) indicates the minimum data that shall be collected.

c) Maintenance data

Maintenance occurs when there is a need to correct failures, or to implement planned (normally periodically, as called preventive maintenance) maintenance activities to prevent failure's happening. Recording of maintenance activities with enough details is necessary for maintenance engineers as well as reliability engineers to implement further analysis, for example, life time analysis could be executed with failures and preventive maintenance data recordings by reliability engineers. According to ISO, corrective maintenance data is required to record, preventive maintenance is recommended to record, and planned preventive maintenance program is optional to record (ISO14224 2006). It is also important to tell, if there is any, when too much PM activities are executed on certain equipment. It will just as harmful as not enough PM (LNS Research 2015).

Data categories in maintenance part include: identification, maintenance data, maintenance resources, and maintenance time. Details could be checked in Table 13.

Table 13 Maintenance data (ISO 14224 2006)

Category	Data to be recorded	Description [a]
Identification	Maintenance record (*)	Unique maintenance identification
	Equipment identification/location (*)	e.g. tag number (see Table 5)
	Failure record (*)	Corresponding failure identification record (not relevant for preventive maintenance)
Maintenance data	Date of maintenance (*)	Date when maintenance action was undertaken or planned (start date)
	Maintenance category (*)	Main category (corrective, preventive)
	Maintenance priority	High, medium or low priority
	Interval (planned)	Calendar or operating interval (not relevant for corrective maintenance)
	Maintenance activity	Description of maintenance activity, see Annex B, Table B.5
	Maintenance impact on plant operations	Zero, partial or total
	Subunit maintained	Name of subunit maintained (see Annex A) [b] (May be omitted from preventive maintenance).
	Component/maintainable item(s) maintained	Specify the component/maintainable item(s) that were maintained (see Annex A) (May be omitted from preventive maintenance).
	Spare part location	Availability of spares (e.g. local/distant, manufacturer)
Maintenance resources	Maintenance man-hours, per discipline [c]	Maintenance man-hours per discipline (mechanical, electrical, instrument, others)
	Maintenance man-hours, total	Total maintenance man-hours
	Maintenance equipment resources [c]	e.g. intervention vessel, crane
Maintenance times	Active maintenance time [d] (*)	Time duration for active maintenance work being done on the equipment (see also definitions in Table 4)
	Down time [d] (*)	Time duration during which an item is in a down state (see also Table 4 and Figure 4)
	Maintenance delays/problems	Prolonged down time causes, e.g. logistics, weather, scaffolding, lack of spares, delay of repair crew
Remarks	Additional information	Give more details, if available, on the maintenance action and resources used

[a] Records to be entered for both corrective and preventive maintenance, except where shown.

[b] For corrective maintenance, the subunit maintained is normally identical to the one specified on the failure event report (see Table 6).

[c] For subsea equipment, the following apply:

— type of main resource(s) and number of days used, e.g. drilling rig, diving vessel, service vessel;

— type of supplementary resource(s) and number of hours used, e.g. divers, ROV/ROT, platform personnel.

[d] This information is desirable for RAM and RCM analyses. It is currently infrequently recorded in the maintenance-management systems. It is necessary to improve the reporting of this information to capture reasons for long down times.

(*) indicates the minimum data that shall be collected.

2.4.1.2 Data format

Data records should be saved in the database by certain number of attributes as ISO suggested. Codes are often used to simplify the data information. And data becomes easy to categorized and analyzed. The benefits include (ISO 14224 2006):

- Facilitation of queries and analysis of data,
- Ease of data input,
- Consistency check undertaken at input, by having predefined code lists,
- Minimization of database size and response time of queries.

Besides of the benefits from predefined codes, detailed information might be lost due to the simplicity and limitation of codes. And codes could also be difficult to be recognized/read directly by personnel. Free text is still needed to cope with predefined codes, as a simple explanation or addition to the codes.

2.4.1.3 Data structure

Data is collected and recorded into certain format. The database for storage of data is supposed to be designed with convenience of reading, upgrading, queries, and analysis (ISO 14224 2006). Data is stored inside frame of data structure, which is a structure that combines all the data categories (equipment data, failure data, maintenance data) together with logical links. It provides the basis of building the database. The logical relations help stakeholders understand each data elements' origins, requirements and impact.

Data structure includes two aspects, physical data and logical data structure. Physical data structure refers to the storage and transmission of data, like hard disk, tapes, cable lines, etc. One major concern in TI context is the compatibility of data exchange between various stakeholders. For operators in NCS, SAP is normally in process management, while Safran, for example, is often used by sub-contractors. The data exchange between the two is time consuming. For engineers, analysts, and stakeholders, they are more concerned about the logical data structure.

For hoisting system, for instance, data collected during O&M activities could be failures, corrective/preventive maintenance related. For a failure incident, the corresponding corrective maintenance activity could be related to it. Similarly, the failure might be a result of one or many failures from its lower level of components/systems. The condition of these items should be referred to in the logic structure. PM activities are similar. Improved efficiency could be calculated by reliability engineers from the data like increased mean time between failures.

Data could be organized in hierarchical structure, network structure, and relational structure (Cl500.net 2015). The above paragraph is an example of hierarchical structure (also seen in Figure 19). The difference of network data structure from hierarchical data structure is that network structure allows a node to have more than one parent. Relational data network organizes data in a two dimensional way. It describe data with two dimensions, and this also means that to build up the structure needs more elaborate work, and to look for it needs a bit more time than the other two methods. However, relational data network is becoming a very popular data structure.

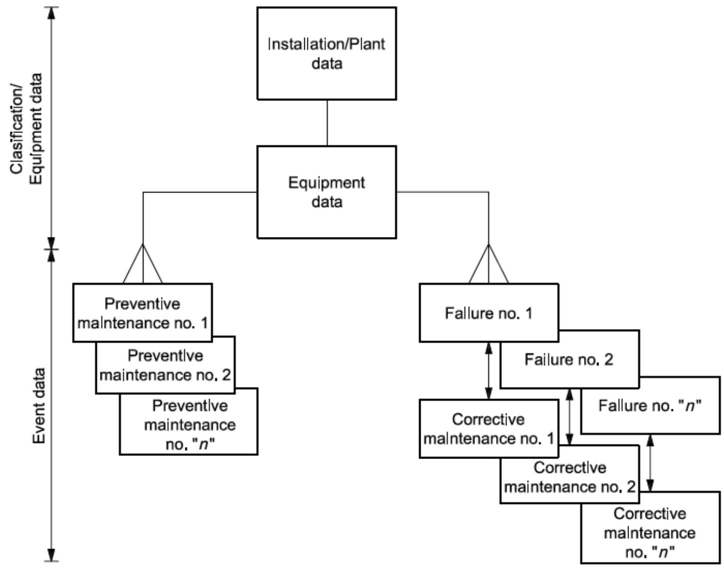

Figure 19 Hierarchical data structure as an example (ISO 14224 2006)

2.4.1.4 *Enterprise integration and interoperability*

Enterprise integration focuses on topics as system interconnection, data interchange, data exchange and distributed computing environment. It aims to provide the right information at the right time and place, and guarantees the efficiency of communication and cooperation between people, machine and computer systems (MIMOSA, Vernadat 1996). Other than information communication and sharing issue, enterprise integration is a strategic challenge, which is designed to respond to rapid changing market and technological upgrade. The enterprise integration serves the needs mentioned above through methods shown below (Nell, Kosanke 1997):

- Identify the right information. It is required that the exact information needed and created during enterprise operation is acknowledged precisely. And the knowledge of information needs to be structured so that the product and administration information, and resources involved in operation process is described clearly. The operation process could thus be optimized accordingly;
- Update information in real-time. Not only operational data needs to be updated during operation process, but also information from changes on environment, customer demands, technology revolution, new legislation, and mass attitude. The up-date of all these information helps to reflect the actual operational condition of the enterprise.
- Provide right information at the right place. This basically requires an information sharing and communication system, which is capable of handling information transaction across heterogeneous environment including separate hardware, different operating systems, different software interfaces, different departments, or even different organizations. The harmonizing characteristics enable the transferring of information across and beyond organization boundaries.
- Coordinate business processes. The modeling of enterprise operation needs to be done in a very precise way, with precise and logical business process defined, and with right information and resources in position whenever is needed. To achieve this, the real-time decision support and evaluation of decision alternatives on operation are the same essential as information sharing and communication system.

- Organize and adapt the enterprise with changing environment. Besides the information update possibility, the availability and accessibility of knowledge on enterprise operation status, market fluctuation, new technology and other environment changes. The data structure should be designed with easy identification and accessibility for relevant information.

Interoperability is a property of a system to work with other systems, present or future, with no restricted access or implementation, and the systems' interfaces should be entirely understandable (AFUL). Information during engineering, construction, commissioning and operation of production facilities is generated, collected, used and modified by many different organizations throughout a facility's lifetime. ISO set up the standard on integration of these lifetime data based on POSC study in 1997 (POSC Caesar Association), and defines the concept as "the ability of different types of computers, networks, operating systems, and applications to work together effectively, without prior communication, in order to exchange information in a useful and meaningful manner" (ISO 15926-2003). Enterprise interoperability is something that goes beyond system's compatibility, as it allows the exchange of services other than pure technique that compatibility defines. Interoperability goes below integration. Integrated system must be interoperable, while interoperable system does not need to be integrated. For interoperability, systems could function independently, while integrated system would fail if service flow is interrupted somewhere (Panetto, Molina 2007).

2.4.2 Integrated work process

Integrated operation is firstly introduced by OLF in 2005. It is defined by OLF as "real time data onshore from offshore fields and new integrated work processes" (OLF 2005). This is discussed in scope of Norwegian Continental Shelf (NCS). Integrated work process (IWP) covers all functional disciplines in O&G industry, including logistics, maintenance, well intervention, production, drilling, and modification (Yu, Liyanage, 2012).

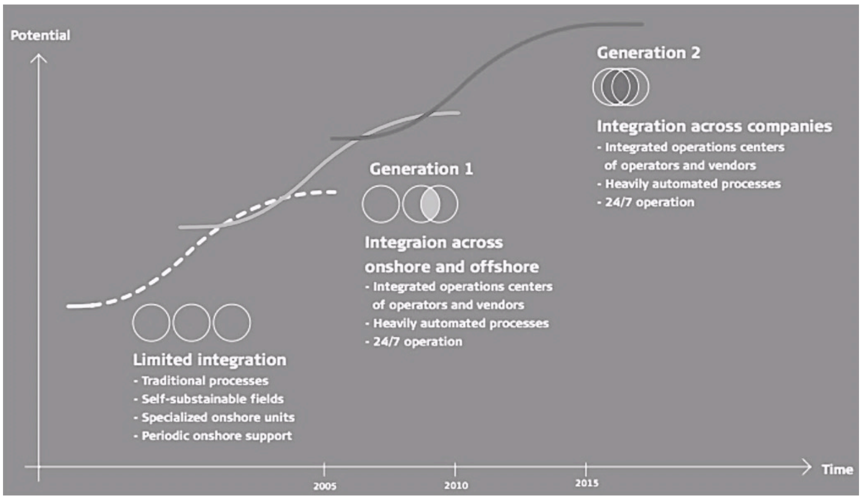

Figure 20 Integrated operation (OLF 2005)

Operation has experienced from previous limited integration of work process to fully integrated work process. In generation 1 (hereafter G1) shown in Figure 20, advanced onshore support centers are established to cope with offshore platform. This allows online and immediate communication on technical and management support. This redefines the work process for the first time. Offshore and onshore disciplines no longer work in an isolated situation. The establishment of connection between internal work processes allows the planning of work to be more flexible, and reasonable. In generation 2 (here after G2), integration extends from internal work process into wider internal and external work process. An integration of different geographical locations, production holders and vendors is executed in G2 (Yu, Liyanage 2012). This makes it possible to implement continuous monitoring of condition of facilities, and to provide onshore-based operational support with full assistance from engineers as well as vendors. Integrated planning helps to reorganize once decentralized work plans (Yu, Liyange 2012), shown in Figure 21.

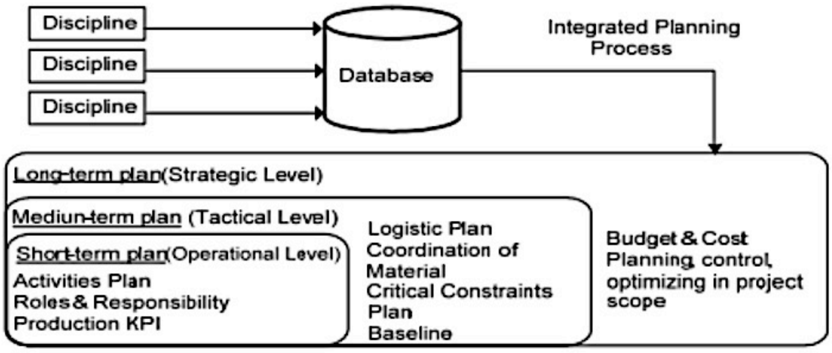

Figure 21 IP process frame (Yu, Liyanage 2012)

The design of work process in an oil company includes many aspects like production, operation, maintenance, documentation, quality management, and financial expectation. In the context of IWP, some critical parts should be taken more care of:

2.4.2.1 Communication of information and business logic

The basis for IWP is that information of operation and maintenance should be available and easy for all parties involved in the process to enhance decisions. Operating conditions should be accessible to all critical stakeholders during operation, and at the same time, feedbacks/requirements from stakeholders should be visible to operators in an efficient way. There are several kinds of communication ways of information. As Yu and Liyanage stated (Yu, Liyanage 2007), 4 major types are utilized widely as of today:

- Point-to-point: integration achieved by rewriting the transacting handling codes to make the communication of information between two applications easier.
- Database-to-database: extension of point-to-point configuration. It is an integration achieved by sharing information among databases that maintains the same kinds of data on all sources.
- Enterprise integration application: is the use of software/computer systems' architectural principles to integrate a set of enterprise computer applications. It allows the sharing of data/information as well as business logics inside the enterprise with no concern of physical distance or discipline boundaries.
- Application server integration: extension of enterprise integration application, but this allows easy and efficient communication of information and business logic.

2.4.2.2 Planning of work in context of IWP

There are several concerning during the designing of integrated work process. Work priorities need to be adequately defined, resources need to be arranged, logistic needs to be planned, and so on. The following aspects are found to be the most critical concerning in IWP planning of offshore operation and maintenance activities.

a) Accommodation plan.

Logistics between onshore and offshore is normally done by ships. The cost of renting ships is very high, and the accessibility of ships to platform needs to be qualified due to waves and weather condition. The arrange of logistic plan should be done with consideration of ship deck air, capacity of holding, accessibility of platform, accommodation space on platform, and etc. For operators in NCS, the work is normally done by SAP. SAP could help the planner to pack all requests in a time range so that the ship's space is made full use of. The work is done by SAP automatically, but it may induce problems too.

On the one hand, the loading capacity of the supply ship is limited. To make full use of its deck space might induce overweight of its loading capacity. The lifting designing engineer who works simultaneously in the project could warn logistic engineer from calculation results. The communication between two parties should be efficient and reliable. On the other hand, the limited deck space and accommodation rooms on platform are limited. Sometimes, some staff or equipment has to be sent back to onshore due to bad planning. In a word, logistics could be very costly (time and money) processes in offshore platforms.

b) Priority of work, and minimization of downtime

In maintenance context, different kinds and severity levels of maintenance notifications need to be classified and prioritized. Some maintenance could be done without breaking down the production, while some needs, some maintenance activities could be done together/simultaneously in purpose of shortening downtime, and some work need to be done before another. Through G1 (Yu, Liyanage 2012), onshore and offshore could be connected. Engineers on offshore platform could notify the maintenance needs to onshore engineers in an efficient way. Maintenance could be assessed from both offshore operators and onshore expertise. Corrective maintenance could be done combined with preventive maintenance with a tolerance of time, for example, so that the production won't be interrupted too often due to maintenance activates. This could be very challenging in traditional organizations, as all disciplines might come up with some maintenance needs. The integrated work process principle sheds a light on the communication and negotiation dilemma. Notice should be put on the perception difference on priority between offshore engineers and onshore engineers (Yu, Liyanage2007).

c) Sufficient training

With the utilization of integrated work process, the planning and implementation of work has changed a lot. Cooperation with different disciplines also shifts from isolated state to simultaneous state. Personnel need to adapt themselves to the changes. Meanwhile, training on business strategy, new communication tools, new interfaces of integrated work process, and new technologies are urgent and critical to failure rates in the early time of utilization of work process integrity.

d) Emergency preparedness

The reporting and decision making system to emergencies like weather conditions, incidents/accidents, technology difficulties or expertise absence at site need to be discussed thoroughly in the context of IWP. Notification of emergency should be done in a time critical way, and should be reported with a suggested plan from the platform engineers to onshore support centers. Depending on the criticality of incidents, necessity of further assessments needs to be discussed with several disciplines involved. Third parties would also give their advices and requirements on safety operation and risk mitigation.

2.4.3 Decision support system

2.4.3.1 Structure of a decision condition

If the scope is limited into maintenance strategy decision in context of TIM, an analytical hierarchy process could be used to set a decision-making structure (Figure 22, Ratnayake & Markeset 2010). In today's business context, sustainability has been a key factor for companies to achieve continuous success. Ratnayake and Liyanage explained about the significance of incorporating sustainability concepts to plant level operations while striking a balance between financial and HSE factors (Ratnayake & Liyanage 2007). Once there is a maintenance need, concerning on HSE and financial impact are chosen to be priorities in a hierarchical decision making practice.

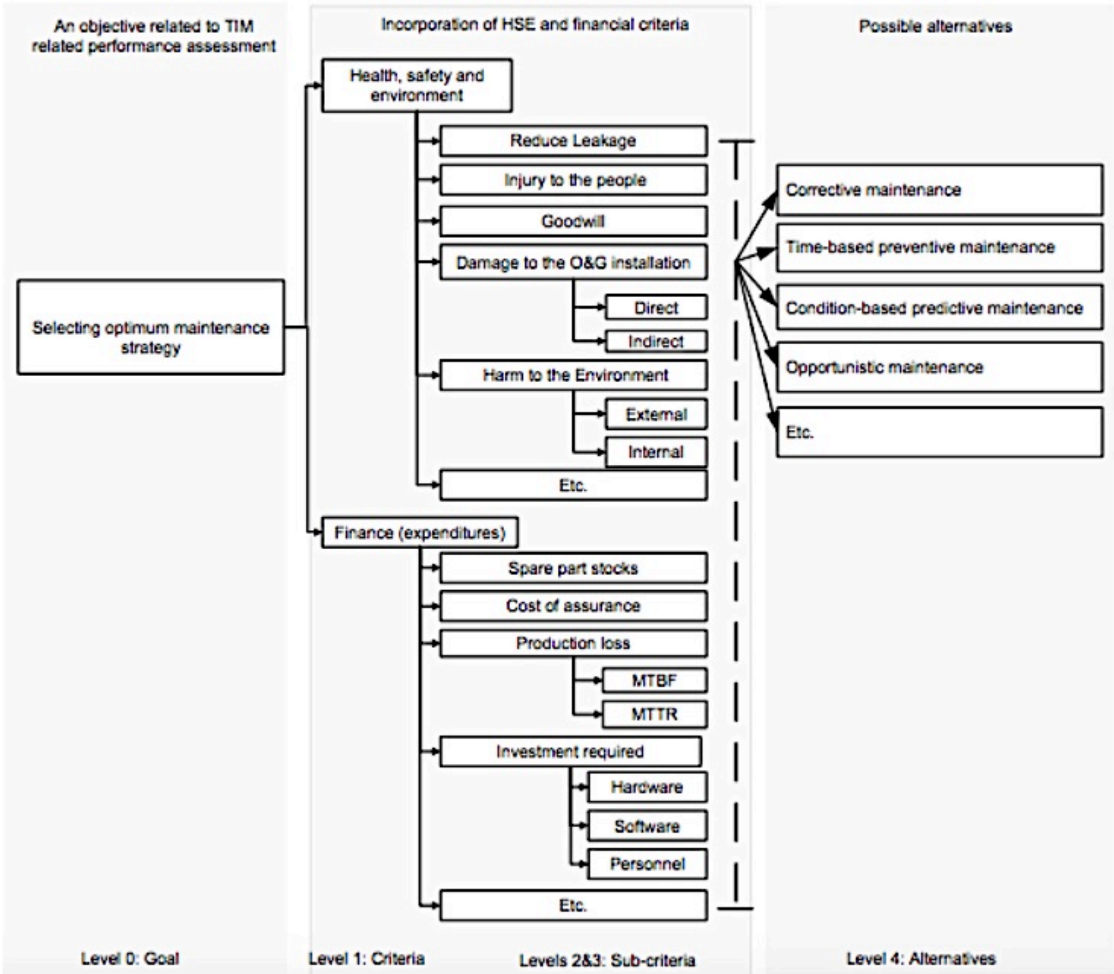

Figure 22 Model for measuring HSE performance whilst giving equal priority for financial consciousness in TI-related decision-making system (Ratnayake & Markeset 2010)

The structure is constituted of five levels. The first level is the maintenance decision objective in context of TIM. The second level is HSE and finance related decision criteria. Some sub-criteria under HSE and finance criteria are the third and fourth level. The fifth level is the possible alternatives to choose from, like corrective maintenance, or preventive maintenance strategy. The model could hopefully lead to a balanced decision with the most critical considerations in place. It could be of great help on reducing the risk of safety operation and environmental impact, and financial target management. And a reliable business image could also be built.

2.4.3.2 Decision support system (DSS)

Decisions are made in all disciplines and from both offshore and onshore. For discipline experts, decisions could be made in a reliable and efficient way with necessary data in hand. However, for many other people, assistance from either experts or machine interface is still needed. That is to say, besides the traditional decision support system, a proactive DDS is also needed in today's decision making practice on maintenance notifications.

There are several decision support system, like Bayesian Belief Network (BBN), and some other quantitative or qualitative methods. FTA could also be used as a decision support tool, as it displays the propagation of single failure and could also be combined with importance measurement to give quantitative indications. For different levels of FTA, decisions are faced by different levels of management. The importance measure of the component in FTA could also be used by decision makers.

Meantime, some proactive decision support systems are developing. Expert system (ES) was actually widely utilized from 1980s (Leondes 2002). With the increasing demand to have intelligent DSS, ES is required by decision makers to incorporate intelligent computing system that could gather and process various data. The intelligent DSS is context aware (Ohbyung et al. 2005), which was supposed that could only be finished by human brain. A ubiquitous decision support system (UbiDSS) is introduced by Ohbyung et al. "When considering a ubiDSS, however, one of the most obvious differences is that the ubiDSS acquires contextual data, as well as data from a conventional database." (Ohbyung et al. 2005), which includes knowledge-based, model management, database management, and dialogue subsystems. The contextual data could be collected from variety of trackers, like various sensors. Contextual data could be too primitive for users to read, and control inference module is needed to convert the data into an inferred context (data-to-decision interface). Then 'action request module' will transmit the contextual data to the knowledge-based system, data management system and model management system in a standard readable format. The UbiDSS frame is shown in Figure 23.

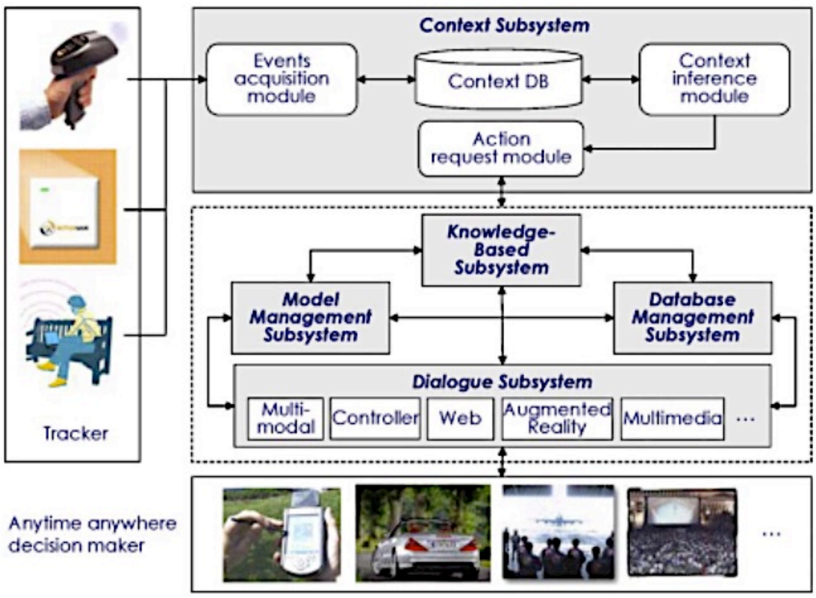

Figure 23 Frame of Ubiquitous Decision Support System (Ohbyung et al. 2005)

2.4.4 Competence management

Competence, according to HSE, means “the ability to undertake responsibilities and perform activities to a relevant standard, as necessary to ensure process safety and prevent major accidents” (HSE COMAH). Competence is a combination of knowledge, skills, experience and personal attitude/intention. And it could be classified into: transferrable, universal and unique competence (Dwarakanath 2009), including skills and knowledge, acknowledge of company culture/value, and abilities or know-how in specific area.

2.4.4.1 Competence management system

Competence management refers to the arrangements of activities within the company to implement and assure competent performance in a logical and integrated way. It means the employee should have clear image of the work expectations, and have the competence to execute tasks in an expected way with predictable achievements. Proper and continuous training is normally needed to keep competence over time, especially in context of TIM, where many new techniques and communication methods are incorporated into operation process. Like any management system, competence management system (CMS) consists planning, designing, implementing, monitoring and reviewing. HSE suggests five steps to build up a CMS, shown in Figure 24.

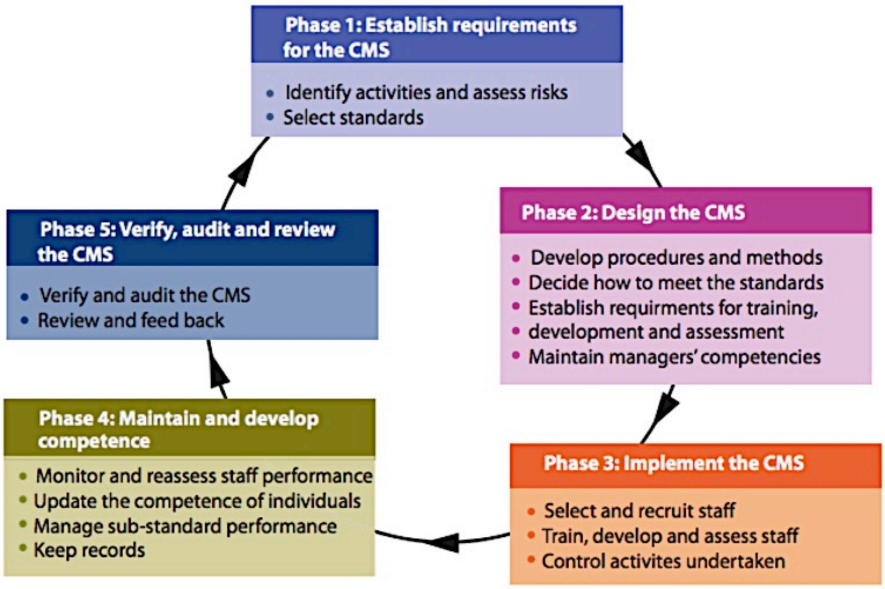

Figure 24 Competence Management System (HSE COMAH)

It is very important to define the requirements for CMS in phase 1, as it is the basis of the CMS and determines the risk potential during operation. Individuals that are currently competent to tasks may become incompetent over time. CMS is a continuous process that monitoring competence continuously, and assess and trained staff in accordance with various tasks.

2.4.4.2 Skill sets and knowledge management

Skill sets are a group of competences that are combined together to meet certain position needs. Unlike qualifications, which are formal certifications issued by proved body, skill sets combine particular category of skills and knowledge together. For different disciplines, skill sets could be technological knowledge, selling skills, strategic skills, or human relations. In the past practice, for instance, skill sets for a supply manager means the buying skills. However, the changes in business environment and increased demand from upper management extend the position's skill set into wider range, like supplier market research, cost analysis, and outsourcing decisions (Giunipero, Handfield, Eltantawy, 2006).

The skill sets in today's business context will require competence of strategic skills for engineers, and necessary technological competence for management. Not only their own business skills are needed, but also the competence to adapt to ever-changing business environment is included. Changes include the market condition, globalized operation, technological evolution, information exchange and communication system improvement, and increased demand from management. All the changes contribute the incorporating of full range of competence into skill sets. The core process for each discipline is expanded as a result. Strategic skills should be specially emphasized in this context. Many researchers support the contribution of strategic skills on organization's value growth (Anderson & Katz, 1998; Giunipero & Pearcy, 2000).

To make full use of all skills and knowledge inside organization, knowledge management (KM) is introduced. As defined by Duhon, "Knowledge management is a discipline that promotes an integrated approach to identifying, capturing, evaluating, retrieving, and sharing all of an enterprise's information assets. These assets may include databases, documents, policies, procedures, and previously un-captured expertise and experience in individual workers." (Duhon 1998) Knowledge management is consisted of four parts, according to Koenig (Koenig 2012), which are:

1) Making organization's data and information available. Data and information could be made available through the use of enterprise portals and content management system, which is normally a computer application that provides a central interface to publish, edit, modify, organize and deleting contents;
2) Lessons learned databases. This was called best practice database. As the word 'best' could vary a lot under different condition and environment, the term was changed to 'lessons learnt'. It captures and makes accessible knowledge and experience that are obtained by individuals during business operation process;
3) Expertise location. This is about the accessibility of experts who has the specific expertise or experience that is needed. The basic idea of this location system is to identify, locate and contact the person who has the knowledge on a particular area;
4) Communities of practice. The communities are groups of individuals who come together in person or virtually to share and discuss strength, weakness, opportunities, threats that organizations have, and discus lessons learnt as well as the best practical solutions.

The development of knowledge management is shown in Figure 25 (Koenig 2012) :

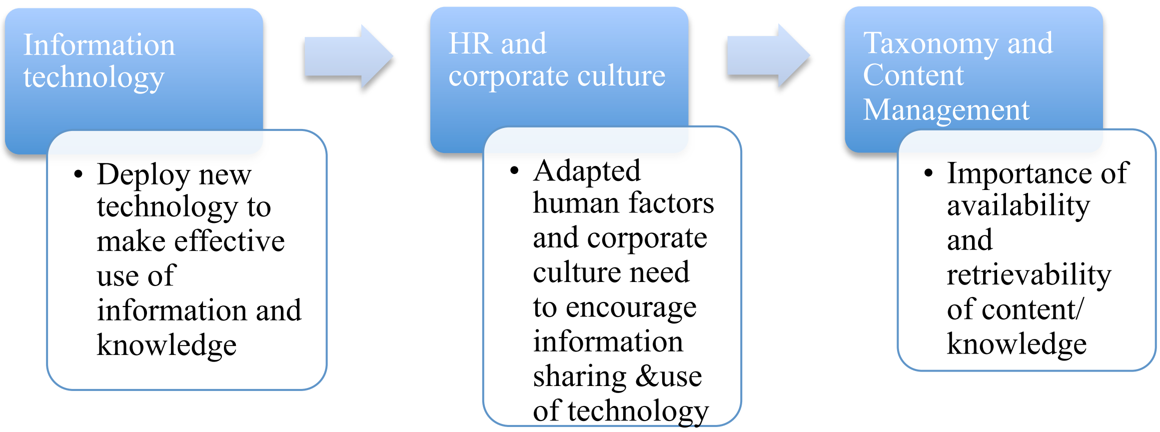

Figure 25 Development of KM (Adapted from Koenig 2012)

2.4.4.3 Interdisciplinary competence

Disciplines in traditional organizations normally have clear boundaries and function independently. As many observers argued (Klein & Newell 1997; Repko 2012;National Research Council 2004), disciplines are recognized as the fundamental for creation of knowledge. It is also reckoned as the way to show each discipline's contribution in a clear way. However, understanding of the inner socially constructed nature of disciplines, as stated by Lattuca (Lattuca 2001), will contribute to one's willingness to cross discipline boundaries and acceptance of others into one's own discipline. Interdisciplinary competence involves the combination of two or more disciplines of competence in the structure of competence management system. It achieves an integration of different disciplinary knowledge, allows the crossing of traditional discipline boundaries, and encourages system thinking.

In context of interdisciplinary competence, the focus is shifted from general knowledge of one's own discipline to knowledge of how each discipline informs its insights into the problem（Repko 2012). The knowledge of other discipline's competence and contribution could bring in a whole image of any problem. This also helps to identify the strength and weakness of separate disciplines. It allows and encourages the learning of knowledge across discipline boundaries. During the procedure, skills could be enhanced, data flow is activated, information and knowledge is exchanged, and social networks and reputation could be built as well. Singular discipline knowledge on either management or specific engineering discipline is no longer the qualified answer of reliable decision-making with consideration of complex data sets and ever changing business & technological environment. This is more important in the context of boundary-less decision-making structure, where everyone in the organization is entitled with right to make various decisions. The interdisciplinary competence could greatly improve the decision-makers' as well as team's ability of dealing with complex problems.

Part 3 Case study

According to research from Faller, the most critical equipment for offshore drilling facility are top drive, drawworks, and mud pumps (Faller, 2008). Drawworks is chosen by the author as the study object in this thesis. The case study part will cover three chapters: chapter 3, 4 and 5. Chapter 3 is aimed to identify the most critical failure modes of drawworks system. The identification will be done through three ways: company practice, literature review, and FMSA analysis. In chapter 4, FTA will be built by the author based on all critical failure modes identified from chapter 3 (as basic events of FTA). FTA is supposed to be the basis for further discussion on data management and decision making process. It provides a structure to indicate criticality and incorporate data into decision-making system. In chapter 5, recommended data architecture and maintenance decision making practice will be elaborated by the author.

3 Failure modes identification of drawworks (Case study)

This chapter is aimed to identify the most critical failure modes of drawworks system. The identification will be done through three ways: company practice, failure modes screening from literature review and technical drawwing, and FMSA analysis, where the seond method develops from structure breakdown, and FMSA is a functionaility breakdown analysis.

3.1 Study boundary

The research object is a drawwork that was installed back in 1995. It is AC motor driven drawworks with expected 2000 horse power manufactured by Dreco Energy Services Ltd. The drawworks is approved by DNV-GL. For this part, the main failure modes are identified by using three methods, which are company practice, screening from literature as well as technical drawing, and systematic FMSA analysis. In FMSA, only single failure is considered instead of combined failure modes.

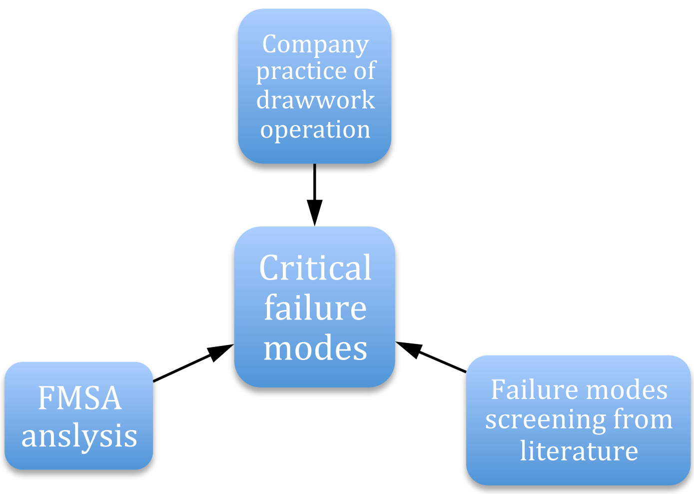

Figure 26 Failure modes identification

3.2 Company practice of drawwork operation

Drawworks is supposed to be quite reliable in most of the time from the view of the company in this case. Time based preventive maintenance and corrective maintenance are executed on the drawworks. The history maintenance data on drawworks in last ten years are shown below in Table 14:

Table 14 Maintenance actions from 2004-2014 in the company

Maintenance action	2004	2005	2006	2007	2008	2009
Preventive maintenanance	14	18	14	18	16	14
percentage	78%	95%	100%	90%	100%	82%
corrective maintenance	4	1	0	2	0	3
percentage	22%	5%	0%	10%	0%	18%

Maintenance action	2010	2011	2012	2013	2014
Preventive maintenanance	16	13	16	16	19
percentage	89%	81%	94%	84%	100%
corrective maintenance	2	3	1	3	0
percentage	11%	19%	6%	16%	0%

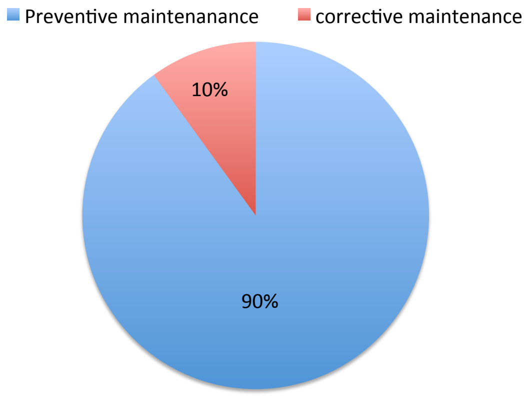

Figure 27 Pie chart of comparison between different maintenance strategies from 2004-2014

From the table above, the ratio of corrective maintenance is much lower than preventive maintenance, but unwanted failure still happens now and then. As Narayan stated in his book (Naranyan 2012), more work could be planned with a high ratio of preventive maintenance, and performance could be improved as a result. Due to different mechanisms and reliability of systems, the proportion of breakdown varies. There is no ideal ratio of preventive maintenance actions for all. For certain system, failure modes and effect analysis should be done systematically to get an expected ratio for different maintenance strategy. As is shown in Figure 27, the main concern is to minimize the risk of incidents that have serious impact on safety, environmental, adverse publicity or production, which can reduce the viability and profitability of an organization, both in the short and long term, and to do so at the lowest total cost.

Figure 28 Risk limitation model (Naranyan 2012)

If the maintenance is classified according to the causes, preventive maintenance activities refer to planned inspection and annual DNV-GL-GL inspection, and corrective maintenance includes check/ adjustment of system, unwanted failure, change of component and modification according to DNV-GL-GL suggestions. In last ten years, 19 corrective maintenance activities on drawworks were done, which is quite acceptable according to the drilling manager in the company. As a general feeling, this Dreco drawworks is very reliable.

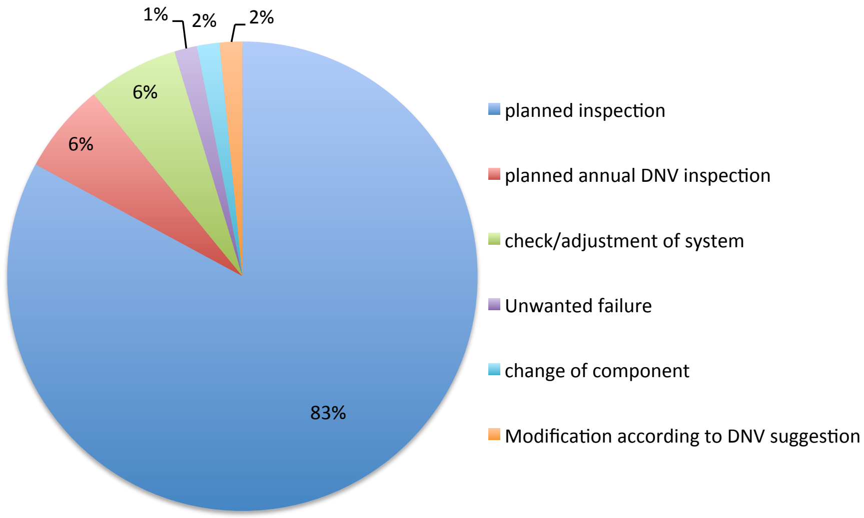

Figure 29 Pie chart of reasons of maintenance from 2004-2014 in the company

However, the company experienced one major failure that led to about 17 days downtime of the total production in 2011. The error occurred during uninstallation of drawworks as part of the five-year-period recertification of DNV-GL in 2011. Bearings were heated to be removed from drum shaft. The temperature was supposed to be at about 100-150 centigrade degree, but the heat is higher in operation and transferred to the drum shaft unexpected. The overheat caused a change in property of material, which lead to a breakage on the shaft.

Though very rarely (relatively) major accident happens, the serious accident in 2011 and the long downtime it brought in still indicate the importance of maintaining drawworks. As industry introducing new techniques on monitoring the condition of drawworks, more detailed risk analysis on the equipment will help understanding the system better.

3.3 Failure modes screening from extended literature and technical drawings

In the section, the failure modes will be identified from both literature review and real case information. The failure modes from literature review are already discussed in chapter 2.1.2. In this case, the Dreco drawworks is equipped with no cathead. Drawwork could be described with structure breakdown method as including hoisting drum shaft assembly, braking system, transmission system, control system, lubrication system, and supporting system.

1) Hoisting drum shaft assembly:

The drawing of the drum assembly could be checked in Appendix A. A metallic clanking noise may indicate a possible misalignment/ failure on drum barrel or shaft. The drum failure may display as breakage of drum barrel, buckling of drum barrel, wearing of drum shaft, and insufficient clutch of drum. Drum failure will definitely breakdown of the whole drilling system and bring in unexpected downtime.

For breakage of drum barrel/ flange, this might be a result of propagation of cracks on drum barrel, lack of routine maintenance, or over-wearing from frequent heavy hoisting. NDT is supposed to be executed on drum barrel by manufacturer and yearly by the third class qualification party (DNV-GL in this case) yearly (Dreco drawworks manual 1994), yet some cracks might still be created during operation. However, it normally needs time to propagate and there are always signals that show the imperfection of its condition, so visual inspection might be helpful in this case as a supplement. Besides, the length of the drum should be taken into serious consideration to make sure no higher than four layers of drill lines are wrapped on it, which might exert excessive spreading forces on the drum flanges (Dreco drawworks manual 1994).

Thickness of drum rim is determined after determining the inward radial force exerted by the wire line for each layer. Once the radial force is determined, horizontal components are found by vector analysis. The allowable bending stress is supposed to be 60% of the material yield strength (Dreco drawworks manual 1994). Over loading might induce buckling of drum barrel.

Wearing of drum shaft and bearing normally is quite noticeable due to the noise it brings. The problem in offshore field is that the high environmental noise may cover a bit of the clanking noise. Over-worn shaft must be replace to keep hoisting efficiency as soon as the problem is uncovered. Proximity probes and vibration transducers could thus be installed on the shaft to detect the rotating condition of the shaft, and they are quite reliable in most cases.

Lack of enough clutch of drum may cause the delayed response of hoisting, and strike of drill line and vibration followed-by. The wear of clutch might be a reason of this, and also the coupling tightness needs also to be considered.

Table 15 Critical failures and maintenance practice on drum shaft assembly

Critical failures	Recommended maintenance programs
Breakage of drum barrel/flange	Corrective maintenance
Buckling of barrel	Predictive maintenance (force transducer)
Wearing of shaft/bearing	Predictive maintenance (visual, oil analysis)
Insufficient clutch	Predictive maintenance (visual)

2) Braking system:

During the hoisting or loading of drill pipes/ casings, electric motor will work as the driving force. The holding/ parking function is activated through employing braking system. Failure of braking will cause very severe consequence on the equipment as well as human lives. This may be induced by disengagement of braking system, an excessive air gap between the drawworks brake pads and the brake rotors, disc braking system failure, or control errors. In this case, the disc braking system is designed as fail-safe device. A redundant emergency braking system is engaged automatically if power or pressure failure ever happens. The loss of the two is not acceptable from the design principle.

Braking system failure might be caused by pneumatic system failure, clearance of calipers, slow response of caliper, overheat that leads to deformation of disc, overweight of load, or control error. The failures could all decrease the friction of the braking discs and accordingly reduce the capacity of parking the loading. A leakage of air supply system might reduce the efficiency of the air-controlled braking system. Clearance of calipers needs to be checked daily according to the operation manual in the company to make sure the capacity of braking.

The requirements for the clearance have to be strictly followed by operators. The brakes are designed to be air cooled. Normally, this allows a quite high rate of energy absorption. However, in situations where braking discs are operated in high temperatures, high pressures, or high-level ratios, localized plastic deformation might occur in the discs. This will end up with uneven energy distribution on the disc and gradually lead to disc failure. Besides, wirelines need to be tested and cut periodically to make sure the strength and reliability during operation.

Human error is also an important threat of failure that should be taken into consideration. As discussed in Mr. Liyanage's article, critical systems is experiencing a process where on the one hand go through a physical miniaturization and on the other advanced functions (Liyanage 2014). At present, large and complex equipment is likely to facilitate with redundancies and 'fail safe' principle (DNV-GL 2012), which resulted in improved reliability of equipment. However, as professor Terje Aven discussed, risk could not be eliminated but should be managed (Aven 2010). Technology and maintenance management principles could not cover all human checks to eliminate risks, and normally data collected from sensors tend to be overwhelming and could be difficult to tell the trend. And data collection is a procedure of sampling which make the data we have obtained to be somehow subjective and failure signals might be hidden as a result. It is not totally because of carelessness or ignorance that make worker miss the signal to fail, but could also be a matter of opportunity (Resaon 1995). By saying so, there are two aspects to illustrate:

- Errors that are made by operators on-site and have immediate effect. This kind of incident happens at the point of contact between a front-line human and some large complex system.

  In a accident recorded by United States department of labor, braking system failure caused the fall of travelling block, which killed one driller (OSHA 2006). The redundant emergency braking system is supposed to be triggered automatically once pressure or power is lost. When the travelling block is falling without control, the main brake system failed totally as a result of deformation from accumulated braking heat. An unexpected disengagement of electric brake finally caused the tragedy. The investigation of the accident revealed that the electric brake coupling handle latch was not bolted which disengage the auxiliary brake from the drawworks. And poor manual inspection program did not work as a effective approach to help avoid this accident.

- Errors that could hide for long time and will only happen when they combine with other specific incidents' occurrences. It may originate from dependencies of redundant systems or common failure of equipment from same supplier. It could be generally said to be 'accidents waiting to happen' (Reason 1990). For instance, maintenance engineer failed to tell a component's trend to fail from a data scatter plot. As a result, the component has to be replaced and downtime of the whole system is increased long time after detection. Besides, human might be aware of risks they are facing and may reckon that everything is under control. While so many incidents that happened in history reveal sometimes they tend to be over optimistic. But human could also have sense to potential disasters. This is the reason that in present condition monitoring system, visual inspection is still an important part of monitoring plan.

  Another accident recorded by U.S. Department of the Interior Minerals Management Service (MMS) shows the severe consequence from contamination and air gap between brake pads and discs (David et al. 2000). The travelling block falls down after failure of braking system. The top drive, 19 joints of riser, and BOP fell on the seabed as a result. The cause is a mix of mechanical failure and human error. During a trimming operation of supply vessel, the driller decided to pick up the load with braking system instead of motor hoisting system, which was not the only choice but was acceptable. According to the investigation of the accident afterwards, the failure of braking system was caused by contamination between brake pads and discs from improper lubricant, and bigger air gap between brake pads and discs. The expected quality was clearly explained and required in the user operation manual. The ignorance of its severity and bad management just contributed to the failure. The accident also implied the importance of professional training. When the driller realized both braking systems failed and tried to pick up the load by motor hoisting system, there was no response. The thing was the driller or other operator did not acknowledge that the brake had to be disengaged in order to activate motor system. This definitely showed the great impact for the lack of acknowledgement of operation sequence. The redundancy of system and all the mitigation methods are helpless if human made such errors.

Table 16 Critical failures and maintenance practice on braking system

Critical failures	Recommended maintenance program
Breakage of caliper/brake discs	Preventive maintenance
Breakage of wire line	Preventive maintenance
Air gap between brake disc and band	Predictive maintenance (visual)
Human error	Corrective maintenance

3) Electric motor and power transmission system :

The drawworks is equipped with two customer furnished A.C. motors with forced air-cooling system. The hoisting/ lowering power is generated by the two motors, and they are designed to be redundant to each other. The loss of both electric motors is not acceptable to the point of risk analysis. The causes for the loss might be among: start failure, control failure, short circuiting, and earth isolation fault. For transmission system in this case, link-belt chain is used. There are three shafts, which are input shaft, jackshaft and drum shaft. The clutches are used to engage a drive or transmission chain thereby transmitting power to the drum and drill line. The selection of chain size and the width of chain, and drum clutch slip torque capacity are the main concerning during designing phase. Proper maintenance is of great need for running this chain transmission system properly. Failure of the transmission system will definitely lead to failure of the drawworks and hoisting system. This is unacceptable on risk analysis perspective. The possible failure causes are therefore listed:

- Short/open circuiting
- Motor start failure
- The chain drive is incorrectly lubricated;
- Worn/ damaged chains or sprockets;
- The sprockets are not properly aligned;

- The chain is incorrectly tensioned (requirement could be seen in Table 1);

For electric motors, reliability relies not only on robust system design, but also tolerance of harsh environment, which may bring in threat of short circuiting, earth isolation fault or bad connection of circuit joints. Things like these easily occur in environment with water, dust and unclean floor. Protection against these unexpected conditions is always a challenge for engineers who spend most of the time in clean and tidy office. Contamination in circuit board is less invisible and hard to detect. Regular inspection is required for these kind of potential failure modes. And material deterioration like breakage of motor case, hose, valve, rotor, and stator could all contribute to the malfunctioning of motor.

The link-belt chain drive needs proper and regular maintenance to deliver satisfying performance and service life. The failure of chain, sprockets, or misalignment could all cause the transmission and drawwork system to fail. As described in API specification 7F, the chain part may get cracked, broken, deformed or corroded due to long time usage in dusty and moisture environment (API 2003). Visual inspection could be an important and necessary part of maintenance strategy to discover undergoing failures. Once any of above is found, the entire chain is advised to be changed even though the other parts still look in good condition. Mistakes might be made at this point for not following the suggested replacement policy. Similar problems probably are in progress and failure may happen soon. Sprockets need also to be checked and changed if necessary when new chains are utilized in the system, or else chain wears out quickly.

Excessive noise during operation might indicate a too large chain pitch, sprockets misalignment, excessive chain slack, loose shaft mounts or insufficient lubrication. Ignorance of uncommon noise may gradually lead to failure of chain/ sprockets parts, which plays a critical role in transmission system. The loss of any of them will definitely cause failure of the whole system. Wearing of thickness of link-plate, if beyond 5% (API 2003), or wearing of sprocket tooth thickness, if beyond 10%, will lead to misalignment of sprocket. The sprockets need to be replaced immediately to avoid its impact on the whole system.

Table 17 Critical failures and maintenance practice on power transmission system

Critical failures	Recommended maintenance program
Short/open circuit	Corrective maintenance (fail safe)
Breakage of motor case/rotor/stator/chain	Corrective maintenance
Leakage of valve/hose	Predictive maintenance (visual)
Insufficient tensioning of chain	Predictive maintenance (visual)
Lube oil condition	Predictive maintenance (oil analysis)

4) Control system:

Control system includes driller's control system and drawwork control system, including hoisting and lowering operation control, braking system control and anti-collision control. Most control commands are sent from driller's control console. The control system is based on and managed with the use of PLC. All control signals are electrical signals. In this case, hoisting, braking and parking are controlled through pneumatic control system (Figure 30).

In the pneumatic control system, valves, tanks, regulators, hoses, and actuators are the normal components. Failure of components/ instrumentations, short circuit, or cooling failure could all contribute to the failure of control system. Critical consequences maybe among the following:

- Overweight on drilling bits.
- Fall/ collision of travelling block
- Damage of well due to fast hoisting speed (Mortensen 1984)

Pressured gas is stored in a tank, where pressure is usually compressed to thousands of pounds per square inch (PSI). The strength of the tank is approved by DNV-GL in this case. Regulators are used to reduce the highly pressurized gas to a more manageable pressure. It is normally installed beside the tank when there is a need of pressure drop in another part of the pneumatic control system. Hoses are used to deliver the pressurized gas. The hoses are normally reinforced with steel wires to keep them strong enough to stand up with the inner pressure. Choices of valves are also sensitive to pressurized gas. The price of valves for high-pressure usage will be usually higher. If there is a pressure difference between input and output of valve, the higher pressure will be used as a reference to the choice of valves. The stopping and starting of the flow depend on open and close operation of the fast-response valve. Valves could be operated manually or remotely using motors and electronics. With all pneumatic control components in position, actuators are as hands to human. The final actions are executed by the actuators. Actuator is normally a cylinder with a disk and a rod inside. The high-pressure gas enters into the house of the actuator, force the disk to move, and thus push the rod with which other objects could be connected to move. Different actions could be achieved by facilitating certain actuators. An accepted response of pneumatic system is a result of cooperation of all these functional components.

Loss of control of pneumatic system might lead to overweight on drilling bits, or even fall/ collision of travelling block. Many causes could lead to the failure or reduced capacity of hoisting. As described above, pressurized air is transmitted in the system. Longtime exposure to high pressure air might lead to leakage on weak points of the system, probably valve joints or hose connections. Another incident that might lead to loss of control of pneumatic system is dew formation. The compressed air is normally dried before use. However, dew formation could still happen in particular condition, which may cause faulty operations of controls (Compressed air& gas institute). When things are not solved and may become more serious and no complementary measures are executed, hoisting/braking capacity will be reduced as a result. If this happens in lowering operation, the reduced capacity to hold the drilling pipes will add overweight to the end of the drilling pipes, which is drilling bit. Although weight on the bit could be read on the instruments, the response to hoisting the drilling pipes no longer involves enough hoisting force that is needed to reduce the weight on bits as it used to be. Drilling bits will be facing with over-worn or breakage. Drilling pipes are also facing a possibility of breakage.

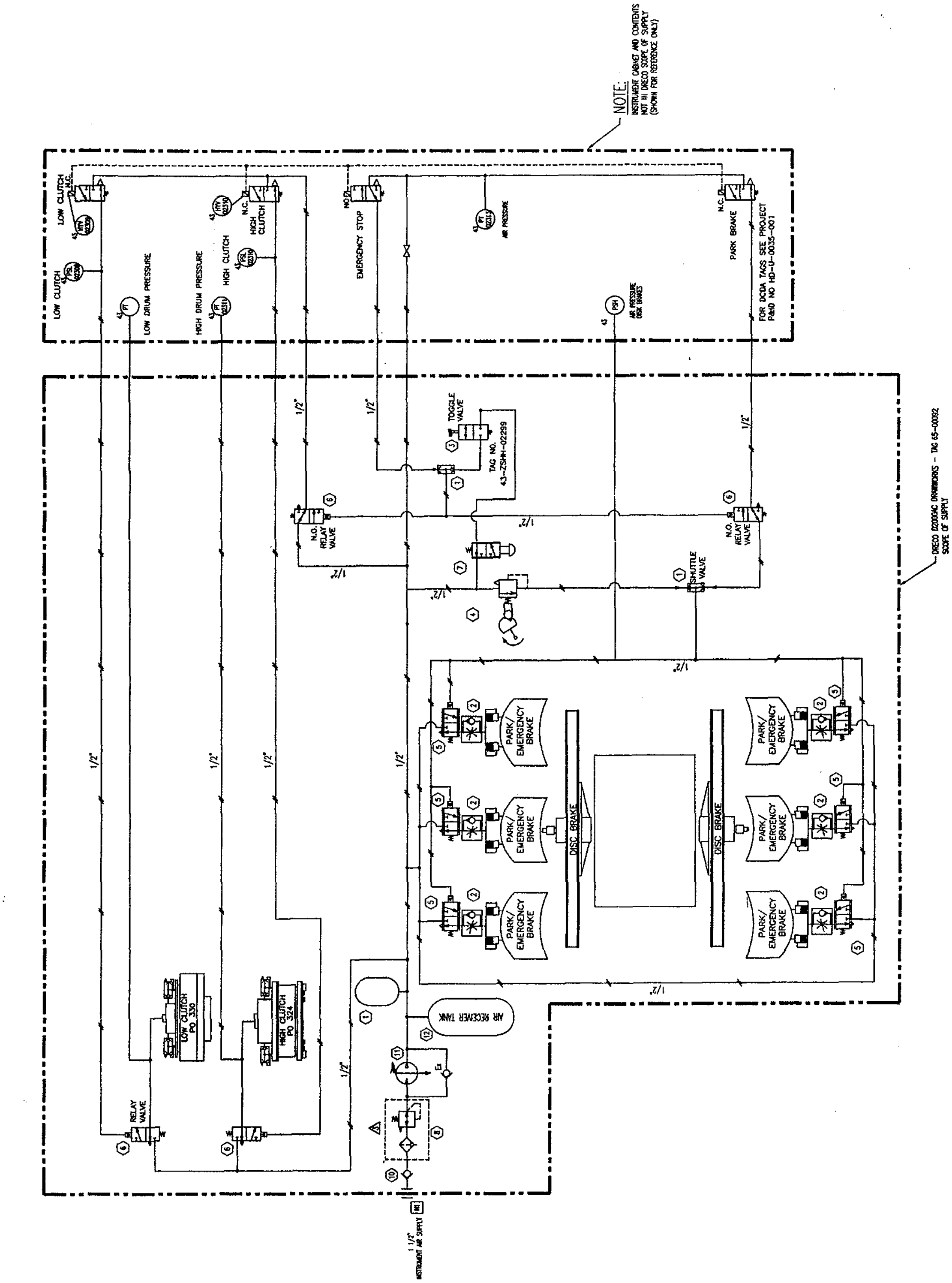

Figure 30 Pneumatic control system (Dreco 1994)

If things happen in lowering operation of BOP package to the well bore, a fall-down of travelling block might be the consequence in the worst situation. The accident of Deepwater Pathfinder occurred on Exxon Corporation's Atwater Valley Block 116 in the Gulf of Mexico could be an example of importance of control of braking system (Gorden 2000). The accident is not caused by the loss of control on pneumatic/ hydraulic system, but misunderstanding of control philosophy. The operation sequence is not totally understood by driller or other operators. The incorrect operating sequence induced the unsuccessful engagement of motor-driven hoisting system. And overheat on brake disc caused the whole braking system to fail. The catastrophic failure caused approximately 20 million USD economic losses according to MMS report (David el at 1999).

Similar failures might show up during hoisting operation. Normally automatic crown safety device is installed on drawworks drum to avoid possible collision between travelling block and the crown block. A possible device is called Crown-O-Matic. A toggle valve is installed on a track above drum of drawworks. It is actuated by another line being binded onto the drum. The drum clutch is activated when toggle valve is actuated. This will trigger the engagement of the mechanical brake. As describe in the accident occurred in Gulf of Mexico in 2008 by MMS, a travelling block stuck the crown block with Crown-O-Matic activated correctly (MMS 2008). The night driller used high/high gear to hoist drilling tool, which is not allowed according to contractor Parker Drilling's operation procedure. The night driller from Chevron did not acknowledge this due to lack of communication with the contractor Parker. Besides, the night driller is too concentrated on instrumentations and accidentally mistook the third tool joint to be the second joint. The speed of the hoisting is too large for the anti-collision device to respond. The Crown-O-Matic did activate but the time is too few to stop the TBA.

Wells with no casing protection are vulnerable to damages (Mortensen 1984). Good control of hoisting-up or lowering-down of drilling pipes in area with no casings installed is very critical. The speed should be low to avoid the damage to the vulnerable surface of the well that has not been protected by cases.

Table 18 Critical failures and maintenance practice on control system

Critical failures	Recommended maintenance program
Instruments failure	Corrective maintenance
Alarm failure	Predictive maintenance (visual)
Pneumatic system failure	Predictive maintenance (visual, pressure, acoustic)
Operation error	Corrective maintenance (competence management)
HMI system failure/update	Preventive maintenance

5) Lubrication system:

The diagram of lubrication system in this case is shown in Figure 31. The oil is pumped from oil sump to different locations of chain transmission system. Lubrication oil is transmitted through hoses, sprayed by spray bar above chain-belts with control of ball valve, and utilized in bearing and shaft contact surface. For main drum shaft, grease are used to lubricate drum shaft from grease bank.

Normally lubrication system could not bring in serious consequence as it is relatively easy to detect and takes longer time to propagate into serious accident. However, the debris in oil and leakage or system could still be a contribution to over-worn of parts. Overheat of oil, or failure of cooling system, could induce to reduced lubrication ability of oil and caused faster wearing.

In this case, there is only one lubrication oil pump and motor. The lack of redundancy might be a potential threat of shut-down of the whole system, as it is not acceptable to run the system without any lubrication. Short-circuit, high wearing in pump and leakage of pump could all contribute to unfunctionality of pump.

Table 19 Critical failures and maintenance practice on lubrication system

Critical failures	Recommended maintenance program
Loss of integrity in lubrication system (pump, oil tank, filter, hose)	Corrective maintenance
Lubrication oil property/contamination	Predictive maintenance (oil analysis)
Stuck of spray hole	Preventive maintenance
Leakage of lubrication system	Predictive maintenance (visual)

6) Supporting system:

Supporting system includes frames, case and seats. The quality is approved by DNV-GL in this case. NDT inspection is done in every 5 years to confirm the strength of all critical supporting system. There is normally no critical consequence induced by failure of supporting system.

Table 20 Critical failures and maintenance practice on supporting system

Critical failures	Recommended maintenance program
Crack/ breakage of derrick/case/seat	Preventive maintenance

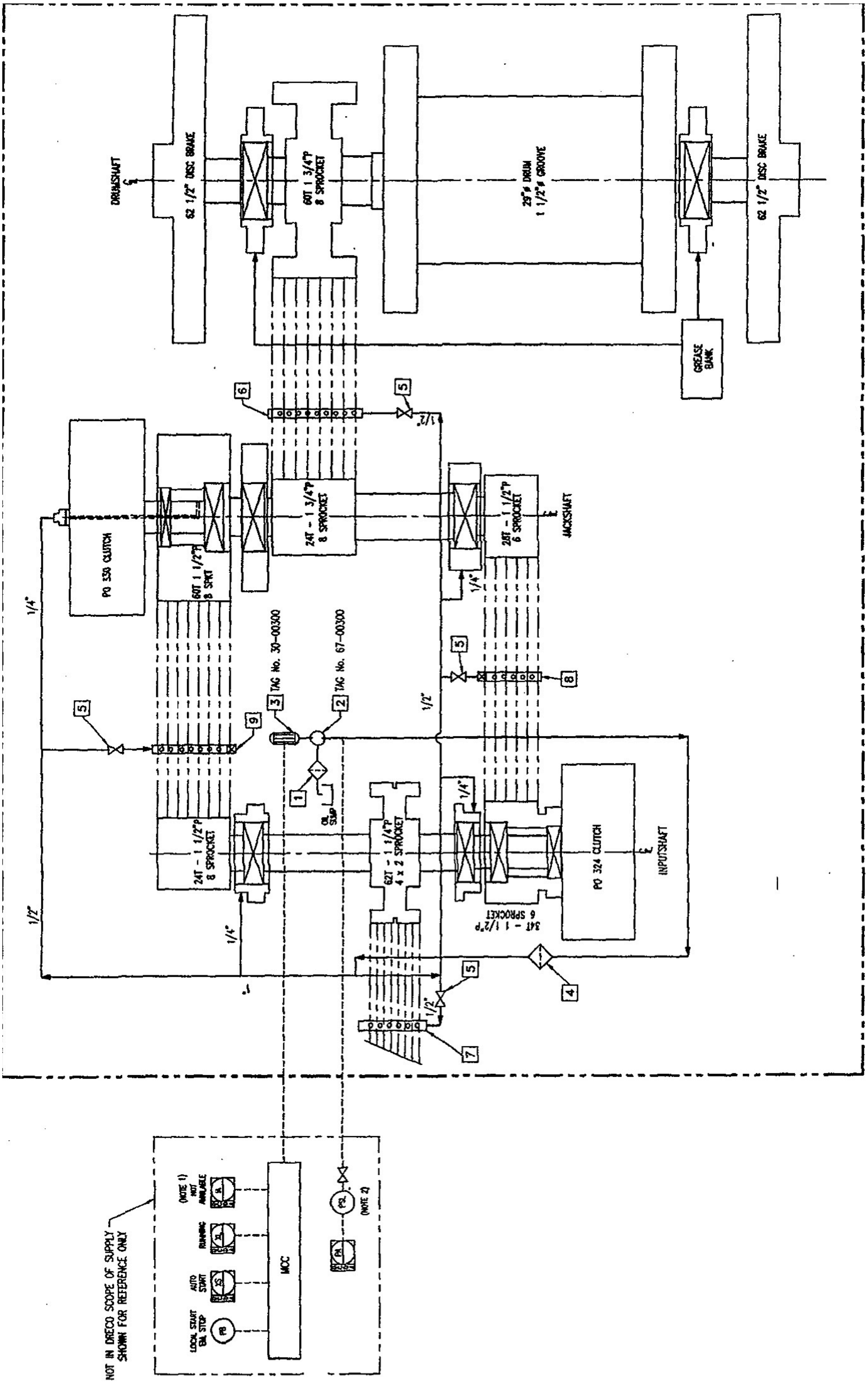

Figure 31 Lubrication schematic (Dreco 1994)

3.4 Failure mode and symptom analysis (FMSA)

To illustrate drawworks in terms of functionality breakdown, drawworks is consisted of five main subsystems (Abouamin et al. 2003): Mechanical system, Variable speed drive system (VSDS), Power management system (PMS), Driller's control system (DCS), Drawworks's control system (CS), which are shown in Figure 32:

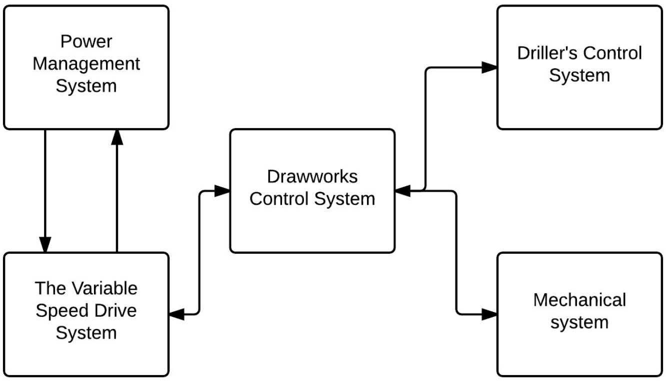

Figure 32 Block diagram of drawworks (Abouamin et al. 2003)

The FMSA table mentioned in former part of the thesis is recommended by ISO 13379 (ISO 13379, 2002), and for the better adaptation to the case, a modified FMSA table is introduced shown as below (Figure 33).

Failure Mode and Syptom Analysis of Drawworks													
System	Sub-system	Fuction or process	Failure syptoms	Failure mode (ISO 14224)	Failure mechanism (ISO 14224)	Cause of failure (ISO 14224)	Local failure effect	System failure effect	DET	SEV	DGN	PGN	MPN= DET* SEV* DGN* PGN

Figure 33 FMSA table (Adapted from ISO13379 2002)

In the FMSA analysis, failure mode, failure mechanism, and cause of failure is analyzed within the scope ISO 14224 defines (ISO 14224, 2006). Like before, consultant companies or company risk analysis department comes up with their own definition for failure modes, failure mechanism, and cause of failure. This normally ends up with complexities of analysis result. By classifying these core outputs within the ISO 14224 definition (Appendix C, D, E), a more structured outcome could be shown, and further studies from the FMSA analysis will be clearer and easier. Single failure of each component of the whole system will induce some impact on local system, and it might also have potential effect on the whole system. The shutdown of the whole system or threat to human safety is not acceptable, and should have the highest value of MPN, which equals=DET*SEV*DGN*PGN. In the research, the main outcome is to reveal the most critical failure modes (could list the ranking also if needed) by ranking the MPN value. The higher the value is, the more critical it will be for condition monitoring priorities.

For DET, SEV, DGN, and PGN, the higher the value is, a better detectability, more critical severity, easier diagnostic, and easier prognostic will be. The value all ranks from 1 to 5. The value, as stated in the chapter 2.3.1, is given by the author with consideration of literature, experience, and company practice. And the most critical system will then be identified from the ranking of the value of MPN.

The full FMSA table could be checked in Appendix B.

3.4.1 Mechanical system

Mechanical system includes the supporting system, drum assembly, clutch assembly, transmission system, pneumatic system, lubrication system and mechanical brake assembly. Mechanical system is the basis for the whole system. Ignorance of mechanical failure might lead to essential systematic failure. The most critical single failure modes could be drawn out from FMSA analysis. The most critical failure modes are listed below according to MPN value from FMSA:

Table 21 Critical failure symptoms for mechanical system

Component/ sub-system	Failure symptoms	MPN	Component/ sub-system	Failure symptoms	MPN
Drum	Fast wearing of brake discs	320	Main shafts	Overheat	240
Drum	Breakage of wireline	320	Pneumatic system	Calipers do not respond	240
Drum	Brake power is not enough	320	Pneumatic system	Pressurized air tank failure	240
Pneumatic system	Brake funcions improperly	320	Pneumatic system	Wrong indication	240
Mechanical brake components	Breakage	320	Pneumatic system	Leakage in closed space	240
Lubrication system	No rise in pressure	320	Pneumatic system	No response to control signal	240
Pneumatic system	Internal dew formation in pneumatic system	256	Mechanical brake components	Big gap between brakes discs and bands	240
Drum	Breakage/ buckling of drum barrel	240	Mechanical brake components	Overheat	240

The derrick tower gives the support of travelling block and crown block. The deformation of tower will definitely lead to failure of hoisting system. The whole operation will have to be stopped due to serious lack of integrity. This might be a result of fatigue, corrosion, or overweight during hoisting. Failure of drum assembly, in form of drum barrel breakage/ buckling, shaft breakage/ buckling, or wire line breakage, will lead to the failure of drawworks. This will force the operation to be shut down.

For pneumatic system, internal dew might form due to circumstance temperature change or overload. The dew will have a bad impact on electronics, valves and other components in the air transmission channel, which will lead to the decreased performance or total failure of pneumatic system. The response time of clutching or braking might be influenced or lost. This will directly reduce the operation efficiency of hoisting operation. If the pneumatic system fails totally, that will trigger the utilization of emergency braking system. Unexpected stop of operation will come along, which induces longer down time and great economic loss. The unexpected stop from pneumatic system could also be from the failure of serious leakage in hoses/ valves. Besides, breakage/ serious leakage of pressurized air tank will cause the depressurization of the whole pneumatic system, which will lead to the engagement of emergency braking system. This will lead to unexpected stop of operation too.

For mechanical brake components, serious wearing of brakes, too big air gap between brake disc and band, or breakage of brake disc will lead to the failure of braking system. As emergency braking system uses the same brake discs as parking service braking system does, the failure of mechanical brake components will lead to the drop of load, which will bring great threat to human safety, structure damage and environment issues.

3.4.2 Variable speed drive system

Variable speed drive system includes converter, power units, cooling system, and operator interface. If converter fails to convert the frequency/voltage as needed, the unstable input of electric motor will lead to decreased efficiency of operation. Short/ open circuit, or failure of electronics might lead to failure of converter, the lack of power input of motor will direct lead to engagement of emergency braking system as its failsafe philosophy defines. This will bring in unexpected stop of operation.

Table 22 Critical failure symptoms for speed drive system

Component/ sub-system	Failure symptoms	MPN	Component/ sub-system	Failure symptoms	MPN
Converter	Fail to start	240	Converter	Failure to convert frequency and voltage as needed	192
Operator interface	Loss of critical signals sent to and from the VSDS	240	Power unit	Unstable power flow	192

3.4.3 Power management system

Power management system includes driving motors and other electrical components. There are two electric motors and each of them is capable of providing enough driving power to hoisting. The two motors design offers the redundancy and therefore robustness and reliability. Failure of one motor will have no impact on the system as a whole, as redundant motor could still work to provide driving power. Due to wearing, inadequate clearance, or unstable voltage input, the motor might output unstable driving force. This might threat the safety and efficiency of hoisting/ lowering operation.

Table 23 Critical failure symptoms for power management system

Component/ sub-system	Failure symptoms	MPN	Component/ sub-system	Failure symptoms	MPN
Driving motors (with redundancy)	Unstable power output	320	Driving motors (with redundancy)	No power/ voltage	192
Driving motors (with redundancy)	Failure of one motor	192	Driving motors (with redundancy)	Faulty power/ voltage	192
Driving motors (with redundancy)	High reading from temperature instrument	192			

3.4.4 Driller’s control system

Driller’s control system includes operator’s control chair, multi-tool control cabinet, and operator workstations. The interactions between human and machine could be achieved through joystick and control cabinet. Failure of joystick will not have influence on the whole system due to redundancy. Fail to respond on command is in scope of control failure, and this might be induced by short/ open circuit, or instrument failure. This will threat the safety of hoisting/ lowering operation, and drop of load might happen in the worst case. Besides, as the system is mainly human-machine interaction, operation error (management error) could be an input to the delayed operation. Critical signals/ alarms might be missed due to carelessness or limited attention. This could be very severe at the time of emergency. Absence of response might induce collision of travelling block or drop of load in the worst situation.

Table 24 Critical failure symptoms for driller’s control system

Component/ sub-system	Failure symptoms	MPN
Multi-Tool Control Cabinet	Failure to response on command	320
Multi-Tool Control Cabinet	Loss of critical signals sent to and from driller's control system	240
Multi-Tool Control Cabinet	No signal	240

3.4.5 Drawworks control system

Drawworks control system includes critical sensors, alarms, main drawworks control system (PLC), and emergency stop system. Failure of any critical sensor, in form of lack of adjustment or faulty indication, might threat the hoisting/ lowering safety.

Table 25 Critical failure symptoms for drawwork control system

Component/ sub-system	Failure symptoms	MPN	Component/ sub-system	Failure symptoms	MPN
Main drawworks control system	Switch failure	320	Main drawworks control system	Loss of critical signals sent to and from driller's control system	240
Main drawworks control system	Failure to response on command	320	Main drawworks control system	No signal	240
Critical sensors	Abnormal reading from sensors	240	Emergency stop	Failure of braking	240
Alarms	False alarm	240	Emergency stop	Failure of braking	225
Alarms	Travelling block position reference failure	240			

For alarms, the anti-collision alarm's failure will put the operator's visual confirmation to be final safe guard against collision. This will put great threat on the safety of facility. Similarly, spurious high/ low alarm level could also be an input to decreased reliability/ safety. If the alarm level is too high, the alarm will come along at a far more dangerous condition. The facility and human lives are already put in danger for a while. If the alarm level is too low, this will just induce more downtime due to fake alarms.

For main drawworks control system, Fail to respond on command is in scope of control failure, and this might be induced by short/ open circuit, or instrument failure. This will threat the safety of hoisting/ lowering operation, and drop of load might happen in the worst case. Critical signals/ alarms might be missed due to carelessness or limited attention. This could be very severe at the time of emergency. Absence of response might induce collision of travelling block or drop of load in the worst situation.

For emergency stop design part, the failure of brake discs, in form of serious wearing, breakage of brake disc, or too big clearance between brake disc and band, will cause the failure of emergency stop. The emergency stop control is actually mechanical triggered with the setting of releasing spring when pressure/ power is off. The failure of spring will cause the failure of emergency stop function. The consequence will be the drop of load, great threat to human safety and huge economic loss.

4 Fault tree analysis on critical failure modes of Drawworks (case study)

In this chapter, FTA will be built by the author based on all critical failure modes identified from chapter 3 (as basic events of FTA). FTA is the core basis for further discussion on data management and decision making process on maintenance notificaitons. It is recommended by the author to work as one of the referece to check consequence criticaility on potential failures, and FTA contributes to data management in decision-making procedure.

4.1 Principles of building FTA models in this case

The company is trying to build a data architecture that combines condition-monitoring data and at the same time optimize decision support system. Fault tree analysis is a proper risk analysis tool to achieve the goal. As describe earlier in chapter 2, the top-down structure of FTA and its failure cause analysis nature fit well to the main purpose of the research. The decision structures could also be interpreted through data and decision-making management related to different levels of FTA.

FTA starts from the critical failure modes analyzed from hazard identification in chapter 3. The occurrence of different basic events might lead to sub-system failure, and this might propagate to more serious failure of higher level of system. From the FMSA analysis in chapter 3, it is recognizable that which system is critical for FTA analysis through the average value of MPN. For the FMSA table in Appendix B, pneumatic system and electric motors (power management system) are read as the most critical system in the drawworks system. And in the end, an overall fault tree analysis will be done to reveal the main concerns that might lead to operation shutdown or serious safety issues.

4.2 FTA on critical systems

The definition of critical systems is those systems, where failures will have the greatest impact on the whole system. Here in this thesis, systems with the highest MPN value read from FMSA table are the most critical systems. As the purpose in thesis is to define critical data sources to assist decision-making from condition monitoring technologies, only measurable factors will be included here in this part. That is to say, mechanical parts instead of management parts are the targets of FTA analysis. Critical control/management system will still be discussed, but no in form of FTA. According to FMSA table in Appendix B, pneumatic system, electric motors, drum assembly and frequency converter are classified as the most critical measurable system (shown in Table 26), where frequency converter determines the frequency and voltage of input power to electric motors and thus will be analyzed together. And critical control systems are discussed along with critical mechanical system (here refers to pneumatic system, and electric motors). For some critical component like drum with average MPN value at 267, will be discussed along with FTA for overall drawworks.

Fault tree analysis in this project will be implemented on component/sub-system level. Further failure mechanism on part level of each sub-system will not be discussed further, as no condition monitoring technique is going to be implemented on such detailed component, and failure statistics in OREDA does not cover so many details. For example, only failure of stator instead of its failure causes will be discussed.

Table 26 Selection of the most critical systems

System	Pneumatic system	Electric motors	Drum	Frequency converter
MPN	202	187	267	204

4.2.1 Pneumatic system of drawworks

The diagram of pneumatic system could be checked in Appendix A. Pneumatic system in this case works as the drive to engage clutch and braking system. Failure of pneumatic system may display mainly as three modes: fail to start clutch, fail to start brake, and unexpected braking. The reason could generally be categorized as mechanical failure and control failure.

Fail of pneumatic system might induce the failure to start clutch. It might be the total failure to engage low/high clutch or slow response to control command. Basic events that might induce the mechanical failure in this scenario include clutch breakage, air tank failure, air hose breakage, valve failure, and regulator failure. The occurrence of these basic events breaks the consistence of power transmission chain inside the pneumatic system. Fail to engage braking system is similar situation while emergent braking system is designed to be engaged once parking service system fails. The simultaneous failure of all redundant braking system might happen due to failure from pneumatic system. For emergent braking system, the loss of pressure inside pneumatic system will trigger the engagement of emergent braking through a spring. The occurrence of these two events at the same time will induce the failure of braking.

For control system failure of pneumatic system, instruments, signal transmission, airflow rate, pressure control and power input could all prompt failure of pneumatic system. Internal dew formation is a great threat for pneumatic driven system. It could be the cause for many kinds of failures, like component corrosion, reduced inner pressure, vibration, and delayed response. As pressure and temperature are critical aspects in pneumatic system, failures from these instruments will put great threat on safe and reliable operation of pneumatic system as well as the whole drilling operation.

FTA for pneumatic system is shown in Figure 34.

4.2.2 FTA of Electric motors for drawworks

Power generation system for drawworks in this case is designed with redundancy. Either of the two motors could provide enough driving force for the operation. The loss of both two motors will end up failure of electric motors system. Failures on electric motor may display as no power output, and unstable power output.

No power output could be induced by either spurious stop, or failure to start. The causes include material degradation, leakage, power input, and control failure. Material degradation on case, stator, coupling, rotor will end up with loss of integrity of motor. The degradation maybe too serious for the actuator to engage the motor properly. Unstable power output might be induced as a result of misalignment of rotating component. And lubrication oil property might accelerate wearing on the rotating part of motor, which will worsen the situation. Electric circuit induced connection looseness, short circuit, and open circuit might cause failure on motors too. Besides, converter error, operation error and other human factors might be hidden causes for spurious stop of motor. Detailed FTA analysis on electric motors is shown in Figure 35.

4.2.3 FTA for overall drawworks system

Fault tree for overall drawworks is established based on the most critical failure modes identified from chapter 3. The top event for drawworks failure is here defined as loss of production. It could be induced by loss of redundant of safety, reduced efficiency, or loss of integrity. And different failures on lower level of system might have potential to propagate to system failure.

Loss of redundancy of safety means the system will face immediate threat without safety redundancies. When drawworks is implementing hoisting or lowering work, or the load is dropping unexpected, there is a need to engage the braking system for control of speed or position. Loss of braking system together with loss of hoisting/lowering control, will introduce great threat on safety of installing as well as human life. Firstly, fail to engage braking system might be a result from mechanical failure and control failure. Large air gap between brake band and disc, and breakage of disc, drum flange, caliper might contribute to braking system's failure. Pneumatic system, as discussed above, is another main contributor for braking system failure. Besides, control failure from operation error, signal transmission, instrument failure, and alarm failure have chances to induce braking failure. Secondly, loss of control of hoisting/lowering might be a result of motors driving system failure, mechanical failure, or control failure. The motors and pneumatic failure propagation could be referred to chapter 4.2.1 and 4.2.2. Other mechanical failures might induce failure of control of hoisting/lowering, like chain transmission system failure, wire line breakage, drum failure, and clutch failure.

Loss of operation efficiency might be a result from electric failure, unexpected engagement of braking, or decreased efficiency of transmission system. For sake of safety guarantee, emergent braking system is designed to be engaged automatically at the loss of power/pressure. However, production is halted no matter it is triggered for safety protection or operation/control error. The propagation process for this scenario could be found in FTA for pneumatic system (P2 branch of FTA). What's more, wearing of chain transmission system will result in low efficiency of power transmission. Contamination, insufficient lubrication, or fatigue might be reasons for the wearing.

Mechanical failure, poor data management, lack of competence, or lack of spare parts could all the reasons for loss of integrity. Due to expensive logistic and limited space on spare parts as well as staff in offshore operation, shortage of necessary operation elements will just bring in more risk of reliable operation. Downtime will be increased if anything on these occurs. Besides, support structure failure, shaft breakage, drum barrel breakage, or tiedown anchor failure would break the integrity of hoisting system, which will halt the production immediately.

The FTA figure for overall drawwork system could be checked in Figure 36.

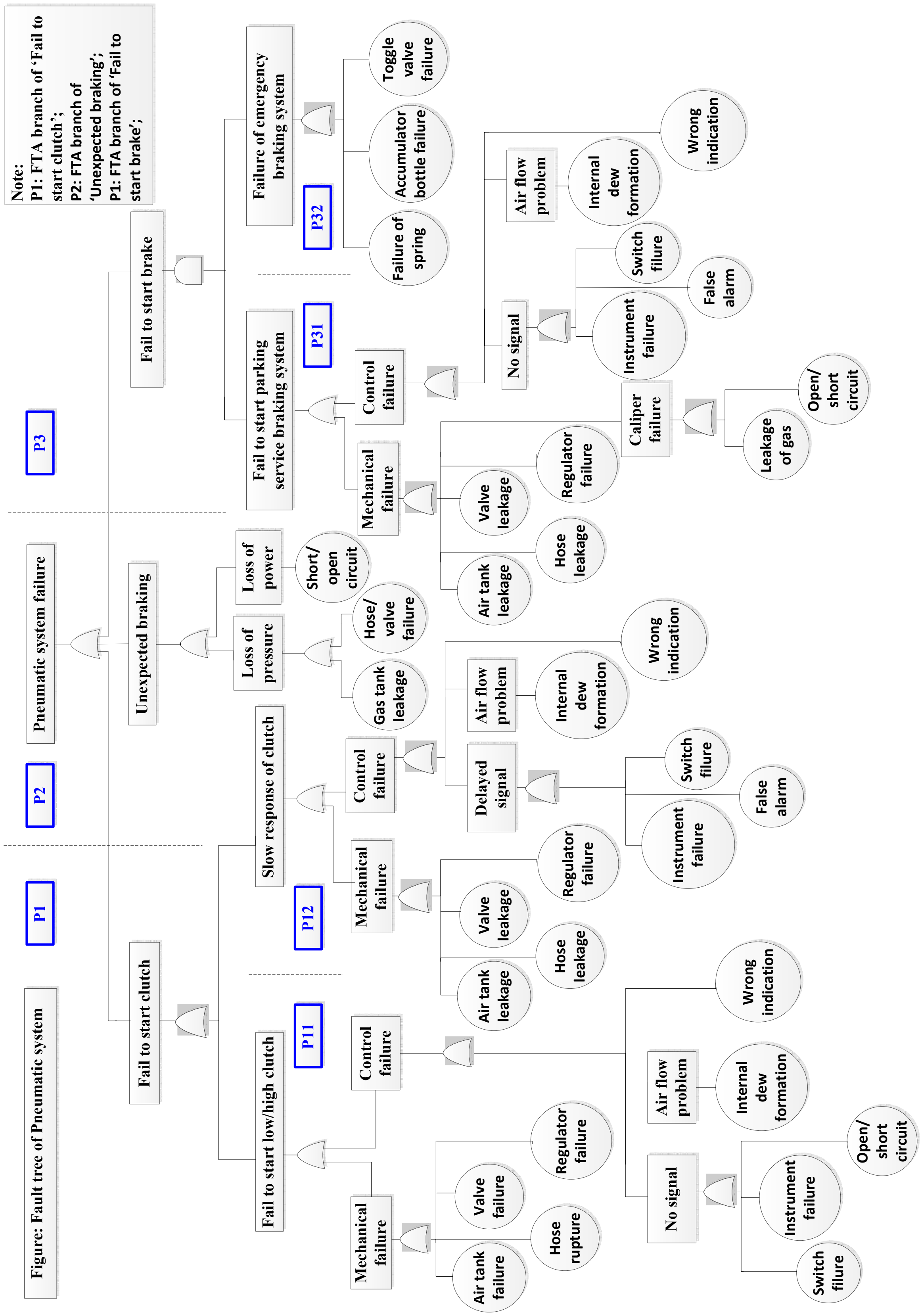

Figure 34 FTA of pneumatic system

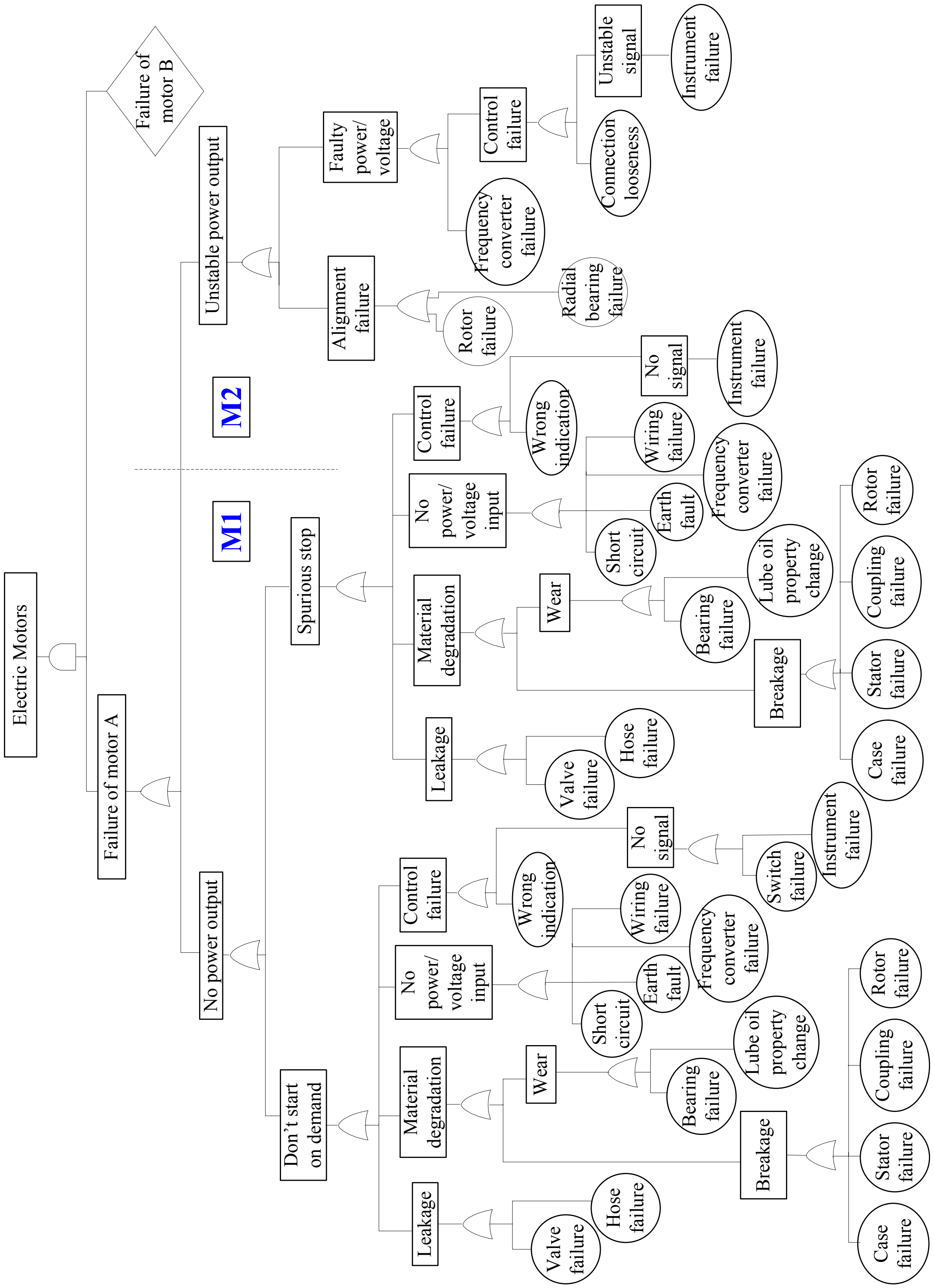

Figure 35 FTA of Electric motors

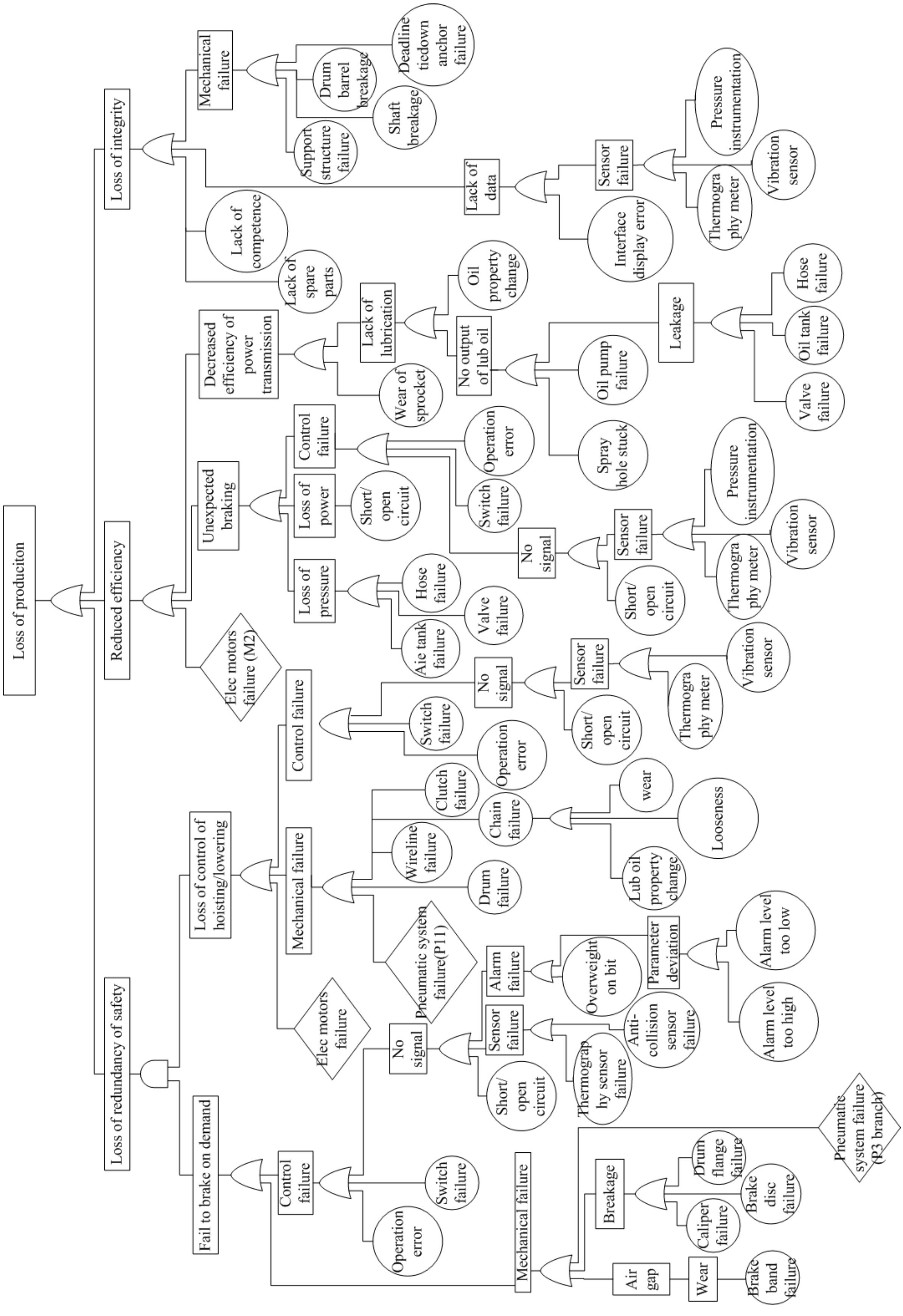

Figure 36 FTA for overall drawworks

4.3 Reliability analysis with Birnbaum's importance mearsure

4.3.1 Limitations

Reliability analysis is supposed to provide a quantitative method to examine the consequence criticality of single component's failure. When there is a decision situation when failure happens, stakeholders could use its importance measure as a reference to assess the need of maintenance.

However, drawworks is not involved in OREDA, the overall system level importance measure could not be done in the project due to lack of data. Electric motors is the only sub-system of drawworks that is recorded in OREDA database. And only maintainable items should be included in the database, which means present reliability analysis could only be done on these components in the thesis. Those parts that are not included in OREDA database will not be analyzed in this project.

Electric motors are just chosen as the example to elaborate the methodology to implement reliability analysis based on FTA analysis. As the FTA model is already built, failure probability for all basic events could be assigned according to company practice or third party recommendations in the future scope of work.

4.3.2 Calculation

Birnbaum's importance measure, as a well-known sensitivity analysis method, is chosen to calculate each component's importance value from FTA. It is quite appropriate to use in operation phase in oil production where each action is related to operaton and maintenance parameters (Aven 1992). Due to limited reliability data, the calculation is only done in one system just to show how to make this kind of analysis.

The equation of Birnbaums's importance measure is:

$$I_i^B = h(1_i, p) - h(0_i, p) \quad (Birnbaum\ 1969)$$

where, p is the system reliability at the time the analysis is implemented, q is the system unreliability, $h(1_i, p)$ is the reliability of the system when component number i is in its best condition, and $h(0_i, p)$ is the reliability of the system when component number is fails to function.

Refer to FTA shown in Figure 35 in chapter 4.2.2, simplified FT (logically simplified for easy calculation) could be drawn as Figure 37.

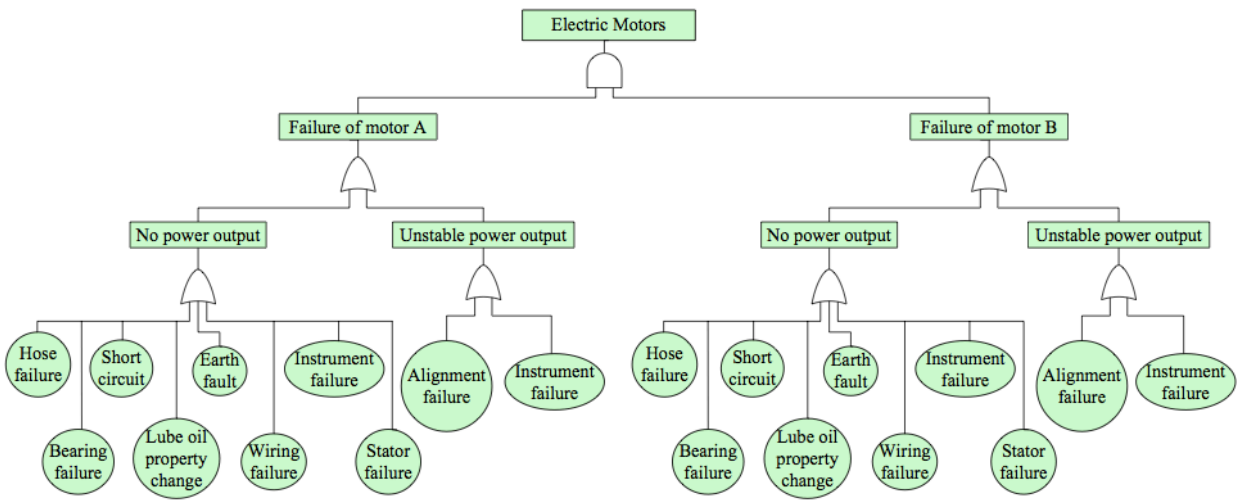

Figure 37 Simplified Fault tree for electric motors

A reliability block diagram could be developed according to the fault tree, shown as Figure 38.

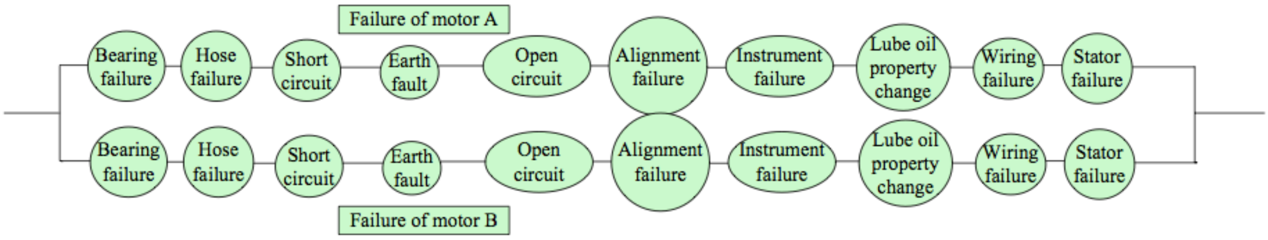

Figure 38 Reliability diagram for Electric motors

According to OREDA database, reliability data could be read or calculated as shown below, in Table 27. For the importance calculation, failure of bearing A is independent from failure of bearing B.

Table 27 Reliability calculation results with Birnbaum's importance measure, as an example

Maintainable items/ functionality	Failure rate (per 10^6 hours)	MTTF	MTTR	Unavailability	Importance measurement
Bearing	4.128	242247	1.4	5.78E-06	0,000308867
Hose/pipe	0.458	2183329	2.6	1.19E-06	0,000308865
Short circuit	0.916	1091665	7.5	6.87E-06	0,000308867
Open circuit	0.458	2183329	7.3	3.344E-06	0,000308866
Earth fault	0.916	1091665	6.7	6.137E-06	0,000308867
Instrument failure	10.094	99069	15.3	1.544E-04	0,000308913
Alignment failure	0.916	1091665	5.1	4.672E-06	0,000308866
Oil property change	0.916	1091665	4.2	3.847E-06	0,000308866
Wiring failure	3.67	272480	29.9	1.097E-04	0,000308899
Stator failure	1.374	727777	9.5	1.305E-05	0,000308869

From Table 27, Instrument failure is the most critical component that has the most importance to the electric motor system. similar analysis could be done on overall system level to check the most critical component/system, while failure data needs to be defined properly.

4.3.3 Automatic calculation of importance measure

If reliability data could be assigned on each level of fault tree, the utilization of professional FTA software like RiskSpectrum will greatly improve the availability of component's importance measurement values. Through the use of profession al FTA software, modeling of FTA of very complex system becomes possible. Further development from the model is relatively easier and available for even not professionals, which is of great help in decision support system.

5 Decision-making practice on maintenance notifications (case study)

In this chapter, maintenance management principles in the company will be explained at the beginning. The explanation would be specified in drawworks and should be possible to be extended to overall maintenance management practice. The present decision-making practice is established with standards, the company's own practice, advice from DNV-GL and industry's best practice. Technical integrity is already the basis of the decision-making process. With the above analysis in the thesis, a data architecture could be developed and it allows different decision makers to react to maintenance needs with comprehensive and necessary data, which present decision making practice lacks. Besides, wider and deeper technical integrity insight is suggested to be incorporated into the recommended decision-making practice on maintenance notifications.

5.1 Present maintenance management on drawworks (case study)

5.1.1 Target group and responsibilities

For the company studied in this thesis, maintenance management on drawworks is implemented with collaboration of offshore operation and maintenance teams and onshore technical teams. Sometimes, some of the maintenance work is outsourced to professional technical service provider. Mainly, they work very closely with company's engineers. For different sections, different responsibilities are assigned. The main target group and responsibilities are described below according to the company's maintenance management principle brochure.

Offshore operation and maintenance team is mainly consisted of technicians. Their work is mainly to implement operation and maintenance work, and keep the production going as expected. The offshore O&M team work in the very front line of the production activities. They get a chance to notice miner anomalies and respond accordingly. The main job responsibilities are listed in Table 28.

Table 28 Responsibility of offshore team

Functions of Offshore operations and maintenance team
Overall responsibility for all equipment (including drawworks) and all activities on board
Installation's budget
Prioritizing and managing activities on board
Planning and execution of maintenance activities
Facilitating execution of operations and maintenance activities

Onshore facility team is consisted of operation engineer, maintenance engineer and discipline engineer. The team cooperates with offshore O&M team as the first decision making level for maintenance notifications. Once facility team gets maintenance notifications from offshore team (could be from onshore CM engineers too, for example) for further assistance, facility team will assess the notifications, and register priority and resources needed in SAP if no further review or assessment is not needed. The functions of facility team is described in Table 29.

Table 29 Responsibility of facility engineers

Functions of onshore facility team
Ensure the quality of maintenance notifications of draworks that arrive from offshore, so that the maintenance engineer has an optimum basis for planning activities in a wider range;
Allocate notifications/orders for technical evaluation, internal planning and execution, planning and implementation by modification contractors or for execution by offshore personnel;
Prioritize notifications/orders in collaboration with offshore, and follow progress on planning and technical evaluation;
Planning work orders;
Budgetary control;
Monitor non-conformity situations and time limits (required end dates) for maintenance activities;
Register information in SAP in agreement with offshore units;
Prioritize as to which work orders shall be planned for execution in the ensuing months;
Ensure that preventive maintenance is executed as planned;
Prioritize maintenance activities to ensure a minimum of risk;
Shall always have control on backlog;
Evaluate proposals for optimization together with project manager responsible, so that preventive maintenance is adjusted in accordance with the equipment's technical condition.

Once further assessment needs to be made on maintenance notifications, facility engineer, discipline engineers or technical safety experts will assess the need of maintenance work, and come up with solutions. Normally, engineers could solve the problem from their own competences, and could also get advices from both original equipment manufacturer and third party risk & safety consultant. The main responsibilities of engineers are listed in Table 30.

Table 30 Responsibilities of engineers

Functions in engineering
Evaluate of notifications;
Ensure that projects deliver an appropriate maintenance program and that the right maintenance strategy has been selected;
Ensure that changes/updates in standards are incorporated in the maintenance program;
Organize field-wide disciplines forums with a view to improve/optimized maintenance and to establish best practice;
Administer and optimize maintenance programs in SAP;
Managing maintenance to secure an acceptable condition of the safety functions and to achieve acceptable equipment availability;
Systematically gathering and organizing maintenance data so as to identify potential improvement areas, and implement improvements within the maintenance function;
Communicate potential consequences of any backlogs and remaining maintenance work and the need to prioritize in the activities management offshore.

Work orders from all parties will be gathered in SAP system. All work orders are predefined with priorities and RED. IPC, with help of some planning tools, will make a 14 days work list based on each work's priority and required end date. Planning of logistics is also part of IPC's work scope. To keep logistic efficiency is a challenge, and to make logistic suitable for platform storage and capacity could be more challenging. The responsibilities of IPC are listed in Table 31.

Table 31 Responsibilities of IPC

Functions in the integrated planning center (IPC)
Organize and facilitate maintenance work offshore (calling out materials, following up materials deliverables, dispatching work folders offshore);
Update execution plans and ensure that logistics facilitate work execution at planned time;
Establish work collections/networks for shutdown jobs and ensure that the content is limited to include genuine shutdown jobs;
Ensure correct prioritization of work in collaboration with specialized maintenance in the event of resource collisions;
Link bed requests to approve jobs in integrated planning (IPL) and assist heli-booking in planning departure plans;
Analyze integrated medium term plan (MTP) with an aim to manage bed quotas and for identification of conflicts/opportunities that cab be handled before short term plans (STP).

Engineering has the overall responsibility for the maintenance program. In disciplines where facility teams have engineers, they are supposed to be assigned the responsibility for the maintenance program. Engineering directors are responsible for implementing the measures that have been identified as necessary in order to ensure the best possible maintenance.

5.1.2 Risk-based maintenance decision

5.1.2.1 Consequence classification of equipment

Normally, consequence classification of drawworks is carried out by EPCIC contractor. For modification projects on drawworks, the consequence classification is done by the supplier of the modification and uploaded to SAP. Every time there is a modification, maintenance engineers are responsible for deciding if the existing classification should be retained or not. Facility engineer is responsible to ensure that drawworks should not be put into operations without consequence classification in SAP.

The company develops a process to classify consequence of equipment, shown in Figure 39. The consequence is ranked and imported into SAP system. It could then be used to establish maintenance program, risk evaluation of notifications, planning and prioritization maintenance work, and to identify spare parts needs.

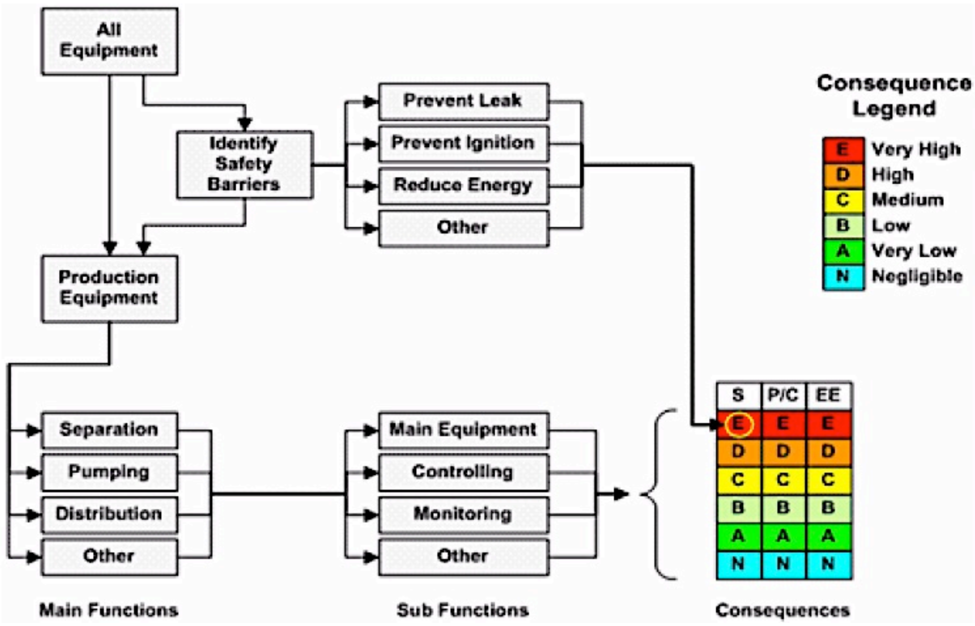

Figure 39 Process for consequence classification of equipment (Panesar, Kumar 2015)

5.1.2.2 Identification of safety barriers

As Petroleum safety authority Norway states, safety barriers must be maintained in an integrated and consistent manner in order to minimize risk (PSA 2013). Safety barriers are groups of equipment/operational and organizational management where the main function is to prevent major accidents happening or escalating and, if necessary, assist in the evacuation of personnel. All equipment (tag numbers) that is part of a barrier function is considered as safety critical equipment and flagged with a code "SFTC" in SAP. The barrier elements must be made clear in the risk assessments.

For measurable technical barrier system on drawworks, the company defines five technical barriers to ensure that any potential major accidents are stopped at the earliest possible stage, which are:

1) Leakage prevention.

• Containment, inspection of piping and static process equipment

2) Ignition prevention
   - Gas detection systems (manual, automatic)
   - Disconnection of ignition source (Shut off ignition source, Disconnection of EX motors in case of overheating)
   - EX (spark insulation on electrical equipment) protection
   - Overpressure protection (room)
3) Restriction of energy supply
   - Emergency shut down, ESDV
   - Emergency stop handle/ pedal
4) Confine escalation of fire/explosion
   - Fire detection system (manual, automatic)
   - Fire pumps
   - Monitors, Monitors with automatic release
   - CO2-system
   - Water mist system, Sprinkler system
5) Secure personnel in case of major accidents
   - Emergency power (Emergency generator w/start battery and chargers, UPS / Inverters w/batteries and charger)
   - Emergency air compressor including batteries and chargers
   - Passive fire protection (Fire and gas dampers, Fire doors / sliding gates and escape hatches)

Once critical hazards have been identified (chapter 3), elements and functions of barriers should be sorted out. Functionality, availability, robustness, response time and triggering events need to be analyzed.

5.1.2.3 Prioritization of corrective maintenance and preventive maintenance

In the company, corrective and preventive maintenance policies are carried out on drawworks. Maintenance notifications related to corrective maintenance need to be assessed for criticality and probability. The consequence will be evaluated firstly. This consequence classification is the basis to start the risk assessment process. Secondly, probability for loss of function will be ranked. Failures that have occurred fall into top probability scope. Based on the consequence and probability, the matrix indicates risk. The corrective maintenance could then be prioritized accordingly. The time limit for rectifying any failures/defects follows from the risk matrix. For practical reasons, a longer time could be selected. However, reasons for doing so need to be notified, since drawworks is so critical for production operation.

Compared to corrective maintenance, preventive maintenance is prioritized for critical equipment like drawworks. That is to say, for similar criticality or risk concerns, preventive maintenance is always preferred to be carried out firstly. Preventive maintenance is arranged with the rules shown in Figure 40. There is a basic start date and basic end date for the maintenance work, but a tolerance is allowed for the work to be finished at required end date (RED) instead of basic end date. The RED is not mentioned in SAP system, while a tolerance table could be used to define the RED. Any delays on RED will be processed as non-conformities.

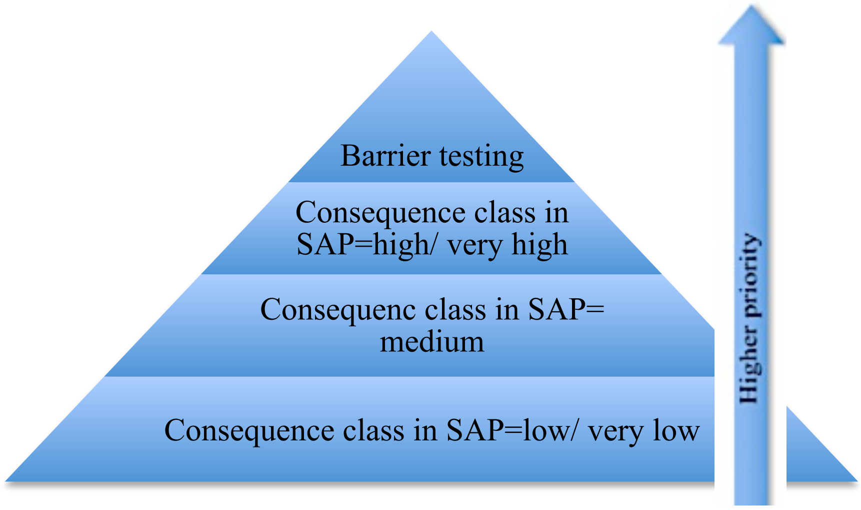

Figure 40 Priority of preventive maintenance activities (Panesar, Kumar 2015)

5.1.3 Maintenance program and process

A preventive maintenance program is developed in the company. It is designed as a way to create values, gain cost efficiency, and take into consideration of development of drawwork's technical condition as well as others. The program should be based on failure modes and failure causes for certain equipment, and should include activities that help prevent these failure modes. Where effective and cost-efficient, CBM should be preferred. Barrier systems for safety operation of drawworks should be maintained so that they could carry out their hoisting/lowering/parking function all the time to improve reliability.

When there are maintenance needs on drawwoks, assessment of those needs, and further on planning and execution of maintenance will be carried out sequentially. The process for assessment could be checked out in Figure 41.

The work order of maintenance program is generated by SAP automatically. Maintenance of drawworks will be assessed with other maintenance needs and ranked according to criticality and probability of occurrence. However, there are always new inputs to this work order. Once the assessment procedure is finished, planning of maintenance activities should be done in a way of continuous improvement and modification (Figure 42). It would not be cost efficient to implement modification/maintenance ever time there is need. Some other work could have been dealt with together or done simultaneously to optimize downtime to make maintenance more efficient. Or failure of drawwork is not so serious, or on an early propagation stage, maintenance work could be done in the controlled future with other preventive maintenance work.

After preparation of maintenance activities, the available material, tools and work packaged need to be checked if they are for the actual jobs or not. The execution of maintenance work will follow steps shown in Figure 43.

To ensure continuous improvement of the maintenance program, reporting proposals for changes in the preventive maintenance program is required. This occurs when the maintenance order is closed and there are proposals for changes to the maintenance program, or there is new input. For corrective maintenance activities on drawworks, the need for changes in present maintenance program and spare parts availability will be evaluated and updated with the implementation of the maintenance program. Critical parts in drawworks should be put in higher priority to avoid great productin loss from major failure. For preventive maintenance, the interval of execution, necessity of preventive maintenance activity, and need to change in program will be assessed continuously during the implementation of preventive maintenance program.

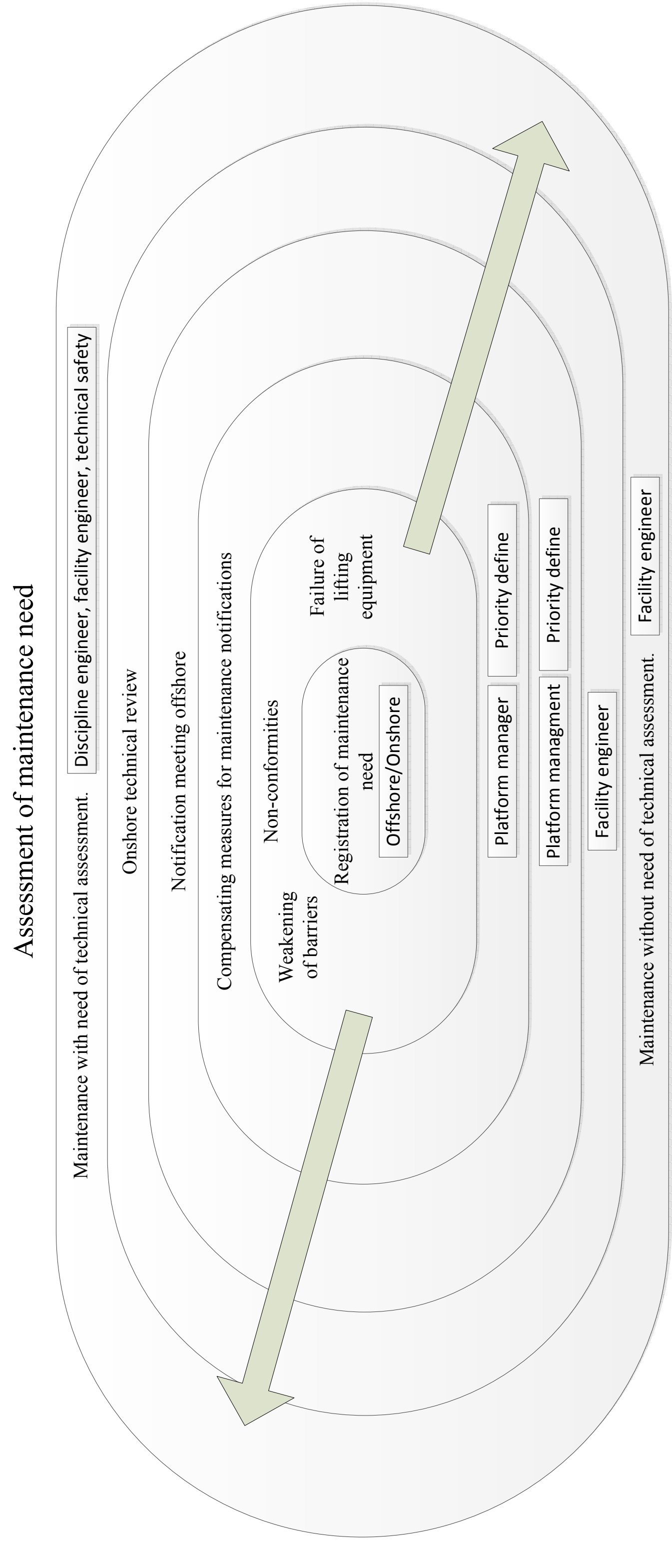

Figure 41 Assessment of maintenance notifications (Adapted from Panesar 2015)

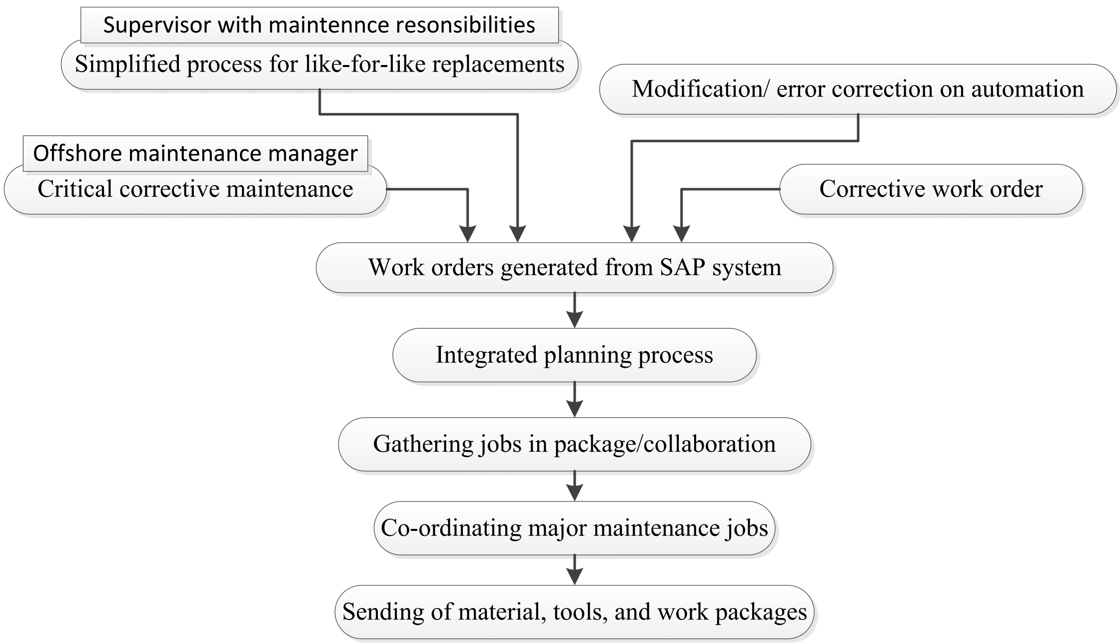

Figure 42 Planning of maintenance activities (Adapted from Panesar 2015)

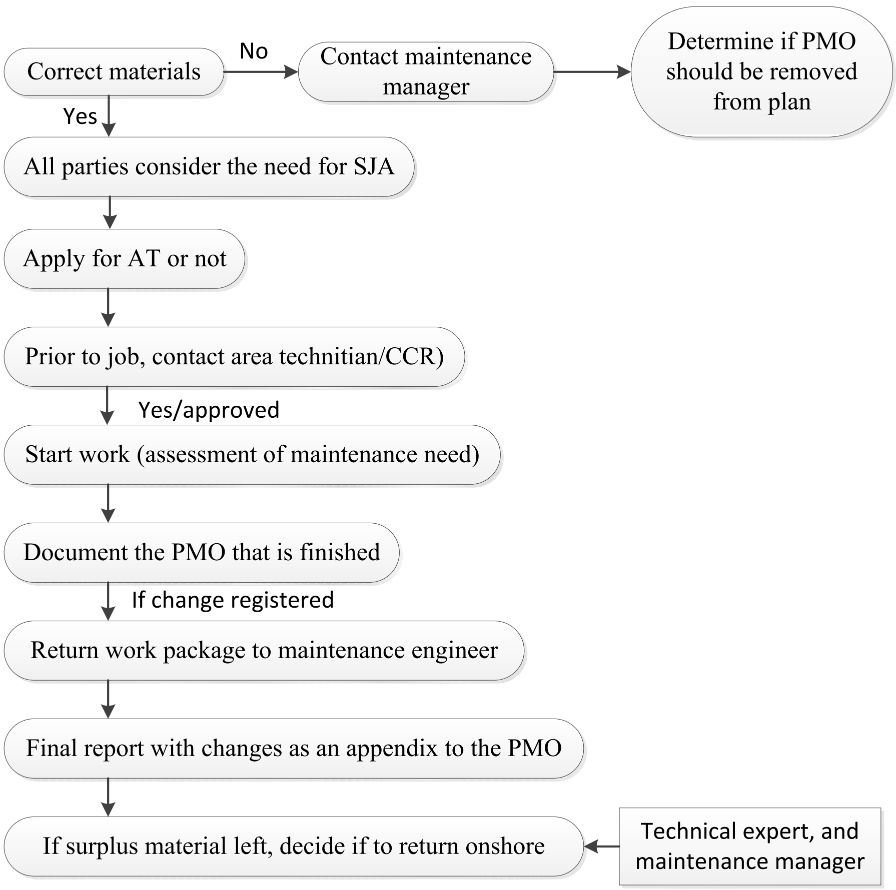

Figure 43 Execution of maintenance activities (Adapted from Panesar 2015)

5.2 Recommended inputs of data-driven decision-making practice on maintenance notifications

In this section, with the example of drawwork maintenance, the author will give some suggestions on maintenance decision-making process with utilization of comprehensive and necessary data. The recommended approach will combine wider range of technical integrity concepts compared to current practice. Through the four bases for achieving technical integrity, the methodology is explained (Figure 18).

5.2.1 Competence management: extended responsibilities of different disciplines

In context of technical integrity, as stated in chapter 2.4.3, contextual data needs to adapted into present decision support system in order to improve reliability and operation efficiency. The purpose of building-up of the new decision support system aims to allow any levels of interventions to have access to contextual data from CM technologies. Contextual data now plays a much more important role in the decision making process in response to maintenance need in the recommended decision-making practice.

Based on previous failure modes identification analysis, offshore operator could keep focus on the signals that is highlighted in FMSA report, and report anomalies to upper management. With the help of ICT, onshore engineers have 100% access to offshore facility condition. This ensures not only failure will be reported, but also, data will be collected to the maintenance engineer onshore, which could provide feedbacks to offshore operators about the signals that might lead to fail. Basically speaking, maintenance notifications could expand its sources from mainly offshore to a combination of onshore and offshore (Figure 44). With this information, maintenance engineer could join in the maintenance work in an earlier stage of possible failure, and offshore operators don't have to wait the failure to come before reporting. By saying so, skill sets for each position/discipline are actually enlarged. Not only own business skills are needed, but also the competence to adapt to ever-changing operating environment is included. This gives a chance to an evolution of work process, which will be discussed in chapter 5.2.4.

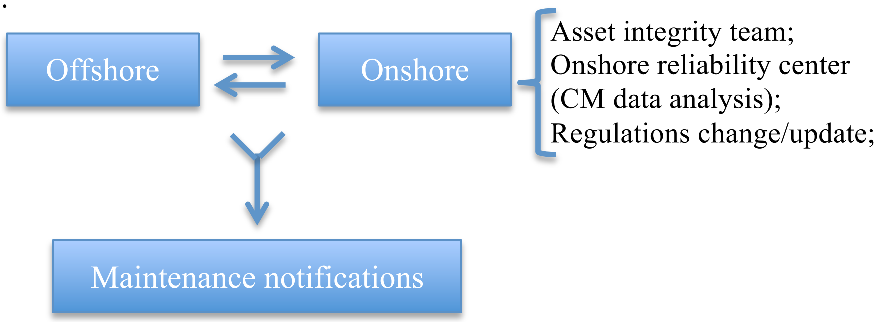

Figure 44 Sources of maintenance notifications

Platform Manager will define the priorities, assess possible HSE and operation risks, and then report to Facility Engineer for staff/resources assistance, and technical review. The review meeting should be held regularly, for instance once a week. Meanwhile, due to the availability and utilization of contextual data onshore, feedback or adjustments requirements could be sent to onshore for further analysis in a periodical or continuous way.

With the maintenance need from offshore engineers, facility engineer could make decision if there is no need for further technical assessment. The facility engineers have the access to online/offline data too, and any decision will not be made without assessing the consequence criticality and possibility of failure. Like before, it is mostly perception of failure from knowledge, skills and experience that decision-makers depend on to make decisions. Facility engineers, as well as technical safety engineers and other stakeholders, need to access and assess contextual data to make further decisions or reports. The extended competence should also take strategic skill into redefined skill sets, as part of extended competence to assist decision making (Figure 45).

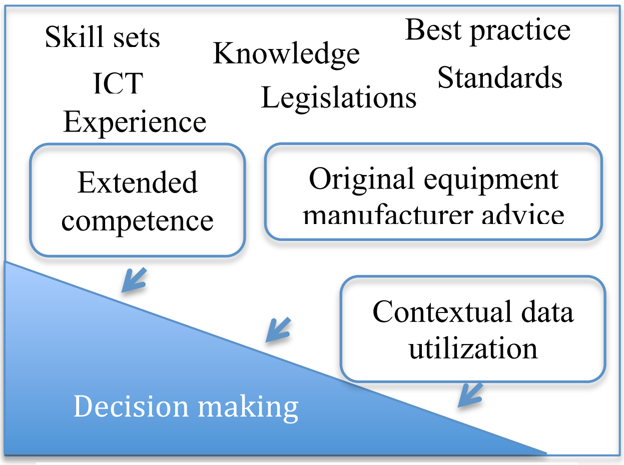

Figure 45 Basis for decision making

5.2.2 Recommended data architecture on maintaining drawworks

The body of data architecture mainly includes history records data, operational data, maintenance data, risk and reliability calculation, and contextual data from CM techniques. Reliability value, here referring to importance measure value from Birnbaum's measure, will be excluded in this part due to unavailability.

Data during drawwork's operation and maintenance activities includes all the description data of the equipment in its functioning context, maintenance data and failure records. General information about drawworks include use/location attributes, equipment attributes and operation attributes. The details of these data could refer to Table 11. These data helps to identify the specific drawworks and its expected functional condition. In this project's context, contextual data is also included in the data architecture. These data is collected from CM techniques in purpose of foreseeing potential failures to improve reliability.

5.2.2.1 Data collection

Data collection in this case include history records on drawwork maintenance activities, industry database, condition monitoring data and so on. Format and range for recording data during maintenance activities could be checked in chapter 2.4.1. For industry database, WOAD, OREDA, and HSE failure records could be referred. In this section, condition monitoring data collection is discussed specially according to the scope definition of the thesis and with consideration of CM utilization.

For condition monitoring data, the author has introduced many kinds of CM techniques that could be/recommended to be used on drawworks, which is discussed in chapter 2.1.2 and chapter 3.3. Data from these CM techniques are collected and are not prioritized according to risk criticality. The thesis tries to give some suggestion on this part. From Figure 36 FTA for overall drawworks, on component level, critical components that lead to potential great production loss/safety issue could be identified. The risk criticality could be checked according to MPN (Monitoring priority number) value shown in FMSA table in appendix B. A list of suggested data sets is shown in Table 32 as an example.

Table 32 Critical components of drawworks as an example

No.	Component/ functionality	Failure symptom	Condition monitoring technique	Possible failure cause	Failure effect	MPN[1]
1	DW operation switch	Fail to function on demand	Visual insp.	Short/ open circuit, or earth isolation problem	Fail to brake/hoist/lower as expected, unexpected emergency braking engagement	320
2	Wireline	Breakage	Visual insp., tension sensor	Fatigue, overweight	Drop of load	320
3	Brake band/disc	Overheat	Thermography, acoustic transducer	Faulty clearance or alignment	Insufficient braking, drop of load	240
		Wearing/ Breakage	Visual insp.	Fatigue, or over holding weight	Drop of load	320
4	Pneumatic system	Fail to engage clutch	Pressure, temperature, flow rate, acoustic, visual insp.	Leakage, wearing	Delayed operation of hoisting/lowering	216
		Fail to engage brake	Pressure, temperature, flow rate, acoustic, visual insp.	Leakage, wearing	Drop of load	320
5	Drum barrel/flange	Deformation, breakage	Visual insp. Noise, radioactive,	Fatigue, overweight	Shutdown of production	267
6	Main shaft	Deformation	Thermography sensor, visual insp.	Overheat due to cooling system failure	Shutdown of production	240
7	Alarm	Abnormal alarm response	Visual insp.	Alarm level too high	Exposure to dangerous condition	240
		Fail to trigger anti-collision alarm	Visual insp.	Alarm failure	Possible collision of TBA and crown block	240
8	HMI	No signal	Visual insp.	Sensor failure, wire breakage	Drop of load, collision of blocks	240

[1] MPN: Monitoring priority number, which develops from FMSA in Appendix B

No.	Component/ functionality	Failure symptom	Condition monitoring technique	Failure cause	Failure effect	MPN
		Neglect of critical signals/alarms	Visual insp.	Operator abstraction	Drop of load, collision of blocks	240
9	Open/short circuit	No power input	Voltage, current,	Breakage, connection	Unexpected emergency braking engagement	240
10	Instrument	Abnormal instrument reading	Thermography, vibration, pressure sensor, etc	Degradation of structure/ material	Threat of hoisting/ lowering safety	240
11	Converter for motors	Wrong/no output	Visual insp.	Short/open circuit, management error	Unexpected emergency braking engagement	228
12	Caliper	Slow/ do not respond	Pressure sensor (lube system), visual insp.	Maintenance error	Delayed response of braking	192
13	Clutch	Metallic clanking	Visual insp.	Corrosion, wear,	Fail to brake/hoist/lower as expected	192
14	Lubrication system	Insufficient lubrication oil supply	Visual insp. Pressure sensor, Oil debris analysis,	Leakage due to wear, breakage, connection looseness	Increased wearing of power transmission system	192
15	Electric motors	Failure of two motors	Thermography sensor, vibration, torque detection, voltage, current, visual insp.	Overheat, open/short circuit	Unexpected emergency braking engagement	187
16	Tiedown anchor	Abnormal vibration	Visual insp.	Over weight on wireline, material failure	Shutdown of production	180
17	Derrick structure	Abnormal vibration	Visual insp.	Over weight on wireline, material failure	Shutdown of production	180

5.2.2.2 Recommended data management of drawworks

Based on present maintenance work order generated from SAP system. New inputs like critical corrective maintenance need, inputs from asset integrity and reliability center, and changes of operation condition will add new inputs to SAP for IPC to plan. In the author's opinion, the assessment procedure of maintenance notifications should be designed as a decision making structure with utilization of necessary data available for each level of management/intervention.

5.2.2.2.1 Contextual data

The basic events in the FTA indicate the most critical single failures that might lead to loss of production (partly or total loss). Any other failures according to this research are either considered impossible to happen or has less critical failure effect on the whole system. Contextual data/information is available in this level of system. Various condition monitoring techniques could be used to collect the real-time data/information.

Condition monitoring data could be both online and offline. Maintenance engineers will deal with the real-time data through ICT system. If automatic diagnose system is available, condition could be easier for engineers as well as managements to read. Onshore engineers, unlike before, could acknowledge the condition of facilities even earlier than operators offshore. Once the data from diagnose system goes abnormal, inspection suggestions could be made for operators offshore to implement visual inspection for confirmation, for instance. Data analysis based communication between the two parties allows the monitoring of facilities to enter into a new reliability level. This adds the source of maintenance needs as well. Gladly, the new input of corrective/preventive maintenance provides IPC a more robust base to plan maintenance activities.

For some basic events that do not support online monitoring techniques (for example, brand disc wearing, hose leakage, etc) should be monitored manually. The contextual information on those most critical components/functionalities is normally inspected by offshore technicians. The critical basic events that described in the FTA in Figure 36 are advised to be added into present maintenance inspection checklist. And the checklist is suggested to combine more information inside, like the failure effect on both local and overall drawworks will help the inspectors to react in a better way.

CM data analysis could indicate the failure probability that is observed to have anomalies signals. Combined with criticality of components table in Table 32, priorities of CM as well as maintenance activities could be modified accordingly.

5.2.2.2.2 Risk criticality of failure

Once anomalies are found in drawworks, FTA propagation diagram (qualitative) and MPN values from FMSA analysis could be used as general indications of the criticality of failure by decision-makers. This helps the corresponding decision-makers to make a more reasonable priority arrangement of maintenance work. As propagation of different basic events develop,s different discipline engineers will be involved into the decision making structure. Besides this, propagation development adds more clarity of reporting system for offshore technicians.

Birnbaums's importance measure values (chapter 4.3) could be used to show the reliable quantitative analysis of criticality. This allows decision makers to suggest more proper inspection plan on the most critical components. If failure is about to happen from diagnose analysis, the criticality difference between different maintenance could provide a basis for fast decision making classification. Responsibilities of offshore engineers should be defined properly with consideration of availability of time and failure consequence. Fast decision making principle is appreciated in today's business environment. Normally, decision making in response with maintenance notificaitons should be done as discussed above. In special cases where time is critical, fast decision making by offshore operators should be allowed depending on the analysis results from FMSA, FTA, Birnbaum's importance measure and maintenance data as well as contextual data. However, reports to upper management are still required to make sure the reliability and awareness of the decision. This could only be done with availability of data, readable and understandable data to be precise. This requires the utilization of a specially designed data-to-decision interface (future scope of work).

5.2.2.2.3 Information integration

Enterprise integration keeps focus on system interconnection, data interchange, data exchange and distributed computing environment. It aims to provide the right information at the right time and place, and guarantees the efficiency of communication and cooperation between people, machine and computer systems (MIMOSA; Vernadat 1996). The integration of information/data could provide the organization with the ability of coping with changes as well as improving reliability and efficiency in decision-making process.

To gain information integration, Nell and Kosanke gave some suggestions (Nell and Kosanke 1997). The author tried to adapt the method to fit this case. The data collection has been explained in chapter 2.4.1 and chapter 5.2.2.1. The data should be updated all the time to give right indication. With the data available, it is also important set up a reliable ICT system that ensures all stakeholders to have access to these data at the right place. The stakeholders could be defined according to specific component involved and risk criticality. For example, onshore reliability center need to know the condition of the facility and operation to decide if and which maintenance engineer or spare parts should be sent to offshore field. This helps to build up real-time decision support system (Figure 46). Stakeholder identification in this case will be discussed in section 5.2.3.

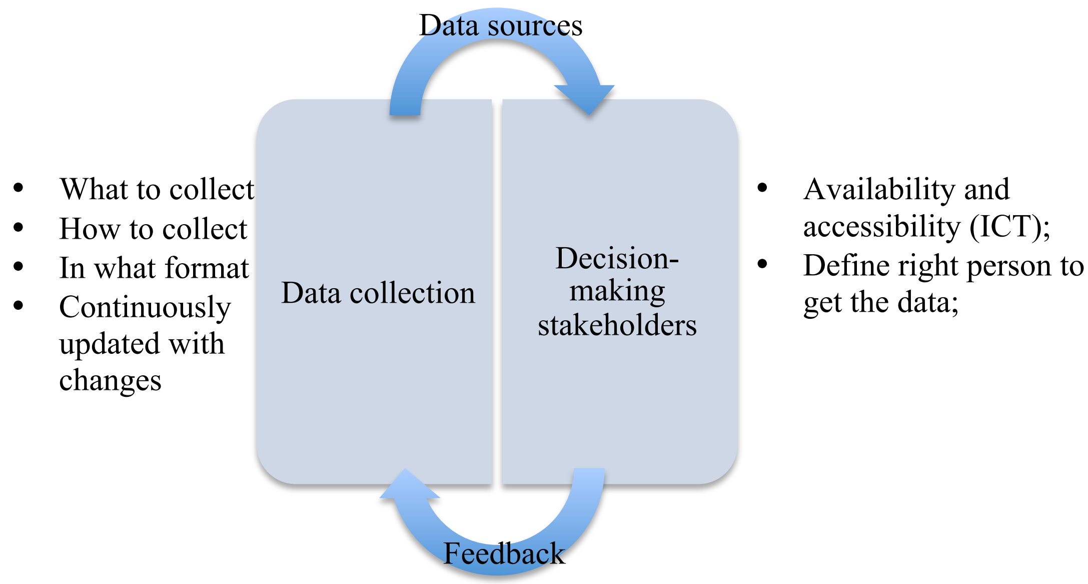

Figure 46 Information integration

5.2.2.3 Recommended data architecture

Data architecture is built in purpose of providing a basis for further risk analysis and decision making. Data sources during drawworks O&M process could be vast. Data is collected both from histories and current condition. History data includes experiences, maintenance history, industry database, and so on. Current data refers to facility condition, working hours, risk analysis-based failure rates, condition monitoring data and so on. A data hub will act as a concentration center for all data. The hub should be designed with easy accessibility, reliability, and availability. The use of SAP system and reporting system in the company could help to achieve the goal.

Collected data could be divided into two parts, for common use and for specific use. Common use data should be available for all stakeholders in the organization. For specific use, different disciplines of decision-makers need decision-making related data. Onshore, offshore and service providers should be considered into the data architecture system, and their accessibility and availability of necessary data should be guaranteed. Data management could act as bridge to provide the right information to the right person at the right place. Reversely decision-makers should have the competence to utilize necessary data sets to assist decision-making and have the accessibility to all relative data. The architecture is shown as below in Figure 47.

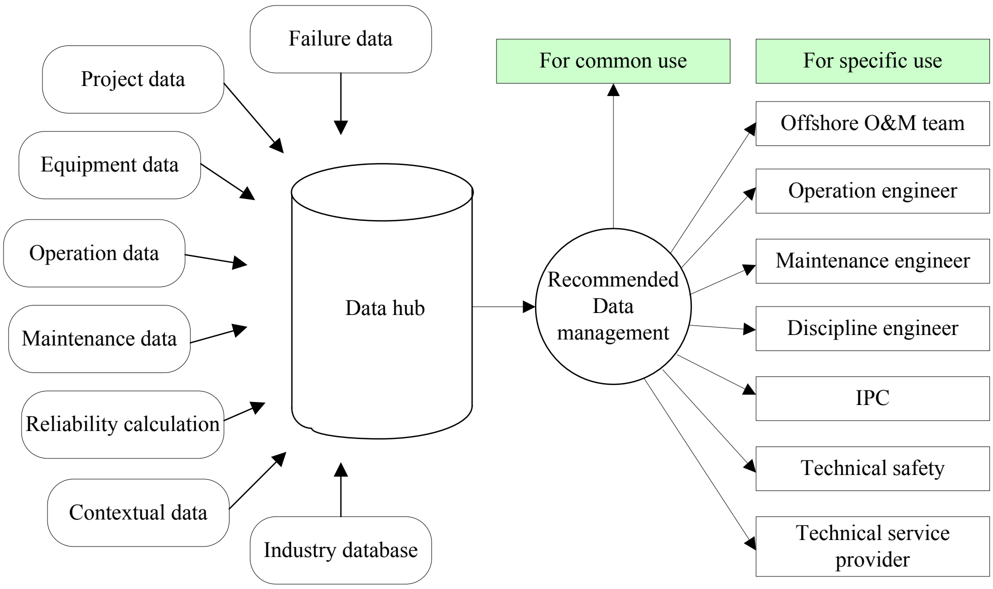

Figure 47 Recommended data architecture (Adapted from Liyanage 2003)

5.2.3 Recommended decision support system (case study)

Decision support system in drawworks maintenance decision-making practice includes management model, ICT system for information transaction and sharing, knowledge-based subsystem, and database management system. The current decision support subsystems work in most time independently. The information integration requires an evolution of information and knowledge sharing and utilization. The flow of information, based on reliable ICT system, should have satisfied precision, cover the right person, and be available at the right place.

Decision-making stakeholders on drawwork maintenance notification are shown in Figure 48. As maintenance notifications arise from either offshore or onshore, a decision is required to be made if there is a need to report the notification, or if extra engineers or resources are need from onshore. Offshore O&M team, and facility team (a group of maintenance engineer, operation engineer, process engineer and discipline engineers) are involved to define the priorities and necessity. All the notifications will be sent to IPC for arrangement of maintenance work list. This is the first level of decision-making. This fits for most of the maintenance notification situations. With the development of decision-making quality, few big anomalies happen in offshore operation. Most of the time, maintenance needs could be taken good care of without further assistance from onshore. This saves time and money. However, it is the IPC's responsibility to plan when the work should be done due to risk criticality and tolerance. To achieve a better reliability on this first decision level, knowledge management and data management could be of great help. The relative topics are discussed in chapter 5.2.1 and 5.2.2.

Figure 48 Decision-making stakeholders

If the problem is too complex for facility team to decide, the reported maintenance need from both onshore and offshore will be forwarded for technical evaluation. Involved stakeholders include discipline engineer, facility engineer, or technical safety staff. Different discipline engineer will be involved according to specific maintenance case. Technical safety staff will contribute his/her work to reduce maintenance-related risk. The result will be sent to IPC for further work list arrangement. This is the second level of decision-making.

Decisions in either level are suggested to be made based on precise data management (by saying precise, it means right information for right person at the right place) and risk analysis. Data is collected and analyzed for common or specific use. Condition of equipment could be acknowledged, reliability could be calculated, and history records and industry database could give indications on occurrence frequency. Meanwhile, risk analysis (here FTA and FMSA) has been done in chapter3 and 4, risk criticality for critical failure has been analyzed in both qualitative and quantitative way. Risk analysis results could be used to identify the data sets that should be collected and analyzed. Reversely, data architecture adds value on failure analysis. It allows failure analysis to be more convincing and reliable. Combination use of data architecture and risk analysis provides decision-makers a whole picture of the decision problem (Figure 49).

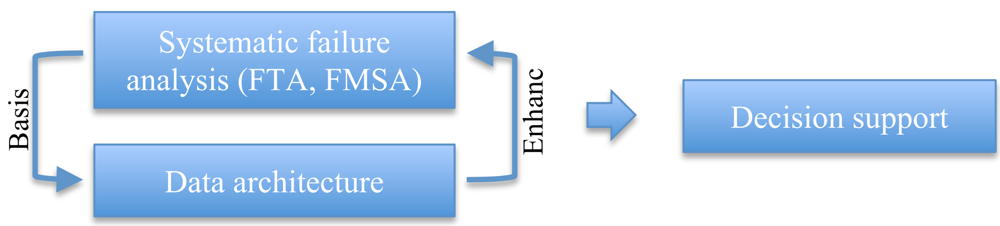

Figure 49 New inputs to decision support

5.2.4 Recommended data-driven decision making process - work process management

As a continuous study of chapter 5.2.3, work process management could be arranged. In this case, the discussion will be mainly about the decision making process before maintenance work is sent to IPC for work order arrangement. Decisions, Data architecture and risk based failure analysis could be integrated together to help making maintenance decisions (Liyanage 2003). According to Liyanage, decisions are advised to be made based on solid data and risk-based failure analysis. A specific data-to-decision interface needs to be designed based on concepts of enterprise integration and interoperability (discussed in 2.4.1). Problems encountered during decision-making process could also adversely provide some improvement suggestions on data management. The flow of decision making could be shown as below in Figure 50.

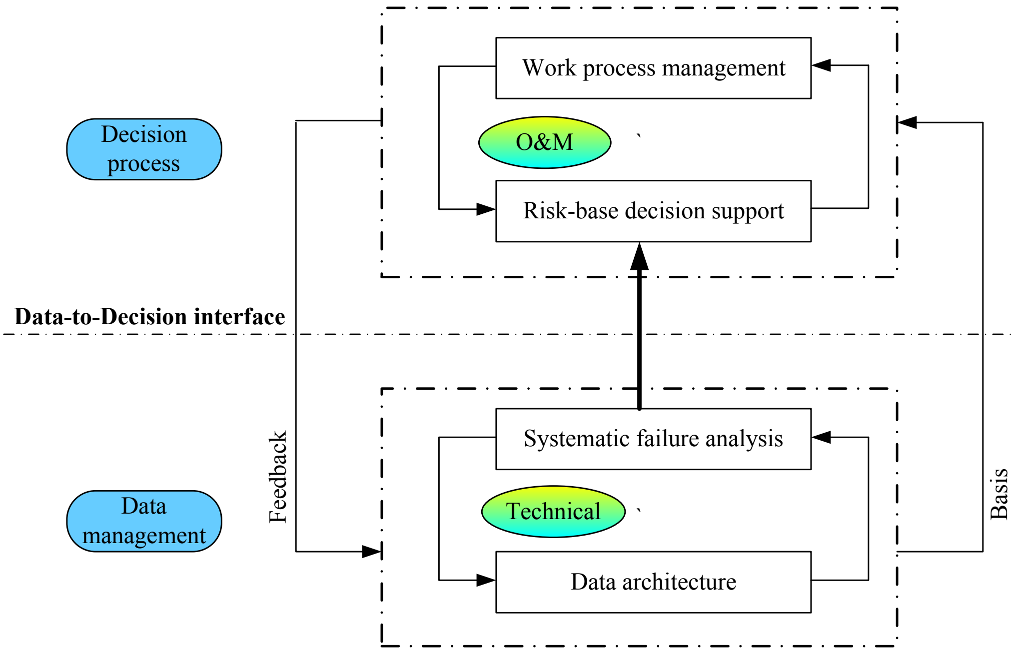

Figure 50 Decision making flow (Adapted from Liyanage, 2003)

In this case, for maintenance notifications of drawworks from either onshore or offshore, a data-driven work process combining decision support system will be illustrated, shown in Figure 51. The work process will mainly focus on the reporting and registering maintenance notifications of drawworks. Notifications from either onshore or offshore need to be evaluated and reported properly to IPC for further arrangement. IPC will arrange the work list according to predefined (by decision-maker) resources needed, required end date, and priority. The reporting system and decision-making requirements are suggested to be redesigned with consideration of risk criticality and CM data. Unlike traditional sources of maintenance needs, the utilization of CM techniques on DW give onshore engineers a chance to discover maintenance needs before offshore technicians even.

5.2.4.1 Recommended flow of decision making on various sources of maintenance notifications

The availability of onshore engineer observation combined with offshore engineers' inspection makes the discovery of early failure easier. If notifications come from offshore, risk criticality and required end data vary from case to case. Platform O&M team will hold notification meetings regularly to discuss the priorities and possible mitigations measures of maintenance notifications. Offshore O&M team are mainly technicians, who are typically better at operation and facility adjustment instead of making strategic choices. If the work could be done by offshore O&M team without assistance from onshore, the corresponding work order and required end date could be defined (with priority and required end date) and registered in SAP system, so that IPC could use it for further work order arrangement. If the offshore team still needs some material or staff to assist the maintenance work, the notification will be sent to facility team for arrangement of these resources, and the notifications will be sent to IPC by facility team. In some cases, the maintenance decisions might have wider influence on cost efficiency and technical safety, which might be out of competency of offshore O&M team. For these complex and risk critical cases, maintenance notifications need to be reviewed by facility team. Facility team will evaluate alternative and cost-efficient solutions, and implement risk analysis based on recommended decision support system (chapter 5.2.3). Work order could be registered in SAP for IPC to arrange if risk criticality could be handled in this stage. Sometimes problems might be too complex for facility team to decide, notifications will be sent to corresponding discipline engineers/facility engineers/technical safety for further technical assessment. The team/man in charge is supposed to be authority of knowledge and experience. Risk-based failure analysis and necessary data are still needed and will work as the basis of decision-making. This is described in chapter 5.2.2. Alternative solutions will be assessed in order to improve cost efficiency and reliability. Work order will then be register in SAP, with priority and required end data clearly defined.

IPC is the team that will arrange the work list of maintenance notifications registered in SAP. The work list is planed based on some planning tools, and priority and required end date, which are predefined by corresponding decision-makers. IPC will create work packages that could meet the maintenance requirements, achieve efficient logistics and minimize downtime. Materials and engineers are preferred to be called out per work order right ahead of planned startup of the work.

The discussion above is the feedforward flow of the maintenance decision making process. Feedbacks are necessary and recommended to help build a continuous improving decision making process. After work list is set by IPC, execution of maintenance work will be implemented by offshore O&M team. Sometimes, for example, the efficiency of logistic might be achieved by IPC, but the offshore installation is not capable of storing all stuff transported there. Something has to be sent back to onshore due to storage or loading capacity. Engineers/supervisors in IPC are advised to have knowledge/competence of offshore design and operation. Such kind of feedbacks to IPC could help improve the quality of work list next time. IPC will mainly use SAP as the basis to plan work list. Coordination and discussion between notification registers (sources of maintenance notifications) are necessary. The possible overlapping of priority or data will happen now and then. And availability of technicians and competences offshore need to be confirmed before work list is made. This helps to achieve a more practical and reliable work list.

Assignments/responsibilities should be put on those who have full competence to deal with work inside his/her position description, and also have knowledge of business strategy (if he/she is in engineering discipline) and risk criticality. Competence management is such an important part that lack of full competency might bring a risk of failure when facing emergent situations. Training on the technical knowledge of drawworks as well as other critical systems will be of great benefit to every decision-making levels. Meanwhile, engineers are advised to learn and keep in heart of business strategies to keep motivated and achieve continuous success. This is a continuous process, where feedback from each side will just improve the understanding of the whole picture better and better.

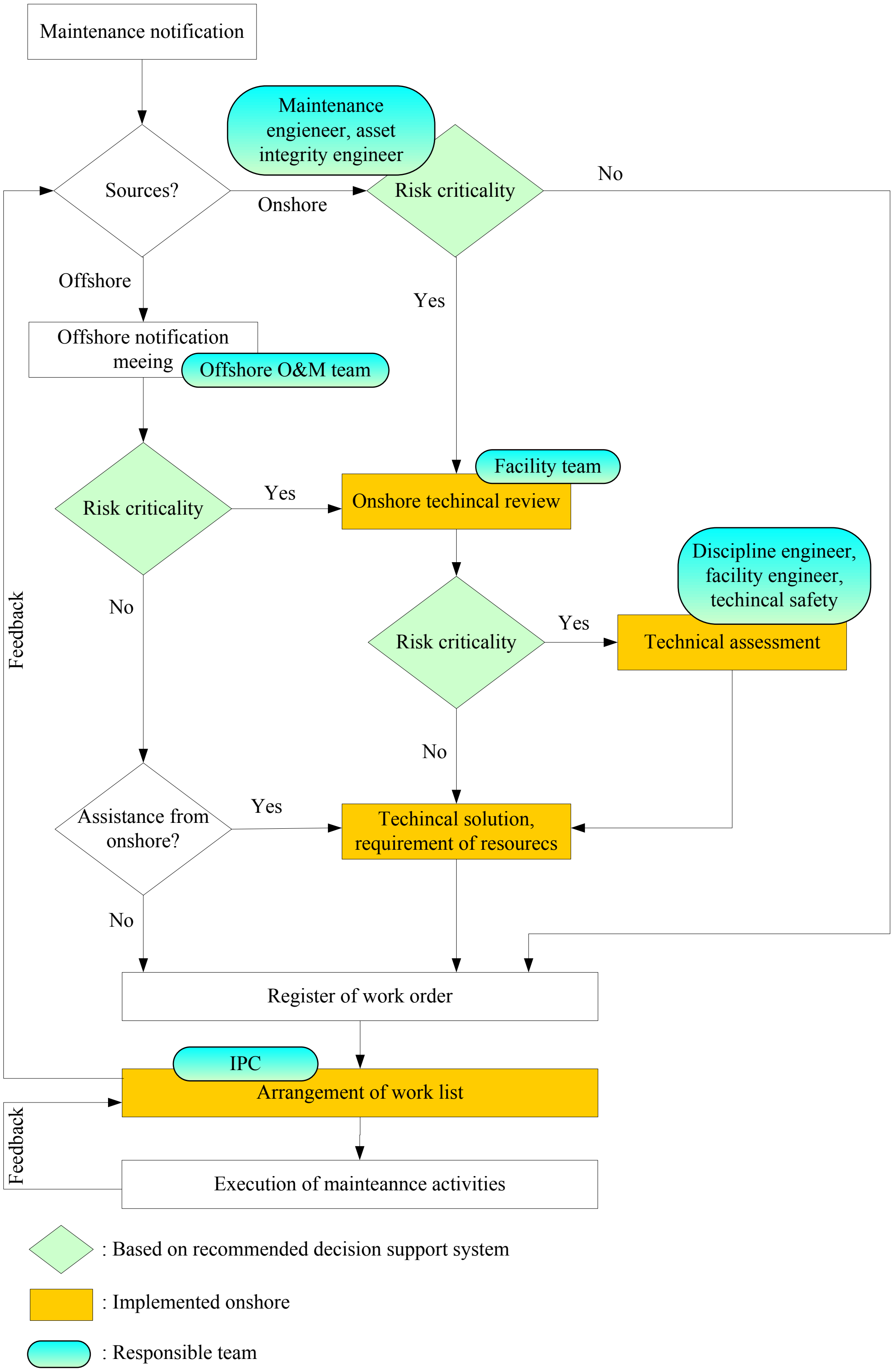

Figure 51 Decision making tree on maintenance notifications

5.2.4.2 Suggested practices of decision making

The green diamond blocks in Figure 51 suggest that any decision made in this point is recommended to be data-dependent. The data are from CM data diagnose analysis, MPN and Birnbaum's importance measure on all critical components. The quality and availability of data is guaranteed by the data architecture described in chapter 5.2.2. The data should be easy to read and understand. Any level of decision-makers could make use of it and is advised to do so. Original equipment manufacturer is normally recommended to be the technical expert on maintaining relative equipment.

Normally, only consequence criticality is discussed during decision-making process. For the concerning of costly offshore operation and maintenance activities, the availability of time needs to be taken into consideration in work process design. Fast decision-making should be possible when time is too limited (according to FTA and FMSA) to implement normal reporting system. For less critical failures (with less critical consequence on the whole system), decisions on maintenance could be made by offshore teams. When some critical failures comes with limited availability of time, a breakthrough of traditional decision-making structure is needed for sake of economic and production contiguity concerning. Offshore technical teams should be able and allowed to implement mitigation measures by reporting to managements who have the right to make decision on maintenance activates instead of reporting the needs from one level to another. The crossover of reporting system should be allowed in case of emergencies. To make this possible, every management should be competent of both business strategy and critical technical concerns. Competence management is an another important aspect in context of technical integrity scope.

To ensure the maximum achievement of technical integrity, ICT system and HMI needs to be designed with fast response and availability. Communications between direct reporting stakeholders are especially important and should be done in a regular and thorough way. The flow of data should be reliable, understandable, relative, and efficient. Basically, the system itself should be designed and built with robustness, redundancy, fail-safe and self detected. The interface for data-to-decision management is especially important. It could be either limitation of decision-making efficiency and reliability, or accelerator for increased efficiency and reliability.

Part 4 Discussion and conclusion

6 Discussion

In this chapter, the discussion will be implemented on how the thesis is initiated, the scope of the thesis, main results from the research, verification of the method, challenges, and contributions. The thesis is also a precious learning process for the author as part of the master program. Based on the limitation at present, future scope of work is suggested.

6.1 Scope, results and importance of thesis

The thesis is brought forward due to the need of incorporating maintenance data into decision-making system on maintenance notificaitons from the company. Later on, the thesis is widened to suggest some critical inputs of establishing data-driven decision-making practice with maintenance notifications. Drawworks is used as the example to elaborate the methodology. The recommended data-driven maintenance decision-making practice will be discussed under concept of technical integrity management. Data management is the most important part of the thesis. Competence management and decision support system will also be discussed as part of author's suggestions.

The main results from the research include:

1) The most critical failure modes of drawworks;
2) Methods to identify which parameter/component should be monitored;
3) Methods to achieve technical integrity in a systematic and practical way;
4) Method of combining data management into decision making process in response with maintenance notifications of drawworks;

The author hopes the methodology and results from this research could suggest some fresh ideas to the whole O&G industry on decision-making process on maintenance notifications.

The thesis is oriented from the need of company's practical need on data utilization. Data from both online and offline, history and present, offshore and onshore are a hidden gold mine. Valuable information is buried inside. The thesis is trying to suggest a way to collect, identify, analyze and make full use of these valuable data. Maintenance related decision-making is hopefully becoming more reliable with comprehensive and necessary data. The thesis also suggest the way to incorporate other technical integrity management elements into decision making practice, like competence management, integrated work process planning, and decision support system with contextual data. These are all supposed to help bringing in a more reliable and cost-efficient decision-making practice.

6.2 Methodology verification

The methodology is described in chapter 1.6 in Figure 52. The general idea is based on the identification of the most critical failure modes. This limits the discussion from the total drawwork system into a simplified drawwork system. The quality of simplification should be ensured by using risk tools as FMSA and FTA, and reliability analysis tool as Birnbaum's importance measure.

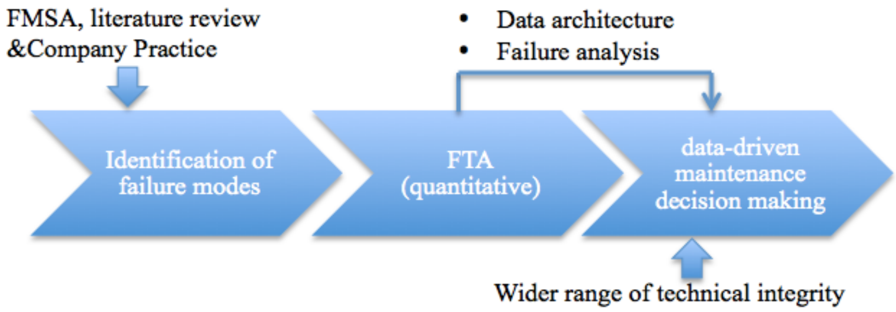

Figure 52 Methodology of research

6.2.1 Failure mods identifications

There are several methods to identify failure modes of system, like HAZID, FMEA, HAZOP, etc. All of them have been widely used by the O&G industry and proved to have the ability to increase safety and reliability. They could be used either singularly or in a combined way. In this research, FMSA analysis is developed by the author with assistance of company engineers. The basis for FMSA is the technical drawing of drawworks. A functional breakdown of the system is done before the analysis. The analysis is aimed to be finished in component level, which allows the further implementation of CM techniques to monitor health condition of critical components. Besides, risk screening from industry practice, literature, and company practice are done by the author to reveal the whole risk picture. Through the three ways (company practice, literature review, FMSA), it is believed by the author that a systematic failure modes identification work is properly done.

6.2.2 Fault tree analysis

Fault tree analysis is a critical part in the whole methodology. It provides the basis for data management and works as reference of decision support system. It is implemented both in qualitative and quantitative way on the drawwork system. Failure propagation is developed through FTA, and this could be used for operators, engineers and management teams to refer to when decisions need to be made. Training could be arranged around the FTA and FMSA analysis to get a general risk picture for each management intervention.

FTA could be a basis for data architecture establishment. On the one hand, by assigning probabilities to basic events in FTA, reliability in component level could be calculated by using Birnbaum's importance measure method. This gives quantitative indications on how possible the component's failure might induce system failure. This adds more value to decision support system too. On the other hand, critical data sources could be identified through the FTA and relative quantitative reliability calculation. Data diagnose system make the data scatter plot readable and understandable. Data could be prepared in a more flexible and reasonable way. Specific decision-making stakeholder could thus get a chance to mix use FTA and necessary/right data, and assess maintenance needs in a robust and reliable way.

With the FTA for the overall drawwork system, contextual data identified from FTA and collected from CM techniques could be combined into the data architecture, which works as the basis of decision making. A data-driven decision support system could be available to use, which is believed to have the ability to improve decision reliability and operation efficiency.

6.3 Contributions

The thesis tries to incorporate wider TIM concepts into maintenance decision making process. Data management is widened through the utilization of contextual data from CM, data sets from FTA, reliability data from Birnbaum's importance measure (see chapter 5.2.2, data architecture) and others as shown in Figure 47. Decision support system is incorporated with reliability data of failure as well as contextual data from CM. Wider competence other than qualification of position is also taken into consideration in case of emergency preparedness.

Data-driven decision making system includes two levels of management. Firstly, IPC needs to plan priorities and allocate responsibilities to corresponding disciplines. The process itself is data-dependent, and is designed with continuous improvement by feedbacks from execution process. Secondly, contextual data from CM, qualitative risk picture and quantitative reliability data together make the decision support system more robust and reliable. The data architecture allows decentralization of decision-making structure and build up a boundary-less organization. By saying so, competence management is combined into the maintenance management as well. This is explained in chapter 2.4.4 and chapter 5.2.2 already. For different failure and consequence, decisions are designed to be assigned to different levels of management through the use of criticality and reliability analysis (FTA, Birnbaum's measure). This is more appreciated in case of emergencies. Clearly defined decision support system with multi levels of data available ensures the efficiency and reliability of maintenance management.

Besides planned preventive maintenance activates, maintenance needs/changes once mainly come from offshore field, where only offshore operators/supervisors could do the observation work. The utilization of online condition monitoring techniques makes it possible for onshore engineers to contribute to maintenance notification feeds. Data from CM techniques is processed by onshore department and signals of failures could be told from diagnosis. Once maintenance needs are assessed, priority defined, and required end data set, it is the job of IPC to plan the priority of work according to these parameters. Feedbacks from execution process also add input to decision makers to keep continuous improvement of decision-making.

The suggested data-driven decision making practice on maintenance notifications also allows fast decision-making. Competence of decision-making stakeholders needs to be obtained to take the responsibility. The availability of time needs to be confirmed, causes and consequences of potential failure needs to be clarified, and safety insurance could be achieved. A simplified reporting system allows the decision-making process to be time efficient in emergent conditions.

6.4 Challenges

The author majors in Offshore Technology with specialization of industrial asset management. The scope of the thesis is largely covered by the study plan of the master program. However, there are some challenges showing up during the research. Maintenance management principles from literature view, company view and third party view need to be studied to get a full picture. Availability of time from company and third party is limited especially third party consultancy company, so that it requires a good understanding of industry default maintenance principles on equipment the author chosed before any interview is made.

Drawworks is set as the example to illustrate the decision-making process on maintenance notificaitons. The author had very limited knowledge on the hoisting system. The structure, failure modes, failure histories, and current and practical maintenance practices need to be studied in a thorough manner before everything is started.

As industry is moving to an era with great appreciation of data/information. How to identify valuable data and find a way to use this data could be a great challenge. The decision-making system should be designed with the ability of incorporating data management into the process. Reversely, the decision-making process should also allow decision-makers to access the data at the right place, and give feedback to upper sources of maintenance notifications to keep continuous improvement.

6.5 Learning

The thesis has been an exciting journey for the author to utilize, organize the knowledge the author has learnt during the whole master program on offshore technology, from decision engineering, risk management, condition monitoring, reliability analysis, to human factors. And some parts of knowledge fields are deepened and widened due to the quality requirement of the thesis. The utilization of technical integrity management in maintenance management structure is the main acknowledgement for the author. A new acknowledge on improving reliability on decision-making is also gained.

During the work of thesis, engineers from the company side have been playing the role of technological expert, maintenance manager, and external thesis supervisor. The author normally communicates with experts from the company through email, and have a bit more than monthly meeting frequency with them. The author got to learn the structure of maintenance management in the company, responsibilities from each stakeholder in maintenance activities and industry practices. The principle of how to define priorities and make decisions on maintenance needs is also learnt during the journey. These all become the basis for the recommended maintenance decision making practice.

6.6 Future scope:

- In the discussion of decision support system, decision-makers will grab relative data from data architecture to assist making decisions. As mentioned above, data sources are so many and they become so massive. The way company treats data is not updated along with utilization of new technologies. A clear *data-to-decision* interface is needed. How to process data to make it understandable and readable for each decision-making stakeholder could be a future scope of work. This is mainly about data modeling and interpretation.
- Fault tree analysis could be done in a quantitative way with failure probabilities assigned to each level of FT. *Probability of occurrence of top event* can be calculated accordingly.
- Reliability analysis with Birnbaum's importance measure could be done on overall system level to reveal the *importance (to the system) of each component*. To do this, reliability of each basic event in fault tree need be assigned according to experience, failure history or industry database. RiskSpectrum or other FTA tools could be used to calculate Importance measure values in an efficient way to assist decision making.
- In the thesis, the discussion is about how to implement decision-making practice on maintenance notification with consideration of technical integrity. As technical integrity management service is on market, the decision-making practice needs to be adapted accordingly once this kind of service is purchased by the company. The *supplier management*, and *data flow* needs to be redesigned to keep its efficiency and reliability.

7 Conclusion

7.1 Summary of thesis

The thesis is a four months and a half project based on the master program on offshore technology. The initiation of the thesis derives from the need of data management from the company. The thesis has benefit a lot from Professor Srividya, Professor Liyanage from the university, Panesar, Kumar, and Isaksen from the company, and Sture from DNV-GL as input of third part consultant. The work could not have been done without their assistance and guidance.

The thesis has achieved all the goals set in chapter 1:

1) Better understanding of interrelationship between facility condition (every critical parameters) and failure mechanisms;
2) Increased reliability and reduced risk for offshore operation;
3) Continuous improvement of maintenance decision-making practice;
4) Data-driven decision making practice on maintenance notifications;

The author believes data/information is valuable and will greatly help improve reliability and efficiency of decision-making. Some risk analysis, and reliability analysis are implemented to give clues of which, how, and why data is collected and processed. Responsibilities of all stakeholders during the maintenance decision making are analyzed and extended if necessary as part of suggestions. With a specially designed data architecture and data management, data got to be used properly during the decision-making procedure.

The research is finally done as defined in the scope in chapter 1. The author gives some suggestions on how to establish data-driven decision-making process on management notifications. Drawwork is used as an example to illustrate the methodology. As the method is designed for general use, duplication of this method to other equipment or company is supposed to be possible.

7.2 Thesis application

The thesis is developed through a methodology defined by the author. It is designed to be a general methodology and could be used on all critical equipment. As Figure 49 shows, the basis for decision support system are failure identification and data management. For failure identification, risk analysis tools used in this methodology are all widely accepted tools and are easy to implement. The data architecture proposed a structure to process and forward data for certain use during decision-making.

The research keeps its focus on both offshore and onshore decision-making in respond with maintenance notifications. The study is mainly about the data-driven decision-making practice on maintenance needs. It could be used as an input and a start of an overall maintenance management structure. However, there are many limitations in this study, as mentioned in chapter 1.7. Further application of the work should be done with consideration of all the limitations in this study.

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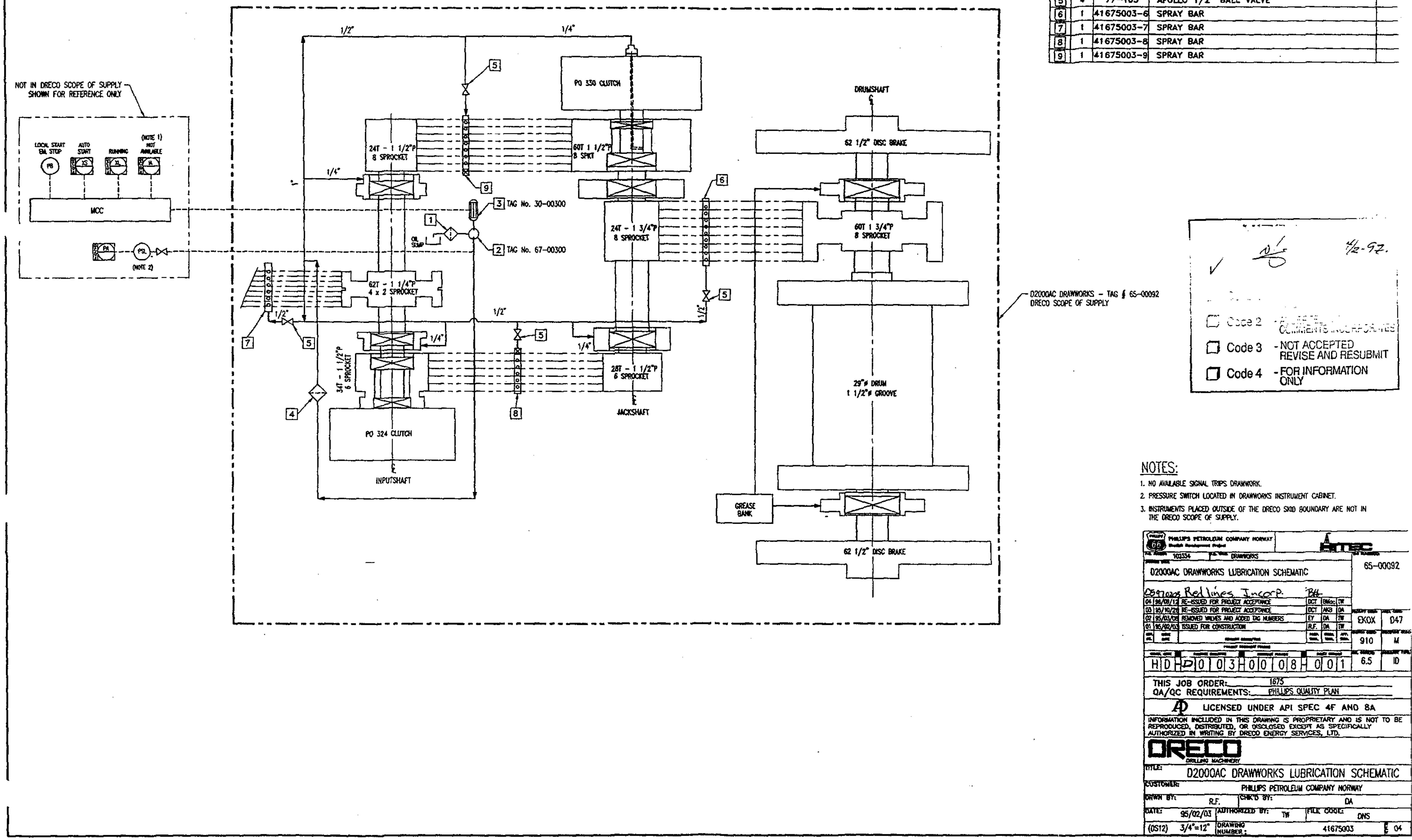
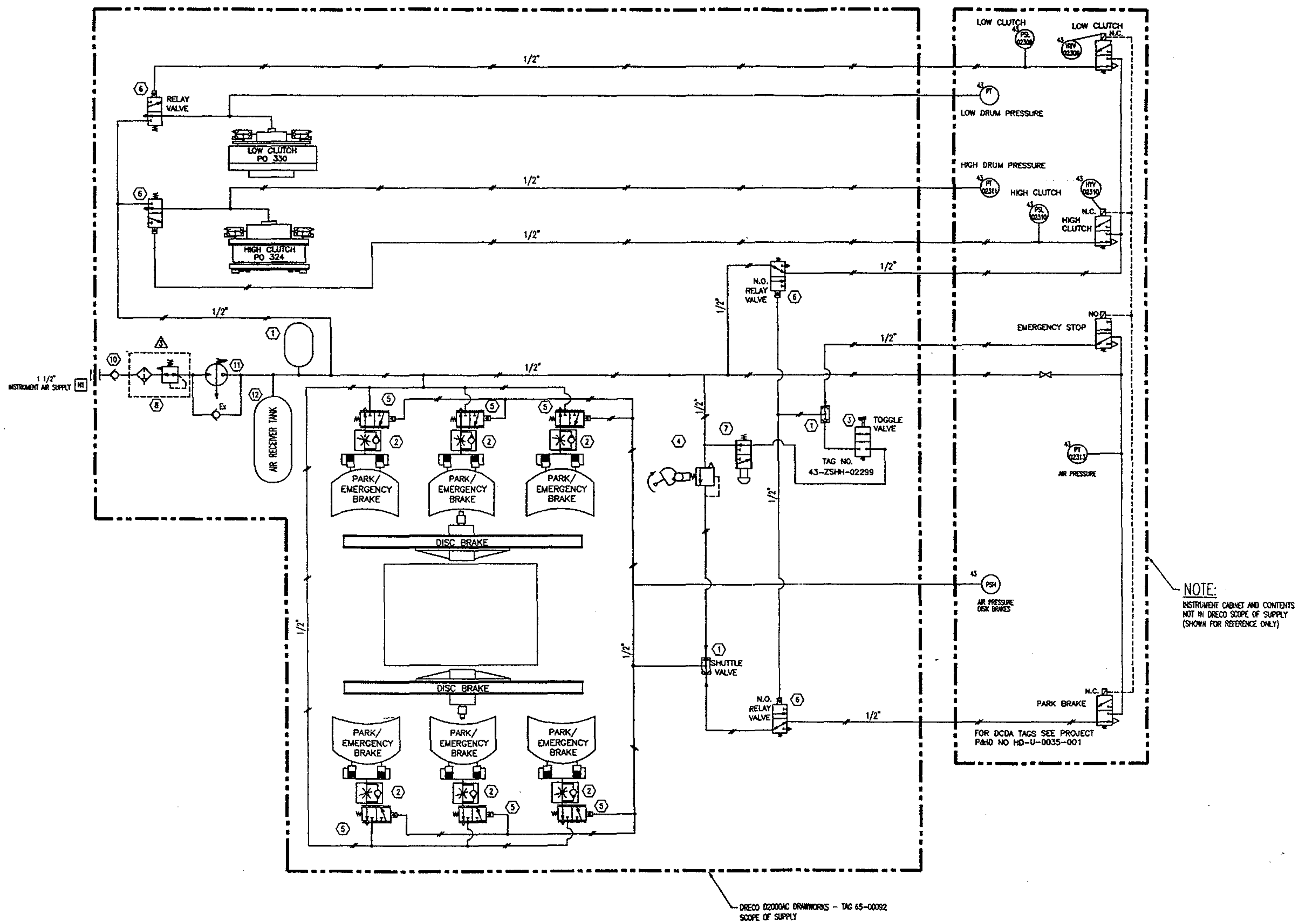
Appendix A : Technical drawings of drawwork from Dreco

I.D.	QTY	PART NO.	DESCRIPTION/SHIPPING MARK	WT
1	1	FST21S-1TB	GRESEN OIL FILTER	
2	1	P25X-942-BE-4.10-2	COMMERCIAL INTERTECH LUBE PUMP	
3	1	M2BA132S6	3 kW AC MOTOR (for LUBE PUMP)	
4	1	ULTIPOR III	PALL OIL FILTER	
5	4	77-103	APOLLO 1/2" BALL VALVE	
6	1	41675003-6	SPRAY BAR	
7	1	41675003-7	SPRAY BAR	
8	1	41675003-8	SPRAY BAR	
9	1	41675003-9	SPRAY BAR	





ITEM	QTY	DESCRIPTION/MATERIALS
1	1	KOMEY 11 GALLON 1 1/4" NPT ACCUMULATOR BOTTLE
2	6	FLOW REGULATOR ~ PARKER PF 800 B
3	1	TOGGLE VALVE ~ DRECO 60PN-1015
4	1	EMERGENCY LOWERING VALVE ~ KOBELT 25428CEKS
5	6	1/2" NPT COMP RELAY VALVE ~ KOBELT 1776A
6	4	BELLOWS RELAY ~ SCHRADER M065-418-26
7	1	CROWN SAVER RESET VALVE ~ SCHRADER M065-418-51
8	1	FILTER REGULATOR SMC MODEL NAW 4000-N04-B
10	1	1/2" CHECK VALVE SMC MODEL NAK-4000-N04
11	1	BOOSTER REGULATOR ~ SMC MODEL NVBA 4100-T04G
12	1	GAS BOTTLE AIR RECEIVER ~ ACCUMULATORS Inc. A15GB3100

4/2-97.

☑ Code 1

☐ Code 2 A -

☐ Code 2 - ACCEPTED WITH COMMENTS INCORPORATED

☐ Code 3 - NOT ACCEPTED REVISE AND RESUBMIT

☐ Code 4 - FOR INFORMATION ONLY

PHILLIPS PETROLEUM COMPANY NORWAY

102334 DRAWWORKS

65-00092

D2000AC DRAWWORKS PNEUMATIC CONTROLS P & ID

Red-Line incorp.

07	97/01/23	RED-LINE MARK-UPS	DCT	DA	DA
06	96/09/12	RE-ISSUED FOR PROJECT ACCEPTANCE	DCT	BMac	TW
05	95/10/12	RE-ISSUED FOR PROJECT ACCEPTANCE	DCT	AKB	DA
04	95/08/03	RE-ISSUED FOR PROJECT ACCEPTANCE	DCT	AKB	DA
03	95/04/04	GENERAL REVISION	AKB	DA	TW
02	95/03/17	CHANGE VALVE 4 & 7 LOCATION	AKB	DA	TW

EKOX D047 910 1

HD-D003-0009-001 6.5 ID

THIS JOB ORDER: 1675

QA/QC REQUIREMENTS: PHILLIPS QUALITY PLAN

LICENSED UNDER API SPEC 4F AND 8A

DRECO DRILLING MACHINERY

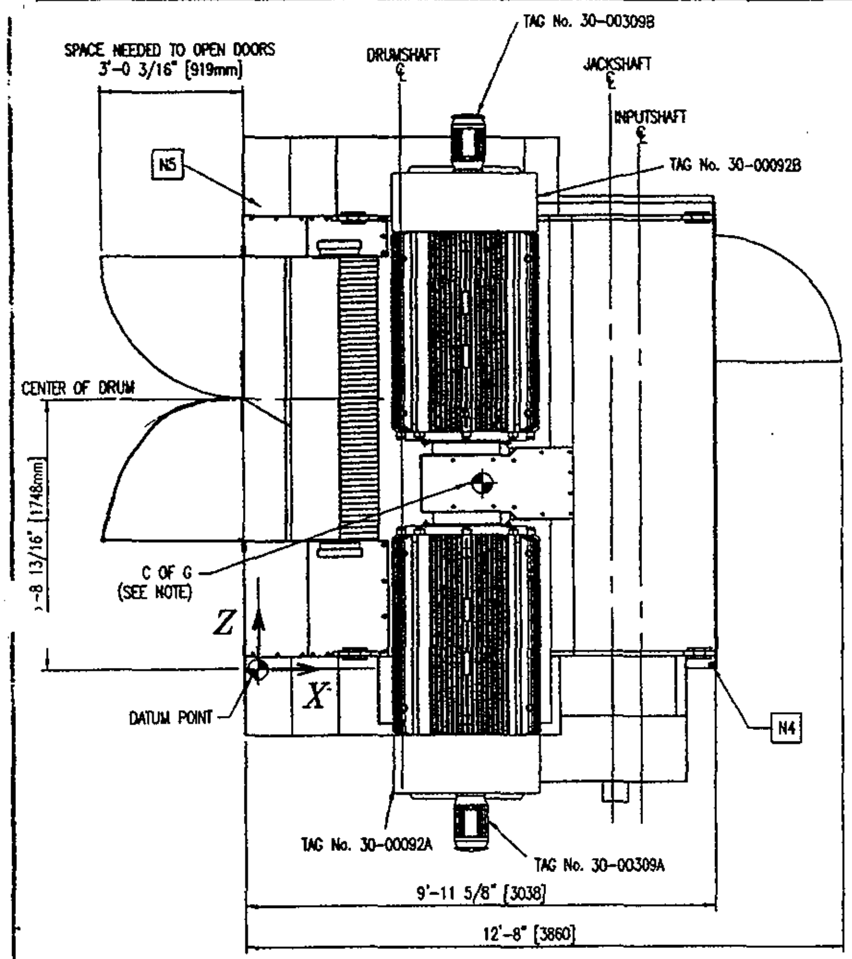
TITLE: D2000AC DRAWWORKS PNUEMATIC CONTROLS P & ID

CUSTOMER: PHILLIPS PETROLEUM COMPANY NORWAY

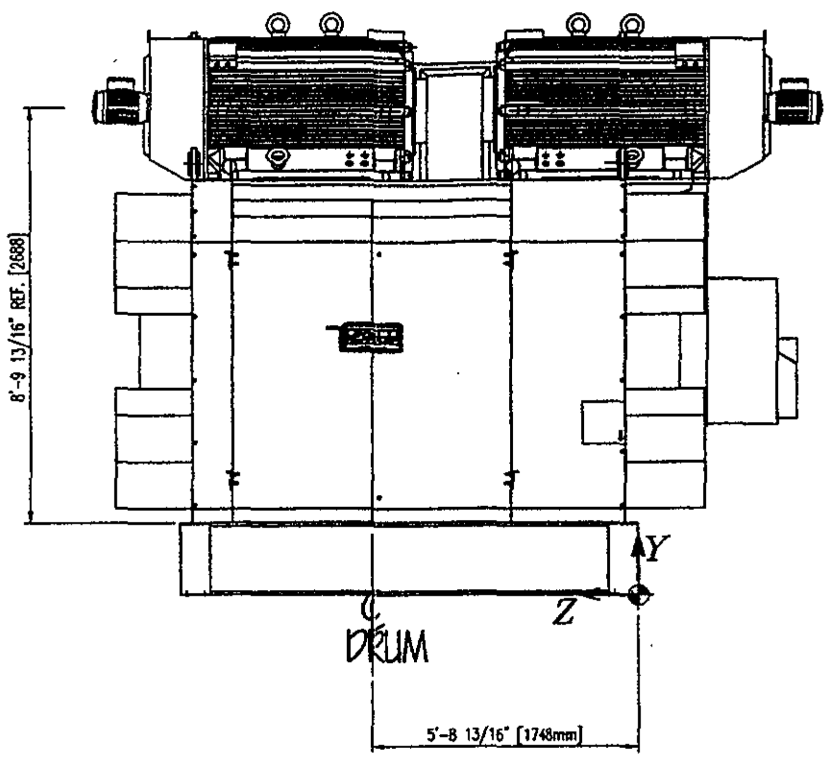
DRWN BY: R.F. CHK'D BY: DA

DATE: 94/01/18 AUTHORIZED BY: TW FILE CODE: DNS

(DS192) 12"=12" DRAWING NUMBER: 41675004 07

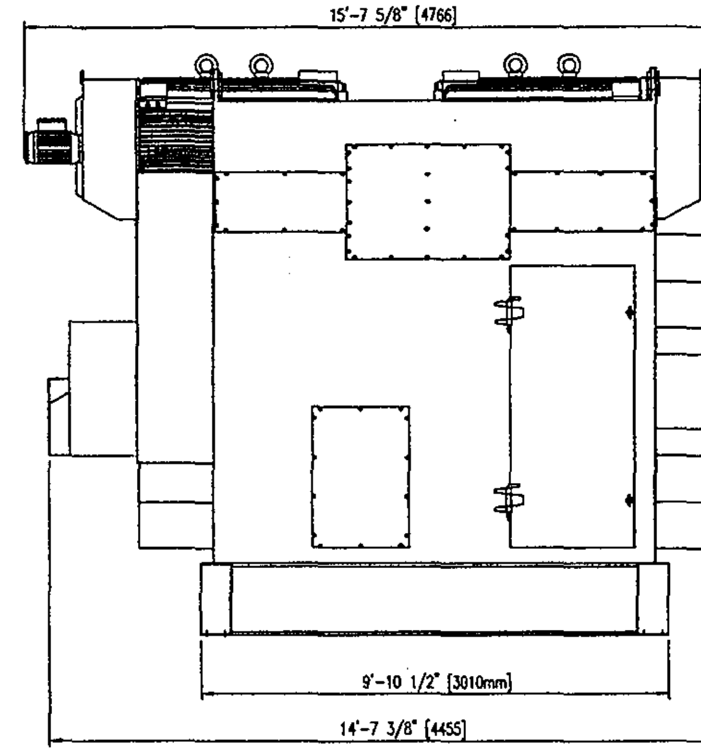


PLAN VIEW



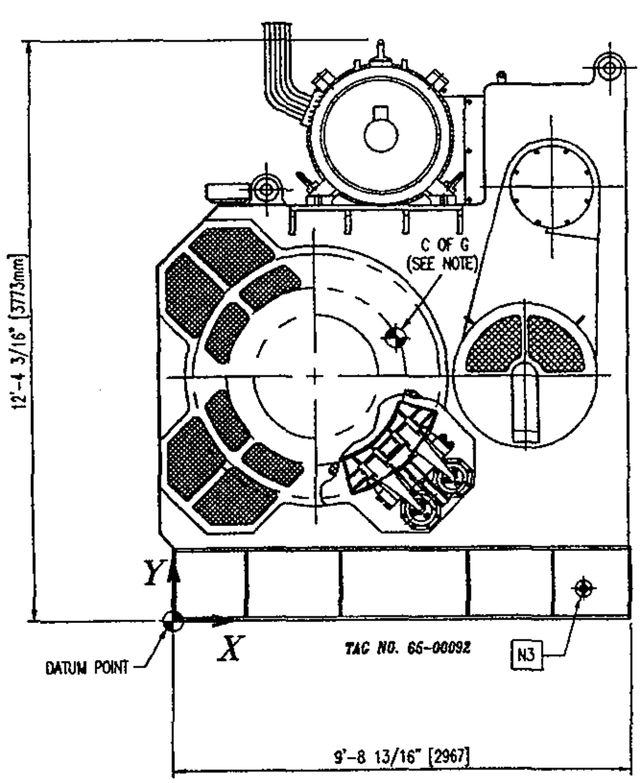
FRONT ELEVATION

NOZZLE SCHEDULE							
ITEM	SERVICE	SIZE NOZZLE	RATING	FACING	NOZZLE LOCATION X	Y	Z
N1	AIR SUPPLY TO DRAWWORKS SKID	ANSI-B16.5-1 1/2"	150 lb.	RF WN	2019	238	3010
N2	DRIP PAN DRAIN	ANSI-B16.5-1"	150 lb.	RF WN	293	108	3010
N3	OIL SUMP DRAIN	ANSI-B16.5-1"	150 lb.	RF WN	2657	198	0
N4	EARTHING BOSS	7/8"ϕ x 1 1/4" HIGH			2929	502	25
N5	EARTHING BOSS	7/8"ϕ x 1 1/4" HIGH			38	502	2984



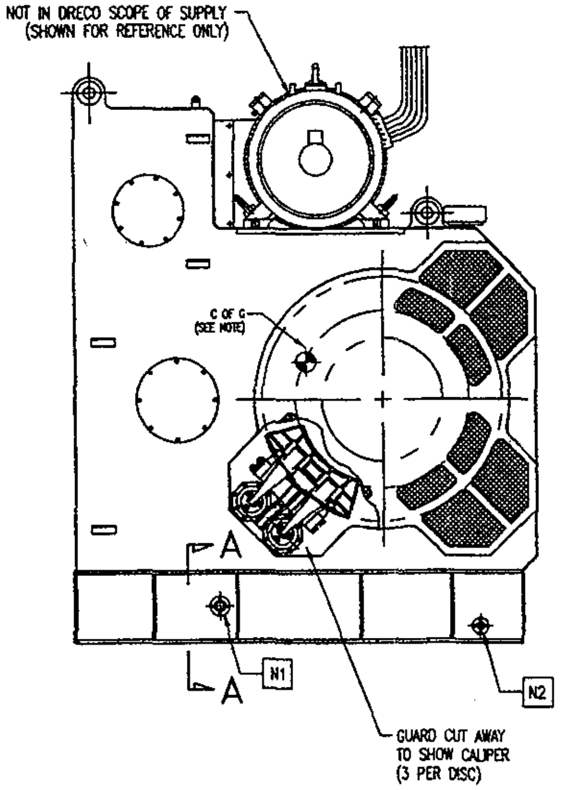
REAR ELEVATION

SIGN.: 4/2-97
☑ Code 1 - ACCEPTED
☐ Code 2 A
☐ Code 2
☐ Code 3
☐ Code 4 - FOR INFORMATION ONLY

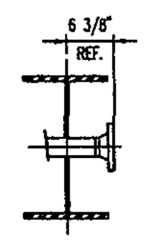


OFF-DRILLER'S SIDE

AC MOTORS ARE NOT IN DRECO SCOPE OF SUPPLY (SHOWN FOR REFERENCE ONLY)



DRILLER'S SIDE



SECTION A-A

NOTE:

1. ESTIMATED OPERATING CENTER OF GRAVITY LOCATION FROM DATUM POINT. (NOT INCLUDING ABB 450 AC MOTORS)
   X = 1442 mm
   Y = 1816 mm
   Z = 1197 mm
2. ESTIMATED OPERATING WEIGHT OF DRAWWORKS = 27 mT (NOT INCLUDING ABB 450 AC MOTORS)
3. TWO (2) ABB450 LM8 AC MOTORS ARE NOT IN DRECO SCOPE OF SUPPLY. SHOWN FOR REFERENCE ONLY.

PHILLIPS PETROLEUM COMPANY NORWAY
HITEC
102334 DRAWWORKS
65-00092
D2000AC DRAWWORKS GENERAL ARRANGEMENT

05	030297	Red lines Incorporated			
04	15.9.11	As-Built			
03	95/08/01	RE-ISSUED FOR PROJECT ACCEPTANCE	DCT	AKB	DA
02	95/02/28	NEW SKID BASE & ADD NOZZLE N3/UPDATE SCHED.	D.W.	K.A.B.	D.A.
01	95/02/03	FOR PROJECT ACCEPTANCE	R.F.	D.A.	T.W.

EKOX D047
910 M
6.8 MA

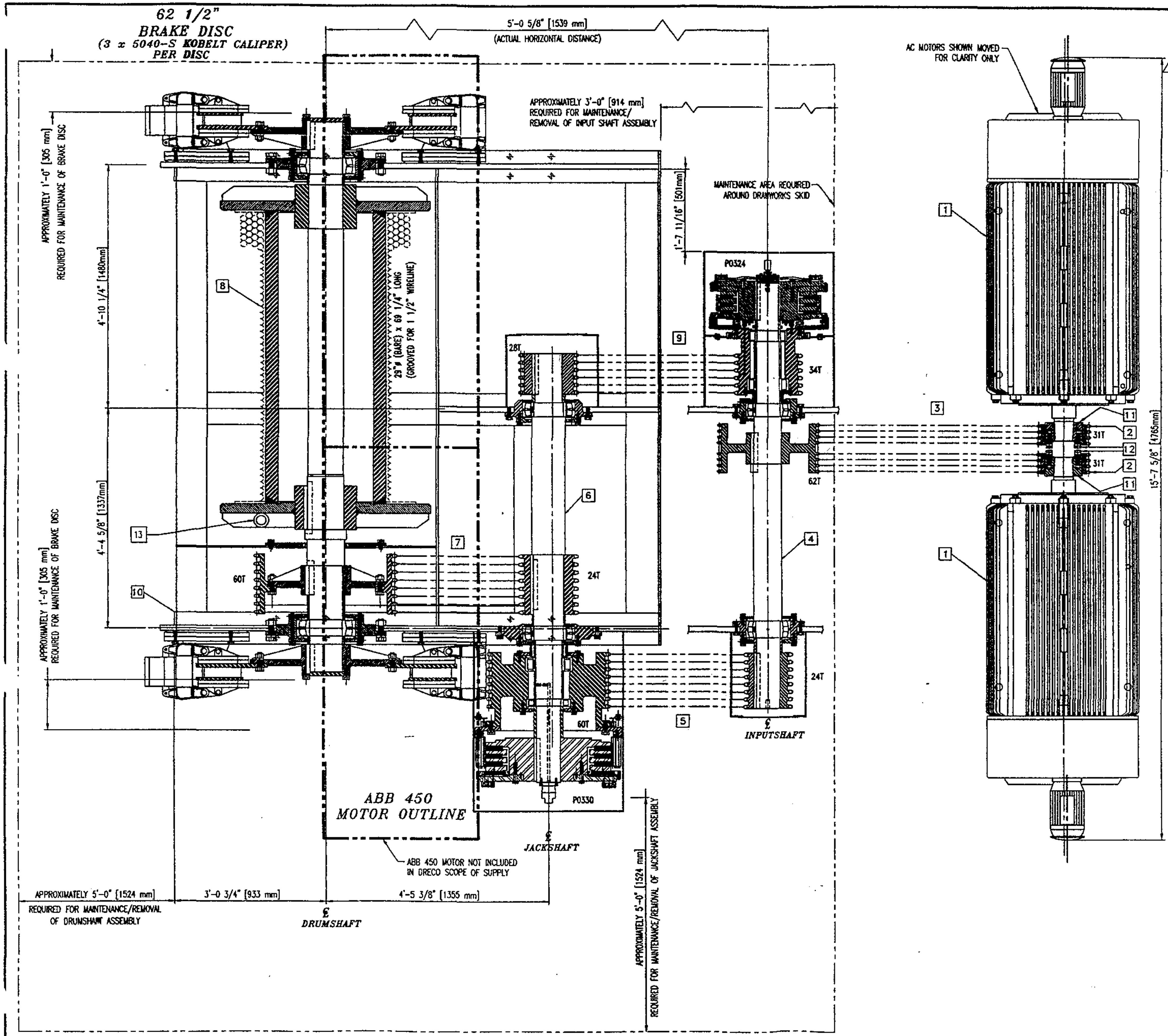
H D - D 0 0 3 - 0 0 1 2 - 0 0 1

THIS JOB ORDER: 1675
QA/QC REQUIREMENTS: PHILLIPS QUALITY PLAN

LICENSED UNDER API SPEC 4F AND 8A

DRECO DRILLING MACHINERY

TITLE: D2000AC DRAWWORKS GENERAL ARRANGEMENT
CUSTOMER: PHILLIPS PETROLEUM COMPANY OF NORWAY
DRWN BY: D. WEISS CHK'D BY: K.A.B.
DATE: 95/02/03 AUTHORIZED BY: D.A. FILE CODE: DNS
(DM8) 1/2"=12" DRAWING NUMBER: 41675001 REV 03



I.D.	QTY	PART NO.	DESCRIPTION/SHIPPING MARK	WT
1	2	450 LM8	ABB MOTOR (SUPPLIED BY OTHERS)	23348
2	2	A9540099	MOTOR SPROCKET	328
3	2	RC100FREW4	LINK-BELT CHAIN – 120 PITCHES~1 1/4" PITCH	254
4	1	41675014	INPUT SHAFT ASSEMBLY	5147
5	1	RC120FREW8	LINK-BELT CHAIN – 108 PITCHES~1 1/2" PITCH	402
6	1	41675015	JACKSHAFT ASSEMBLY	6663
7	1	RC140FREW8	LINK-BELT CHAIN – 104 PITCHES~1 1/2" PITCH	564
8	1	41675025	DRUM SHAFT ASSEMBLY	21941
9	1	RC120FREW6	LINK-BELT CHAIN – 96 PITCHES~1 1/2" PITCH	216
10	1	41675074	SHELL w/ SKID	18956
11	2	A9551111	SPROCKET HUB	172
12	24	–	1" NS BOLTS (14 tpi) A320 Gr. L7	12
13	1	41675091	DRUM CLAMP	47

TOTAL WEIGHT = 78 050# [35 435 kg]

HITEC A.S.
SIGN.: DATE: 4/2-97
☑ Code 1 - ACCEPTED
☐ Code 2 A - PROVISIONAL ACCEPTANCE INTERFACE
☐ Code 2
☐ Code 3
☐ Code 4

NOTES: 1. INPUT SHAFT SHOWN OUT OF POSITION FOR CLARITY.
2. ABB 450LM8 AC MOTORS ARE NOT IN DRECO SCOPE OF SUPPLY.

PHILLIPS PETROLEUM COMPANY NORWAY

HITEC

102334 DRAWWORKS

D2000AC DRAWWORKS PLAN VIEW

65-00092

04	96/11/20	CHANGED PITCH FROM 1 1/2" TO 1 1/4"	LM	SMac	TW
03	95/08/03	RE-ISSUED FOR PROJECT ACCEPTANCE	DCT	AKB	DA
02	95/03/11	GENERAL REVISION	DCT	DA	TW
01	95/02/06	ISSUED FOR CONSTRUCTION	RF	DA	TW

EKOX D047 910 M 6.5 MA

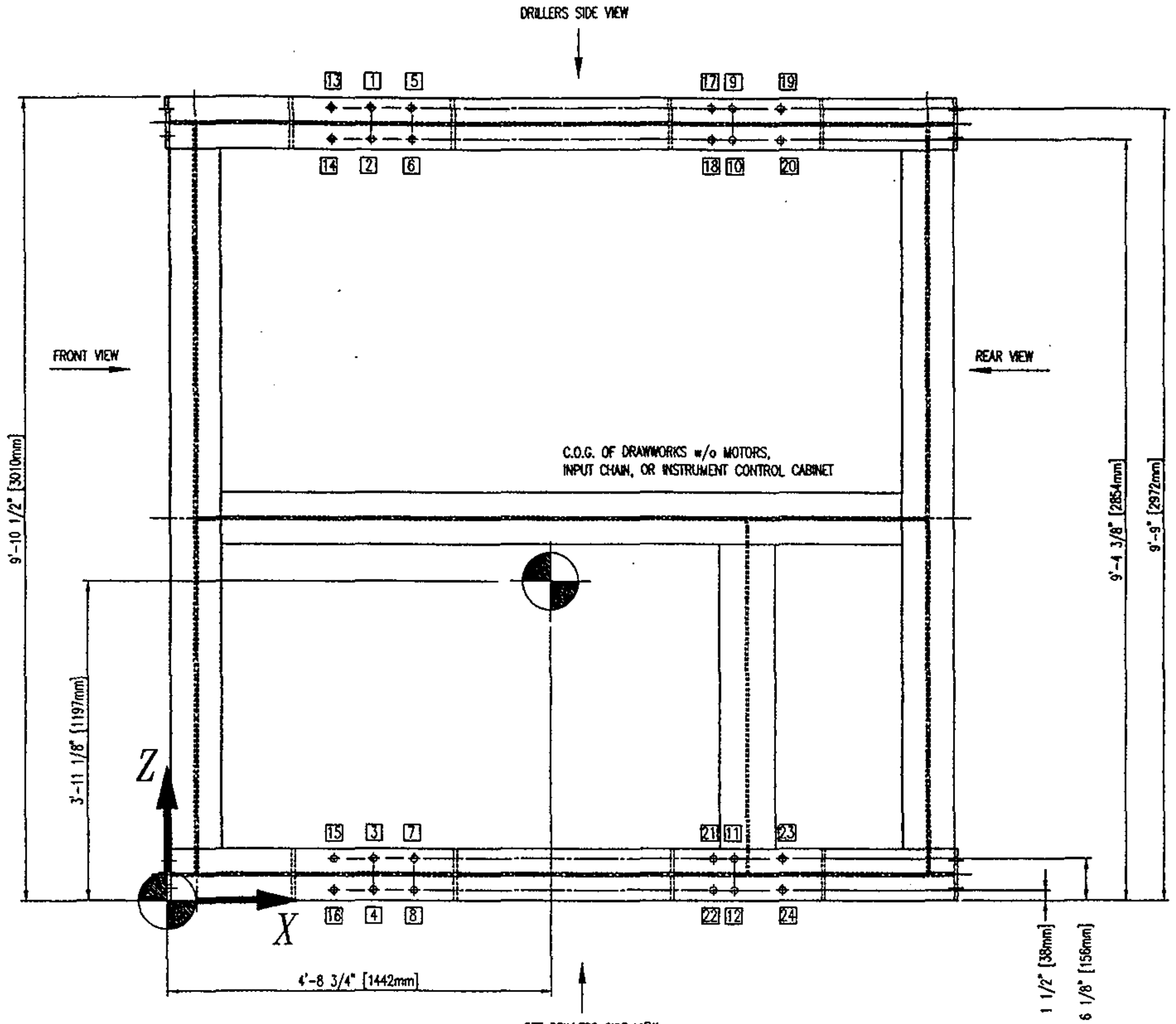
HD-D003-0012-002

THIS JOB ORDER: 1675
QA/QC REQUIREMENTS: STANDARD

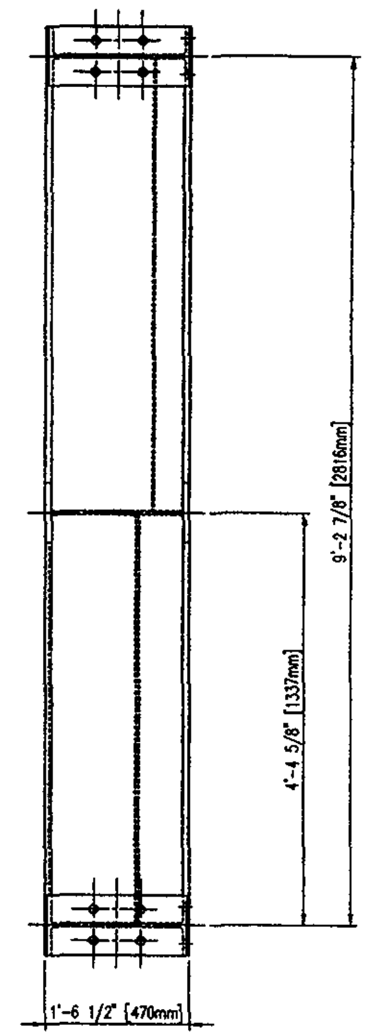
LICENSED UNDER API SPEC 4F AND 8A

DRECO DRILLING MACHINERY

TITLE: D2000AC DRAWWORKS PLAN VIEW
CUSTOMER: PHILLIPS PETROLEUM COMPANY NORWAY
DRWN BY: R.F. CHK'D BY: DA
DATE: 94/10/13 AUTHORIZED BY: TW FILE CODE: DNS
(DS16) 1"=12" DRAWING NUMBER: 41675002 04



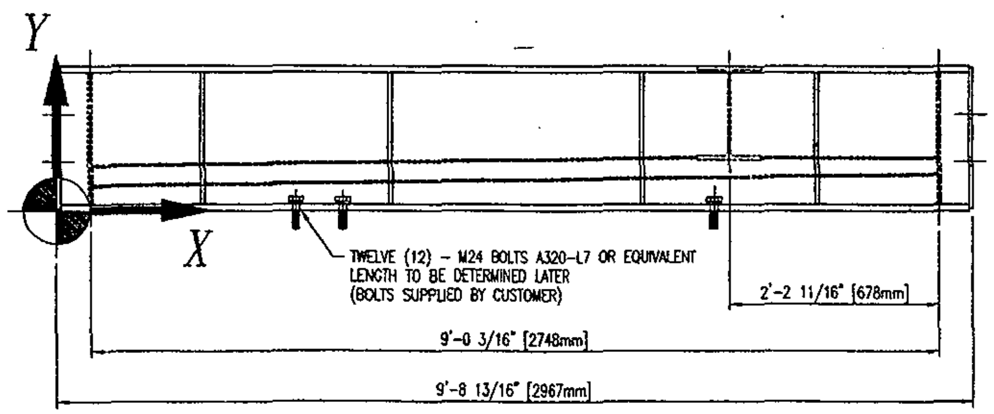
PLAN VIEW



REAR VIEW ELEVATION

TIE DOWN POINT	BOLT LOCATION X	Y	Z
1	2'-6 3/4" [781 mm]	0	9'-9" [2972 mm]
2	2'-6 3/4" [781 mm]	0	9'-4 3/8" [2854 mm]
3	2'-6 3/4" [781 mm]	0	6 1/8" [156 mm]
4	2'-6 3/4" [781 mm]	0	1 1/2" [38 mm]
5	3'-0 3/4" [933 mm]	0	9'-9" [2972 mm]
6	3'-0 3/4" [933 mm]	0	9'-4 3/8" [2854 mm]
7	3'-0 3/4" [933 mm]	0	6 1/8" [156 mm]
8	3'-0 3/4" [933 mm]	0	1 1/2" [38 mm]
9	6'-11 7/8" [2130 mm]	0	9'-9" [2972 mm]
10	6'-11 7/8" [2130 mm]	0	9'-4 3/8" [2854 mm]
11	6'-11 7/8" [2130 mm]	0	6 1/8" [156 mm]
12	6'-11 7/8" [2130 mm]	0	1 1/2" [38 mm]
• 13	2'-0 3/4" [629 mm]	0	9'-9" [2972 mm]
• 14	2'-0 3/4" [629 mm]	0	9'-4 3/8" [2854 mm]
• 15	2'-0 3/4" [629 mm]	0	6 1/8" [156 mm]
• 16	2'-0 3/4" [629 mm]	0	1 1/2" [38 mm]
• 17	6'-8 7/8" [2054 mm]	0	9'-9" [2972 mm]
• 18	6'-8 7/8" [2054 mm]	0	9'-4 3/8" [2854 mm]
• 19	7'-6 3/4" [2305 mm]	0	9'-9" [2972 mm]
• 20	7'-6 3/4" [2305 mm]	0	9'-4 3/8" [2854 mm]
• 21	6'-8 7/8" [2054 mm]	0	6 1/8" [156 mm]
• 22	6'-8 7/8" [2054 mm]	0	1 1/2" [38 mm]
• 23	7'-6 3/4" [2305 mm]	0	6 1/8" [156 mm]
• 24	7'-6 3/4" [2305 mm]	0	1 1/2" [38 mm]

• NOTE: TIE DOWN POINTS 13 TO 24 ARE NOT USED.



OFF DRILLERS SIDE VIEW ELEVATION

HITEC A.S.
SIGN.: [signature] DATE: 4/2-97
☑ Code 1 - ACCEPTED
☐ Code 2 A - PROVISIONAL ACCEPTED OF INTERFACE INFO FROZEN
☐ Code 2 - ACCEPTED WITH COMMENTS INCORPORATED
☐ Code 3 - NOT ACCEPTED REVISE AND RESUBMIT
☐ Code 4 - FOR INFORMATION ONLY

PHILLIPS PETROLEUM COMPANY NORWAY

HITEC

102334 DRAWWORKS

D2000AC DRAWWORKS FOUNDATION & BASE LAYOUT

65-00092

049703 Redlines Incorp.

03	95/08/25	REVISED BOLT HOLES FOR DNV APPROVAL	EY	AKB	DA
02	95/08/03	RE-ISSUED FOR PROJECT ACCEPTANCE	DCT	AKB	DA
01	95/02/03	FOR PROJECT ACCEPTANCE	R.F.	D.A.	T.W.

EKOX | D47 | 910 | D | 6.9 | MG

H D - D 0 0 3 - 0 0 1 3 - 0 0 1

THIS JOB ORDER: 1675
QA/QC REQUIREMENTS: PHILLIPS QUALITY PLAN

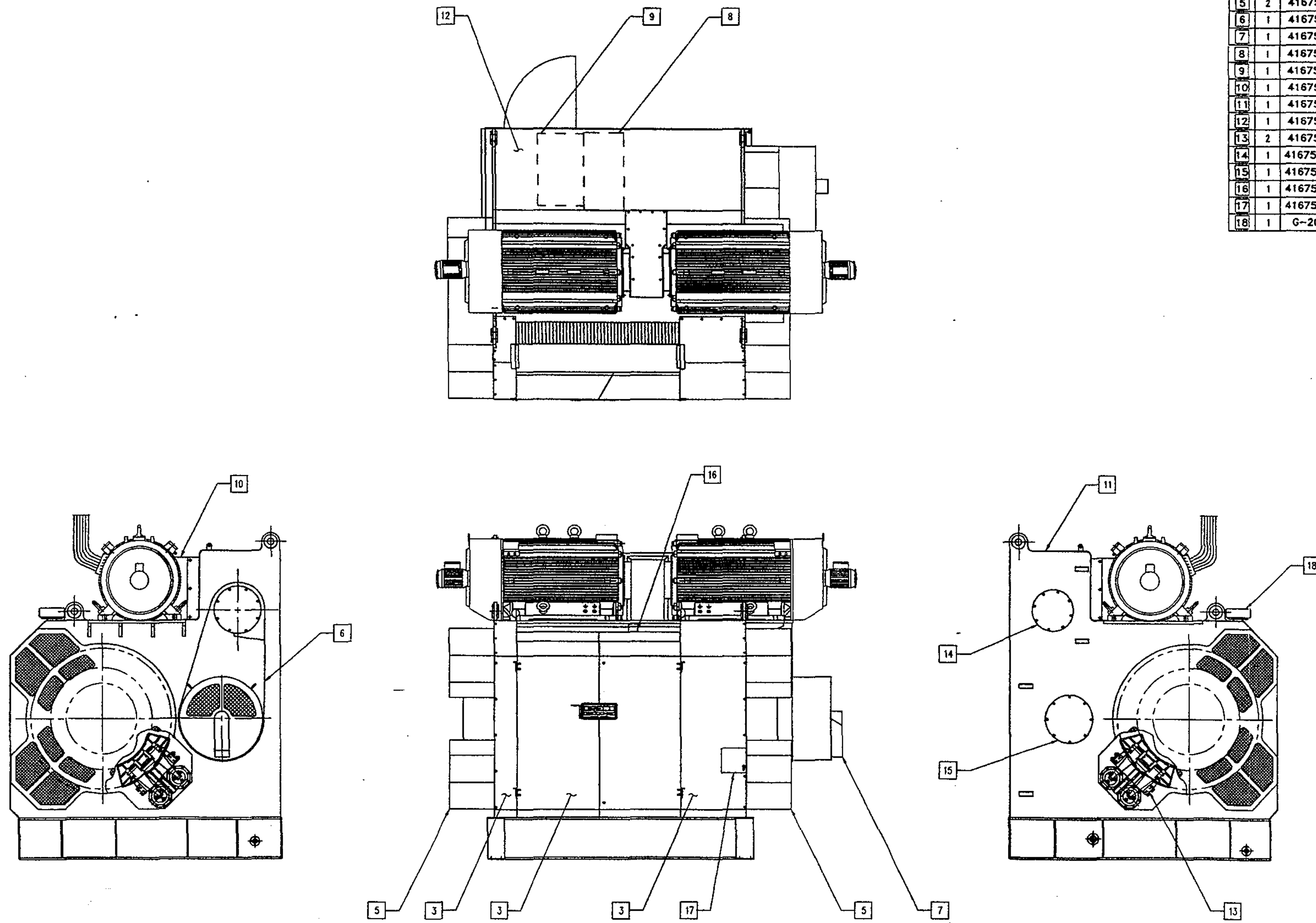
LICENSED UNDER API SPEC 4F AND 8A

DRECO DRILLING MACHINERY

TITLE: D2000AC DRAWWORKS FOUNDATION & BASE LAYOUT
CUSTOMER: PHILLIPS PETROLEUM COMPANY OF NORWAY
DRWN BY: R.F. CHK'D BY: D.A.
DATE: 95/02/03 AUTHORIZED BY: T.W. FILE CODE: DNS
(DM16) 1"=12" DRAWING NUMBER: 41675000 03

I.D.	QTY	PART NO.	DESCRIPTION/SHIPPING MARK	WT
1	1	41675002	PLAN VIEW	78050
2	1	41675086	FRONT DRUM GUARD	375
3	1	41675085A	DRILLERS-SIDE FRONT GUARD	210
4	1	41675085B	OFF-DRILLERS-SIDE FRONT GUARD	324
5	2	41675088	BRAKE DISC & CALIPER GUARD	1554
6	1	41675079	EXTERNAL INPUTSHAFT - JACKSHAFT CHAINGUARD	396
7	1	41675084	GUARD FOR P0330 CLUTCH	189
8	1	41675078	INTERNAL INPUTSHAFT - JACKSHAFT CHAINGUARD	335
9	1	41675083	GUARD FOR P0324 CLUTCH	149
10	1	41675077	MOTOR SPROCKETS CHAIN GUARD	243
11	1	41675076	TOP PLATE	373
12	1	41675096	INSTRUMENTATION LAYOUT	-
13	2	41675093	CALIPER PAD MOUNTING	492
14	1	41675020C	INPUT SHAFT DRILLER's SIDE COVER	20
15	1	41675020D	JACKSHAFT DRILLERS SIDE COVER	23
16	1	41675020E	TOGGLE VALVE CHANNEL	15
17	1	41675020F	FRONT CONTROL PANEL HATCH	8
18	1	G-20-H	OTECO TURN BACK ROLLERS (1 SET)	100

TOTAL WEIGHT = 82 856# (37 617 kg)



SIGN.: 4/2-97.
Code 1
Code 2 A
Code 2
Code 3
Code 4

PHILLIPS PETROLEUM COMPANY NORWAY
102334
DRAWWORKS
HITEC
65-00092

D2000AC OVERALL ASSEMBLY

02 97/02/13 Red-Lines Incorp.

01	95/08/04	ISSUED FOR PROJECT ACCEPTANCE	DCT	AKB	DA

EKOX | D47 | 910 | M | 6.8 | MA

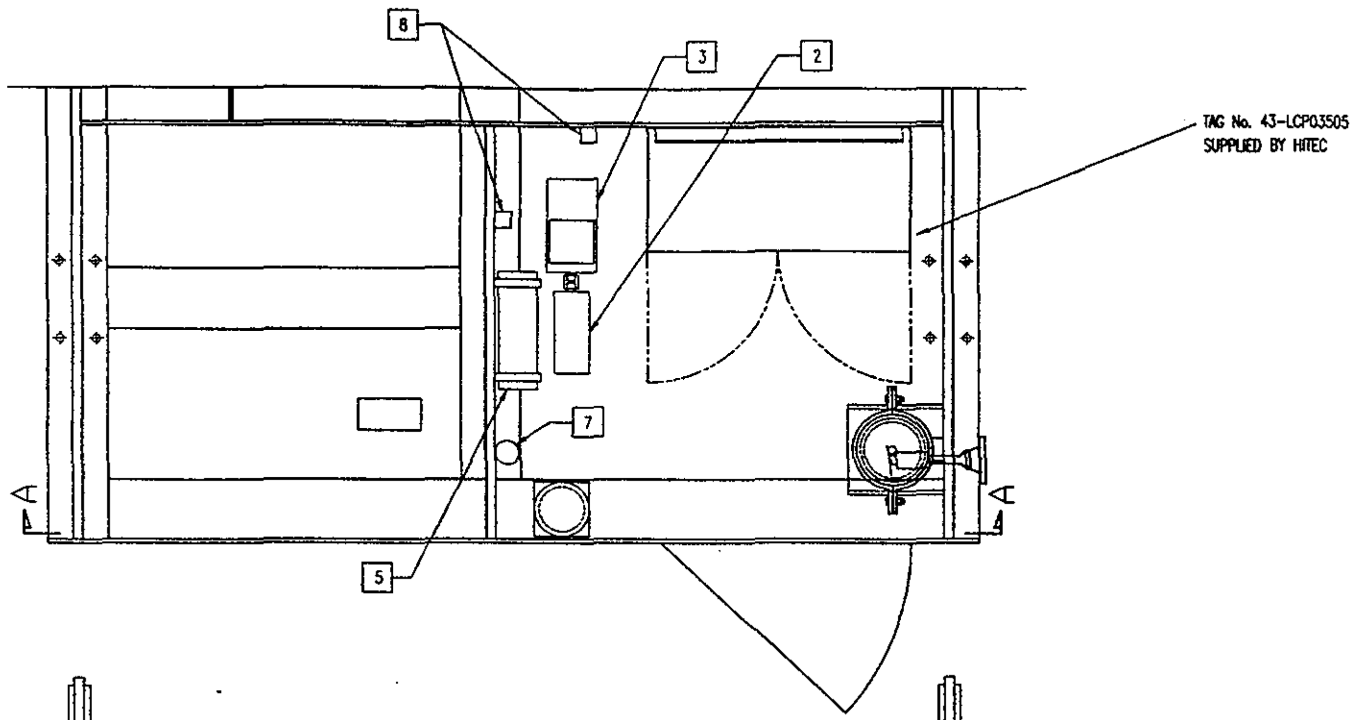
H D - D 0 0 3 - 0 0 3 6 - 0 0 1

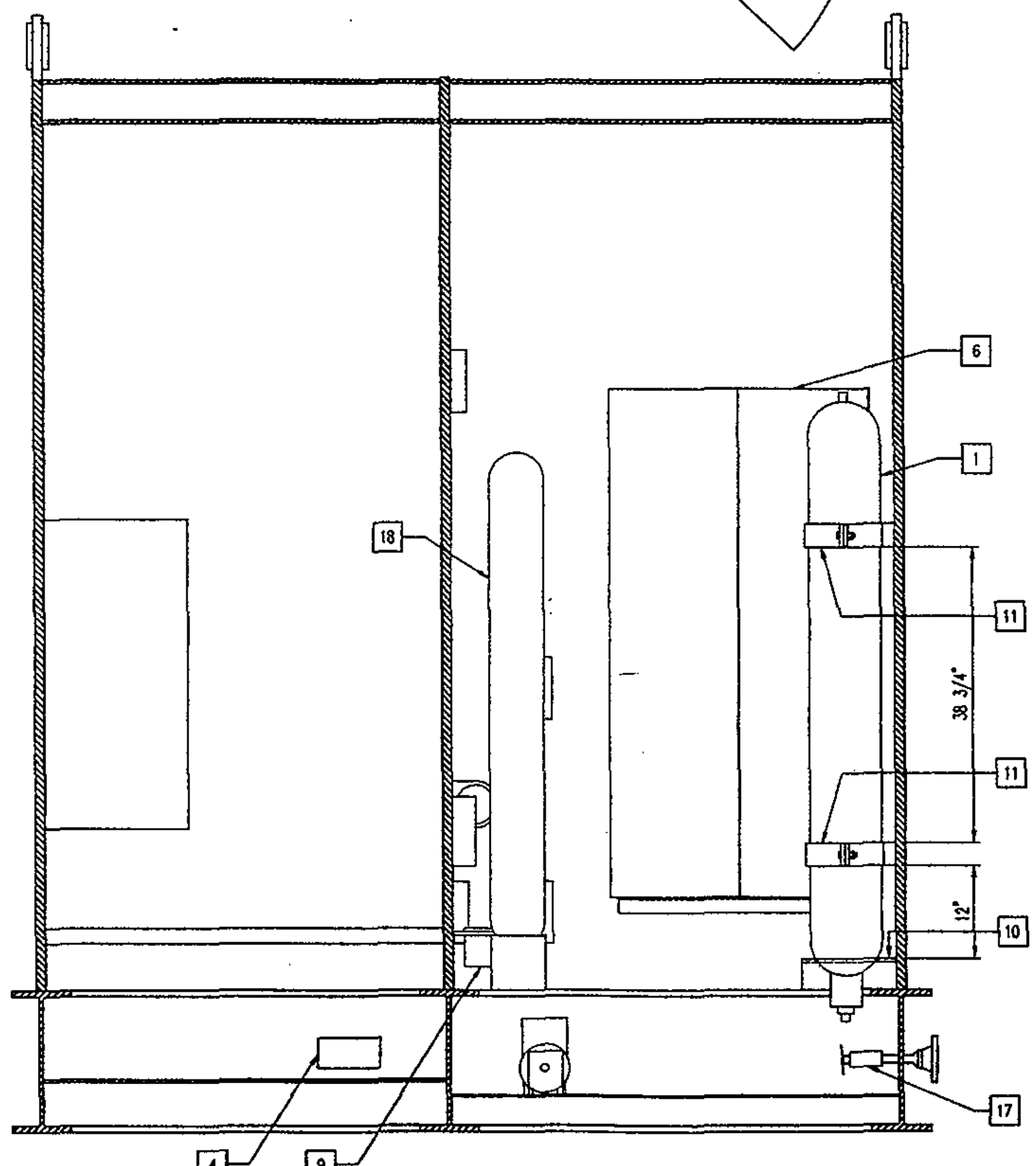
THIS JOB ORDER: 1675
QA/QC REQUIREMENTS: STANDARD

LICENSED UNDER API SPEC 4F AND 8A

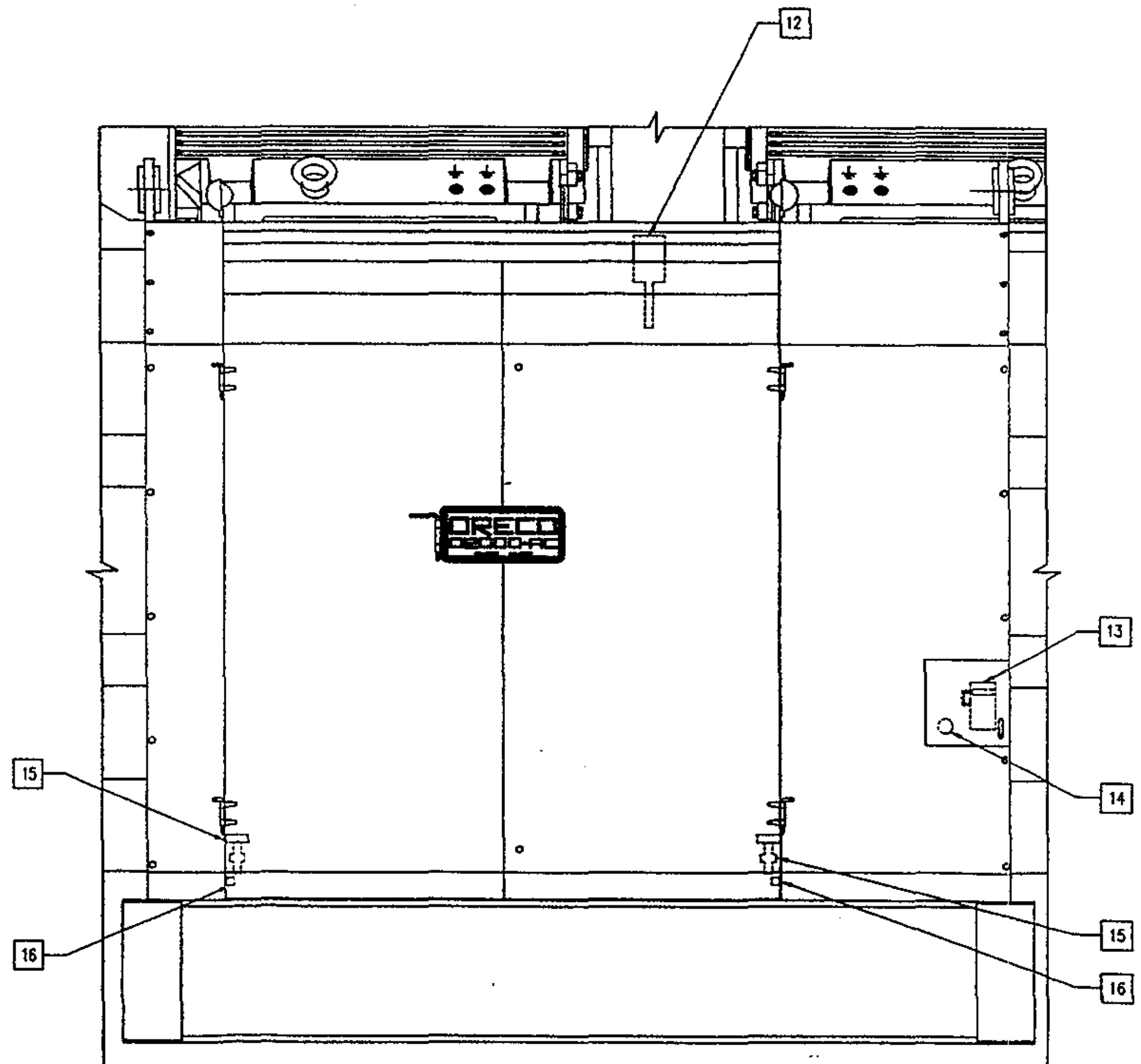
DRECO DRILLING MACHINERY

TITLE:	D2000AC OVERALL ASSEMBLY
CUSTOMER:	PHILLIPS PETROLEUM COMPANY NORWAY
DRWN BY: DCT	CHK'D BY: AKB
DATE: 95/08/02	AUTHORIZED BY: DA — FILE CODE: DNS
(DS8) 1/2"=12"	DRAWING NUMBER: 41675019 — 01





VIEW A-A



PARTIAL FRONT VIEW

I.D.	QTY	PART NO.	DESCRIPTION/SHIPPING MARK	WT
1	1	A15GB3100	ACCUMULATORS Inc. GAS BOTTLE AIR RECEIVER	–
2	1	P25X-942-BE-L18-2	COMMERCIAL INTERTECH LUBE PUMP	–
3	1	M2BA132S6	ABB 3 kW AC MOTOR (for LUBE PUMP)	–
4	1	FLR4151EFNN	GRESEN OIL FILTER	–
5	1	NVBA 4100-T04G	SMC BOOSTER REGULATOR	–
6	1	REF	INSTRUMENT CABINET – (HITEC SUPPLIED)	–
7	1	NAW 4000-N04-8	SMC FILTER REGULATOR	–
8	4	M085-418-26	SCHRADER BELLOWS RELAY	–
9	1	ULTIPOR III	PALL FILTER	–
10	1	41675020A	AIR BOTTLE BASE	–
11	2	41675020B	AIR BOTTLE BRACKETS	–
12	1	60PN-1015	DRECO TOGGLE VALVE	–
13	1	2542BCEKS	KOBELT EMERGENCY LOWERING VALVE	–
14	1	M065-41851	SCHRADER CROWN SAVER RESET VALVE	–
15	6	1776A	KOBELT 1/2" NPT COMP RELAY VALVE	–
16	6	PF8008	PARKER FLOW REGULATOR	–
17	1	NAK-4000-NV4	SMC 1/2" CHECK VALVE	–
18	1	11 GAL.	KOMEY 1 1/4" NPT ACCUMULATOR BOTTLE	–

HITEC A.S.
DATE: 4/2-97.

NOTE: 1. INTERNAL INPUTSHAFT TO JACKSHAFT CHAIN CASE & P0324 CLUTCH COVER OMITTED FOR CLARITY.

2. INSTRUMENT CABINET SUPPLIED BY HITEC.

3. TUBING OMITTED FOR CLARITY.

PHILLIPS PETROLEUM COMPANY NORWAY

HITEC

102334 DRAWWORKS

65-00092

DRAWWORKS INSTRUMENTATION LAYOUT

039723 Red-Lines Incorp.

02	96/09/12	ISSUED FOR PROJECT ACCEPTANCE	DCT	BMac	TW
01	95/06/02	ISSUED FOR PROJECT ACCEPTANCE	DCT	AKB	DA

EKOX D47

910

H D - D 0 0 3 - 0 0 3 7 - 0 0 1

6.8

THIS JOB ORDER: 1675
QA/QC REQUIREMENTS: STANDARD

LICENSED UNDER API SPEC 4F AND 8A

DRECO DRILLING MACHINERY

TITLE: DRAWWORKS INSTRUMENTATION LAYOUT

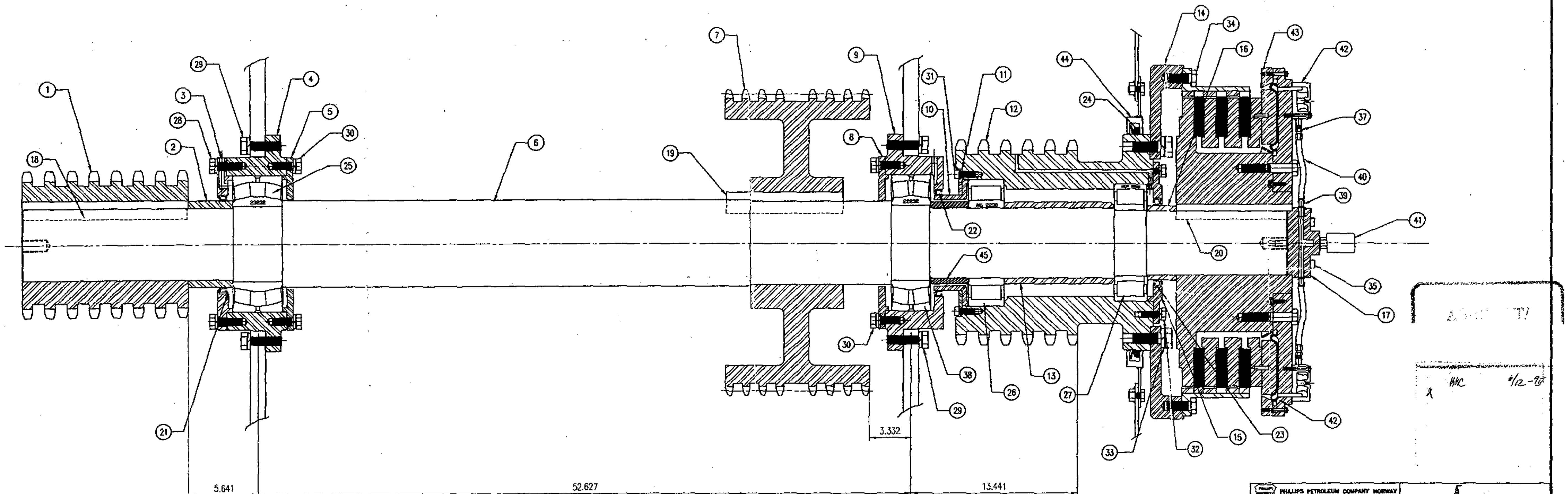
CUSTOMER: PHILLIPS PETROLEUM COMPANY NORWAY

DRWN BY: DCT CHK'D BY: AKB

DATE: 95/03/30 AUTHORIZED BY: DA FILE CODE: DNS

(DM16) 1"=12" DRAWING NUMBER: 41675096 REV 02

ITEM	QTY	PART NO.	DESCRIPTION/MATERIALS	WT	M.T.C	ITEM	QTY	PART NO.	DESCRIPTION/MATERIALS	WT	M.T.C	ITEM	QTY	PART NO.	DESCRIPTION/MATERIALS	WT
31	6		SOCKET HEAD CAPSCREW 1/2"ϕ X 1 1/4" LONG	-		16	1	41675013	CLUTCH SPACER	5		1	1	41675008	24T 120-8 SPROCKET	280
32	8		HEX HEAD CAPSCREW 1/2"ϕ X 1 1/2" LONG C/W LOCK WASHERS	-		17	1	A9540103	ENDPLATE	14		2	1	A9540041	SPACER	13
33	12		HEX HEAD CAPSCREW 7/8"ϕ X 2 1/2" LONG C/W LOCK WASHERS	-		18	1	41675021/A	KEY	8		3	1	A9540020	RETAINER PLATE	38
34	12		HEX HEAD CAPSCREW 3/4"ϕ X 2 1/4" LONG C/W LOCK WASHERS	-		19	1	41675021/B	KEY	8		4	1	41675005	BEARING HOUSING	110
35	2		HEX HEAD CAPSCREW 1/2"ϕ X 2 1/4" LONG	-		20	1	41675021/C	KEY	3		5	1	41675053	RETAINER PLATE	24
36	-		-	-		21	1	416044	NATIONAL SEAL	-		6	1	41675010	INPUT SHAFT	1289
37	2	SS40064AN	UNION	-		22	1	CR79961	CRS SEAL	-		7	1	A9540102	62T 100P-4 DOUBLE SPROCKET (2 x 120 PITCHES CHAIN)	675
38	1	22232 CC	SKF - BEARING	-		23	1	455480	NATIONAL SEAL	-		8	1	41675054	RETAINER PLATE	21
39	2	SS6006	UNION	-		24	1	V450A	FORSHEDA V-RING	-		9	1	A9540039	BEARING HOUSING	115
40	2	-	3/8" TUBING (LENGTH TO SUIT)	-		25	1	23232 CC	SKF - BEARING C3 CLEARANCE	132		10	1	A9540022	RETAINER PLATE	13
41	1	B-3	ROTORSEAL, AIRFLEX PART NO. 145106BQ	X		26	1	NU 2230 E	SKF - BEARING C3 CLEARANCE	42		11	1	A9540047	BEARING RETAINER	5
42	2	XA4255	QUICK RELEASE VALVE BY TWIN DISC	X		27	1	NUP 2228 E	SKF - BEARING C3 CLEARANCE	31		12	1	41675017	34T 120-6 SPROCKET (96 PITCHES CHAIN)	772
43	1	PO324	TWIN DISC CLUTCH	X		28	8		HEX HEAD CAPSCREW 5/8"ϕ X 2" LONG C/W LOCK WASHERS	-		13	1	41675011	BEARING SPACER	46
44	1	41675022	FORSHEDA RING HOUSING ASEMBLY	51		29	16		HEX HEAD CAPSCREW 3/4"ϕ X 2 3/4" LONG C/W LOCK WASHERS	-		14	1	41675012	PO324 CLUTCH ADAPTER PLATE	503
45	1	A9540040	SPACER	9		30	16		HEX HEAD CAPSCREW 5/8"ϕ X 1 3/4" LONG C/W LOCK WASHERS	-		15	1	41675018	BEARING RETAINER	40



PHILLIPS PETROLEUM COMPANY NORWAY
102334 DRAWWORKS
INPUT SHAFT ASSEMBLY
65-00092
Dct 95/10/26 95/10/26 95/10/26
01 | 95/08/24 | FOR PROJECT ACCEPTANCE | DCT | AKB | DA
EKOX | D47
910 | M
H D H D 0 0 3 H 0 0 3 9 H 0 0 1 | 6.8 | MA

THIS JOB ORDER: 1675
QA/QC REQUIREMENTS: PHILLIPS QUALITY PLAN

LICENSED UNDER API SPEC 4F AND 8A

DRECO DRILLING MACHINERY

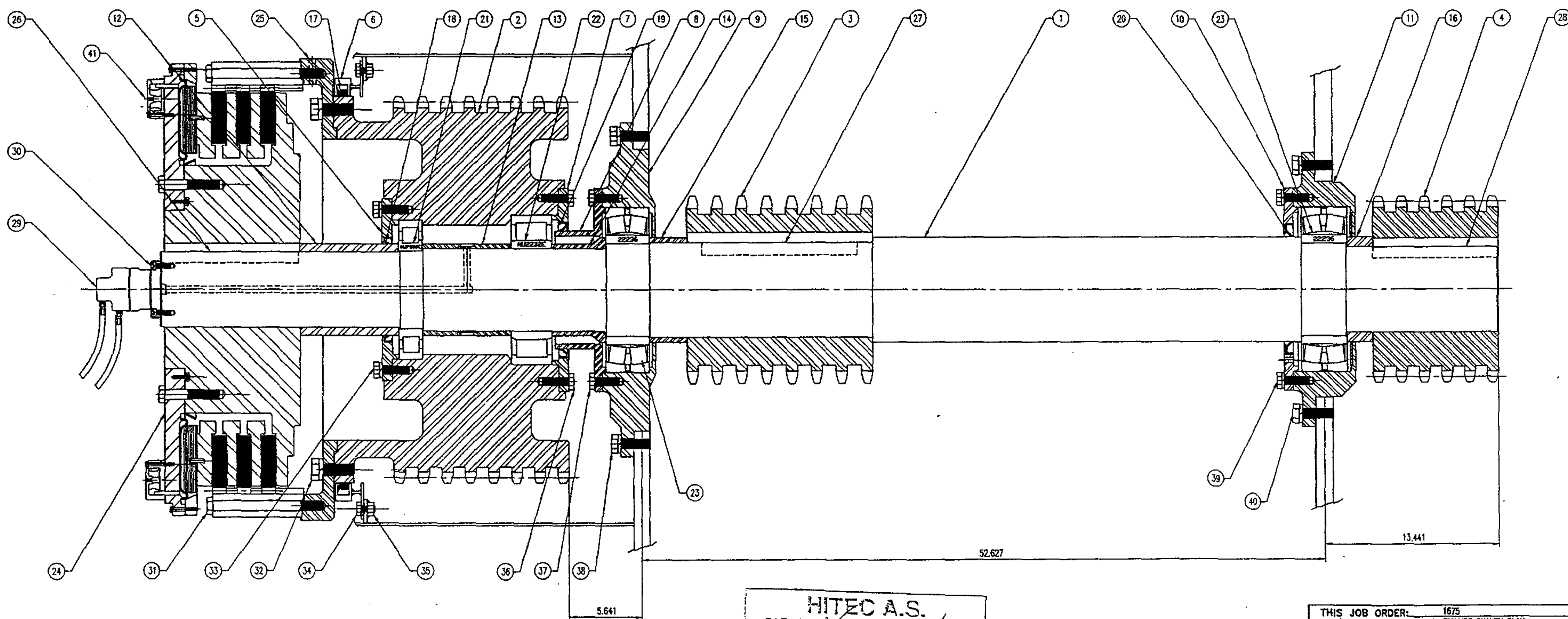
TITLE: INPUT SHAFT ASSEMBLY
CUSTOMER: PHILLIPS PETROLEUM COMPANY NORWAY
DRWN BY: R.F. | CHK'D BY: DA
DATE: 95/02/15 | AUTHORIZED BY: TW | FILE CODE: DNS
D48 | DRAWING NUMBER: 41675014 | REV 01

ITEM	QTY	PART NO.	DESCRIPTION/MATERIALS	WT
29	1	145583 AJ	AIRFLEX ROTORSEAL FBA	10
30	4		SOCKET HD CAPSCREW 3/8" x 1 1/2" LG	1
31	12		HEX HD CAPSCREW 3/4" x 8 1/2" LG c/w LW's	7
32	12		HEX HD CAPSCREW 7/8" x 2 1/2" LG c/w LW's	5
33	6		HEX HD CAPSCREW 5/8" x 2 1/4" LG c/w LW's	3
34	12		HEX HD CAPSCREW 3/4" x 1" LG	2
35	12		HEX HD NUT 3/4" THREAD	1
36	8		HEX HD CAPSCREW 5/8" x 2" LG	3
37	8		HEX HD CAPSCREW 5/8" x 2" LG	3
38	8		HEX HD CAPSCREW 3/4" x 2 1/2" LG c/w LW's	4
39	8		HEX HD CAPSCREW 5/8" x 2" LG c/w LW's	3
40	8		HEX HD CAPSCREW 3/4" x 2 1/2" LG c/w LW's	4
41	2	XA4255	TWIN DISC QUICK RELEASE VALVES	4

ITEM	QTY	PART NO.	DESCRIPTION/MATERIALS	WT
15	1	41675024	SPACER	7
16	1	A9540092	SPACER	9
17	1	V-750A	SKF FORSHEDA V-RING	2
18	1	416364	NATIONAL OIL SEAL	1
19	1	456462	NATIONAL OIL SEAL	1
20	1	417602	NATIONAL OIL SEAL	1
21	1	NUP 230E	SKF BEARING C3 CLEARANCE	23
22	1	NU 2232E	SKF BEARING C3 CLEARANCE	53
23	2	22236CCW33	SKF BEARING C3 CLEARANCE	130
24	1	PO 330	TWIN DISC CLUTCH	1700
25	1	A9540037	CLUTCH PLATE ADAPTOR FOR PO330 (PO230)	235
26	1	41675023A	KEY	7
27	1	41675023B	KEY	10
28	1	41675023C	KEY	6

ITEM	QTY	PART NO.		WT
1	1	41675016	JACKSHAFT	1140
2	1	41675007	SPROCKET 60T 120P-8	2160
3	1	41675006	SPROCKET 24T 140P-8	395
4	1	A9540054	SPROCKET 28T 120P-6	295.
5	1	A9540031	BEARING RETAINER	25
6	1	A9540120	FORSHEDA V-RING HOUSING ASSEMBLY	95
7	1	A9540014	BEARING RETAINER	35
8	1	41675030	BEARING RETAINER	33
9	1	A9540017	BEARING HOUSING	280
10	1	A9540036	BEARING RETAINER	35
11	1	A9540032	BEARING HOUSING	175
12	1	41675033	SPACER	26
13	1	41675032	SPACER	14
14	1	41675031	SPACER	10

TOTAL WEIGHT = 6,963# [3 158 kg]



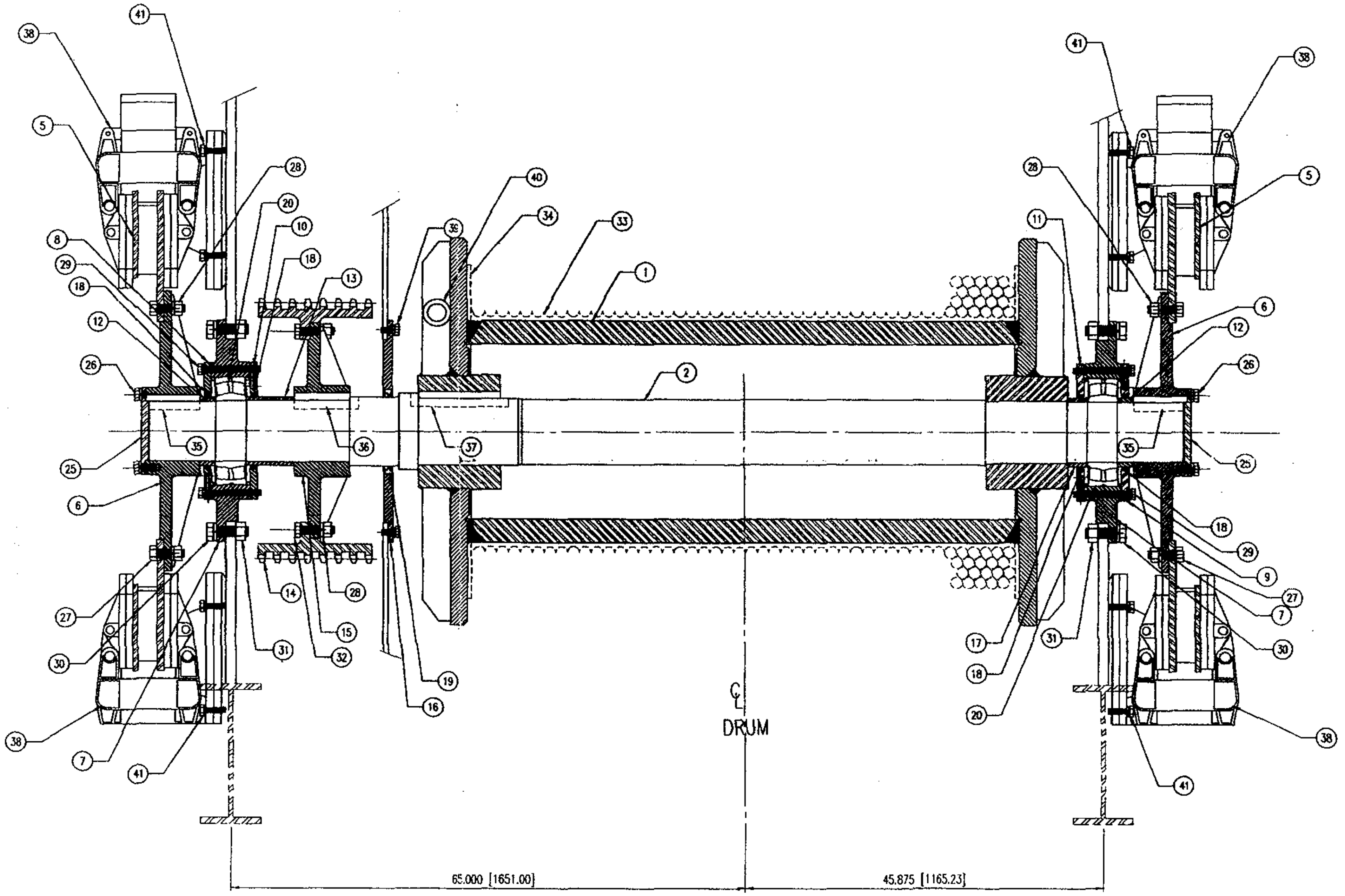
HITEC A.S.
SIGN.: DATE: 4/2-97.
☑ Code 1 ACCEPTED
☐ Code 2 A - PROVISIONAL ACCEPTANCE INTERFACE INFO REQ'D

PHILLIPS PETROLEUM COMPANY NORWAY
102334 DRAWWORKS
D2000AC JACKSHAFT ASSEMBLY
HITEC 65-00092
02/97/02 Red Lines Incorp
01 95/08/24 FOR PROJECT ACCEPTANCE DCT AKB DA
EKOX 047
910
6.8
H D - D 0 0 3 - 0 0 4 0 - 0 0 1

THIS JOB ORDER: 1675
QA/QC REQUIREMENTS: PHILLIPS QUALITY PLAN
LICENSED UNDER API SPEC 4F AND 8A

DRECO DRILLING MACHINERY

TITLE:	D2000AC JACKSHAFT ASSEMBLY
CUSTOMER:	PHILLIPS PETROLUEM COMPANY OF NORWAY
DRWN BY: D. WEISS	CHK'D BY: D.A.
DATE: 95/02/14	AUTHORIZED BY: D.A. FILE CODE: DNS
(DM48) 3"=12"	DRAWING NUMBER: 41675015 01



M.T.C	ITEM	QTY	PART NO.	DESCRIPTION/MATERIALS	WT
	1	1	41675040	DRUM BARREL	10470
	2	1	41675027	DRUM SHAFT	2019
	5	1	41675071	4" X 62.5" AIR COOLED BRAKE DISC SET	2200
	6	2	A9540005	FLANGED DISC BRAKE HUB	480
	7	2	A9540004	MAIN BEARING CARRIER	850
	8	1	A9540007	BEARING RETAINER PLATE	73
	9	1	A9540009	BEARING RETAINER PLATE	59
	10	1	A9540008	BEARING RETAINER PLATE	73
	11	1	A9540027	BEARING RETAINER PLATE	52
	12	2	A9540012	SPACER	18
	13	1	41675028	SPROCKET SPACER	125
	14	1	41675009	60 140-8 DRUM SPROCKET	1225
	15	1	A9540010	FLANGED SPROCKET HUB	355
	16	1	A9540028	V-220A SEAL RETAINER	190
	17	1	41675035	DRUM SPACER	8
	18	4	CR 90006	CR OIL SEAL TYPE CRWH1 R 10 X 9 X 5/8	-
	19	1	V220A	FORSHEDA V-RING - SKF	-
	20	2	22240 CC/W33	SPHERICAL BEARING - C3 CLEARANCE	192
	25	2	41675036	END CAP	82
	26	8		HEX HEAD CAPSCREW 7/8" NC X 1 3/4" LONG C/W LOCK WASHER	-
	27	32		HEX HEAD CAPSCREW 1 1/8" NC X 3 1/2" LONG	-
	28	44		HEX NUT & LOCK WASHERS - 1 1/8" NC	-
	29	16		HEX HEAD CAPSCREW 3/4" NC X 7 1/4" LONG C/W LOCK WASHERS	-
	30	16		HEX HEAD CAPSCREW 1 1/4" NC X 4 1/2" LONG C/W LOCK WASHERS	-
	31	16		HEX NUT - 1 1/4" NC	-
	32	12		HEX HEAD CAPSCREW 1 1/8" NC X 4 1/4" LONG C/W LOCK WASHERS	-
	33	-	REF	GROOVING - (LAGGING) 1 1/2" ROPE FURNISHED BY LEBUS	-
	34	-	REF	WEAR SLEEVE - 1 1/2" ROPE FURNISHED BY LEBUS	-
	35	2	A9540078/A	KEY	20
	36	1	A9540078/B	KEY	12
	37	1	A9540078/C	KEY	18
	38	6	5040 KOBELT	SPRING APPLIED - AIR RELEASED	3420
	39	8		HEX HEAD CAPSCREW 3/4" NC X 1 3/4" LONG C/W LOCK WASHERS	-
	40	1		1 1/2" CABLE CLAMP	-
	41	32		HEX HEAD CAPSCREW 3/4" NC X [illegible] LONG C/W LOCK WASHERS	-

AS-BUILT/

4/12 96

PHILLIPS PETROLEUM COMPANY NORWAY

102334 DRAWWORKS

DRUM SHAFT ASSEMBLY

65-00092

DCT 95/08/28

95/08/28

01 95/08/24 FOR PROJECT ACCEPTANCE DCT AKB DA

EKOX D47

910 M

H D H D 0 0 3 H 0 0 4 1 H 0 0 1 6.8 MA

THIS JOB ORDER: 1675

QA/QC REQUIREMENTS: PHILLIPS QUALITY PLAN

LICENSED UNDER API SPEC 4F AND 8A

DRECO DRILLING MACHINERY

TITLE: DRUM SHAFT ASSEMBLY

CUSTOMER: PHILLIPS PETROLEUM COMPANY NORWAY

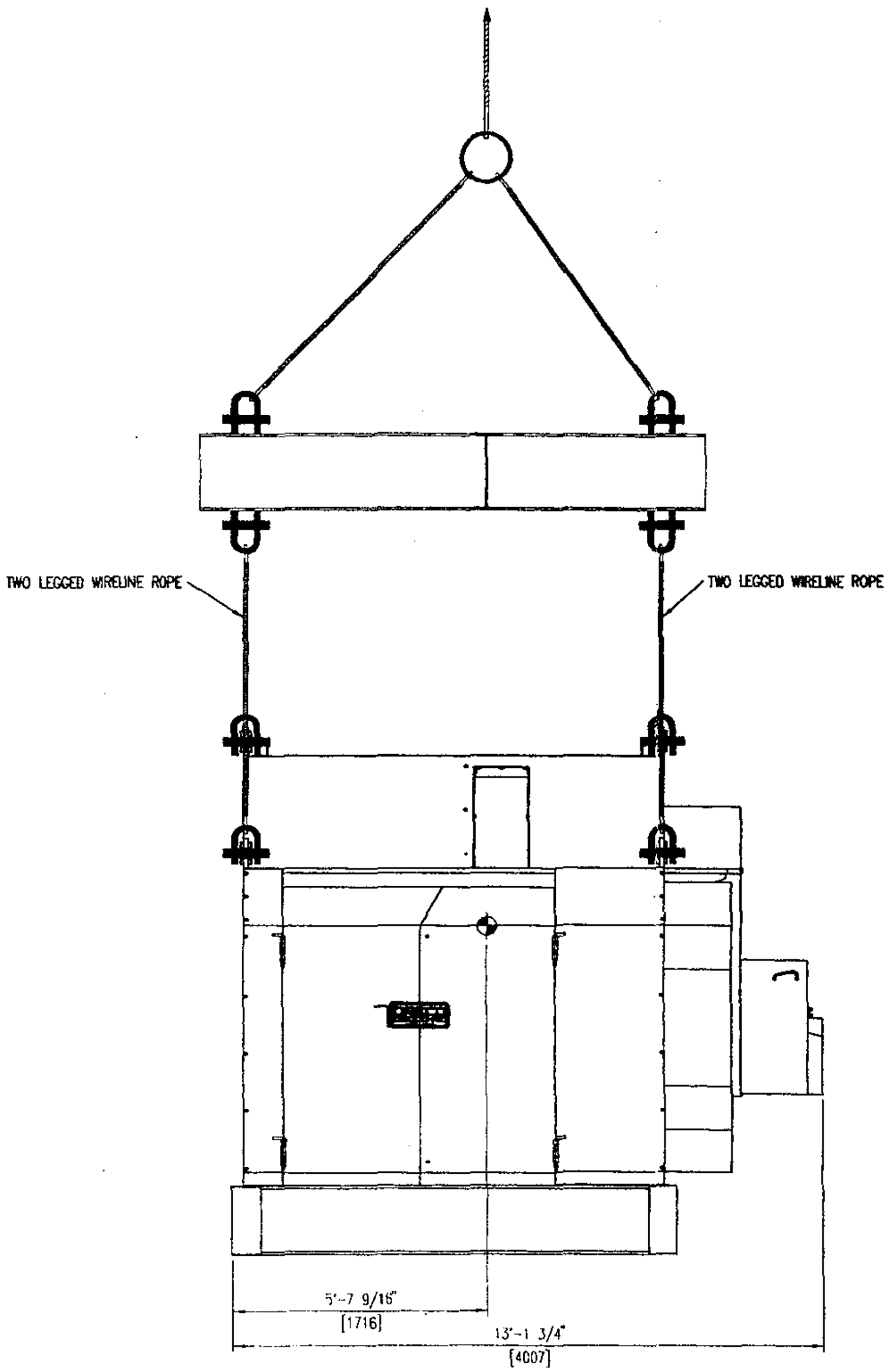
DRAWN BY: R.F. CHK'D BY: DA

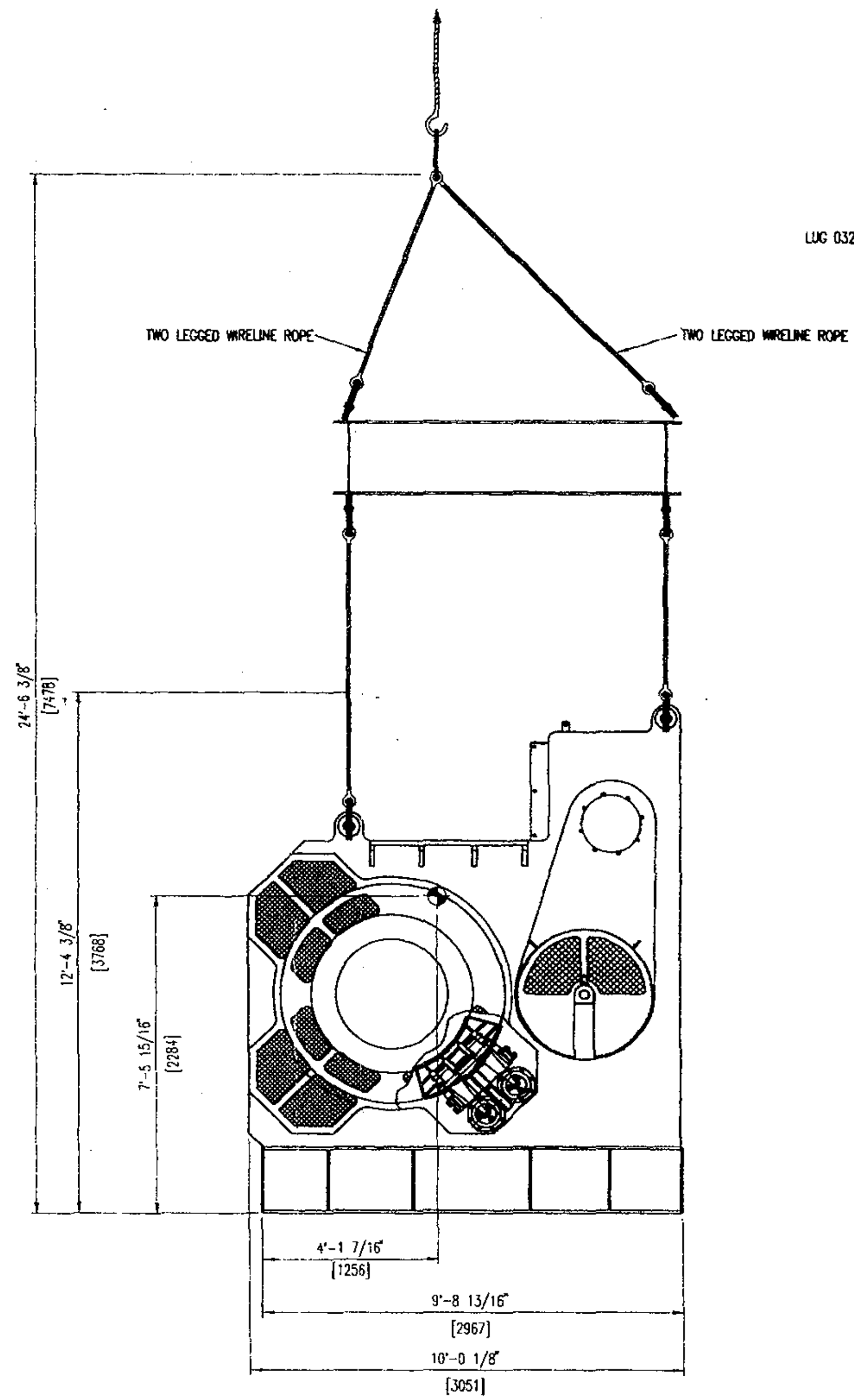
DATE: 95/02/15 AUTHORIZED BY: TW FILE CODE: DNS

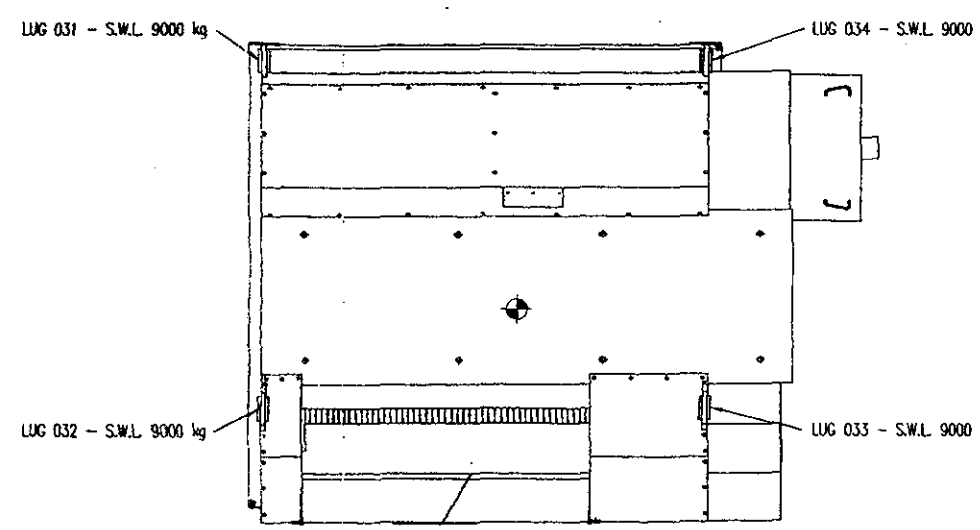
MD24 DRAWING NUMBER: 41675025 01

TOTAL WEIGHED WEIGHT OF 65-00092 AS SHOWN = 26 939 kg

WEIGHT DOES NOT INCLUDE MAIN MOTORS, WIRE ROPE, INPUT CHAIN & INSTRUMENT CONTROL CABINET







AS-BUILT

6/12-95

= CENTER OF GRAVITY

NOTE: DIMENSIONS ENCLOSED IN [ ] ARE IN mm.

PHILLIPS PETROLEUM COMPANY NORWAY	AMEC	
102334 — DRAWWORKS		65-00092
D2000-AC DRAWWORKS LIFTING DIAGRAM		
01 95/06/12 FOR PROJECT ACCEPTANCE DCT AKB DA	EKOX	D47
	910	M
HD-D0 03-0042-001	6.8	MA

THIS JOB ORDER: 1675

QA/QC REQUIREMENTS: STANDARD

LICENSED UNDER API SPEC 4F AND 8A

INFORMATION INCLUDED IN THIS DRAWING IS PROPRIETARY AND IS NOT TO BE REPRODUCED, DISTRIBUTED, OR DISCLOSED EXCEPT AS SPECIFICALLY AUTHORIZED IN WRITING BY DRECO ENERGY SERVICES, LTD.

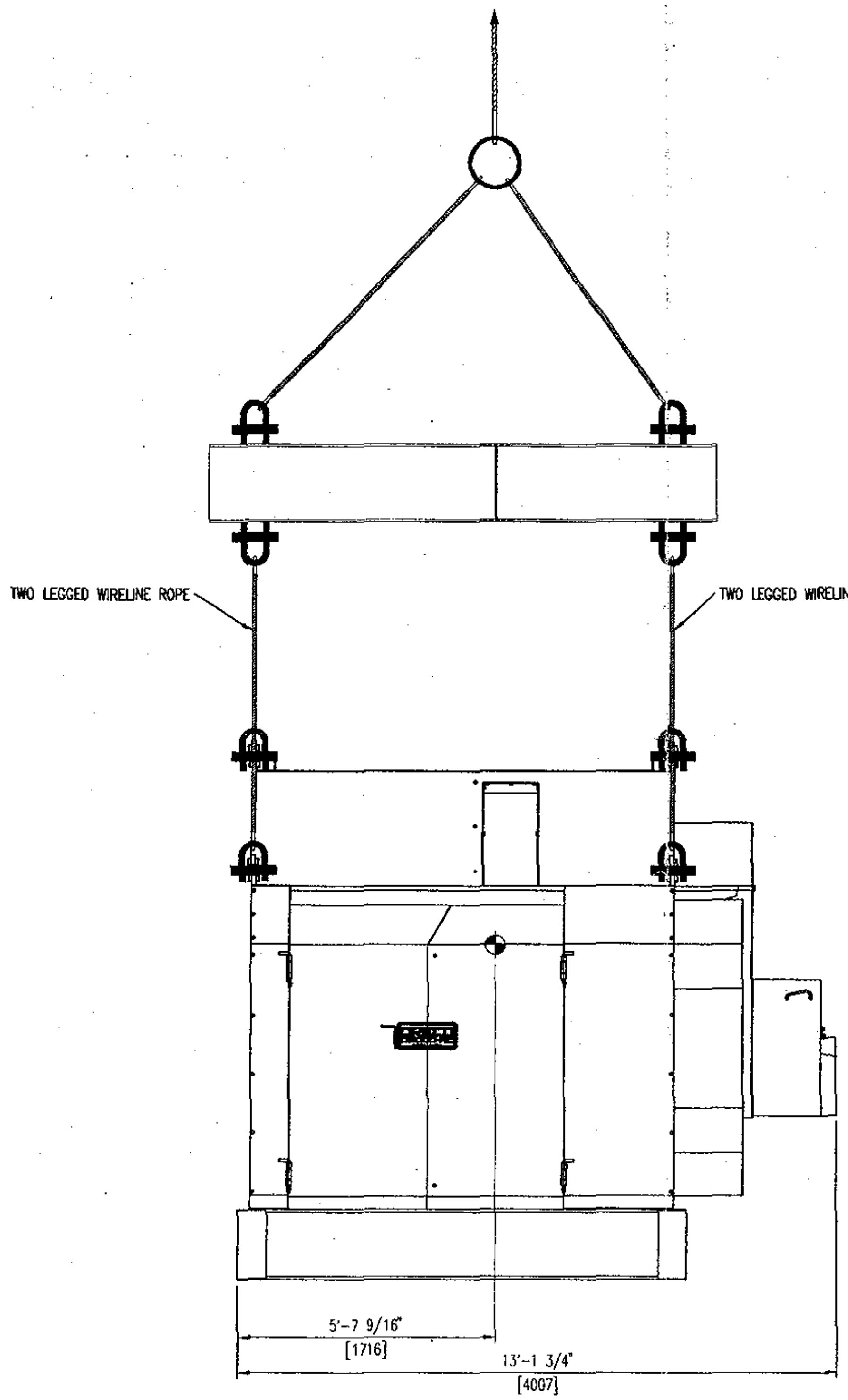
DRECO DRILLING MACHINERY

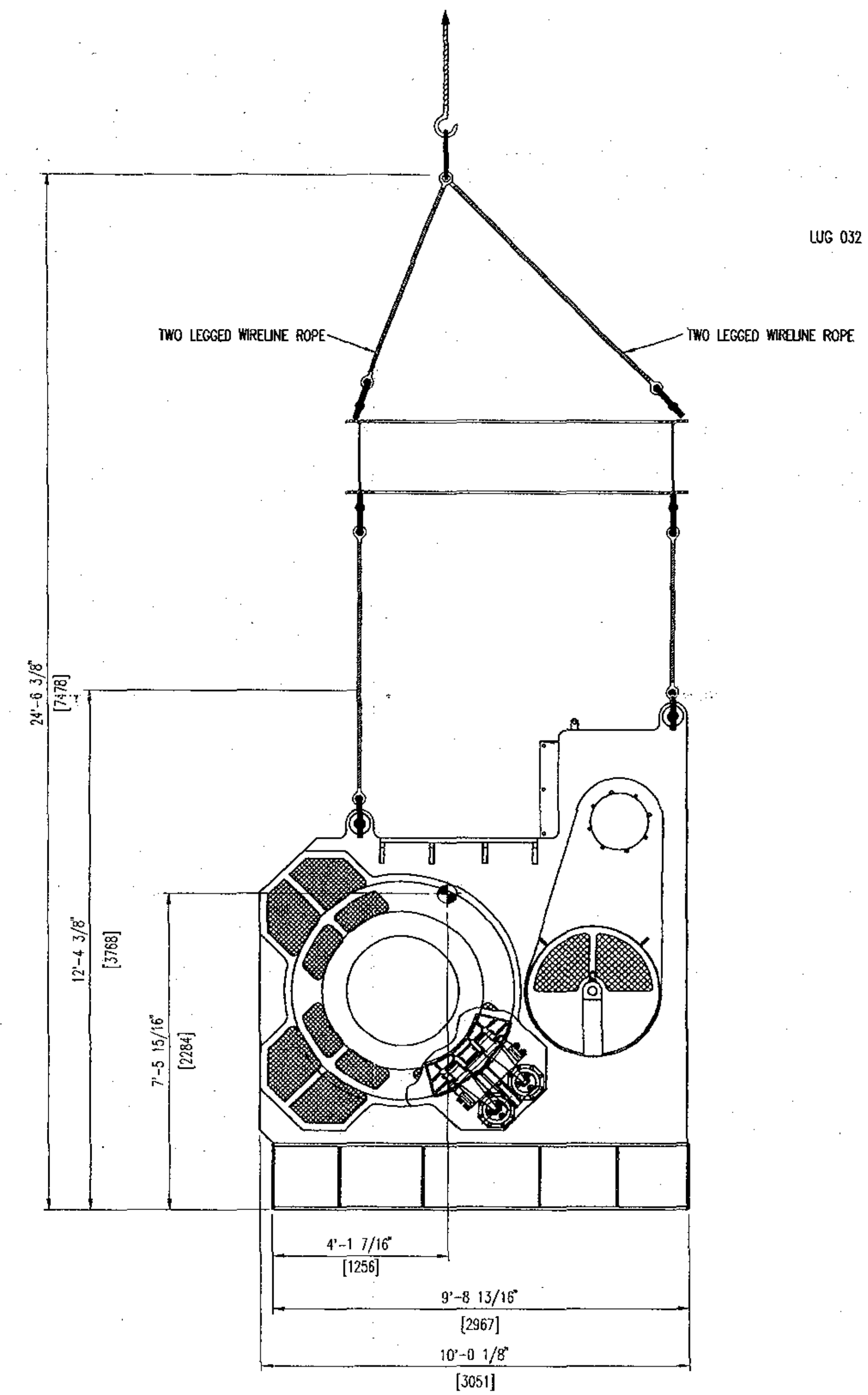
TITLE:	D2000-AC DRAWWORKS LIFTING DIAGRAM
CUSTOMER:	PHILLIPS PETROLEUM COMPANY NORWAY
DRWN BY: DCT 95/10/20 DCT	CHK'D BY: 95/10/20 AKB
DATE: 95/06/06	AUTHORIZED BY: 95/10/20 DA — FILE CODE: DNS
(DM8) 1/2"=12"	DRAWING NUMBER: 41675095 — 01

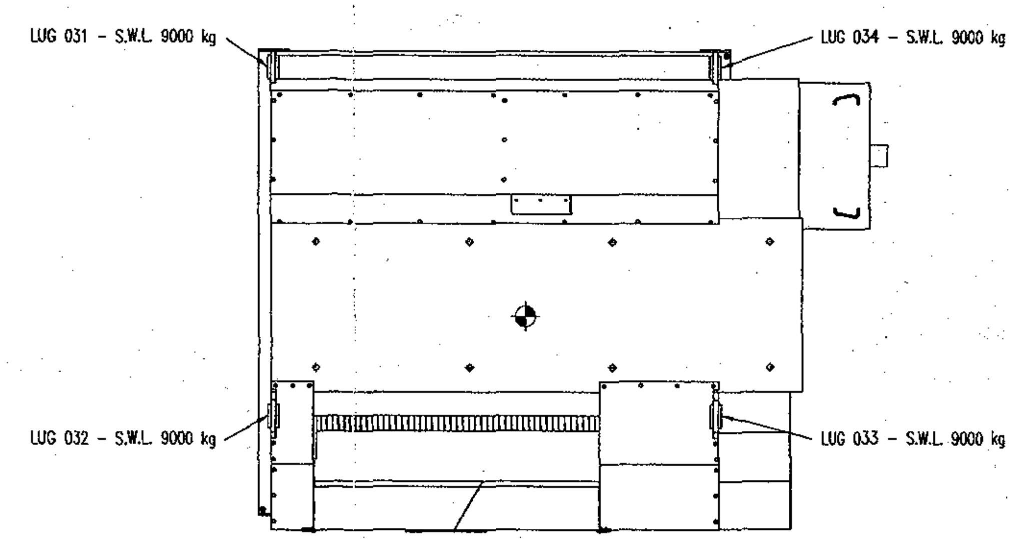
D-2000-AE DRAWWORKS (TAG No. 65-00092) PROPOSED LIFTING INSTRUCTIONS

TOTAL WEIGHED WEIGHT OF 65-00092 AS SHOWN = 26 939 kg

WEIGHT DOES NOT INCLUDE MAIN MOTORS, WIRE ROPE, INPUT CHAIN & INSTRUMENT CONTROL CABINET







AS-BUILT

= CENTER OF GRAVITY

NOTE: DIMENSIONS ENCLOSED IN [ ] ARE IN mm.

PHILLIPS PETROLEUM COMPANY NORWAY

Eldfisk Development Project

HITEC

102334 DRAWWORKS

65-00092

D2000-AC DRAWWORKS LIFTING DIAGRAM

01	95/06/12	FOR PROJECT ACCEPTANCE	DCT	AKB	DA	EKOX D47

910 M

HD-D003-0042-001 6.8 MA

THIS JOB ORDER: 1675
QA/QC REQUIREMENTS: STANDARD

LICENSED UNDER API SPEC 4F AND 8A

DRECO DRILLING MACHINERY

TITLE: D2000-AC DRAWWORKS LIFTING DIAGRAM

CUSTOMER: PHILLIPS PETROLEUM COMPANY NORWAY

DRWN BY: DCT 95/10/20 DCT | CHK'D BY: AKB 95/10/20 AKB

DATE: 95/06/06 | AUTHORIZED BY: DA 95/10/20 DA | FILE CODE: DNS

(DM8) 1/2"=12" | DRAWING NUMBER: 41675095 | 01

D-2000-AE DRAWWORKS (TAG No. 65-00092) PROPOSED LIFTING INSTRUCTIONS

Fri Oct 20 15:25:10 1995

Appendix B : FMSA analysis

Failure Mode and Syptom Analysis of Drawworks													
System	**Sub-system**	**Fuction or process**	**Failure syptoms**	**Failure mode (ISO 14224)**	**Failure mechanism (ISO 14224)**	**Cause of failure (ISO 14224)**	**Local failure effect**	**System failure effect**	**DET**	**SEV**	**DGN**	**PGN**	**MPN=DET *SEV*DGN *PGN**
Mechanical system		Hoist, lower, stop, park, hold opeartoin							4	4	4	3	194
	Supporting structures	Support of drawworks	Abnormal vibration	FTI-Fail to function as intended	1.2 Vibration	3.3 Maintenance error: Looseness of fastening blot	Noise	None	5	3	3	3	135
			Deformation of structure	BRD-Breakdown	1.4 Deformation	3.3 Maintenance error: Material failure, lifting weight beyond capacity	Structure failure	Shutdown of production	4	5	3	3	180
			Corrosion	FTS-Fail to start on demand	2.2 Corrosion	3.2 Operation error: Chemical corrosion, longtime exposure of salty sea water	Decreased structure strength	Threat of shutdown	4	3	4	4	192
	Drum	Wrapping on/off wire lines	Metallic clanking										267
			Metallic clanking	NOI-Noise	1.5 Looseness	3.2 Operation error: Lossness of connection	Noise, wearing	None	5	3	3	3	135
			Fast wearing of brake discs	LOA-Load drop	1.3 Clearance/ alignment failure	3.3 Maintenance error	Unenough braking	Insufficienty braking, drop of load	4	5	4	4	320
			Breakage/ buckling of drum barrel	STD-Structure deficiency	2.5 Breakage	3.1 Off-design service: Material property change, fatigue, or over holding weight	Faliure of drawworks	Shutdown of production	3	5	4	4	240

Failure Mode and Syptom Analysis of Drawworks													
System	**Sub-system**	**Fuction or process**	**Failure syptoms**	**Failure mode (ISO 14224)**	**Failure mechanism (ISO 14224)**	**Cause of failure (ISO 14224)**	**Local failure effect**	**System failure effect**	**DET**	**SEV**	**DGN**	**PGN**	**MPN=DET *SEV*DGN *PGN**
			Breakage of wireline	STD-Structure deficiency	2.5 Breakage	3.1 Off-design service: Fatigue, or over holding weight	Possible drop of load, faliure of drawworks	Drop of load	4	5	4	4	320
			Brake power is not enough	STP-Fail to stop on demand	1.5 Looseness	3.2 Operation error: Disconnection, loose items	Unenough braking	Insufficienty braking, drop of load	4	5	4	4	320
	Clutch (low and high clutch)	Transmission of power, speed shifting	Not enough clutch of drum	DOP-Delayed operation	2.4 Wear	3.2 Operation error: Abrasive and adhesive wear	Delayed operation	Reduced operation efficiency	4	3	4	3	144
			Abnormal noise	AIR-Abnormal instrument reading	1.1 Leakage	3.2 Operation error: Pneumatic system leakage	Noise	None	5	3	3	3	135
			Metallic clanking	NOI-Abnormal noise	1.2 Vibration	3.2 Operation error: Unstable air pressure	Noise	None	5	3	3	3	135
				FTS-Fail to start on demand	2.2 Corrosion	3.2 Operation error: Chemical corrosion, longtime exposure of salty sea water	Decreased structure strength	Threat of shutdown	4	3	4	4	192
				INL-Internal leakage	2.7 Overheating	3.1 Off-design service: Material damage due to overheating/burning	Change of material might lead to failure of clutch	None	3	3	4	4	144

Failure Mode and Syptom Analysis of Drawworks													
System	**Sub-system**	**Fuction or process**	**Failure syptoms**	**Failure mode (ISO 14224)**	**Failure mechanism (ISO 14224)**	**Cause of failure (ISO 14224)**	**Local failure effect**	**System failure effect**	**DET**	**SEV**	**DGN**	**PGN**	**MPN=DET *SEV*DGN *PGN**
			Delayed/ no response to operation	FTS-Fail to start on demand	3.1 Control failure	3.4 Expected wear and tear; 5.3 Combined causes	Delayed operation	Decreased operation efficiency	3	4	4	4	192
				UST-Spurious stop	4.3 No power/ voltage	3.2 Operating error	Failure of drawworks	Breakdown of production	4	5	3	4	240
			Deformation of structure	BRD-Breakdown	1.4 Deformation	3.3 Maintenance error: Material failure	Structure failure	Shutdown of production	3	5	4	3	180
	Chains	Transmission of power	Noise	SER-Minor in-service problems	1.5 Looseness	3.3 Maintenance error: The chain is not correctely tensioned	Low transmission efficiency	Low hoisting /lowing efficiency	3	4	3	3	108
			Noise	NOI-Abnormal noise	5.1 Blockage/ plugged	3.3 Maintenance error: Not enough lubrication	Wearing of chain	None	5	3	3	3	135
	Main shafts	Rotating support of power transmission system	Noise	VIB-Vibration, NOI-Noise	1.3 Clearance/ alignment failure	3.2 Operation error: Faulty clearance or alignment, wearing	Vibration	None	5	3	3	3	135
			Overheat	ELU-External leakage-utility medium	1.1 Leakage	3.2 Operating error: Failure of cooling system	Change of material property	Shutdown of production	4	5	4	3	240
			Deformation of structure	BRD-Breakdown	1.4 Deformation	3.0 General: material failure	Structure failure	Shutdown of production	4	5	3	3	180
	Pneumatic system	Power of braking and speed changing											202

Failure Mode and Syptom Analysis of Drawworks													
System	**Sub-system**	**Fuction or process**	**Failure syptoms**	**Failure mode (ISO 14224)**	**Failure mechanism (ISO 14224)**	**Cause of failure (ISO 14224)**	**Local failure effect**	**System failure effect**	**DET**	**SEV**	**DGN**	**PGN**	**MPN=DET *SEV*DGN *PGN**
			Unusual noise	AIR-Abnormal instrument reading	1.1 Leakage	3.1 Off-design service, 3.2 Operating error	Noise	None	5	3	3	3	135
			Vibration	VIB-Abnormal vibration	6.0 General: unstable air pressure	3.2 Operating error	Noise	None	4	3	4	3	144
			External dew formation outside of pneumatic system	Minor in-service problems	6.0 General: Temperature difference from outside environment	3.1 Off-design service	Dew drop on the outer surface of system	Impact on corrosion, lubricaion	4	3	4	3	144
			Internal dew formation in pneumatic system	Minor in-service problems	6.0 General: Temperature difference from outside environment	3.1 Off-design service: Expansion of pressurized air lead to sharp drop of temperature; overload:	Dew-induced pneumatica componenets failure	Decreased operation efficiency	4	4	4	4	256
			Brake funcions improperly	STP-Fail to stop on demand	2.4 Wear	3.3 Maintenance error	Unexpected braking, fail to brake	Delayed drilling, drop of load	4	5	4	4	320
			Calipers responds slowly	ELU-External leakage-utility medium	1.4 Deformation	3.3 Maintenance error	Slow responding of calipers	Delayed response of braking	4	4	4	3	192
			Calipers do not respond	ELU-External leakage-utility medium	1.4 Deformation	3.3 Maintenance error	No response of calipers	Faliure of braking	4	5	4	3	240
			Grinding	FRO-Fail to rotate	1.5 Looseness	3.2 Operating error: improper adjustment	Unexpected utilization of brakes	Unexpected braking force	3	4	4	3	144

Failure Mode and Syptom Analysis of Drawworks													
System	**Sub-system**	**Fuction or process**	**Failure syptoms**	**Failure mode (ISO 14224)**	**Failure mechanism (ISO 14224)**	**Cause of failure (ISO 14224)**	**Local failure effect**	**System failure effect**	**DET**	**SEV**	**DGN**	**PGN**	**MPN=DET *SEV*DGN *PGN**
				OHE-Over heating	2.7 Overheating	3.2 Operating error	Change of material property	None	4	4	3	3	144
			Pressurized air tank failure	AIR-Abnormal instrument reading	1.1 Leakage	3.2 Operating error	Failure of pneumatic system	Stop of production due to automatic utilization of emergency braking	4	5	4	3	240
			Wrong indication	AIR-Abnormal instrument reading	1.1 Leakage	3.3 Maintenance error	Excessive pressure on some section of pneumatica system	None	5	4	4	3	240
			Leakage in closed space	FTI-Fail to function as intended	1.4 Deformation	3.3 Maintenance error	Failure of pneumatic system	Stop of production due to automatic utilization of emergency braking	4	5	4	3	240
			No response to control signal	FTS-Fail to start on demand	3.1 Control failure	3.2 Operating error: Short circuit, failure of electronics/ valves	Failure of main braking system, failure of speed change	Stop of production due to automatic utilization of emergency braking	4	5	4	3	240

Failure Mode and Syptom Analysis of Drawworks													
System	**Sub-system**	**Fuction or process**	**Failure syptoms**	**Failure mode (ISO 14224)**	**Failure mechanism (ISO 14224)**	**Cause of failure (ISO 14224)**	**Local failure effect**	**System failure effect**	**DET**	**SEV**	**DGN**	**PGN**	**MPN=DET *SEV*DGN *PGN**
				LOO-Low output	5.1 Blockage/ plugged	3.3 Maintenance error	Failure of pneumatic system	None, as there is emergency braking system	4	3	4	3	144
	Mechanical brake components	Braking	Big gap between brakes discs and bands	LOA-Load drop	1.3 Clearance/ alignment failure	3.2 Operation error: Faulty clearance or alignment	Unenough braking	Insufficienty braking, drop of load	4	5	4	3	240
			Overheat	INL-Internal leakage	2.7 Overheating	3.1 Off-design service: Material damage due to overheating/burning	Change of material might lead to failure of clutch	None	3	5	4	4	240
			Delayed/ no response to operation	FTS-Fail to start on demand	3.1 Control failure	3.4 Expected wear and tear; 5.3 Combined causes	Delayed operation	Decreased operation efficiency	4	3	4	4	192
			Breakage	STD-Structure deficiency	2.5 Breakage	3.1 Off-design service: Fatigue, or over holding weight	Possible drop of load, faliure of drawworks	Drop of load	4	5	4	4	320
	Lubrication system	Lubricating transmission, rotating systems											170
			Unenough lubrication	FTI-Fail to function as intended	5.1 Blockage/ plugged	3.2 Operating error	Wearing	None	3	4	4	3	144
			Leakage	ELU-External leakage-utility medium	1.4 Deformation	3.2 Operating error	Reduced inner pressure	None	4	3	4	3	144

Failure Mode and Syptom Analysis of Drawworks													
System	**Sub-system**	**Fuction or process**	**Failure syptoms**	**Failure mode (ISO 14224)**	**Failure mechanism (ISO 14224)**	**Cause of failure (ISO 14224)**	**Local failure effect**	**System failure effect**	**DET**	**SEV**	**DGN**	**PGN**	**MPN=DET *SEV*DGN *PGN**
			Insufficient flow of lubrication oil	LOO-Low output	5.1 Blockage/ plugged	3.2 Operating error	Decreased capacity of lubricaiotn system	None	4	3	4	3	144
			Wearing of lubricated components	STD-Structure deficiency	2.4 Wear	3.4 Expected wear and tear	Wearing	None	3	4	4	3	144
					5.2 Contamination	3.2 Operating error	Wearing	None	3	4	4	3	144
			Change of property of lubrication oil	OHE-Over heating	1.6 Sticking	3.3 Maintenance error	Decreased ability/ unfunctioning of lubrication	None	4	4	4	3	192
					2.7 Overheating;	3.1 Off-design service	Decreased ability/ unfunctioning of lubrication	None	4	4	4	3	192
		Lubrication oil pump (no redundancy)	Noise	AIR-Abnormal instrument reading	1.1 Leakage	3.2 Operating error	Failure of pump	None	4	3	4	3	144
			Errosion on barrel ports and port plate	BRD-Breakdown	1.2 Vibration	3.3 Maintenance error	Failure of pump	None	4	3	4	3	144
			Pressure pulse	ERO-Erratic output	1.4 Deformation	3.3 Maintenance error	Wearing, looseness of connection	None	4	3	4	3	144

Failure Mode and Syptom Analysis of Drawworks													
System	**Sub-system**	**Fuction or process**	**Failure syptoms**	**Failure mode (ISO 14224)**	**Failure mechanism (ISO 14224)**	**Cause of failure (ISO 14224)**	**Local failure effect**	**System failure effect**	**DET**	**SEV**	**DGN**	**PGN**	**MPN=DET *SEV*DGN *PGN**
			No rise in pressure	INL-Internal leakage	2.2 Corrosion	3.3 Maintenance error	Loss of function of pumping	Stop of production due to automatic utilization of emergency braking	4	5	4	4	320
			Insufficient flow of lubrication oil	LOO-Low output	5.1 Blockage/ plugged	3.2 Operating error	Decreased capacity of lubricaiotn system	None	4	3	4	3	144
		Control of lubricaitng system	No response to control signal	FTS-Fail to start on demand	3.1 Control failure;	3.2 Operating error: Short circuit, failure of electronics/ valves	Decreased ability/ unfunctioning of lubrication	None	4	4	4	3	192
					3.2 No singal/ indicative alarm	3.2 Operating error: Short circuit, failure of electronics/ valves	Decreased ability/ unfunctioning of lubrication	None	4	4	4	3	192
Power management system		Power mangement							4	4	4	3	181
	Driving motors (with redundancy)	Power generation											187
			Unusual noise	AIR-Abnormal instrument reading	1.5 Looseness	3.2 Operating error	Noise	None	4	3	3	3	108

Failure Mode and Syptom Analysis of Drawworks													
System	**Sub-system**	**Fuction or process**	**Failure syptoms**	**Failure mode (ISO 14224)**	**Failure mechanism (ISO 14224)**	**Cause of failure (ISO 14224)**	**Local failure effect**	**System failure effect**	**DET**	**SEV**	**DGN**	**PGN**	**MPN=DET *SEV*DGN *PGN**
			Vibration of motor	VIB-Vibration	1.2 Vibration	3.2 Operating error	Looseness of connection	None	4	3	3	3	108
			Failure of one motor	BRD-Breakdown	1.6 Sticking	3.2 Operating error: Failure of bearing/ shafts	Failure of one motor	None, there is redundancy	4	4	4	3	192
				FTS-Fail to start on demand	2.7 Overheating	3.1 Off-design service	Failure of one motor	None, there is redundancy	4	4	4	3	192
						3.2 Operating error: failuer of cooling system	Failure of one motor	None, there is redundancy	4	4	4	3	192
					3.2 No signal/ indication alarm	3.2 Operating error	Failure of one motor	None, there is redundancy	4	4	4	3	192
				STD-Structural defeciency	2.5 Breakage	3.2 Operating error	Failure of one motor	None, there is redundancy	3	4	3	3	108
				STP-Fail to stop on demand	3.1 Control failure	3.2 Operating error: Short circuit, failure of electronics/ valves	None	None	4	3	4	3	144
					3.4 Out of adjustment	3.3 Maintenance error	None	None	4	3	4	3	144
					2.4 Wear	3.3 Maintenance error	None	None	4	3	4	3	144
				UST-Spurious stop	3.1 Control failure	3.2 Operating error: Short circuit, failure of electronics/ valves	Failure of one motor	None, there is redundancy	4	3	4	4	192

Failure Mode and Syptom Analysis of Drawworks													
System	**Sub-system**	**Fuction or process**	**Failure syptoms**	**Failure mode (ISO 14224)**	**Failure mechanism (ISO 14224)**	**Cause of failure (ISO 14224)**	**Local failure effect**	**System failure effect**	**DET**	**SEV**	**DGN**	**PGN**	**MPN=DET *SEV*DGN *PGN**
					3.3 Faulty signal/ indication alarm	3.2 Operating error: Short circuit, failure of electronics/ valves	Failure of one motor	None, there is redundancy	4	3	4	4	192
			Leakage in closed space	ELU-External leakage-Utility medium	2.5 Corrosion 2.6 Fatigue	3.3 Maintenance error: Corrosion/ fatigue induced breakage	Motor runs unstably	None	4	3	4	3	144
			Unstable power output	ERO-Erratic output	1.3 Clearance/ alignment failure	3.3 Maintenance error	Decreased capacity of power output	Threat of hoisting/ lowering safety	4	5	4	4	320
					4.4 Faulty power/ voltage	4.2 Management error	Decreased capacity of power output	Threat of hoisting/ lowering safety	4	5	4	4	320
				HIO-High output	3.1 Control failure	4.2 Management error	Higher speed than expected	Threat of hoisting/ lowering safety	4	5	4	4	320
				LOO-Low output	3.1 Control failure	4.2 Management error	Lower speed than expected	Decreased operation efficiency	4	4	4	4	256
			Noise	NOI-Noise	1.5 Looseness	3.3 Maintenance error	Noise	None	3	3	4	3	108
			High reading from temperature instrument	OHE-Overheating	4.1 Short circuit	3.2 Operating error	Failure of one motor	None, there is redundancy	4	4	4	3	192

Failure Mode and Syptom Analysis of Drawworks													
System	**Sub-system**	**Fuction or process**	**Failure syptoms**	**Failure mode (ISO 14224)**	**Failure mechanism (ISO 14224)**	**Cause of failure (ISO 14224)**	**Local failure effect**	**System failure effect**	**DET**	**SEV**	**DGN**	**PGN**	**MPN=DET *SEV*DGN *PGN**
					2.7 Overheating	3.1 Off-design service	Change of material property	None	4	3	4	3	144
			No power/ voltage	PDE-Parameter deviation	4.1 Short circuit	3.2 Operating error	Failure of one motor	None, there is redundancy	4	4	4	3	192
					4.2 Open circuit	4.2 Management error	Failure of one motor	None, there is redundancy	4	4	4	3	192
					4.5 Earth isolation fault	4.2 Management error	Failure of one motor	None, there is redundancy	4	4	4	3	192
			Faulty power/ voltage	SER-Minor in-service problems	4.4 Faulty power/ voltage	3.2 Operating error: wrong output from speed converter	Extra wearing due to unexpected working condition	None	4	4	4	3	192
	electrical components	Power management assistance	Spark	FTF-Failure to function on demand	4.0 General	3.2 Operating error	Failure of the branch of circuit	None, there is redundancy	3	4	4	3	144
			Overheat	AIR-Abnormal instrument reading	2.7 Overheating	3.2 Operating error	Change of material property	None	3	3	4	3	108
			Breakage	Minor in-service problems	6.1 No cause found	3.2 Operating error	Failure of the branch of circuit	None, there is redundancy	3	4	4	3	144
The variable speed drive system		Varying the frequency and voltage supplied to the electric motor							4	4	4	3	204

Failure Mode and Syptom Analysis of Drawworks													
System	**Sub-system**	**Fuction or process**	**Failure syptoms**	**Failure mode (ISO 14224)**	**Failure mechanism (ISO 14224)**	**Cause of failure (ISO 14224)**	**Local failure effect**	**System failure effect**	**DET**	**SEV**	**DGN**	**PGN**	**MPN=DET *SEV*DGN *PGN**
	Converter	Varying the frequency and voltage supplied to the electric motor	Fail to start	FTS-Fail to start on demand	4.1 Short circuit	3.2 Operating error	Failure of converter	No input to motor, trigger of emergency braking	4	5	4	3	240
					4.2 Open circuit	3.2 Operating error	Failure of converter	No input to motor, trigger of emergency braking	4	5	4	3	240
					4.0 General	3.2 Operating error: failure of electronics	Failure of converter	No input to motor, trigger of emergency braking	4	5	4	3	240
			Failure to convert frequency and voltage as needed	ERO-Erratic output	4.4 Faulty power/ voltage	4.2 Management error	Extra wearing due to unexpected working condition	Decreased operation efficiency	4	4	4	3	192
	Power unit	Power input and power output	Unstable power flow	AIR-Abnormal instrument reading	3.1 Control failure	4.2 Management error	Extra wearing due to unexpected working condition	None	4	4	4	3	192
	Cooling system	Cooling of converter	Overheat	FTS-Fail to start on demand	1.4 Deformation	3.2 Operation error: Failure of cooling fan	Overheat of converter	None	4	3	4	3	144
	Operator interface	Human-machine interface for adjusting the speed	Failure to response	FTF-Failure to function on demand	3.1 Control failure	3.2 Operating error	Loss of control of motor speed	None	4	3	4	3	144

Failure Mode and Syptom Analysis of Drawworks													
System	**Sub-system**	**Fuction or process**	**Failure syptoms**	**Failure mode (ISO 14224)**	**Failure mechanism (ISO 14224)**	**Cause of failure (ISO 14224)**	**Local failure effect**	**System failure effect**	**DET**	**SEV**	**DGN**	**PGN**	**MPN=DET *SEV*DGN *PGN**
			Loss of critical signals sent to and from the VSDS	DOP-Delayed operation	3.2 No signal/ indication alarm	4.2 Management error	Fail to respond to emergencies	Unpredicted incidents on safety	3	5	4	4	240
Driller's control system	(Operator's control chair)	Human-machine interface							4	4	4	4	214
	Multi-Tool Control Cabinet	Human-machine interface	Failure of joystick	FTS-Fail to start on demand	3.2 No signal/ indication alarm	3.2 Operating error	Loss of joystick control input	None, there is redundancy	4	3	4	3	144
			Failure to response on command	FTF-Failure to function on demand	3.1 Control failure	3.2 Operating error	Loss of control of drawworks drilline/ braking system	Drop of load/ traveling block	4	5	4	4	320
			Loss of critical signals sent to and from driller's control system	DOP-Delayed operation	3.2 No signal/ indication alarm	4.2 Management error	Fail to respond to emergencies	Drop of load/ traveling block, collision of crown block	3	5	4	4	240
			No signal			3.2 Operating error: open/ short circuit	Fail to respond to emergencies	Drop of load/ traveling block, collision of crown block	3	5	4	4	240

Failure Mode and Syptom Analysis of Drawworks													
System	**Sub-system**	**Fuction or process**	**Failure syptoms**	**Failure mode (ISO 14224)**	**Failure mechanism (ISO 14224)**	**Cause of failure (ISO 14224)**	**Local failure effect**	**System failure effect**	**DET**	**SEV**	**DGN**	**PGN**	**MPN=DET *SEV*DGN *PGN**
	Operator workstatio n(s)	Working station of driller	Unconfortab ility	STD-Structural defeciency	1.4 Deformation	3.3 Maintenance error	Failure of chair	None	4	2	4	4	128
DW control system		Hoist, lower, stop, park, hold opeartoin							3	5	4	4	236
	Critical sensors	Monitoring parameter of system	Abnormal reading from sensors	AIR-Abnormal instrument reading	3.2 No signal/ indication alarm	3.2 Operating error	Failure of instruments	None, fail-safe mode of instruments	3	3	4	4	144
					3.3 Faulty signal/ indication alarm	3.2 Operating error	Wrong reading from sensors	Threat of hoisting/ lowering safety	3	5	4	4	240
					3.4 Out of adjustment	3.3 Maintenance error	Wrong reading from sensors	Threat of hoisting/ lowering safety	3	5	4	4	240
	Alarms	Alarm to dangers/ improper condition	False alarm	SHH-Spurious high alarm level	3.3 Faulty signal/ indication alarm	3.2 Operating error	Fail to alarm at dangerous condition	Exposure to dangerous conditoin	4	5	4	3	240
				SLL-Spurious low alarm level	3.3 Faulty signal/ indication alarm	3.2 Operating error	Shutdown of drawworks in safe conditoin	Increased downtime	4	5	4	3	240
			Travelling block position reference failure	NOO-No output	3.2 No signal/ indication alarm	3.2 Operating error	Neglection of of anti-collision system	Possible collision without visual inspection	3	5	4	4	240

Failure Mode and Syptom Analysis of Drawworks

System	Sub-system	Fuction or process	Failure syptoms	Failure mode (ISO 14224)	Failure mechanism (ISO 14224)	Cause of failure (ISO 14224)	Local failure effect	System failure effect	DET	SEV	DGN	PGN	MPN=DET *SEV*DGN *PGN
	Main drawworks control system (PLC)	Functioning of drawworks	Switch failure	FTF-Failure to function on demand	3.1 Control failure	3.2 Operating error: short/ open circuit, or earth isolation problem	Loss of control of drawworks drilline/ braking system	Emergency braking trigerred unexpected during hoisting/ lowering operation	4	5	4	4	320
		Human-machine interface	Failure to response on command	FTS-Fail to start on demand	3.2 No signal/ indication alarm	3.2 Operating error	Loss of joystick control input	None, there is redundancy	4	3	4	3	144
			Failure to response on command	FTF-Failure to function on demand	3.1 Control failure	3.2 Operating error	Loss of control of drawworks drilline/ braking system	Drop of load/ traveling block	4	5	4	4	320
			Loss of critical signals sent to and from driller's control system	DOP-Delayed operation	3.2 No signal/ indication alarm	4.2 Management error	Fail to respond to emergencies	Drop of load/ traveling block, collision of crown block	3	5	4	4	240
			No signal			3.2 Operating error: open/ short circuit	Fail to respond to emergencies	Drop of load/ traveling block, collision of crown block without alarm	3	5	4	4	240

Failure Mode and Syptom Analysis of Drawworks													
System	**Sub-system**	**Fuction or process**	**Failure syptoms**	**Failure mode (ISO 14224)**	**Failure mechanism (ISO 14224)**	**Cause of failure (ISO 14224)**	**Local failure effect**	**System failure effect**	**DET**	**SEV**	**DGN**	**PGN**	**MPN=DET *SEV*DGN *PGN**
	Emergency stop	Automatically triggerred emergency braking system when there is no pressure/ power	Failure of braking	FTS-Fail to start on demand	1.4 Deformation	3.3 Maintenance error: Wearing of brake discs	Failure of braking	Drop of load/ traveling block, collision of crown block	4	5	4	3	240
					5.0 General: incorrect operation sequence	3.2 Operating error: e.g. motor hoisting system clutched, braking holding system cannot be utilized	Failure of braking	Drop of load/ traveling block, collision of crown block	3	5	5	3	225

Appendix C : Failure causes (ISO 14224 2006)

Code number	Notation	Subdivision code number	Subdivision of the failure cause	Description of the failure cause
1	Design-related causes	1.0	General	Inadequate equipment design or configuration (shape, size, technology, configuration, operability, maintainability, etc.), but no further details known
		1.1	Improper capacity	Inadequate dimensioning/capacity
		1.2	Improper material	Improper material selection
2	Fabrication/ installation-related causes	2.0	General	Failure related to fabrication or installation, but no further details known
		2.1	Fabrication error	Manufacturing or processing failure
		2.2	Installation error	Installation or assembly failure (assembly after maintenance not included)
3	Failure related to operation/ maintenance	3.0	General	Failure related to operation/use or maintenance of the equipment but no further details known
		3.1	Off-design service	Off-design or unintended service conditions, e.g. compressor operation outside envelope, pressure above specification, etc.
		3.2	Operating error	Mistake, misuse, negligence, oversights, etc. during operation
		3.3	Maintenance error	Mistake, errors, negligence, oversights, etc. during maintenance
		3.4	Expected wear and tear	Failure caused by wear and tear resulting from normal operation of the equipment unit
4	Failure related to management	4.0	General	Failure related to management issues, but no further details known
		4.1	Documentation error	Failure related to procedures, specifications, drawings, reporting, etc.
		4.2	Management error	Failure related to planning, organization, quality assurance, etc.
5	Miscellaneous [a]	5.0	Miscellaneous - general	Causes that do not fall into one of the categories listed above
		5.1	No cause found	Failure investigated but no specific cause found
		5.2	Common cause	Common cause/mode
		5.3	Combined causes	Several causes are acting simultaneously. If one cause is predominant, this cause should be highlighted.
		5.4	Other	None of the above codes applies. Specify cause as free text.
		5.5	Unknown	No information available related to the failure cause

[a] The data acquirer should judge which is the most important cause if more than one exist, and try to avoid the 5.4 and 5.5 codes.

Appendix D : Failure mechanism (ISO 14224 2006)

Failure mechanism		Subdivision of the failure mechanism		Description of the failure mechanism
Code number	Notation	Code number	Notation	
1	Mechanical failure	1.0	General	A failure related to some mechanical defect but where no further details are known
		1.1	Leakage	External and internal leakage, either liquids or gases: If the failure mode at equipment unit level is coded as "leakage", a more causally oriented failure mechanism should be used wherever possible.
		1.2	Vibration	Abnormal vibration: If the failure mode at equipment level is vibration, which is a more causally oriented failure mechanism, the failure cause (root cause) should be recorded wherever possible.
		1.3	Clearance/ alignment failure	Failure caused by faulty clearance or alignment
		1.4	Deformation	Distortion, bending, buckling, denting, yielding, shrinking, blistering, creeping, etc.
		1.5	Looseness	Disconnection, loose items
		1.6	Sticking	Sticking, seizure, jamming due to reasons other than deformation or clearance/alignment failures
2	Material failure	2.0	General	A failure related to a material defect but no further details known
		2.1	Cavitation	Relevant for equipment such as pumps and valves
		2.2	Corrosion	All types of corrosion, both wet (electrochemical) and dry (chemical)
		2.3	Erosion	Erosive wear
		2.4	Wear	Abrasive and adhesive wear, e.g. scoring, galling, scuffing, fretting
		2.5	Breakage	Fracture, breach, crack
		2.6	Fatigue	If the cause of breakage can be traced to fatigue, this code should be used.
		2.7	Overheating	Material damage due to overheating/burning
		2.8	Burst	Item burst, blown, exploded, imploded, etc.
3	Instrument failure	3.0	General	Failure related to instrumentation but no details known
		3.1	Control failure	No, or faulty, regulation
		3.2	No signal/ indication/alarm	No signal/indication/alarm when expected
		3.3	Faulty signal/ indication/alarm	Signal/indication/alarm is wrong in relation to actual process. Can be spurious, intermittent, oscillating, arbitrary
		3.4	Out of adjustment	Calibration error, parameter drift
		3.5	Software failure	Faulty, or no, control/monitoring/operation due to software failure
		3.6	Common cause/ mode failure	Several instrument items failed simultaneously, e.g. redundant fire and gas detectors; also failures related to a common cause.

Failure mechanism		Subdivision of the failure mechanism		Description of the failure mechanism
Code number	Notation	Code number	Notation	
4	Electrical failure	4.0	General	Failures related to the supply and transmission of electrical power, but where no further details are known
		4.1	Short circuiting	Short circuit
		4.2	Open circuit	Disconnection, interruption, broken wire/cable
		4.3	No power/voltage	Missing or insufficient electrical power supply
		4.4	Faulty power/voltage	Faulty electrical power supply, e.g. overvoltage
		4.5	Earth/isolation fault	Earth fault, low electrical resistance
5	External influence	5.0	General	Failure caused by some external events or substances outside the boundary but no further details are known
		5.1	Blockage/plugged	Flow restricted/blocked due to fouling, contamination, icing, flow assurance (hydrates), etc.
		5.2	Contamination	Contaminated fluid/gas/surface, e.g. lubrication oil contaminated, gas-detector head contaminated
		5.3	Miscellaneous external influences	Foreign objects, impacts, environmental influence from neighbouring systems
6	Miscellaneous [a]	6.0	General	Failure mechanism that does not fall into one of the categories listed above
		6.1	No cause found	Failure investigated but cause not revealed or too uncertain
		6.2	Combined causes	Several causes: If there is one predominant cause this should be coded.
		6.3	Other	No code applicable: Use free text.
		6.4	Unknown	No information available

[a] The data acquirer should judge which is the most important failure mechanism descriptor if more than one exist, and try to avoid the 6.3 and 6.4 codes.

Appendix E : Failure modes (ISO 14224 2006)

Equipment class [a]								Failure modes			
Combustion engine	Compressor	Electric generator	Electric motor	Gas turbine	Pump	Steam turbine	Turbo expander	Description	Examples	Code [b]	Type [c]
X	X	X	X	X	X	X	X	Failure to start on demand	Doesn't start on demand	FTS	1
X	X	X	X					Failure to stop on demand	Doesn't stop on demand	STP	1
X	X	X	X	X	X	X	X	Spurious stop	Unexpected shutdown	UST	2
X	X	X	X	X	X	X	X	Breakdown	Serious damage (seizure, breakage)	BRD	3
X	X		X	X	X	X	X	High output	Overspeed/output above acceptance	HIO	2
X	X	X	X	X	X	X	X	Low output	Delivery/output below acceptance	LOO	2
X	X		X	X	X	X	X	Erratic output	Oscillating, hunting, instability	ERO	2
X				X		X		External leakage – fuel	External leakage of supplied fuel/gas	ELF	3
	X			X	X	X	X	External leakage – process medium	Oil, gas, condensate, water	ELP	3
X	X	X	X	X	X	X	X	External leakage – utility medium	Lubricant, cooling water	ELU	3
X	X			X	X	X	X	Internal leakage	Leakage internally of process or utility fluids	INL	3
X	X	X	X	X	X	X	X	Vibration	Abnormal vibration	VIB	3
X	X	X	X	X	X	X	X	Noise	Abnormal noise	NOI	3
X	X	X	X	X	X	X	X	Overheating	Machine parts, exhaust, cooling water	OHE	3
X	X			X	X	X	X	Plugged/choked	Flow restriction(s)	PLU	3 (2)
X	X	X	X	X	X	X	X	Parameter deviation	Monitored parameter exceeding limits, e.g. high/low alarm	PDE	2 (3)

Equipment class [a]								Failure modes			
Combustion engine	Compressor	Electric generator	Electric motor	Gas turbine	Pump	Steam turbine	Turbo expander	Description	Examples	Code [b]	Type [c]
X	X	X	X	X	X	X	X	Abnormal instrument reading	False alarm, faulty instrument indication	AIR	2 (3)
X	X	X	X	X	X	X	X	Structural deficiency	Material damages (cracks, wear, fracture, corrosion)	STD	3
X	X	X	X	X	X	X	X	Minor in-service problems	Loose items, discoloration, dirt	SER	3
X	X	X	X	X	X	X	X	Other	Failure modes not covered above	OTH	—
X	X	X	X	X	X	X	X	Unknown	Too little information to define a failure mode	UNK	—

a See Table A.4. The codes shown apply to equipment classes marked with "X".

b A proposed abbreviated code for the failure-mode.

c One of the three failure-mode types listed below; depending on type of failure, more than one of these categories can apply (e.g. a severe leakage can lead to stoppage of the equipment):

1) desired function is not obtained (e.g. failure to start);

2) specified function lost or outside accepted operational limits (e.g. spurious stop, high output);

3) failure indication is observed, but there is no immediate and critical impact on equipment-unit function. These are typically non-critical failures related to some degradation or incipient fault condition.

Equipment class [a]								Failure modes			
Cranes	Heat exchangers	Heaters and boilers	Piping	Vessels	Winches	Turrets	Swivels	Description	Examples	Code [b]	Type [c]
X	X	X	X	X	X	X	X	Abnormal instrument reading	False alarm, faulty instrument indication	AIR	2 (3)
X			X		X			Breakdown	Breakdown	BRD	3 (1)
	X			X				Insufficient heat transfer	Cooling/heating below acceptance	IHT	2
	X	X	X	X			X	External leakage – process medium	Oil, gas, condensate, water	ELP	3
X	X	X		X	X		X	External leakage – utility medium	Lubricant, cooling water, barrier oil	ELU	3
						X	X	Failure to connect	Failure to connect	FCO	1
X						X	X	Failure to function as intended	General operation failure	FTI	1(2)
X					X	X	X	Failure to rotate	Failure to rotate	FRO	1
X					X			Failure to start on demand	Failure to start on demand	FTS	1
					X			Failure to stop on demand	Failure to stop on demand	STP	1
						X		Failure to disconnect	Failure to disconnect when demanded	FDC	2
		X						Insufficient heat transfer	Missing, or too low, heat transfer	IHT	2
X	X	X	X				X	Internal leakage	Leakage internally of process or utility fluids	INL	3
							X	Low oil supply pressure	Low oil supply pressure	LBP	2
					X			Low output	Performance below specifications	LOO	2
X					X			Load drop	Load drop	LOA	2
						X		Loss of buoyancy	Loss of buoyancy in idle position	LOB	2
						X		Mooring failure	Mooring failure	MOF	2

Equipment class [a]								Failure modes			
Cranes	Heat exchangers	Heaters and boilers	Piping	Vessels	Winches	Turrets	Swivels	Description	Examples	Code [b]	Type [c]
X			X		X	X		Noise	Excessive noise	NOI	3
X		X	X		X			Overheating	Overheating	OHE	3
	X	X	X	X			X	Plugged/choked	Flow restriction due to contamination, objects, wax, etc.	PLU	3
			X				X	Power/signal transmission failure	Power/signal transmission failure	PTF	2
X					X			Slippage	Wire slippage	SLP	2
X					X			Spurious operation	Unexpected operation	SPO	2
X	X	X	X	X	X	X	X	Structural deficiency	Material damages (cracks, wear, fracture, corrosion)	STD	3
X	X	X	X	X	X	X	X	Parameter deviation	Monitored parameter exceeding limits, e.g. high/low alarm	PDE	2 (3)
X			X		X			Vibration	Excessive vibration	VIB	3
X	X	X	X	X	X	X	X	Minor in-service problems	Loose items, discoloration, dirt	SER	3
X	X	X	X	X	X	X	X	Other	Failure modes not covered above	OTH	—
X	X	X	X	X	X	X	X	Unknown	Too little information to define a failure mode	UNK	—

[a] See Table A.4. The codes shown apply to equipment classes marked with "X".

[b] A proposed abbreviated code for the failure mode.

[c] One of the three failure-mode types listed below; depending on type of failure, more than one of these categories can apply (e.g. a severe leakage can lead to stoppage of the equipment):

1) desired function is not obtained (e.g. failure to start);
2) specified function lost or outside accepted operational limits (e.g. spurious stop, high output);
3) failure indication is observed, but there is no immediate and critical impact on equipment-unit function. These are typically non-critical failures related to some degradation or incipient fault condition.

Equipment class [a]					Failure modes			
Fire detectors [b]	Gas detectors [b]	Input devices	Control logic units	Valves	Description	Examples	Code [c]	Type [d]
X		X	X		Failure to function on demand	Failure to respond on signal/ activation	FTF	1
				X	Failure to open on demand	Doesn't open on demand	FTO	1
				X	Failure to close on demand	Doesn't close on demand	FTC	1
				X	Delayed operation	Opening/closing time below spec.	DOP	2
X	X	X	X	X	Spurious operation	e.g. false alarm	SPO	2
X	X [e]	X	X	X	High output	Overspeed/output above acceptance	HIO	2
X	X [f]	X	X	X	Low output	Delivery/output below acceptance	LOO	2
	X [g]				Very low output		VLO	2
X		X	X		Erratic output	Oscillating, hunting, instability	ERO	2
X	X [h]	X			No output	No output	NOO	1
X	X				Spurious high alarm level	e.g. 60 % of Lower Explosion Limit (LEL)	SHH	2
X	X				Spurious low alarm level	e.g. 20 % of Lower Explosion Limit (LEL)	SLL	2
				X	Plugged/choked	Partial or full flow restriction	PLU	1
		X		X	External leakage – process medium	Oil, gas, condensate, water	ELP	3
		X		X	External leakage – utility medium	Lubricant, cooling water	ELU	3
				X	Internal leakage	Leakage internally of process or utility fluids	INL	3
				X	Leakage in closed position	Leak through valve in closed position	LCP	
				X	Abnormal instrument reading	False alarm, faulty instrument indication	AIR	2 (3)

Equipment class [a]					Failure modes			
Fire detectors [b]	Gas detectors [b]	Input devices	Control logic units	Valves	Description	Examples	Code [c]	Type [d]
				X	Structural deficiency	Material damages (cracks, wear, fracture, corrosion)	STD	3
X		X	X	X	Minor in-service problems	Loose items, discoloration, dirt	SER	3
X	X	X		X	Other	Failure modes not covered above	OTH	—
X	X	X	X	X	Unknown	Too little information to define a failure mode	UNK	—

[a] See Table A.4. The codes shown apply to equipment classes marked with an "X".

[b] Failure coding for fire and gas detectors: For fire and gas detectors, it is important that all failures are recorded; also those detected during scheduled testing and those detected in operation, e.g. replacement of a detector head should be recorded, even if this is done as part of the preventive maintenance programme. Typical failure modes are the following:

- failure to function: The detector does not respond when exposed to its relevant stimulus (e.g. gas or heat). This failure mode is normally observed during functional testing;
- spurious operation: The detector gives an alarm signal when it is not exposed to relevant stimulus. This failure mode is normally observed during operation and logged by control-room personnel;
- others: Additionally, some failure modes related to low/high output, adjustments and overhauls will typically be found in the log books.

[c] A proposed abbreviated code for the failure mode.

[d] One of the three failure-mode types listed below; depending on type of failure, more than one of these categories can apply (e.g. a severe leakage can lead to stoppage of the equipment):

1) desired function is not obtained (e.g. failure to start);
2) specified function lost or outside accepted operational limits (e.g. spurious stop, high output);
3) failure indication is observed, but there is no immediate and critical impact on equipment-unit function. These are typically non-critical failures related to some degradation or incipient fault condition.

[e] e.g. reading 10 % LEL to 20 % LEL without test gas; reading above 80 % LEL on test gas.

[f] e.g. reading between 31 % LEL to 50 % LEL upon test gas (assuming a nominal set point of 65 % LEL).

[g] e.g. reading between 11 % LEL to 30 % LEL upon test gas.

[h] e.g. reading less than 10 % LEL upon test gas.