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Abstract

Taking a general investigation of maintenance activities in various industries, three maintenance philosophies are commonly applied, which are corrective maintenance, time-based periodic maintenance and condition-based predictive maintenance.

Corrective maintenance which is implemented after breakdown of the equipment could lead to great losses in personnel safety, environment and assets. Therefore, the application and development on preventive maintenance – especially condition-based predictive maintenance – have been continuously optimized to reduce failures as much as possible so that equipment downtime and maintenance cost can be reduced while reliability and safety level of machinery enhanced.

Besides, e-maintenance is an emerging maintenance management concept that makes use of information and communication technology (ICT) to assistant maintenance activities by linking supports from experts of different parties. By adopting such technique, advantages such as fast response, integration of resources, remote monitoring and decision making can be realized.

Compared with first-class industrial companies where the relatively sophisticated maintenance philosophy covering both condition monitoring and e-maintenance has been applied, COSL until now is still in the primary stage in developing systematic maintenance system centering the importance of condition monitoring. Also e-maintenance is rarely employed.

This study will discuss the development, characteristics, and relevant impacts of several techniques commonly used in condition monitoring as well as those of e-maintenance. Moreover, combined with current practices of maintenance methodologies in COSL, possible improvement in maintenance system will be explored.

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Chapter 1 Introduction

1.1 Introduction and background

With consistently increasing attention on RAMS (reliability, availability, maintainability and supportability) of equipment in parallel with safety, environmental protection and cost-reduction in offshore industry, a set of maintenance strategies have been developed to meet the requirements of interested parties. As one of them, preventive maintenance especially condition-based preventive maintenance - predictive maintenance - has become prevalent and is expected to continue to play an important role in future. Techniques such as vibration monitoring, oil and debris analysis, non-destructive testing (NDT) etc. have been applied to diverse plants based on their respective characteristics and performance. Meantime, e-maintenance which is developed to both reduce equipment failures and maximize benefits by advanced condition monitoring and communication technology becomes sprung up in offshore oilfield development.

Comparing with maintenance activities in the same industry worldwide, China Oilfield Services, Ltd. (COSL) as the company who is committed to exploring international market still lacks of effective maintenance management system. What has been adopted by COSL is relatively simple and less cost-effective. Corrective maintenance and periodic maintenance account for large part of current maintenance system. Predictive maintenance and e-maintenance are still in initial stage and not broadly applied. This study will compare state-of-art maintenance philosophies with actual maintenance applications on some drilling platforms in COSL to explore possible improvement in future.

1.2 Research questions

- 1) What are the main maintenance philosophies used in contemporary industries
 - a) Run-to-failure corrective maintenance
 - b) Schedule-based periodic maintenance
 - c) Condition-based predictive maintenance

- 2) What are the advantages of various condition monitoring techniques
 - a) Vibration monitoring
 - b) Tribology and oil analysis
 - c) Non-destructive testing
 - d) Infrared thermography technique
 - e) Process parameters monitoring

- 3) How can e-maintenance be used to optimize existing maintenance system
 - a) Remote maintenance
 - b) Collaborative maintenance
 - c) Real-time Maintenance
 - d) Predictive maintenance

- 4) What are the problems of current maintenance applications in COSL Drilling

- a) There are many aspects that can be improved to reduce the occurrence of corrective maintenance
 - b) The execution of the periodic maintenance is too inflexible to effectively retain the good condition of the equipment
 - c) The application of condition based predictive maintenance is limited
- 5) What needs to be taken into consideration to construct a suitable maintenance system
- a) Obtain the support and investment from the company
 - b) Establish an managerial system optimizing the combination of different maintenance strategies
 - c) Set up an advanced condition monitoring system to minimize unexpected failures
 - d) Keep continuous improvement on maintenance application
 - e) Employ feasible e-maintenance technologies

1.3 Objective

The main objective of this study is to discuss present maintenance strategies and condition monitoring techniques applied in various industries to recommend possible improvements in maintenance management in COSL Drilling.

Sub-objectives:

- 1) Narrate state-of-art in condition-based predictive maintenance
- 2) Sketch the development of e-maintenance worldwide
- 3) Describe the current maintenance application in COSL Drilling
- 4) Suggest the possible improvement in maintenance in COSL Drilling using condition monitoring and e-maintenance

1.4 Delimitations

This paper is limited to the application of maintenance methodologies applied in oil and gas industries and specially emphasize on drilling platforms in COSL.

1.5 Acknowledgement

I would like to express my appreciation to my academic advisor, Professor Markeset Tore, who provided me guidance and support during my thesis writing. Professor Markeset is a knowledgeable expert in the areas of management of operation and maintenance. Without his instruction, this thesis could not have reached its present form.

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Chapter 2 State-of-art in maintenance strategies and techniques

2.1 General overview of different maintenance strategies

Maintenance is the combination of all technical, administrative and managerial actions during the life cycle of an item intended to retain it in, or restore it to, a state in which it can perform the required function (EN 13306:2010). BS EN 13306:2010 categorizes maintenance into two main groups: corrective maintenance and preventive maintenance. Each group is further subdivided into several branches, as shown in Figure 2.1. For purpose of clarity, this paper refers to predetermined preventive maintenance as periodic maintenance or PM, while refers to condition-based preventive maintenance as predictive maintenance or PdM.

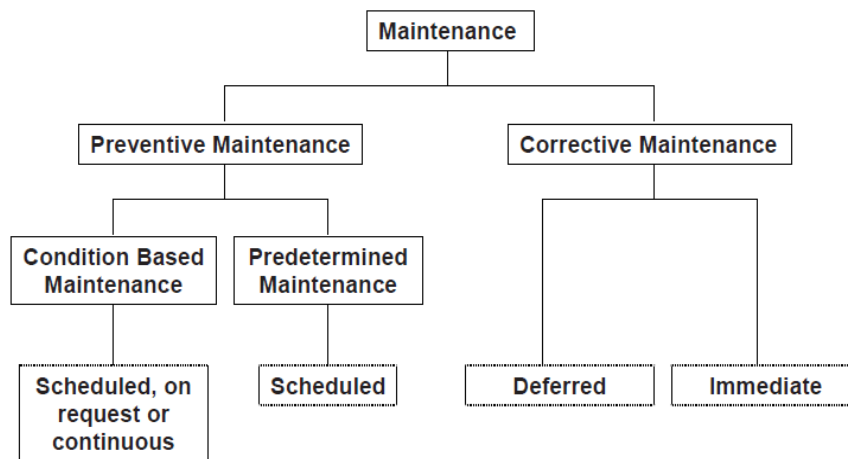


Figure 2.1 Maintenance Overview (EN 13306:2010)

2.1.1 Corrective maintenance (CM)

Corrective maintenance is carried out after fault recognition and intended to put an item into a state in which it can perform a required function (EN 13306:2010). In simple terms, CM occurs when there is failure on certain component or apparatus, which to some extent has the same meaning with repair.

As shown in figure 2.1, CM can be divided into two types – deferred and immediate. Deferred CM – also called planned CM – usually refers to that on non-critical equipment putting little influence on production, such as a telephone or a loudspeaker. Such maintenance activities can be conducted together at a planned period afterwards without worrying about their negative impacts. In contrast, immediate CM refers to that on critical equipment affecting significantly on operation, such as Top Drive on the drilling rig. In such case the problem must be coped with as much as possible despite there is no plan preparing for it. Thus it is also called unplanned CM.

No matter which one of them, such maintenance type has many disadvantages such as curtailment in equipment life, consumption of spare parts, and reduction in benefits. For unplanned CM, more severe consequences may happen such as delay in operation/production, increased probability of accidents, or lowered safety for both personnel and machinery.

Despite unexpected outcomes listed above, CM cannot absolutely be eliminated because no one and no technique can predict all the problems that could happen. Many factors such as

aging, corrosion and erosion, unexpected damages, etc. could result in unexpected failures. On the other hand, however, the activities related to CM can be reduced as much as possible if proper PM or PdM methods are applied. If the equipment is maintained ahead of time or monitored by suitable sensor/detector, the problems will be timely detected and repaired such that the downtime caused by the unexpected failures will be reduced.

2.1.2 Periodic maintenance (PM)

Periodic maintenance is the one that carried out in accordance with established intervals of time or number of units of use but without previous condition investigation (EN 13306:2010).

2.1.2.1 Advantages of periodic maintenance

Compared to CM, PM has some advantages, such as:

- Reduction in failures and downtime
- Reduction in inventory
- Extended equipment life
- Increased equipment reliability
- Decrease in maintenance cost and economic loss

A typical example is the author's work experience. One day during patrol inspection of the equipment onboard, the cable of a submersible pump being laid and fastened along the leg of the platform was found to be loose because of the flapping of the waves. Following measures were implemented to retighten the cable by steel banding tapes. The submersible pump kept working without being damaged. From this example PM effectively prolongs the service life of submersible pump thanks to the periodic maintenance – visual inspection. Also the maintenance cost, influence to drilling operation and economic loss in inventory are cut down.

2.1.2.2 Disadvantages of periodic maintenance

In spite of those advantages mentioned above, PM has some shortcomings that cannot be ignored:

- 1) The content of PM normally comprises of simple terms. Figure 2.2 is an example of PM, where maintenance contents are derived from user's manuals. What are included in such maintenance system are nothing more than clean, visual check, audio identification, fastening screws, or lubrication. It cannot be denied that these activities to some extent could prevent further deterioration of the equipment. However, many other problems cannot be detected by only such kind of superficial inspections.
- 2) PM is executed based on the service period or running hours of the equipment. In some cases, such maintenance strategy cannot reflect objective equipment conditions. For example, a machine with frequent heavy workload compared to the one with light workload will stand more severe wear and thus need more maintenance. However, such requirement cannot be met if the maintenance is only carried out periodically.
- 3) Some activities required by PM could be delayed or even forgotten due to operation needs. For instance, if well-cementing are under operation, relevant facilities have to be in ready-for-use status so that they can come into service at any time. Under such

situation, the equipment cannot be shutdown to carry out regular maintenance. It may not affect too much if there is only one delay. However, the whole maintenance system could be disturbed if there occur many similar situations.

	verify smooth operation. 检查随动液 压软管运动时是否正常	2010.07.26	30天	已完成	钻井 二班	10.7.27	正常
94223412 2#BOP移动滑车 执行人签名: 王涛							
3	Check for leaks in hydraulic hoses, pipes, and hydraulic components. 检 查液压软管、管线和液压元件是否有裂 痕	2010.07.26	30天	已完成	钻井 二班	10.7.27	正常无裂痕
4	Check the hydraulic cylinders, piston rods, seals and casings. 检查 液压缸, 活塞拉杆, 密封和保护套	2010.07.26	30天	已完成	钻井 二班	10.7.27	正常
5	Check visually all visible bolted connections. 观察所有螺栓连接情况	2010.07.26	30天	已完成	钻井 二班	10.7.27	正常紧固
6	Inspect the telescope hose reel to verify smooth operation. 检查随动液 压软管运动时是否正常	2010.07.26	30天	已完成	钻井 二班	10.7.27	正常
94223432 2#井口气动绞车 执行人签名: 王涛							
7	Check motor and brake for proper operation, damage. 检查马达和刹车是 否正常	2010.07.26	30天	正常	钻井 二班	10.7.27	正常
8	Clean outside of product. 清理外部 杂物	2010.07.26	30天	已完成	钻井 二班	10.7.27	已清理
94223433 3#井口气动绞车 执行人签名: 王涛							
9	Check motor and brake for proper operation, damage. 检查马达和刹车是 否正常	2010.07.26	30天	已完成	钻井 二班	10.7.27	正常
10	Clean outside of product. 清理外部 杂物	2010.07.26	30天	已完成	钻井 二班	10.7.27	已清理
94223434 4#井口气动绞车 执行人签名: 王涛							
11	Check oil level. 检查油位	2010.07.26	30天	正常	钻井 二班	10.7.27	油位正常
	Clean outside of product. 清理外部 杂物	2010.07.26	30天	已完成	钻井 二班	10.7.27	已清理
94230111 1#二层台气动绞车 执行人签名: 李平							
13	Inspect the oil level of the motor						

Fig. 2.2 Preventive Maintenance System applied on most platforms in COSL

- Most of maintenance tasks in PM system are implemented based on visual or audio inspection, which rely too much on the subjective monitoring and judgment of the maintenance staff, such as physical ability, working capability, personal experience, sense of responsibility, etc. These factors more or less influence the maintenance quality. For example, a newbie is not likely to be sensitive to abnormal smell or noises.

2.1.3 Predictive maintenance (PdM)

Predictive maintenance is condition-based maintenance carried out following a forecast derived from repeated analysis or known characteristics and evaluation of the significant parameters of the degradation of the item (EN 13306:2010). PM and PdM have some common attributes such as they all devote to improving the reliability of the equipment, extending the service time, reducing the failure, lowering the relevant cost and so on. On the other hand, however, PdM has gained growing preference owing to its objectivity, pertinence and cost-effectiveness in guiding maintenance activities. According to the survey done by Mobley (2002) of 500 plants that have applied PdM, some advantages are as following:

- The number of failures is reduced by 55%. Unlike PM which is carried out based on the running time, the execution of PdM is in accordance with objective machinery conditions. Figure 2.3 indicates a typical application of PdM. By applying proper monitoring techniques, early warning signals are detected to decide whether the equipment requires necessary maintenance. The advantage of such strategy is that it ensures the timely maintenance before the breakdown, while avoiding over-maintenance or lacking-

maintenance due to the ignorance of dissimilar operating conditions.

- 2) Mean time to repair (MTTR)/downtime are reduced by 60%. In modern industries especially in offshore industry, a few minutes of downtime will result in huge loss. For this reason the downtime has become an important benchmark which is used to measure and determine, for example, the daily rate of the drilling rig. Condition-based PdM can effectively identify the problems in advance and inform personnel to perform timely maintenance so that the equipment is reserved in good state and thus the downtime is reduced.

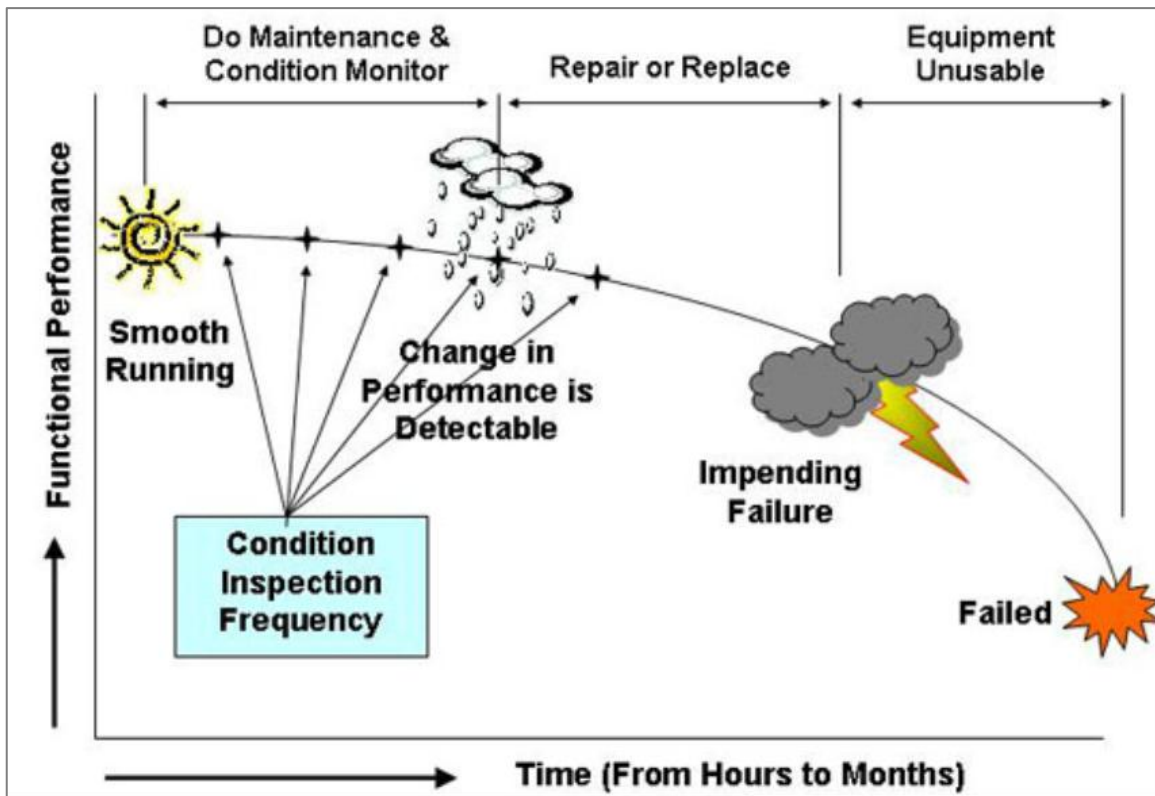


Figure 2.3 condition monitoring during equipment degradation process (Sondalini)

- 3) The operating life of the machinery – and MTBF (mean time between failures) as side benefits – increases 30%. No matter which part of the equipment fails, it will cause negative interaction to the other components. Such kind of influence may not directly affect current use of the equipment. In the long run, however, the service life of the whole machine may be shortened. By using PdM to monitor equipment state and thus reduce the failures, the average equipment lifetime in a certain period as well as in the whole equipment life is prolonged.
- 4) The availability of the equipment increases 30%. It is well-known that the availability follows an equation, which is

$$\text{Availability} = \frac{MTBF}{MTBF + MTTR}$$

If the denominator is deemed as a constant which refers to total service life of the equipment, then 30% decrease in numerator – as shown in previous paragraph – will result in 30% decrease in the availability of the machinery. This is reasonable. Compared to PM where random failures during the fixed period have the chance to arise, PdM using proper monitoring instruments can anticipate even tiny abnormalities such that they can

be corrected in time before the occurrence of the failure. The availability is therefore improved with less breakdown and longer service life.

- 5) Maintenance cost is reduced by 50%. Maintenance involves a series of aspects such as personnel, tools, spare parts, support from the expert or OEM (Original Equipment Manufacturer), etc. Each of them will consume considerable expenditure. By applying PdM, unexpected expense is lowered owing to the reduction in malfunction.
- 6) The inventory is reduced by more than 30%. Instead of being stored in the warehouse, some spare parts of which lead time is relatively short can be ordered when the early warning signals are detected by condition monitoring techniques. It is therefore unnecessary to have too much spare parts backup for the failures.
- 7) Enhanced safety of people. In order to realize certain function(s), the equipment is always connected with physical or chemical mediums such as electricity, high-pressure air/oil, and chemicals which are harmful to human body. Normally those substances are protected against people by coverings, pipes or vessels. In case of failure, however, they may expose or even blast. PdM while reducing equipment failures by alerting the abnormalities in advance also lowers the risks of personnel injury.

Besides what are mentioned above, there are other superiorities such as reduced unscheduled maintenance, reduced overtime, reduced penalties resulting from delayed operation, etc. All of these benefits, basically speaking, are thanks to the reduced failures because of the application of condition monitoring techniques.

Nevertheless, it should be noticed that not all the facilities require PdM. In addition, there is no single condition monitoring technique suitable for all the machines. To decide which one should be chosen, it is necessary to fully understand the properties of these techniques.

2.2 Condition monitoring techniques

The establishment of PdM is based on the condition monitoring of the equipment, which is a generalized method for establishing a machine's health using measured parameters which reflect changes in the machine's mechanical state (Markeset, 2012). It is therefore necessary to clarify the characteristics of different condition monitoring techniques to select suitable technique(s) for each piece of equipment.

2.2.1 Vibration monitoring

A vibration is a periodic motion or one that repeats itself after a certain interval of time (Mobley, 1999). The simplest of periodic motion is harmonic function. It is expressed by the equation $X = X_0 \sin(\omega t)$. When several harmonic vibration sources act together, however, the total curve tends to be non-harmonious, as shown in Figure 2.4.

Normally there is more than one influencing factor determining the vibration profile of one machine or component. For example, the vibration signature of the pump shaft may consist of misalignment, imbalance, looseness, bearing defects, resonance, installation problems of pump foundation, etc. Therefore it may be difficult to distinguish all the vibration sources in such non-harmonic curves.

Based on the theory of Fourier transform while relying on the development of computer technology, however, such time-domain vibration curves can be transformed to a series of standard sine/cosine functions and further frequency-domain graph (Figure 2.5) through Fast Fourier Transform (FFT) by sophisticated instruments. Based on the fact that each vibration signal has its unique amplitude and frequency, it is relatively easy to recognize the vibration sources by comparing the information in the graph with characteristic data of different forces.

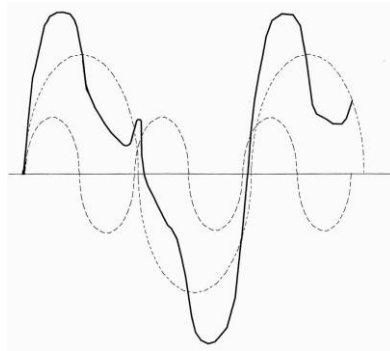


Figure 2.4 total (non-harmonic) time-domain vibration curves (Mobley, 1999)

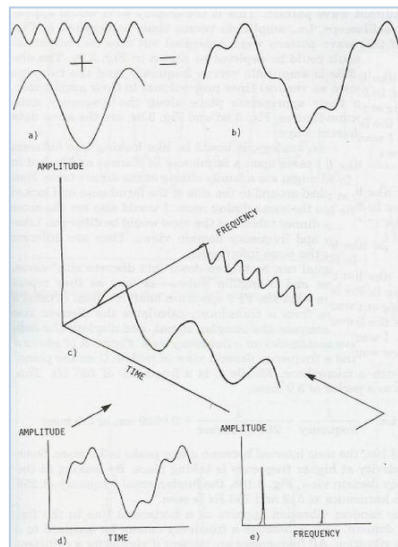


Figure 2.5 Graphic indication of the theory of Fourier Transform (Markeset, 2012)

The reason why vibration analysis is employed by PdM is based on the following facts, which outline the foundation of the approaches used to detect and quantify the root causes of failure (Mobley, 1999):

- All common machinery problems have respective vibration frequency characteristics that can be identified.
- Vibration signals displayed in frequency domain consist of discrete peaks representing different vibration sources.
- The frequency characteristics of one machine will remain constant until some abnormalities change the vibration features.

Based on the above, it is clear that regardless of speed or mode of operation, all machinery in motion creates vibration signals which reflect its operating condition. When being used properly, vibration data provide the means to maintain optimum operating conditions and

efficiency of critical plant systems (Mobley, 1999). It provides incipient warning of latent serious problems in the machinery. Figure 2.6 shows advantages of vibration analysis superior to the other techniques.

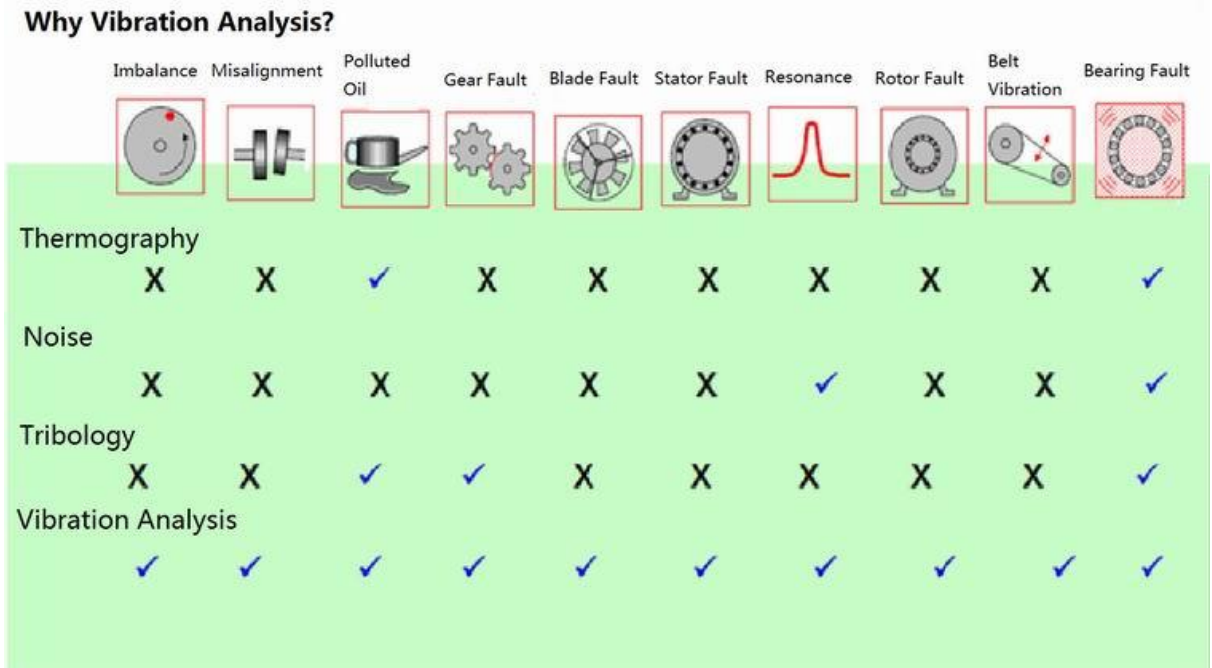


Figure 2.6 advantages of vibration analysis superior to other techniques (Dong, 2012)

2.2.2 Tribology and oil analysis

Tribology is the general term that refers to design and operating dynamics of the bearing-lubrication-rotor support structure of machinery (Mobley, 2002). As an effective technique used to diagnose early faults, the application of tribology can be traced back to early 1940s, where it was first used by a railway company in the United States. By the 1980s, tribology has been utilized in a variety of industries and it ranks only second to vibration monitoring.

The principle of tribology is that in a running machine, there are continuous physical or chemical interactions between components – for instance the force between two rotating gears, or reaction between water elements and metal parts – which result in abrasion of equipment components. By adopting such technique, following features of wear debris can be determined and therefore maintenance work performed to reduce possible failure (Markeset, 2012):

- Quantities implies the degree of wear
- Morphology indicates different wear process, such as adhesive wear, abrasive wear, cavitation, corrosive wear, cutting wear, etc.
- Size distribution demonstrates the change in wear activities
- Composition of the particles shows possible sources of wear

As stated by Girdhar and Scheffer (2004), identification and analysis of wear debris can pinpoint the type of wear and also identify the source, which could be any component under distress. Compared with vibration analysis, lubricant analysis has following advantages (Markeset, 2012):

- Only unhealthy machine contribute excessive amounts of debris.
- Path of debris from the source to the sampling point is much clearer than that of vibration signal.
- The component of a vibration signal caused by a fault can easily be masked by the vast array of large components emanating from perfectly healthy machine components.

2.2.2.1 Properties of debris and oil

To decide which tribology technique should be selected, it is necessary to clarify the types of particles and the role of lubricating oil. The types of particles are generally classified into two types: external contaminants and internal debris. Both are further divided into specific groups, as shown in table 2.1. Also, the types of particles can be distinguished from their shapes, as shown in table 2.2.

There are still other ways to define the types of particle in the oil, such as the products of oxidation and nitration, environment dirt, moisture, polymer contaminants, etc. No matter how the particles are classified, each serves the analysis and reduction of unwanted impurities.








More than illuminating the wear particles, making clear of oil composition is the critical function of lubricating oil analysis. The lubricant typically has several major features such as lubricating, cooling, cleaning, anti-corrosion, protecting equipment components from extreme load, etc. For the sake of realizing such multiple functions, amount of additives are added into the oil in order to optimize its performance. The typical ones are:

- Anti-wear and anti-pressure additives that inhibit physical interaction, such as Cooper, Lead, Boron
- Rust inhibitor and oxidation inhibitor that prevent from chemical corrosion, such as Phosphorus, Zinc
- Detergents and dispersants that inhibit debris precipitation, such as Calcium, Magnesium
- Foam depressants that inhibit foaming due to high velocity, such as Silicon
- Viscosity improvers that ameliorate lubricating property

Table 2.1 types of particles in lubricating oil

External contaminants		Internal debris	
Type	Sources	Type	Sources
left over	invade during manufacturing, transportation, installation, or commissioning	abrasive	particles between adjacent moving surfaces
absorbed	intrude due to breathing hole, or improper sealing	adhesive	motion between hard surfaces
induced	introduced during maintenance or repair	erosive	physical impact due to fluid with high velocity
escaped	released from filter	corrosive	chemical reactions
		fatigue	repeated stress

Table 2.2 Types of debris shape found in oil (Hunt, 1996)

Particle shape	Typical names	Possible origins
	spheres	metal fatigue, Welding sparks, Glass peening beads
	pebbles and smooth, ovoid	quarry dust, atmospheric dust
	chunks and slabs	metal fatigue, bearing pitting, rock debris
	platelets and flakes	running-in metal wear, paint or rust, copper in grease
	curls, spirals and slivers	machining debris, produced at high temperature
	rolls	probably similar to platelets but in a rolled form
	strands and fibers	polymers, cotton and wood fibers, occasionally metal

Normally there are baselines for each additive so that the changes of compositions in the lubricating oil could be identified by adopting suitable techniques. One example is the oil analysis of Caterpillar diesel engine, where the baselines and explanations of each additive are involved, as partly shown in table 2.3.

Table 2.3 baselines and explanation of additives in lubricating oil (COSL, 2012)
(Translated from test report of lubricating oil of diesel engine on one drilling platform)

Fe:100 – 200; Cr:30 – 60; Al:15 – 40; Cu:5 – 40; Ag: 5 – 10; Pb: 5 – 14 (Units: PPM)	
Elements	Indications
Fe,Cr,Si	abnormal wear of the cylinder jacket or piston ring due to corrosive substances in combustion gases
Cu	abrasion in diverse bronze bushings (main bearing bushing, rod bearing bushings, valve rocker bushings, drive bearing bushings, piston pin bushings, slave rod bushings)
Ag	wear in silver parts involved in bearing protectors, piston pumps, gears, spindle, bearings, piston pin, etc.
Pb	external contamination
Al	abrasion in piston skirts, cam bearings, rocker cover

2.2.2.2 Typical oil analysis techniques

1) Spectrometric analysis

It is based on the underlying principle of atomic physics involving complementary energy changes within atoms which give rise to the emission or absorption of light (Collacott, 1977). Spectrometry development today has generated sets of analysis methods. Basically it is

divided into two branches: radiation spectrometry and mass spectrometry.

Radiation spectrometry includes emission spectrometry, atomic absorption spectrometry, nuclear magnetic resonance spectrometry and Raman scattering spectrometry. The common characteristic of these techniques is that they allow the composition and structure of matter to be ascertained based on investigation of the spectra yielded by the interaction between atoms and molecules, and various types of electromagnetic radiation, emitted, absorbed, or scattered by the former(CEA). Take atomic absorption for example. As shown in Figure 2.7, a hollow cathode lamp emits light attribute of the elements to be inspected. The solution where the wear particle is put in is “flamed” by the nebulizer. The particles is then “lightened” and wavelength sorted by the monochromator. Afterwards, the detector turns the light energy transferred from monochromator into electrical signals so that qualitative and quantitative characteristics of the particle can be received and determined by data processor.

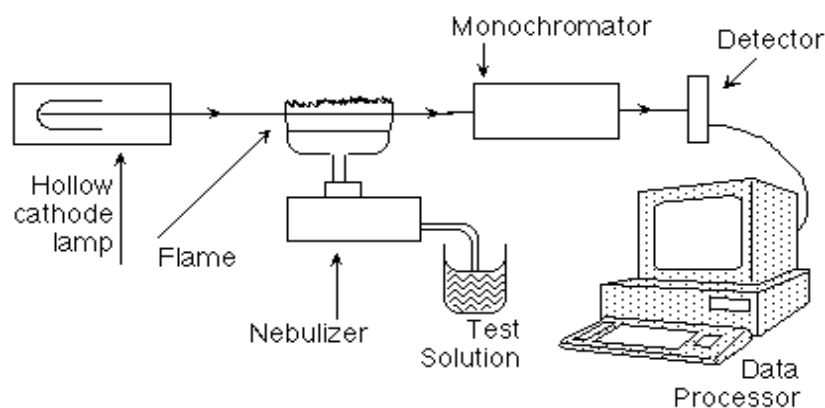


Figure 2.7 illustration of the atomic absorption principle (NMSU)

The physics behind mass spectrometry is that a charged particle passing through a magnetic field is deflected along a circular path on a radius that is proportional to the mass to charge ratio, m/e . (Hunt) In an electron impact mass spectrometer, an electron beam with high energy supersedes an electron in the organic molecule to form a molecular ion. Such molecular ion is unstable and tends to scraps to smaller ions. These ions are collected, focused into a beam and accelerated into a magnetic field where the ions are swerved along circular paths according to their masses. By changing the magnetic field, the ions are focused on the detector and therefore recorded.

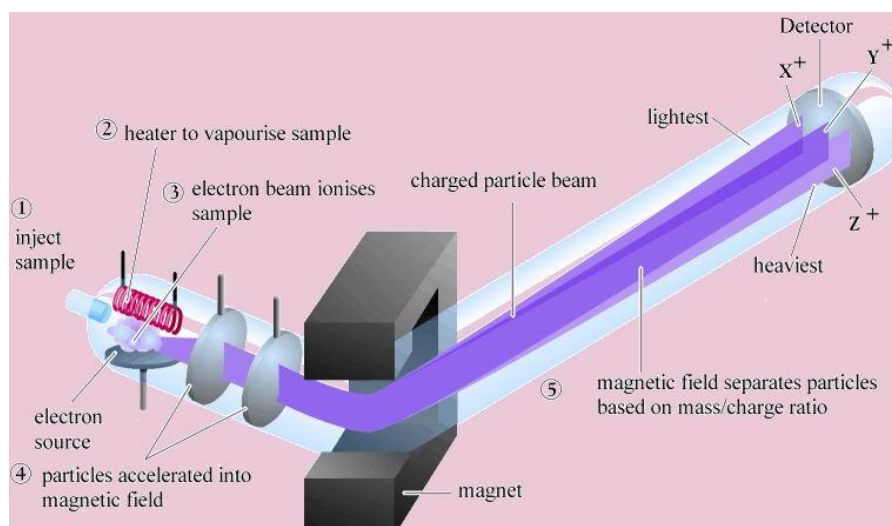


Figure 2.8 indication of mass spectrometry principle (source: www.chem.ucalgary.ca)

2) Ferrography

The principle of ferrography is that the magnetic force attracting the ferrous particles is proportional to their volume. A lubricant sample which is diluted with a solvent is allowed to flow down a low-angle substrate while passing through a bipolar magnetic field. The particles precipitate on the substrate surface due to the magnetic force as well as gravity. After removing the residual lubricant and drying, the contaminants are examined and determined under a microscope.

Being different from other oil analysis methods, ferrography can merely applied to detect ferromagnetic materials. In reality, spectrometry and ferrography are used together so that they can complement each other since spectrometry is normally limited to the particles less than 5 microns whereas ferrography can detect the particulate contamination between 10 microns and 100 microns. Further, ferrography is able to evaluate the type, shape, size and quantity of the particles, which therefore is easy to judge the contaminant sources, as shown in Figure 2.9.



Figure 2.9 Particulate types distinguished by analytical ferrography (Beatty, 2004)

3) Fourier transform-infrared analysis (FT-IR)

Before introducing FT-IR, it is necessary to make clear of infrared analysis (IR). Strictly speaking, IR is an absorption form of spectrometric analysis. It uses the light with a particular wavelength to transmit through the oil sample film. By measuring the amount of energy absorbed, the quantity of matched chemical elements is determined.

The principles of FT-IR and IR are more or less the same. The biggest difference between them, however, is that IR is a dispersive testing means where limited types of substances can be detected each time. In contrast, FT-IR can measure all infrared frequencies simultaneously in a very short time by utilizing an optical instrument called interferometer. Afterwards, the interferogram generated by interferometer is deciphered by Fourier transformation so that the frequency spectrum produced is understandable by professional staff. A typical FT-IR system is shown in Figure 2.10. By employing such technique, both the quantity and composition of the additives, external contaminants and internal debris are ascertained.

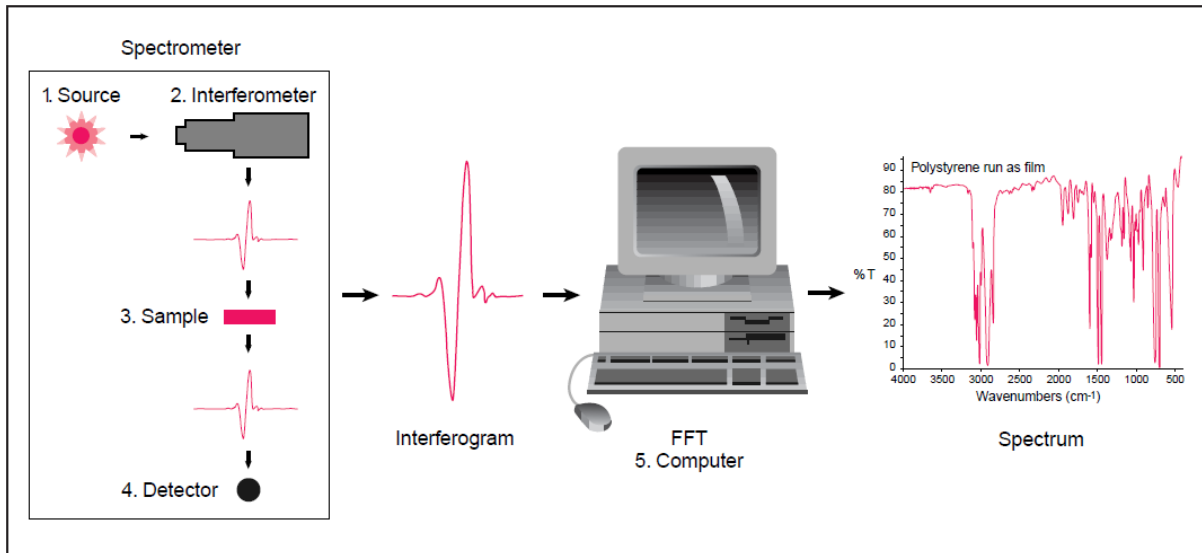


Figure 2.10 main constituents of FT-IR system (Spires, 2001)

2.2.3 Non-destructive testing (NDT)

Nondestructive testing are noninvasive techniques to determine the integrity of a material, component or structure or quantitatively measure some characteristic of an object (Salta, 2012). Such technique particularly refers to the detection of surface and internal defect of the solid material. Several techniques are available such as eddy current, magnetic particle testing, penetrant testing, radiographic testing, ultrasonic testing, etc.

1) Ultrasonic testing (UT)

Ultrasound is acoustic energy in the form of waves having a frequency above the human audible range. Due to a mismatch of acoustic properties between materials, the sound will partly reflect at interfaces. The quantity of reflected energy is dependent upon the acoustic impedance ratio between two materials (Rao.B.K.N, 1998). If the impedance ratio is quite different like an open crack with steel/air interface, the adequate reflection will occur for the detection of the flaw.

Ultrasonic testing is used to detect the inner defects of the materials with smooth surfaces. The smallest detectable flaw depends on the wave length. The theoretical measureable flaw is $\frac{1}{4} \lambda$, where λ is the ultrasonic wavelength.

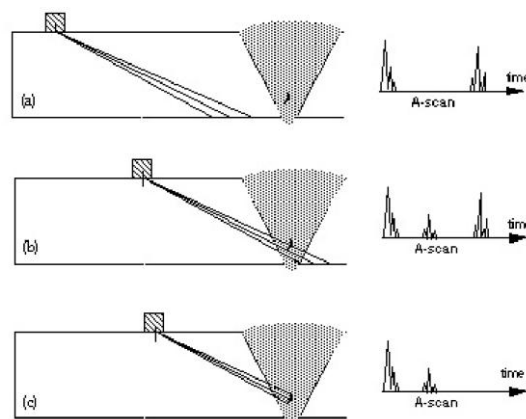


Figure 2.11 indication of ultrasonic testing (Lawson, 1996)

2) Magnetic particle testing (MPT)

The principle of magnetic particle testing is that the cracks on the surface of ferromagnetic materials allow the magnetic flux to leak. When the material is subjected to a magnetic field, the very small particles flowing over the surface will be attracted to the flux leakage from the cracks.

The magnetic particle method is applied only to ferromagnetic materials. If the operator is vigilant, the small defects with 0.5mm long \times 10 μ m deep for a polished surface can be identified.



Figure 2.12 surface flaws detected by MPT (source: <http://treborqs.com/services>)

3) Eddy current testing

Unlike magnetic particle testing which relies on the ability to magnetize a material, eddy currents are best suited to non-magnetizable materials (Rao.B.K.N, 1998). The essential requirement is that, however, the tested material must be electrical-conductive.

The principle of eddy current testing is that a coil excited by an alternative current will produce an alternating magnetic field. This magnetic field induces a secondary current within the conductive material close to it. This secondary current then generates an opposing magnetic field, i.e. eddy current magnetic field. When there is flaw at surface or sub-surface of the material, the eddy current magnetic field – which has been calibrated before the test – will be changed and detected by the instrument.

Eddy current testing can detect the discontinuities at the surface or subsurface, with 10-12mm maximum flaw depth for non-magnetizable materials. It is possible to detect the flaws through a coated surface, but with limited coating thickness.

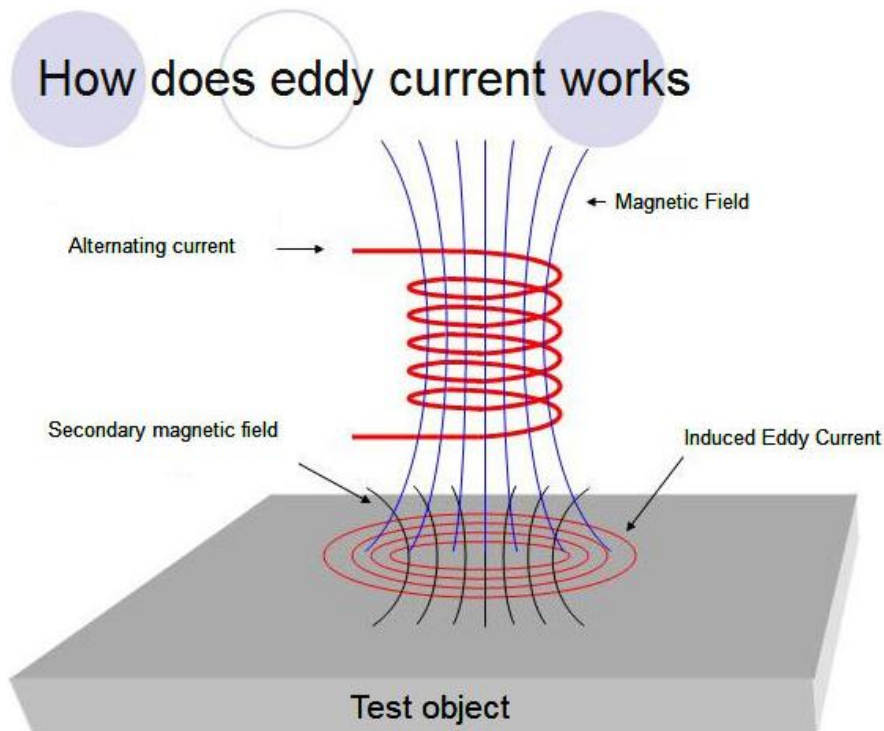


Figure 2.13 how does eddy current work (Source: www.energygostar.co)

4) Penetrant testing

The principle of penetrant testing is that the surface to be inspected is coated with a film of a special penetrant. Then the penetrant will draw into surface cracks by capillary action (Rao.B.K.N, 1998). After cleaning the surface with suitable cleaner, a layer of developer is applied. This layer will draw the penetrant out of the cracks and proliferate it over a large area, which makes the crevices more visible.

Penetrant testing is applied to the material which is non-porous. However, it can only detect the surface cracks which have to be cleaned without paint coat, grease, rust, or the other contaminants.



Figure 2.14 penetrant testing of a flange with cracks (Source: www.indiamart.com)

5) Radiographic testing

The principle of radiography is that the radiation can pass through the objects while attenuating in strength according to the density or thickness of the materials. If there are

defects enclosed in the objects, the radiation will attenuate less than material itself. Then those defects will be detected through photographic film.

Radiographic testing is applied to detect the volume defects (such as holes) enclosed in the solid objects. The detection limit is about 1% to 2% of the total thickness of the material by applying “double wall, double image” method.

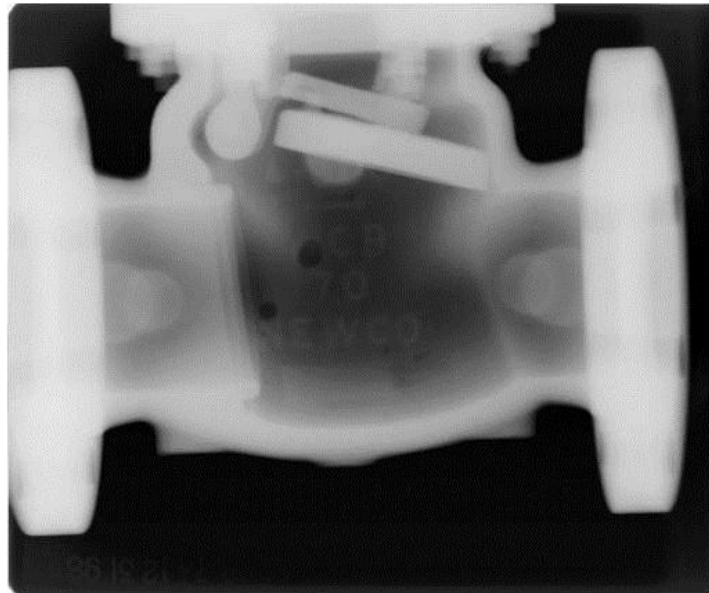


Figure 2.15 radiographic testing of a valve with flaws in it
(Source: <http://asntregion19.webs.com/>)

As seen from the above, NDT is a comprehensive term that covers a variety of techniques. Each technique has its own application domain. It is difficult to detect all types of defects by applying a single method. In addition, there are always several considerations such as cost, quality, and safety when deciding which technique should be selected. From manual operation to automatic scanning, from laboratory testing to on-site detection, it is necessary to consider the cost which customer can accept, the portability of the instrumentation, as well as uncertainty of defective sperm, quantitative and intuitive imaging.

2.2.4 Infrared thermography (IR) technique

Infrared thermography is the technique that makes use of specialized instrumentation to monitor infrared energy emitted by the machinery to determine its operating condition. It is based on the fact that all objects with temperature above absolute zero emit electromagnetic energy. Part of its spectrum – infrared band which is around 1 to 14 microns and out of human eye’s range – is utilized by thermography. IR instrument utilizes an optical lens system to collect the invisible energy radiated from an object and focus it onto the infrared detector. The energy is then converted to an electronic signal and further amplified to an image or digital display which is readable and understandable.

Thermography today has developed relatively mature instrument – infrared thermometer, which is further divided into spot thermometer and infrared imaging. Spot thermometer can only measure single-point temperature on a machine, whereas infrared imaging provides full-color temperature exhibition of wider area.

Thermography has been utilized in a quantity of industries such as electricity & electronics, automobile, aviation, glass, plastic, chemical, metallurgy, and so on (www.infratec.de). When being related to PdM, 3 systems are normally mentioned: electrical system, mechanical equipment, and photovoltaic power system.

1) Electrical system

There is always conversion between electricity and thermal energy, which forms the basis of thermal detection of electrical abnormalities. If there is something wrong with certain part in the electrical system, the thermal energy radiated at the fault point will be different from other similar parts.

For example, the bus ties in the power system are always charged with high voltages. And the wire terminals or terminal blocks are indispensable in the power distribution to the electrical equipment. If improperly connected, tightened or maintained, the current flowing through the terminals will emit amount of heat due to the increased resistance caused by air gap or rust. It is easy by using a thermal imager to generate clear indication of anomaly such that the fault location can be pinpointed by comparing with nearby references. Figure 2.16 and 2.17 are the indications of anomalousness detected by thermal imager. Similarly, thermography is broadly applied in the troubleshooting of other electrical equipment (Mobley, 2002):

- Switchgear, circuit breakers with their terminals and wire connections
- Capacitors, thyristors, fuses
- Generators, transformers
- Motors



Figure 2.16 Thermal imaging of fault cable connection (Source: FLUKE Product Brochure)

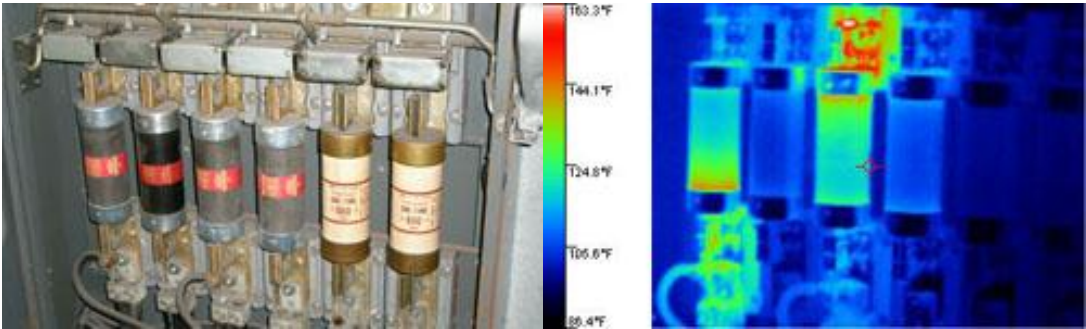


Figure 2.17 Thermal imaging of fuses (source: Florida bearings, Inc.)

2) Mechanical equipment

Like the principle of transmission between electrical power and thermal energy, there is energy conversion between mechanical movement and heat. For example, the inappropriate installation and assembling are the typical mechanical problems met by maintenance staff. The thermal energy caused by anomalous friction due to such problems can be ferreted out by thermal imager. Similarly, other mechanical faults which can be identified by thermography are:

- Rotating equipment such as gear, gearbox, shaft, bearing, drive belts, pump, compressor
- Insulation such as boiler, duct, vessel

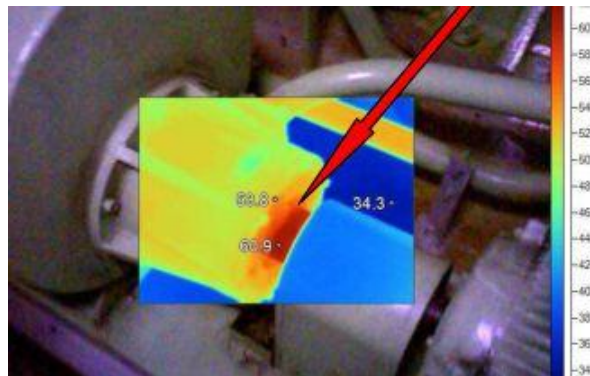


Figure 2.18 Thermal imaging of a rotating shaft (Source: Gamma-Tech)

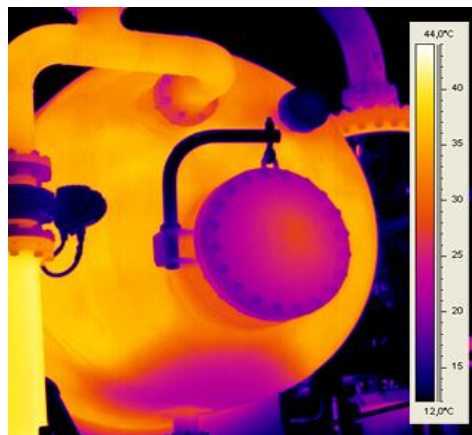


Figure 2.19 Thermal imaging of a vessel (Source: Aker Solutions)

3) Photovoltaic power system

Photovoltaics (PV) is a method of generating electrical power by converting solar radiation into direct current electricity using semiconductors that exhibit the photovoltaic effect (wikipedia). Photovoltaic system employs a group of solar cells which contain photovoltaic materials, such as silicon cells or metallic thin films cells, to convert solar energy to electrical power. However, the popularization of PV cells is impeded by the low conversion efficiency due to some deficiencies. For example, the conversion efficiency of silicon PV cells is limited by free carrier recombination because of bulk material defects, while that of metallic film PV cells is restricted by the lateral non-uniformities in current flow.

To better such a sophisticated product, lock-in thermography (LiT) which is first invented in 1984 is introduced to spot the defects. LiT means that the power dissipated in the object under investigation is periodically amplitude-modulated, the resulting surface temperature modulation is imaged by a thermo camera running with a certain frame rate, and that the generated IR images are digitally processed according to the lock-in principle (Breitenstein et al., 2011). By stimulating a PV cell with pulsed light, heat, or electrical signals, a lock-in amplifier tuned to the stimulus' excitation frequency allows the system to detect subtle thermal responses beyond the noise floor limitations of an IR camera (Tarin and Overstreet, 2010). Besides, LiT has a noticeable superiority that it can eradicate the problems caused by the reflections from other thermal sources such as human body radiation, lights, etc.

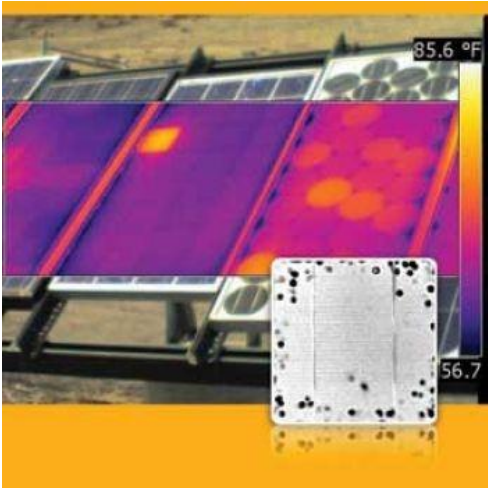


Figure 2.20 The defects found by lock-in thermography (Tarin and Overstreet, 2010)

2.2.5 Process parameters monitoring

As argued by Mobley (2002), process parameter in the PdM can be employed to improve the efficiency of the machinery. For example, the operating efficiency of a pump can be calculated by brake-horsepower formula if following parameters are measured.

$$BHP = \frac{Flow (GPM) \times Specific Gravity \times Total dynamic Head (Feet)}{3960 \times Efficiency}$$

Nonetheless, providing that the process parameters are not utilized in such a profound and professional way, it still presents valuable information to the maintenance staff about potential faults. One example is shown in Figure 2.16. By being noticed with such real-time data monitoring, possible failures are relatively easy to identify.

2.3 E-maintenance

The concept of e-maintenance is introduced along with the boom of information and communication technology (ICT) at early 2000. E-maintenance is sometimes considered as the progressive type of PdM for its utilization of optimized resources, services and management (such as e-technologies, e-monitoring, e-diagnosis, e-prognosis, etc.) to enable proactive problem solving and decision making process. (Crespo-Marquez and Iung, 2008)

Engine Detail				
ENGINE5				
TAG NAME	DESCRIPTION	VALUE	ALARM SETPOINT	UNITS
CAT5_ENGSPD	Engine Speed	1198.5	1416.0	Rpm
CAT5_FUELRATE	Instantaneous Fuel Rate	222.2	N / A	liter/hr
CAT5_TOTFUEL	Total Fuel Cosumed	44585.9	N / A	liter
CAT5_ENGHOURS	Engine Hours	331	N / A	hr
CAT5_OILPRESS	Engine Oil Pressure	418.0	169.0	Kpa
CAT5_COOLANTTEMP	Engine Coolant Temperature	87	102	DegC
CAT5_SYSVOLT	System Voltage	26.3	19.5	Volts
CAT5_FUELPRESS	Engine Fuel Pressure	428.5	N / A	Kpa
CAT5_EXTEMPRIGHT	Exhaust Temperature Right	519	728	DegC
CAT5_EXTEMPLEFT	Exhaust Temperature Left	503	728	DegC
CAT5_INLETREST_L	Air Filter Inlet Restriction - (Left)	0.3	7.0	Kpa
CAT5_INLETREST_R	Air Filter Inlet Restriction - (Right)	0.0	7.0	Kpa
CAT5_FUELDP	Fuel Filter Differential Pressure	6.5	105.0	Kpa
CAT5_OILDP	Oil Filter Differential Pressure	76.5	105.0	Kpa
CAT5_TBOUTPRESS	Turbo Outlet / Boost Pressure	96.0	N / A	Kpa
CAT5_AFTERCOOLTEMP	Aftercooler Temperature	39	102	DegC
CAT5_CRANKCASEPRESS	Crankcase Pressure	0.8	2.0	Kpa
CAT5_LUBOILTEMP	Lubricant Oil Temperature	81.0	107.0	DegC
CAT5_LOADFACTOR	Load Factor	55	N / A	%

CLOSE

Figure 2.21 process parameters of a diesel engine

2.3.1 The basic elements of e-maintenance framework

It can be known from the definition that e-maintenance is actually a comprehensive system which covers both technical issues and human activities. As stated by Arnaiz et al. (2010), e-maintenance is linked with two main factors:

- 1) Advanced technologies which enable improved efficiency in optimizing maintenance-related workflow. Through a variety of condition monitoring techniques such as fixed sensors or portable inspection instrumentation, and different communication technologies such as intranet, internet, or wireless communication, a group of maintenance activities as well as involved personnel are integrated into a whole system where the maintenance work is implemented in a fast and effective way.
- 2) Cohesive collaboration which gives the ability to monitor plant floor assets, link the production and maintenance operation system, collect feedback from remote customer

sites and integrates it to upper level enterprise applications (Jantunen et al., 2009). As shown in Figure 2.22, a group of parties related to maintenance are incorporated such that the available sources can be utilized as much as possible. Through the use of e-maintenance, the pertinent data vs. information vs. knowledge vs. intelligence become available and usable at the right place, at the right time for making the best anticipated maintenance decision all along the product life cycle (Arnaiz et al., 2010).

2.3.2 The advantages of e-maintenance

- 1) Remote maintenance. By using communication technologies such as internet, the operators can log in the system anytime from anywhere. This allows them to take remote actions, such as setup, control, configuration, diagnosis, de-bugging/fixing, performance monitoring, and data collection and analysis (Hung et al., 2003) without physically appearing at the place where the questionable equipment is located. Such characteristics of e-maintenance bring about significant influences on, for example, quick responding, timely intervention, less downtime, cost reduction, and so on.
- 2) Collaborative maintenance. E-maintenance provides a platform allowing cooperation among departments and levels in a company as well as among different enterprises which are pertinent to the maintenance workflow, as shown in Figure 2.22. E-maintenance offers the chance to share valuable experiences if an anomalous condition is occurring in the inspected machine. In such way the overall maintenance performance is accelerated by efficient decision making based on the selection or optimization of the information and knowledge shared between interested parties.

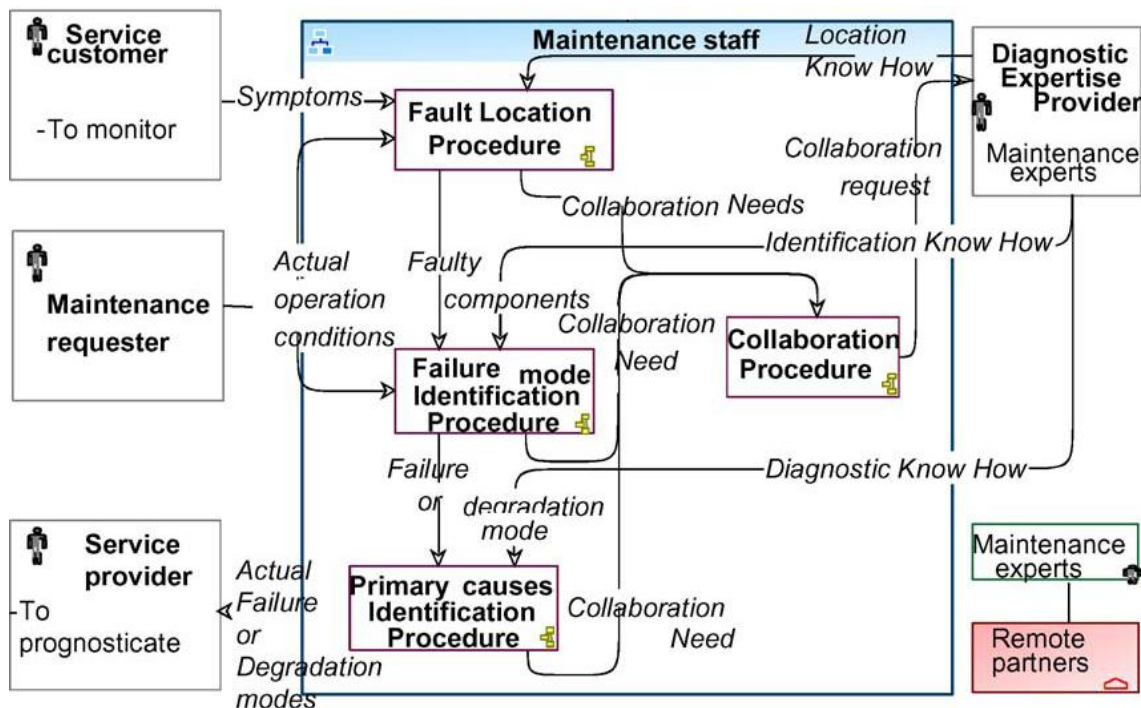


Figure 2.22 collaboration structure of interested parties via e-maintenance (Iung et al., 2009)

- 3) Real-time maintenance. Remote monitoring of equipment conditions accompanied with alarm settings in the system enable the operators to respond to the abnormalities rapidly. Besides, high rate communications allow to quickly obtain several expertise and to accelerate the feedback reaction in the local loop connecting product, monitoring agent,

and maintenance support system (Crespo-Marquez and Lung, 2008). The maintenance activities therefore are implemented in a timely manner.

- 4) Predictive maintenance. As mentioned previously in the beginning of section 2.3, e-maintenance is an evolutionary form of PdM which combines condition monitoring in the problem-solving process. By employing diverse techniques or smart sensors, the status of the machinery is monitored and fed back to both the system and operators such that subsequent measures are determined and executed to minimize unexpected failures.

2.3.3 The challenges of e-maintenance

- 1) Establishment of collaborative business process

E-maintenance is actually the life cycle maintenance covering design, manufacturing, utilization and disposal of the machinery, which requires the participation of service seller (e.g. manufacturer, technical provider), servicer receiver (e.g. maintenance crew onboard), service customer (e.g. oilfield operator) and maintenance experts who are skillful in respective fields of technology. These parties on the one hand seek for better performance of the products while on the other hand pursuing benefits through the utilization of products. Therefore the establishment of an e-maintenance system for each involved party necessitates the comparison between costs (e.g. physical infrastructure cost, labor cost) and possible profits created by the system.

For instance, the service customer may only need unscheduled monitoring or diagnosis of certain equipment especially at the point of failure, which in the opinion of customer should not cost too much. For the service seller, however, such irregular remote maintenance may lead to the difficulties in arranging the technical personnel or the other resources, which increases additional cost in company's management. Thus they may quote high price for such kind of services. Comparatively reasonable solutions have to be agreed on to benefit all the interested parties.

- 2) Technical barriers resulting from different technical criteria

Nowadays the development of ICT has brought about numerous information processing systems established on different computer architectures and communication protocols. The construction of an e-maintenance system involves a variety of cross-platform information integration issues, such as the development of data transformation mechanisms, the design of communication messages, the selection of data transmission protocols, and the construction of a safe network connection (Crespo-Marquez and Lung, 2008). A customized e-maintenance system has to be discussed and explored for the compatibility of all affected parties, which could be quite complex and huge if the system covers a large range of equipment with totally different techniques.

- 3) Knowledge centralization and distribution

Expert support is one of the major characteristics of e-maintenance system. On the one hand, by centralizing the knowledge in several specialists in the central offices, information analyzing and decision making process relevant to maintenance will be fast and efficient; on the other hand, the strong logic and self-diagnosis of the computerized system make it possible to automatically detect and indicate the fault location and, if necessary, shut down

the questionable equipment. Such excessive concentration on either expert support or computer technology while increasing the burden of support team could weaken the ability and willingness of the site engineer to learn and solve the problems. Care needs to be taken to find a balance between centralization and distribution of the knowledge so that the problems will be timely fed back to and solved by support crew, while site engineers can positively participate in the problem-solving process.

Chapter 3 Status quo of maintenance activities in COSL Drilling

COSL (China oilfield services, Limited) is a stated-owned subsidiary company of CNOOC (China National Offshore Oil Corporation). It is founded in 2001, which is based on the combination and restructuring of seven companies which are used to be engaged in drilling, technical services, geophysics, etc. Drilling department as the first contributor in COSL accounts for 51 percent of company's income according to the annual report of 2011. There are totally 27 jack-up drilling rigs, 7 semi-submersible drilling rigs, 2 accommodation rigs, 4 module rigs and 8 land drilling rigs under the management of COSL Drilling. Among them some are newly constructed, whereas quite a few have been serviced for more than 20 years. To maintain the rigs and the equipment onboard in good condition is not only a matter of economic analysis, but also a matter related to the future development in the competitive international market. Then what is the maintenance application in COSL Drilling now?

3.1 Corrective maintenance in COSL Drilling

According to author's work experience, CM account for almost 50 percent of total working hours on newly-built rigs which have been in use for only 1 to 2 years. Sometimes it reaches 80 or even 100 percent during certain period owing to the complication and sophistication of the repair work. On the contrary, for the rigs which have been served for more than 3 or 5 years, the statistical data of CM is down to about 20 percent, as said by the Equipment Supervisor on rig COSL Confidence which has been in serve for 3 years. For the ones that have been employed for more than 20 years, the percentage of CM gradually increases to around 30~50 percent, depending on the effects of upgrading, renewal or overhaul.

It seems that the equipment conditions comply strictly with the well-known bathtub curve, as shown in black color in Figure 3.1. However, no matter new rigs or old ones, there are still some aspects that can be improved to lower the probability of failures to a relatively low level, as shown in green color in the Figure.

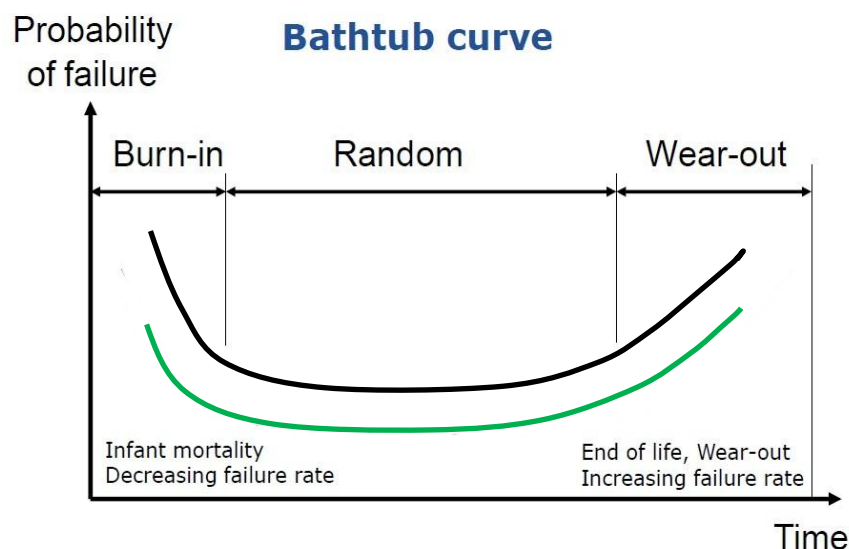


Figure 3.1 Bathtub curve of typical equipment life cycle

To explore the possible reasons of CM, the author distributed a questionnaire survey – where 9 potential reasons are included – to 20 drilling rigs in COSL. Until the end of thesis writing, 17 rigs have replied their feedback, of which statistics is listed in Table 3.1.

Table 3.1 questionnaire on possible reasons of CM on drilling rigs of COSL

Possible reasons:										
1. CM caused by left-over problems during rig construction or dock repair 2. CM caused by the quality of spare parts 3. CM caused by lacking of skills 4. CM caused by unfamiliarity with user's manual 5. CM caused by lacking of effective tools 6. CM caused by "saving the cost" 7. CM caused by operational problems 8. CM caused by confliction with drilling operation 9. CM caused by improper periodic maintenance										
Rigs	Percentage of Possible Reasons									Total
	1	2	3	4	5	6	7	8	9	
BH4	35%	10%	35%	0%	5%	0%	5%	5%	5%	100%
BH5	30%	50%	5%	0%	6%	0%	5%	0%	4%	100%
BH7	30%	35%	5%	0%	10%	0%	5%	10%	5%	100%
BH9	35%	25%	5%	5%	5%	5%	10%	5%	5%	100%
BH10	30%	45%	5%	0%	5%	0%	5%	5%	5%	100%
BH12	40%	35%	5%	0%	5%	0%	5%	5%	5%	100%
HYSY921	20%	50%	5%	5%	0%	0%	5%	0%	5%	100%
HYSY922	30%	45%	2%	5%	0%	0%	10%	3%	5%	100%
HYSY924	40%	35%	5%	0%	5%	0%	5%	5%	5%	100%
HYSY931	40%	30%	6%	0%	6%	0%	6%	6%	6%	100%
HYSY935	34%	35%	7%	1%	6%	1%	5%	6%	5%	100%
HYSY936	40%	20%	10%	0%	5%	5%	0%	10%	5%	100%
HYSY941	20%	40%	5%	0%	0%	0%	5%	20%	10%	40%
HYSY942	2%	10%	5%	2%	2%	2%	5%	2%	10%	100%
NH2	35%	42%	5%	0%	0%	0%	8%	5%	5%	100%
NH4	10%	30%	30%	10%	0%	0%	20%	0%	10%	110%
NH5	30%	20%	25%	8%	3%	5%	6%	2%	1%	100%
Average	29.5%	32.8%	9.7%	2.1%	3.7%	1.1%	6.5%	5.2%	5.7%	N/A

Before analyzing the statistics, some problems need to be clarified:

- There exists thoughtlessness when performing such investigation. The term "CM that cannot be avoided such as equipment age" is not covered in the questionnaire. This leads to such result that, for instance, HYSY942 attributes 60 percent of CM to inevitability, whereas the rest rigs ascribe 100 percent of CM to the 9 reasons in the questionnaire.
- Because of the subjectivity of such survey, the data collected may relay too much on personal estimation, which may more or less deviate from the truth.

- There is a mistake of NH4, where the total percentage equals to 110%.

Despite these flaws, the result of survey is still valuable for analyzing and understanding of current CM activities on drilling rigs of COSL.

1) Left-over problems during rig construction or dock repair account for 29.5% of CM

There are two major contributors to such problems. The first one is that before delivering the equipment, the manufacturer usually performs factory test and/or on-site commissioning, of which objective is to ensure that the equipment will perform as what it is designed to do. However, the actual running hours of equipment during such test or commissioning is really limited, where it is difficult to uncover potential failures. For instance, the new deck crane which is first installed on rig HYSY942 had passed the commissioning in the shipyard. All functions had been approved to be satisfied by the ship owner and Classification Society. Nonetheless, after only 37 hours' working offshore, the gears between motor shaft and hydraulic pump were crushed (Figure 3.2) because of the poor alignment, which spent almost 14 hours to replace.



Figure 3.2 the damaged gear of Deck Crane

Another factor is the installation of equipment and its accessories – such as fixing bolts, pipe, cable, etc. – during shipbuilding or dock repair. In this period multiple tasks are assigned to a number of workers with different specialties at different levels. Some problems tending to give rise to failures are hidden because of cross operation, or unskillfulness, carelessness, lack of responsibility of the worker. A typical example is the welding slag left in the hydraulic pipeline causing the clog of actuated valves, which result in extra unexpected CM.

2) Quality of spare parts accounts for 32.8% of CM

Nowadays most of critical drilling equipment is procured from oversea OEM of which products are more reliable. At the same time, an increasing number of local manufacturers participate in the market competition of offering the spare parts with required specifications. Normally local-made spares are much cheaper than the imported ones due to the saving in tariff, logistics costs, etc. Therefore some maintenance personnel are inclined to seek for domestic substitutes instead of the ones from OEM. Perhaps it is the truth that the price of single component is cheaper. However, the service time of such alternatives is shorter either because of the technological bottleneck and the other influencing factors. This from another

perspective increases the frequency of CM activities.

3) Lacking of skills accounts for 9.7% of CM

Because of the rapid expansion in recent years, a batch of newly-built or purchased drilling rigs have been put in use. Accordingly many more new employees, whether hired from universities or recruited from social technicians, are enrolled in the company. It should be admitted that those employees are schooled with certain degree of skills. Also the company provides with necessary trainings especially for those engaged in special types of work. Owing to the diversity and complexity of the equipment, however, it is hard to guaranteed that the people who implement respective jobs are qualified with all relevant knowledge and abilities. For instance, a tyro is liable to solve the problems in superficial way, where the faults are not settled thoroughly and tend to recur.

4) Unfamiliarity with user's manual accounts for 2.1% of CM

Attributing to the aforementioned reason that the company expand rapidly, some beginners are still lack of full reading, understanding, and complying with the contents in the user's manual. The author had experienced a risk where the gears in the gearbox of Drawworks worked without lubricating oil for almost half a year because of a closed valve! There may be several reasons leading to such situation, such as negligence during shipyard commissioning, no flow meter or pressure meter after the valve, not easy to access and check gear box during operation, etc. But the fundamental reason is that the maintenance personnel are lack of recognition with the structure, processes and performance of the equipment. Fortunately the Drawworks maintains its function and quality without damages. Or else it would have resulted in significant accident. Despite the limitation of the author's work experience on only a handful of platforms, there is reason to believe that CM aroused by such influencing factor is existing among the other rigs.

5) Lacking of effective tools accounts for 3.7% of CM

As said by an experienced maintenance person who has worked offshore for more than 20 year, "for the maintenance staff, documents and drawings are as the brain, while tools as the hands". Professional tools can considerably improve the work efficiency of maintenance activities. In contrast, unsuitable tools increase extra difficulties and even engender secondary damage to the equipment.

There was an example about the Drawworks which is produced by Nation Oilwell Varco (NOV). In order to synchronize the rotation speed of all 4 motors, there is an encoder in alignment with the shaft of each motor via a coupling connection so that the rotation signal can be transferred back to the control system (Figure 3.3). Despite the coupling element allows a limited degree of flexibility, it is easy to break down with high rotation speed which can reach up to 800 RPM. If one coupling is down, the control system receiving the fake input signal will generate a fault output which makes the rotation speed of corresponding motor different from the other ones, which further hurts the driven gear due to the out-of-sync.

Because of the narrow space and lacking of effective shaft-alignment instrument, it is hard to precisely install new coupling between the shaft of motor and that of encoder. The result is that the coupling has to be changed with a new one almost every month – the shortest time recorded is 8 days, which dramatically increases the frequency and workload of CM.

The place
where the
coupling
is
installed



Figure 3.3 the coupling installation of Drawwork Encoder

6) “Saving the cost” accounts for 1.1% of CM

It may be a little strange when seeing such relationship between two terms. Nevertheless it is the truth when applying to certain occasion. For example, the BOP (Blow-Out Preventer) control system on one platform is an electrical-pneumatic-hydraulic driven system which finally employs high-pressure hydraulic oil to control the actions of BOP. The required amount of hydraulic oil is 5000 liters, which equal to almost 24 barrels with the capacity of 208 liters. At some time in the past, the drilling fluids invaded in the hydraulic oil system as a result of internal leakage in the BOP, where some control valves were blocked subsequently. It took a couple of hours to dismantle, clean and reinstall the valves, and additional several hours to replace the polluted oil in the oil tank. But, the contaminated oil in the pipelines was not replaced due to the large needs of oil, which may cost another several thousands of dollars. Consequently, in the winter of that year, the pipelines as well as valves were frozen because of the residual water elements in the oil, which spent several days to heat and restore the whole system.

7) Confliction with drilling operation accounts for 6.5% of CM

It is common in domestic drilling market that the command of Oil Company’s representative onboard has the highest priority. In order to gain time to obtain more benefit, some representatives would not like to stop drilling operation for a while to maintain the equipment. In spite of no apparent evidence proving that this directly leads to the failure or malfunction, the equipment staying long in sub-healthy state will undoubtedly increase the chance of breakdown.

8) Operational problems account for 5.2% of CM

Such factor arises as a result of reckless manipulation or negligence of operational procedures, which, if discussed further, is caused by unfamiliarity, irresponsibility, laziness of the operator. Such problem may not be common on all rigs. According to author’s work experience, however, it is probably true on certain platforms where tyro accounts for most of operating staff.

9) Improper PM accounts for 5.7% of CM

Improper PM includes over maintenance, delayed maintenance, or omitted maintenance. It is maybe a little difficult to verdict how much CM is triggered by inappropriate PM since until now there is no effective statistics on such kind of matter. Nonetheless, irregular preventive maintenance which neglects the actual needs will undoubtedly aggravate the deterioration of machinery components.

There was a real case the author experienced. A service seller who provides overhaul of the diesel engine used a smart portable instrument to collect the vibration signal of the bearing which is periodically lubricated. In a short time the service staff pointed out that the bearing is short of lubrication by reading the waveforms on the instrument display. After pumping required amount of grease, the waveform obviously became smooth. This example is the only one that the author had ever observed – but not the only one that had ever happened – proving that the equipment conditions can still become worse despite with PM.

10) CM caused by unforeseen failures

This term is forgotten to be included in the questionnaire. Yet according to the author's work experience as well as telephone interview with several colleagues, such failure cause accounts for about 20 percent to 40 percent of total CM activities. The major contributors are aging, cascade effect of other failure parts, accidental damage caused by extreme weather such as freezing, typhoon, etc.

3.2 Periodic maintenance in COSL Drilling

PM has been employed by COSL Drilling for several years. And now it is still a major tool to guide offshore maintenance activities. There are three PM software in use, which are Preventive Maintenance System (PMS), Asset Management operating System (AMOS) and Total Maintenance Management (ToMM).

3.2.1 Preventive Maintenance System (PMS)

PMS developed by Dalian Marine University is adopted by COSL around 2005. The developer consulted the specialists of COSL on the demands of site operation so that the items involved in the software can meet the actual requirement.

There are five main categories designed in this software, which are maintenance planning, spare parts management, reports & records management, offshore-to-onshore synchronization, and system maintenance. Each of them is further subdivided in detailed branches. Objectively speaking, the basic elements of maintenance management have been included in this software. For instance:

- Equipment information including code, name, model, manufacturer, specifications, etc.
- Maintenance planning, including equipment code, name, maintenance content, intervals, planned maintenance date, actual execution date, duty team/person, etc.
- Inventory management, including part name, part number, manufacturer, stock quantity, drawing number, stock in, stock out, etc.
- Maintenance & overhaul records, including equipment number, equipment name, duty team/man, man-hour, failure cause, fault phenomenon, consumption of spares, etc.

Figures 3.4 and 3.5 are two examples of PMS user interface.

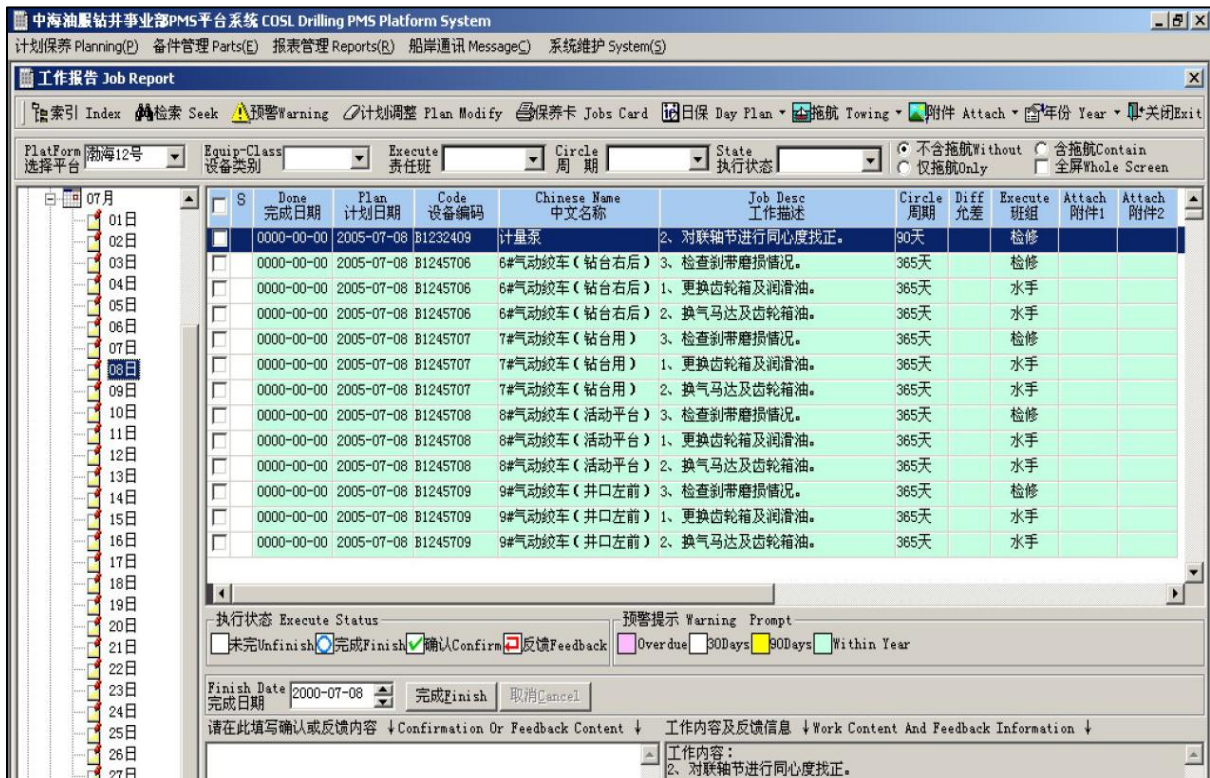


Figure 3.4 “Job Report (Maintenance Planning) windows of PMS

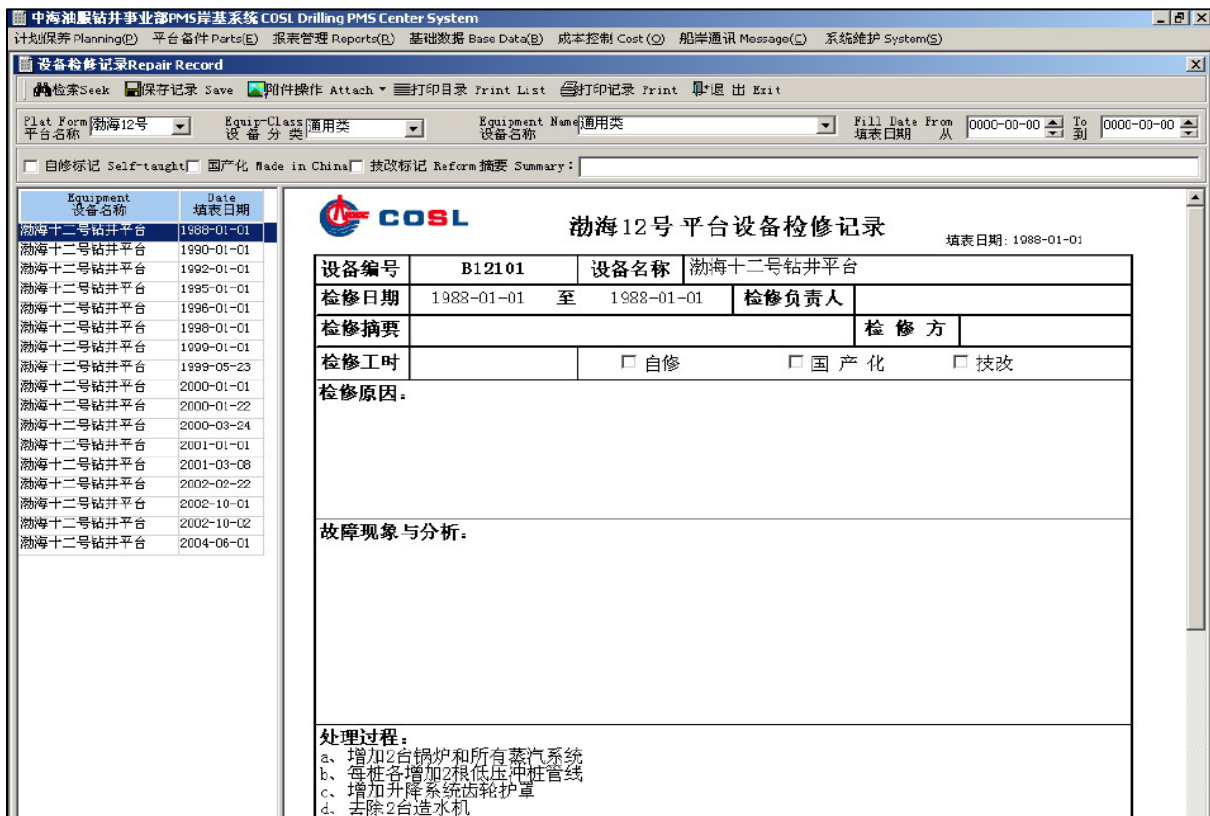


Figure 3.5 “Maintenance Records” window of PMS

The biggest drawback of PMS may be the isolation of each other between maintenance-related items, which leads to the arduous workload during the utilization of software. For instance, there is no integrated links between maintenance activities and the consumption of spare parts. The maintenance personnel have to fill in maintenance history records, and fill in another record of spares consumption afterwards. This brings about some problems such as:

- Difficult to know during which maintenance work the spare part is used
- Difficult to find what time the spare part is used
- Difficult to calculate mean time to failure (MTTF) of the parts
- Etc.

3.2.2 Total Maintenance Management (ToMM)

ToMM consists of 11 modules, as shown in Figure 3.6. It can be seen that, the same with PMS system, the basic elements related to maintenance management are designed in this software. As described in the internal document of COSL Drilling, however, only three of these modules are actually utilized: system management, preventive maintenance, and maintenance management. The content in these three blocks mainly includes:

- Equipment profile
- Routine preventive maintenance (scheduled PM)
- Emergency repair work (unscheduled CM)
- Statistics of running hours of the equipment

Figure 3.7 is an example of Work Order Close window, in which the contents are more or less same with those in PMS.

Because of the relatively simple and separate functions, the application of ToMM is limited and only employed on two drilling rigs now. Some functions such as records management, procurement management are not actually developed and used.

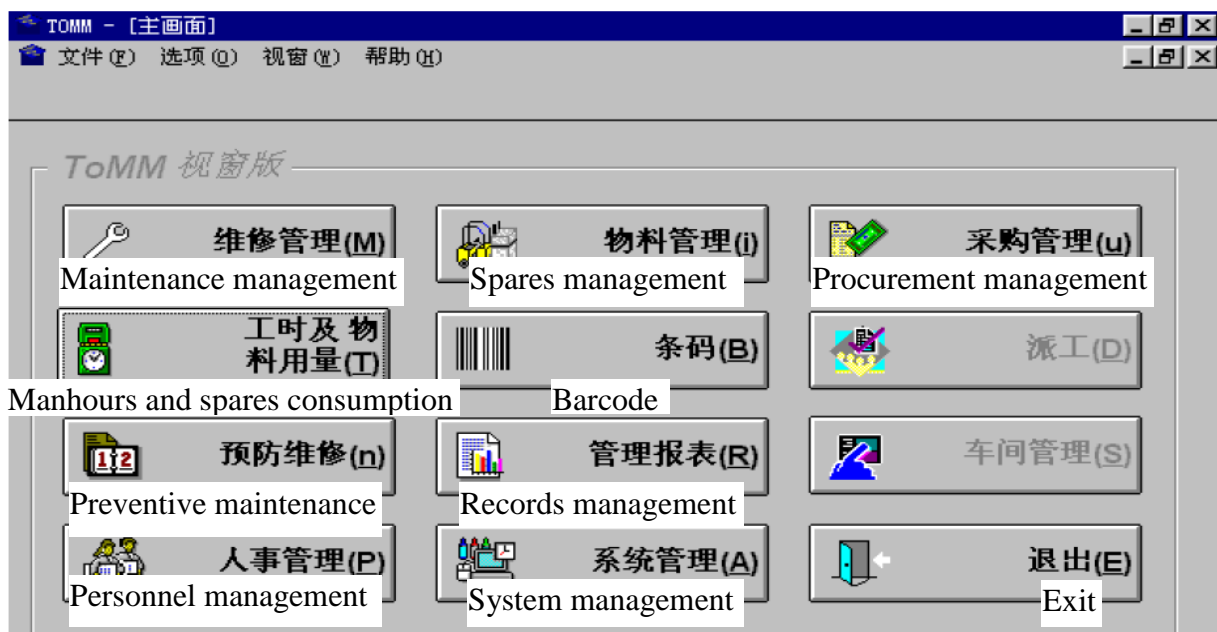


Figure 3.6 ToMM home screen



Figure 3.7 Work Order Close window of ToMM

3.2.3 Asset Management Operating System (AMOS)

AMOS as the member of computerized maintenance management system (CMMS) has been applied in comprehensive industries for more than 22 years. It is introduced by COSL in recent years especially after the acquiring of Awilco in 2008, where AMOS had been employed on its seven rigs. Compare with PMS and ToMM, AMOS is complex but efficient. Some superiorities of AMOS are:

- 1) Comprehensive coverage of maintenance-related activities

As shown in Figure 3.8, AMOS offers multiple detailed categorizations under each item in the menu bar. The considerations associated with a certain job are designed in the software as much as possible.

- 2) Powerful “filter” function

There is a Filter window in any screen of AMOS which can sieve the data based on the known information. The Filter window will automatically pop up whenever a new interface is opened. Also the system operator can click the Filter icon in the toolbar. One example is shown in Figure 3.9. By inputting the keywords in the blanks, relevant information will be displayed at the bottom of the window, which is easily accessed by the system operator.

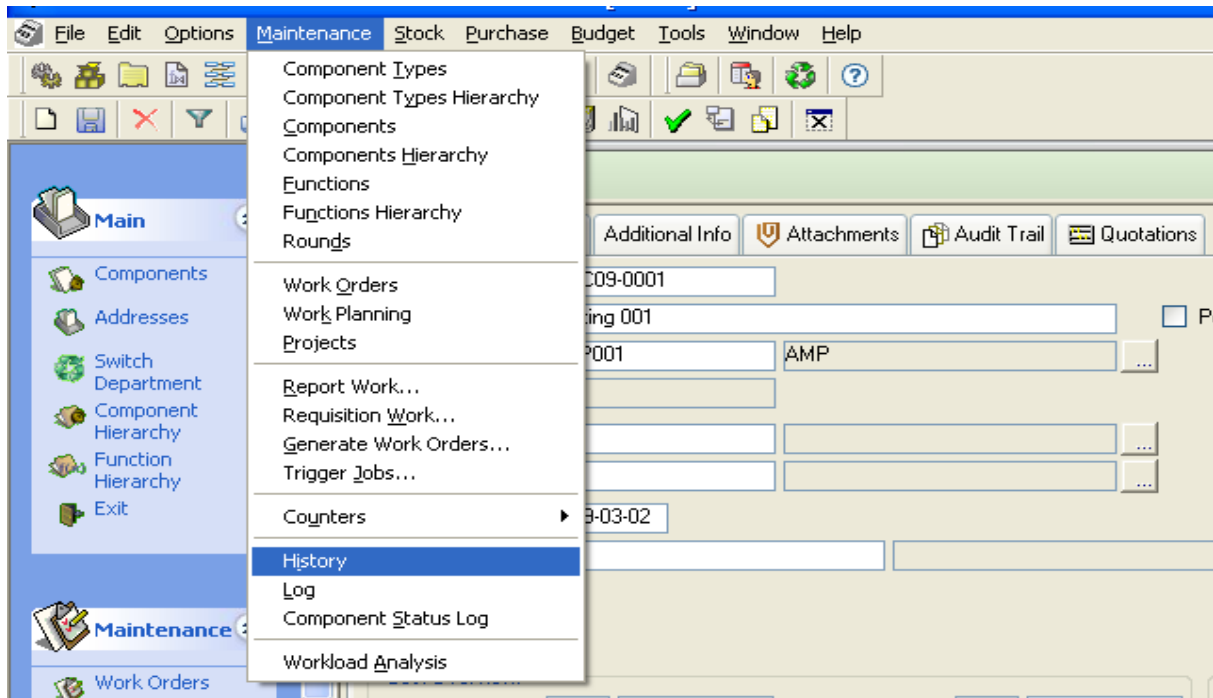


Figure 3.8 submenu of Maintenance in AMOS

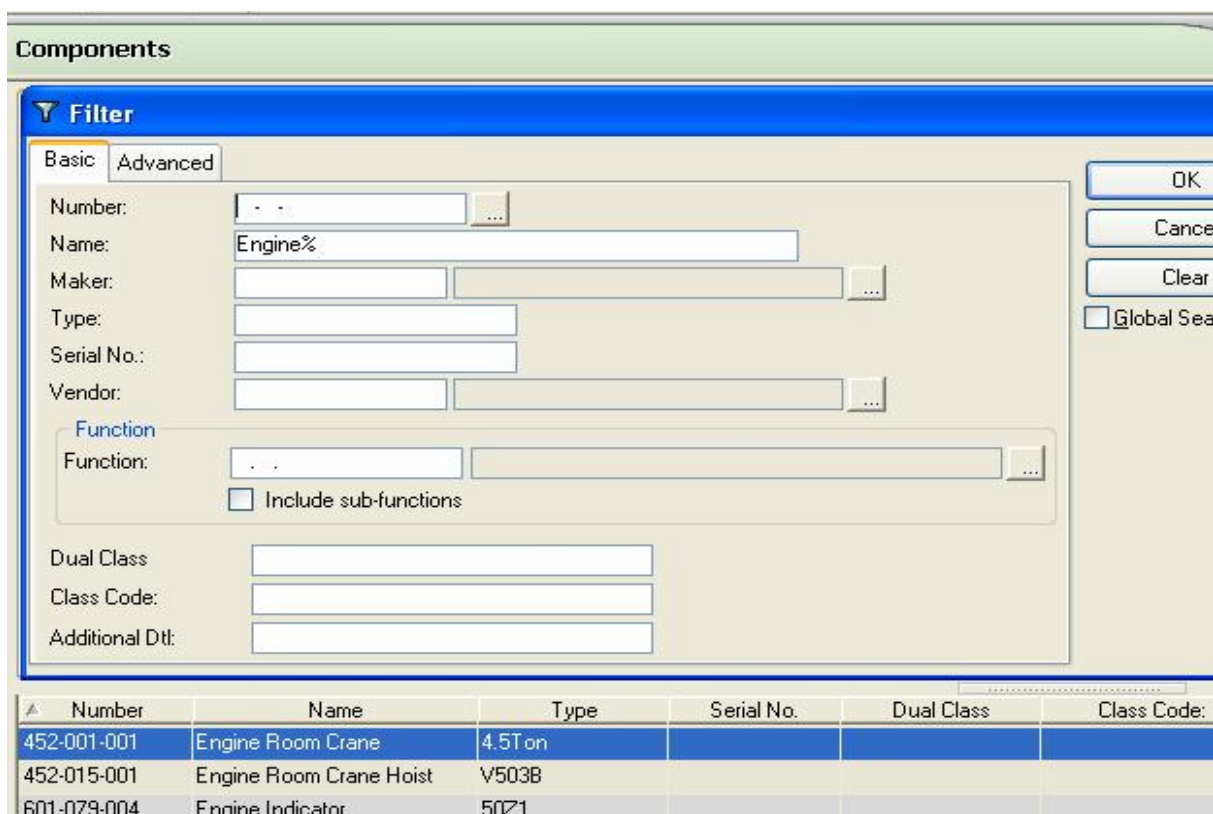


Figure 3.9 Filter interface under Component window

3) Integral and detail information

Figure 3.10 is an example of Work Order window. It can be seen that there are many options integrated in the toolbar, such as job description, required parts, etc. In this case the system operator does not need to switch between different windows to fill in required information.

Besides, the eligible information will be displayed at the bottom once the search criteria are defined. Thus it is easy to find which of them are demanded so that the work order can be generated as soon as possible.

Work Orders

General | Details | Additional Info | Job Description | Required Parts | Required Disciplines | Included Jobs | Attachments | Financials | Permits to Work

Number: 936/11-00209 Triggered By: Frequency Created By: System Administrator
 Title: S0003 - Renew the Certificate History Template:
 For Component: 112.24.00 CCS Mobile Offshore Unit Safety Cert Status: Planned
 For Function: 112.24.00 CCS Mobile Offshore Unit Safety Certificate Type: Periodic
 Frequency: 60 Month(s) Project:
 Parent WO: / - Estimated Misc. Cost: CNY 0.00

Number	Title	Resp. Discipline	Component	Priority	Status	Due	Func. Description
936/11-00234	00001 - Overhaul Electric Motor	ElectricalSupervisor	711.01.01	5	Planned	2011/11/11	LO Transfer Pump EL Motor
936/11-00098	00001 - Overhaul Electric Motor	ElectricalSupervisor	327.02.01	5	Planned	2011/10/31	Drill Water Pump No 2 EL Motor
936/11-00052	10296 - Check Cold Drink Dispenser 1M	ElectricalSupervisor	551.12.00	5	Planned	2011/10/27	Cold Drink Dispenser
936/11-00139	10001 - Inspect Electric Motor 6M	ElectricalSupervisor	325.09.02	5	Planned	2011/11/3	High Pressure Mud Pump No 1 Cooling
936/11-00012	10292 - Inspect Main Alternator 12M	ElectricalSupervisor	861.02.00	5	Planned	2011/10/26	Main Alternator No 2
936/11-00072	10002 - Check Centrifugal Pump 3M	ElectricalSupervisor	813.02.00	5	Planned	2011/10/29	Main Fire Pump No 2
936/11-00053	10297 - Inspect Cold Drink Dispenser 6M	ElectricalSupervisor	551.12.00	5	Planned	2011/10/27	Cold Drink Dispenser
936/11-00013	10293 - Inspect Main Alternator 36M	ElectricalSupervisor	861.03.00	5	Planned	2011/10/26	Main Alternator No 3
936/11-00151	11015 - Inspect Motor Control Center 12M	ElectricalSupervisor	873.34.00	5	Planned	2011/11/3	690V Lifting System MCC No 2
936/11-00232	10001 - Inspect Electric Motor 6M	ElectricalSupervisor	584.02.01	5	Planned	2011/11/11	Potable Water Pump No 2 EL Motor
936/11-00226	00001 - Overhaul Electric Motor	ElectricalSupervisor	584.01.01	5	Planned	2011/11/11	Potable Water Pump No 1 EL Motor
936/11-00031	G0004 - Megger Test Galley/Laundry Machi	ElectricalSupervisor	551.01.00	5	Planned	2011/10/27	Marine range w/oven(4 hot plates) No
936/11-00110	10001 - Inspect Electric Motor 6M	ElectricalSupervisor	324.41.01	5	Planned	2011/10/31	Mud Mixing Pump No 1 EL Motor
936/11-00071	10003 - Inspect Centrifugal Pump 12M	ElectricalSupervisor	813.01.00	5	Planned	2011/10/29	Main Fire Pump No 1
936/11-00146	10001 - Inspect Electric Motor 6M	ElectricalSupervisor	325.11.02	5	Planned	2011/11/3	High Pressure Mud Pump No 3 Cooling
936/11-00002	10942 - Inspect PDP Test/Repair Panel 12k	ElectricalSupervisor	323.19.00	5	Planned	2011/10/21	PDP Test/Repair Control Panel

Figure 3.10 Work Order window

4) Convenient label print function

Until now there are not mandatory rules in COSL on the form of inventory label. Thus the appearance of the label is really multifarious on different rigs. Using “Label Print” function in AMOS, however, the information will be automatically created by internal data links (Figure 3.11). Furthermore, the barcode at the bottom of the label facilitates the stock check. By comparing the data collected by the barcode scanner with the information inputted beforehand in AMOS system, the differences in no matter SFI code, quantity, or the other information are easy to distinguish.

Label Print

Print Setup Print

LOCATION : HYSY941 \ Store
 CSN : 651.01.05.03.319 ERP NO : 80403767
 P/N : 6F-0496 ORIGIN : Import
 NEW P/N :
 NAME : Tee-Pipe
 CHN NAME :
 EQUIPMENT : ME Electrical & Starting System
 PRICE : USD 0 DATE : 2012-08-28

[Barcode]

Figure 3.11 part of screen capture of Label Print window

5) Strong compatibility with customized tables

Figure 3.12 is an Excel table generated by AMOS. The key point is that this table is strictly the same with the one normalized in COSL Drilling Integrated Management System. Once the regular maintenance and recording work are implemented, the table will be created by AMOS automatically. In such case the maintenance crew does not need to manually fill in the various tables again. The work efficiency is thus improved with less workload.

钻井事业部综合管理体系						
COSL Drilling		记录编号:	L3. 2-EQU-P/010		版本号:	1.0
		记录名称:	定时设备运转时间周统计表		日期:	Monday, August 01, 2011
定时设备运转时间周统计表						
单位: HYSY941						
设备编号	设备名称	设备描述	启动日期	当前日期	当前运行时间	
871.01.02	AC690V Main Generator Panel No 2		6/26/2006	7/3/2012	43560	
871.01.03	AC690V Main Generator Panel No 3		6/26/2006	7/3/2012	43560	
871.01.04	AC690V Main Generator Panel No 4		6/26/2006	7/3/2012	43560	
871.01.05	AC690V Main Generator Panel No 5		6/26/2006	7/3/2012	43560	
871.01.20	Synchronizing Panel	PMA300	6/26/2006	7/3/2012	43840	
871.01.21	Jacking MCC Port Feeder Panel	SICACON 8PT	6/26/2006	7/3/2012	8760	
871.01.22	Jacking MCC Stbd Feeder Panel	SICACON 8PT	6/26/2006	7/3/2012	8760	
871.01.23	Jacking MCC Aft Feeder Panel	SICACON 8PT	6/26/2006	7/3/2012	8760	

Figure 3.12 customized table generated by AMOS

6) Data synchronization and remote supervision

As told by a user, one of the AMOS's functions he prefers is that he can see the real-time execution of maintenance offshore from onshore office. This is one function of AMOS – automatic synchronization between the servers established at different places. By employing AMOS, the management level of a rig, even of the whole company can access the database to see what are happening on the rigs. Such supervision to some extent promotes the better execution of maintenance tasks.

3.3 Predictive maintenance in COSL Drilling

In fact some of PdM techniques have been applied on drilling rigs in COSL, such as:

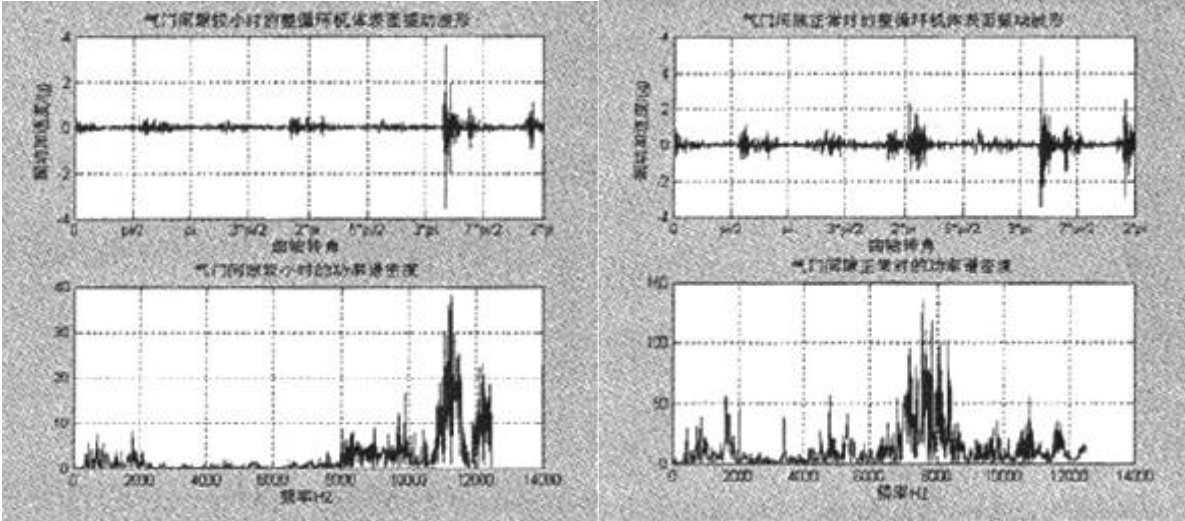
- Wear and oil analysis of important equipment such as Top Drive and diesel engine
- Non-destructive testing of high pressure pipes, critical supporting beams or points
- Process parameters on certain critical equipment such as diesel engine, Drawworks

Those condition monitoring techniques to some extent help maintenance staff onboard acquaint with the state of the machinery at the time of inspection or testing. However, there are still some shortcomings that can be improved when applying predictive management.

1) Insufficient application of condition monitoring techniques

Most of the techniques stated above belong to periodic condition monitoring: wear and oil analysis is done by the third party (service provider) based on the running hours; also non-destructive testing is usually executed at the circle of certain years. It should be admitted that not all condition monitoring techniques need to be carried out continuously. Some techniques, however, would be better to be applied with consecutive supervising on site so that the risk of failure and the maintenance workload can be reduced as much as possible. In aforementioned equipment, for example, the one that can add incessant condition monitoring technique may be diesel engine.

Although electronic control module (ECM) as a mature technical unit provides with constant observing of process parameter, the critical parameter – vibration signal which can directly reflect the mechanical conditions is not included. Vibration monitoring of diesel engine is not a fresh technique. The conditions of valve clearance, cylinder liner, main shaft, bearing as well as other components can be detected through respective spectrum (Figure 3.13). It would be better if a fixed vibration monitoring system is installed onboard. By doing so the abnormalities in vibration signature will be easily accessed by responsible staff via comparison of data or spectrum so that following measures – either corrected by maintenance crew or maintained by service provider can be chosen.



(a) Small valve clearance (b) normal valve clearance
 Figure 3.13 indication of wave form and power spectral density of air clearance

2) Lack of integral data acquisition, analysis and comprehension

Under current maintenance system on drilling rigs in COSL, a certain number of condition analyses of the equipment are carried out by the service sellers who are professional in respective domains. This is understandable. The defects or problems will be informed to responsible people so that necessary maintenance will be followed. However, the biggest problem of such outsourcing method is that the maintenance staff is only notified with warning information but not the data analysis and comprehension. This may lead to such situation that the maintenance crew relies too much on service provider, but pay little attention on general trends of deterioration. It may be indifferent for the equipment that just put in use for several years. For the ones utilized for decades, however, the stereotypical sampling or testing intervals may not detect the worsening in time. It is sagacious to establish a data processing system/procedure so that the person in charge is alert to the changes in machinery conditions. Subsequently necessary adjustment in monitoring interval or technique

can be applied to lower the probability of failures.

3) No systematical economic evaluation

Normally condition-based PdM costs certain expenditure, such as expense of instruments, outlays on purchasing techniques, or the fees paid for the service sellers who have to go onboard to execute the testing. The purpose of expense on such kind of things is to maintain good equipment conditions so that more revenue will be created with little downtime, spares consumption, and so forth. However, as far as author knows, there is no person or ad hoc group that conducts a survey on how much benefits PM has brought in. Some people think that the more the monitoring techniques, the better the equipment conditions will be. Nonetheless, people with such kind of thinking neglect the fact that additional monitoring techniques may generate extra failures. But how about it if there is no condition monitoring technique applied? The result is obvious – a great deal of loss will occur especially with the failures of critical equipment. It is therefore necessary to estimate the gain and loss of any condition monitoring techniques in a predictive system so that the profits can be maximized as much as possible.

3.4 E-maintenance in COSL Drilling

E-maintenance while being gradually applied in some international offshore oil companies is still in embryo in COSL Drilling, where only primary form of e-maintenance has appeared such as real-time data transition of well logging, or aforementioned AMOS system. However, the main differences between previously defined e-maintenance and existing applications are:

1) Limited means of communication

According to the investigation report of PMS management in COSL (Yu, 2011), the common satellite bandwidth between each rig and onshore office is 128 kbps, relying on which the receiving and sending of email, the operating of ERP system, the transition of well-logging data, and the necessary phone calls have to be implemented. Under such narrow bandwidth, it is hardly effective to instantaneously transfer the data or information of the questionable equipment from the offshore to the onshore. The only matter close to “real-time” may be the consultation with the service provider upon the puzzled problems through telephone or email. Nevertheless, the oral expression of fault phenomenon by phone is somewhat difficult to describe clearly, while writing an email for explanation is somewhat less efficient.

2) Limited participation

Almost all of maintenance-relevant activities are executed solely on the rigs with little connection to onshore support. Only when there are puzzling problems will maintenance staff ask for help from the service providers or from the colleagues who use similar equipment. Even in such case, however, the limited communication means makes it difficult to involve all relevant people in discussion at the same time. The opinions have to be forwarded (if by email) or repeated (if by phone) among different parties such that it is unrealistic to settle the problems in a short time.

3) Limited application of condition monitoring technique

The premise of establishing an e-maintenance system is to install condition monitoring

instrumentation so that the data concerning equipment status will be timely collected and monitored. Unlike oil production platforms, drilling rigs may not require plenty of machinery parameters to be monitored. However, even if under current situation, the application of condition monitoring is still insufficient. For instance, vibration monitoring of diesel engine which is cost-effective and has been broadly used in many other industries is not utilized; the Mud Pump, which is the critical equipment in drilling operation, is not furnished with vibration sensors which is easy to monitor no matter electrical motors or cylinder liners.

4) Limited collaboration with service companies

E-maintenance has actually embedded in certain intellectual system, such as HAWK in NOV’s Cyberbase. Such function allows remote access of the software program onboard from NOV’s onshore support center, which makes the maintenance or fault diagnosis easy to be carried out. Despite such system has been applied on several rigs, there has been no such kind of service activated until now.



Figure 3.14 E-maintenance function embedded in Cyberbase systems

3.5 Main limitations of current maintenance activities in COSL

- 1) As stated in section 3.1, there are still many aspects that need to be improved to reduce the occurrence possibility of CM. No matter which one leads to the final breakdown of equipment, the interrupt of normal operation and the fault-handling process will result in unnecessary economic loss.
- 2) PM in some cases wastes unnecessary time and resource, and may even lead to extra malfunctions. For instance, a machine with light loads needs less maintenance than that with heavy loads; the periodic injection of grease at fixed quantity may increase the rotational friction of the bearing if the motor is not used frequently. Both of them cannot

be foreseen by scheduled PM. Time and other resources spent on such maintenance therefore become low cost-effective.

- 3) As discussed in section 3.3, the development of PdM is still in infancy. The condition monitoring techniques adopted by COSL Drilling, in author's opinion, is introduced either by OEM (such as ECM on diesel engine, process parameters on Top Drive) or by following the applicable rules and regulations (such as NDT of high-pressure pipelines). Because of lacking relevant researches on data analyzing and economic assessment, some other techniques which may better existing equipment performance are not utilized.

Chapter 4 Suggestion on Optimizing Maintenance Management Using Condition Monitoring in COSL Drilling

4.1 General structure of a good maintenance system

COSL Drilling in recent years is devoted to cut the cost through various means. For example, the company tries to manage the spare parts not utilized for more than three years so that the overstock could be avoided and inventory lowered in subsequent warehouse management; in addition, technical updating and innovation done by maintenance staff is encouraged to reduce outsourcing expenditure. However, there may be some inherent deficiencies in such kind of practices. Ambiguous understanding of equipment status due to the lack of condition monitoring techniques makes it difficult to decide which parts should be or not be ordered; the spontaneous technical innovation on limited amount of machinery cannot maintain the overall performance at a high level. In author's opinion, a maintenance program is necessary to be established for the sake of long-term management and optimization of the asset. Theoretically, following elements are required if a good maintenance program wants to be established.

4.1.1 Management support

A maintenance program usually demands to perform certain investigation beforehand, set up an effective maintenance strategy, apply necessary monitoring hardware and software, employ specialized staff, and provide training or technical support. All of them require the consensus and approval of company's management layer so that certain funding is allowed to invest. The decision makers should be clear that the establishment of a preminent maintenance program cannot be built in a day. The payback may not be returned until several months or even a couple of years later; the maintenance strategy or techniques may have to change according to the actual application and investigation. Challenges and opportunities when implementing a maintenance program should be analyzed as thoroughly as possible so that possible risks can be lowered by rules and rigorous executions.

4.1.2 Clear maintenance strategy

A clear definition of maintenance strategy will be helpful in guiding on-site maintenance activities. COSL Drilling as the company aiming at becoming an international drilling contractor has realized its importance and has made some general rules. For example, in an internal document of COSL Drilling named <Identification and Management of Critical Equipment>, the principle of maintenance strategy are defined:

The development of maintenance strategies for equipment shall be a work process of selecting strategies with analytical and systematic methods based on the Risk Based Maintenance (RBM) philosophy. RBM analysis involves the following tasks in sequence:

- 1) *Assessing the equipment criticality for each equipment and analyzing the failure model and failure mechanism for each critical equipment;*
- 2) *Selecting a maintenance strategy for each equipment unit according to the identified criticality (risk) level;*
- 3) *Establishing maintenance priority of equipment based on criticality, namely the higher criticality, the higher maintenance priority;*
- 4) *Establishing inventory management plan for key spare parts.*

Several other issues are defined afterwards based on such definition, as partly shown in [Appendix I](#). However, these rules are the general requirements that cannot come into play if without enough support from either managerial or technical issues.

4.1.2.1 Management of corrective maintenance

As stated earlier in Section 3.1, there are a number of reasons leading to CM. Some of them, however, can be reduced through proper measures. For instance, CM caused by the poor-quality spare parts can be lessened by purchasing the ones with good quality; CM caused by unskillfulness of maintenance staff can be decreased by pertinent training. There are three key points in managing CM, which are:

- 1) Statistics reflecting actual problems. From the investigation in Section 3.1 it can be seen that for each contributor of CM, the deviation varies much from different rigs. The deviation may be the result of subjective experience or judgment of the respondents. A system for objectively collecting the data is indispensable for the management of CM.

For instance, despite there are guidelines on periodic checking the hydraulic pipelines, the pipes are inclined to break after a certain period without early warning. If the MTTF of the pipe is, for example two years, there is 50 percent chance that the pipe will still work whereas 50 percent chance that the pipe has been down before the end of two years, as shown in normal distribution curve in Figure 4.1. Based on such assumption, therefore, it is necessary to be clear about the possibility of the failure of concerned equipment so that corresponding measures will be carried out in advance to avoid unexpected CM.

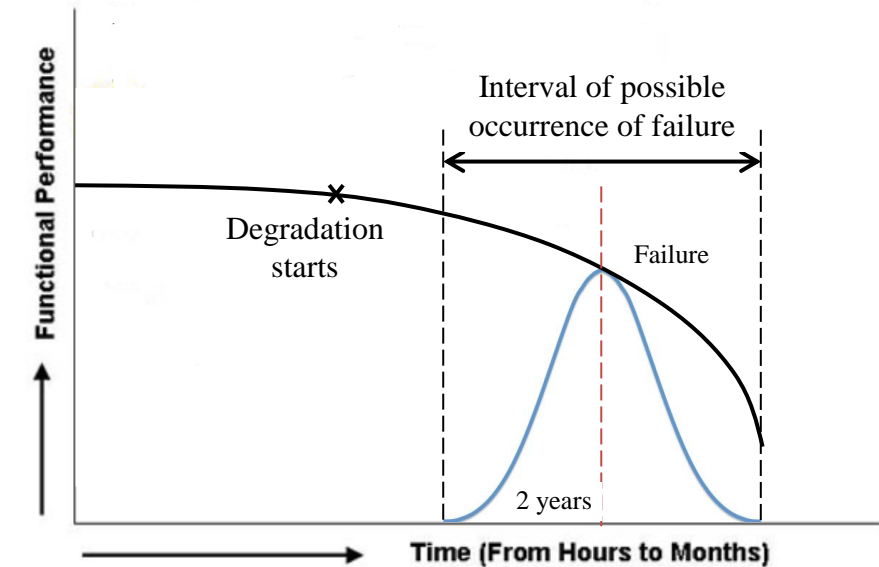


Figure 4.1 the possibility of the equipment failure

- 2) Change in management. There still exists such thinking: the person who can cope with the emergency failures is the best maintenance engineer. This is partly true because the person who can quickly handle the failure must have rich knowledge and work experience. From another point of view, however, such thought may frustrate those who can maintain the equipment in good condition and have little unplanned CM to manage. An environment encouraging maintenance staff to focus on prevention but not correction of the facilities should be established.

- 3) Applying condition monitoring techniques. As stated in Chapter 2, various monitoring techniques can be utilized to effectively manage CM to a relatively low level. Take the failure of the gears caused by left-over problem for example. For such kind of machinery with high rotation speed, vibration detector and temperature sensor can effectively detect the abnormalities during the running of the gearbox. Also a portable thermal imager is alternative. During whatever commissioning or service period, condition monitoring techniques when being applied properly will timely disclose the potential problems so that unplanned CM could be minimized.

4.1.2.2 Management of periodic maintenance

Preventive maintenance plays a major role in maintenance activities in COSL Drilling and is still under perfecting through the promotion of both software (such as AMOS mentioned in Section 3.2) and management system (as shown in [Appendix II](#)). Considering the shortages mentioned in Section 2.1.2, following aspects may be adopted to improve the effectiveness of PM:

- 1) Enrichment of PM contents. This can be done through several ways besides being obtained from user's manual or relevant rules and regulations:
 - Elder employees' experience. The elder workers know the equipment they deal with as knowing their kids. In some situation their work experience is even more valuable than those written in the user's manual.
 - Experience from similar equipment. It is common that the facilities with the same model are used in more than one location or more than one rig. If certain problem or failure occurs on one of them due to some reasons, the maintenance of the other ones can learn from such experience so that the same failure can be avoided.
 - Specialists' recommendations. The specialists normally have abundant knowledge in respective responsible machinery. Their suggestions are instructive and forward-looking in guiding maintenance activities.
- 2) Integrated database. Despite the database of PM of each rig has been backed up in equipment management department of COSL Drilling, it is just for use in case of data loss. There is no data compilation to, for example, classify the similar equipment in the same group so that a change in the maintenance content will be informed to all relevant rigs. It may be advisable to create a database that can systematically manage the modification and upgrade of the PM content so that all involved units can be maintained in a better way.
- 3) Good communication with the oilfield operator. PM is the scheduled maintenance which may conflict with normal drilling operation. The attitude towards PM is various in different oil company. Some are reasonable whereas some are reluctant to spend time on maintenance. No matter which kind of operator does COSL Drilling work for, good communication and relationship should be established through patient and justifiable explanation to facilitate the execution of PM.
- 4) Applying condition monitoring techniques. There is always a trend of decline for each piece of equipment. The early warning signal of such deterioration indicating the possible failure cannot be always detected by the human senses. No matter how vigilantly the PM

is carried out, such scheduled but not condition-based maintenance may not be the actual needs of the equipment. By applying some mature condition monitoring techniques, however, a variety of problems especially of critical equipment causing considerable influence to drilling operation can be revealed so that the potential breakdown is avoided. In addition, numerous advantages and benefit can be achieved, as discussed in Section 2.1.3.

4.1.2.3 Management of predictive maintenance

PdM is an optimized maintenance philosophy which has been developed worldwide. However, the superiority of PdM does not necessarily mean that it is suitable for all the equipment. Several considerations should be thought over before and during the application of PdM.

- 1) Economic assessment. The implementation of PdM requires the investment in developing software, purchasing and installing sensors or detectors, establishing communication system, and training the technician to be familiar with the operation and troubleshooting of the system. These all need the capital expenditure. Therefore, necessary researches and analyses should be performed beforehand. For example, FMECA (Failure Mode Effects and Criticality Analysis) can be used to estimate the significance of a component or certain equipment, as shown in [Appendix III](#). The decision on whether condition monitoring is indispensable is relatively easy to make by comparing the investment with the probable loss without monitoring techniques.
- 2) Complexity and feasibility. Sometimes a PdM system is designed with a lot of functions intending to realize diversification and integration, but resulting in cumbersome operation and maintenance of the system. Care should be taken when establishing the PdM system. No matter the sensors or the human-machine interface, it would be better to choose those which are easy to access, operate, repair, and replace.
- 3) Personnel training. PdM as intellectual system necessitates the qualification of the system operator. The operator has to know how to open the displays they need, where to find the parameters, how to make alarm settings, etc. Training is thus essential for the good management of PdM. Besides the training provided by the manufacturers before the system comes into service, the establishment of effective training mechanism so that the knowledge and skills will stay known by whoever operates the system is indispensable.

4.2 Role of condition monitoring in optimizing maintenance system

As discussed earlier in Section 4.1.2, the negative influences of CM and PM can be partly, if not all, weakened by applying appropriate condition monitoring techniques.

- 1) Condition monitoring in reducing CM. 10 types of reasons leading to CM have been introduced on section 3.1. Some of them can be effectively reduced through proper condition monitoring techniques. For example:
 - The deterioration of gearbox (Reason 1, CM caused by left-over problems during rig construction or dock repair) will be timely detected if a vibration sensor is installed;
 - The mistakenly closed valve in the lubricating oil pipeline (Reason 4, CM caused by unfamiliarity with user's manual) will not happen if a flow meter is used;

- The possible bearing degradation of the generator (Reason 9, CM caused by improper PM) can be minimized if vibration monitoring is applied.

A probable example could be the condition monitoring on the Mud Pump. According to the statistics of HYSY942 in 2009, the downtime caused by the failure of Mud Pump accounted for 20% percent of the totality. If an effective monitoring technique could be used, such data could become much lower. As introduced by SKF, a set of portable data collector (FFT analyzer) including training fee is about 290 thousands RMB, which is only about one quarter of the day rate of the drilling rig. However, such small investment could give early warning signals on equipment conditions such that the deficiencies will be handled in advance. The economic loss due to the downtime is therefore minimized.

- 2) Condition monitoring in improving PM. The examples related to such issue can be found everywhere. A simple case is the electrical clogging indicators mounted with the oil filter. Such indicator makes use of pressure difference before and after the filter to trigger a switch such that the system receiving the signal from the switch will alert to the operator to change and clean the filter. Such condition monitoring reduces unnecessary periodic check of the filter on one hand, while on the other hand ensuring the filter will be timely maintained by receiving the alarm signal.

4.3 Establishment of condition-based maintenance system

4.3.1 Efficient data acquisition and analysis

- 1) User-friendly software. The premise of conditioned-based predictive maintenance is that existing plant staff must be able to understand the operation of both the data logger and the software program (Mobley, 2002). Unlike normal computer used in daily life, the system and its supporting software designed for various industries are quite different. According to the author's experience, a sophisticated system providing quite a number of advanced functions may not be accepted because of the complex operations. It would be better to use simple human-machine interfaces and operating procedures so that the maintenance staff will conveniently access the data and information they need.
- 2) Selecting parameters. The equipment especially the sophisticated one is made of a number of components or sub-systems where many operating parameters are monitored. Three considerations should be taken into account when determining which one should be chosen: criticality, lag time and readability (understandability). Criticality determines whether the parameter will directly and timely reflect equipment condition; lag time determines how long the parameter will tell equipment status at the time the signal is captured; readability determines how quick the personnel will understand the data collected.

Take the electric-hydraulic driven crane for example. It would be better to equip with monitoring technique on gearbox since it is the critical part between the driving motor and driven pump. Three techniques are the candidates: lubricating oil analysis, thermal detection or vibration monitoring. Apparently the oil analysis is not applicable since it will take too long time get back the analysis report. Either the thermal detector or vibration monitoring can be the choice. However, it should be noticed that there is a little bit delay in measuring the temperature, whereas professional knowledge is required to read the vibration signal.

- 3) Selecting transducers. The selection of transducers is actually the comparison of pros and cons between similar products, for example measurement range, applicable environment, accuracy, auxiliary components, price, etc. Table 4.1 is an example about the comparison of the temperature sensors.

Table 4.1 comparison between different temperature sensors (<http://www.ni.com>)

Sensors	Signal condition required	Accuracy	Sensitivity	Comparison
Thermocouple	<ul style="list-style-type: none"> • Amplification • Filtering • Cold-Junction Compensation 	Good	Good	<ul style="list-style-type: none"> • Self-powered • Inexpensive • Rugged • Large Temperature Range
RTD	<ul style="list-style-type: none"> • Amplification • Filtering • Current Excitation 	Best	Best	<ul style="list-style-type: none"> • Very Accurate • Very Stable
Thermistor	<ul style="list-style-type: none"> • Amplification • Filtering • Current Excitation 	Better	Best	<ul style="list-style-type: none"> • High Resistance • Low Thermal Mass

- 4) Defining alarm limits. For package equipment, the condition monitoring sensors are usually mounted and alarm thresholds set before the delivery. For a newly installed sensor without factory testing, however, the alarm threshold has to be determined during the practical grope combing with the experience of similar equipment. The equipment history especially the failures should be recorded in detail accompanied with the data logging at the point of failure so that the threshold value for alarm setting is determined objectively.
- 5) Data acquisition frequency. Not all the parameters require 7×24 monitoring. For the transducers with mature technology and stable performance, the data acquisition for the selected parameters can follow a flexible period. This on the one hand prolongs the service life of the monitoring components, while on the other hand lowers the requirement on data storage capacity.

4.3.2 Training and technical support

The establishment of condition monitoring system is the combination of multiple disciplines. The parameters and the significance of their readings involved in the system require being understood by the operator; also the specialized software designed uniquely for both technical integration and customization entails the qualification of the operator so that fault operation leading to data loss or even system crash could be avoided. Neither of them will be achieved if lacking of necessary trainings or supports.

It is common that the system supplier will arrange necessary training concerning basic operation and maintenance procedures of the system. However, there usually are not detailed stipulations in the contract on to what extent should the training be performed. Many tiny

problems which were not disclosed before may puzzle the system operator in later utilization because of the ignorance or inconsideration during the design and commissioning phase. It is therefore imperative that the selected system or system vendors provide a comprehensive support package that includes both training and technical support (Mobley, 2002).

4.3.3 Evaluation of costs and benefits

Reducing the costs and increasing the benefits is one of the most desirable objectives of applying condition monitoring. Therefore there must be reasonable assessment on the possible profit if a monitoring system is desired. Compared to the production platforms, it may be unnecessary for the drilling rigs to comprehensively apply condition monitoring. This is because that a complicated system calls for not only considerable investment but also high maintenance cost subsequently. The monitoring of too many conditions may reduce the failures. However, the cost spent on maintaining the system could be higher than the loss brought by the failures themselves. It should be noticed that the major loss on the drilling rigs is the one taken off by the oilfield operator as punishment for the downtime. When performing economic evaluation, the focus should be on possible influences of the failures to the normal operation, but not the loss of the component/equipment itself.

4.4 Recommendations on developing e-maintenance

Due to the growing sophistication of modern automatic equipment, it becomes less realistic to manage all problems on the platform relying only on maintenance personnel offshore. Thus it is the irreversible trend to set up systematic maintenance system where both onshore and offshore experts can be involved to cope with increasing complex equipment problems. Based on the current development of maintenance management in COSL Drilling, following aspects may have to be drawn attention if an e-maintenance system wants to be established.

- 1) Establish a sound condition monitoring system first. E-maintenance is the advanced type of PdM where its various advantages can be realized only when the data acquisition of equipment conditions is effectively transmitted from monitoring devices to central processing system and further to onshore supporting personnel by communication technology. No matter remote maintenance or collaborative maintenance, no matter real-time maintenance or predictive maintenance, none of them can be realized without reliable condition monitoring to perform necessary data collection and the data analysis.
- 2) Perform systematic investigation. E-maintenance is a comprehensive term covering multiple techniques and involving various parties such that a large quantity of investment is required. For the sake of economical utilization of e-maintenance system afterwards, it is indispensable to carry out an investigation beforehand. Such investigation included but is not limited to:
 - The criticality and priority of the equipment. Like predictive maintenance, not all the equipment requires e-maintenance. For the small and non-critical equipment, the costs on capital expenditure (such as sensor installation, system configuration) and operating costs (such as communication cost, expert support) could be higher than run-to-failure maintenance. Thus necessary analysis, for example FMECA should be used here to assist analyzing and determining which ones should be contained in e-maintenance system.

- The frequency of e-maintenance. E-maintenance does not necessarily mean the continuous monitoring. Based on equipment characteristics, equipment history and the trend of equipment conditions, the frequency of e-maintenance can be determined accordingly such that the good machinery condition is maintained while the service costs, communication costs and the other costs can be cut down as much as possible.
 - The compatibility of the system. One of the advantages of e-maintenance is that the experts in onshore offices can provide support to several offshore units at the same time. The premise of such function, however, is that the e-maintenance system must be compatible with those systems specially designed for and installed on respective rigs. Investigation on such kind of matter can help optimize the construction and configuration of e-maintenance system so that it could be designed and operated in a most cost-effective way.
- 3) Develop a long-term relationship with service provider. As shown in Figure 2.22, the service providers play an important role in e-maintenance system. Their professional knowledge in respective domains could be the great help in problem-solving process. Because of the limitations such as narrow bandwidth, relatively expensive service cost for single rig or system, etc., such kind of remote support from the service seller has not been generally accepted by COSL. However, accompanied with the expansion of the company, a growing number of rigs will be equipped with similar sophisticated control system such as Cyberbase, which accordingly arouse the requirements for remote service. It would be better to build a good relationship with the manufacturers so that both the products and latter services they provided are inclined to benefit all the interested parties.
- 4) Cultivate inter-discipline talents. The inter-discipline talents here refer to the internal employees who are competent and willing to be trained as experts to assist field operation. There are at least two reasons for this issue:
- The service provider may be professional in their specialties, but they may unfamiliar with the others. Sometimes the problem occurred is the result of several malfunctions where the fault phenomenon is really peculiar that no one can settle it individually. In such case the one who is capable of thinking from multiple aspects could give hints on how to solve the problems.
 - The cultivation of internal talents could reduce the dependence on the service provider, thus reduce the service cost while maintaining the normal operation of the equipment.

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Appendix I

Part of COSL document <Identification and Management of Critical Equipment>

4.2 Daily Management of Critical Equipment

- 1) Field operators should follow procedures, and the maintenance personnel should carry out maintenance and repair timely and effectively;
- 2) Set up the *Critical Equipment Checklist* for operating unit, with the aim of unified management;
- 3) Equipment operation, maintenance and management personnel shall have the corresponding qualifications, and be familiar with the relevant rules and standards of COSL Drilling about equipment management;
- 4) The critical equipment in operating unit should be inspected regularly, the inspection report shall include but not limited to: inspection responsible person, inspection results, description of critical equipment integrity;
- 5) According to the results of regular inspection, the meeting of critical equipment running status analysis and report should be hold monthly, in order to summarize the running status of critical equipment and develop solutions for the existing main questions. The results shall be submitted to material and equipment department of operating company, and if necessary it should be submitted to material and equipment department of COSL Drilling for reference. The relevant information shall be filled into *Monthly Report of Critical Equipment Running Status Analysis*;
- 6) Regular training plan for personnel using, operating and maintenance critical equipment should be developed by each operating unit. COSL Drilling and material and equipment department of operating company organize unscheduled selective inspection and subsequent overall examination, according to the situations of field training. And if necessary related leaders of COSL Drilling and operating company could be invited for the inspection and examination;
- 7) Tour inspection of critical equipment shall be handled with reference to section 4.4.7 of *Equipment Usage and Maintenance Management Manual L3.2-EQUP/003*.

4.3 Maintenance and Repair of Critical Equipment

4.3.1 Basic Principles

The development of maintenance strategies for equipment shall be a work process of selecting strategies with analytical and systematic methods based on the Risk Based Maintenance (RBM) philosophy.

A maintenance strategy shall be selected for each critical equipment. The maintenance strategy of critical equipment shall be established based on the Risk Based Maintenance (RBM) philosophy. RBM analysis involves the following tasks in sequence:

- 5) Accessing the equipment criticality for each equipment and analyzing the failure model and failure mechanism for each critical equipment;
- 6) Selecting a maintenance strategy for each equipment unit according to the identified criticality (risk) level;
- 7) Establishing maintenance priority of equipment based on criticality, namely the higher criticality, the higher maintenance priority;

- 8) Establishing inventory management plan for key spare parts.

The management of operating unit critical equipment has already been included in the preventive maintenance system (PMS) of material and equipment department of COSL Drilling. As a result, the examination and maintenance should be carried out following the requirements of PMS.

4.3.2 Maintenance of Critical Equipment

Equipment maintenance strategy is categorized as preventive maintenance (PM) and corrective maintenance (CM). Preventive maintenance (PM) is mainly used for critical equipment/system, in order to reduce or prevent loss of functional failure or degradation. While corrective maintenance (CM) is mainly used for equipment/system after its failure, in order to restore its function.

The critical equipment preventive maintenance (PM) is categorized as three types: interval based maintenance, condition based maintenance and statutory based maintenance. And the corrective maintenance is categorized as two types: scheduled maintenance and unplanned maintenance. Detailed maintenance procedure should be referred to *Equipment Usage and Maintenance Management Manual L3.2-EQU-P/003*.

4.3.3 Inspection of Critical Equipment

- 1) Operating unit self-inspection: the equipment superintendent should organize personnel to carry out regular self-inspection for critical equipment, according to the requirements of *Outline of Ship Survey Drilling Platform* of COSL Drilling and issue an inspection report;
- 2) Operating company inspection: material and equipment department of operating company shall carry out a special inspection for the main critical equipment of operating units every year and issue an inspection report;
- 3) COSL Drilling inspection: material and equipment department of COSL Drilling itself or authorizing the qualified third party shall carry out a special selective inspection for critical equipment of operating unit every year and issue an inspection report;
- 4) Statutory inspection: this inspection of critical equipment is carried out following the requirements of classification society;
- 5) Operating units should deal with all the questions from every party timely. Questions beyond the ability of the unit should be timely reported stepwise to higher level to get shore-based support and the dynamic tracking should be kept until the issue has been thoroughly improved.

4.3.4 Repair of Critical Equipment

The repair of critical equipment includes self-repair and repair on commission. Detailed information should be referred to *Management of Equipment Update and Repair Project L3.2-EQU-P/004*.

4.4 Management of Spare Parts

- 1) The operating unit management team shall organize regular assessment for the spare parts of the critical equipment, which are necessary for maintenance, stored offshore or onshore;

- 2) The inventory of spare parts shall be kept in a cost-effective level;
- 3) Operating unit shall ensure that the spare parts inventory of critical equipment meeting the minimum requirements of equipment safety operation. The number of inventory should be checked periodically, and supplementary inventory shall be ordered in time if the inventory is close to or lower than the minimum requirements;
- 4) Spare parts needed for periodic repair shall be ordered timely according to equipment specification, repair time and operation requirements, in order to ensure normal repair of equipment;
- 5) The onshore stored spare parts with long delivery time, high cost and criticality can be regarded as common reserved resource and shared with other units.

4.5 Reliability Assessment of Critical Equipment

According to service life and service condition of critical equipment, qualified third party shall be authorized to assess the reliability of equipment by using advanced technology and equipment and third party personnel, from the view of safety, environment protection and function. As a result, the assessment could offer effective basis for maintenance, repair and update of equipment.

4.6 Update/Technical Modification

The update and technical modification of critical equipment shall be carried out according to maintenance records, inspection results, evaluation data etc.

- 1) If the equipment has reached the maximum service life or could not be repaired due to serious damage, the operating unit shall apply replacement by approval of COSL Drilling;
- 2) If the equipment capacity and function can't meet the requirement of operating unit or the safety of equipment can't be assured, the operating unit shall apply update or technical modification by approval of COSL Drilling;
- 3) The application of equipment update or technical modification shall be proposed by the operating unit responsible for the equipment and adequate reasons for update or technical modification shall be given. The technical specification should be developed. After reported and approved according to limits of authority, it could be executed;
- 4) Equipment, which is verified existing potential safety hazard after integrity inspection by a third party and proved valueless for repair, could be applied for the plan of update and modification.

5. Emergency Plan of Critical Equipment

- 1) Operating unit management personnel should develop emergency plan under the condition of critical equipment failure, and the emergency plan should be reported to operating company and material and equipment department of COSL Drilling for reference;
- 2) The emergency plan of critical equipment should include emergency leading group, emergency reporting procedure, emergency accident handling procedures, emergency handling process with or without spare parts;
- 3) Operating units should organize exercise of emergency plan of critical equipment failure periodically. The emergency leading group of the exercise unit is responsible for evaluation of the exercise and recording.

Appendix II

Part of COSL document <Equipment Usage and Maintenance>

4.3.3 Implementation of Maintenance

- 1) Equipment maintenance should follow the policy of “clean, tight, lubricate, adjust and anti-corrosion”, maintenance point should be assigned to position, and specific personnel should be responsible for equipment which need specific lubrication;
- 2) Operating Unit should establish management policy for equipment and cabin fixation. Commonly, the operator should be the maintainer and cleaner;
- 3) Operating Unit should establish patrol inspection system; define patrol period, path and inspection content. Equipment supervisor and Senior Toolpusher should examine and evaluate patrol inspection system weekly and confirm by signature;
- 4) For discrete usage equipment or equipment suspend for long time (except equipment sealed up), besides the routine maintenance according to PMS, equipment should perform an active operation at least once within every 10 days, and accomplish *Suspended Equipment Operating Record L3.2-EQU-P/003-R003*;
- 5) For sealed equipment, seal application to Material & Equipment Department of Operating Company is needed before sealed up, and report seal reason, seal method and management during sealing. Before re-enable equipment, re-enable application to Material & Equipment Department of Operating Company is needed, and the equipment need clean, lubricate and necessary check & inspection before reuse. Seal and re-enable of boiler need permission from classification society;
- 6) Operating Unit should create lubricating oil usage list, change of oil should submit written application and get approved by Material & Equipment Department of COSL Drilling. Lubricating oil list should be updated afterwards, and submit to Material & Equipment Department of Operating Company for record;
- 7) Operating Unit should establish systems of oil storing, usage, cleaning, inspection, renewal and type changing;
- 8) Equipment should be cleaned by appropriate detergents and technique. Detergent which may cause environment pollution is forbidden to use. While cleaning equipment, forbidden to use technique which may damage the equipment, i.e. corrosion, mechanical damage, insulation damage and protection damage. Forbidden to use seawater to flush machine, electrical equipment and deck;
- 9) Equipment Supervisor should print maintenance worksheet at least once a week, and deliver to specific engineers and toolpushers to implement;
- 10) Maintainer should record maintenance content, measurements, part replacement, problem revealed, failure analysis and remediation adopted in detail according to the requirement of maintenance worksheet. If problem exceeds capability of maintainer, the problem revealed should reported to superior manager in time;
- 11) Following worksheet within planning should be accomplished before due date:
 - a) Key equipment;
 - b) Equipment which need mandatory regular testing;
 - c) Equipment which need regular testing under classification society regulations.
- 12) If maintenance worksheet is limited by site condition, and could not maintain in a short period of time, the maintenance should be implemented while the condition meets the requirement, and record in to maintenance system; Worksheet of noncritical equipment, which may not meet the requirement of maintenance in long period (one

- maintenance period) , should report to equipment superintendent for approval, and closed in the system afterwards, with reason notation in the system;
- 13) If maintenance worksheet of key equipment exceed 14 days, equipment supervisor should organize risk assessment, and report to equipment superintendent in written, with the summary of assessment and risk control measure which recorded in comment:
 - a) Plan: Postpone reason of maintenance and solution;
 - b) Inspection: Whether the condition of equipment satisfy the requirement of operation;
 - c) Identify: Risk exist in maintenance process;
 - d) Communication: Adequate communication of potential risk within postpone of maintenance worksheet;
 - e) Control: Measures adopted to effectively manage the risks.
 - 14) If maintenance worksheet of key equipment could not be executed in long period (a maintenance period), equipment supervisor should report to equipment superintendent, and equipment superintendent is Responsible for assess the risk which may occur by the delay of maintenance, and adopt appropriate risk control measure;
 - 15) Key equipment maintenance worksheet which exceeds 6 months must be reported to Material & Equipment Department of Operating Company by equipment superintendent, with the state of reason and risk control measure. Review and approval by Material & Equipment Department of Operating Company is needed;
 - 16) Equipment supervisor should create list of maintenance worksheet which may not meet the requirement of implementation, report to equipment superintendent every shift, and equipment superintendent should organize rationality assessment of maintenance worksheet;
 - 17) In complex or high-danger maintenance operations, superior manager of maintainer should organize risk assessment while arranging work. Ensure the safety prevention in place. If necessary, superior manager of maintainer should instruct in site.

4.3.4 Inspection and Feedback

- 1) Material & Equipment Department of COSL Drilling should perform quality inspection of equipment maintenance management of Operating Company at least once a year, and perform spot check based on inspection result and equipment operating quality of Operating Unit. The inspection could be performed with internal audit of integrated management system or other inspection project. Problem revealed during inspection should be responded according to the requirement of *Non-conformance Management L3.2-QUA-P/014*;
- 2) Operating Company should perform equipment maintenance implementation quality inspection in each Operating Unit at least once a year. The inspection could be performed with internal audit of integrated management system or other inspection project. Problems revealed during inspection should be responded according to the requirement of *Non-conformance Management L3.2-QUA-P/014*. Inspection should include:
 - a) Integrity and accuracy of basic database of equipment maintenance management software;
 - b) Update equipment maintenance basic database after equipment renewal or overhaul;
 - c) Quantity of delayed key equipment maintenance worksheet;
 - d) Quantity of unfinished maintenance worksheet;

- e) Downtime caused by equipment failure;
 - f) HSE accident/event caused by lack of maintenance;
 - g) HSE accident/event occurred during maintenance;
 - h) Timely and integrity of recorded accomplished maintenance worksheet;
 - i) Timely and integrity of recorded corrective maintenance work which out of the plan;
 - j) Closed cycle management problems revealed during maintenance;
 - k) Integrity of equipment feature and actual operating status;
 - l) Equipment information and certificate, document and record etc.
- 3) Equipment supervisor should perform spot check and verify implementation status of maintenance worksheet at least 10 pieces per week, senior toolpusher should perform spot check and verify implementation status of maintenance worksheet at least 5 pieces per week, and record related information;
 - 4) Equipment superintendent should perform inspection of PMS on-site at least 1 week per month; verify timeliness and accuracy of maintenance worksheet implementation, actual maintenance and operation status of equipment, and positioning management. Submit inspection report to Material & Equipment Department of Operating Company afterwards.

4.3.5 Improvement of Maintenance System

Through the assessment of PMS implementation quality and equipment operating status, COSL Drilling could adopt following measures to improve PMS continuously:

- 1) Upgrade software system of maintenance management;
- 2) Critical evaluation and definition of equipment;
- 3) Adjust maintenance period and content;
- 4) Improve technique and quality of personnel.

Appendix III

FMECA analysis of air compressor

Description of Unit				Description of Failure			Effect of Failure		Failure Rate	Severity Ranking	Risk Reduction Measures	Comments
Ref. No.	Component name	Function	Operational Mode	Failure Mode	Failure Cause or Mechanism	Detection of Failure	On the Subsystem	On the System Function				
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)
1	air inflow filter	filter the inlet air	normal	blocked	air impurities	low pressure output	insufficient air supply to the compressor	insufficient air outflow and low pressure output	5	3	measure the air pressure differential and set alarm level*	
2	inlet valve	control the inlet airflow	normal	deactivated	blocked due to the impurities	low pressure output	insufficient air supply to the compressor	insufficient air outflow and low pressure output	3	3	regular check and clean	
3	unloading valve	control the system pressure	normal	activated at low pressure	setting value is too low	low pressure output	low pressure output	cannot meet preset pressure setting	3	3	label the desired value at conspicuous position	
				deactivated at high pressure	setting value is too high blocked due to the impurities	high pressure without unloading	reduced life cycle of system components	high pressure output	3	3	set the alarm level of high pressure	
4	electrical system	control and monitor running of the compressor	normal	cannot start system	loss or fault of wire connection	system cannot start	cannot start	system stopped	4	8	routine maintenance	
					fuse broken							
					overload protection relay activated							
					no power input							
5	system pressure sensor	monitor system pressure	normal	cannot function	sensor failure	no or extreme abnormal display	start and stop frequently or no response to pressure change	disrupted compressed air output	2	8	routine check and maintenance, apply redundant pressure gauge	
6	pneumatic control lines	system control	normal	air leakage	erosion	abnormal running performance**	abnormal function	abnormal function	3	6	routine check and clean	
				air jammed	impurities							

Description of Unit				Description of Failure			Effect of Failure		Failure Rate	Severity Ranking	Risk Reduction Measures	Comments
Ref. No.	Component name	Function	Operational Mode	Failure Mode	Failure Cause or Mechanism	Detection of Failure	On the Subsystem	On the System Function				
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)
7	heat exchanger	cool down both lubricating oil and air	normal	cannot cool down the temperature of oil and air	jammed by impurities	high temperature of oil and air	high temperature	system stopped	4	8	install temperature sensor and set alarms	
8	oil separator	separate the oil from air	normal	oil mixed with water	water elements in the air	deteriorated oil	reduced life time of worn elements	reduced function time due to the worn parts	5	6	add water filter	
9	oil tank	store the oil	normal	quantity of oil decrease fast	seal leakage	oil leakage on ground	reduced life time of worn elements	reduced function time due to the worn parts	2	6	routine check	
10	compressor	compress air	normal	no compressed air discharge	piston rod broken down	noise and vibration	severe physical damage to other components	no compressed air output	1	9	vibration monitoring	
					coupling between rod and driver damaged	noise and vibration	severe physical damage to other components	no compressed air output	1	9	vibration monitoring	
				very low pressure of compressed air	piston worn	noise and vibration	deterioration of components	low pressure output	1	9	vibration monitoring	
11	safety valve	protect and limit system pressure	normal	cannot activated when overpressure	jammed due to long standby status	regular test	induce overpressure and explosion	system collapsed	1	10	regular test	
12	supporting beam	support the equipment	normal	vibration	looseness	vibration	worn, crack or rupture induced by vibration	reduced function time	1	9	vibration monitoring	

* detect pressure difference between the pressure before and behind the air filter.

** cannot load or unload, or load and unload frequently.

Failure Rate		
1	Unlikely	1/50 years
2	Remote	1/10 years
3	Occasional	1/5 years
4	Probable	1/2 years
5	Frequent	> 1/year

Severity Ranking	
1-2	Failure is of such minor nature that the customer (internal or external) will probably not detect the failure.
3-5	Failure will result in slight customer annoyance and/or slight deterioration of part of system performance.
6-7	Failure will result in customer dissatisfaction and annoyance and/or deterioration of part of system performance.
8-9	Failure will result in high degree of customer dissatisfaction and cause non-functionality of system.
10	Failure will result in major customer dissatisfaction and cause non-system operation or non-compliance with government regulations.