New Condition Monitoring Techniques to use for increasingly flexible Plant Operation

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Abstract

Combined Cycle Power Plants exist entirely through the Return on Investment business model. As such these power plants are built, maintained and operated within tight budgetary and production revenue constraints. From an Operations and Maintenance viewpoint CCPP's are constantly faced with prioritising activities and tasks based on very limited manpower and tightly budgeted funds.

A variety of O&M tools are available within the modern market, however the dynamics and resource issues associated with CCPP translate into systems that obey PARETO.

- *CCPP facilities need fast, cost effective results and systems that solve 80% of problems with relative costs of 20% in terms of capex, revenue and resource.*

The term 'Condition Monitoring (CM)' is only 1 ingredient and the isolated use of CM can only provide limited results within a complete Operations and Maintenance Environment.

Focus 1 – The accurate detection of cost critical fault conditions:-

- *Consistent and well targeted plant inspection systems*
- *Enveloped acceleration on Rolling Element Bearings and Gearboxes.*
- *Velocity to detect unbalance, misalignment, looseness or cavitation.*
- *Oil analysis to assess cleanliness, water content and wear contaminants within gearboxes and plain bearing lube systems.*
- *Thermal methods to assess gas path, thermal symmetry and electrical condition of panels*
- *Peak Pressure and PV curve analysis on Diesel & Gas engines.*

Focus 2 – Integrate & optimise:-

- *Eliminate calendar, pre-shut or hour based routines and tasks that are obsolete through the use of CM methods.*
- *Correlate oil, vibration, thermal, operational rounds data and maintenance history.*
- *Wherever possible retain knowledge*
- *Use consistent and proven knowledge to auto generate cost critical remedial tasks.*

1.0 Scope

This technical paper addresses the following aspects of Plant Condition Monitoring as they relate to **New Power Plant:**

Methods, advances and applications
Focus areas for optimisation of CM
CM within the Operations and Maintenance environment

The final section is on base costs and relative benefits.

Condition Monitoring is best applied as part of a complete Maintenance and Operations system and should only be applied where, the detection methods are reliable and the cost of monitoring is a fraction of the plant reliability benefit.

2.0 Methods advances and applications

2.1 Test & Inspection (TPM)

There are many sources of machinery health and production availability information available to an organization's maintenance and operations staff. Two of the most commonly used sources of information are scheduled inspection of machinery and condition monitoring.

Inspection Routes can be split into 3 areas

Rounds – Where an operator or engineer completes a set circuit as a cursory status check. Will often involve the making of notes or observations.

Adjustments – Often associated with the TPM philosophy, this type of route involves the checking of settings, making the required changes, **lubrication**, cleaning etc.

Measurements – Gathering of plant panel data, oil levels, hours running, temperatures, overall vibration readings, quality tests.

All of the above can be achieved through the use of a clipboard, data entry grid and the use of a data entry clerk. Unfortunately paper based Inspection data almost invariably ends up in a filing cabinet somewhere and is only reviewed in the event of a problem or breakdown.

Why Gather – Test & Inspection Data?

Instant notification of 'new' fault	Calculation of OEE
Production & Maintenance input	Custodial maintenance
Paper systems cost little or nothing	TPM & Safety inspections

2.1.1 Methods of Inspection Data gathering

Paper Systems – Log sheets, inspection instructions, production line test / fault books.

Electronic Clipboard – Involves the gathering of data in an electronic format using a hand held device and the downloading of this data into a software package.

SUMMARY – Test & Inspection

Paper Base Systems – Collated information difficult to integrate into O & M systems and produce benefit [entry cost is NIL]
Electronic Systems – Look for a flexible system with all required data entry formats and the ability to interface with CMMS and CbM packages [Software entry cost £1000, Hardware entry cost £500 (non-industrial) £1500 (industrial)]

WHATS NEW – Test & Inspection

Palm top PC's moving towards CE operating system that will reduce costs by 50% in a few years.
CMMS vendors are moving towards TPM modules & Hand Held PC work order issue
Integrated Test and Inspection with CMMS & CbM now available from 2-3 vendors.

2.2 Vibration Analysis

Vibration measurement systems fall into the following categories:

Single Value Methods
- Hand Held meters
- SPM Units
- Acoustic Emission Units
- Vibration Pens
- 4-20mA sensors

Time Frequency Methods
- Hand Held Data-collectors
- On line systems

Why Use – Vibration?

Provides early warning of mechanical failure
Non intrusive method
Entry cost is as low as £700
Established evaluation limits
Manufacturers usually publish vibration limits

2.2.1 Single Value Measurements

The variety of single value measurements is endless, from the ISO filtered levels mentioned in ISO 10816 [1] to the 'magic numbers' offered by some of the technology vendors; promising to solve all of your plant condition problems within one simple solution. ISO 10816-3 is summarised as a supporting appendix to this text.

Please note single value methods are either 'generic' or 'specific'. The generic case is where a value will indicate the presence of 'a problem' but cannot categorise the problem into a specific fault (e.g. Unbalance, looseness, misalignment, cavitation etc.). The specific methods concentrate on issues such as bearing faults and try to eliminate the influence of 'other' faults through the use of algorithms and electronic design.

The following table outlines the more common types of measurement with comments on applications and a brief technical description of the method.

Single Value Method Summary

Method	Description	Applications
ISO Filtered Velocity	2Hz – 1kHz filtered Velocity	Works as a general condition indicator.
SPM	Carpet and Peak related to the demodulation of a sensor resonance around 30kHz.	One of the better single value bearing indicator methods. Some problems on larger bearings and gear units.
Acoustic Emission	Distress & dB, demodulates a 100kHz carrier which is sensitive to stress waves.	Better general indicator than ISO velocity, without the ISO comfort zone.
Vibration Meters / pens	Combine velocity, bearing and acceleration techniques (sometimes include thermal)	Look for ISO Velocity, envelope & high frequency acceleration for best performance.
4-20mA sensors	Filtered data converted to DCS/PLC compatible signal.	ISO velocity version available, envelope version still awaited. Can be used to 'home in' on specific problems by special order.

Single value vibration methods have two major advantages and only one real disadvantage; these are low cost, simple interpretation and lack of accuracy respectively. The overall CM system implications of single value methods are discussed within the later sections of this text.

Single value data are easy to trend and interpret as shown by the inset plot below.

2.2.2 Time Frequency Measurements

This type of measurement involves the detection and display of specific components of a time history sensor output. The use of specific frequency components lends itself to the detection of faults down to a single mechanical component (e.g. bearing, gear, impeller).

Once again, various methods, techniques and signal conditioning systems are used to detect specific components of the raw time history data.

2.2.2.1 Displacement (Low Frequency)

Where the measurement of absolute movement is required, measured using LVDT's or eddy current probes. Particularly useful in detecting the relative position of a rotor versus a structure and in the diagnosis of plain bearing faults through the use of orbit plots.

2.2.2.2 Velocity (Mid Frequency)

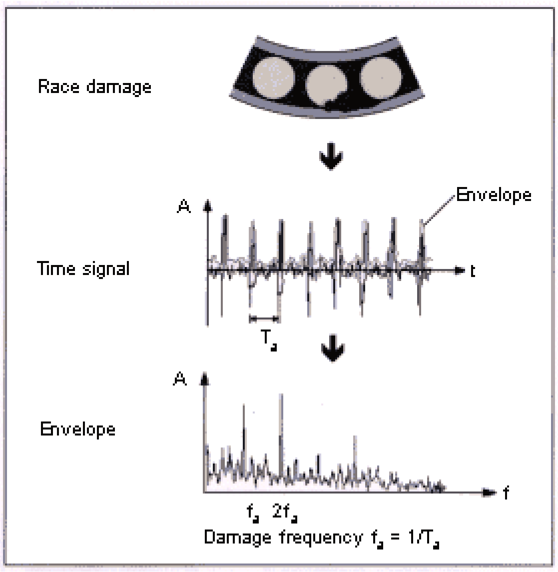
The most commonly used method for fault identification, mainly due to the scalar consistency of the method (i.e. 25mm/s is high almost irrespective of the machine type). Used to detect signs of mechanical problems in the frequency range 20Hz – 2000Hz. Detection capabilities cover the following fault conditions.

Unbalance, Misalignment, Looseness, Resonance, Cavitation, Blade problems, Turbulence

2.2.2.3 Acceleration (High Frequency)

Amplitude Demodulation Methods

Used to extract impacts from the standard acceleration spectra through the extraction of the amplitude-modulated component and the display of the demodulated components within an auto-spectrum plot.



Impacts are created as a rolling element collides with a damaged area.

These impacts show as transients within the time domain. The Demodulator extracts these transients.

Extracted impact frequencies are then displayed on an envelope spectrum (shown opposite)

There are two main types of envelope measurement, namely:

Band Pass Filtered Enveloping
Allows the time history associated with the excitation of a specific frequency band pass through to the demodulator circuit. This method avoids the possibility of phase cancellation and is better at isolating the transient activity.

High Pass Filtered Enveloping
Sets a High Pass filter and allows all measured time data above the HP filter pass to the demodulator, this method is regarded as less effective by vibration practitioners.

General Acceleration

Where rotating machine related frequency components are expected above 2kHz, velocity measurement is not accurate due to sensor noise levels. Acceleration time frequency analysis tends to be used for the detection of fault components from: -

Any gear assembly (gearbox, timing gear, gear pump)
Where amplitude demodulation methods are not available (to detect a 'haystack' within the high frequency spectra)
High speed screw assemblies.
Turbochargers
Blading problems on turbo-machinery
High frequency resonances
Detection of gear and rub related transients

SUMMARY – Vibration

Combined Vibration Meter – Low Cost and easy to use (look for ISO Vel & Enveloped acceleration) [£700 - £1500]
Acoustic Emission Meter – Reasonable alternative Combined Vibration Meter (good for low frequencies) [£800 - £2000]

Time Frequency (Datacollector) – Required for specific and more accurate fault diagnosis, choose band pass envelope method as bearing assessment technique. [£5000 - £14000]

ALTERNATIVE - Consider service provision to 'test the water'. [£600 per month for 50-70 assets]

WHATS NEW – Vibration

Data collectors set to drop in price, now available from £5k (£8k 1 year ago)
Better combined Vibration meters available.
ISO Standards improved but still don't include bearing condition assessment

2.3 Thermal Techniques

Thermal measurement systems fall into the following categories

Point/Zone Measurement
- Dedicated temperature sensor
- Hand held

Thermal Picture
- Thermography Camera (Still or Video)

Why Use – Thermal Measurement?	
Pinpoints specific hot spots	Simple to interpret
Non intrusive method	Hand held laser sighted Pyrometer £500
Implications of electrical failure are SEVERE	Abundance of Thermal service providers

2.3.1 Point/Zone Measurement

These methods measure the temperature of a specific sensor touching the structure or the emitted temperature from a radiating area. They come in hand held and fixed variants and are very convenient and robust.

2.3.2 Thermography

Infrared detection systems provide a thermal picture of the target object, both accurate and visually clear.

The following table outlines the more common types of measurement with comments on applications and a brief technical description of the method.

Thermal Measurement Summary Table		
Method	**Description**	**Applications**
Point temperature	Usually a thermocouple or RTD. Often ‘imbedded’, can be provided as an encapsulated sensor for permanent fit.	Can be used on all accessible surfaces. Walk around versions take time to settle and are less robust than the pyrometer.
Area Pyrometer	Measures the emitted IR radiation from a surface. Often with a Laser sight or area indicator.	Very good for walk around temperature checks on machines and panels.
Temperature Paint / Stickers	Chemical indicators calibrated to change colour at a specific temperature.	Great for inspection rounds.
Thermography	Hand held still or video camera sensitive to emitted IR.	The ultimate, high-resolution thermal picture. Camera costs £10k up, service £500 per day. Camera use and interpretation does require ‘good’ training.

What’s New – Thermal Measurement	
Cameras are lighter, cheaper.	Still cameras offer a saving over video.
Hand held laser pyrometers have memory, route Output	Competitive service provision driving down costs

2.4 Oil Analysis

The science of oil analysis falls into 4 main areas, which are listed below:

- Fluid Physical Properties (Viscosity, appearance)
- Fluid Chemical Properties (TBN, TAN, additives, contamination, % water)
- Fluid Contamination (ISO Cleanliness, Ferrography, Spectroscopy, dissolved gases[Transformer])
- Machine Health (wear metals associated with plant components)

Why Use – Oil Analysis?	
Powerful Machine Health indicator	Reduces wear & tear on critical assets
Gearboxes don't always respond to vibration monitoring	Reduce cost of oil replacement & disposal
A good lube analysis costs from as little as £20	One of the few transformer monitoring methods

Laboratory based oil analysis can provide the Fluid components, however the return of well informed machine health data from an oil analysis service provider will require the following:

A real understanding of the machine and the associated contamination risks.
The ability to analyse oil data and relate that to the specific machine using the lubricant.
Wear mode analysis through machine knowledge, particle shape, texture and composition

2.4.1 Some pitfalls

Beware the following types of oil analysis service provider:

Free analysis with the supply of oil - The oil lab should be independent as far as possible from the lubrication supply, free service means there is a hidden charge and any margin calls will fall on the side of 'replace the oil'.
'Lights out' analysis facilities – These are production line facilities that provide a production line output, they tend to automate the diagnosis and the Machine Health aspects are virtually useless.
Oil analysis labs that sub contract both the Fluid and the Machine Health components of the analysis. This results in the provision of a 'Lights out' quality of analysis with an added mark up on price.

2.4.2 On site screening

If your reliance on optimal lubrication and hydraulic oil cleanliness is very high OR the volume of oil for analysis is prohibitively expensive OR the option of lab based oil analysis is not there (shipping, nuclear, highly contaminated). The use of on-site testing methods warrants consideration.

2.4.2.1 Visual appearance and smell

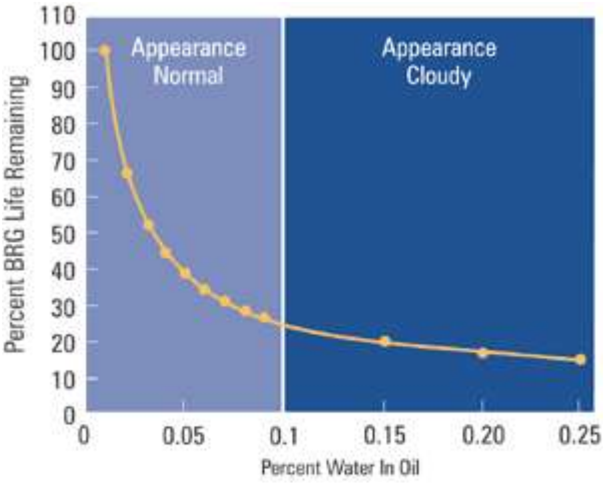
In the most extreme cases metal particles can be seen to glitter and water will come out of solution to provide a water layer. In these cases the full laboratory analysis route is rather 'late'.

Here are a few simple guides to the visual inspection of oil for water content and odour relating to contaminants.

2.4.2.1.1 Water Contamination

As little as 1 % water can reduce the life of a Journal bearing by 90 % [2]

The plot inset below shows how little water is required to make the oil appear cloudy. When one considers the dramatic effect of oil on mechanical components such as rolling element and journal bearings, the level of vigilance is clear.



A hot plate crackle test will also indicate the presence of water as a contaminant.

2.4.1.1.2 Smell

A lot of caution should be exercised when smelling oil samples. Do not place the bottle directly under your nose. Remember that there may be toxic chemicals in the sample. Rather, wave your hand above the opening to waft the scent toward your face. Sometimes it helps to heat the oil, which increases the likelihood of detecting certain contaminants and degradation by-products.

Typical Odours From:

Oxidation - sour or pungent odour, acrid (rotten egg) smell or something similar to stale cheese
Thermal Failure - smell of burnt food
Bacteria - stench, road-kill smell
Running High Temperatures - no odour
Contaminants - solvents, refrigerants, degreasers, hydrogen sulphide, gasoline, diesel, kerosene and process chemicals
Amino Acids - fish odour
Nitro Compounds - almond-like scent
Esters (Synthetic Lubricants) and Ketones - perfume odour

2.4.2 Other On site screening Alternatives

Viscosity Tests – Basic systems test at ambient temperature, the better systems offer temperature setting and measurement combined.

Chemical Tests –TAN, TBN etc. (can be bought as a lab kit from most oil analysis hardware providers)

ISO screening – A variety of methods are available, most are reliable and repeatable for oil screening

Combined analysers – These vary from a multi-function device that is virtually automatic to those with an excess of operations to collate the complete set of analysis results. Always look for the average sample processing time when considering a Combination Oil analyser (you may be unpleasantly surprised). The better analysers will take Contamination level, ferrous index and viscosity from a single sample.

2.4.3 Transformer Oil Sampling

The sampling and analysis of transformer oil is one of the 'must do's' of the Predictive Maintenance world. If nothing else the following 4 tests must be included in any analysis:

Dielectric Strength (kV)

Dielectric strength is the ability of transformer oil to withstand electrical stress without failure. Moisture, sediment and conducting particles tend to reduce the dielectric strength of the oil.

Moisture Content (PPM)

Water in power equipment is attracted to areas of greater electrical stress and this is where it is most dangerous. Moisture accelerates the deterioration process of paper and oil, as well as badly maintained breathers and oil leaks. The moisture detected in the oil, by doing a moisture test, is directly related to the operating temperature of the transformer windings where the continuous migration of moisture is taking place as the temperature varies.

PCB Content

Polychlorinated Biphenyl is classified as a toxic material. No legislation has been finalised to date, however, a risk analysis should be carried out to identify and manage the product to prevent any contamination. COSHH 1994 and EPA 1990 provide guidelines for the reduction and handling of PCB's.

SUMMARY – Oil Analysis

Looking and smelling can provide useful 1st Screen
Choose an analysis service provider that will provide Machine Health feedback [Typical analysis £20]
On site screening & analysis can be expensive and should be weighed against benefit
Viscosity Testers [£700+], ISO Testers [£2000+] Combination Testers [£9k +]
Transformer sampling and analysis should always be considered

What's New – Oil Analysis

Most labs provide more for less cost.
Oil Disposal costs are increasing pressure to monitor NOT Change.

On Line systems & sensors technology will reduce cost

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2.5 On-line monitoring of CbM data

The complete coverage of this area is entirely beyond the scope of this technical paper. On-line systems are available to measure all CbM related data where a sensor exists. The scope includes the following areas of CbM:

- Vibration in all of its guises
- Temperature
- Oil Debris and optical particle count
- Pressure Volume analysis on Diesel and Gas Engines
- And will normally accept inputs from SCADA, DCS, 4-20mA sensors etc.

Why Use – On Line Systems

Plant is extremely Critical	Access is difficult for staff
Staff not available for walk around testing	Mean Time Between Failure is short

What's New – On Line Systems

Pressure sensors available for gas engine temperatures	Web based systems available for NO Capex
System costs are much lower [4k entry]	

3.0 Integration of CbM, Plant Inspection and CMMS

Operations and Maintenance are becoming impossible to separate, they are the main arteries that feed the optimal plant operation and without synergy and information exchange between the two.

The only real path is through Integration and visibility. Thankfully integration is no longer a 'pipe dream', system do exist are affordable and can be implemented within a reasonable time frame [3].

The following areas of plant operations and maintenance need to integrate to complete the O & M picture, these are:

- CbM (Oil, Thermal, Vibration, On-line, Pressure Volume …)
- Test and Inspection (TPM, Rounds, Lubrication, Plant & Process Gauge Data)
- CMMS (Automation of triggered tasks, do work when required, consider process implications)
- Knowledge (Turn experience into a building block and re-use the expertise)
- Reporting & Metrics (Tools to help make sense of the benefits and information)

The best way to explain the benefits of integration is to show an example of integration at work within a plant environment. Appendix 2 shows an Integrated Work flow example that shows the following sequence:

- Operations Inspections and measurement of running hours trigger the issue of an oil sampling WO
- The data from the oil sample is assessed
- When the oil assessment shows a problem, a vibration reading WO is triggered
- In the case where the oil is BAD and the vibration levels are BAD, an overhaul WO is raised
- In the case where the Oil is BAD but the vibrations are OK, an oil change WO is raised

The above sequence and Appendix 2 show how previously scheduled calendar tasks can be removed from the program as a result of a Condition triggered task. Also the ability to decide on condition via a knowledge system creates an environment where tasks can be optimised based upon plant related dependencies.

The completion of such integration using 3 or more software packages is virtually impossible. The solution is NOT interface, it must be integration.

4.0 Conclusions & Summary

The various topics within this text are summarised within each section. However, the following points are worthy of repeating.

4.1 Combined methods will always provide better results than single methods, e.g. Oil, vibration; thermal and pressure volume will speak volumes about the condition of a Diesel Generator.

4.2 For rolling element bearing assessment, Band Pass based Amplitude Demodulation (Enveloping) is the choice of most experts.

4.3 An annual Thermographic survey is strongly recommended with focus on electrical and gas path investigations.

4.4 Oil sampling on critical oil baths is advised through an independent laboratory that has a proven track record in debris analysis. Transformer oil analysis should be completed annually.

4.5 Capex free On-line is now available and offers analysis, Web browsing of data and SMS/email of any impending problem.

4.6 The integration of Test & Inspection, CbM and CMMS information and the use of a plant knowledge base are optimal - worthy of serious consideration.

5.0 References

[1] ISO 10816-3 Mechanical Vibration – Evaluation of machine vibration by measurements on non-rotating parts.

[2] Water – The forgotten contaminant. Mark Barnes. *www.noria.com* Learning Centre, Best Practice Articles.

[3] Advanced Control Technology Club, 20th Plenary Meeting on Condition Monitoring Diagnosis, October 2001. Tom Scott ‘Closing the Maintenance Loop’.

Appendix 1 – Summary of ISO10816-3

ISO 10816-3 Relates to the evaluation of velocity levels measured on the bearings of rotating machinery. This standard supersedes the previous ISO 2372.

The measuring device must filter and sum the velocity energy between 2Hz and 1kHz, and the standard only applies to machines with shaft speeds between 120rpm and 15000rpm.

The following Machines are included

Steam Turbines < 50MW speed < 1500rpm
Industrial Gas Turbines up to 3MW
Generators
Electric Motors
Rotary Compressors
Pumps (non reciprocating)
Blowers or Fans
(Not of lightweight or sheet metal construction)

Machines that are excluded from ISO 10816-3

Steam turbines with speeds > 1500rpm [ISO 10816-2]
Industrial Gas Turbines > 3MW [ISO 10816-4]
Hydraulic units [ISO 10816-5]
Machines Coupled to reciprocating parts [ISO 10816-6]
Reciprocating pumps & compressors
Submerged motor – pumps
Wind Turbines

The summary table inset below shows the maximum severity levels in mm/second and inches/second RMS for the included machines above within the shown power ranges.

ISO 10816-3 CONDITION	Maximum Allowable levels mm/sec RMS			
Damage	>.4.5	> 7.1	> 7.1	>11.0
Restrict Operation	4.5	7.1	7.1	11.0
Unrestricted	2.8	4.5	4.5	7.1
New condition	1.4	2.3	2.3	3.5
	Rigid	Elastic	Rigid	Elastic
	15kW- 300kW		300kW - 500MW	

ISO 10816-3 CONDITION	Maximum Allowable levels in/sec RMS			
Damage	>0.18	> 0.28	>0.28	>0.43
Restrict Operation	0.18	0.28	0.28	0.43
Unrestricted	0.11	0.18	0.18	0.28
New condition	0.06	0.09	0.09	0.14
	Rigid	Elastic	Rigid	Elastic
	15kW- 300kW		300kW - 500MW	

Appendix 2 - Integrated System Work Flow example

Work Order **Collect Plant Inspection Data** Weekly

PLANT DATA CAN BE COLLECTED BY ELECTRONIC CLIPBOARD OR MANUALLY INPUT INTO THE SOFTWARE

IF Running Hours **Increased by 3000**

THEN	Work Order	(Part 1)	Take Oil Sample & send for analysis
		(Part 2)	IMPORT Oil Data

SOFTWARE PACKAGE MUST BE CAPABLE OF **IMPORTING DATA** AND ALLOW THE **CONDITION ASSESSMENT** OF THE OIL TO BE UPDATED. THE CONDITION ASSESSMENT PROCESS CAN BE COMPLETED USING AN **EXPERT SYSTEM** UTILISING PLANT EXPERIENCE AND KNOWLEDGE.

IF Oil Condition **Assessed as Critical**

THEN	Work Order		Collect Vibration data

SOFTWARE MUST ALLOW THE **COLLECTION OF VIBRATION DATA** USING A METER OR DATA-COLLECTOR, MUST ALSO ALLOW THE **CONDITION ASSESSMENT** OF THE VIBRATION INFORMATION.

IF Vibration Data **Assessed as Critical AND** Oil Condition **Assessed as Critical**

THEN	Work Order	(Part 1)	Overhaul Gearbox
		(Part 2)	Exclude 2 yearly Gearbox Overhaul
		(Part 3)	Exclude any other Change Oil WO for 1 year

IF Vibration Data **Assessed as Normal AND** Oil Condition **Assessed as Critical**

THEN	Work Order	(Part 1)	Change Oil
		(Part 2)	**Exclude any** other Change Oil WO for 1 year