UNIT 16 CONDITION BASED MAINTENANCE (CBM)

Objectives

After studying this unit, you will be able to:

- understand conditions which should to be satisfied for implementing condition based maintenance,
- understand steps involved in implementing condition based maintenance,
- understand the scope and details of important condition monitoring techniques,
- understand the benefits of using condition based maintenance,
- understand economic aspects of implementing condition based maintenance.

Structure

16.1 INTRODUCTION

It has been observed that one third of all maintenance costs is wasted as the result of unnecessary or improperly carried out maintenance. Maintenance of plant equipment based on its perceived condition is a more cost effective strategy than either maintenance based on time or usage hours. Maintenance after the breakdown incurs interruption to production or service, more maintenance activity and extra spares usage. Planned preventive maintenance can result in unnecessary maintenance activity and downtime and in excessive spares usage, whilst being ineffective in preventing breakdown.

In condition based maintenance (CBM) the equipment is maintained when measurements indicate an incipient failure. The condition of the machine may be determined continuously or at regular intervals by monitoring vibration, wear debris, temperature and performance parameters. Any change in any of these parameters would mean a change in the condition or health of the machine. Following conditions should be satisfied before implementing a condition based maintenance programme:

- The existence of failures, which do not occur at regular intervals.
- These failures are either a safety hazard or incur significant costs in lost production, breakdown maintenance labor and materials.
- A monitoring method exists that can give sufficient advance warning of the impending failure for the maintenance/production system to act to avoid failure.
- The monitoring and corrective maintenance costs less than the lost production and breakdown maintenance including associated overheads.
- The monitoring method is compatible with the existing company procedures and workforce attitudes and expertise.

Condition based maintenance should not be looked at as a substitute for more traditional maintenance management methods. It is, however, a valuable addition to a comprehensive, total plant maintenance management programme.

16.2 IMPLEMENTING CONDITION BASED MAINTENANCE

Implementing condition based maintenance involves measurement or monitoring of appropriate physical variables or signatures of the machine using instrumentation and interpreting the signatures to indicate if maintenance of the machine is called for or not. Flow diagram of the condition monitoring procedure, as given in Unit.2, is shown in Figure16.1.

Key steps involved in implementing the procedure are as follows :

16.2.1 Listing and Identification of Plant Machines

Listing and numbering of all machines in the plant should be carried out. This is necessary in order to locate all machines within the plant, identify them in the maintenance program and retrieve data.

16.2.2 Selection of Critical Machines

Critical machines are those whose failure may cause loss of production, unacceptable quality, or cause safety hazard to personnel. The criticality level will influence the monitoring frequency. Equipment history records and downtime losses help in identifying critical machines for condition monitoring purpose. Wherever history records are not available the knowledge and experience of maintenance and operation personnel will be of great help in identifying the critical machines.

Following guidelines are found useful in identifying the critical machines in a plant :

- Parts of a continuous process
- Parts of a single production line
- Equipment without standby
- Parts of a production line without (or with inadequate) intermediate storage capacity
- Parts of a line transferring dangerous fluids
- Machines operating at high temperature, pressure or voltage
- Machines containing high inertia high speed components
- Machines arranged in very compact layouts with high maintenance cost

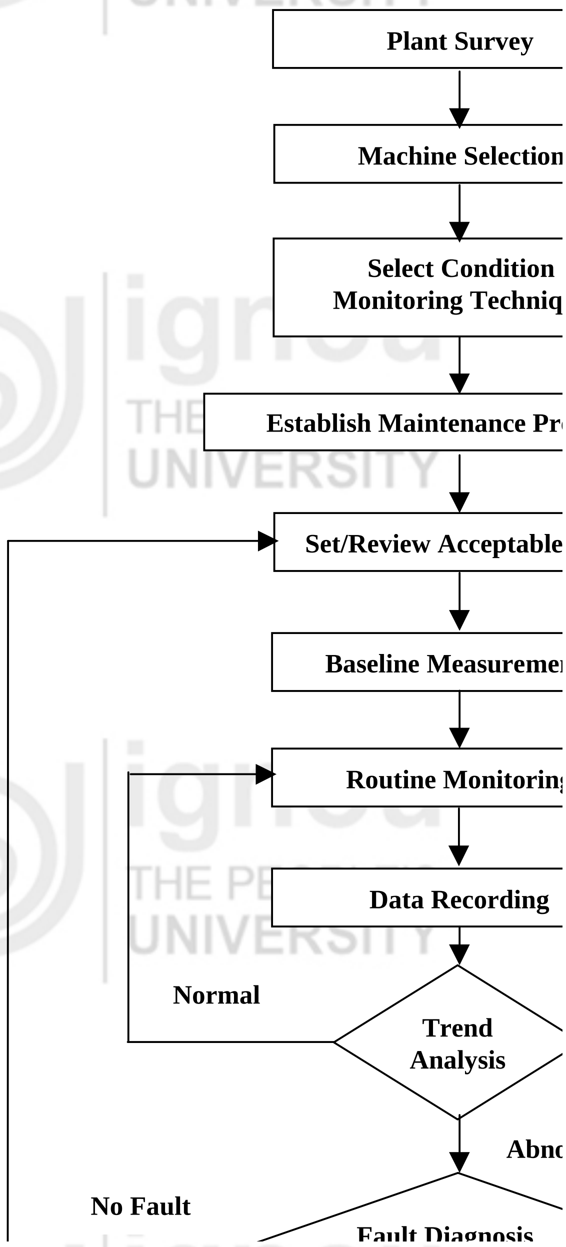

Figure 16.1 : Flow diagram of a condition monitoring procedure

Activity A

Visit your plant and find out the basis on which machines were identified for condition based maintenance?

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16.2.3 Selection of Condition Monitoring Technique

Once critical machines have been identified, the nature of maintenance action is to be based on anticipated failure consequences and failure frequency. The consequences are generally evaluated with respect to safety and economics. Condition monitoring is applied to components having considerable failure consequences and a non-negligible failure frequency. Such components are known as significant components and are determined by carrying out failure modes, effects and criticality analysis (FMECA). A component is considered significant if its risk priority number (RPN), exceeds a predetermined value in a particular scale.

Risk priority number is given as :

$$RPN = FI \times FC \times FDP$$

Where, FI is failure intensity, FC is failure criticality and FDP is fault detection probability. Values of FI, FC and FDP could be fixed on a scale of 10.

In order to monitor the condition of these significant components, monitoring parameters could be identified enabling us to follow the failure developments. Selection of suitable monitoring parameters is based on the study of failure progression and engineering knowledge concerning measuring equipments. *Figure 16.2* explains the method for selection of a condition monitoring technique. Table 16.1 gives the monitoring techniques commonly used for condition monitoring.

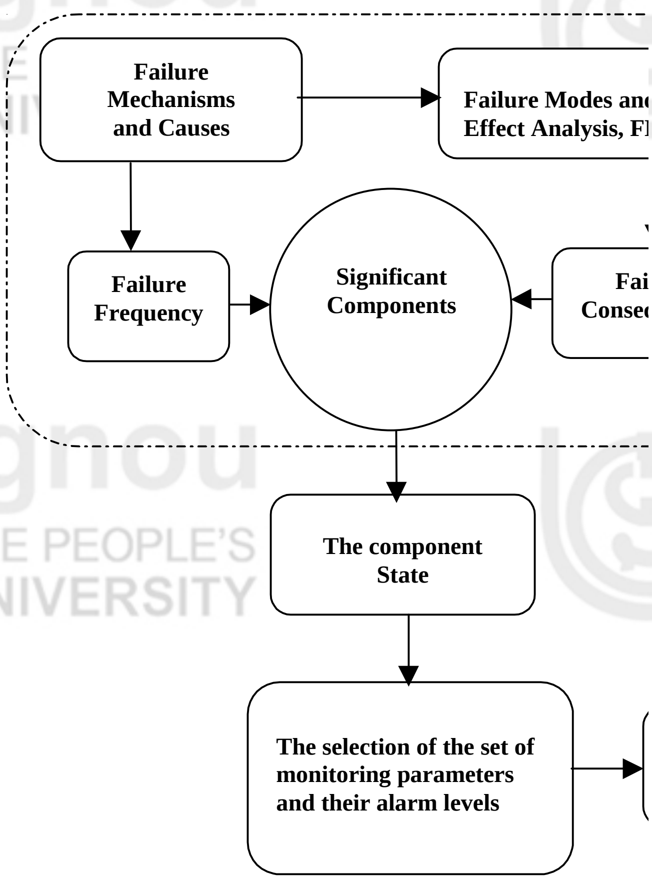

Figure 16.2: A sequential method for the selection of a condition monitoring technique

An ideal condition monitoring technique should have the following attributes :

i. Simplicity in use with pass-fail indication on a simple scale, where the technique involves the use of an instrument, simplicity implies no range control and automatic calibration.

ii. Insensitivity to sensor location so that repeatability is not lost by careless technicians.

iii. Insensitivity to the load condition of the machine so that measurements are not omitted because of inconvenience. This precludes off-load monitoring techniques unless regular off-load periods are programmed.

iv. Robust equipment to withstand the type of maltreatment common in industrial situations. For example, instruments should withstand dropping and cables withstand water, oil and heavy boots.

v. Intrinsically safe techniques in both the technical sense and manner of use. Safety procedures can bog down a monitoring programme in red tape.

Table 16.1 : Monitoring Techniques in Common Use

Monitoring Technique	Existence of problem indicated by	Analysis of nature of problem achieved by	Instruments Available
Visual Monitoring	Overall Appearance	Color, Shape and Texture	- Magnifying glass - Stroboscope - Dye penetrants - Magna-flux - Eddy current - Ultrasonics
Temperature Monitoring	Surface Temperature	Temperature Change	- Temperature indicating tapes and paints - Infra-red detectors - Thermography
Vibration Monitoring	Over-all Vibration Level	Frequency Content, Change in amplitude and phase shift	- Overall monitors - Spectral analysis - Shock pulse monitoring
Wear debris Monitoring	Amount of Debris	Size distribution, Morphology and Chemical composition of the Debris	- Magnetic plugs - Ferrography - Particle counter - Spectrography
Performance Monitoring	Rate and Quality of Output	Input and output relationship, Variation in output quality, Monitoring relationship between two output parameters	Performance Monitoring Systems for car engines, ship engines, gas turbines and steam power plants are in use.

Unfortunately very few techniques meet all of the above attributes. This does not mean that other techniques are unusable, merely that problems associated with the technique may reduce the advantages of condition based maintenance.

16.2.4 Setting of Severity Limits

For every parameter being monitored (vibration, temperature, wear debris, etc), a maximum limit has to be decided, taking into account the performance required from the particular component. This could be done by using information from several sources :

- National or international standards
- Diagnostic equipment manufactures
- Equipment manufacturer
- Experience on a similar machine

After an incipient problem is found, the major task is to estimate the "lead-time" available for a planned downtime so that necessary maintenance could be arranged. Not much research has been undertaken on this subject. There are a few proprietary studies available on some specific kind of equipment, but even such data are often hard to obtain.

16.2.5 Establishing a Monitoring Program

Establish a monitoring program specifying the components to be monitored, locations of measurements, methodology of monitoring and the periodicity of monitoring. Following factors are considered for fixing up the periodicity of making the measurements :

- Criticality of the equipment
- Availability of the standby equipment
- Operating conditions
- Cost of making a check
- Cost of break-down repair
- Cost of preventive maintenance
- Cost of down-time
- The total cost of maintenance
- Mean time between failures (MTBF) and mean time between repair (MTTR)
- Personnel safety

16.2.6 Setting up of an Information and Data Recording System

Implementing condition-based maintenance requires the setting of an information system to meet the basic requirements of :

- Collection and processing of large quantity of information not previously available, regarding the condition of each part of a machine.
- Initiate corrective maintenance actions within the lead-time (the period of time between the off-limits condition and an emergency shutdown). In this respect there may be two different situations which the examiner may encounter :
  - The condition of machine is not yet close to breakdown. In this case the normal procedure through the maintenance planning section will be followed.
  - The condition of machine is already well within the lead-time (near to break-down). In this situation the information must be directly passed on to the maintenance supervision for carrying out emergency corrective maintenance actions.

In order to operate the condition based maintenance program correctly, the maintenance supervision should know :

- Condition of machine
- Part of machine probably defective
- Probable defect
- Time during which failure must be repaired

By scrutinizing and correlating of diagnosis against actual findings during repair work, it will be possible :

- To control the examiner training
- To improve the correlation between parameters chosen for condition measurement and actual defects found
- To obtain severity curves specific to each machine

16.2.7 Impart Training to Maintenance Personnel

Training is the most important element for a successful condition-based maintenance program. It is not sufficient to read a measurement and simply interpret it according to pre-written instructions because these can be misleading. It is important that the operator understands how the plants equipment is constructed, and its past history, as well as troubles, how they appeared and how they were remedied. The ideal diagnostic-instrument operator should :

- Know basics of condition based maintenance
- Know the diagnostic instrument's operation and the principles on which this is based
- Have a deep knowledge of the machinery to be monitored, obtained thorough experience in its maintenance and repair
- Have analytical capability
- Be able to correlate the measurements given by instruments with the real condition of machine
- Have a sense of responsibility and an understanding of the consequences of his decisions.

Once the potential operator has been selected, his skill should be developed through courses on :

- Fundamentals giving mathematical and physical understanding of instruments to be used
- Fundamentals of mechanical, electrical, electronics, computer hardware and software related subjects (lubrication, balancing, alignment, ball bearing assembling, etc.)
- Fundamentals of maintenance management and condition based maintenance
- Instrument operation
- Development of diagnostic skills.

16.2.8 Establishing a Schedule of Maintenance Jobs to be carried out

Under condition-based maintenance, the examination team supplies the engineer with all information concerning the conditions of the machines, while other staff supports him with necessary information. Maintenance is carried out before the failure occurs. Objective is to decrease the number of failures as much as possible and carry out maintenance only when necessary. Maintenance engineer takes decisions and coordinates the maintenance teams on the basis of data, and becomes true manager of the department. Structure of maintenance department becomes more flexible.

Activity B

Meet the technicians of your maintenance department and find out if any special training is required to strengthen the condition monitoring programme in the plant?

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16.3 CONDITION MONITORING TECHNIQUES

16.3.1 Visual Monitoring

Optical techniques are used to enhance the powers of the naked eye. The three main ways in which this is done are: magnification, providing access, and freezing or slowing movement.

Magnification can be provided by a magnifying glass, telescope or microscope

- Binoculars are widely used to inspect remote equipment such as smoke or fume stacks, walls, roofs, steam traps, switchgear and other electrical equipment
- Hand held microscopes are valuable for onsite inspection of wear surfaces or debris

Access can be provided to the insides of plant machines or vessels by light probes, boroscopes and videoimagescopes.

- The simplest light probe is a torch which can be used in conjunction with mirrors on sticks to illuminate and observe dark internal parts of units
- Boroscopes are purpose built devices of small diameter (0.2-0.6") designed to illuminate and view the inaccessible component. There are both rigid and flexible versions with heads capable of illuminating and viewing any different magnifications and angles to the bore
- Motion analyzes allow the high and low speed analysis of visual events. A tiny video camera mounted at the head captures the image, transmitting it electronically to video monitor and motion analysis system.

Comparison can be made between these techniques as follows:

	Rigid Boroscopes	***Flexible Boroscopes***	***Motion analyzes***
Resolution	Excellent	Fair	Fair
Access- through hole	Excellent	Excellent	Fair
- straight tube	OK	Excellent	Fair
- bent tube	No	OK	OK
- tortuous path	No	Fair	OK
Light intensity	High	Fair	Fair
Viewing sensitivity	Good	Fair	High

Timed viewing becomes necessary with moving components to freeze or slow the motion. The three types of instrument used are stroboscope, photographic camera and video camera.

- The stroboscope illuminate the component with a short duration pulsed light at a selectable frequency, which can be triggered by the movement of the component. This appears to freeze the motion so that the component can be observed by eye or by any of the instruments described. Off-tuning the strobe frequency causes the component to appear to move slowly. This technique enables an off-load inspection to be carried out on-load, e.g. the condition of belt drives may be examined this way

- The camera systems are used to slow and record components in motion. Photographic systems can operate up to 1000 frames/sec giving a slowing by a factor of 50. The video systems operate normally to the same frame frequency and exceptionally to12000 frames/s, but there is more flexibility in replay since single frames can be played back.

Storing the information obtained by any of the optical techniques can readily be carried out using video recorders, which then permit computer analysis.

Visual monitoring techniques can be used on or off load, providing visibility to remote, small or moving components.

16.3.2 Temperature Monitoring

Temperatures of the mechanical or structural components of a unit are monitored to ensure that they remain within permitted limits, or that deterioration is detected.

Location of the measurement is critical to both the application and the choice of technique. Measurements made at a surface are more difficult than that those made within a fluid or a solid, because the sharp discontinuity in the temperature profile that occurs in the convective boundary layer is sensitive to the presence of the temperature sensor. Sensors for surface measurement are therefore restricted to thin devices such as thermal label indicators which alter the profile only slightly whilst maintaining good thermal contact.

For immersed and in-body temperature measurement use:

- Liquid expansion sensors such as mercury or alcohol in glass or metal
- Bimetallic expansion sensors
- Thermorcouple, thermistor or platinum resistance sensors.

For surface temperature measurement:

- Self-adhesive thermal labels, which respond to temperature rise by changing colors are cheap and ideal. They contain up to 8 bands each changing at a different temperature. Reversible and non-reversible versions exist. The non-reversible are ideal for routine monitoring
- Temperature paints and crayons work the same way but are not so convenient to use
- Thermocouple sensors designed for surface contact are most convenient and come with a variety of hand-size indicators, but suffer from systematic error due to interference with the heat flow and non-repeatability caused by poor conductive contact
- Non-contact infrared temperature measurement devices sense the infra-red radiations from the surface and deduce from this the surface temperature. Metal surfaces should be painted or otherwise covered with a non-metallic surface. Hand-held, non-contact temperature meters are very convenient and reasonably priced.

Scanning thermographic cameras are now widely available to present a temperature pattern on a two dimensional display. These are appropriate when the monitoring is used to detect a localized hot or cold spot, e.g. a breakdown in lagging or a failed electronic component. Instruments range from simple monochrome systems having the size of a dictionary to shoulder mounted systems with video output and disc data storage.

Typical temperature rises in a working system involving electrical installations as given by Agema are :

- Minor problem, 1ºC-10ºC
- Problem, 10ºC-35ºC
- Serious problem, 35ºC-75ºC
- Critical problem > 75ºC

Display of absolute temperature (and hence colors portrayed) depends on the emissivity, ambient temperature and object distance. All of these can be compensated for in advanced systems. Following are the examples of different changes in colors with decreasing temperature :

A			**B**
Red	Strong thermal radiation	Higher temperature	White
Orange			Yellow
Yellow	Average thermal radiation	Average temperature	Orange
Green			Red
Blue	Low thermal radiation	Lower temperature	Purple
Indigo			Blue
Violet			Indigo

Malfunctions that can be monitored using temperature monitoring are :

- Faults in Electrical Components
  - switch gear contact resistance
  - solid state controller failure
  - cabling faults
  - insulation faults leakage, arcing
  - motor stator shorts
- Coolant Failure
  - in bearings
  - spot welding
  - transformer cooling circuit blockages
- Incorrect Heat Generation
  - furnace burners
  - belt drives
- Incorrect Heat Transmission
  - lagging
  - refractory
  - dust blockages
- Rolling Element Bearings
  - temperature relates to load/speed/ lubricant
- Hydrodynamic Bearings
  - temperature relates to lubricant/coolant

16.3.3 Lube Oil Monitoring

A used sample of oil consists of :

- The base oil and its additives which provide the lubricating and cooling properties of the lubricant
- The contaminants in the form of solids, liquids and gases, which get carried away by the lubricant as it circulates through the system. Mechanical deterioration is primarily indicated by the presence and type of wear debris. Table 16.2 shows relationship between wear characteristics and particle features.

Table 16.2 : Relationships between wear characteristics and particle features

Wear Characteristics	**Wear particle feature**
Severity	Quantity (concentration) Size Morphology
Rate	Quantity Size Morphology
Type	Size Morphology
Source	Composition

Table 16.3 : Oil properties, which can be monitored

Property	Units	Description	Comments
Viscosity (Kinematic)	mm^2s^{-1}	A measure of the oil's resistance of flow	Oil viscosity drops substantially with rise in temperature
Viscosity index (VI)		A measure of the oil's resistance to dropping in viscosity	From 0 to 300, the higher the value the less change of viscosity with temperature
Density (ρ)	Kgm^{-3}	A measure of the oil's mass per volume	Typical oil would be from $880kgm^{-3}$ (20 °C) to 830 kgm^{-3} (100°C), varying with pressure
Total acid number (TAN)	mg $KOHg^{-1}$	Amount of potassium hydroxide neutralizing 1g acid sample	Increase with oxidation and in the presence of high sulphur diesel fuels
Total base number (TBN)	mg $KOHg^{-1}$	Acid equivalent to KOH needed to neutralize 1g base	Included to restrict acids in their corrosive effect
Water content	ppm	Dissolved, but at higher levels may form a fine dispersion of droplets	Unhelpful both for the power fluid and for the lubricant (Even at 100 ppm)
Pour point	°C	Lowest temperature at which the oil will just pour from a container	Oils are normally used at least 10°C above the pour point
Flash point	°C	Temperature at which vapours given off ignite in presence of a flame	Typical between 150°C and 250°C for a mineral oil

Morphology

Lubricant condition

Lubricant is monitored to determine its effectiveness and hence allow change on condition. *Table 16.3* explains the oil properties, which can be monitored. *Table 16.4* gives pollutants and their effect on lubricating oil. The major modes of failure and their associated monitoring techniques are shown in *Table16.5*.

Table 16.4 : Pollutants and their effect on lubricating oil

Lubricant property	Pollutants influencing changes in properties
Acidity	Oxidation products, sulphurous products
Alkalinity	Possible additives
Ash	Base mineral constituents
Flash point	Fuel dilution
Insolubles	Carbonaceous products; dust wear products; corrosion products; additive degeneration products
Specific gravity	All
Viscosity	Fuel dilution, water oxidation products

Viscosity index	Different oil mixes

Table 16.5 : Failure modes and techniques

Failure mode	Techniques
Viscosity	Viscosity comparator, e.g. inclined plate
Oxidation	Viscosity comparator
Corrosives	Corrosion tests
Solids	Millipore filters, particle counters
Water	Crackle test (oil drop on hot plate)
Microbes	Culture slides
Additives depletion	Spectrometric analysis for additive elements Blotter spot test for alkalinity. Total base number

Wear debris

Wear debris monitoring is concerned with the condition of the primary wearing components of machinery, and is achieved by monitoring and analyzing the wear particles that are washed away by the fluid. The quantity and size of wear debris generated indicates an increasing trend in abnormal conditions. The major wear debris monitoring techniques are shown in *Table16.6*. All these techniques can be operated off-line with the sample being collected on or off load condition.

Table 16.6 : Major wear debris monitoring techniques used

Technique	Off/on-line	Particle	Quantify	Size/ Morphology
Spectrometric oil analysis	Off	<10µm	Sample sent to laboratory to obtain ppm of elements	No
Magnetic plugs	On	>100µm	Debris meter	Yes
Filter	Off/On	>5µm	Debris tester	Yes
Ferrography	Off/on	1µm << 200µm	Direct reader Ferrograph	Analytical Ferrograph

Some of the oil sampling methods used are:

- Through sampling value
- By suction sampling
- Through drain stream
- Through magnetic chip detector housing

The sampling frequency depends on:

- Function – i.e. importance of the machinery
- Age– time since overhaul
- Operating schedule, loading characteristics of the machine
- Safety considerations
- Rapidity of failure from defect initiation
- New equipment with possible infant mortality requires frequent sampling

During sampling following precautions are recommended :

- The sampling container must be absolutely clean, showing no visible trace of dirt, water, or other matter; it should be discarded after use
- Extreme care is necessary during sample withdrawal to ensure that no foreign contaminants are introduced; if the sample is taken by gravity flow, the first few milliliters should be discarded before filling the sample bottle
- Sampling must be done during operation or shortly after shut down of the machinery while the lubricant is at normal operating temperature, and before particulate settling can occur
- A complete identification with following information must accompany the sample
  - ➢ Machine or system identification
  - ➢ Date of sampling
  - ➢ Total operating hours
  - ➢ Hours since last lubricant or fluid change
  - ➢ Hours since last filter change
  - ➢ Lubricant or fluid type, and addition since last sample
  - ➢ Person to be informed of the results of the analysis

Spectrometric oil analysis determines parts per million (ppm) of the pertinent elements. Reporting delays are typically one day plus post time with facilities to fax or electronically transfer data. The limit on the size of particle that spectrometric oil analysis will detect means that the technique will miss some large debris resulting from tooth breakage or the early stage of bearing damage.

The filter method is cheap to set up needing only an oven, a filter set, a debris tester and if analysis is required a binocular microscope. Sensitivity down to 5µm covers reasonable wear but the debris tester mainly detects ferrous material, being only slightly sensitive to non-ferrous materials and nonmetals. This method has proved to be widely effective.

The use of magnetic plug limits the size range and has no advantage over filtering except for on-line monitoring.

The ferrography system is most effective with ferrous debris but the tests are more expensive so the technique is not as widely applied as Spectrometric Oil Analysis or filtering.

There are a number of on-line systems, which appear to prove successful for use where the process is sufficiently critical to warrant the cost.

Transformer oil

The common modes of failure on transformers can be detected early on by monitoring the gases dissolved in the oil. The ratios of specific hydrocarbons created by overheating and arcing lead to diagnosis.

Common modes of failure are inter-turn shorts, overheating of the insulation, integral switchgear high resistance or arcing.

Table 16.7 gives guidelines for possible diagnosis in case of diesel engine, gearbox and hydraulic system based on common contaminants present. Some of the equipment manufacturers provide guidelines of the contaminants limits allowed for their equipment.

Table 16.7 : Common contaminants and possible diagnosis

Symptom	Diagnosis
Diesel Engine	
Silicon, iron, chromium, aluminium	Damage to the air filter, cracks or absence of clips on the air manifold system allowing the ingress of abrasive silicon dust and subsequent damage to the cylinder liner/piston/piston ring
Sodium, copper, lead	Coolant leak with damage to the main bearings or the ingress of salt through the air manifold
Chromium	Bore polishing and damage to the piston rings
Copper	Material leeching from the oil cooler
Copper and lead	Main bearing damage
High viscosity	Degradation of the lubricant through oxidation and nitration, or high soot loading, or incorrect lubricant top up
Low viscosity	Fuel dilution (low flash point) or incorrect lubricant
Low total base number	Lubricant degradation
Low total acid number	Lubricant degradation
High oxidation (infrared)	Lubricant degradation
High nitration (infrared)	Lubricant degradation
Gearbox	
Silicon, iron	Abrasive wear resulting from ingress of dust
Iron, chromium, nickel	Wear of bearing material (rolling element)
Low viscosity	Wrong lubricant
High viscosity	Lubricant degradation or wrong lubricant
Hydraulic system	
Silicon, iron	Abrasive wear resulting from ingress of dust
Increasing total acid number	Lubricant degradation
Low or high viscosity	Wrong lubricant

16.3.4 Vibration Monitoring

Vibration monitoring is based on the concept that provided the operating conditions have not been changed; an increase in vibration is an indication of an impending failure. The greater the increase in vibration level the greater is the deterioration. A machine vibrates when the frame, having mass and elasticity, is subjected to periodical forces. The forces may be produced by components attached directly to the frame; they may be developed by reaction forces or transmitted to the frame from rotor via the bearings. Forces transmitted the rotor may be centrifugal due to unbalance or they may be impulsive such as are caused by teeth meshing in a gear train or by fluid striking an impeller blade. Knowing the machine details (such as shaft speed, number of gear teeth, number of impeller blade, etc.), it is possible to calculate the frequency at which vibration will be produced by a particular component. By comparing a list of such frequencies with the frequencies at which an increased vibration is detected it is possible to identify the source of the increase.

Thus a vibration monitoring system should provide:

a) A measure of the increase in vibration level to indicate the urgency of the need for attention

b) A measure of the frequency at which the increase occurs to permit a diagnosis of the problem and

c) Phase shift in vibration is also a useful parameter in diagnosing machine problems

Table 16.8 : Identification of causes of vibration

Cause	Identification
Unbalance	Major component of the vibration is at shaft RPM
	Major component at 1× RPM usual 2&3 × RPM sometimes
Damaged rolling element bearing	Major components at ball/roller speeds
Oil Whirl	Major component at approximately half the shaft speed
Damaged or worn gears	Tooth meshing frequency predominates
Reciprocating forces	1st, 2nd & higher orders of shaft speed
Mechanical looseness	Major component at 2 × shaft speed
Bad belt drivers	1, 2, 3 & 4 × RPM of belts

Thus, vibration is a useful tool to detect the presence of mechanical trouble in its early stages of development. Different problems cause vibration in uniquely different ways. This is clearly shown in vibration identification Chart in Table 16.8. Close inspection of this chart reveals that the key to identifying each trouble is primarily the frequency at which the vibration occurs.

As vibrations are movements of the machine around a rest point, they may be quantified in terms of displacement, velocity or acceleration.

- Displacement is more sensitive to low frequency vibrations, and is best suited for measurements where clearance between parts is critical.
- Velocity gives the same relative size to low and high frequency and is more pronounced in intermediate ranges and is well suited for general condition monitoring measurements.
- Acceleration is more sensitive to high frequency vibrations and will thus be used for monitoring of vibrations where the frequency range of interest covers high frequencies.

The most accepted way to quantity the levels is to measure a time average of the square of the vibration as it varies (RMS value). Vibration levels are quantified in —

Displacement micron (μm)

Velocity mm/s

Acceleration m/s^2 or 'g'

For measuring velocity and acceleration values, a logarithmic scale is often used. In this scale vibration is given in "decibels" (dB).

Velocity (v dB) $= 20 \log_{10} (v_1/v_2)$

Where v_1 = measured velocity in linear units (mm/s)

v_2 = reference velocity (usually 10^{-5} mm/s)

Acceleration (a dB) $= 20 \log_{10} (a_1/a_2)$

Where a_1 = measured acceleration in linear units (m/s^2)

a_2 = reference acceleration (usually 10^{-2} m/s^2)

Functional elements of a vibration measuring instrument are as shown in Figure 16.3. The transducer element converts the vibratory signal to an electrical signal. There are several type of such transducers, which can be used, the choice of which depends on several factors. Piezoelectric type seismic vibration transducer is of self generating type and is most widely used. The output of this transducer is proportional to the acceleration of the vibrating object, to which the transducer is attached. Eddy current proximity type of vibration transducers are used for measuring shaft vibrations. The output of such transducers is proportional to displacement. The signal conditioning include amplifier or filters or differentiators, integrators etc, and convert the signal so that [illegible] displayed [illegible] the requirements.

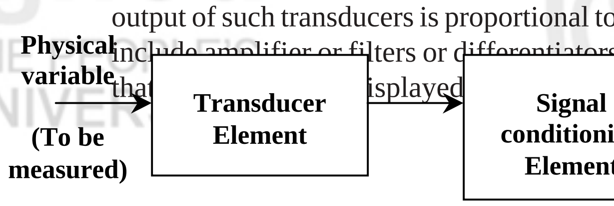

Figure 16.3 : Functional elements of a vibration measuring instrument

Piezoelectric accelerometers are rigidly attached to the vibrating surface by using a stud or by a magnet provided for that purpose. Vibration measurements are normally carried out in three directions i.e. vertical, horizontal and axial, and the transducers are normally mounted on the bearing housing. Proximity probes used for shaft vibration are fixed in bearing housing. Two proximity probes are mounted at right angle to each other to display the shaft orbit.

To check if there is a problem with the machine, the measured vibration levels are regularly compared with a reference level. National and international standards are available, which could be used as guidelines to start with (VDI 2056, BS 4675 and ISO 2372). Several standards exist for shaft displacement measurement. Some of such standards are VDI 2059, API specifications, Erskine's criterion etc. But it is always desirable that one develops his own guideline for reference level.

Vibration monitoring systems

Any of the following three types of the monitoring system can be used :

- Periodic manual monitoring
- Automatic surveillance and
- Continuous monitoring systems

The selection of appropriate monitoring system depends upon the cost of downtime and the criticality of the machine. When selecting a monitoring system it is essential to take into consideration the details of each individual machine to be monitored. The important factors influencing the selection are:

- Application of machine
- Continuous or intermittent operation
- Machine type
- Speed (driver and driven units)
- Type of drive
- Type of transmission
- Bearings and
- Machine operating environment

Periodic manual monitoring

This is the routine on-site manual measurement of machinery vibration levels, taken at set intervals. Its principal purpose is to detect and plot changes in those levels, which may indicate the onset of a problem. To ascertain the cause of an increase in the vibration level a vibration analyzer, measuring amplitude, frequency and phase, is used for diagnostic purpose. Figure 16.4 shows a manual monitoring system.

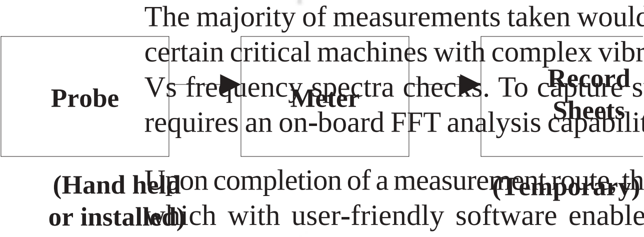

Figure 16.4 : Manual measurement recording and computer storage and analysis type off-line system

Periodic manual monitoring has now been automated through the development of the microprocessor based data collector. It is used in conjunction with a personal computer, suitable software and printer to generate hard copy reports.

The automatic data collector is portable, hand-held and battery operated. It is microprocessor controlled and programmed from the host computer. LCD display guides the operator through a measurement route indicating all the required information such as machine type, test point, measurement direction, units of measurement, alarm level and machine speed.

The majority of measurements taken would be overall vibration levels. However, certain critical machines with complex vibration signature can benefit from amplitude Vs frequency spectra checks. To capture such vibration spectra the data collector requires an on-board FFT analysis capability.

Upon completion of a measurement route, the data collector is off-loaded to the computer, which with user-friendly software enables the maintenance manager to generate a wide range of text and graphic reports. The advantages of such a system are :

- Periodic readings are taken in a controlled and disciplined manner
- Operator error is reduced to a minimum as there is no requirement for selecting the range and unit of measurement
- Manual transcription errors are eliminated
- Frequency spectra analysis offers considerable advantages compared to just trending overall vibration levels
- Automatic generation of alarm reports, trend graphs and machinery vibration signatures.

Figure: 16.4 Manual Measurement Recordi
Storage and Analysis Type Off-li

Figure 16.5 shows a manual measurement automatic recording, storage and analysis type off-line computerized system.

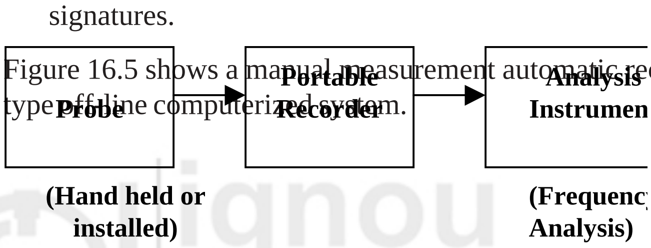

Figure 16.5 : Manual measurement automatic recording storage and analysis type off-line computerised system

Automatic surveillance

A typical system consists of an array of transducers permanently mounted on machinery wired to multiplexers and controlled by commercially available personal computers, which are programmed to automatically scan and collect both vibration and process data. The sensors are interrogated at pre-progammed intervals, simultaneously measuring displacement, velocity, acceleration, and spike energy from any one transducer.

When a problem area is identified, the system automatically increases its sampling rate until such time as the offending machine is corrected. In addition, spectra capture via FFT analysis can be automatically performed for detailed assessment of machinery faults. It being an on-line, system operating personnel can see all dynamic data at a glance.

Unlike continuous monitoring system, where a signal conditioning card is required for each channel of measurement, in this system only one signal conditioning card per measured vibration parameter is needed, which can be applied to as many as sixty channels. It is very cost effective option for protecting a large number of strategic rotating machines. Figure 16.6 shows an on-line computer based condition monitoring system.

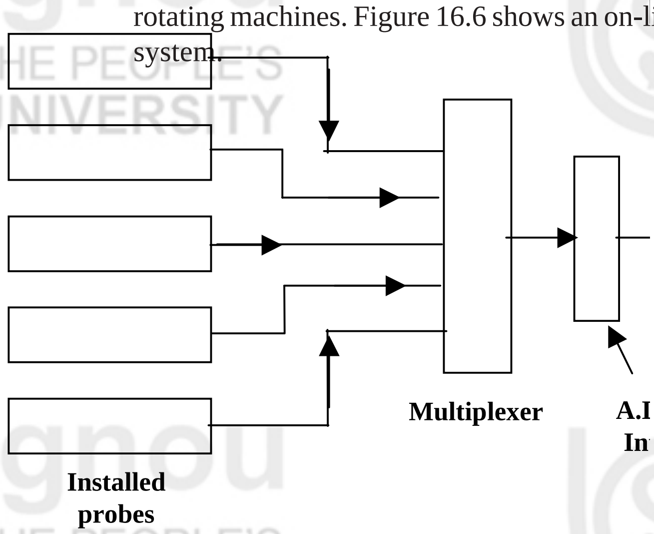

Figure 16.6 : On-line computer based condition monitoring system

Continuous monitoring

Continuous monitoring is intended for the on-line continuous protection of critical machinery. It incorporates all the key features of periodic manual monitoring and automatic surveillance in one self-contained unit. Transducers are hard-wired to a microprocessor based plant information center, which is located in the process control room or near to a high concentration of machines in the plant.

It provides the operator with comprehensive machine and plant performance data and enables engineers to make objective maintenance decisions based on historical machinery trends. A plant information center continuously monitors vibration amplitude, axial position, temperature, thrust, speed, bearing /gear condition, together with inputs from virtually any other process parameter that requires monitoring.

The visual display unit can simultaneously present upto 30 channels of information with a vertical bar showing as a percent of the alarm set point. In the event of an alarm an FFT spectrum analysis automatically captures the vibration spectrum so that it can be compared with stored baseline signatures to identify a particular machinery problem. Alarm events and operator acknowledgements are automatically stored for retrieval purposes at a latter date. To assist in evaluating a machine's condition, various maintenance reports are possible. These include long-range trend reports based on 52 weekly averages, fourteen-day, 24 hours or even one minute trends. It gives the added protection of continuous monitoring with automatic warning and machine shutdown facilities. The [illegible] of a typical on-line computer based system is shown in Figure16.7.

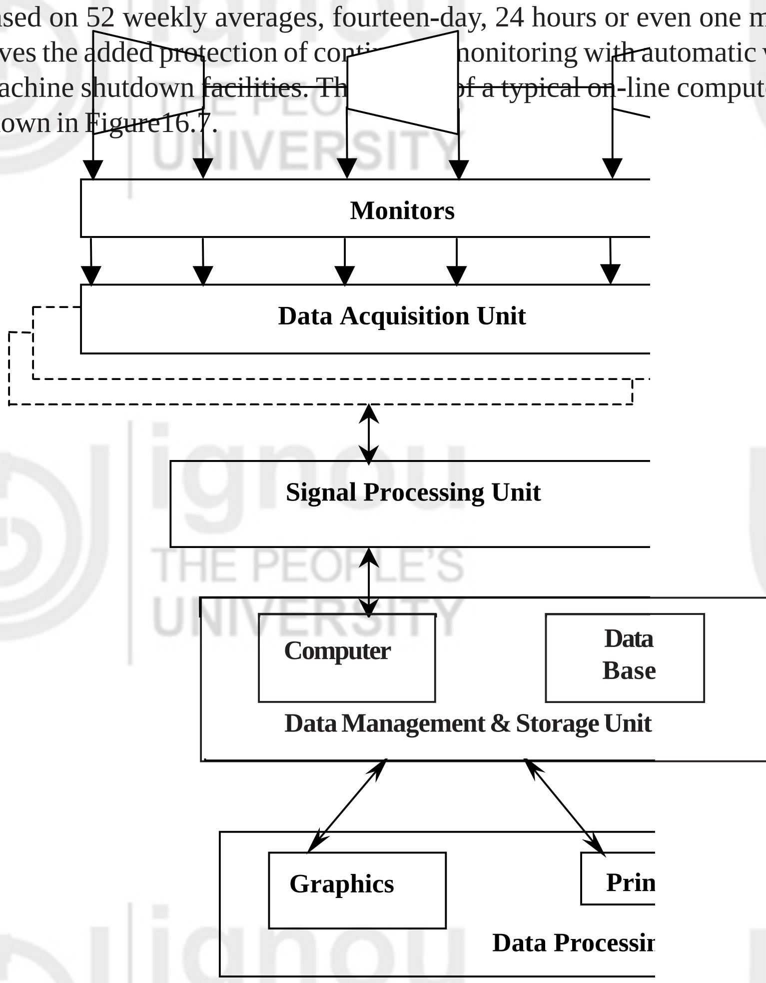

Figure 16.7 : Computerised machinery monitoring system

Due to complexities of integrated process plants most situations will require a combination of periodic manual monitoring, automatic surveillance and continuous monitoring systems. These can be integrated to provide the maintenance manager with comprehensive machine and process information at a single data terminal.

Shock pulse measurement

Shock pulse measurement is a special method assigned to condition monitoring of roller bearings. The most common type of failure is fatigue break up in the races or rollers of the bearings. When the rollers are passing these spalled areas, high frequency vibration pulses are transmitted through the bearing. The shock pulse meter picks up these transients through a piezoelectric accelerometer detecting vibration at its own resonance frequency, 32 kHz. At this high frequency, the normal machinery vibrations will usually not affect the measurements. Therefore the method is rather sensitive to the bearing condition.

A further development of the shock pulse meter is an instrument called Bearing analyzer. In addition to the wear condition of the bearing this instrument also gives what they call a lubrication number. According to the handbook, this is directly correlated to the lubrication film thickness in the bearing.

One disadvantage with the instrument is that it requires knowledge of the bearing design as well as parameters such as rpm and shaft diameter.

16.3.5 Performance Monitoring

Most machines, which are involved in industrial production have as their main function the transportation or transformation of energy or materials. The monitoring of their performance usually involves measurement of their output or sometimes relationships between their input and output.

The performance of a plant unit is a useful measure of its condition, for prognosis and need for maintenance action. The variety of units and their functions means that performance monitoring techniques are limited only by the innovation of condition monitoring engineers.

Performance monitoring of process units such as pumps, fans, boilers, heat exchangers, filters is readily carried out using information necessary for process control. It is often appropriate to use independent sensors since the monitoring may be covering the operation of the control sensors as well as the controlled unit. Typical examples are:

Filters	differential pressure rise
Fan	pressure, flow and power decrease
Fluid system blockage	pressure increase, flow and power decrease
Fluid system leak	pressure decrease, flow and power increase

Manufacturing performance or quality monitoring is appropriate where a product is made to defined tolerances. The quality control information should be used directly for condition monitoring. This may be in the form of proportion of non-conformance or of the actual value of the quality controlled variable, known as the 'characteristic'.

Statistical process control is a widely applied approach to quality control. The component is measure or otherwise checked for compliance with the specification. Usually a sample of 5 in 100 is checked and the characteristic, as the 'mean', plus its spread, in the form of 'range' or 'standard deviation', are calculated and trend plotted on 'control charts'. These charts are assessed for deviation, trend towards deviation, scatter and offset with respect to limits set by statistical criteria similar to those used in condition monitoring. 'Mean characteristic' and 'standard deviation of the characteristic' are appropriate for use in condition monitoring.
Typical characteristics are:

Dimension	bore diameter
Ovality	journal
Concentricity	spindle

Surface roughness	bearing
Composition	steel billet
Color	paint finish

Activity C

Identify the condition monitoring techniques being used in your plant. Also find out the warning limits for the monitoring parameters.

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16.4 BENEFITS OF CONDITION BASED MAINTENANCE

Benefits of condition based maintenance program are as follows:

a. It reduces catastrophic machine failures. Damage caused because of catastrophic failures is usually much more intensive.

b. It minimizes the repair time and helps in reducing the costly downtime. Regular monitoring and analysis of machine condition helps in identifying defective component(s) and plan for the maintenance work.

c. It helps in reducing the maintenance cost.

d. It reduces spare parts inventories. Many spare parts could be purchased just in time for the repairs to be made during scheduled machinery shutdowns.

e. Under this program machinery performance is optimized, as machinery always operates under specified conditions.

f. Its application saves energy requirements, as the machinery is always allowed to operate under optimal operating conditions.

g. Application of CBM reduces the need for standby equipment or additional floor space to cover excessive downtime. Thus capital investment on equipment or plant is less.

h. Prevention of catastrophic failures and early detection of incipient machine and systems problems increases the useful operating life of the plant machinery.

i. Maintaining optimal machine performance level helps in producing quality product.

j. It reduces overtime requirement to makeup for lost production due to break-downs or poorly performing machines.

k. It helps in reducing penalties that may result because of late deliveries caused because of breakdowns or poorly performing machines.

l. It helps in reducing warranty claims caused due to poor product quality caused because of poorly performing machines.

m. Predictive maintenance techniques help in verification of new equipment condition before acceptance. Vendor could be asked to correct the deficiencies before the final payment is released.

n. Regular monitoring of machinery helps in reducing destructive failures, which could cause personal injury or death. Increased safety helps in reduction in penalties levied against a company for unsafe machinery.

o. Increased safety helps in reduction in insurance premiums for the plants.

p. Predictive maintenance techniques help in determining whether or not repairs on existing plant machinery have corrected the identified problems. This eliminates the need for second outage that many times is required to correct improper or incomplete repairs.

q. The understanding of the operation and condition of the plant is improved, resulting in more respect for maintenance work force from the rest of the plant workers. Thus helps in improving maintenance workforce self esteem and motivation.

r. It helps in achieving reduced life cycle costs.

Activity D

Find out in what ways condition based maintenance has helped in improving the overall maintenance of your plant?

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16.5 ECONOMICS OF CONDITION BASED MAINTENANCE

When a condition based maintenance system is used in a plant, the benefits obtained from avoided costs are offset by the investment costs. A real benefit arises when the avoided cost savings exceed the investment.

CBM Initial Cost Benefit = Avoided Costs – CBM Investment

Where

Avoided Costs = Scheduled Maintenance reduction + In-service Repair reduction

And

Investment Costs = Equipment Capital and Installation Costs + Training and Operational Costs

In 1988 a survey of 500 plants that have successfully implemented condition-based maintenance was conducted by Technology for Energy Corporation to identify the impact of condition-based maintenance on the economic operation of process and manufacturing industry. The industries included electric power generation, pulp and paper, food processing, textiles, iron and steel, aluminium and other manufacturing or process industries. Each of the participants had an established condition-based maintenance program with a minimum of three years of program implementation. Benefits of the comprehensive predictive maintenance program were found to be as follows:

- Maintenance costs reduced by 50-80 %
- Machine break-down reduced by 50-60 %
- Spare parts inventory reduced by 20-30%
- Machine downtime reduced by 50-80 %
- Overtime payments reduced by 20-50%

- Machine life increased by 20-40%
- Productivity increased by 20-30%
- Profits increased by 25-60%

In addition, the survey indicated dramatic improvements in machine life, production, operator safety, product quality, and overall profitability. As a general guide for a typical industrial plant a reasonable level of initial investment in condition monitoring is about 1 % of the total capital value of the plant, which is being monitored. In case the plant has some special safety requirement, an initial investment of the order of 5 % of the total capital value is likely to be more appropriate. The setting up expenditure is likely to consist of 40 % on equipment and 60 % on training and experience acquisition.

Activity E

From your finance department find out the capital value of your plant, cost of condition monitoring equipments being used in plant and the cost incurred for training the man power on condition monitoring systems.

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16.6 SUMMARY

Condition based maintenance in a valuable addition to a comprehensive, total plant maintenance programme. Under this programme the equipment is maintenance when measurements indicate an incipient failure. The condition of machine is determined continuously or at regular intervals by visual, temperature, wear debris, vibration and performance monitoring. Implementing condition-based maintenance involves identification of plant machines, selection of critical machines, selection of monitoring techniques, setting up of a systematic monitoring program, setting up of an information and data recording system, training of manpower and setting up of appropriate maintenance schedule. Application of condition-based maintenance is recommended if the benefits obtained from avoided costs by its implementation are able to offset the investment costs required to implement it. As a general guide for a typical industrial plant a reasonable level of initial investment in condition monitoring is about 1% of the total capital value of the plant, which is being monitored. In case the plant has some special safety requirement, an initial investment of the order of 5% of the total value is likely to be more appropriate.

16.7 KEY WORDS

Condition Monitoring: The continuous or periodic measurement and interpretation of data to indicate the condition of a machine to determine the need of maintenance.

Oil Analysis: Two techniques are there; one is the analysis of the actual lubricant for its condition; other is the analysis of the wear particles in the lubricating oil to determine what part of the machine is wearing.

Predictive Maintenance: An advanced preventive maintenance technique based on monitoring methods to determine the condition of the machine.

Thermography: The use of infrared technologies to measure temperature differentials.

Vibration Analysis: A predictive maintenance technique focusing on vibration of rotating equipment to discover and then monitor the defects of the machine components, allowing maintenance activities to be planned before a break-down takes place.

Wear Particle Analysis: A type of lubricant analysis that examines suspended wear particles in the lubricant; allows wear to be identified and corrected before a failure occurs.

16.8 SELF ASSESSMENT QUESTIONS

1. What is condition based maintenance?
2. What conditions should be satisfied so that condition based maintenance programme could be implemented?
3. What are the key steps involved in implementing condition based maintenance in any plant?
4. Explain condition-monitoring procedure with the help of a flow diagram?
5. What guidelines would you suggest for selecting critical machines for condition monitoring purpose?
6. How will you select condition-monitoring technique once a critical machine has been identified?
7. What is significant component?
8. What are the attributes of an ideal condition monitoring technique?
9. How will you fix severity limits for a particular monitoring parameter?
10. What should be the basis for fixing the periodicity of monitoring?
11. What should be the requirements for an ideal diagnostic-instrument operator?
12. What type of skill development courses will be more helpful for maintenance personnel for successful implementation of condition monitoring in any plant?
13. Why it is necessary to have planned maintenance management system in any plant for successfully implementing condition based maintenance?
14. Explain the basis of identifying and analyzing a problem, while making use of visual monitoring technique? Name some of the instruments used in visual monitoring?
15. Explain the basis of identifying and analyzing a problem, while making use of temperature monitoring technique? Name some of instruments used for temperature monitoring?
16. Explain the basis of identifying and analyzing a problem, while making use of wear debris monitoring technique? Name some of the instruments used for wear debris monitoring?
17. Explain the basis of identifying and analyzing a problem, while making use of vibration monitoring technique? Name some of the instruments used for vibration monitoring?
18. Explain the basis of identifying and analyzing a problem, while making use of performance monitoring?
19. What are the methods used for lube oil sampling? What precautions should be taken while taking a sample?
20. What parameters are used for machine vibration monitoring? Also identify the conditions under which you will recommend their use for machine condition monitoring?

21. What linear and logarithmic units are used for measuring vibration monitoring parameter?

22. What benefits are obtained by implementing a condition based maintenance system in any plant?

23. What investment guidelines you will recommend for setting up of a condition monitoring programme in a typical industrial plant?

16.9 BIBLIOGRAPHY AND SUGGESTED READINGS

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2. Rao B. K. N. (Editor), " *Handbook of Condition Monitoring*", Elsevier Science Ltd, 1996.

3. Davies A. (Editor), " *Handbook of Condition Monitoring —Techniques and Methodology*" Chapman & Hall, 1998.

4. Neale M. and Associates, " *A Guide to the Condition Monitoring of Machinery*", London Her Majesty's Stationary Office, 1979.

5. Wilso A., "*Asset Maintenance Management- A Guide to Developing Strategy & Improving Performance*", Industrial Press Inc. New York, 2002.

6. Nakra, B.C., Yadava, G. S. and Thuestad L., "*Vibration Measurement & Analysis*", National Productivity Council, 1989.

4. **Methodology of Maintenance Audit**

   i. Explain the steps involved in a 'Maintenance Audit'?

   ii. What preliminary preparations are required before a maintenance audit can be commenced?

   iii. How can be questionnaire for 'Maintenance Audit' prepared?

   iv. What difference lies in the plant visits taken up at the auditee's plant and a comparable plant?

   v. Describe the salient features to be covered in a maintenance audit report?

5. **Study of Key Result Areas**

   i. What are the key result areas that can be covered in a maintenance audit?

   ii. Give some indices for Maintenance Materials Management Performance?

   iii. What is the main difference of auditing result areas compared to auditing management processes?

   iv. What are the various maintenance management sub-processes and how an audit studies these processes?

19.10 ANNEXURE

Sample Maintenance Audit Questionnaire

1. Does a documented Maintenance Policy exist? (If yes, please attach a copy of it)
2. Where does the Maintenance policy find a place
   - Number of places in the plant
   - Only in selected company publications
   - Others (Pl. Specify)
3. What are the objectives of the maintenance function and what is the process of monitoring the realization of this objective within a time frame.
4. Give organization structure of the Unit and indicate how the various departments including Operations are linked with Maintenance Dept.?
5. Give the Organogram of the total maintenance department including electrical, Mechanical, Instrumentation, civil etc.
6. Give a diagrammatic sketch of the overall maintenance system. (Pl. use separate sheet)
7. List down all the sections and give the list of major equipments in each section.
8. Has criticality analysis been carried out and what is the scheme of classifying the equipment?
9. What is the key Maintenance Indices/parameters being calculated by the plant? Specify including their values for the past three years (1995-98).
10. Data required on other Maintenance indices:
    - Maintenance Cost
    - Plant Availability (%) - (section-wise) and Utilization
    - Maintenance overtime hours as a % of normal working hours section-wise for last three years
    - Value of consumables and spares consumed year wise for last 5 years
    - Maintenance man-hours per ton of Clinker and Cement
    - Ratio of value of maintenance spares/materials to the value of plant and machinery.

- Ratio of Contract Maintenance Cost to the Total maintenance cost

11. Indicate the various maintenance documentation existing in the plant:

    - Total no. of machines and availability of O & M Manual for these machines.
    - Erection & Commissioning Drawings
    - Work Order System
        - Preventive Maintenance
        - Breakdown Maintenance
        - Major overhauls
        - Condition Monitoring
    - Planning & Scheduling charts (Including PERT charts for major overhauls)

    (Enclose filled-in formats of the above)

12. Is there a centralized maintenance-planning cell? If so, what are its functions?

13. How are the maintenance activities scheduled including scheduling of Manpower, Materials, other resources etc?

14. Whether standard maintenance jobs have been identified (machine wise, section-wise) and the time/other resources (tools/instruments/procedures) have been identified?

15. What is the system for following up pending maintenance activities and their related maintenance documents for the same?

16. Are History Cards maintained machine-wise/section-wise?

17. Give details of summary information (frequency and cost) from the history cards the various natures of failures for the past three years?

18. Give details of repair time machine-wise/section-wise for major failures.

19. Whether the maintenance function has been computerized. Pl. give the following details

    1. On what platform. (Operating System/Front-End Tools etc.)
    2. Network/Stand alone
    3. Number of Users and User ID.
    4. Various reports and queries generated (Pl. attach samples).

20. Whether the Spare parts/maintenance materials management has been computerized. Pl. give the following details

    1. On what platform. (Operating System)
    2. Network/Stand alone
    3. Number of Users and User ID.
    4. Various reports and queries generated (Pl. attach samples).

21. How the maintenance management system is linked with the spare parts management system. (Provide samples of filled-in documents)

22. How many occasions have plant been shut down due to non-availability of spares and what is the average length of times the plant was down.

23. How is the spares procurement done?

- Vendors Selection and Evaluation
- Quality check
- Specifications for spares
- Preservation and Care

24. How many training programmes are organized for the

	General Programme		Specific Programme	
1 Maintenance Executives	External	Internal	External	Internal
2 Supervisory Staff/Foreman				
3 Mechanics/Fitter/Electrician				
4 Workmen				

25. Provide the list of training programmes organized in last 3 years (category wise, section wise, skill wise, duration, course coverage)
26. Whether training need assessment is carried out and give details
27. Does the training for shop floor personnel include hands-on skill training
28. Educational qualification of maintenance technicians/workers (Please give break up)
29. How is shut down maintenance/overhaul planned?
30. Do you follow project management techniques such as PERT/CPM etc., and use computerized project management software? If yes, whether it is linked with the maintenance system.
31. Provide PERT charts/Bar charts for major shutdown maintenance/overhauls over the last 3 years.
32. What is the percentage of contract man-hours to the normal man-hours?
33. Give a brief write-up on the TPM practices adopted.