COURSE CODE: *MCE 509*

COURSE TITLE: *Mechanical Maintenance*

NUMBER OF UNITS: 2 *Units*

COURSE DURATION: *Two hours per week*

COURSE DETAILS:

Course Coordinator: **Dr Salami Olasunkanmi ISMAILA** *ND, BSc, MSc, PhD*
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Office Location: **Room 1, PG Building.**
Other Lecturers: **None**

COURSE CONTENT:

Machine inspection, rate of wear and replacement time prediction. Basic technologies and equipment for repairs of internal combustion engines, pumps and small output power generating plants, machine tools, vehicles, earth-moving equipment and lifting devices. Special techniques in machine repairs. Planning and organization of service and maintenance shops. Planning of the spares stock and related problems.

COURSE REQUIREMENTS:

This a compulsory course for all students in the Department of Mechanical Engineering. Students are expected to participate in all course activities and have minimum of 75% attendance to be able to write the final examination.

READING LIST:

1. Adejuyigbe, S.B. (2002). *Production Management (Design, Planning, Implementation and Control)* Topfun Publications, Akure, Nigeria

2. Krishnamoorthi, K.S. (1992) Reliability Methods for Engineers, *ASQ Quality Press*, Milwaukee, WI.

3. National Aeronautical and Space Administration (NASA). Reliability Centered *Maintenance Guide for Facilities and Collateral Equipment*. National Aeronautics and Space Administration, Washington, D.C. February 2000.

4. Okah-Avae B. E. (1996). *The Science of Industrial Machinery & Systems Maintenance*. Spectrum Books Ltd. Sunshine House, Emmanuel Alayande Street, Oluyole Industrial Estate, Ibadan, Nigeria.

LECTURE NOTES

1.0 INTRODUCTION

The primary aim of any establishment should be to manufacture and sell a product or number of products in order to satisfy a demand. However, most establishments usually state their primary objectives as:

(i) make profit (ii) maximize profit (iii) satisfy a social need/ employ labour (iv) provide useful commodity.

These enumerated objectives should be secondary as if a company can sufficiently identified a market and sufficiently serviced it, all other objectives shall be met.

To achieve the primary objective of satisfying a demand, it is very important that products are produced in the right quantity, quality, at the right time and right cost. For these requirements to be met, goods must be made in the most efficient and economic manner. The machines and equipment must operate efficiently and effectively at the required level of production. There must be very few or no stoppages on production lines which require effective planning, scheduling and good administration of maintenance activities.

Maintenance requirements have an impact on production scheduling and other functions performed by the production control department. Time lost due to maintenance may interfere with schedules from the production department. Therefore, maintenance requirements should be considered in choosing machines or equipment for replacement or increasing the capacity of installed machines and equipment.

The maintenance department in any organization is saddled with the responsibility of the maintenance of facilities, equipment, and machines.

1.1 DEFINITION OF MAINTENANCE

Maintenance is any activity that is carried out on any facility either to restore to or to retain the facility in a good and acceptable working conditions. Maintenance involves all technical and other procedures performed in order to retain the satisfactory working condition of a machine or part or restoring it to an acceptable working condition so that the set tasks can be performed at the scheduled time and under given conditions.

Maintenance is often not given the priority it deserves in the overall operating strategy of a facility. Maintenance programs are managed and funded by people, and human nature seems to abide by the old tenet, "If it isn't broke, don't fix it." Compared to other departments, maintenance departments have no real "product" and - as such - produce no real income. Many managers view money spent on maintenance as money thrown down a black hole. In spite of any life-cycle "proofs" to the contrary, managers look for ways to cut maintenance budgets first when any other need arises.

Adejuyigbe (2002) stated that the maintenance functions stem at supporting role to keep equipment;

(i) To be able to operate effectively;

(ii) To maintain quality standard at all times;

(iii)To maintain the quantitative and cost standards of output.

He enumerated the objectives of plant maintenance to include the following;

- To achieve minimum breakdown and to keep the plant in good working condition at the lowest possible cost;
- To keep the machines and other facilities in operational level, and used act optimum (profit making) capacity.
- To ensure the availability of the machines; buildings and services required by other section, buildings and services required by other section of the factory for efficient performance. The most important responsibility of plant engineering is that of maintaining the plant facilities and equipment. It is only when the equipment is adequately maintained that it can be expected to operate and perform properly, and thereby yielding a high quality product at a reasonable cost.

1.2 NEED FOR MAINTENANCE

One of the factors that can ensure availability of installed facilities for efficient use is an effective and efficient maintenance engineering system. Gone were the days when maintenance was not given adequate attention. For any company with mechanized and automated systems, more attention is now given to maintenance function. Therefore, the need for maintenance increases with technological advancement in production facilities. Other factors which seem to emphasize the need for effective maintenance system are:

(i) strong competition (ii) tight production schedules (iii) increased machine utilization

(iv) increased production level

Inadequate or lack of effective and efficient maintenance system especially in a manufacturing enterprise gives rise to several undesirable consequences. These consequences include:

(i) Excessive machine breakdown

(ii) Frequent emergency maintenance work

(iii) Shortened life-span of the facility

(iv) Poor use of maintenance staff

(v) Loss in production output

(vi) Inability to meet delivery dates

(vii) Excessive overtime

(viii) Loss of lives

These factors may contribute to high costs of production and consequently loss in profitability.

1.3 FUNCTIONS OF MAINTENANCE ENGINEERING

The function of maintenance engineering can be divided into primary and secondary:

The primary functions of maintenance are:

(i) Maintenance of existing machines and equipment

(ii) Maintenance of existing buildings

(iii) Inspection and lubrication of machine and equipment

(iv) Generation and distribution of utilities e.g. water, electricity etc.

(v) Installation of new machines and equipment

(vi) Modifications of existing machines, equipment and buildings

The secondary functions include the following:

(i) Sanitation (ii) Disposal of used items (iii) Storekeeping (iv) Fire protection

(v) Janitorial service

1.4 TEROTECHNOLOGY

Terotechnology is a word derived from the Greek root word "tero" or "I care," that is now used with the term "technology" to refer to the study of the costs associated with an asset throughout its life cycle - from acquisition to disposal. The goals of this approach are to reduce the different costs incurred at the various stages of the asset's life and to develop methods that will help extend the asset's life span.

Terotechnology uses tools such as net present value, internal rate of return and discounted cash flow in an attempt to minimize the costs associated with the asset in the future. These costs can include engineering, maintenance, wages payable to operate the equipment, operating costs and even disposal costs. Also known as "life-cycle costing." Terotechnology is multidisciplinary approach to obtaining maximum economic benefit from physical assets. Developed in the UK in the early 1970s, it involves systematic application of engineering, financial, and management expertise in the assessment of the lifecycle impact of an acquisition (buildings, equipment, machines, plants, structures) on the revenues and expenses of the acquiring organization. Practice of terotechnology is a continuous cycle that begins with the design and selection of the required item, follows through with its installation, commissioning, operation, and maintenance until the item's removal and disposal and then restarts with its replacement.

The activities of the maintenance department cannot be totally described by the term ‘maintenance’. In order to describe vividly the functions of the maintenance department, the word ‘Terotechnology’ was coined.

The practise of terotechnology is concerned with the specification and design for reliability and maintainability of plant, machinery, equipment, buildings and structures together with their installation, commissioning, maintenance, modification, and replacement, and with feedback of information on design, performance, and costs.

Terotechnology's division is the operations team that caries out the daily operations of Facilities Management Services which optimize assets with professional Facilities Management and Operation & Maintenance (O&M) Services for Mechanical & Electrical (M & E) Systems, Civil Works, Landscape, Janitorial and other facility specialization. Rather than bearing addition business burdens, a 'single point responsibility' through direct maintenance, subcontract & vendor management will save time, money and effort.

2.0 TYPES OF MAINTENANCE

2.1 Breakdown Maintenance:

Breakdown maintenance is referred to by many different names: reactive maintenance, repair, fix-when-fail, and run-to-failure (RTF) maintenance. When applying this maintenance strategy, a piece of equipment receives maintenance (e.g., repair or replacement) only when the deterioration of the equipment’s condition causes a functional failure. The strategy of breakdown maintenance assumes that failure is equally likely to occur in any part, component, or system. Thus, this assumption precludes identifying a specific group of repair parts as being more necessary or desirable than others. The major downside of breakdown maintenance is unexpected and unscheduled equipment downtime. If a piece of equipment fails and repair parts are not available, delays occur while the parts are ordered and delivered. If these parts are urgently required, a premium for expedited delivery must be paid. If the failed part is no longer manufactured or stocked, more drastic and expensive actions are required to restore equipment function. Cannibalization of like equipment or rapid prototyping technology may satisfy a temporary need but at substantial cost. Also, there is no ability to influence when failures occur because no (or minimal) action is taken to control or prevent them. When this is the sole type of maintenance practiced, both labour and materials are used inefficiently.

Labour resources are thrown at whatever breakdown is most pressing. In the event that several breakdowns occur simultaneously, it is necessary to practice a kind of maintenance in an attempt to bring all the breakdowns under control. Maintenance labour is used to "stabilize" (but not necessarily fix) the most urgent repair situation, then it is moved on to the next most urgent situation, etc. Replacement parts must be constantly stocked at high levels, since their use cannot be anticipated. This incurs high carrying charges and is not an efficient ay to run a storeroom. A purely reactive maintenance program ignores the many opportunities to influence equipment survivability.

2.2 Preventive Maintenance (PM):

Maintenance repairs performed on a regular schedule to minimize component degradation and extend the life of equipment. Preventive maintenance is performed after a set amount of elapsed calendar time or machine run time, regardless of whether the repair is needed. While more cost-effective than reactive maintenance, preventive maintenance still requires substantial human resources and replacement parts inventories.

It may be a daily maintenance (cleaning, inspection, oiling and re-tightening), designed to retain the healthy condition of equipment and prevent failure through the prevention of deterioration, periodic inspection or equipment condition diagnosis, to measure deterioration. It entails understanding and maintaining all the physical elements of manufacturing-machine components, equipment, and systems- so that they consistently perform at all levels required of them. Such maintenance is usually scheduled by providing for monitoring inspections and special operating procedures.

The intent of PM is to "prevent" maintenance problems or failures before they take place by following routine and comprehensive maintenance procedures. The goal is to achieve fewer, shorter, and more predictable outages.

<u>Advantages of PM</u>

1. It is predictable, making budgeting, planning, and resource levelling possible.
2. When properly practiced, it generally prevents most major problems, thus reducing forced outages, "reactive maintenance," and maintenance costs in general.
3. It assures managers that equipment is being maintained.
4. It is easily understood and justified.

Disadvantages of PM

1. It is time consuming and resource intensive.

2. It does not consider actual equipment condition when scheduling or performing the maintenance.

3. It can cause problems in equipment in addition to solving them (e.g. damaging seals, stripping threads).

It is further divided into periodic maintenance and predictive maintenance. Just like human life is extended by preventive medicine, the equipment service life can be prolonged by doing preventive maintenance.

a. Periodic Maintenance (Time based maintenance - TBM):

Time based maintenance consists of periodically inspecting, servicing and cleaning equipment and replacing parts to prevent sudden failure and process problems.

b. Predictive Maintenance:

This is a method in which the service life of important part is predicted based on inspection or diagnosis, in order to use the parts to the limit of their service life. Compared to periodic maintenance, predictive maintenance is condition-based maintenance. Predictive maintenance programs measure equipment on a regular basis, track the measurements over time, and take corrective action when measurements are about to go outside the equipment operating limits. Repairing equipment as-needed requires fewer man-hours and parts than preventive maintenance. However, tracking the measurements requires new tools, training, and software to collect and analyze the data and predict repair cycles. It manages trend values, by measuring and analyzing data about deterioration and employs a surveillance system, designed to monitor conditions through an on-line system.

2.3 Corrective Maintenance:

It improves equipment and its components so that preventive maintenance can be carried out reliably. Equipment with design weakness must be redesigned to improve reliability or improving maintainability.

2.4 Condition Based Maintenance

The condition of the equipment or some critical parts of the equipment are continuously monitored using sophisticated monitoring instruments so that failure may be predicted well before it occurs and corrective steps are taken to prevent failure.

2.5 Design Out Maintenance

A design out maintenance is a design oriented curative means aimed at rectifying a design defect originated from improper method of installation or poor choice of materials etc. It calls for strong design and maintenance interface. Design out maintenance aims to eliminate the cause of maintenance.

2.6 Opportunistic Maintenance

When equipment is taken down for maintenance of one of few worn out parts, the opportunity can be utilized to change or maintain other parts which are wearing out even though they have yet to fail. This maintenance strategy is for non-monitored components.

2.7. Proactive Maintenance

Unlike the three type of maintenance, strategies, which have been discussed earlier, proactive maintenance, can be considered as a new approach to maintenance strategy. Dissimilar to preventive maintenance that based on time intervals or predictive maintenance that based on condition monitoring, proactive maintenance concentrate on the monitoring and correction of root causes to equipment failures. The proactive maintenance strategy is also designed to extend the useful age of the equipment to reach the wear-out stage by adaptation a high mastery level of operating precision.

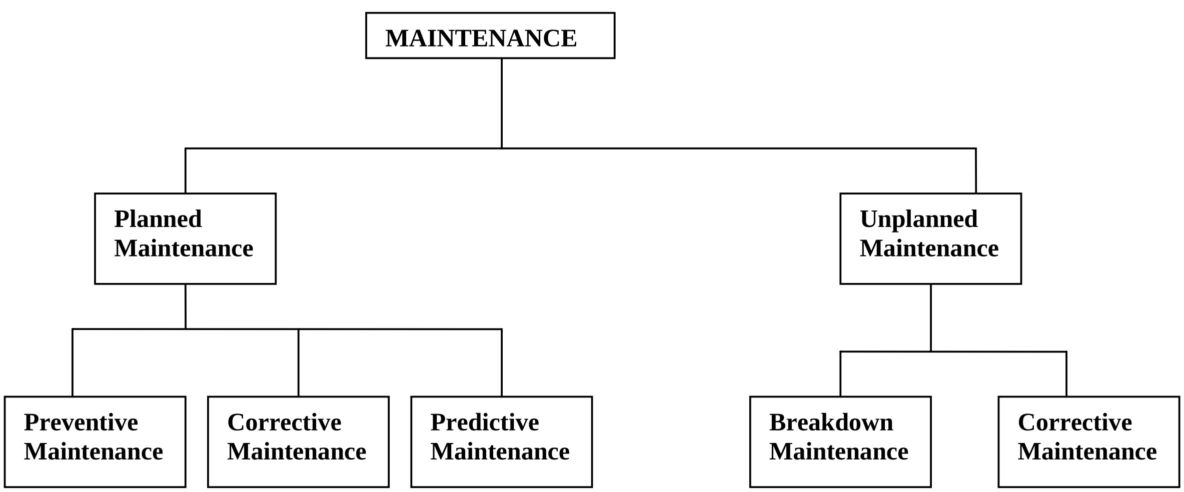


Figure 1: Diagrammatic representation of Types of Maintenance

2.7 Reliability Centred Maintenance (RCM)

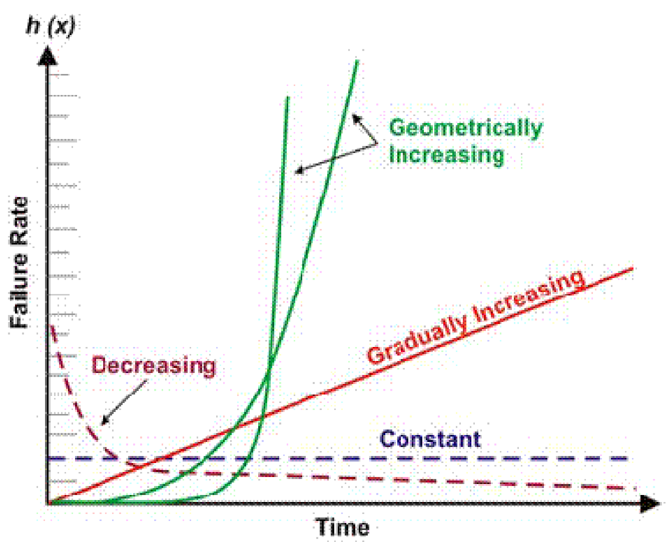
Recently, reliability centered maintenance has been defined as “an approach to maintenance that combines reactive, preventive, predictive, and proactive maintenance practices and strategies to maximize the life that a piece of equipment functions in the required manner.” RCM is an approach that tried to create an optimum mixture of an intuitive approach and a rigorous statistical approach to deciding how to maintain facility equipment.

3.0 FAILURE RATE AND RELIABILITY

3.1 Failure Rate

Failure is any event that adversely affects system criteria. For example, the criteria could include output in a sold-out condition, or maintenance cost or capital resources in a constrained budget cycle, environmental excursions or safety, etc.

Failure rate is the **time rate of change of the probability of failure**. Since the latter is a function of time, failure rate is also a function of time. However, in terms of failure rate, one can obtain physical information as to which factor is controlling the failure behaviour and/or when it is controlling the failure behaviour. The failure rate is a basic component of many more complex reliability calculations. Depending upon the mechanical/electrical design, operating context, environment and/or maintenance effectiveness, a machine’s failure rate as a function of time may decline, remain constant, increase linearly or increase geometrically (Figure 2)



Depending upon machine type, the failure rate may decrease, remain constant, gradually increase or geometrically increase as a function of time

Figure 2: Failure Patterns of Machinery in relation with time

Example 1: A TV producer tested 1000 units in an accelerated reliability evaluation program. In that program, each unit is turned on-and-off 16 times each day to mimic a typical TV usage for a week.
Based on a failure-to-perform criterion, failure data are obtained for the first 10 days of test:

day-1	day-2	day-3	day-4	day-5	day-6	day-7	day-8	day-9	day-10
18	12	10	7	6	5	4	3	0	1

The **failure rate** is defined as the "**probability of failure per day**," denoted by λ_i, i=1, 10:

For the first day (i=1): λ (1) =18/1000/day;

For the second day (i=2): λ (2) =12/ (1000-18) =12/982/ day.

For the third day (i=3): λ (3) = 13/ (1000-18-12) = 13/970/day.

Note that the failure rate for day-1 is based on a total of 1000 TV sets, in which 18 failed during the day; the failure rate for day-2 is based on a total of (1000-18) sets; and for day-3, a total of (1000-18-12) sets; etc. In this way, we can obtain λ (t) up to t=10 days. Clearly, for this procedure to yield reliable λ (t), the number of the TV sets tested each day must be large relative to the number of failures in that day. However, we also note that the time required in gathering the data is only 10-days, a relatively short time period compared to what might be needed to generate a set of time-to-failure data {t_i, i=1,N).

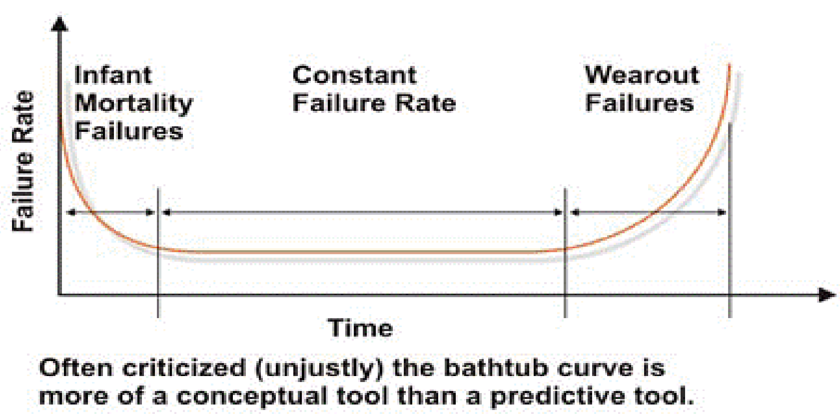


Figure 3: Profile of Equipment Failure (Bath Tub Curve)

Failures do not generally occur at a uniform rate, but follow a distribution in time commonly described as a "bathtub curve." The life of a device can be divided into three regions:

(i) *Infant Mortality Period*: This period is that of 'running in', where the failure rate progressively improves. The failure rate is generally high but short before decreasing due to design or manufacturing errors, defective parts, defects in materials, misuse, misapplication, out of manufacturing tolerance. Failure at this period can be avoided by subjecting the product to specified period of simulated tests, in hope that most early failures are weeded out, vigorous tests during commissioning, design improvement, stricter material selection, tightened quality control, and the use of **redundancy**, which is built into the product to provide a **fail-safe** feature.

(ii) *Useful Life Period*: At this period, failure rate is at its lowest and remains constant for products that do not contain fatal defects or that have survived the infancy period.

This constant-rate mode is generally due to random events from without, rather than by inherent factors from within. Such events are beyond the control during the periods of design, prototype development, manufacturing, etc. but may be result through either accident or poor operation or maintenance. Failures may be reduced by following good operating and maintenance procedures. The constant rate period is often used to formulate the pricing,

Guarantee and servicing policies of the product; the latter is of particular importance in commerce. Product with a constant failure rate has the unique attribute that its probability of failure is independent of the products past service life; this aspect aids the ease of mathematical modelling in repair frequency, spare-part inventory, maintenance schedule, etc.

(iii) *Wear Out Period*: The period occurs toward the tail end of the product useful life and is associated with increasing failure rate. The failure is because of old age of the equipment material fatigue, corrosion, contact wear, insulation failure, and so on. Products with rapidly increasing failure rates require corrective measures such as regularity of inspection, maintenance, replacement, etc. The central concern in the wear-out period is the ability to predict the probable service life with a suitable model, so that a prudent schedule for preventive maintenance can be formulated.

Generally, the infant mortality mode is a **quality control** issue, while the wear-out mode is a **maintenance** issue. The random failure or constant rate mode, on the other hand, is widely used as the basis for product **reliability** considerations.

3.2 *Failure patterns*

Three types of failure patterns can be identified as follows:

1. Random Failure Pattern: This is a situation when the probability of failure of a component is constant and independent of time. Such components do not wear out or deteriorate under normal operating conditions. An example is the fuse that can be blown off whether old or new.

The probability density function is given by:

$X(t) = \lambda e^{-\lambda i}$, where λ is the average failure rate and $\frac{1}{\lambda}$ is the average time to failure. The probability density function is shown in Figure 3.

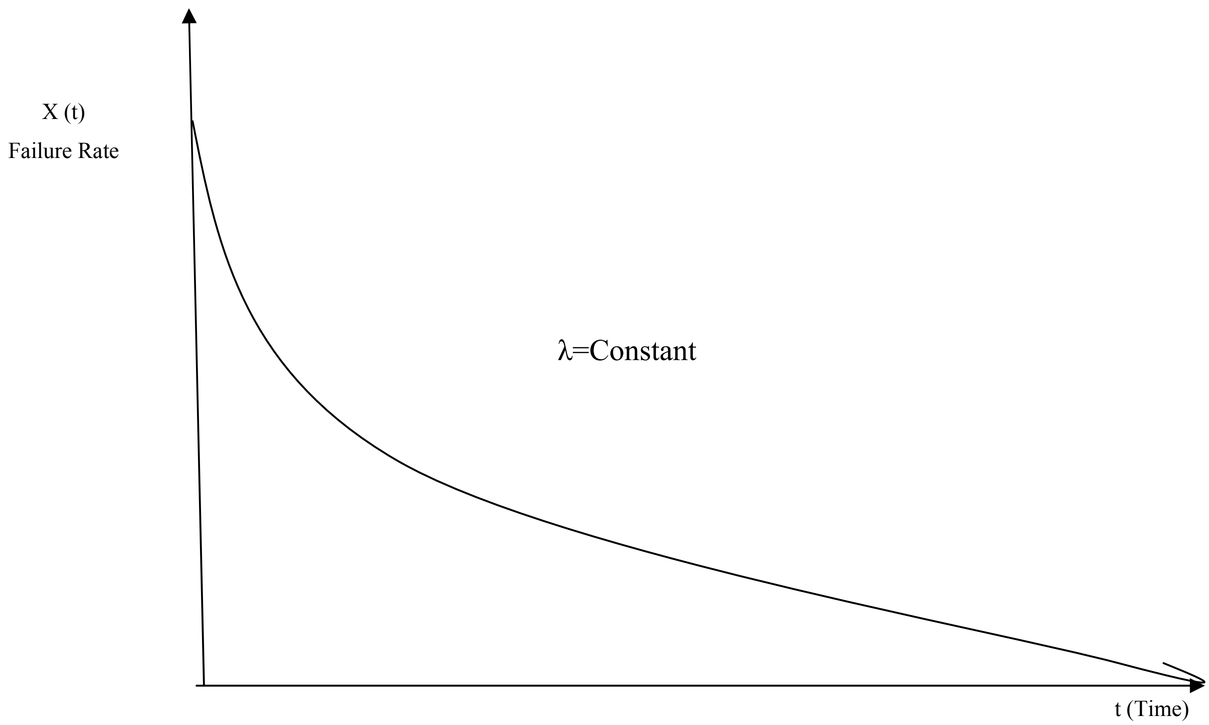


Figure 3: Exponential Probability Density Function

2. Running-in Failure Pattern:

This term is usually refers to the period of starting a machinery when it is new or after a major overhaul, which normally involves the changing of principal working components and parts. Problems of running- in may be a result of human imperfections either in design/manufacture or during installation. The probability function of such a failure is shown in Figure 4.

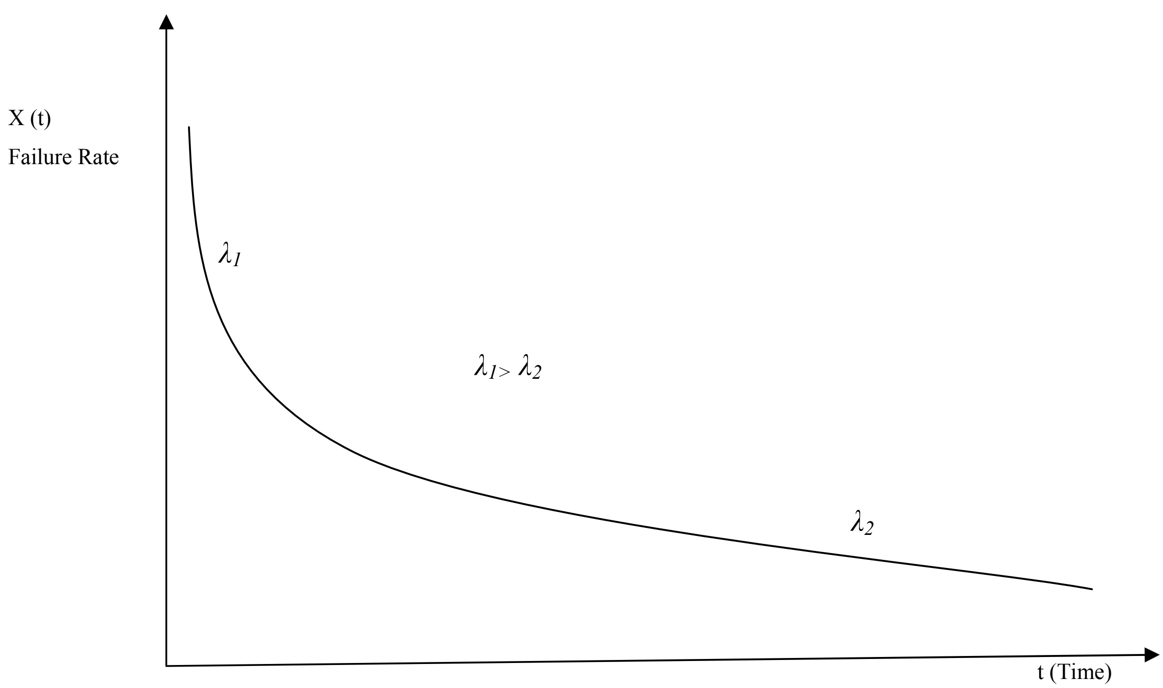


Figure 4: Hyper-Exponential Probability Density Function

3. Wear-out Failure Pattern: Deterioration of machinery is expected to increase with use and its age. Machinery would therefore fail after some operating conditions at an age. Failure patterns, which exhibit wear, are represented by the Normal Probability Function, which is given by:

X (t) = $\frac{1}{\sigma\sqrt{2\pi}} e^{-\left(\frac{t-t_m}{2\sigma^2}\right)}$, where t_m is the mean and σ is the variance.

3.3 Reliability

The term "**reliability**" in engineering refers to the probability that a product, a system or a particular component will perform without failure under the specified condition and for a specific period of time. Thus, it is also known as the "**probability of survival**." To quantify reliability, a test is usually conducted to obtain a set of "time-to-failure" sample data; say {t_i, i=1, N). The sample can then be fitted to a probability density function, f (t), or to a probability cumulative function, F (t). The "reliability function" is defined as R (t) = 1- F (t). Hence, the behaviour of R (t) is conjugate to that of F (t), the cumulative probability of failure in time. However, failure of an engineering product, or system, may stem from such random factors as material defects, loss of precision, accidental over-load, environmental corrosion, etc. The effects on failure of these random factors are only implicit in the collected data {t_i, i=1, N); and it is difficult to ascertain which factor is predominant and when it is predominant, from using F (t).

3.3.1 *Indices of Reliability*

Reliability can be specified by two parameters namely:

1.Mean time between failures (MTBF)

MTBF is the critical characteristic for repairable system and is the mean or average time between two successive failures of the system. MTBF can be obtained by running an item or equipment for a predetermined length of time under specified conditions and calculating the average length of time between failures. If for example, an item fails six times in an operating period of 60,000 hrs, MTBF is 10, 000 hrs. However, if the identical items operating under similar conditions are studied, MTBF is given by:

MTBF = (Total operating hours of all items)/Total number of failures that occur

For example if 20 identical items operate for 5, 000 hrs during which 40 failures occur and are rectified,

$$\text{MTBF} = \frac{5000 \times 20}{40} = 2,500 \text{ hrs}$$

MTBF can also be expressed as the inverse of failure rate, λ as follows:

$$\text{MTBF} = \frac{1}{\lambda}$$

The exponential distribution, the most basic and widely used reliability prediction formula, models machines with the constant failure rate, or the flat section of the bathtub curve. Most industrial machines spend most of their lives in the constant failure rate, so it is widely applicable. Below is the basic equation for estimating the reliability of a machine that follows the exponential distribution,

where the failure rate is constant as a function of time:

$$R_{(t)} = e^{-\lambda t}$$

Where:

R (t) = Reliability estimate for a period of time, cycles, miles, etc. (t).
e = Base of the natural logarithms (2.718281828)
λ = Failure rate (1/MTBF)

If for example, we assume a constant failure rate of 0.1 for a prime mover and running for six years without a failure, the projected reliability is 55 percent, which is calculated as follows:
R(6) = 2.718281828-(0.1* 6)
R(6) = 0.5488 = ~ 55%

In other words, after six years, about 45% of the population of similar prime mover operating in similar application can be expected to fail. It is worth reiterating at this point that these calculations project the probability for a population. Any given individual from the population could fail on the first day of operation while another individual could last 30 years. That is the nature of probabilistic reliability projections.

2. Mean time to failure (MTTF)

This is used for components or items that are not repairable such as filament lamps, fuses, resistors, capacitors, etc. The value of MTTF can be calculated from life test results, which can be obtained by stressing a large number of components under known conditions for a period and noting the number of failures.

MTTF = (Length of test time) / (Number of failures).

Another method which though is more accurate but costly is run to failure specified number of components under specified conditions.

$$\text{MTTF} = \frac{1}{\eta}\sum_{i=1}^{i=n} T_i$$

Where T_i = length of time taken by the i^{th} specimen to fail

n = total number of specimens.

MTTF = $\frac{1}{\lambda}$ where λ is failure rate and is independent of time

3.3.2 Calculating System Reliability

System reliability depends on the reliabilities of the various components in the system. Therefore, to calculate the reliability of a system, the system should be divided into subsystems. A system may be connected in series or parallel.

Systems in Series

In the series system, the ability to employ subsystem B depends upon the operating state of subsystem A. If subsystem A is not operating, the system is down regardless of the condition of subsystem B (Figure 5).

To calculate the system reliability for a system is series, there is the need to multiply the estimated reliability of subsystem A at time (t) by the estimated reliability of subsystem B at time (t). The basic equation for calculating the system reliability of a simple series system is

$$Rs_{(t)} = R1_{(t)} \times R2_{(t)} \times \ldots \times Rn_{(t)}$$

Where:

Rs (t) – System reliability for given time (t)

R1-n (t) – Subsystem or sub-function reliability for given time (t)

So, for a simple system with three subsystems, or sub-functions, each having an estimated reliability of 0.90 (90%) at time (t), the system reliability is calculated as 0.90 X 0.90 X 0.90 = 0.729, or about 73%.

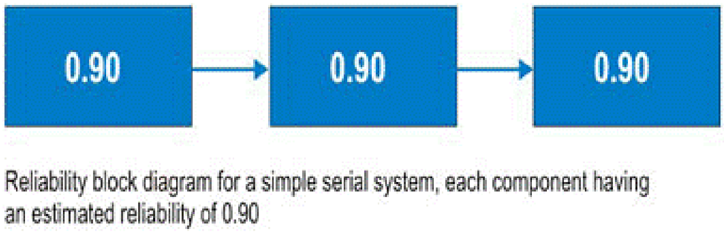


Figure 5: Simple Serial System

<u>Systems in Parallel</u>

Design engineers sometimes incorporate redundancy into critical machines. Reliability engineers call these parallel systems and may be designed as active parallel systems or standby parallel systems. The block diagram for a simple two component parallel system is shown in Figure 6.

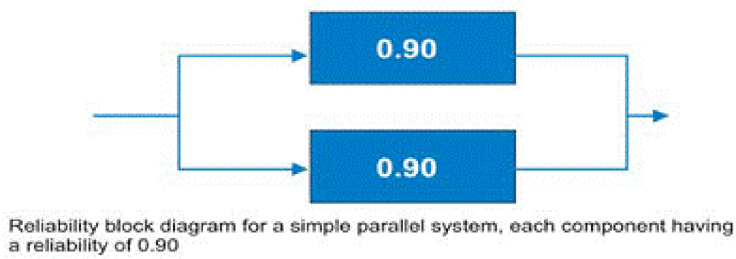


Figure 6: Simple parallel system

To calculate the reliability of an active parallel system, where both machines are running, use the following simple equation:

$$Rs_{(t)} = 1 - \left[(1 - R1_{(t)}) \times (1 - R2_{(t)}) \times \ldots \times (1 - Rn_{(t)})\right]$$

Where:
Rs (t) – System reliability for given time (t)
R1-n (t) – Subsystem or sub-function reliability for given time (t)

The simple parallel system in our example with two components in parallel, each having a reliability of 0.90, has a total system reliability of 1 – (0.1 X 0.1) = 0.99. Therefore, the system reliability was significantly improved.

3.3.3 Availability

Maintenance Managers/Engineers usually employ availability Ratio for planning purposes.
The reliability of a system gives the probability a certain job can be done without system breakdown, however, the manager needs to know how much time the system would be available over a planning period.
The maintainability, which is a factor of the time required and resources needed to restore equipment in case of failure, in conjunction with reliability determine the availability of a machine.

If the average repair time is $\overline{T}$, the availability of the machine, AV in terms of MTBF is

$$AV = \frac{MTBF}{MTBF + \overline{T}}$$

Availability Ratio is the portion of the total time a machine should function to that the machine actually functions.
If the total is T hours and the machine is actually in working condition for U hours while it is down for D hours, then
T = U + D

$$\text{Availability Ratio, AR} = \frac{U}{U + D}$$

$$\text{Unavailability Ratio, UR} = \frac{D}{U + D}$$

The total time, T does not include planned operational shutdowns due to production schedules or routine preventive maintenance.

4.0. TROUBLESHOOTING GUIDE FOR SMALL ENGINE

The following chart lists a variety of common problems and nearly all possible causes. Diagnostic procedures will then be needed to determine which actually apply. The 'possible causes' are listed in *approximate* order of likelihood.

While this chart lists many problems, it is does not cover everything that can go wrong. However, it can be a starting point for guiding your thinking in the proper direction.

Problem: Engine will not start or is hard to start.
Possible causes:

1. Fuel tank is empty or shutoff valve is closed, or fuel line or fuel tank cap vent is clogged.
2. There is water in the fuel.
3. Carburettor is over choked.
4. Carburettor is improperly adjusted or needs service.
5. Ignition system or its wiring is defective or ignition switch is off or timing way off (e.g., broken flywheel key).
6. Deadman or other cutoff switch is open or defective.
7. Spark plug is fouled, improperly gapped, or damaged.
8. Engine compression is poor.
9. Operator needs to read user manual. :)

- **Problem: Engine starts easily but dies after a few seconds.**

Possible causes:
1. Fuel tank is empty or shutoff valve is closed, or fuel line or fuel tank cap vent is clogged.
2. Carburettor is over choked.
3. Carburettor is improperly adjusted or needs service.

- **Problem: Engine idles roughly, unevenly, or surges.**

Possible causes:
1. Carburettor is dirty.
2. Air leak in carburettor or intake manifold (e.g., bad O-ring, gasket, primer).
3. Carburettor is improperly adjusted or needs service.

- **Problem: Engine misses under load.**

Possible causes:
1. Spark plug is fouled, improperly gapped, or damaged.
2. Breaker points are pitted or improperly gapped, breaker arm is sluggish, or condenser is bad.
3. Carburettor needs adjustment or service.
4. Fuel line, fuel filter, or fuel tank cap vent is clogged, or fuel shutoff valve partially closed.
5. Valves not adjusted properly or valve springs weak.
6. Exhaust ports blocked (2- stroke).

- **Problem: Engine knocks.**

Possible causes:
1. Magneto is not timed properly.
2. Carburettor is set too lean.
3. Engine has overheated.
4. Carbon build-up in combustion chamber.
5. Flywheel is loose.
6. Connecting rod is loose or worn.
7. Cylinder is excessively worn.

- **Problem: Engine vibrates excessively.**

Possible causes:
1. Engine is not mounted securely.
2. Blade or other driven equipment is unbalanced.
3. Crankshaft is bent.
4. Counterbalance shaft is not timed correctly.

- **Problem: Engine lacks power (possibly after warm-up).**

Possible causes:
1. Old gas, bad spark plug, very thick/dirty oil.
2. Choke is partially closed.
3. Carburettor needs adjustment or service.
4. Ignition not timed correctly.
5. Air filter is clogged.
6. There is a lack of lubrication.
7. Valves are not sealing properly.
8. Piston rings are not sealing properly.
9. Head loose or head gasket blown or damaged.
10. Exhaust ports blocked (2- stroke).

- **Problem: Engine operates erratically, surges, and runs unevenly.**

Possible causes:
1. Fuel line or fuel tank cap vent is clogged.
2. There is water in the fuel.
3. Fuel pump is defective.
4. Governor is not set properly, sticking, or binding.
5. Carburettor needs adjustment or service.
6. Loose carburettor/intake pipe resulting in vacuum leak.

- **Problem: Engine overheats.**

Possible causes:
1. Magneto is not timed properly.
2. Carburettor set too lean.
3. Air intake or cooling fins are clogged.
4. Shroud or blower housing missing.
5. Excessive load.
6. Insufficient or excessive oil.
7. Improper oil viscosity (4 stroke) or mixture (2 stroke)
8. Valve clearance is too small.
9. Excessive carbon build-up in combustion chamber.

- **Problem: Crankcase breather passing oil.**

Possible causes:
1.Too much oil in crankcase.
2.Engine speed is excessive.
3.Oil fill cap or gasket is damaged or missing.
4.Breather mechanism is dirty or defective.
5.Piston ring gaps are aligned.
6.Piston rings are worn.

- **Problem: Engine backfires.**

Possible causes:
1. Carburettor set too lean.
2. Magneto is not timed correctly.
3. Valves are sticking.

5.0 MODERN TECHNIQUES IN MAINTENANCE

The modern techniques in maintenance include the following:

5.1 Use of Condition Monitoring (CM) Technologies

The following methods are available to assess the condition of systems/equipment, to determine the most effective time to schedule maintenance:

(i) vibration monitoring and analysis

(ii) thermography

(iii) lubricant and particle wear analysis (oil analysis)

(iv) non-destructive testing.

(v) Acoustic Emission monitoring

5.1.1 Vibration Monitoring and Analysis

Theory, Applications, and Techniques

Analysis of system and equipment vibration levels is one of the most commonly used CM techniques. Vibration monitoring helps determine the condition of rotating equipment and structural stability in a system. It also helps identify noise sources, as severely vibrating equipment is noisy.

Basic Vibration Theory

Vibration is simply the movement of a machine or machine part back and forth from its position of rest. A weight hanging on a spring is the simplest example of how vibration works. Until a force is applied to the weight to cause it to move, we have no vibration. By applying an upward force, the weight moves upward, compressing the spring. If we released the weight, it would drop below its neutral position to some bottom limit of travel, where the spring would stop the weight. The weight would then travel upward through the neutral position to the top limit of motion, and back again through the neutral position. The motion will continue in exactly the same manner as the force is reapplied. Thus, vibration is the response of a system to some internal or external force applied to the system. With a few exceptions, mechanical troubles in a machine cause vibration. The most common problems that produce vibration are:

- unbalance of rotating parts
- misalignment of couplings and bearings
- bent shafts
- worn, eccentric, or damaged parts
- bad drive belts and drive chains
- bad bearings
- torque variations
- electromagnetic forces
- aerodynamic forces
- hydraulic forces
- looseness
- rubbing
- resonance

The amount of time required to complete one full cycle of a vibration pattern is called the period of vibration. If a machine completes one full cycle in 1/60th of a second, the period of vibration is said to be 1/60th of a second. The period of vibration is a simple and meaningful characteristic often used in vibration detection and analysis. Another simple characteristic is the frequency. Frequency is related to period by the following formula:

frequency =1/period

Frequency is the inverse of period. In reality, frequency is a measure of the number of complete vibration cycles that occur in a specified amount of time. The frequency of vibration is usually expressed in cycles per minute (CPM). Specifying vibration frequency in CPM makes it easy to relate this characteristic to another important specification of rotating machinery: revolutions per minute (RPM). So, if you have piece of machinery that operates at 3600 RPM, you can expect certain problems to create vibration at a frequency of 3600 RPM. Frequency is sometimes expressed in cycles per second, or Hertz (Hz). The relationship between Hz and CPM is expressed by the following equation:

$CPM = Hz \times 60$

Vibration displacement is defined as the total distance travelled from one extreme limit to the other (the "peak-to-peak displacement"). Peak-to-peak vibration displacement is usually expressed in mils, where 1 mil equals 1/1000th of an inch (0.001 in.). Since a vibrating piece of machinery is moving, it has a velocity. The vibration velocity constantly changes. At the top limit of the motion the speed is zero since the weight must come to a stop before it can go in the opposite direction. The speed of velocity is greatest as the weight passes through the neutral position. Since the velocity of the part is constantly changing throughout the cycle, the highest "peak" is selected for measurement. Vibration velocity is expressed in inches per second. Since vibration velocity is directly related to vibration severity, for the most general purpose vibration measurements, it is the preferred parameter for measurement. As a rule of thumb, vibrations occurring in the 600 to 60,000 CPM frequency range are generally best-measured using vibration velocity. Under conditions of dynamic stress, displacement alone may be a better indication of severity, especially when the machine part exhibits the property of brittleness, the tendency to break or snap when stressed beyond a given limit. For example, consider a slowly rotating machine that operates at 60 RPM, and that exhibits vibration of 20 mils peak-to-peak displacement caused by rotor unbalance. In terms of vibration velocity, 20 mils at 60 CPM is only 0.0585 in./sec, which would be considered "good" for general machinery and little cause for immediate concern. However, keep in

mind that the bearing of this machine is being deflected 20 mils. Under these conditions, fatigue may occur due to stress (resulting from the displacement) rather than due to fatigue (caused by the velocity of displacement). Generally, the most useful presentation of vibration data is a graph showing vibration velocity (expressed in inches/second) on the vertical axis and frequency on the horizontal axis. By analyzing this data, a trained vibration technician can ascertain what kinds of problems exist. The trained technician has, in effect, learned to "read" vibration signatures; he has learned to interpret what the different
peaks in the different frequency ranges indicate.

All rotating machinery will exhibit a certain degree of vibration. The question then becomes "How much is too much?" There are no realistic figures for selecting a vibration limit, which, if exceeded, will result in immediate machinery failure. The events surrounding the development of a mechanical failure are too complex to set reliable limits. However, there are some general guidelines that have been developed over the years that can serve as general indication of the condition of a piece of machinery.

When setting up a vibration monitoring program that uses hand-held vibration instrumentation, it is necessary to ensure that the measurements are taken consistently.

A slight variation in the location where a measurement is taken on a piece of machinery can significantly alter its accuracy. This issue becomes especially difficult to police when several technicians take measurements at different times on the same piece of machinery.

Information Obtained through Vibration Monitoring

If applied by a trained professional, vibration monitoring can yield information regarding: wear, imbalance, misalignment, mechanical looseness, bearing damage, belt flaws, sheave and pulley flaws, gear damage, flow turbulence, cavitation, structural resonance, and material fatigue.

The maintenance supervisor/manager must make the decision whether it makes economic sense to perform this function with in-house labour forces or whether it should be outsourced to a contractor specializing in vibration monitoring and analysis. In making this decision, maintenance supervisors/managers should consider whether they have sufficient in-house labour to dedicate to vibration monitoring. Vibration monitoring theory is complicated, the equipment is expensive, moreover, the analysis of the data collected is a skill that must be practiced regularly. Once he has completed the basic vibration training (costing several thousands of dollars), a maintenance technician must be committed and allowed to work at least 3 days per month in vibration analysis if he is to stay competent with the technology and analysis techniques.

Detection Interval/Amount of Data Collected

Narrow band vibration analysis can provide several weeks or months of warning of impending failure. In establishing a vibration monitoring program, one must first determine how often to take sampling data. Different vibration frequencies forebode different upcoming failures. The frequency of data collection depends on machine type and failure category. Typically, it is not cost effective to take real-time vibration data; spot checking facility equipment once per month (or once per quarter) with hand-held vibration monitoring equipment usually provides sufficient warning of impending problems. Facility rotating equipment (e.g., fans, pumps) does not deteriorate fast enough to warrant continual real time data collection.

Maintenance technicians should realize that accumulating more data is not necessarily indicative of a better vibration monitoring program. Even after the first costs of the vibration monitoring and data acquisition system have been absorbed, there is an "overhead" associated with data collection. The data must be analyzed and interpreted. Even with the sophisticated software available to assist the maintenance technician with these tasks, it takes an ongoing time investment.

Spectrum Analysis and Waveform Analysis

Spectrum analysis is the most commonly employed analysis method for machinery diagnostics. In this type of analysis, the vibration technician focuses on analyzing specific "slices" of the vibration data taken over a certain range of CPM. Spectrum analysis can used to identify the majority of all rotating equipment failures (due to mechanical degradation) before failure. Waveform analysis, or time domain analysis, is another extremely valuable analytical tool. While not used as regularly as spectrum analysis, the waveform often helps the analyst more correctly diagnose the problem.

Torsional Vibration

Torsional vibration is often used to detect the vibration associated with the measurement of gear vibration and torque. It proves most helpful in situations where, due to transmission path attenuation, the casing vibration signal has a signal-to-noise ratio insufficient to detect the problem (i.e., the noise obscures the signal). Torsional vibration is especially effective in situations where unsteady

forces excite the resonance of the structure or housing. Measure torque by using pairs of matched sensors spaced at a sonic interval to take advantage of the phase difference in the signals.

Limitations

The effectiveness of vibration monitoring depends on sensor mounting, resolution, machine complexity, data collection techniques, and the ability of the analyst. This last factor, the ability of

the analyst, is probably the most important aspect of establishing an effective vibration monitoring program. The analyst must be someone who possesses a thorough understanding of vibration theory
moreover, the extensive field experience necessary to make the correct diagnosis of the vibration spikes that may appear in the data acquired. Complex, low speed (<120 RPM), variable speed, and reciprocating machinery are extremely difficult to monitor effectively. Additionally, single channel analysis cannot always accurately determine the source of the vibration on complex machines.

Equipment Required

For permanent data collection, vibration analysis systems include microprocessor - based data collectors, vibration transducers, equipment-mounted sound discs, and a host personal computer with software for analyzing trends, establishing alert and alarm points, and assisting in diagnostics. Portable hand-held data collectors consist of a hand-held data collection device (about the size of a palm-top computer) and a magnetized sensing device.

5.1.2 Thermography

Infrared Thermography (IRT) is the application of infrared detection instruments to identify temperature differences. The test instruments used are no contact, line-of-sight, thermal measurement and imaging systems. Because IRT is a no contact technique, it is especially attractive for identifying hot/cold spots in energized electrical equipment, large surface areas such as boilers and building walls, and other areas where "stand off" temperature measurement is necessary. Instruments that perform this function detect electromagnetic energy in the short wave (3 to 5 microns) and long wave (8 to 15 microns) bands of the electromagnetic spectrum. The short wave instrument is the best choice for facilities inspections due to the varied inspections (electrical, mechanical, and structural) encountered. However, the short wave instrument is more sensitive than long wave to solar reflections. The maintenance technician will need to be aware of this when performing outdoor inspections in areas such as transformers, motor control centres, switchgear, substations, switchyards, or power lines. In such cases, sunlight reflected from shiny surfaces may make those surfaces appear to be "hotter" than the adjacent surfaces when they really are not. To be effective in facilities applications, IRT instruments must be portable, sensitive to within 0.20 °C over a range of temperatures from -100 to +3000 °C, and accurate within +/-3 percent. In addition, the instrument must be capable of storing an image of the thermogram for later analysis. IRT inspections are identified as either qualitative or quantitative. The *quantitative* inspection attempts the accurate measurement of the temperature of the item of interest. To perform a quantitative inspection requires detailed knowledge and understanding of the relationship of temperature and radiant power, reflection, emittance, and environmental factors, as well as the limitations of the detection instrument. This knowledge and understanding must be applied in a methodical fashion to control the imaging system properly and to obtain accurate temperature measurements. Quantitative measurements of temperature are extremely time-consuming, and are rarely needed in facilities applications.

The *qualitative* inspection is interested in relative differences, hot and cold spots, and deviations from normal or expected temperature ranges. The knowledge and understanding discussed above is needed to perform a meaningful qualitative inspection. However, qualitative inspections are significantly less time consuming because the thermographer is not concerned with highly accurate temperature measurement. In qualitative inspections the thermographer obtains accurate temperature *differences* (DT) between like components. For example, a typical motor control centre will supply three-phase power, through a circuit breaker and controller to a motor. Ideally, current flow through the three-phase circuit should be uniform so the components within the circuit should have similar temperatures. Any uneven heating, perhaps due to dirty or loose connections, would quickly be identified with the IRT imaging system. Because the many variables that influence the quantitative inspection (reflection, emittance, etc.) are the same between like components, the thermographer can quickly focus on the *temperature differences*. The factors so important to a highly accurate quantitative temperature measurement have very little influence on the temperature differences between like components.

Theory and Applications

IRT can be used to identify degrading conditions in facilities electrical systems such as transformers, motor control centres, switchgear, substations, switchyards, or power lines. In mechanical systems, IRT can identify blocked flow conditions in heat exchanges, condensers, transformer cooling radiators, and pipes. IRT can also be used to verify fluid level in large containers such as fuel storage

tanks. IRT can identify insulation system degradation in building walls and roof, as well as refractory in boilers and furnaces. Temperature monitoring, infrared thermography in particular, is a reliable technique for finding the moisture- induced temperature effects that characterize roof leaks, and for determining the thermal efficiency of heat exchangers, boilers, building envelopes, etc.

Deep-probe temperature analysis can detect buried pipe energy loss and leakage by examining the temperature of the surrounding soil. This technique can be used to quantify ground energy losses of pipes. IRT can also be used as a damage control tool to locate mishaps such as fires and leaks. In soliciting consultants to perform thermography, one should remember that (unless requested otherwise) the thermographer will normally provide only an exception report that identifies finds/faults (i.e., his analysis will be of qualitative temperature differences).

In summary, IRT can assess the in-service condition of electrical and mechanical systems. Once this is done, the maintenance supervisor/manager can prioritize work based on the temperature difference criteria. The greater the DT, the more urgent the problem.

Limitations

Thermography is limited to line of sight. Errors can be introduced due to colour of material, material geometry, and by environmental factors such as solar heating and wind effects.

Logistics

Equipment Required

· Equipment ranges from simple, contact devices such as thermometers and crayons to full colour imaging, computer-based systems that can store, recall, and print the thermal images.

· The “deep-probe” temperature technique requires temperature probes, analysis software and equipment to determine the location of piping systems.

Operators

· Operators and mechanics can perform temperature measurements and analysis using contact-type devices with minimal training on how and where to take the temperature readings.

· Because thermographic images are complex and difficult to measure and analyze, training is required to obtain and interpret accurate and repeatable thermal data and to interpret the data. With adequate training and certification, electrical/mechanical technicians and/or engineers can performed this technique.

· Maintenance personnel can apply deep-probe temperature monitoring after being trained, although this service is often contracted.

Training Available

· Training is available through infrared imaging system manufacturers’ and vendors.

· The American Society of Non-destructive Testing (ASNT) has established guidelines for non-destructive testing (NDT) thermographer certification.

These guidelines, intended for use in non-destructive testing, may be used as guidelines for thermography in CM if appropriately applied. Certification is not easily obtained. When deciding which maintenance technician should be certified as a thermographer, the maintenance manager should consider general background, work experience, and any previous thermographic experience or thermographic training.

5.1.3 Lubricant and Wear Particle Analysis

Purpose

Lubricating oil analysis is performed for three reasons:

1. To determine the machine mechanical wear condition
2. To determine the lubricant condition
3. To determine if the lubricant has become contaminated.

A wide variety of tests can provide information regarding one or more of these areas. The test used will depend on the test results sensitivity and accuracy, the cost, and the machine construction and application. The three areas are not unrelated; changes in lubricant condition and contamination, if not corrected, will lead to machine wear. Because of the important relationships, commercial analysis laboratories will often group several tests in cost effective test packages that provide information about all three areas.

Machine Mechanical Wear Condition

The criteria for analyzing the lubricating oil to determine the machine's condition are generally the same as for performing vibration analysis. This analysis is applicable to all machines with motors 7.5 HP or larger, critical machines, or high cost machines. Generally the routine sampling and analysis periodicity will be the same as the vibration analysis periodicity (when using a portable vibration data collector). For machines with a condition history (a year or more of data), this is typically performed quarterly.

Lubricant Condition

Lubricating oil is either discarded or reconditioned through filtering and/or replacing additives. Analyzing the oil to determine the lubricant condition is, therefore, driven by costs. Small machines, those with oil reservoirs 1 gal or less, have the oil changed on an operating time basis. An automobile is the most common example of time-based lubricating oil maintenance. In this example, the costs to replace the automobile oil (the replacement oil, labour to change the oil, and disposal costs) are lower than the cost to analyze the oil (i.e., the cost of sample materials, labour to collect the sample, and the analysis). In the case of automobile oil, time-based replacement is cheaper than analysis due to competition and the economies of scale that have been created to meet the consumer need for replacing automobile oil.

In the case of lubricating oil used in facility equipment, simply replace and discard the machine lubricating oil if it is cheaper than analyzing it. When making this decision, the maintenance manager must have firm prices for materials used to take samples and the labour hours it will take to collect, package, and send the samples out for analysis. Remember, though, that one oil sample is sufficient for many tests.

Lubricant Contamination

Lubricating oil can become contaminated due to the machine's operating environment, improper filling procedures, or through the mixing of different lubricants in the same machine. If a machine is "topped off" with oil frequently, the maintenance technician should send the oil out for analysis periodically to check the machine for any serious problems.

Standard Analytical Tests

Lubricating oil and hydraulic fluid analysis should proceed from simple, subjective techniques such as visual and odour examination through more sophisticated techniques. The more sophisticated (and expensive) techniques should be used when conditions indicate the need for additional information and the equipment cost or criticality justifies the cost.

Visual and Odour

Simple inspections can be performed weekly by the equipment operator to look at and smell the lubricating oil. A visual inspection looks for changes in colour, haziness or cloudiness, and particles. This test is very subjective, but can be an indicator of recent water or dirt contamination and advancing oxidation. A small sample of fresh lubricating oil in a sealed, clear bottle can be kept on hand for visual comparison. A burned smell may indicate oxidation of the oil. Other odours could indicate contamination. Odour is more subjective than the visual inspection because people's sensitivity to smell varies, and there is no effective way to compare the odor between samples. The operator must be careful not to introduce dirt into the system when taking a sample.

Viscosity

Viscosity is a measure of oil flow rate at a specified temperature. A change (increase or decrease) in viscosity over time indicates changes in the lubricant condition, or it may indicate lubricant contamination. Viscosity can be tested using portable equipment, or it can be tested more accurately in a laboratory using the ASTM D445 procedure. Viscosity is measured in centistoke (cSt), and minimum and maximum values are identified by the ISO grade. Testing oil viscosity is usually part of a commercial laboratory standard test package.

Water

Water in lubricating oil and hydraulic fluid contributes to corrosion and formation of acids. Small amounts of water (less than 0.1 percent) can be dissolved in oil and can be detected using the crackle test or infrared spectroscopy (minimum detectable is 0.05 percent or approximately 500 ppm by both methods), the ASTM D95 distillation method (minimum detectable is 0.01 percent/100 ppm), the ASTM D1744 Karl Fischer method (minimum detectable is 0.002 percent/100 ppm). If greater than 0.1 percent water is suspended or emulsified in the oil, the oil will appear cloudy or hazy. Free water in oil collects in the bottom of oil reservoirs and can be found by draining them from the bottom.

Percent Solids/Water

A simple, inexpensive test is used to provide a gross estimate of solids and/or water in the oil. A sample is centrifuged in a calibrated tube and the resulting volume is measured. The test is effective for amounts in the range of 0.1 to 20 percent of volume and is usually part of a commercial laboratory standard test package.

Total Acid Number (TAN)

Total acid is an indicator of the lubricating oil condition and is monitored relative to the TAN of new oil. In some systems, the TAN will also be used to indicate acid contamination. TAN is measured in milligrams of potassium hydroxide (KOH) per gram of oil (mg KOH/g). KOH is used in a titration process and the end point is indicated by colour change (ASTM D974) or electrical conductivity change (ASTM D664).

Total Base Number (TBN)

Like the TAN test method, the TBN test measures alkalinity (ability to neutralize acid) of oil sample. This test is used on oil with high detergent additives such as diesel and gasoline engines. KOH is used in a titration process and the end point is indicated by electrical conductivity change (per ASTM D664 or ASTM D2896). When comparing test results from your oil against baseline data from the oil supplier, make sure that the same test method was used for your oil as was used in generating the baseline data. Results can vary significantly between test methods.

Spectrometric Metals

Also known as emission spectroscopy, this technique examines the light (spectrum) emitted from the sample during testing, and identifies up to 21 metals. Metals are categorized as wear, contaminate, or additive metals. The procedure identifies both soluble metal and metal particles up to 5 to 10 microns (5-10 mm).

The test cost is moderate, and is usually part of a commercial laboratory standard test package. Other techniques (e.g., absorption spectroscopy and X-ray spectroscopy) are used by some laboratories to identify metals.

Infrared Spectroscopy

This technique is also known as infrared analysis, infrared absorption spectroscopy or spectrophotometry, and Fourier Transform Infrared (FTIR) spectroscopy. The technique examines the infrared wavelength that is absorbed by the oil sample. The test is used to identify non-metallic contamination and lubricant conditions (e.g., oxidation, antioxidant, other additive depletion). In the future, it may become possible to couple computer expert system analysis with known oil spectrums, in an effort to produce highly accurate diagnosis of small changes in the oil condition. Costs vary, depending on the level of sophistication required. Infrared spectroscopy is usually part of a commercial laboratory standard test package.

Analytical Ferrography

More detailed than Direct Reading (DR) ferrography, analytical ferrography is often initiated based on changes in DR, spectrometric metal increases, or increased particle count. The analysis is sometimes performed on a regular basis on expensive or critical machines. The test process is labor intensive and involves the preparation of sample and examination under magnification. Results vary with the analyst's capability, but the procedure can provide detailed information regarding wear: e.g., wear type (rubbing, sliding, cutting), colour, particle types (oxide, corrosive, crystalline), and other nonferrous particles. This detailed information can be critical in finding the root cause of wear problems. Costs are moderately high; the test is performed on a fixed price basis (per sample) from a commercial laboratory.

Special Tests

Special tests are sometimes needed to monitor lubricant conditions on some expensive or critical Systems. Usually the special test is used to monitor a lubricant contaminate, a characteristic, or additive depletion. This section identifies some of the special tests available. Special tests are rarely needed for routine monitoring of lubricants. The list of special test presented here is not meant to be all-inclusive ¾ only a list of samples. Test procedures are constantly being developed and refined. The annual ASTM Standards provides a description of current test methods,

Glycol Antifreeze

Glycol contamination can be detected using infrared spectroscopy (see Infrared Spectroscopy, discussed earlier) at levels greater than 0.1 percent (1,000 ppm), which is usually adequate for condition monitoring. However, additional tests can be specified to identify if small amounts of glycol are present. ASTM D2982 will indicate if trace amounts are present. ASTM D4291 uses gas chromatography to quantify small amounts of glycol.

Karl Fischer Water

Water contamination can be detected using infrared spectroscopy (see Infrared Spectroscopy, p 74) at levels greater than 0.05 percent (500 ppm), which is usually adequate for condition monitoring. Using a titration process with a Karl Fischer reagent, low levels of water can be detected and quantified. The test, ASTM D1744, is useful when accepting new oil or evaluating clean up efforts.

Cost of the test is moderate.

Foamlug

Some oil may have anti-foam agents added to improve the lubrication capability in specific applications such as gear boxes or mixers. ASTM test D892 can be used to test the oils foam characteristics. The test blows air through a sample of the oil and measures the foam volume. Cost of the test is moderately high.

Rust Prevention

Some systems are susceptible to water contamination due to equipment location or the system operating environment. In those cases, the lubricating oil or hydraulic fluid may be fortified with an inhibitor to prevent rust. The effectiveness of rust prevention can be tested using ASTM D665 (or ASTM D3603). Results are pass/fail and the cost of the test is high.

Rotating Bomb Oxidation Test (RBOT)

Also known as the Rotary Bomb Oxidation Test, ASTM D 2272 is used to estimate oxidation stability and the remaining useful life of oil. The test simulates aging, identifying when rapid oxidation takes place and indicating that antioxidants have been depleted. The test is not a one time test; it must be performed over time, starting with a baseline test of the new oil. Subsequent tests are necessary to develop the trend line. Because of the high cost and the multiple tests required, this test is usually only performed on large volume reservoirs or expensive oil.

Application

Typically, lubricating oil analysis should be performed on a quarterly basis on all machines with motors 7.5 HP or larger, and on all critical or expensive machines. The analysis schedule should be adjusted in the same way that the vibration analysis schedule is adjusted. Analyze more frequently for machines that are indicating emerging problems; less frequently for machines that operate under the same conditions and are not run on a continuous basis. A new baseline analysis will be needed following machine repair or oil change out. All hydraulic systems, except mobile systems, should be analyzed on a quarterly basis. Mobile systems should be considered for analysis based on the machine size and the cost effectiveness of performing the analysis. Generally, it is more cost effective in mobile equipment to maintain the hydraulic fluid based on the fluid condition.

However, for small systems, the cost to flush and replace the hydraulic fluid on a time basis may be lower than the cost to analyze the fluid on a routine basis. Grease is usually not analyzed on a regular basis. Although most of the testing that is done on oil can also be done on grease, there is a problem getting a representative sample. To get a representative sample that is a homogeneous mixture of the grease, contaminants, and wear, the machine must usually be disassembled. Once a machine has failed and must be disassembled, analysis of the grease to diagnose the failure can sometimes be useful. A concern common to all machines with lubricating oil systems is keeping dirt and moisture out of the system. Common components of dirt, such as silica, are abrasive and naturally promote wear of contact surfaces. In hydraulic systems, particles can block and abrade the close tolerances of moving parts. Water in oil promotes oxidation and reacts with additives to degrade the performance of the lubrication system. Ideally, there would be no dirt or moisture in the lubricant; this, of course, is not possible. The lubricant analysis program must therefore monitor and control contaminants. Large systems with filters will have steady state levels of contaminates. Increases in contaminates indicate breakdown in the systems integrity (leaks in seals, doors, heat exchangers, etc.) or degradation of the filter. Unfiltered systems can exhibit steady increases during operation.

Operators can perform a weekly visual and odour check of lubricating systems and provide a first alert of contamination. Some bearing lubricating systems have such a small amount of oil that a weekly check may be impractical.

Motors, Generators, Pumps, Blowers, Fan

For machines with less than 5 gal in the lubrication system, the analyst is mostly concerned with machine condition. Lubricant condition and contamination are of interest because they provide some indication of machine condition.

Routinely monitor viscosity, percent solids/water, and spectrometric metals. Monitor trends and discard or refresh the oil when viscosity changes 10 percent from the baseline. Viscosity normally increases above the baseline with the oil service time. If the viscosity decreases below the baseline, it usually means that the oil is contaminated, probably from adding the wrong type of makeup oil. There should be no water present (minimum detectable water is 0.1 percent). If there is water, the source of the water needs to be identified and corrected. For machines with more than 5 gal of oil in the system, add infrared spectroscopy (minimum amount of water detectable is 0.05 percent) and particle counting. Changes in particle count can indicate increased contamination or increased wear. Correlate particle count with spectrometric metals. The rate of particle count change indicates how quickly the lubricant is degrading. Visual particle counting can be used to identify the source of the contamination. In addition, perform DR ferrography for expensive or critical machines. In all machines, changes in spectrometric metals or DR should be investigated further using analytical ferrography and correlated with vibration analysis.

Gearboxes

Same as above, except for gearboxes with less than 5 gal of oil, add particle counting. Implement DR ferrography for high cost or critical gearboxes. Monitor trends and correlate with vibration readings.

Chillers

In addition to the items identified above, add Total Acid Number (TAN) and DR ferrography.

Diesel Engines

Use the same procedure as for chillers except substitute Total Base Number (TBN) for TAN when oil has high detergent additives. A decrease in viscosity below the baseline may indicate fuel contamination. Coolant leakage (glycol and other characteristics) is identified from the infrared spectroscopy analysis.

Compressors

Centrifugal compressors should be treated the same as chillers. Reciprocating compressors should be treated the same as diesel engines.

Hydraulic Systems

Perform the same oil analysis as that performed on gearboxes. Monitor particle count by ISO category. Each hydraulic system will have limiting clearances that will determine critical particle sizes. Note that some hydraulic systems use fluids other than oil (water or glycol). For these systems, oil analysis does not apply; however, perform particle control the same as for oil-filled hydraulic systems.

Large Reservoirs

For reservoirs over 500 gal, consider performing an Rotating Bomb Oxidation Test (RBOT) to assess the oxygen stability. Cost is usually the deciding factor. At least three tests are needed to develop a trend. Once the trend has been established, additional retesting should be performed at least once a year. Maintenance dollar are saved when replacement or refreshing of a large volume of oil (or smaller volume of expensive oil) can be deferred.

Lubrication Analysis

As one can see from reading the above, there are numerous lubrication tests.
Commercial laboratories performing the tests have charts available that summarize the various lubricant tests, monitoring interval, and application.

Sampling

Oil samples must be collected safely and in a manner that will not introduce dirt and other contaminates into the machine/system, or into the sample. It may be necessary to install permanent sample valves in some lubricating systems. The oil sample should be representative of the oil seen in the machine. The sample should, therefore, be collected from a mid-point in reservoirs and upstream of the filter in circulating systems. Sample collection bottles and tubing can be procured through testing laboratories. The testing laboratory can also provide guidance as regards to the cleanliness level needed. Oil sample pumps for extracting oil from reservoirs must be used properly to avoid contamination. Samples must be collected from the same point in the system to ensure consistency in the test analysis; therefore, the maintenance procedure must provide detailed direction on where and how to collect samples. The equipment operators can collect samples. Each sample is marked with the system/machine name, sample location point (the system may have multiple sample points), date, elapsed operating time for the system/machine, and other comments such as last “topping off” or filtering operation. The analyst will also need to know the amount of oil in the reservoir to make recommendations to correct abnormalities.

5.1.4 Non-Destructive Testing

Non-Destructive Testing (NDT) evaluates material properties and quality of manufacture for expensive components or assemblies without damaging the product or its function. Instead of statistical sampling techniques that use only surface measurements or require the destructive testing of selected components from a production lot, NDT is used when these testing techniques are cost prohibitive or ineffective. Typically, NDT has been associated with the welding of large high stress components such as pressure vessels and structural supports. Process plants such as refineries or chemical plants use NDT techniques to ensure integrity of pressure boundaries for systems processing volatile substances.

Techniques

The following section discussed various NDT techniques:

(i) Radiography

Radiography is performed to detect sub-surface defects. Radiography or X-ray is one of the most powerful NDT technique available in industry. Depending on the strength of the radiation source, radiography can provide a clear representation (radiograph) of discontinuities or inclusions in material several inches thick. X-ray or gamma ray sensitive film is placed on one surface of the material to be examined. The radiation source is positioned on the opposite side of the piece. The source may be either a natural gamma emitter or a powered X-ray emitter. The source is accurately aligned to ensure the proper exposure angle through the material. When all preparations and safety precautions are complete, the radiation source is energized or unshielded. Gamma or X-rays pass through a material and expose film placed under the material. By developing the film in a manner similar to photographic film, an image of defects or inclusions in the material is produced. More advanced radio luminescent film does not require photographic processing. Multiple “shots” from varying angles provide a complete picture of the thickness of the material. Dual angles are required to determine the size and orientation of an inclusion.

Once the type, size, and orientation of each inclusion are defined, these can be classified as either acceptable inclusions or unacceptable defects. Defects in the material must be accurately located to facilitate minimal material removal, yet ensure the defect has been completely eliminated. Minimizing material removal also minimizes repair cost and reduces the likelihood of additional defects created by the repair. The repair is then re-evaluated to ensure the defect removal and subsequent repair were conducted properly.

Radiography, though a versatile tool, is limited by the potential health risks. Use of radiography usually requires the piece be moved to a special shielded area, or that personnel be evacuated from the vicinity to avoid exposure to the powerful radiation source required to penetrate several inches of dense material. Temporary shielding may also be installed, but the installation and removal of thousands of pounds of lead is labor intensive and rarely worth the expense. Radiography technicians are trained in radiation health physics and material properties. These technicians can visually distinguish between welding slag inclusions, porosity, cracking, and fatigue when analyzing radiographic images.

(ii) Ultrasonic Testing (Imaging)

Ultrasonic testing provides detection of deep sub-surface defects. Ultrasonic (UT) inspection of welds and base material is often an alternative or complementary NDT technique to radiography. Though more dependent on the skill of the operator, UT does not produce the harmful radiation entailed with radiography. UT inspection is based on the difference in the wave reflecting properties of defects and the surrounding material. An ultrasonic signal is applied through a transducer into the material being inspected. The speed and intensity with which the signal is transmitted or reflected to a transducer provides a graphic representation of defects or discontinuities within the material. A couplant fluid is often used to provide a uniform transmission path between the transducer, receiver and the material of interest. Transducer configurations differ depending on the type of system used. Some systems use a single transducer to transmit and receive the test signal. Others use a transmit transducer in conjunction with a separate receive transducer. Dual transducer systems may be configured with both transducers on the same surface of the material or with transducers on the opposite surfaces of the material.

Three scan types are most commonly used: “A Scan,” “B Scan” and “C Scan.” A Scan system analyzes signal amplitude along with return time or phase shifts the signals travel between a specific surface and discontinuities. B Scan systems add signal intensity modulation and capability to retain video images. C Scan Systems include depth gating to eliminate unwanted returns. UT inspection is a deliberate process covering a small area (4 to 8 sq in.) at each sampling. Consistency in test method and interpretation of results is critical to the reliable test results. Surface preparation is also critical to reliable UT results. Any surface defects such as cracks, corrosion, or gouges will adversely affect the reliability of UT results. Due to the time and effort involved in surface preparation and testing, UT inspections are often conducted on representative samples of materials subjected to high stress levels, high corrosion areas and large welds. By evaluating the same sites at regular intervals, one can monitor the condition of the material. One hundred percent UT inspection is typically reserved for original construction of high stress components such as nuclear reactor vessels or chemical process vessels.

(iii) Magnetic Particle Testing

The NDT technique uses magnetic particle detection of shallow sub-surface defects.
Magnetic Particle Testing (MT) techniques are useful during localized inspections of weld areas and specific areas of high stress or fatigue loading. MT provides the ability to locate shallow sub-surface defects. Two electrodes are placed several inches apart on the surface of the material to be inspected. An electric current is passed between the electrodes producing magnetic lines. While the current is applied, iron ink or powder is sprinkled in the area of interest. The iron aligns with the lines of flux. Any defect in the area of interest will cause distortions in the lines of magnetic flux, which will be visible through the alignment of the powder. Surface preparation is important since the powder is sprinkled directly onto the metal surface and major surface defects will interfere with sub-surface defect indications. Also, good electrode contact and placement is important to ensure consistent strength in the lines of magnetic flux. A major advantage for MT is its portability and speed of testing. The hand-held electrodes allow the orientation of the test to be changed in seconds. This allows for inspection of defects in multiple axes of orientation. Multiple sites can be inspected quickly without interrupting work in the vicinity. The equipment is portable and is preferred for on-site or in-place applications. The results of MT inspections are recordable with a high quality photograph or transfer to tape. Fixing compounds are available to "glue" the particle pattern in-place on the test specimen. Interpretation of results depends on the experience of the operator.

(iv) Dye Penetrant

Dye Penetrant is used to detect surface defects. Dye penetrant (DP) inspections provide a simple method for detecting surface defects in nonporous materials. DP allows large areas to be quickly inspected. Once the surface has been cleaned, a penetrating dye (magenta or fluorescent color) is sprayed liberally on the entire surface. The dye is allowed to penetrate for several minutes. The excess dye is then wiped from the surface leaving only the dye that has been drawn into surface defects. A developer (usually white) is sprayed on the entire surface (same area as the dye application). The developer draws the dye from the defects, producing a visual indication of the presence of surface defects. The defective areas are then identified for repair and the remaining dye and developer are removed.

(v) Hydrostatic Testing

Hydrostatic Testing (Hydro) is an NDT method for detecting defects that completely penetrate pressure boundaries. Hydros are typically conducted prior to the delivery or operation of completed systems or subsystems that act as pressure boundaries. As the name implies, hydrostatic tests fill the system to be tested with water or the operating fluid. The system is then sealed and the pressure is increased to approximately 1.5 times operating pressure. This pressure is held for a defined period. During the test, inspections are conducted to find visible leaks to well as monitor pressure drop and make-up water additions. If the pressure drop is out of specification, the leak(s) must be located

and repaired. The principle of hydrostatic testing can also be used with compressed gases. This type of test is typically called an air drop test and is often used to test the integrity of high pressure air or gas systems.

Applications

1. *Radiography*. Radiographic techniques are readily applicable to metal components, including weld deposits. Specialized applications for plastics or composite materials are possible, though typically these materials are not most economically inspected with radiography. For thick cross-sections, radiography is often the only reliable method for inspection.
2. *Ultrasonics*. UT techniques are applicable to metal components including weld deposits. Specialized applications for plastics or composite materials are common. When possible, UT is a preferred method over radiography for in-place applications, due to expense and safety precautions required by radiography. UT is especially useful since it only requires access to one surface of the material. Ultrasonic techniques provide excellent penetrating power for thick cross-sections.
3. *Magnetic Particle*. MT techniques are applicable only to materials that conduct electric current and magnetic lines of flux. Only shallow defects are detectable with MT inspection. Typically, these techniques are most effective on welded areas. The speed of testing allows multiple inspections to be conducted along different axes to detect defects in different orientation planes.
4. *Dye Penetrant*. DP inspections are applicable for any nonporous material that is chemically compatible with the dye and developer. This is the simplest NDT technique in which to gain proficiency.

5. *Hydrostatic Testing*. Hydros test the integrity of pressure boundaries for components and completely assembled systems that contain pressurized fluids or gases. Identification of defects that penetrate the entire pressure boundary is the primary application for hydrostatic testing.

Limitations

1. *Magnetic Particle*. MT techniques are applicable only to materials that conduct electrical current and influence magnetic lines of flux. The difference in the influence of the lines of flux between base material and the defect is the basis for MT inspection. Only small areas (30 sq in.) between the two electrodes can be inspected. Surface preparation is important, though not as critical as with UT.

Consistent electrode contact is critical. Loose contact will weaken the magnetic lines of flux to the point where the influence of a defect may not be visible in the filing pattern. Operator skill is important, though this is a relatively simple technique. No historical record is produced for each test, unless specific steps are taken to photograph the result of each test.

2. *Ultrasonics*. UT techniques are one dimensional. Unless special techniques are applied, defects that parallel the axis of the test will not be apparent. Components constructed using laminate techniques or layered construction present special problems for UT techniques, since the boundary between each layer may be interpreted as a defect. The thicker the layers of base material, the more likely UT will provide usable results.

3. *Radiography*. Effective use of radiography mandates expensive equipment, extensive safety precautions and skilled technicians to interpret the images. Expensive tracking and security for radiation sources is mandatory. Safety precautions often demand evacuation of areas adjacent to the piece being examined or installation of extensive shielding. Even with these limitations, radiography is often the most effective method of assuring integrity of critical welds, structural members, and pressure boundaries. As material thickness increases, radiography is often the only acceptable method to achieve a 100 percent penetration.

4. *Dye Penetrant*. Minute surface discontinuities such as machining marks will become readily apparent. The inspector must be trained to distinguish between normal surface discontinuities and defects that must be repaired. The dye and developer are usually sprayed or painted on the piece to be inspected, so overspray and protection of internal surfaces are prime concerns for systems with stringent chemistry and cleanliness control. Product cleanliness standards may prohibit the use of DP inspection.

5. *Hydrostatic Testing*. Cleanliness and chemistry control of the fluid must be consistent with the operating standards of the system. Close attention should be given to controlling system thermodynamic parameters during the test to prevent over pressurization of the system. Over pressurization could lead to unintended damage to the system. Individual component hydros do not ensure system integrity. A final hydro of the completed system is used to ensure the integrity of the assembled system's pressure boundary.

6. Hydros will not identify defects that are present, but have not completely penetrated a pressure boundary. The pressure applied to the system is generally not sufficient to enlarge existing defects to the point of detection by the test. Hydrostatic testing requires a pressure source capable of expeditiously filling and pressurizing the system, extensive instrumentation and monitoring equipment, along with a sufficient quantity of fluid to fill the system. A method of isolating pressure relief devices and connecting the pressure source to the system must be provided.

6.0 MAINTENANCE PLANNING

An effective maintenance planning is essential in an organization. It is good practice to conduct some form of analysis to identify the appropriate maintenance tasks to care of equipment.

The analysis will result in a list of tasks that need to be sorted and grouped into sensible chunks, each forming the content of a checklist. The most obvious next step is to schedule the work orders generated into a plan of work for the workshop teams. Less common, however, is to use this checklist data to create a long-range plan of forecasted maintenance work.

This plan serves two purposes:

(i) The results can be used to determine future labour requirements, and

(ii) They feed into the production plan.

The schedule of planned jobs is issued to the workshop and when the work is completed, feedback from these work orders, together with details of any equipment failures, is captured for historical reporting purposes.

A logical response to this shop floor feedback is that the content of the checklists should be refined to improve the quality of the preventive maintenance, especially to prevent the recurrence of failures.

The purpose of maintenance measures should be to monitor the health of the maintenance organisation. Where everything is in control, the metrics (Table 1; NASA, 2000) will reflect the success that has been achieved. Conversely, they should also be used to highlight problem areas and irregularities in order to drive the desired behaviours or areas for improvement.

There is value in constructing a hierarchy of the equipment system showing assemblies, subassemblies and individual components. This helps to keep track of which section of the system is being considered at any time, and the list of components helps to identify the spare parts requirements for the system.

Of vital importance is the clear identification of the root cause of each failure, as this will affect the selection of a suitable maintenance task. Also important from a planning perspective is to identify the time it will take to carry out each task independently. The sum total of these task times gives a good indication of how long the total work order will take.

Table 1: Metrics for Maintenance performance

Metric	Variables and Equations	Benchmark
Equipment Availability	% = Hours each unit is available to run at capacity / Total hours during the reporting time period	> 95%
Schedule Compliance	% = Total hours worked on scheduled jobs / Total hours scheduled	> 90%
Emergency Maintenance Percentage	% = Total hours worked on emergency jobs / Total hours worked	< 10%
Maintenance Overtime Percentage	% = Total maintenance overtime during period / Total regular maintenance hour during period	< 5%
Preventive Maintenance Completion Percentage	% = Preventive maintenance actions completed / Preventive maintenance actions scheduled	> 90%
Preventive Maintenance Budget/Cost	% = Preventive maintenance cost / Total maintenance cost	15% – 18%
Predictive Maintenance Budget/Cost	% = Predictive maintenance cost / Total maintenance cost	10% – 12%

The following are a few points to consider when constructing a preventive maintenance program:

Preventive maintenance tasks must:

(i) aim at the failure process

(ii) be specific

(iii) include specifications or tolerances

(iv) wherever possible, aim for predictive rather than preventive tasks

(v) measure or check for conditions against a standard

(vi) report the results

(vii) create a follow-on task to repair or replace at the next opportunity

(viii) *"Check and replace, if necessary"* tasks destroy planned times

(ix) Frequencies and estimated times for each task must be accurate and meaningful

Try wherever possible to plan shutdown time for "non-running" tasks. Keep "running" tasks to be done during periods of normal production. Structure the maintenance program to allow for this.

In many cases however, there is no such regular routine in place. Opportunities for the maintenance teams to conduct planned maintenance need to be negotiated and agreed with the production teams on an "as-needed" basis. Unfortunately, this is very often reduced to the maintenance department begging for access to the equipment. Furthermore, this plea is often met with the unsympathetic response from the production teams that they have to run the equipment in order to meet their targets and they therefore cannot afford to release it for maintenance.

7.0 PLANNING OF THE SPARES STOCK

Spares stock management plays an important role in achieving the desired plant availability at an optimum cost. Industries nowadays are going for capital intensive, mass production oriented, and highly improved technology. They cannot afford to have downtime for such plant and machinery. Non-availability of spare parts, as and when required for repairs, may contribute to as much as 50% of the total down time. In addition, the cost of spare parts is more than 50% of the total maintenance cost in the industry. While maintenance department complains of the non-availability of the spare parts to meet their requirement, finance department faces the problem of increasing locked up capital in spare parts inventory. This is why spare parts management is essential in any organisation.

The unique problems faced by the organisation in controlling/managing the spare parts include an element of uncertainty to know when a part is required and the quantity that is required. This is because the failure of a component, either due to wearing out or due to other reasons, cannot be predicted accurately. Moreover, spare parts may not be easily available in the market as they may not be fast moving items. The original equipment manufacturer has to supply the spares in most of the cases, may have introduced new models and phased out the old models. Hence, the spares for old models may not be readily available especially for imported equipment as the design changes are taking place faster in the developed countries. Furthermore, the number and variety of spare parts are too large making the close control more and more tedious. For instance, the number of items of spares in a medium scale engineering industry may be around 15,000 and that in a large-scale chemical industry may be around 100,000. In addition, there is a tendency from the stage of purchase of the equipment to the stage of the use of the spare parts, to request for more spare parts than are actually required and accumulation of is very low. These problems are faced spares takes place. Finally, the rate of consumption of spare parts for some is very high and for some by systematic spare parts manager.

The objective of spare parts management is to ensure that spares are available at the right price, right quality, right quantity and at the right time for maintenance and repairs of the plant and machinery.

There is a need for systematic actions while managing spare parts as given below:

a. Identification of spare parts

b. Forecasting of spare parts requirement

c. Inventory analyses

d. Formulation of selective control policies for various categories

e. Development of inventory control systems

f. Stocking policies for capital & insurance spares

g. Stocking policies for rotable spares or sub- assemblies

h. Replacement policies for spare parts

i. Spare parts inspection

j. Indigenisation of spares

k. Reconditioning of spare parts

l. Establishment of spare parts bank

m. Computerization of spare parts management.

Every organisation should proceed systematically and establish an effective spare parts management system. Codification helps the organisation minimizing duplication of spare parts stocking thereby reducing inventory, aids the accounting process, and facilitates the computerisation of spare parts control systems. The inventory analyses carried out based on different characteristics of the spare parts, such as annual consumption value, criticality, lead time, unit cost and the frequency of use, help the company in establishing suitable policies for selective control. This also helps in focusing our efforts on real problem areas.

A good inventory control system will help systemizing the ordering procedure and achieving an optimum level of inventory. In addition, efforts should be made to evolve optimum replacement policies for selected spare parts, for which cost of down time and cost of replacement are very high. Therefore, we have to identify such spare parts and carry out the exercise for evolving optimum replacement policies.

For the spare parts that are very expensive and those that are to be imported, it is essential that the useful life for such spares is extended by appropriate applications of reconditioning and repair techniques. In addition, efforts should be made to indigenise the spare parts in view of the hard-to-get foreign exchange involvement. Moreover, for similar industries establishing of spare parts bank goes a long way in reducing the total inventory holding of the expensive spare parts and reduces the stock holding cost. For different industries, it will be helpful to establish spare parts banks and a suitable information system for the exchange of spares. Lately, the application of computers for the processing of spare parts information and operating an effective spare parts control system will be very helpful for the organisation and maintenance engineering and management will ensure timely actions for an efficient and effective spare parts management.

7.1 Identification of Spare Parts

When a spare part is required to put back in operation equipment, which is under breakdown, it becomes necessary to identify the part for getting the same issued from the store or for purchasing the same from the vendor. While identifying the spares, it becomes essential to give the complete description including the size and type of the spare to draw from the stores and it becomes essential for all concerned i.e., the maintenance personnel and stores personnel are aware of such description. If it is the vendor, he may not be satisfied with the description and he may require the manufacturer's part number.

It is a cumbersome and time-consuming task during every transaction to identify a spare part by its description and manufacturer's part number accompanied by the parent equipment's name, make, and model designation. Therefore, it is essential to give a numerical name or code to each spare part. This process of giving code to each spare part is called codification. Since, the range of spares used in any organisation is too large and there are quite a few spares meant for specific equipment, it is always preferred to use codes which are significant i.e., from the code number one will be able to find out

- Equipment type, make & model
- Type/class of the spare-part
- Size (in some cases)

If the spare part code is to incorporate the equipment type etc., then the codification of equipment becomes a prerequisite for spare part codification.

The number of digits required for spare part code depends on the actual requirement i.e., the range of equipment in use and the types and number of spare parts in the organisation. It is very common to come across 9 to 16 digit codes for spare parts. For instance, a 10-digit code may signify,

1st digit - imported or indigenous

2nd, 3rd, & 4th digits - machine type, make, & model

5th, 6th & 7th digits - spare-part class

8th, 9th, & 10th digits - size or serial number.

By classifying and codifying all the spare parts, it becomes easy to minimize the duplication of spare parts thereby effecting reduction in the inventory. Codification also helps easy accounting and computerisation in addition to easier communication between concerned parties.

In addition to codifying the spare part, it will be of immense benefit to codify the location of spare parts. Stock location number helps the stores personnel to locate the part and issue the same as and when the same is requested for. In addition, the stock verification and upkeep programme becomes less and less cumbersome.

After codifying the spare parts and assigning stock location numbers, all the users: maintenance engineering and management should be aware of and be supplied with the relevant codes and stock location numbers in the form of a spare parts catalogue.

The spare parts catalogue should contain the following information:

Spare parts codification plan

Spare part code

Spare part description

Drawing number

Manufacturer's code & part number

Stock location number.

The spare parts catalogue may be produced in sufficient copies to make available for all the users such as the maintenance personnel, stores personnel and purchase personnel. This is a very important aspect often neglected in the organisation.

The next step in identification of spare parts is to put an identification tag or mark with the code to enable the stores personnel identify during the time of issue. If sufficient care is not taken to incorporate the code, a lot of time is spent in locating the part and that time is actually added to the down-time which is really very expensive in case of vital spare parts. There are a variety of stickers, which are scratchproof, waterproof and temperature-proof available in the market. Efforts should be made by the organisations to make use of such identification tags and it will go a long way in reducing the downtime.

7.2 Inventory Analysis and Selective Control

For the successful spare parts management, it is essential to analyze the spare parts inventory based on various characteristics such as the frequency of issues, the annual consumption value, the criticality, the lead-time, and the unit price. This is essential as it would not be possible to exercise the same type of control for all items and it may not really be effective. Inventory analysis aids selection of policies for selective control.

Commonly used inventory analyses are:

(1) FSN Analysis

(2) ABC Analysis

(3) VED Analysis

(4) SDE Analysis

(5) HML Analysis

FSN Analysis:

This is a Classification based on Frequency of Issues/Use:-

F, S & N stand for fast moving, slow moving, and Non-moving items. This form of classification identifies the items frequently issued; less frequently issued for use and the items which are not issued for longer period, say, 2 years. For instance, the items can be classified as follows:

Fast Moving (F) = Items that are frequently issued say more than once a month.

Slow Moving (S) = Items that are issued less than once a month.

Non-Moving (N) = Items that are not issued\used for more than 2 years.

This classification helps spare parts management in establishing most suitable stores layout by locating all the fast moving items near the dispensing window to reduce the handling efforts. In addition, attention of the management is focused on the Non-Moving items to enable decision as to whether they are required in the future or they can be salvaged. Experience shows that many industries, which are more than 15 years old, have more than 50% of the stock as non-moving spares.

Even if a few of them are disposed off and the locked up capital is made available, it will make available additional working capital to the organisation. Action for disposal should be taken based on the value of each item of spare.

SDE Analysis:-

Classification based on the lead-time:

This classification is carried out based on the lead-time required to procure the spare part. The classification is as follows:

Scarce (S): Items, which are imported, and those items, which require more than 6 months' lead time.

Difficult (D): Items, which require more than a fortnight but less than 6 months' lead-time.

Easily available (E): Items, which are easily available i.e., less than a fortnights’, lead-time.

This classification helps in reducing the lead-time required at least in case of vital items. Ultimately, this will reduce stock-out costs in case of stock-outs. A comprehensive analysis may ultimately bring down lead-time for more & more number of items. This will also result in streamlining the purchase and receiving systems and procedures.

VED Analysis:-

This is the Classification Based on Criticality:

Several factors contribute to the criticality of a spare part. If a spare is for a machine on which many other processes depend, it could be of very vital importance. In addition, if a spare is, say, an imported component for which procurement lead-time could be very high it's non- availability may mean a heavy loss. Similarly, spares required for fighter aircraft at the time of war could be of great value in terms of fighting capability. In general, criticality of a spare part can be determined from the production downtime loss, due to spare being not available when required.

Based on criticality, spare parts are conventionally classified into three classes, viz. vital, essential, and desirable.

VITAL (V): A spare part will be termed vital, if because of its non-availability there will be very high loss due to production downtime and/or a very high cost will be involved if the part is procured on emergency basis. In a process industry, most spare parts for the bottleneck machine or process will be of vital nature. For example, bearings for a kiln in a cement plant will be considered as vital

ESSENTIAL (E): A spare part will be considered essential if, due to its non-availability, moderate loss is incurred. For example, bearings for motors of auxiliary pumps will be classified as essential.

DESIRABLE (D): A spare part will be desirable if the production loss is not very significant due to its non-availability. Most of the parts will fall under this category.

The VED analysis helps in focusing the attention of the management on vital items and ensuring their availability by frequent review and reporting. Thus, the downtime losses could be minimized to a considerable extent.

ABC Analysis:-

Classification Based on Consumption:

Another method of classifying spares is based on **annual consumption value.** As it is true for any inventory situation, Pareto's principle can be applied to classify maintenance spares based on consumption value.

Pareto principle: The significant items in a given group normally constitute a small portion of the total items in a group and the majority of the items in the total will, in aggregate, be of minor significance.

This way of classification is known as ABC classification.

CLASS A: 10% of total spares contributing towards 70% of total consumption value.

CLASS B: 20% of total spares which account for about 20% of total consumption value.

CLASS C: 70% of total spares which account for only 10% of total consumption value.

In a specific spares control system, it is quite possible that in a single year, many spares would not have been consumed at all. In such cases, it is better to perform ABC analysis on longer consumption period data, say 3 years. Then only spares will not be left out in this classification.

Policy for 'A' items

* Maximum control
* Value Analysis
* More than one supplier
* Control by top executives.

Policy for 'B' items

* Minimum control
* Bulk Orders
* More items from same supplier.

HML Analysis:-

Classification based on unit price:

This classification is as follows:

High Cost (H): Item whose unit value is very high.

Medium Cost (M): Item whose unit value is of medium value.

Low Cost (L): Item whose unit value is low.

This type of analysis helps in exercising control at the shop floor level i.e., at the use point. Proper authorisation should be there for replacing a high value spare. Efforts may be necessary to find out the means for prolonging the life of high value parts through reconditioning and repair. Also, it may be worthwhile to apply the techniques of value analysis to find out a less expensive substitute.

Some other Classifications based on other characteristics:

A) Capital Spares:

These are vital spares for critical equipment. The stock-out cost for such spares is very high and the unit cost is very high. The number of items consumed during the lifetime of the equipment may be 1 or 2 or 3. Hence, the decision has to be made as to the number of items to be stored.

B) Insurance Spares:

An insurance item is a spare part that will be used to replace a failed identical part in operating equipment whose penalty cost for downtime is very high. Hence, by definition, it is an insurance against such failures for which the down time costs are very high. They do not become obsolete until the parent equipment is retired from service no matter if they do not move for many years.

C) Overhaul spares:

Spare parts, which must be replaced every time the equipment is dissembled and re-assembled.

D) Wear and Tear Spares:

Spare parts, which have regular wear and tear in the course of operation of the equipment and need to be replaced after definite number of hours of equipment operation.

E) Consumable spares

These are regularly used items such as fasteners, seals, bearings, etc. These are to be stored by the materials department.

7.3 Inventory Control Systems

To ensure smooth functioning of a system, it is essential to develop a suitable inventory control to achieve optimization of spare parts cost. For fast moving and slow moving items, the following procedure can be followed taking into consideration various cost elements.

While managing the spare-parts inventory, there are four cost elements to be considered:-

1. Cost of the spare part
2. Cost of ordering
3. Cost of storage
4. Cost of stock-out.

The cost of storage includes

1. Rent for the stores
2. Depreciation on storage and handling facilities
3. Handling charges
4. Salaries of stores staff and clerks
5. Taxes
6. Insurance
7. Costs of stationery etc.

The cost of ordering includes:

1. Rent for purchase department
2. Depreciation for Office facilities
3. Salaries
4. Postage & Telephone expenses
5. Stationery expenses
6. Travel expenses
7. Incoming Inspection
8. Entertainment & Misc. expenses.

7.3.1 Concept of Economic Order Quantity

For ideal conditions, there should be no stocks at all. Every item should arrive just before it is required in right quantity. This however is not practical for two reasons. Firstly, the supplies and requirements are not so certain and, secondly, the costs of placing orders and follow-up work will be very high, by ordering in such small batches. Therefore, for a particular annual consumption as we go on increasing the quantity of order, the average stock increases and, hence, carrying charges go on increasing. There are two basic inventory decisions managers must make as they attempt to accomplish the functions of inventory just reviewed. These two decisions are made for every item in the inventory.

1. How much an item to order when the inventory of that item to be replenished,
2. When to replenish the inventory of that item.

The economic order quantity (EOQ) model is the oldest and the best -known inventory model; its origins date all the way back to the 1915. The purpose of using the EOQ model is to find that particularly quantity to order, which minimises total inventory costs. Let us look for a moment at these costs.

Inventory Costs:

There are two basic inventory costs;

i. Ordering Costs,
ii. Carrying or holding Costs.

Ordering Costs are the cost of getting the item into the firm's inventory. Therefore, ordering costs are the cost of *replenishing inventory*. They are occurred each time an order is placed and are expressed *Monetary Unit Cost (MU)* such as $ or TL per order. **Ordering Costs** start with the requisition sent to purchasing office, include all cost of issuing to purchase order and of following it up, and continue with such steps as receiving the goods and placing them into inventory, and end with the buying firm paying the supplier. Salaries constitute the major ordering cost while stationary is another ordering cost.

Ordering costs generally react inversely to carrying costs. As the size of orders increases, fewer orders are required, thus reducing ordering costs.

Economic Ordering Quantity (E.O.Q).

$$EOQ = \sqrt{\{(2DO)/(Hp)\}}$$

Where D = Annual consumption/demand of items in Units

O = Cost per order

H = Carrying charges per year expressed as fraction

p = Unit price

E.O.Q = Economic Order Quantity in Units.

Example

A company uses about 200 bearings per month. It pays a broker ₦ 80 per order to locate a supplier and handle the ordering and delivery arrangements. Its own storage and handling costs are estimated at 30% per year. Each bearing is estimated to cost ₦ 2000. What is the most Economical Order Quantity?

Solution:

Economic Order Quantity = $EOQ = \sqrt{\{(2DO)/(Hp)\}}$

The purchase price is relevant for computing carrying charges (only) and they must be in the same units as demand. We will (arbitrarily) use months.

$$\text{EOQ} = \sqrt{\{(2(200)(80)\}/\{(0.30)(2000)/12\}} = 25.4 \text{ bearings} \approx 25 \text{ bearings}$$

BIBLIOGRAPHY

Adejuyigbe, S.B. (2002). *Production Management (Design, Planning, Implementation and Control)* Topfun Publications, Akure, Nigeria

American Society of Non-Destructive Testing, *Recommended Practice Number SNT-TC-1A* (Columbus, Ohio, 1992).

American Society for Testing and Materials (ASTM), *Annual Book of ASTM Standards, Section 5* (Philadelphia, PA, DATE).

API670, *Vibration, Axial-Position Bearing-Temperature Monitoring System* (American Petroleum Institute, New York, NY, DATE).

Bernowski, K. (1997) “Safety in the Skies,” *Quality Progress*, January.

Design and Manage Life Cycle Cost (M.A. Prace, Farmer Grove, OR, 1978).

General Motors Specification A 1.0*, Laser Alignment Specification for New and Rebuilt Machinery and Equipment* (1993).

Dovich, R. (1990) Reliability Statistics, ASQ Quality Press, Milwaukee, WI.

Harris, Tedric A., *Rolling Bearing Analysis* Second Addition (John Wiley & Sons, New York, NY, DATE).

Infraspection Institute, *Guideline for Infrared Inspection of Building Envelopes and Insulated Roofs* (Shelburne, VT, DATE).

Infraspection Institute, *Guideline for Infrared Inspection of Electrical and Mechanical Systems* (Shelburne, VT, DATE).

Infraspectio`n Institute, *Guideline for Measuring and Compensating for Reflected Temperature, Emittance and Transmittance* (Shelburne, VT, DATE).

Lundberg, G., and A. Palmgren, *Dynamic Capacity of Rolling Bearings*, Acra Polytech, Mechanical Engineering Series 1, R.S.A.E.E., No. 3, 7 (1947).

Krishnamoorthi, K.S. (1992) Reliability Methods for Engineers, *ASQ Quality Press*, Milwaukee, WI.

National Aeronautical and Space Administration (NASA). Reliability Centered *Maintenance Guide for Facilities and Collateral Equipment*. National Aeronautics and Space Administration, Washington, D.C. February 2000.

National Aeronautical and Space Administration (NASA), *Reliability Centered Maintenance Guide for Facilities and Collateral Equipment* (December, 1996).

Nowlan, F.S. and H.F. Heap, *Reliability-Centered Maintenance* (Dolby Access Press, San Francisco, CA 1978).

Okah-Avae B. E. (1996). *The Science of Industrial Machinery & Systems Maintenance*. Spectrum Books Ltd. Sunshine House, Emmanuel Alayande Street, Oluyole Industrial Estate, Ibadan, Nigeria.

Troyer, D. (2006) Strategic Plant Reliability Management Course Book, Noria Publishing, Tulsa, Oklahoma.

World Class Maintenance Management, Terry Wireman, Industrial Press Inc., 1990, pp. 7, 73.