FES/BarDyne
Technology
Transfer
Publication

#2

Dr. E. C. Fitch, P.E.
President
Tribolics, Inc.
Stillwater, Oklahoma U.S.A.

Extending Component Service Life Through Proactive Maintenance

Abstract

Today, the cost of running equipment to breakdown failure is too great in terms of downtime, parts inventory, maintenance personnel, and repair. Fortunately, there is an attractive new alternative known as "proactive maintenance."

This paper presents an overview of proactive maintenance and offers ways of extending the service life of system components. In a nutshell, proactive maintenance is concerned with the detection and correction of aberrant root cause failure conditions. The paper illustrates how such aberrant conditions can be identified and corrected and the penalty that is assessed for ignoring the symptoms of root cause aberrations.

Introduction

Proactive maintenance is an activity conducted to detect and correct root-cause aberrations that lead to failure. Hence, proactive maintenance in conjunction with reactive maintenance will significantly extend the service life of components and systems. In other words, the countdown of component service life has already started if any one of the root-causes of failure is allowed to persist long enough to initiate either material or performance degradation. The longevity of system components can be greatly extended by maintaining root-cause parameters within acceptable limits through the practice of "detection and correction" of root-cause aberrations as required by a proactive maintenance program. Acceptable limits mean that the values of critical root-cause parameters are within the range of operational severity that will lead to an acceptable service life of the component.

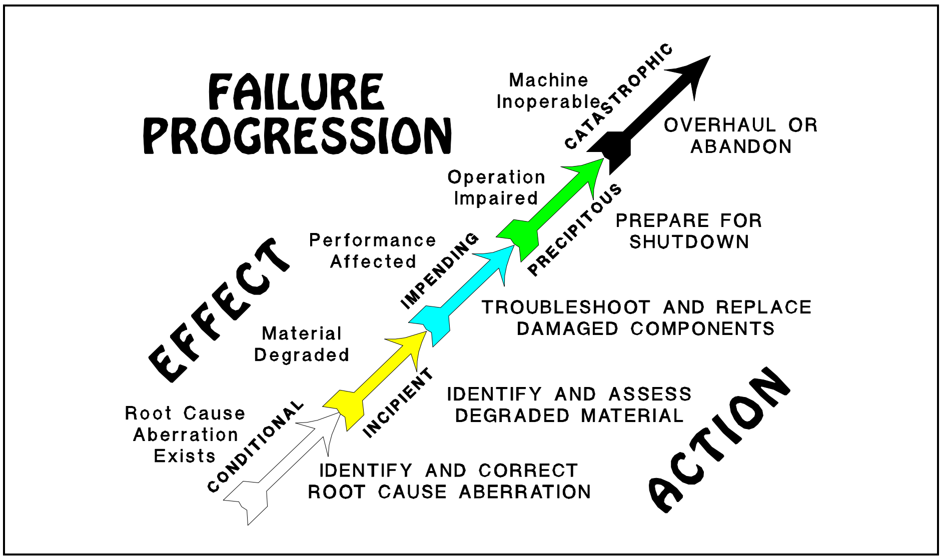
In fluid type mechanical systems, the stability of eight recognized root-causes of failure must be achieved to realize anything close to true component immortality. These critical (life dependent) component stability states are:

- Fluid Contamination Stability
- Fluid Leakage Stability
- Fluid Chemical Property Stability

- Fluid Physical Property Stability
- Fluid Cavitation Stability
- Fluid Temperature Stability
- Fluid Component Wear Stability
- Mechanical Loading Stability

Aberrations that can occur in each of the root-cause parameters result first in material deterioration, followed in turn by performance degradation, and finally resulting in the total loss of component and/or system functionality. Such abnormalities occur due to the conditions of use and the limits placed on the critical parameters associated with each of the root-causes. The conditions of use that lead to root-cause abnormalities (a state now termed conditional failure) produce material deterioration (incipient failure) that is the direct cause of performance degradation (impending failure) and that finally results in the state of functional impairment (i.e., breakdown--precipitous or catastrophic--failure), as Fig. 1 illustrates.

Figure 1
The Progression of Failure



In order to appreciate component failure characteristics, it is important to become familiar with service life parameters and life sustaining conditions that are typical of various components. These characteristics stem from a controlled root-cause condition and progress to a conditional failure state and finally to a totally dysfunctional state. Methods for detecting and correcting root-cause aberrations and recognizing component expiration characteristics are essential in achieving the pseudo state of component immortality. The key factor in any proactive maintenance program is knowing what to look for--that is, what root-cause abnormalities can occur that initiates the unforgiving component failure process. A look at some of these critical root-cause parameters will provide the reader a basis for detecting many conditions that persistently threatens component service life.

Fluid Contamination Stability

To achieve contamination stability in fluid dependent mechanical systems, the contamination in the fluid must be recognized and identified, analyzed and quantified, excluded and removed, and maintained at a level below the critical tolerance of the individual components of the system. The importance of these factors is reflected by the value of the contamination level of the fluid--see Fig. 2.

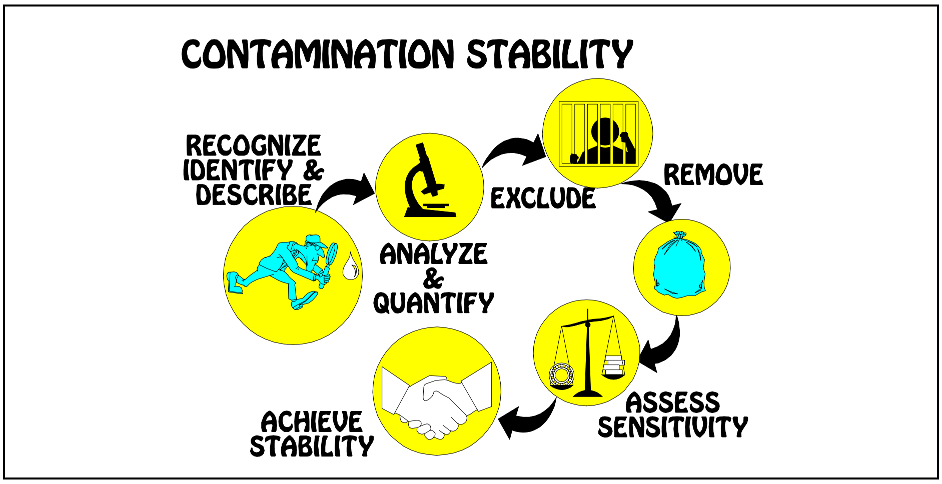


Figure 2
Achieving Contamination Stability

Three factors affect the material and performance degradation of a component--operation severity, fluid contamination level, and the component contaminant sensitivity or tolerance as Fig. 3 shows. Note that the contamination level is dependent on the filter efficiency (BETA) and the amount of contaminant that ingresses the system.

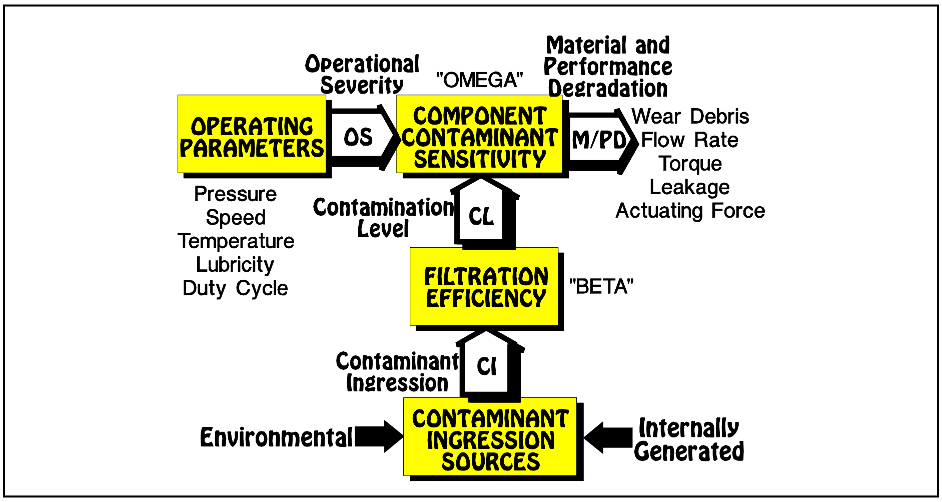


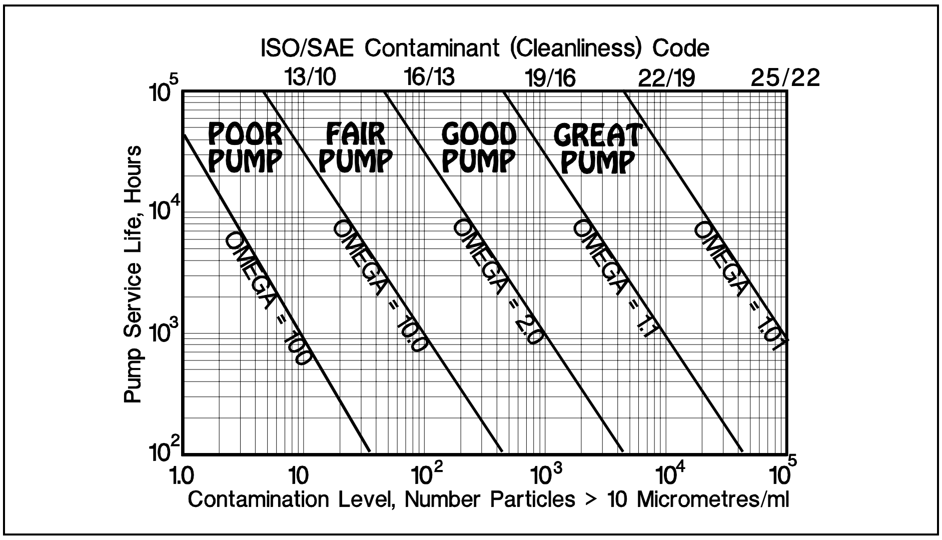
Figure 3
Contamination Stability Aspects

Particulate contamination in the fluid can cause three distinct types of failure modes to occur in system components--

- Contaminant Wear--particle abrasion and impingement erosion.
- Particle Jam--particle bridgement of control orifices.
- Contaminant Lock--silt lock, particle override, and obliteration.

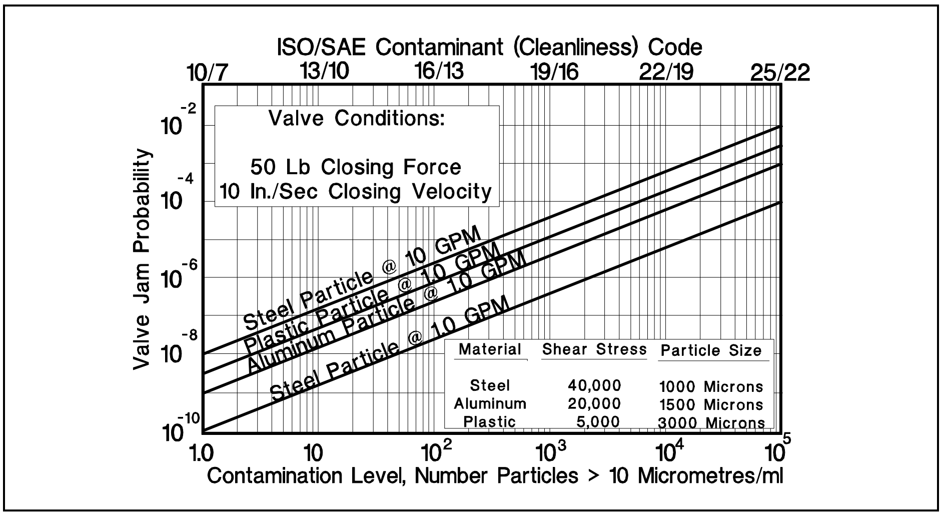
Contaminant wear is a failure mode that occurs due to the entrainment of solid particles in the fluid. When particles in the leakage or slippage fluid pass through clearance spaces, a three body type abrasion wear can take place. The particle becomes embedded in the softer of the two materials and proceeds to cut and destroy the harder surface. This is the wear condition that typically occurs in rotary pumps. The pump service life is a function of the Omega rating (a term that reflects the component contaminant sensitivity at operating conditions) of the pump and the contamination level subjected to the pump--see Fig. 4. Impingement erosion is the second form of contaminant wear and occurs particularly at control valve orifices and at other surfaces where high velocity fluid can impinge or strike the surface.

Figure 4
Pump Service Life vs.
Contamination Level



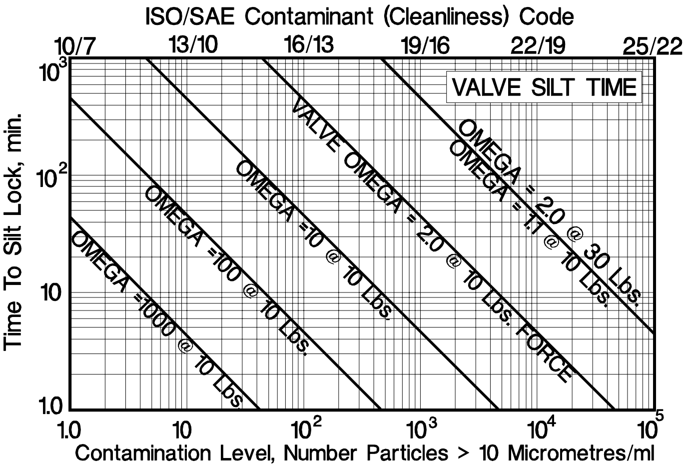
Particle jam occurs when one or more particles bridge across an orifice or clearance space and prevents or impedes the movement of fluid or mechanical elements. A shear jam is the term used to express a condition where a single tramp particle or group of particles happen to arrive at the point of closure of a valve at the exact moment to prevent closure. In this case, the shear strength of the particle(s) and the available closing force determine whether closure can occur. The probability that a shear jam will actually take place for a given contamination level is shown by the graph in Fig. 5 for a given closing force, speed of closure and particle shear strength.

Figure 5
Valve Jam Probability vs.
Contamination Level



Silt lock is a seizure condition that normally occurs at the entrance of a clearance space between the silt land of a spool and the valve bore. Relatively few particles are needed to bridge the entrance of a clearance and cause seizure, but a tremendous quantity of particles are needed to actually close off the clearance space. As the clearance space becomes sealed off, the silt force increases and finally reaches a steady state value. Whenever the silt force exceeds the force available to actuate the valve, silt lock or seizure has occurred. Every valve possessing silt lands has a specific silt lock susceptibility defined by the valve's Omega rating. The graph shown in Fig. 6 gives the time required to silt lock a valve having a given Omega rating and actuation force for a full spectrum of contamination levels.

Figure 6
Valve Silt Time at Rated Operating Pressure

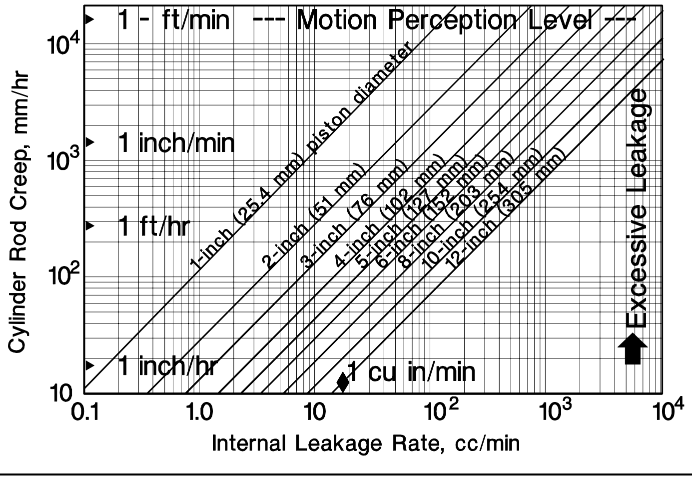


Maintaining the contamination level of the fluid within acceptable limits is essential in avoiding contaminant wear, jam, and lock. Thus the monitoring of contamination level satisfies the detection aspect of proactive maintenance for contamination stability. An aberrant level of contamination must be corrected (improve filtration and/or reduce ingression) if material and performance failure of the components is to be avoided.

Leakage Stability

All fluid systems exhibit leakage--external and/or internal. External leakage is the most apparent because it leaves its tracks no matter where it occurs. Internal leakage shows up in cylinder rod creep (see Fig. 7), depressurization of system, loss of pump flow output, and loss of position-hold capability of a cylinder.

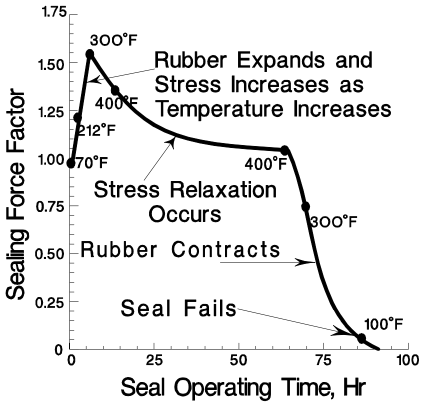
Figure 7
Cylinder Rod Creep Chart



The major factors affecting component and system leakage are worn or damaged seals, vibration sensitive fittings, improperly manufactured or installed hoses, and variations in fixed clearance sealing surfaces. By understanding the various leakage mechanisms and knowing how to effectively counteract them, leakage stability can be satisfactorily achieved.

The key factor in stabilizing sealing integrity is to maintain a positive sealing force. Elastomers used in seals are subject to stress relaxations that cause significant expansion and contraction of the sealing material and result in wide variations in sealing force--see Fig. 8. Seals can also swell or shrink due to elastomer/fluid incompatibility that can cause them to lose their sealing force and/or extrude into the clearance space and destroy the seal. Seals can also shrink due to high compression set of the elastomer following the vulcanization process.

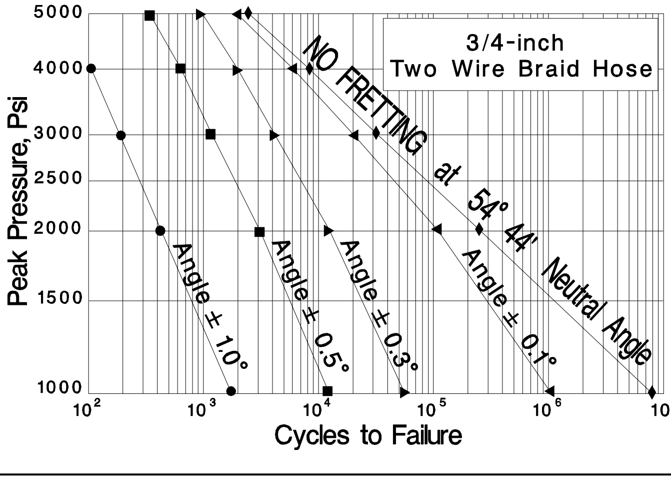
Figure 8
Elastomer Stress Relaxation



Line fittings are notoriously sensitive to machine vibration. If a fitting cannot maintain a proper sealing force, it will leak. A combination bite-type plus O-ring seal has proved to resist vibrations the best.

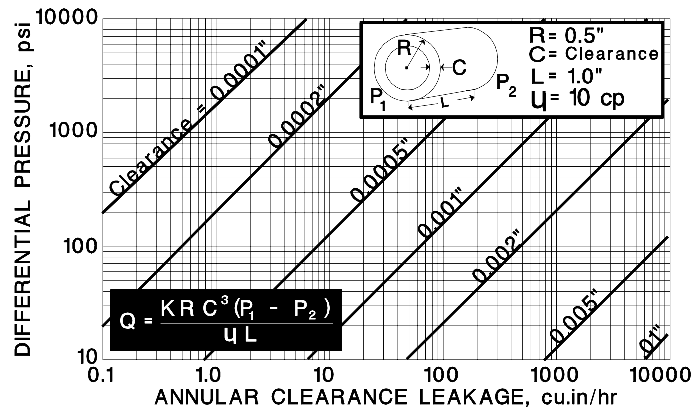
Hose failures have historically been blamed on misapplication and abuse. New hose technology has helped to identify where hose defects can occur--in the rubber chemistry, fabrication processes, and assembly practices. For example, when flow surges and pressure spikes occur, the failure mode has always been considered to be fatigue. But when the required neutral angle (54 deg. 44 min.) of the hose braid has not been achieved during the fabrication processes, the cycles to failure are significantly reduced as shown in Fig. 9. In assembly, if the wire braid of the hose is not integrally attached to the hose coupling, coupling blow-off is imminent in service. Finally, if the wire braid is exposed to the environment through skiving or cutting the protective cover during coupling attachment, wicking of moisture into the braided section can occur that results in the corrosion of the steel braid and failure. Keep in mind that if the hose inner liner is punctured during coupling assembly, high pressure fluid can penetrate to the end of the hose and blow off the coupling and/or it can migrate to the outer protective cover causing blisters, bulging around the end of the coupling, and finally emerge as external leakage.

Figure 9
Fretting Wear of Hose Wire Braid



Internal leakage occurs in all fluid systems. By and large, internal leakage is detrimental to the overall operation. Excessive internal leakage generates heat, reduces system efficiency and helps contribute to the deterioration of the system fluid. Technologists must recognize components and conditions where excessive internal leakage can and does occur. Generally speaking, clearance flow in valves increases proportional to the differential pressure and inversely to the viscosity of the fluid. Valve leakage is proportional to the cube of the clearance--thus increasing the clearance by a factor of three will increase the leakage by a factor of 27 (see Fig. 10).

Figure 10
Annular Type Clearance Leakage



Fluid Chemical Stability

Without good fluid chemical stability, system components will fail to perform as intended and result in a greatly reduced service life. The chemical properties of a fluid are significant indicators of component degradation in performance. Thus, the condition of a fluid can play a vital diagnostic function for all types of fluid systems.

Fluids in storage and service are constantly degrading because of exposure to the stresses of the system and the perils of the environment. Unfortunately when chemical degradation of a fluid takes place, the chemical composition of the fluid changes and the chemical reactions produce soluble and insoluble compounds that appear as resins, sludges, and acidic materials. These degradation products have an adverse effect on the fluid's performance by causing physical changes to occur--e.g., an increase in viscosity (see Fig. 11). Besides changes in physical properties of the fluid, four other changes usually take place:

- Odor--from the decomposition products
- Color--from combustion and reaction products
- Acidity--from the degradation of additives and the base stock of the fluid (see Fig. 12)
- Insoluble Products--reaction products are usually insoluble and precipitate.

Figure 11
Viscosity Change vs. Inhibitor

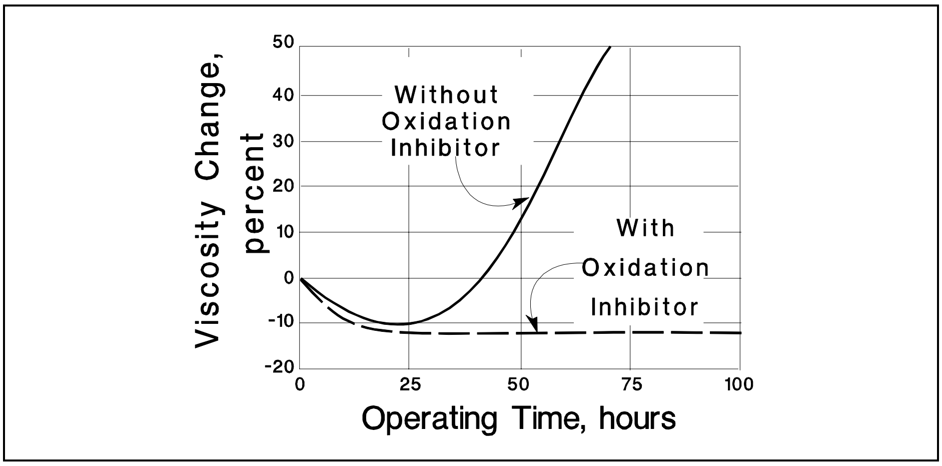
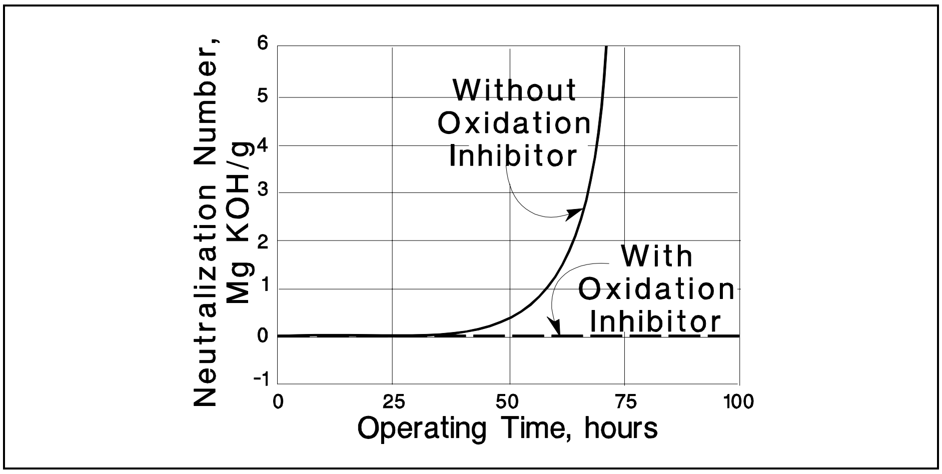


Figure 12
Neutralization Number vs. Inhibitor

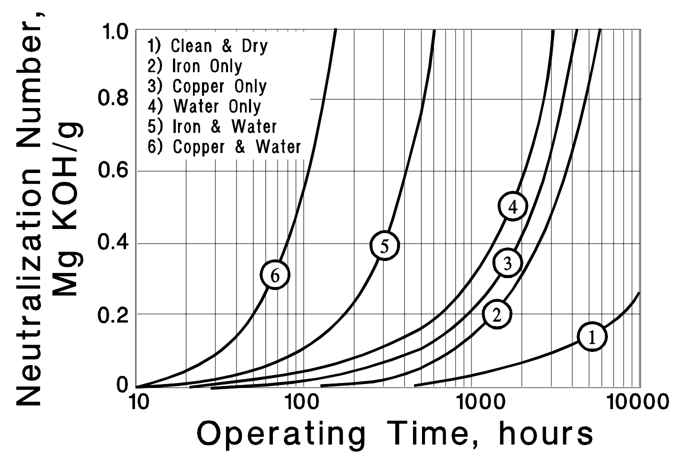


The rate that chemical decomposition of a fluid takes place is a function of the base stock and the additive package as well as the operating conditions during use. The chemical decomposition process is accelerated by the levels of temperature, pressure, contamination, aeration, moisture, metal particles and/or large surface areas (see Fig. 13), and mechanical agitation. Effective ways of controlling the deterioration of the fluid are through:

- Fluid analysis--to detect changes in chemical and physical properties of the fluid
- Fluid additives--selection of formulations including antioxidants, rust and corrosion inhibitors, and antiwear stabilizers.
- Fluid filtration--to remove catalytic materials and high surface area particles (concentrations of small particles)
- Fluid operating severity--limit the level of temperature and the amount of ingressed air, water, and dirt.

By the application of proactive maintenance methods, the service life of a hydraulic or lubricating fluid can be extended far beyond normal estimates.

Figure 13
Catalytic Effect On Fluids



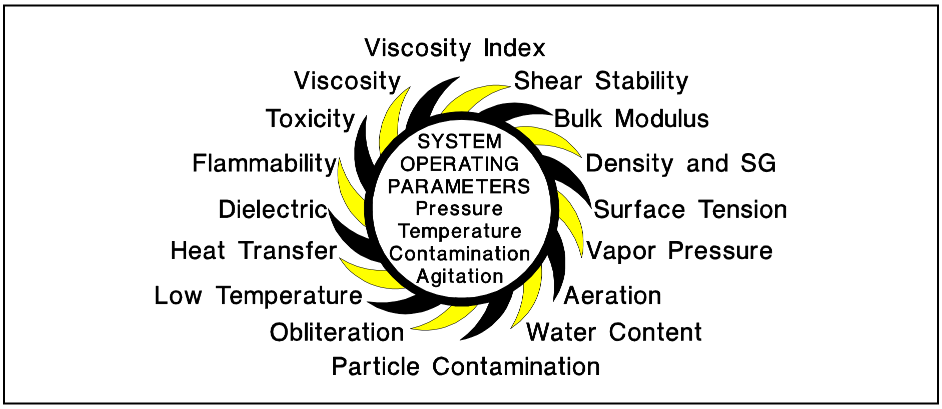
Fluid Physical Stability

The physical properties of a fluid are expected to vary with the state conditions of the system (e.g., pressure and temperature), the chemical composition of the fluid, mechanical agitation and shear, and finally with the type and concentration of contaminants. However, if physical stability of the fluid exists, then the physical parameters will return to their original values once the influential disturbance or the change in the operational state is no longer present. It is necessary that system fluids be specified that have physical properties that may change during use but not so much that the change significantly impairs operability or service life under defined ranges of operating conditions.

Physical properties of a fluid normally vary due to changing operating conditions but exhibit no change in the fluid's chemical composition. Changes in operating conditions can be so severe at times that eventually it can affect the fluid's physical properties so drastically that the fluid becomes totally unsuitable for its intended use. Thus the severity of service conditions determines the rate and extent that a fluid degrades. As with other system components, all mechanical-type system fluids subjected to service stresses can and will, in time, degrade, wear out and fail. Hence, maintenance personnel must make a practice of monitoring a fluid's physical properties for fluid serviceability in order to protect and preserve the integrity of the system.

The physical properties of a system fluid are identified in Fig. 14. Engineers consider the physical properties stable as long as the properties return to their original values when the system state parameters have their original reference values. The situation becomes serious and unpredictable when the properties fail to return to their respective reference points. Of course physical changes brought about by the chemical decomposition of the fluid are totally irreversible and the effected properties will never return to their original values.

Figure 14
Physical Stability
Properties of Fluids

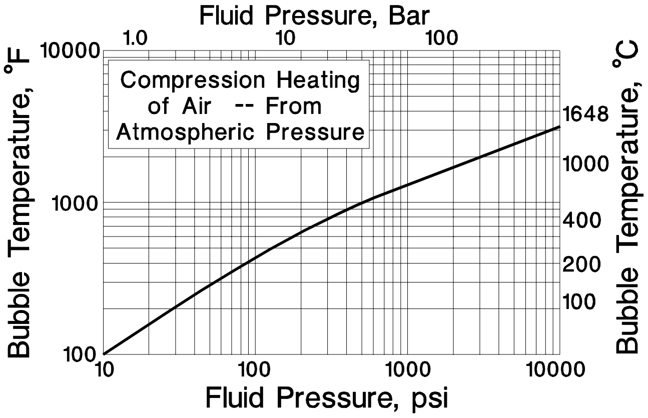


Cavitation Stability

This critical system state must exist if the performance and service life of the fluid and components are to be acceptable. Evidence of cavitation in a fluid system is noise, chatter, vibration, jerkiness, physical damage to components, high fluid temperature, loss of pump prime, decrease in volumetric efficiency, lack of system stiffness, loss of power and control, increase in fluid/material oxidation, and poor heat transfer characteristics.

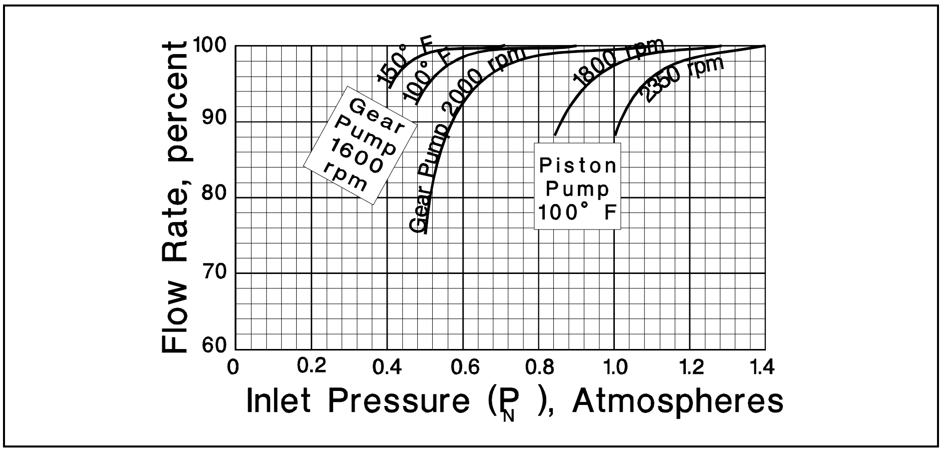
Cavitation is the formation and collapse of cavities in a moving liquid. When cavities form, the reduced pressure of the fluid makes the liquid appear to rupture (literally break apart). Air will occupy the cavities if the pressure falls below the saturation pressure of the air in the liquid. Similarly, air and vapor will occupy the cavities if the pressure falls to at least the vapor pressure of the liquid. When the bubbles collapse at higher pressure, the implosions occur in microseconds that can quickly fatigue and fracture adjacent material and cause an accelerated increase in fluid temperature (see Fig. 15).

Figure 15
Heat of Compression
of an Air Bubble



All pumps have limitations on their suction capabilities. For example, the output flow versus inlet pressure for a specific pump, pump speed and oil temperature as shown in Fig. 16. Thus for a given pump, fluid, temperature, and speed, the system must maintain a specific inlet pressure at the pump to achieve cavitation stability.

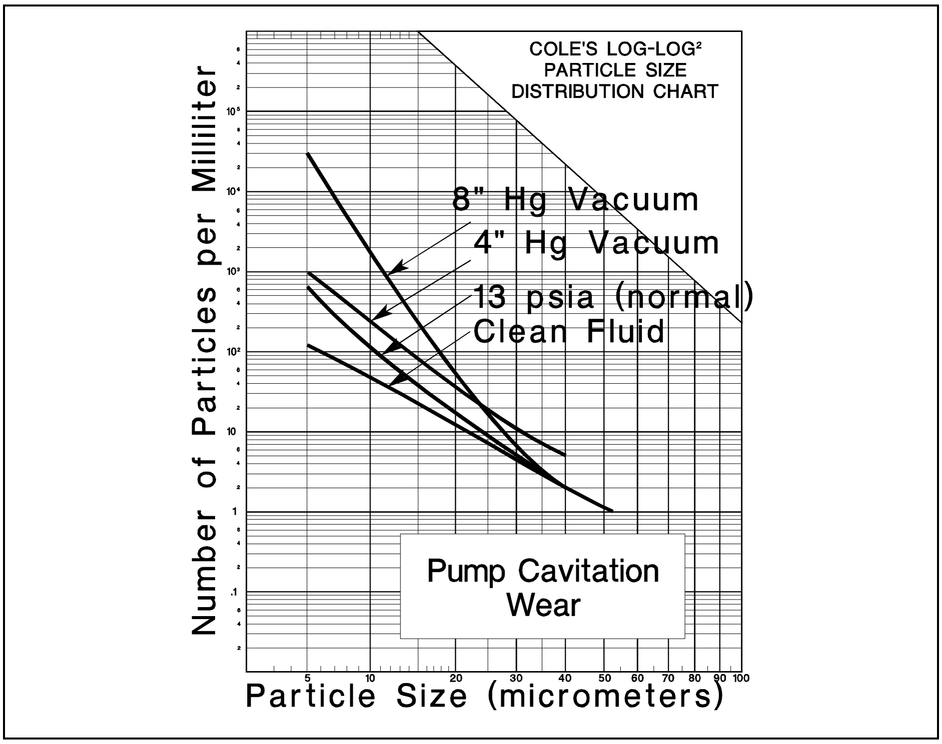
Figure 16
Pump Cavitation Conditions



Cavitation damage of adjacent material results from the implosions of vapor (not air) bubbles. Cavitation damage depends on many factors--the exposed material, fluid velocity, vapor pressure of fluid, air content, surface tension, and fluid viscosity.

Figure 17 shows the effects of reduced inlet pressure on pump damage as reflected by the amount of wear debris generated at each suction pressure level. In general, the number of particles less than 30 micrometres in size increases with cavitation severity. The increased concentration of particles indicates the enlargement of pump clearances, loss of volumetric efficiency, and finally the catastrophic destruction of the pump.

Figure 17
Pump Cavitation Damage



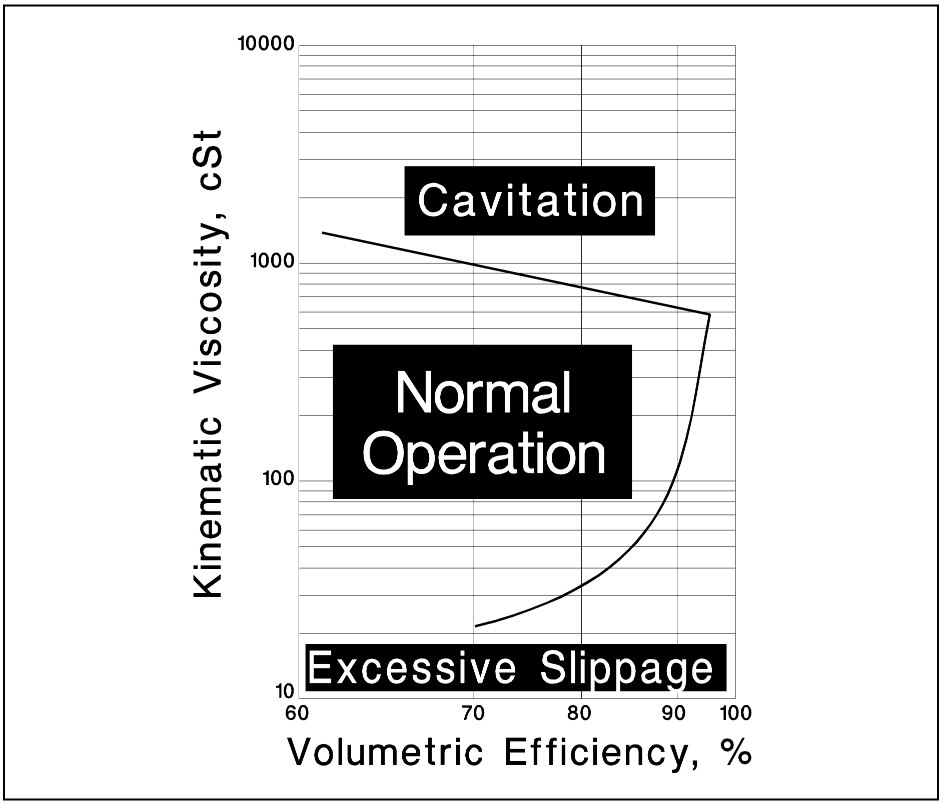
Temperature Stability

All fluid systems have practical limitations on the acceptable operating temperature range--both high and low. Whenever the system fluid temperature violates these limits, temperature stability is lost and both material and performance degradation ensues. When temperature is too low, fluid viscosity is high and may reach the point where the fluid actually congeals and will no longer flow. This loss of fluid mobility affects pumpability, and the system's response to input commands, and degrades important elastomer properties. At high temperatures, low fluid viscosity causes increased leakage, both internal and external. High temperatures also accelerates wear, destroys hydrodynamic lubrication regimes, causes thermal lock, increases oxidation rate, affects fluid compressibility, and expedites the depletion of critical additives in the fluid.

The temperature effects on materials and components are significant--e.g., elastomer's (seals and hoses) stiffness increases at lower temperature and can become brittle at sub-zero temperatures. At high temperature, most materials weaken and creep can "set in" causing a reduction in cross-sectional area until the material can finally no longer support the load and fracture occurs. A material's thermal expansion can create high thermal stresses and cause significant dimensional changes that often result in motion interference, thermal lock, and increased leakage.

To illustrate how the performance of a pump can be destroyed when temperature stability is lost, see Fig. 18. Under low temperature, the viscosity is high and a drastic drop in the oil's static pressure occurs as the suction attempts to draw the oil into the pump's inlet. This pressure reduction results in the creation of vaporous bubbles that violently implode on the high pressure side, creating very loud noises, strong vibrations, and wear of internal pump parts. Note in this figure that when the viscosity goes down due to high temperature, the volumetric efficiency also goes down because of increased internal leakage or slippage in the pump. This increased leakage condition accelerates the contaminant wear of all mating parts of the pump.

Figure 18
Fluid Temperature/Viscosity vs. Pump Volumetric Efficiency

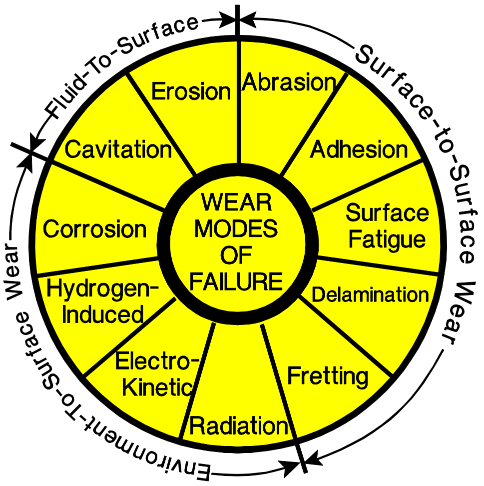


Wear Stability

Wear is the unwanted displacement or removal of surface material that alters the topography of a structure. Some wear is always occurring in an operating system. As long as the wear is mild, wear stability exists but when wear becomes excessive, incipient failure occurs. Finally, when surface wear reaches a stage where sufficient wear debris is produced, performance of the system is affected and impending failure occurs.

Wear results from overstressing a surface material. The actual mode of material removal depends on the composition of the surface and the nature of the stressing system, including the environment. The eleven recognized wear modes that can be active in fluid systems are presented in Fig. 19. The frequency with which the various wear modes are encountered in practice depends upon the type of equipment, the environment, and the duty cycle severity. Wear stability can be tracked and assessed by wear debris monitoring and analysis--e.g., using tribometric or ferrographic techniques.

Figure 19
Wear Modes in Fluid Type Mechanical Systems



Mechanical Stability

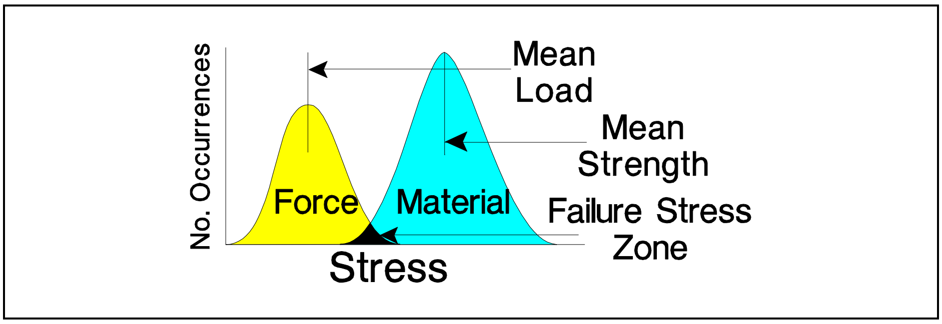
Many mechanical elements throughout the system determine whether the system can satisfy its intended purpose. The loading of control elements and machine members, the stability of feedback elements, and the properties of engineering materials are critical factors in achieving the essential state of mechanical stability. When mechanical stability is lost, failure is usually imminent either control-wise or structure-wise.

Mechanical failure is any change in the control function, material properties, the size and/or shape of a structure, machine, or machine system that threatens the machine operation or that renders the machine incapable of successfully performing its intended function. Factors that must be emphasized are those that reveal potential areas of machine weakness with respect to loading, design, material selection, manufacturing, system utilization, and machine maintenance.

The cause of mechanical failure is that the imposed service load stresses are greater than the material strength. Two generic types of mechanical loading exists--static and dynamic. A static load exhibits no motion or change, that is it is a dead load. A dynamic load is a force exerted by a moving body on a resisting member, usually in a relatively short period of time and involves inertia, momentum, mass, acceleration, velocity, damping, and displacement. When a fluid-type mechanical system loses its mechanical stability, the structural performance of a component is in the process of failing or it has already experienced failure. In general, such loss of performance can be traced to the following modes of failure: ductile or brittle fracture, buckling, creep or fatigue. The actual failure may be the synergistic result of several independent actions or modes; for example, one mechanism may create stress raisers while another mechanism may actually cause the initiation and propagation of a crack and subsequent fracture.

One of the key factors in mechanical stability concerns the mean strength of the material and the mean load imposed. In fact, the safety factor is the ratio of mean strength to mean load. As shown in Fig. 20, both the load and strength are actually stress distributions. It is the overlap of strength and load distributions that define the failure zone of the system and this situation is often unwisely ignored.

Figure 20
Strength/Loading Distribution with
Failure Stress Zone



The Proactive Approach

Proactive maintenance is not an activity that reacts to material and/or performance type failure conditions of a system. Rather, it has been developed to prevent such system degradation from occurring in the first place. In reality, proactive maintenance is a preemptive first strike against failure--a true failure-avoidance activity.

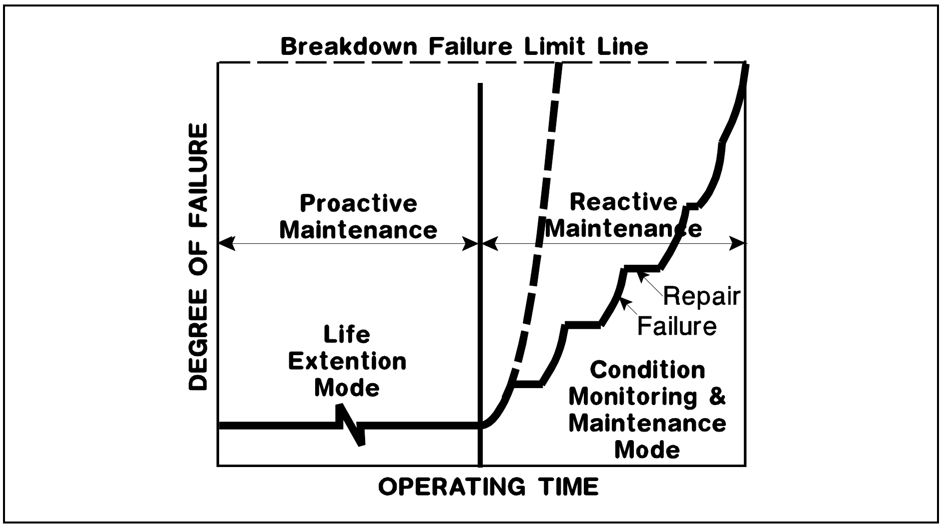
Preventive maintenance focuses on performance degradation-type monitoring to obtain operational symptoms. Predictive maintenance relies on material degradation-type monitoring techniques to obtain latent, early-stage failure symptoms. Proactive maintenance on the other hand monitors the machine system health (the operating condition of the various root causes of failure) to detect aberrant or abnormal conditions that could eventually produce material and performance degradation. Note that proactive maintenance does not react to a failure condition; it ascertains whether a root-cause abnormality or symptom exists and then focuses action on the correction of the aberrant condition.

For proactive maintenance to be effective, it must gather and analyze equipment condition data from all sources. For example, it should utilize information gained in preventive maintenance, such as inspection of the fluid, any internal and external leakage assessment of the system components, and PQT (pressure/flow/temperature) data from selected circuitry. It should also take advantage of the monitoring that has been conducted for predictive maintenance; for example: wear debris, noise level, vibration, rotational speeds of pumps and motors, and heat sources in the system. Obviously there is some overlap that exists between proactive root-cause parameters and those associated with predictive and preventive maintenance.

In proactive maintenance, root-cause aberrations produce symptoms that must be monitored to alert maintenance personnel that corrective action is required. If root-cause aberrations are not identified and corrected, some effect or result inevitably occurs that is irreversible (that is, material degradation takes place that ultimately leads to performance deterioration and breakdown).

From the moment a machine is placed in service, a natural progression of component degradation and failure occurs. As Fig. 21 shows, proactive maintenance reflects a life extension mode capable of extending the service life of the machine almost indefinitely because it addresses both the detection and correction of root-cause aberrations. Although such aberrations are machine life threatening, they may not at any given moment have reached the point where they cause sufficient material damage that would lead to immediate performance degradation and machine breakdown.

Figure 21
Proactive vs.
Reactive Maintenance



The rewards that can be gained from implementing a proactive maintenance program are substantial. Once such a program is in operation, the time and expense of reacting to conventional maintenance problems (removing, repairing, rebuilding, and/or replacing worn-out components and equipment) becomes almost insignificant. By applying proactive maintenance, maintenance budgets can be cut because fewer maintenance people are needed, machine downtime is reduced because the correction of root-cause aberrations do not normally require the shutdown of machines, and finally the parts inventory can be substantially reduced because worn-out parts and failed components become an operational rarity.

Reference to Subject Matter

The material in this paper is an overview of the complexities of proactive maintenance for mechanical systems. Because of space limitations, the details of the subject cannot be treated in depth. These details are included in Dr. Fitch's latest book entitled Proactive Maintenance for Mechanical Systems, published October 1992 by Elsevier Science Publishers, Ltd., 256 Banbury Road, OXFORD OX2 7DH, England and used as the text in his seminars on Proactive Maintenance.

These public seminars are presented frequently in the United States by FES, Inc., 5111 N. Perkins Rd, Stillwater, OK 74075, and in Europe by ELSEVIER SEMINARS, 256 Banbury Road, Oxford, England. Private, in-house seminars are also offered by FES, Inc.