FES/BarDyne Technology Transfer Publication

#12

Maintenance Strategy for Hydraulic Service Reliability

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Abstract

Maintenance theory and practices are part of an engineering discipline known as Machine System Etiology. It encompasses such factors as maintenance strategies that are needed for identifying the cause and origin of abnormal conditions, which occur in machine systems, and involves techniques for correcting root-cause aberrations. The cost of performing reactive maintenance (sometimes called "breakdown maintenance) is becoming absolutely prohibitive in terms of machine downtime, avoiding an extensive parts inventory, having access to skilled maintenance personnel, and constantly performing substantial repair. Fortunately, an attractive new strategy has now become available known as proactive maintenance, which can identify potential problem areas long before machine functionality is affected.

This position paper addresses the subject of proactive maintenance and a new strategy for implementing the subject in actual machine systems. It not only defines the terms that are used but also shows the relationship of various terms to one another. The maintenance strategies presented in this paper represent the latest advancements in the field of etiology. Effective strategies are introduced for predicting failures and preventing hydraulic system downtime. These strategies have already resulted in maintenance personnel gaining an important new foothold in hydraulic system maintenance as well as a valuable new perspective of proactive maintenance fundamentals.

Introduction

Advancements in hydraulic power have been a veritable force behind many of the improvements that have occurred in both stationary and mobile equipment. The characteristics of this newly found force have historically resulted in an ever-increasing use of higher power and better-control techniques for machine systems. Today, there is hardly any production machinery, which exists that has not taken full advantage of hydraulically powered components and systems.

Hydraulic equipment permits the articulation of many different types of machine elements. When included in drive trains, hydraulic power greatly reduces the number of clutches, gear boxes, drive shafts and pivot points that are usually needed. In recent years, hydraulic systems have almost completely replaced mechanical drives and linkages for control purposes and auxiliary power functions on all but the smallest machines and continue to even replace many of these for primary power functions.

If sufficient flow and pressure are available, hydraulic power and control systems required for operating functions provide almost instantaneous response even when it comes to reversing the direction and speed of motion of nearly every operation whether it be turning a drum, hoisting a line or tilting a bucket. One of the most important contribution that hydraulics has made to equipment design has been its ability to increase the power and productivity of equipment without increasing its overall size or its degree of complexity. Of course, these contributions have not been achieved without seeing a corresponding increase in system pressure and temperature and component failure.

The Notion of Failure

The term ***failure*** is by definition, the state of dysfunctionality or the inability of a system to perform its normal functions at the necessary level of activity. The factors that dictate what life expectancy can be attained by hydraulic components and systems are dependent on the following:

1. Specific design margins of specified for system components.
2. The duty cycle and the severity associated with its required performance.
3. The ferocity of the service environment.
4. The randomness of the material properties used in the component construction.
5. The "chance aspects" of machine breakdown, which are addressed in the subject of quality control.
6. Finally the degree of maintenance and the regularity which specific machines receive throughout their lifetime.

It is now a foregone conclusion that if three critical risk factors (e.g., contamination, thermal energy, and fluid stability) could be effectively controlled, then the life expectancy of a hydraulic system would be a deterministic aspect and would no longer be classified as a random event.

Mechanical failure is recognized as the inability of a system to withstand at least one of three types of failure modes—structural, wear, and/or motion impediment Structural failures occur when a system loses its mechanical stability—that is, the system experiences either a fracture or material distortion. Wear occurs when surface contact exists between adjacent moving surfaces or when entrained particles in the fluid impinge on critical control surfaces. Motion impediment type failures produce some form of lock or port blockage that impedes the movement of adjacent surfaces past one another or the flow of system fluid. Components in mechanical systems that are generally subject to mechanical failure

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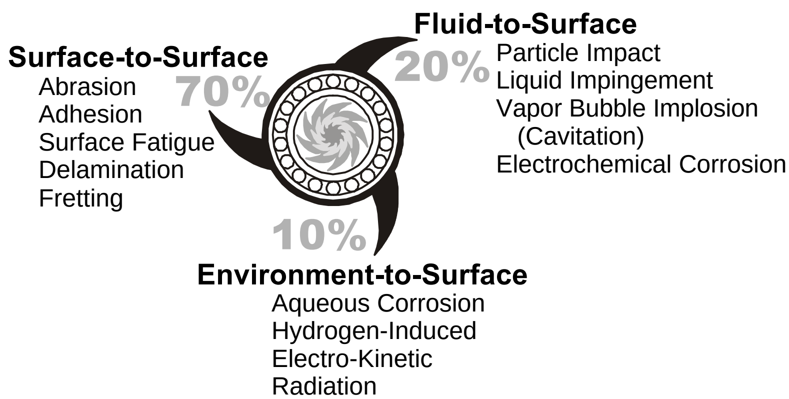
include all load-bearing elements (shafts, gears, springs, fasteners, linkages, and hydraulic cylinders). Hence, the only way to avoid experiencing mechanical failures is to make sure that the values of the actual stresses in the system never exceed the material's strength—that is, avoid over-loading, over-speeding, over-pressurizing, excessive contamination and heat, etc.

Wear type failures are mechanical impairments that occur due to surface degradation by some form of active wearing process. Wear modes are classified as being surface-to-surface wear, fluid-to-surface wear, and/or environment-to-surface wear. These wear modes are illustrated in Fig. 1.

Figure 1
Wear Modes in
Hydraulic Systems



The frequency in which various wear modes occur in practice depends upon the type of equipment, the environment and the duty cycle severity. A table giving the relative frequencies of the various wear modes is presented below:

Abrasion (including contamination)	22 – 60%
Surface Fatigue (including cavitation)	8 – 20%
Adhesion	7 – 15%
Corrosion	5 – 13%
Fretting	5 – 13%
Erosion	4 – 8%

A technologist who is able to recognize and analyze the wear degradation of critical surfaces, possesses the ability to detect failure long before it becomes evident to the operator who is limited to the evidence of performance degradation in a machine. Since wear is a material degradation process, monitoring the rate that wear is occurring provides a rigorous basis for predicting the system service life far earlier than what a performance degradation based system failure technique can provide.

Motion impediment type failures are basically reversible type failures; whereas, structural and wear type failures are irreversible. There are two basic types of motion impediments found in hydraulic systems—surface-to-surface lockup and/or seizure and flow passage blockage (clogging and/or plugging). Clogging being the build-up of particles or debris across a flow passage while plugging results from the simultaneous arrival of particles at the flow entrance, which impedes the flow of fluid.

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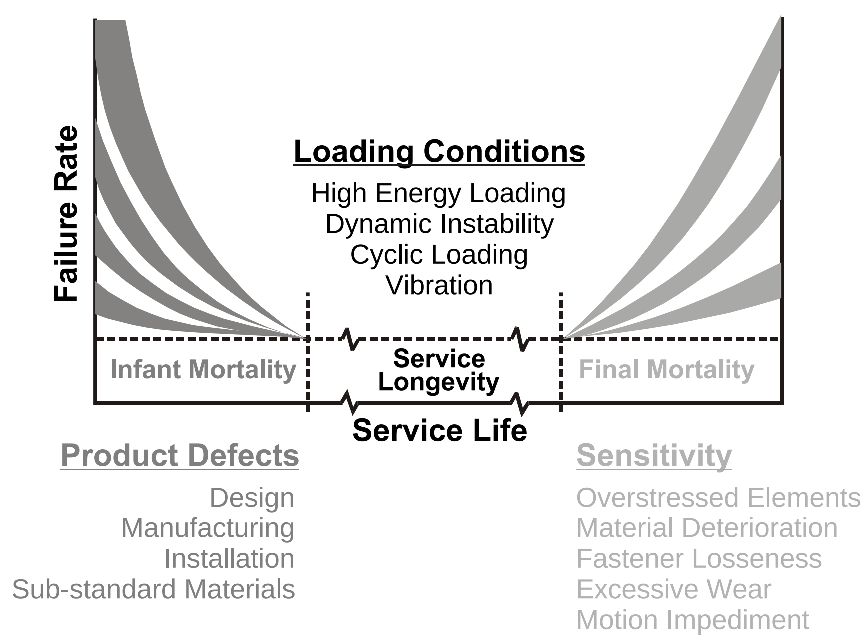
It must be recognized that the underlying cause of mechanical system failures is due to unstable operating states associated with the system and which can eventually be detected by one of the following precursory failure conditions:

- Uncontrolled—static or dynamic instability of the system
- Over-stressed—ruptured, fractured, fatigued, or distorted elements
- Deteriorated—corroded, dissolved, disintegrated or decomposed materials.
- Degraded—worn, oxidized, irradiated, evaporated, precipitated, and/or hydrolyzed component materials.
- Obstructed—plugged, clogged, jammed, silt locked, seized, loosened, extruded, or obliterated
- Operational severity—high vibration magnitude, shock loading, steep thermal gradients or thermal shock conditions, unexpectedly high energy levels, or a critical sensitivity to loading conditions.
- Damaged—mishandled, abused, misused, or severe duty cycle imposed.
- Exposure to ferocious environmental service conditions.

Three distinct failure rate periods occur during the working life of components and systems – infant mortality period, normal service longevity period, and final wear-out or mortality period. Figure 2 attempts to identify some of the factors that contribute to the failures occurring in the three failure rate periods.

Figure 2
Failure Rate Factors



The Onset of Failure

The onset of failure usually becomes evident through our senses and such symptomatic conditions are known in etiology as precursory failures. If no intervention occurs at this level of failure, the failure progresses to what is known

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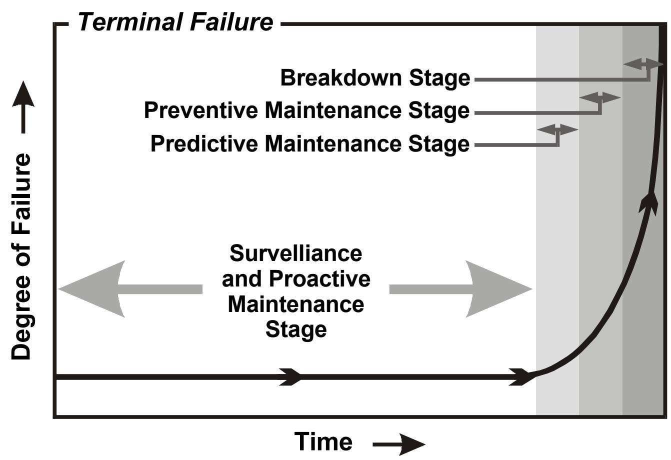
as the root-cause failure stage, in which failure aberrations are actually in their developmental stage. With still no external intervention, the failure of a component or system continues to progress to higher and higher severity levels of failure as illustrated in Fig. 3. For example, root-cause aberrations have the tendency to progress to the incipient failure stage. It is at this stage where material damage actually starts occurring unless the aberrant root-cause conditions are corrected an/or eliminated.

Figure 3
Progression Towards
Terminal Failure



Following the incipient failure stage, a stage called impending failure eventually takes place, as expressed in Fig. 4. This stage is manifested by the degradation of system performance and prompted by the continued loss of critical surface material. Due to the damage that occurs, this is the stage where failure becomes totally irreversible.

If the damaged elements or components are not repaired or replaced and the root-cause of failure eliminated, normal operation continues to produce greater and greater amounts of damage until the level reaches the precipitous failure stage. At this stage functional impairment is on the verge of occurring or it has already taken place and terminal failure and/or the debilitating state where the component, system or machine becomes completely dysfunctional or inoperable ultimately follows. These failure stages are shown in Fig. 4 as a progression of failures along with the effect that each failure stage has on the system as a whole, the maintenance that is needed, and the specific maintenance action that is required. Note that the failure stages are listed in the order of their progression from precursory to terminal failure.

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Figure 4
The Onset and Progression
of Failure in Hydraulic Systems

System Condition	Type of Failure	Stage	Type of Maintenance	Maintenance Action
Symptomatic State Exists	Precursory	1	Surveillance	Verify and Correct Failure Precursor
Root-Cause Aberration Exists	Root-Cause	2	Proactive	Identify and Correct Root - Cause Aberration
Material Degradation Had Occurred	Incipient	3	Predictive	Assess Material Damage
Performance Deterioration is Evident	Impending	4	Preventive	Perform Troubleshooting and Replace Damanged Components
Operational Impairment Exists	Precipitous	5	Breakdown	Schedule Overhaul
Dysfunctional and Sudden Collapse	Terminal	6	Salvage	Remove, Repair, Restore, or Replace Machine

FAILURE

Failure Stages from Beginning to End

Precursory—a symptomatic condition which becomes evident through our senses and is an outward sign that a change of internal state or operating condition is taking place. This level of failure provides sensory evidence that a potential root cause aberration is about to occur which could eventually lead to higher levels of failure until terminal failure ultimately occurs and the component, system or machine becomes completely dysfunctional or inoperable.

Root-Cause—a failure condition indicating that a root cause aberration or abnormality exists, and where no degradation in material or performance has yet occurred; however, without intervention, root-cause aberrations will inevitably progress to more severe types of failures in the system.

Incipient—a condition wherein the first signs of material degradation become apparent through non-intrusive means of detection and where the operator has still not perceived any change in machine performance.

Impending—a condition in which serious deterioration in performance is beginning to occur and where such deterioration begins to be evident to the operator.

Precipitous—is the intense, unrestrained, and accelerated attack on mechanical elements that ultimately culminates in operational impairment, unabated wear-out, and in the degradation of both material surfaces and functional performance.

Terminal—a condition of total dysfunction of the system as evidenced by a complete cessation of actuator mobility, system operation and the total impairment of machine functions. This stage of failure is generally the result of tribological changes at load bearing surfaces, the reduction of stressing areas in critical

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component elements, and/or the deterioration of material properties. Terminal failure itself is manifested by the actual catastrophic collapse of system motility.

Figure 4 presents the progression of failures and. also shows the effect that each failure stage has on the system as a whole, the type of maintenance that is called for, and the specific maintenance action needed.

Reference Machine State

In order to establish the proper maintenance needed by a machine, a sensible understanding is required as to what the designer considered as acceptable magnitudes for the operating parameters of his system during the machine work cycle—that is, what was the design reference state of his hydraulic system. Unfortunately, it is often difficult if not impossible for the user to gain access to such design information and therefore, it is usually necessary to apply an indirect approach for securing the necessary information about a machine system—this critical knowledge is known as the Reference Machine State. This reference state if properly obtained, can serve as an effective substitute for the often-sketchy Design Reference State, which the designer generally fails to complete, formalize, preserve, and release to his customers.

The importance of the Reference Machine State is that it is capable of providing a reliable base line for each of the critical operational parameters. The magnitudes of these system parameters should in general, correspond to the actual values exhibited by the system parameters immediately after the machine has been broken-in and has operated acceptably under realistic work and environmental conditions. Possessing such base-line state conditions for each of the critical operating parameters of the system provides a vital reference to compare all parameter values in the future and for making decisions based almost solely on the changes between the current parameter measurements and on their base-line values.

From the foregoing presentation, the Reference Machine State of a machine system can be used to establish the acceptable range of parameter variations that is acceptable to occur in the course of time and service. It provides a basis for establishing the critical influence of specific parameters on the performance of a system. The identity of the reference state parameters, which can substitute for the elusive design parameters are presented in Table 1.

Each parameter cited in Table I is critical to the operation and service life of the system and the Reference State of these parameters should be carefully established. By knowing the reference and the current states of these parameters of a hydraulic system, the amount of deviation can be established which will reveal the degree of material and performance degradation that the machine has suffered. It also provides the necessary information in a deterministic form to establish the rate of performance deterioration and the residual life of both the components and the system. Thus to make a valid assessment of the condition of a hydraulic system, pertinent information relevant to the critical reference state parameters must be obtained and recorded. Such information is essential to the technologist in selecting the appropriate tests to conduct on the hydraulic system and for interpreting the results of the tests to relate the specific machine hydraulics.

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Table 1
Reference State Parameters

System Performance Parameters	Wear Severity Parameters
1. Power regulation characteristics • System pressure • System flow rate	1. Abrasion wear (contaminant wear)
2. System thermal stability • System fluid temperature • Heat dissipation characteristics	2. Surface fatigue wear
3. Fluid distribution characteristics • Actuator forces • Actuator movements • Cylinder rod creep or drift	3. Adhesion wear
4. Prime mover/pump shaft speed • Compatibility with pump filling characteristics	4. Corrosion wear
5. Fluid cavitation • Cold start-up • Wrong viscosity oil • Pump suction restricted	5. Fretting wear
6. Fluid leakage—internal and external • Reservoir oil reference level • Rod creep or drift • Rod severely abraded • Piston bore severely abraded	6. Erosion wear
7. Fluid properties • Color and odor • Viscosity • Oxidation stability • Fluid entrained wear metal spectrum • Fluid chemical absorbency IR spectrum	**Fluid Contamination Parameters**
8. Component noise levels	1. Abrasion wear (contaminant wear)
9. Line pressure perturbation and shock level	2. Surface fatigue wear
	3. Adhesion wear
	4. Corrosion wear
	5. Fretting wear
	6. Erosion wear
	Fluid Contamination Parameters
	1. Injected contaminant
	2. Ingested contaminant • Air breather ingestion • Wiper seal ingression • Reservoir filler cap left off
	3. Filtration performance rating
	4. System contamination level
	5. Component contaminant sensitivity
	6. Contaminant service life
	7. Water contamination

Role of Maintenance

Maintenance is any activity performed to avoid, detect, forestall, correct or counteract failure in order to maintain a plant's or machine's functional integrity and its physical facilities in an optimum or acceptable working order. Unfortunately, the entire field of maintenance and its management remain a relatively primitive art and is far from being a modern science.

In the early days of industrial power and motion control and particularly throughout much of the 20th Century, maintenance has been synonymous with the word "repair"—an activity involving various amounts of craft, skill, brute-force, and common sense. Users have a tendency to "maintain" machines only when something breaks and needs to be fixed (i.e., they basically choose to practice a *run-to-failure* type maintenance activity). They must realize that a run-to-failure type maintenance strategy is completely outmoded and needs to be updated. This can be achieved by revitalizing the activity; that is, transforming it into a modern "proactive maintenance program." Users already know that an examination of the failed parts provides much of the evidence and information needed to establish what failed and possibly what was the failure mode. But seldom, if ever, does such an examination reveal the real culprit that caused the failure to occur in the first place—the" *root-cause*."

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Thus, operators have often been forced to subscribe to a corrective maintenance policy that is usually an unscheduled emergency type activity. Such an activity is often performed on a "crash-crisis" basis, which can best be described as a repair or replacement type maintenance activity—often referred to as breakdown maintenance. Such a maintenance strategy is a reaction to the "effects" of mechanical distress and performance impairment rather than to proactions that can be actively pursued to eliminate the root-causes of failure.

With technology advancing at today's incredible pace, machines and plants are becoming increasingly more automated and operators are tending to focus considerably more attention on maintenance management which includes problem identification and solving. In fact, the "Just-in-Time" delivery philosophy being practiced in many industries, often places great emphasis on the availability and reliability of production machinery. As a result, any maintenance strategy that gives more latitude in scheduling repairs has been of great value to most modern organizations.

There is no question today that operators have gained a much greater insight and appreciation for the subject of maintenance than they had in the past. To be fair, their new interest has paralleled the development and availability of diagnostic and monitoring instruments that have contributed significantly to many important advances in maintenance technology. Maintenance attitudes have changed as more and more companies began to realize that maintenance is truly the single largest "controllable" cost factor still available to them. As a result, reliability and maintenance investigators have advanced many new and improved strategies that deserve to be studied, reviewed, and considered.

In general, there are two diverse types of maintenance action that can be applied to keep machinery operating—one is based on a proactive maintenance policy while the other is based on passivity or a "wait until it quits" policy. Proaction gives a preemptive first strike against failure and provides a strong measure of control that is necessary for increasing both the reliability and longevity of a system. The wait and see approach to conventional reactive maintenance offers no leniency (that is, it is not a user-friendly method) since it has been traditionally practiced simply as a reaction to performance impairment and equipment breakdown. Hence, the new "user friendly" maintenance strategy is "proaction not reaction" and this approach has gained a foothold under the name of proactive maintenance.

The root-causes of failure stem from unstable system conditions such as identified in Fig. 5. In the case of a wearing type failure activity, there is a time period that elapses between the start of an unstable system condition and the point where wear debris is actually generated and/or when performance degradation occurs. During this time period, proactive maintenance must be performed in order to identify the root-cause condition and avoid functional failures as reflected in Fig. 6. Any unstable system failure condition that requires proactive maintenance is known as a root-cause failure.

A review of the root-causes of mechanical fluid system failures should reveal the seriousness of the precursors to system failure and the identification of root cause aberrations. From this point on, incipient failure progresses from the moment that material degradation commences to the time when impending failure begins. When impending failure finally occurs, a sufficient quantity of wear debris has been sloughed from the critical surfaces of components to initiate the deterioration of both component and system performance.

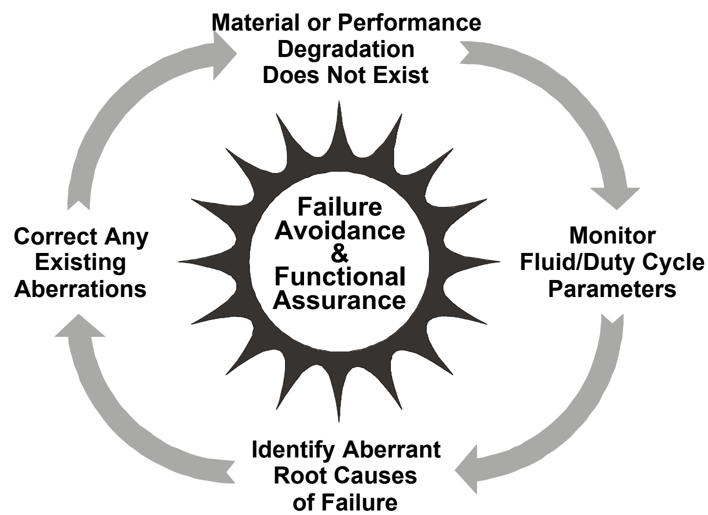
Figure 5
Critical Stability Factors in Maintenance

Unstable System Conditions

"The Roots of Failure"

- Excessive Fluid Contamination
- High Fluid Leakage
- Fluid Chemical Instability
- Fluid Physical Instability
- Fluid Cavitation
- Fluid Temperature Instability
- Severe Wear Conditions
- Material Distortion/Alignment

Figure 6
Proactive Maintenance Activities



When impending failure becomes truly evident through performance degradation, then machinery personnel must administer preventive type maintenance, an activity in which they identify and verify degraded operating conditions in both material and performance. This type maintenance is accomplished through inspections and trouble-shooting and the condition is corrected by servicing and overhauls. The goal being to correct the degraded component conditions by the 4-R treatment (removing, repairing, rebuilding, and/or replacing the affected elements) in order to extend the life of the overall system. It should be realized that this preventive type maintenance rarely corrects the root-cause aberrations that caused the impending failure in the first place. Hence, sequential field failures may reoccur until the root cause has been identified and corrected.

Once component and system failures are allowed to continue past the impending failure stage, precipitous failure ultimately occurs where an accelerated wear-out deterioration of the component's internal parts and performance takes place—finally reaching a serious functional impairment stage. At this point in the component's life, the 4-R treatment is the only solution. Thus, at this final stage in

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the service life of components and systems, terminal failure exists. Here, the only course of action is to restore or replace the component, system or machine this action is often called a salvage maintenance type activity.

Reference

1. Fitch, E. C., and I. T. Hong. *Maintenance Strategies for Hydraulic Service Reliability*. Stillwater, Oklahoma: BarDyne, Inc., pending publication.