

# Systems and Methods for Real-Time Condition Monitoring of Mechanical Machinery

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## ABSTRACT:

Catastrophic machinery failure in most cases can be avoided if the early symptoms are detected and appropriate action is taken. This is the essence of new condition monitoring technology which, if well conceived, can extend machine and component lives by as much as an order of magnitude. This paper discusses current condition monitoring methods including available sensor technology. Applications and rationale are also discussed.

THE USERS OF MECHANICAL MACHINERY -- either mobile or stationary -- are increasingly demanding safe and reliable performance from their equipment over an acceptable and predictable period of time. A properly cared for and maintained piece of equipment from a reputable manufacturer will usually achieve this end. However, today's modern machinery has become so complex and sophisticated that mechanics and technicians are often unable to efficiently carry out requisite preventive and reactive maintenance.

The use of on-line diagnostic instrumentation has been increasingly cited as a means to augment the efficient use of maintenance personnel and to reduce production losses due to downtime. This instrumentation can detect anomalous machine performance and many will direct corrective action before significant harm

is done to critical components. Such early-warning devices are not only employed to avoid catastrophic failure but they also can be an effective control against the high day-to-day cost of maintaining mechanical systems.

Further, in the case where catastrophic failure has occurred, the application of well-conceived diagnostic monitors can be effective in identifying the root cause of failure, allowing early return to operation. It has been estimated that when a hydraulic system fails, approximately 60 percent of the downtime is used to diagnose the problem while only 40 percent is used to repair or correct the problem. Also, many preventive maintenance procedures call for the time-based blind replacement of system components, regardless of their condition. To circumvent superfluous replacement costs, some diagnostic instrumentation include the ability to measure component degradation rates and estimate residual component lives.

The advent of new sensor and computer technology has more than ever made machine-health monitoring a viable and cost-effective choice among large users. It is the objective of this paper to apprise the readers of new and ongoing research in diagnostic monitoring and to identify certain methods and techniques now available. Special emphasis is placed on hydraulic contamination control and the use of real-time contaminant monitoring.

## MOTIVATION

In many cases the economic justification for the use of on-line diagnostic monitoring instrumentation on mechanical machinery is substantial. Often the avoidance of unscheduled downtime

serves as adequate justification for many users. Downtime due to catastrophic failure is sudden and abrupt with little or no warning. These types of failures can dismember a crucial process from a large assembly line or completely shutdown large materials handling equipment. Degradation failures, on the other hand, are gradual occurrences and can be more easily identified and measured by maintenance personnel.

The integrity and reliability of a machine can be significantly enhanced when the residual life of operating components can be assessed. Instruments designed to monitor fluid contaminant levels and tribological wear can often estimate residual life. This is important information to a preventive maintenance program directed towards identifying optimal component replacement points. Additionally, this ability sets the stage for "on condition" machine maintenance as opposed to the scheduled and breakdown maintenance approaches used today (See Figure 1).

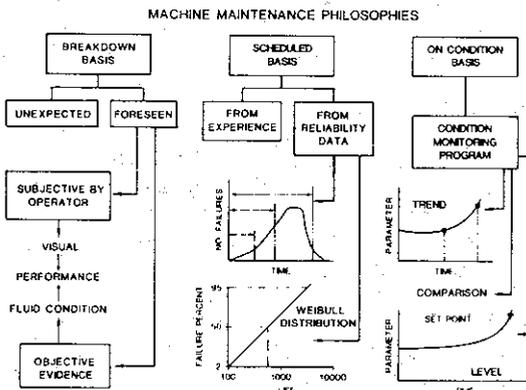


FIGURE 1

Incipient failure occurs when the conditions are right for failure (e.g., loss lube system pressure, heavily contaminated oils, etc.) but no actual degradation has occurred (figure 2). An uncorrected incipient failure condition will develop into impending failure. Here substantial degradation is already occurring and if left uncorrected, precipitous failure (rapid degradation), and finally catastrophic failure is imminent (see figure 3). Equipment operators and maintenance technicians must be alerted to both incipient and impending failure conditions if downtime and harm to other components are to be avoided. Further, a more comprehensive understanding of the root causes of failure, as illustrated in figure 4 can often preclude the need for equipment maintenance and service.

INCIPIENT FAILURE DETECTION

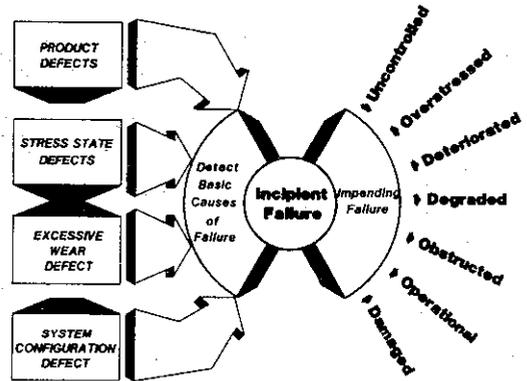


FIGURE 2

Clearly, by monitoring the health of a machine, the normal operating life can often be extended many fold. Advanced diagnostic instruments can tell technicians when to replace rings, seals, bearings, lubricants, and filters. Replacing critical parts and components before harm is done (incipient failure) will revitalize the system to its original state of health. In the case of hydraulic or lubrication systems, oils can become heavily contaminated or lose their lubricity before problems are identified and component replacements are carried out. The wear process in mechanical machinery is complex and occurs on several fronts (see figure 5).

The economic justification for on-line diagnostic monitoring should be predicated on a number of factors. The extent and importance of each depends on the machinery and instrumentation used. If system diagnostic monitoring is used, many of the following benefits might be achieved:

- \*\* Reduced downtime and unscheduled maintenance
- \*\* Avoidance of redundant and premature part replacement
- \*\* Continuous and comprehensive analysis of complex equipment

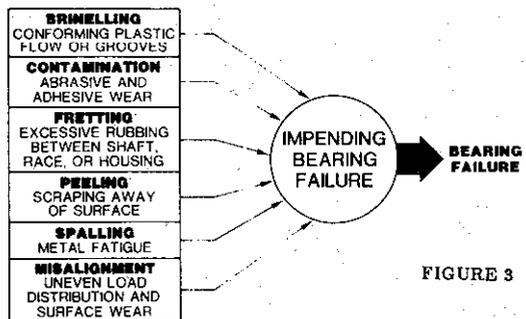


FIGURE 3

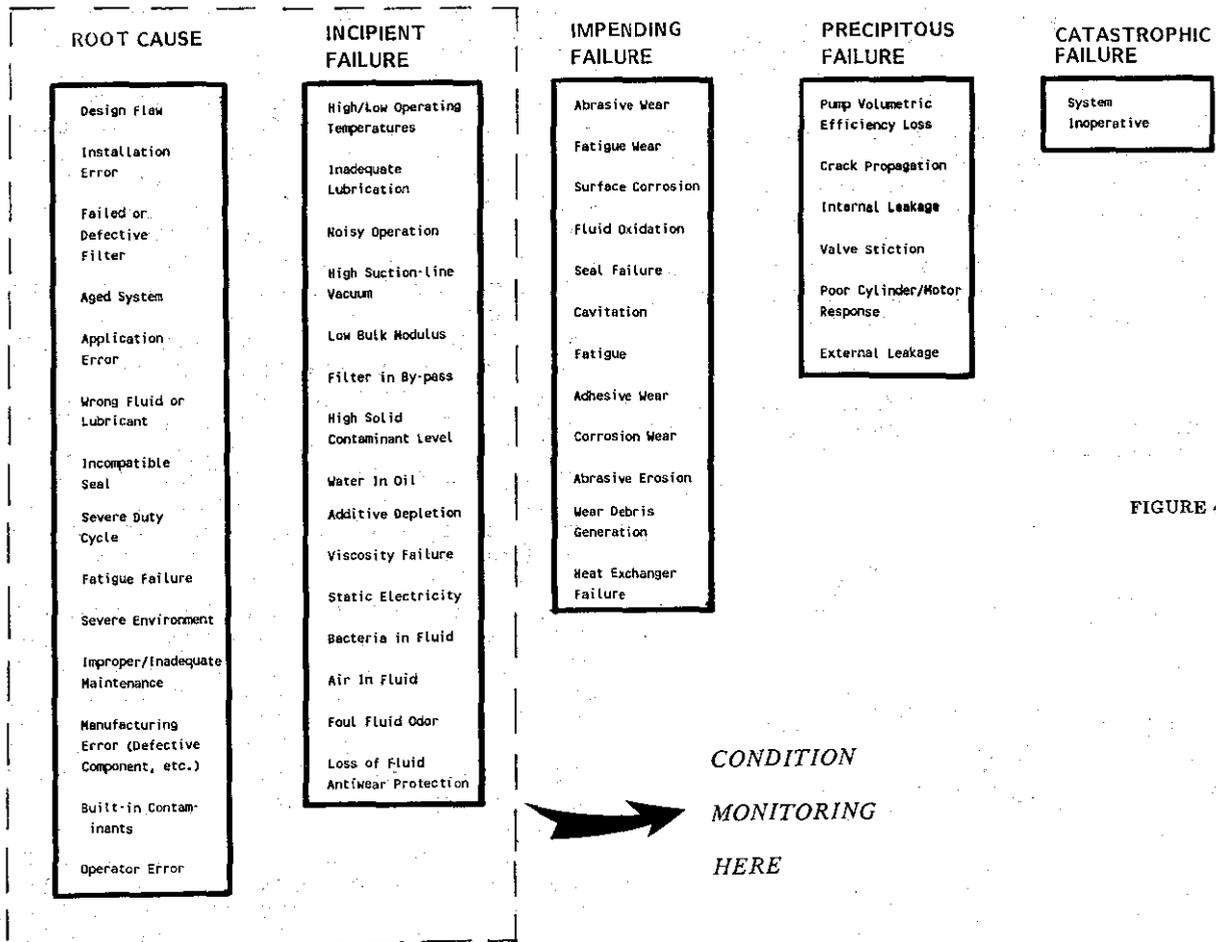


FIGURE 4

- \*\* Residual machine and component life estimation
- \*\* Extended machine life
- \*\* Increased safety and reliability
- \*\* Increased energy efficiencies
- \*\* Identification of improper operating conditions and part assembly

#### KEY INTERNAL-STATE PARAMETERS

The key internal-state parameters of a system are the carriers of the recognizable symptoms of an ailing component (figure 6). By monitoring the internal-state parameters, these symptoms can be monitored and their status communicated to the intellect of a diagnostic instrument. As in human medicine, machine failure diagnosis is accomplished by communicating and interpreting such parameters into meaningful assessments of condition and health. The cause-and-effect relationships must be thoroughly studied and documented such that failure diagnosis can be carried out and implemented.

New microcomputer technology has made it possible to process real-time data from multiple sources simultaneously

to achieve system diagnostics and prognostics. Computer software can contain the algorithms and subroutines that compare a system's current conditions against that of a known healthy system. Some instruments also contain the rationale to diagnose causality and suggest preventive or remedial action.

Depending on the mechanical system of interest, the key internal-state parameters could include from one to as many as ten operating variables. The following is a list of the most common parameters and the symptoms they may reveal:

Temperature. lubricity loss, material deterioration, misalignment, aeration, overload.

Pressure/Force. fatigue, mechanical/volumetric efficiency, cycle variance, duty cycle change.

Vibration. gear teeth pairing, bearing wear, fatigue, velocity change, displacement variance, cycle variance.

Proximity. Bearing wear, bear/rotor imbalance, cylinder wear, displacement variance.

Contamination. abrasion, corrosion, wear debris, sludge, erosion, adhesion, lubricity loss, material incompatibility.

Lubricity. oxidation, water ingress, air ingress, microbial growth, fluid shear down, excessive operating temperatures, sludge, magnetism, radiation.

Sound. cavitation, valve wear, gear mesh variance, bearing wear cycle variance, fatigue, combustion efficiency loss, aeration.

Flow Rate. Volumetric efficiency loss, displacement change, cylinder/vane/gear/wear, contamination, internal leakage.

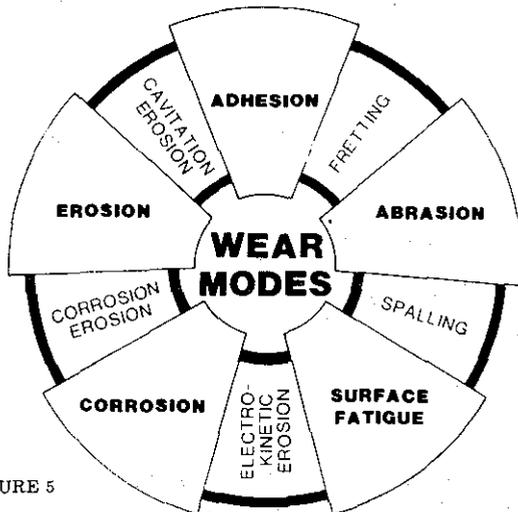


FIGURE 5

#### MACHINE-HEALTH MONITORING METHODS, PRIOR ART

Diagnostic monitoring must begin with some form of detection or sensing device. Often a simple light or indicator attached to a sensor is an adequate diagnostic instrument, leaving inferences and follow up decisions to the technician. Temperature and pressure transducers are the most simple forms of sensors and can often identify abnormal and unhealthy conditions. Although these sensors do not diagnose causality or suggest remedial action, they are important diagnostic tools that can pay for themselves many times over.

Using pattern recognition, vibration analysis techniques can effectively identify impending and incipient failure conditions. A number of manufacturers offer vibration sensing instruments including some with built-in computer diagnostic rationale. The algorithms employed can measure and interpret frequency and amplitude modulation of

gear systems and other rotating or cyclic machinery. The vibration signature of a machine can usually be best picked up at bearing caps using accelerometers and then transmitted to the monitor for signal conditioning and processing.

In their simplest form, vibration monitoring can provide a go/no-go indication of vibration severity. More advanced models provide frequency spectrum or signature analysis which can be used to identify the component that is failing. Even more sophisticated monitors can process vibration signals in detail to reveal the type and source of the defect within the component. Vibration monitors are known to be effective at identifying the misalignment of many types of rotating machinery caused by foundation settling, base deterioration, and bearing wear, among other things. On heavy turbo machinery for instance, vibration orbits ten to "blossom" just prior to sudden catastrophic failure. In vibration monitoring, the machine can be shut down in the impending failure phase, avoiding costly and sudden failure. According to J. Zatezato president of IMS, Inc., poor alignment is responsible for fifty percent of all machinery failures.

Using statistical analog monitors, the duty cycle severity of a hydraulic system can be monitored on a real-time basis. These in-line units receive data such as pressure, temperature, and flow from sensors and transducers attached at different points in the system. These data are simultaneously processed by the built-in microprocessor to identify and record duty cycle severity levels. Duty cycle can be used as a measure of fatigue taking place in components, hoses, and fittings. Statistical monitoring can also identify improper system operation as well as drop offs in mechanical and volumetric efficiency. In a different form, these devices can effectively serve as data loggers to capture and store duty cycle data for interrogation and analysis later. Although this form of monitoring is not "real-time", it can serve as a valuable diagnostic tool.

Further, it is not uncommon to find components which have a long history of successful operation but degrade and fail rapidly in a different application or environment. This continues to be a vexing problem in the mobile equipment industry where jobs and applications can change day to day. Failure prediction can often be accomplished when statistical monitoring of key parameters is employed as a diagnostic tool. The rationale that identifies the impending failure condition must be programmed into a computerbased instrument. Several of these products are now on the market.

## PARAMETER SENSOR SELECTION

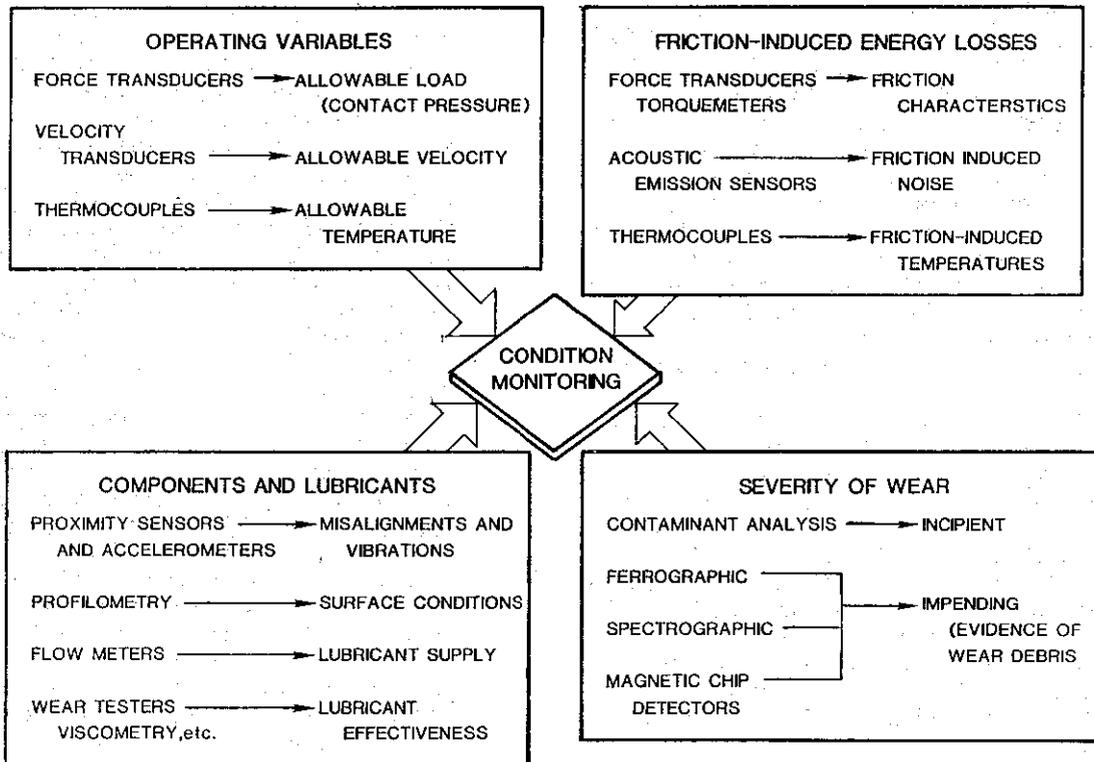


FIGURE 6

Cyclic machinery present excellent potential for early-warning failure detection using sound monitoring. Examples of machinery and installations which have been monitored by the analysis of their air-borne sounds include the following:

- \*\* High precision gear trains.
- \*\* Diesel engine structures.
- \*\* Jet engine malfunctions.
- \*\* Machinery in submarines.
- \*\* Cavitation in pumps.
- \*\* Wear in hydraulic valves.

One approach to sound monitoring involves the application of trend analysis. Here the actual sound is compared and measured against any range of sounds that may be produced under normal operating conditions. When a part or component experiences accelerated wear or goes through some other physical change, the character of the acoustic signal is altered. By monitoring these characteristics on a continuous basis, it is possible to detect changes in mechanical condition and to pinpoint the individual component which is deteriorating. Sound monitoring has increasingly received broader use and acceptance in machine-health diagnostics.

Proximity monitors can be used to identify anomalous axial and rotary movements of mechanical systems such as rotor assemblies. These noncontact displacement transducers can be mounted on

suitable surfaces to a rotor to transmit signals which then can be converted into readily interpreted data. These data can indicate radial or axial movements of the rotor relative to the stator assembly, providing early warnings to bearing deteriorations and rotor imbalance. In many cases, thrust bearing failures occur almost instantaneously, allowing only seconds from the first indication of trouble. Therefore, if axial position monitors are employed to protect the equipment, they must be capable of activating the shutdown system.

### REAL-TIME CONTAMINANT MONITORING

The cost of wear to the U.S. economy has been estimated to exceed one percent of our Gross National Product. The essence of much of this wear can be sourced to either a lubricant failure or the presence of contamination. One study conducted by the U.S. Navy puts the cost of contaminant related wear on marine and aviation equipment at approximately 60 percent of the cost of fuel.

In the past, contamination control was accomplished, albeit sometimes with only nominal success, by using more and more filters of greater and greater efficiency. However, filters, being the man-made objects that they are, subject the system to their inadequacies of de-

sign and manufacture, often causing catastrophic consequences. The point is, regardless of how well a system is filtered, contaminant levels for many independently occurring reasons, will frequently exceed acceptable limits. Unlike other feedback and control systems existing on modern day machinery, when it comes to contamination there are no checks-and-balances. With this in mind, the need for real-time contaminant monitoring onboard machinery has become of critical importance (figure 7). Without proper surveillance equipment to monitor the contaminant level in the system's fluid, only breakdown and failure can signal and halt life-deteriorating conditions.

There are many distinct benefits for using real-time contaminant monitoring. First of all, the presence of abnormal amounts of solids in a lubricant or hydraulic fluid signals an incipient failure condition. Meaning, if left unattended, rapid abrasive and fatigue wear will occur and impending failure is imminent. A contaminant monitor will alert operators and maintenance personnel to the presence of anomalous contaminant levels at the time the condition occurs. This allows action to be taken either immediately or scheduled at the earliest possible point.

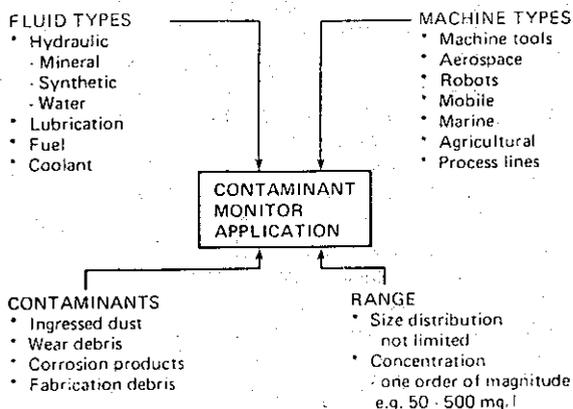


FIGURE 7

Currently, no field-ready real-time contaminant monitor is available for commercial use. Clearly, this void has been due to the extraordinary difficulty in developing economical, accurate, and reliable devices. The author is aware of numerous unsuccessful efforts in this field by many organizations. At this time, however, an introduction of a practical monitor does appear near a hand.

There are several possible configurations for an inline monitor. These configurations are:

- Go/No-Go Alarm.** In this configuration, before installation, the user sets the contaminant level threshold on the device. Then once installed, whenever the contaminant level in the fluid exceeds the preset threshold, an alarm goes off. This alerts the user to take corrective action immediately. Once done, the unit is reset.
- Automatic Inline Particle Counter.** This device works similar to laboratory type particle counters. Light attenuation is employed as the sensing means. Although they can be installed directly on the equipment, their reliability is limited due to the many field conditions that regularly distort readings. They are also very high priced and generally not durable enough for mobile equipment applications.
- Direct Read-Out Contaminant Monitor.** Several configurations of this device are possible although none are yet commercially available. The basic design uses an in-line sensor installed in the live zone of the hydraulic or lube oil system. It is capable of reading the approximate contaminant level on a continuous real-time basis. The read-out would be in the form of a digital or an analog indicator. The device could also transmit data to an on-board microcomputer for storage and trend analysis. Although not a particle counter per se, a reliable indication of contaminant level is achieved.
- Wear Debris Monitor.** These instruments and alarms are now being used by the aviation industry for engine and turbine oil analysis. Since they can only measure wear debris levels in oils, their application is limited to impending failure conditions, i.e., situations where rapid wear is already taking place.

#### REAL-TIME CONDITION MONITORING

The concept of condition monitoring employs and integrates sensor and condition detection methods into a single microcomputer/software package. Multiple information inputs are received by a centralized computer such that these data, and their interrelationships, can be continuously processed to enable preventive maintenance to be scheduled and carried out with maximum economy and machine up-time. By definition, there are four recognized modes and objectives of real-time condition monitoring (see also figure 8):

1. Detection of abnormality by

- change in parameter trend.
2. Fault recognition by diagnostic analysis.
3. Degree of failure and component residual life, by failure analysis and prognostic rationale.
4. Direction for preventive and remedial action and degree of urgency.

Condition monitoring is accomplished by selecting suitable parameters, or data inputs, to reflect the the symptoms of failure or the states of health. The application of real-time or "on-condition" monitoring, as opposed to time-interval monitoring, offers a number of distinct advantages:

1. Confidence in extending equipment operating and maintenance times beyond normal intervals.
2. Early detection of failure condition such that remedial action can preclude component degradation and catastrophic failure.
3. Detection of dynamic changes and alterations in system performance and health.

These advantages can be easily translated to terms of substantial reductions of maintenance cost, equipment downtime, loss of productivity, safety, and equipment readiness. Machine candidates offering the best cost-benefit for condition monitoring are presented in figure 9.

For effective diagnostics to take place, condition monitoring must consider

the critical parameters (both external & internal) in appraising and establishing a system's continued operational viability. These parameters, or conditions, require sensors, transducers, and other detection devices to obtain and transmit their readings to the microprocessor. For a fluid-power system, the required parameters might include linear and angular displacement, velocity, force/acceleration, temperature, particle levels, lubricity, and time.

Condition monitoring requires the ability to process information, including the reporting of inferences derived, as data are received. Although microcomputers make this possible technically, the diagnostic rationale and reference data base must be programmed from extensive laboratory and field experience which have shown distinct and repeatable cause-and-effect relationships. In many mechanical disciplines this body of research and experimentation has already taken place, but few have integrated, synthesized and packaged this vast knowledge into a single diagnostic tool.

To date, the aviation industry has set the greatest precedent in condition monitoring, motivated mostly by safety concerns as opposed to direct cost-benefit considerations. More primitive engine diagnostic systems are finding their way into the automobile industry; none of which have been employed for continuous on-line operation.

## CONDITION MONITORING BLOCK DIAGRAM

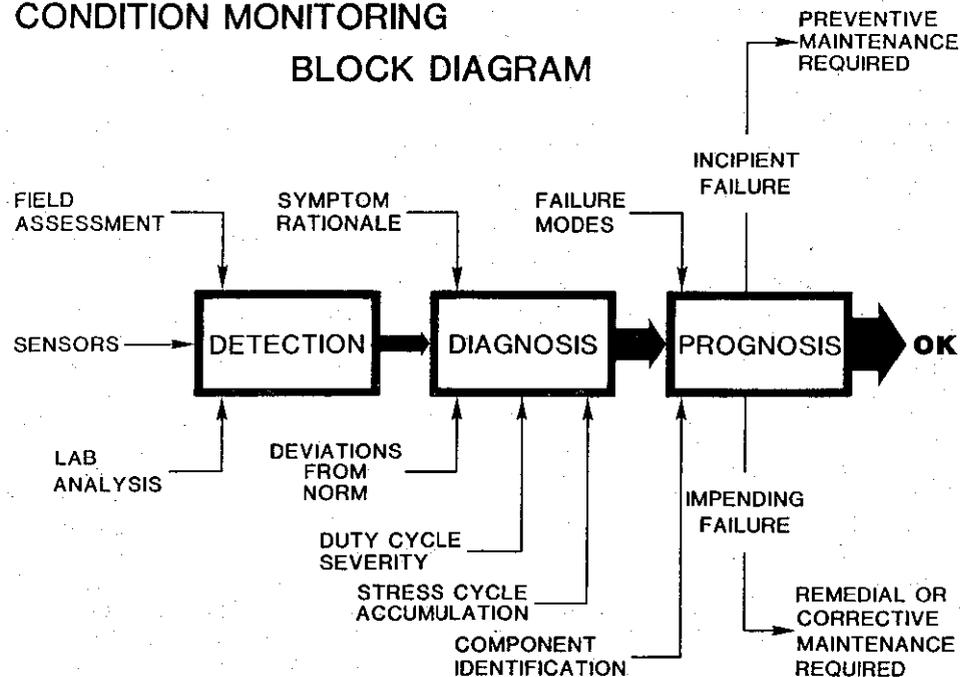


FIGURE 8

## MACHINE CANDIDATES FOR CONDITION MONITORING

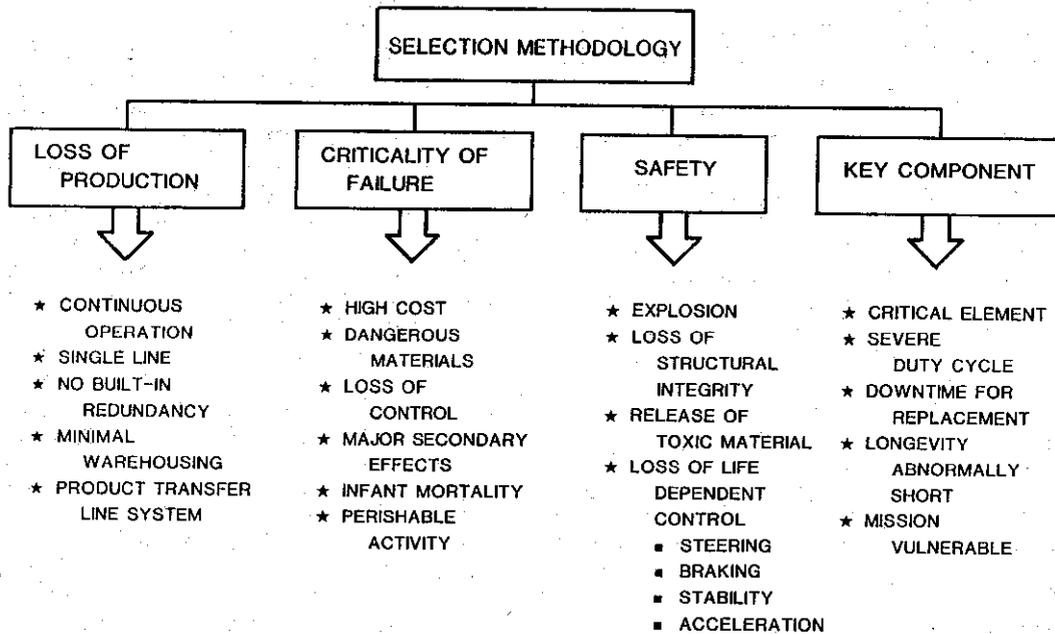


FIGURE 9

## APPLICATION RECOGNITION AND ASSESSMENT

Not all mechanical systems are ideal candidates for machine health monitoring. Each potential application must be judged against the direct and indirect economic incentives as well as all safety considerations. Although the issue of safety can be more easily assessed and prioritized, the cost/benefits of diagnostic instrumentation are much harder to quantify and must be viewed in terms of both long-term and short-term rewards.

The most ideal machine health monitoring applications are best extrapolated from the fundamental motivations that would apply (figure 9). A survey conducted by the author has shown that where safety is involved, such as in commercial aircraft, fault detection instrumentation becomes readily justifiable (although passing weight, size, and FAA requirements is often difficult). Taking the safety factor out of the decision criteria, most users place the avoidance of unscheduled downtime at the top of the list. These two are followed by lower maintenance costs (parts & labor) and extended machine lives.

The ideal application of diagnostic instrumentation, using the above criteria, might be described as a machine that is both expensive and sophisticated, provides a crucial and depended upon work function, has extensive maintenance requirements, and presents a safety risk upon failure. Obviously, few mechanical

system can be described with all of the above terms, but many meet one or more.

## SUMMARY &amp; CONCLUSIONS

It should be stated that machine health monitoring is best viewed in light of the proven capabilities of the instrument to provide useful and meaningful information. Such instrumentation should not present maintenance problems themselves and should by all means be adaptable to the machine environment and operating conditions.

The economic justification of machine monitoring equipment might best be viewed much like one views an insurance policy. When up time is considered crucial, failure prediction and prevention must also be crucial. We are only now entering into an age when such insurance policies are being accepted as pragmatic long-term alternatives that provide true and achievable investment returns.

Still there is much room for new research to advance the state of this field of technology. As the reliability of diagnostic instrumentation is no greater than the theory upon which it is based, much of this new research will need to be directed towards better understanding the underlying cause-and-effect relationships. Additionally, the use of diagnostic rationale depends on the ability to detect and sense the appropriate parameters reflecting the key symptoms. Therefore, new and ongoing sensor

research will need to be carried forth as well.

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